BUREAU OF RECLAMATION

Executive Summary

Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

U.S. Department of the Interior November 2021

Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Executive Summary

Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

prepared by

Natural Resources Consulting Engineers, Inc.
Jacobs Engineering Group Inc.

Cover Photo: United States Bureau of Reclamation

Contents

List of Tables

List of Figures

Project Definition and Background

Following on the Colorado River Basin Supply and Demand Study (Basin Study)[1] and the Moving Forward[2] efforts, the U.S. Bureau of Reclamation's (USBR) WaterSMART (Sustain and Manage America's Resources for Tomorrow) Program selected and provided funding for this Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin Pilot Study (Pilot Study), which was financially matched by three non-Federal partners to explore methods of quantifying agricultural water savings through the knowledge shared by participants and an evaluation of existing case studies. Through a voluntary and collaborative process, the general objectives of the Pilot Study were to:

- Identify and describe methods currently in use to quantify agricultural water conservation.
- Evaluate those methods for consistency and accuracy with Reclamation's Lower Colorado River water accounting methods.
- Evaluate existing case studies using a combination of research and applied science.
- Recommend approaches to improve methods of quantifying agricultural water conservation in the Lower Colorado River Basin (LCRB).

The project team acknowledges the assistance and information provided by many individuals and organizations during this Pilot Study.

Review of Literature and Recent Conservation Activities

A review of the technical literature and of recent conservation activities was undertaken to identify consumptive use (CU) quantification methods. The literature reviewed included documentation of specific CU quantification methods, application of such methods, and comparisons between methods. Some of the literature reviewed focused on certain conservation activities rather than CU quantification. As part of the literature review, an annotated bibliography was prepared documenting over 150 references that were reviewed in greater detail.

Quantification Methods

The reviewed literature covered several CU quantification methods, or method classes. Ultimately, the reviewed CU quantification methods were summarized in the following categories, focused largely on ET quantification methods:

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[1] 2012. *Colorado River Basin Water Supply and Demand Study. U.S. Bureau of Reclamation.* U.S. Department of the Interior Bureau of Reclamation. Available at: https://www.usbr.gov/lc/region/programs/crbstudy.html

[2] U.S. Bureau of Reclamation (Reclamation). 2015. *Colorado River Basin Stakeholders Moving Forward to Address Challenges Identified in the Colorado River Basin Water Supply and Demand Study: Phase 1 Report.* U.S. Bureau of Reclamation. Available at: https://www.usbr.gov/lc/region/programs/crbstudy/MovingForward/index.html

- Water balances
  - Soil water balances and field-level water balances
  - Project-level water balances
  - Delivery and other flow measurements
- Micrometeorology
  - Eddy covariance
  - Bowen ratio energy balance
  - Surface renewal energy balance
  - Scintillometry
- Lysimetry
- Reference evapotranspiration/crop coefficient modeling and spatial crop surveys
- Remote sensing evapotranspiration modeling
  - Reflectance-/Vegetation Index-based methods
  - Energy balance models/thermal methods
- Other (micro-lysimeters, sap flow, etc.)
- Combined methods

Conservation Activities

The literature review was focused primarily on the following four conservation methods:

- Deficit irrigation
- On-farm irrigation system conversion
- Seasonal fallowing
- Crop rotations/alternative cropping

Other conservation methods that were considered include (but are not limited to):

- District/distribution system conveyance system improvements
- On-farm conveyance system improvements
- Advanced irrigation scheduling

Case Study Selection

A framework was developed to assist the identification of case study opportunities and final case study site selection with the following considerations:

- Geographical diversity within the LCRB
- Diversity of agricultural conservation activities
- Diversity of water savings quantification methods

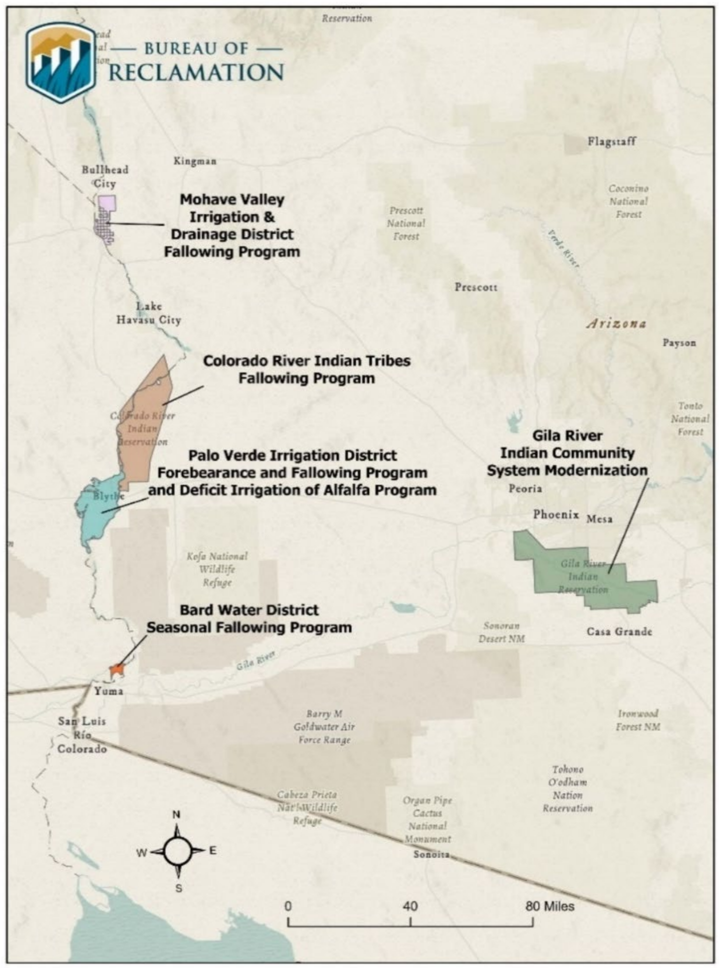
Nine candidate case study projects were identified throughout the LCRB. The final six case studies were selected from among the available choices to represent a variety of conservation activities, quantification methods, and project locations (*Figure 1*).

- Gila River Indian Community (GRIC) Irrigation System Modernization
- Bard Water District (Bard) Seasonal Fallowing Program
- Palo Verde Irrigation District (PVID) Forbearance and Fallowing Program
- PVID Moderate Deficit Irrigation Program
- Colorado River Indian Tribes (CRIT) Fallowing Program
- Mohave Valley Irrigation and Drainage District (MVIDD) Fallowing Program

The case studies were evaluated with the goal of gaining knowledge on CU quantification methods and approaches. The case study evaluation process included:

- In-person field visits
- Interviews with case study participants
- Review of documentation relating to the conservation project(s) and quantification methods
- Identification of the relationship of the conservation activity and quantification method to Reclamation's Colorado River Decree Accounting, where applicable
- Identification of challenges and lessons learned
- Consideration of the accuracy of methods used in the project
- Consideration of costs and complexity of program implementation
- Assessment of opportunities for improvement of the quantification method(s)

Figure 1 Map of the Project Locations of the Six Case Studies



Summary of Case Studies

A full analysis for each case study was completed. A brief description of each of the case studies is provided below and summarized in *Table 1*.

Table 1 Summary of Case Study Conservation Measures and Consumptive Use Quantification Methods

Potential Case Study	Location		Conservation Activity			Quantification Method			Comparison Method[1]		Time Period	
	On-/Off Mainstream	State	Deficit Irrigation	Fallowing	Efficiency Improvements	Water Balance	Micrometeorology	Reference ET	In Time	In Space	Single Year	Multi-Year Mean
GRIC System Modernization[2]	Off-Mainstream	AZ			•	•			•			•
Bard Water District Seasonal Fallowing Program[3]	On-Mainstream	CA		•		•				•		•
PVID Forbearance and Fallowing Program[3]	On-Mainstream	CA		•		•				•	•	•
PVID Moderate Deficit Irrigation Program[4]	On-Mainstream	CA	•			•	•	•		•		•
CRIT Fallowing Program[5]	On-Mainstream	AZ		•		•		•	•			•
MVIDD Fallowing Program[6]	On-Mainstream	AZ		•		•		•	•			•

[1]Method used to identify the change in consumptive use relative to conditions without the conservation method. The methods either compare the same area "in time" or effectively compare areas of conservation with areas not under conservation ("in space").
[2]Comparison on per-acre basis.
[3]Based on Decree Accounting Reports.
[4]Developing empirical relationship between irrigation deficit and yield.
[5]Specifically accounted for non-ideal growing conditions.
[6]Used remote sensing-based crop surveys.

Gila River Indian Community System Modernization

GRIC is located just south of Phoenix in Central Arizona. GRIC has been undertaking an extensive rehabilitation, rebuild, and expansion of existing irrigation infrastructure on and/or serving the Gila River Indian Reservation. This effort is referred to as the Pima-Maricopa Irrigation Project (P-MIP). The P-MIP irrigation water delivery and distribution system is planned to serve up to 146,300 acres of land on the Reservation and includes the rehabilitation and reconstruction of existing irrigation infrastructure within BIA's San Carlos Irrigation Project (SCIP) service area and other areas on the Reservation. Project construction began in 1998 and will continue through 2030. The project includes rehabilitation, modernization, and construction of canals, pipelines, turnouts, and measurement and control structures. The overall efforts by GRIC also include consolidation of operation and maintenance of the P-MIP system by the formation of an operating entity the Gila River Indian Irrigation and Drainage District (GRIIDD). The CU quantification for these improvements was based on diversion measurements, represented by supply measurements at the Reservation boundary. Other flow measurements and farm deliveries were also used.

Bard Water District Seasonal Fallowing Program

Bard is located in southeastern California. For the present study, Bard will refer specifically to the Bard Unit of the Yuma Project Reservation Division. The Bard seasonal fallowing program has been going, in different forms, since 2016. The present program is funded by the Metropolitan Water District of Southern California (MWD). Under the agreement with MWD, participating growers do not grow or harvest crops or irrigate fields from fallowed land from April 1 through July 31. Thus, this program is a seasonal (partial year) fallowing program, enabling growers to grow crops during the rest of the year in contrast with other fallowing programs analyzed in this study. Conserved water is made available to MWD for diversion or storage in Lake Mead for future use. CU is quantified using a district-wide water balance based on the Decree Accounting reports. The reduction in CU is assumed to be equal to the CU for the Bard Unit divided by the area irrigated during fallowing multiplied by the fallowed area. CU is quantified for an average of multiple years, including the year of conservation.

Palo Verde Irrigation District Forbearance and Fallowing Program

PVID is located in southeastern California. PVID serves over 131,000 acres of land, most of which is in the Colorado River floodplain, but roughly 27,000 acres are on the Palo Verde Mesa. In 2004, MWD entered into a 35-year agreement with PVID and landowners within PVID's service area wherein MWD pays for valley land to be fallowed. Annual payments to farmers vary in response to actual acreage fallowed. The forborne water is then made available for use by MWD on a direct acre-foot for acre-foot basis. Maximum limits have been placed on the amount of land fallowed. The CU quantification is based on a district-wide water balance based on the Decree Accounting reports. The PVID quantification includes both historical inter-annual averages and conservation year CU, though, the conservation year is not included in a multi-year mean. The fallow field reduction in CU is computed using water-toll area (used for water assessment). As with other fallowing programs, it is important to note that the quantification method includes verification of the fallowed land.

Palo Verde Irrigation District Moderate Deficit Irrigation Program

In late 2018, a deficit irrigation experiment in PVID's service area was initiated by researchers with the University of California (UC) Division of Agriculture and Natural Resources, UC Davis, and the U.S. Department of Agriculture Agricultural Research Service. The purpose of the study is to measure the impacts of "moderate" deficit irrigation during the summer on applied irrigation water, CU, yield, yield quality, soil salinity, and alfalfa plant stand[3]. The deficit irrigation strategy in the study is to eliminate one to three irrigation events during the summer (July – September). The study is being conducted in two border irrigated fields and two furrow irrigated fields. Each field included a section (or multiple sections) irrigated per the grower's convention and two deficit irrigation treatments. To quantify CU, the research team used farm turnout records for applied irrigation water

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[3] Montazar, A., O. Bachie, D. Corwin, and D. Putnam. 2020. "Feasibility of Moderate Deficit Irrigation as a Water Conservation Tool." Agronomy. 10(11): 1640. https://doi.org/10.3390/agronomy10111640

and micrometeorological methods for ET. The micrometeorological methods were eddy covariance and surface renewal.

Colorado River Indian Tribes Fallowing Program

The Colorado River Indian Reservation is located on both sides of the Colorado River in western Arizona and eastern California, with most of the land in Arizona. The Reservation is home to the CRIT. Starting in 2016 and continuing to present, CRIT has participated in system conservation programs to create conserved water for storage in Lake Mead. Currently, CRIT's program is part of a three-year system conservation agreement with Reclamation, the Arizona Department of Water Resources, and Central Arizona Water Conservation District under the State of Arizona's Drought Contingency Plan. Conserved water in each case has consisted of CU reductions due to temporary fallowing of irrigated cropland on CRIT's Arizona lands. Field parcels being fallowed were required to have been in active irrigated crop production for at least four of the previous five years. The CU reduction was quantified using the reference ET/crop coefficient approach, which was adjusted based on regional remote sensing studies. A five-year average modeled crop ET for each fallowed field was used to estimate the CU reduction. A diversion reduction was estimated by applying a system-wide irrigation efficiency.

Mohave Valley Irrigation and Drainage District Fallowing Program

MVIDD is in western Arizona. MVIDD's irrigation water is from wells in the Colorado River alluvial aquifer. In 2020, MVIDD began a fallowing program for system conservation. For this program, an enrollment process was created whereby participating farmers voluntarily enter into an agreement with MVIDD to fallow land that had been verified as actively cultivated in three or more of the five most recent years. The CU reduction was quantified using the reference ET/crop coefficient approach paired with remote-sensing-based crop surveys. A five-year mean modeled crop ET for each fallowed field was used to estimate the CU reduction. A diversion reduction was estimated by using the district's per-acre diversion cap.

Synopsis and Recommendations

A summary decision tree was developed to condense the results and observations from the case studies into a single summary (*Figure 2*). While this simplified summarization is not comprehensive, it is helpful as an illustration of the very challenges that led to this Pilot Study effort. When viewing, or seeking to apply the decision tree, it is important to review the associated commentary in TM4.

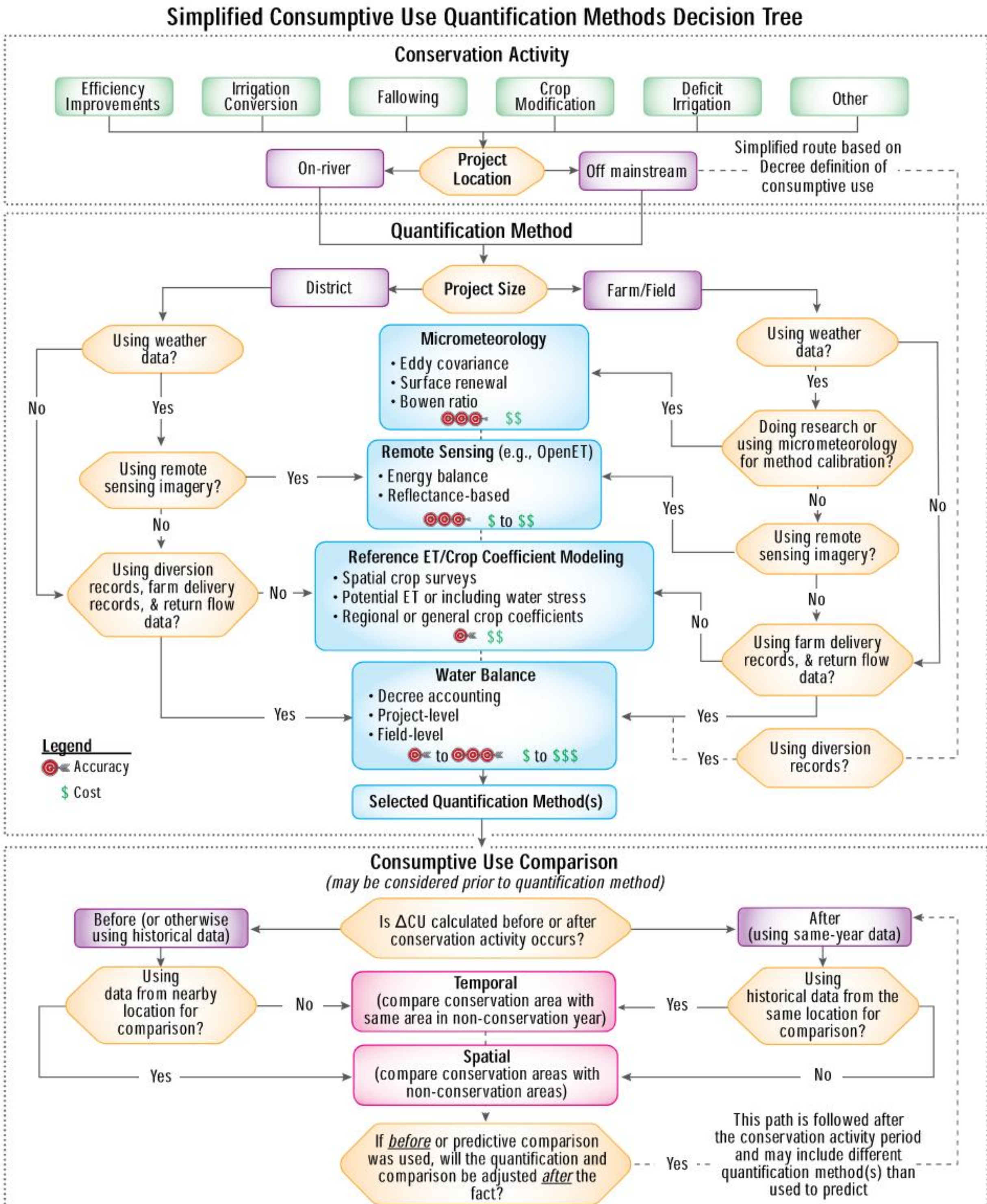
One thing not fully captured in the decision tree is the full set of assumptions associated with each quantification method, which are discussed at length in TM4. Such assumptions are very situation-dependent, as demonstrated in the case study discussions. The tradeoffs between different assumptions can be observed by reviewing the different quantification methods selected in each case study project. Associated with the various method assumptions, there is often a tradeoff between cost and accuracy. The assumptions are also specific to site and conservation method. Data availability can also limit the available CU methods.

In addition to accuracy, assumptions, and cost, it is important to consider the similarity of the areas or times being used in CU comparisons and the amount of time used in making comparisons. Increasing availability of remote sensing ET products and the use of statistical analyses were presented as options to address some of these challenges.

Decisions regarding CU quantification methods should be agreed upon collectively by all parties involved in a conservation program. Such processes should be transparent and should allow for adaptation and improvements as resources, technologies, etc. become available or the state of the science advances. When agreeing upon a set of quantification and comparison methods, it is important to acknowledge that CU methods should be reviewed and changed as necessary.

Each of the studied cases have employed CU quantification methods that are in some way different than those applied by the others. None of the quantification methods would be applicable in all cases and therefore, no "best" option is identified herein as multiple methods, or combinations may be equally valid, and cost and other non-technical factors must be considered. However, certain principles can be learned from each case. The importance of data collection, e.g., regarding crops grown and grower practices, flow measurements, and weather, to name a few, is evident for all of the cases. Each could also benefit from refinement. For all cases, the ever-improving CU quantification methods, technology, and data products should be evaluated and incorporated in a continuous process. No CU quantification methodology should be considered final or closed to improvement particularly as conditions (e.g., climate, infrastructure, political, management, cropping, irrigation methods), quantification and measurement technologies, and other information change.

Figure 2 Simplified Decision Tree for Selection of Consumptive Use Quantification Methods



Notes:

This is a simplified representation based on the case study analyses, it is not a comprehensive guide for selecting quantification or comparison methods, though it may be helpful in identifying general technical considerations for method selection.

The logic steps are not absolute (e.g., micrometeorology is not strictly limited to field-scale research). In some instances, using multiple quantification or comparison methods may be more appropriate than just using one.

The effect of a comparison method is dependent upon similarity between the compared conditions (e.g., applying a comparison method for areas or time periods affected by water shortage).

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Acknowledgements

The project team acknowledges the assistance and information, including contributions to this memorandum, provided by the following listed individuals during the case study evaluation phase, stakeholder reviewers of the manuscript, and others who may have inadvertently not been acknowledged herein:

Gila River Indian Community (GRIC)

- David DeJong, Pima-Maricopa Irrigation Project (P-MIP) Director
- Christopher Blackwater, Bureau of Indian Affairs (BIA)
- Kyle Varvel, BIA
- Bill Eden, P-MIP Senior Civil Engineer
- Mark Moore, Gila River Indian Irrigation and Drainage District (GRIIDD)
- Delbert Johnson, GRIIDD

Bard Water District (Bard)

- Nick Bahr, Bard General Manager
- Bill Scott, Board Director
- Jerry Nakasawa, Board Vice President
- Meghan Scott, Bard Legal Counsel

Palo Verde Irrigation District (PVID)

- Ned Hyduke, General Manager
- JR Echard, Operations Manager
- Jack Seiler, Board President
- Ryan Seiler, Grower
- Grant Chaffin, Grower
- Kim Bishoff, District Controller
- Paula Hayden, PVID Fallow Coordinator
- Ali Montazar, University of California

Colorado River Indian Tribes (CRIT)

- Amelia Flores, Chairwoman
- Tommy Drennan, Councilman
- J.D. Fisher, Councilman
- Anisa Patch, Councilwoman
- Devin Heaps, Water Resources Director
- Guillermo Garcia, Hydrologist
- Miguel Gonzales, CRIT Farms
- Rebecca Loudbear, CRIT Attorney General

Mohave Valley Irrigation and Drainage District (MVIDD)

- Kerri Hatz, MVIDD General Manager
- Charles (Chip) Sherrill, Chairman
- Vince Vasquez, Board Director
- Michael Pearce, MVIDD Legal Counsel
  Chris Stall, Land IQ, Consultant

Contents

BUREAU OF RECLAMATION

Technical Memorandum 1 – Project Definition and Summary of Workshop #1

Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

U.S. Department of the Interior

January 2021

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Technical Memorandum 1 – Project Definition and Summary of Workshop #1

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Cover Photo: United States Bureau of Reclamation

Contents

List of Tables

List of Figures

Project Definition

The Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin Pilot Study (Pilot Study) is a logical next step in the long-standing commitment of United States Bureau of Reclamation (Reclamation) and the Lower Colorado River Basin (LCRB, Lower Basin) stakeholders to ensure the resiliency, reliability, and sustainability of the Colorado River. The objective of this study is to work collaboratively with a diversity of stakeholders to explore the current methods used to quantify certain agricultural water conservation activities in the Lower Basin, including the relationship of those quantification methods to the Lower Basin consumptive use accounting, and to recommend approaches to improve agricultural water conservation quantification methods.

Background

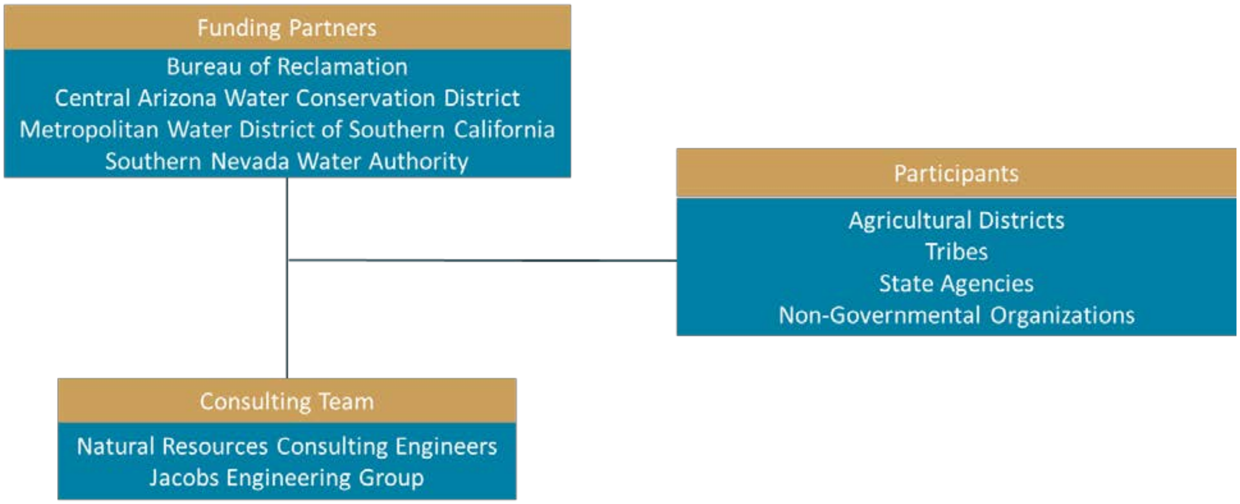
Since 2007, numerous efforts such as the Intentionally Created Surplus (ICS) Program and the Pilot System Conservation Program have been implemented, with the goal of bolstering the Colorado River System. In 2010, an unprecedented effort was started to define current and future (50-year) imbalances in water supply and demand in the Colorado River Basin and the adjacent areas of the Basin States that receive Colorado River water. In the Colorado River Basin Supply and Demand Study (Basin Study), strategies were identified to address the evolving supply-demand imbalance, including agricultural water conservation. In response to the findings of the Basin Study, Reclamation and the Basin States, in collaboration with the Ten Tribes Partnership and conservation organizations, initiated the Moving Forward effort in 2013 to build on future considerations and next steps identified in the Basin Study. Three multi-stakeholder workgroups were created to document past and projected future trends and explore the opportunities and challenges of various water management actions. The Agricultural Water Conservation, Productivity, and Transfers Workgroup identified accurate quantification of agricultural water conservation savings as a challenge warranting further exploration.

In 2019, Reclamation began pursuing funding for a new activity under the WaterSMART (Sustain and Manage America's Resources for Tomorrow) Program called Water Management Options Pilots. The goal of these pilots is to identify water management solutions to issues identified in recently completed efforts. In 2020, WaterSMART selected and provided funding for this Pilot Study, which was financially matched by the non-Federal partners to explore methods of quantifying agricultural water savings through knowledge shared by participants and an evaluation of existing case studies. Natural Resources Consulting Engineers, Inc. (NRCE) and Jacobs Engineering Group Inc. (Jacobs) were selected to assist Reclamation and the non-Federal partners in this effort. The funding window, and therefore the schedule for completion of this Pilot Study is the end of 2021.

Project Team Organization

The Pilot Study project coordination team consists of some key LCRB stakeholders but other participants, particularly from the agricultural districts and tribes, are key to the success of this project. The project team organization is presented in *Figure 1*.

Figure 1 Project Team Organization



Objectives

The specific objectives of this Pilot Study are as follows:

- Identify and describe methods currently in use to quantify agricultural water conservation.
- Evaluate those methods for consistency and accuracy with Reclamation's Lower Colorado River water accounting methods.
- Evaluate existing case studies using a combination of research and applied science.
- Recommend approaches to improve methods of quantifying agricultural water conservation in the LCRB.

While it is important to identify the objectives of this Pilot Study, it is also important to clarify what this study is not:

- It is not a policy study.
- Participation is not mandatory.
- It is not an attempt to change accounting practices.
- It is not a hypothetical analysis of potential future application or savings.
- It is not a water use/efficiency audit.

The results of this study will be used to:

- Document and share information and experiences to promote a common understanding.

- Identify best methods/practices for quantifying agricultural water savings to the extent possible. It is important to note that the intent of this study is not to impose a standard methodology for quantification; instead it is necessary to recognize that differing soil, drainage, irrigation methodology, crop, crop growing season, and other factors affect the application of agricultural water savings methodologies and quantification of the amount of water saved.

- Address the need for transparency between project partners and help answer potential questions about quantitative benefits.

Summary of Workshop #1

Workshop #1 was conducted virtually over the course of two half-day sessions on November 9 and 10, 2020. The purpose of this workshop was to review the 2012 Basin Study and the follow-on 2015 Moving Forward Effort to ensure that the Pilot Study builds on and does not duplicate the results of those two efforts. The proposed Pilot Study tasks, milestones, and schedule were reviewed and workshop participants were encouraged to help refine the scope of the Pilot Study. In addition, the project team described how consumptive use savings from conservation measures are administratively accounted for by Reclamation in the annually published *Colorado River Accounting and Water Use Report: Arizona, California and Nevada* required by the Decree of the Supreme Court of the United States in *Arizona v. California* 547 U.S. 150 (2006). Finally, the project team presented the Pilot Study case study concept and requested participants help frame the process.

The following sections summarize the shared information and discussions in the workshop. A copy of the presentation slides is included in the Appendix.

Participants

Over 50 people participated in Workshop #1. *Table 1* is a list of the workshop attendees. All attendees participated on both days unless otherwise indicated.

Table 1 Workshop 1 Participants

Funding Partners			
Reclamation Dan Bunk Jeremy Dodds John Shields Amber Cunningham Nancy DiDonato Pam Adams Chris Wallis (day 1 only) KayLee Nelson Nohemi Olbert	**CAWCD** Chuck Cullom Deanna Ikeya	**MWD** Aaron Mead Larry Lai Noosha Razavian Jessica Arm (day 1 only) Kira Alonzo Laura Lamdin	**SNWA** Seth Shanahan Casey Collins
Agricultural Districts/Cities			
IID Tina Shields Dylan Mohamed Ben Brock	**PVID** Andrew Slagan Bert Bell JR Echard	**MSIDD** Tony Solano Shelly Walker	**City of Yuma** Douglas Nicholls (day 1)
WMIID Ken Baughman	**Bard Water District** Nicholas Bahr	**Noble Law** Wade Noble Meghan Scott	
Tribal Representatives			
Bureau of Indian Affairs Jonathan Cody Johnita Whiteman (day 1) Denni Shields (day 1)	**Quechan Tribe** Frank Venegas Jay Weiner	**CRIT** Margaret Vick (day 1) Zach Stevens (day 2)	**Ak-Chin Indian Community** Tom Harbour
Navajo Nation Crystal Tulley-Cordova	**Cocopah Tribe** Michael Smith	**Fort McDowell Yavapai Nation** Gerry Walker (day 1)	
State Agencies			
ADWR Bret Esslin Vineetha Kartha	**Colorado River Board of California** Rich Juricich	**University of California Cooperative Extension** Ali Montazar (day 1)	
Consultants			
NRCE Tom Ley Ryan McBride Burdette Barker Miles Daly	**Jacobs** Lela Perkins Armin Munever Chris Kurtz Jason Smesrud		

Overview of Previous Planning Studies

Armin Munever, Global Technologist of Integrated Water Resource Management with Jacobs, provided an overview of related previous planning studies, focusing on the 2012 Basin Study and the subsequent 2015 Moving Forward Effort. Armin was the Project Manager and Technical Lead for both projects.

2012 Basin Study

The objectives of the 2012 Basin Study were to assess the current and future water supply and demand imbalances in the Colorado River Basin (see *Figure 2*) through 2060, and to develop and evaluate opportunities for resolving those imbalances. The study was conducted by Reclamation and the Basin States in collaboration with stakeholders throughout the Basin. As a planning study, it did not result in decisions, but provided a technical foundation for future activities.

Figure 2. Colorado River Basin Map

A unique scenario planning approach evaluating multiple potential water supply and demand trajectories was utilized in the study, and it was determined that imbalances are likely in the future due to both declining supplies and increasing demands.

A broad assessment of options to address long-term reliability was undertaken using multiple criteria evaluation and decision analysis to develop water management portfolios of strategies for long-term sustainable solutions. Potential agricultural activities identified to address the supply/demand imbalance included:

- Advanced irrigation scheduling
- Deficit irrigation
- On-farm irrigation system improvements
- Controlled environment agriculture
- Conveyance system efficiency improvements
- Fallowing of irrigated lands

The potential Colorado River water savings associated with these activities were estimated to be up to 1 million acre-feet (MAF)/year by 2060.

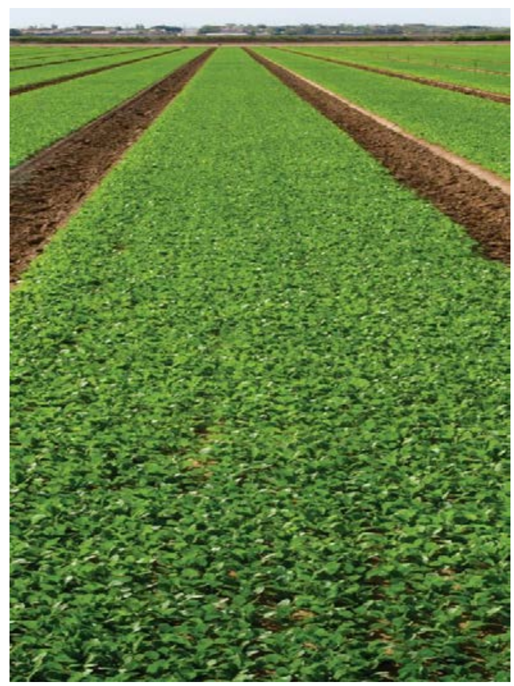
Key findings from the Basin Study that are valuable to consider for future planning include:

- Potential climate impacts, growing demand, and multiple competing resources will challenge the system in the future. The system is vulnerable under status-quo operations. Action greatly reduces that vulnerability and makes the system more resilient but does not eliminate vulnerability.

- A wide range of solutions are needed to mitigate and adapt to such shortfalls, which are likely to affect each sector (agricultural, municipal, energy, and environmental, for example) dependent on the Colorado River and its tributaries.

- In the near term, all portfolios considered in this study show that water conservation and reuse are cost-effective ways to reduce vulnerability. However, in the longer term (2040 to 2060), more tradeoffs emerge in terms of acceptable level of risk and the options to mitigate that risk.

2015 Moving Forward Effort



Phase 1 of the Moving Forward Effort was initiated in 2013 and funded by Reclamation and the Basin States to build on the technical foundation established by the Basin Study in addressing the challenges identified for the Basin. In the Moving Forward Effort, an even broader stakeholder framework was utilized. That framework included the formation of a Coordination Team and three multi-stakeholder workgroups that focused on: municipal and industrial water conservation and reuse; agricultural water conservation, productivity, and transfers; and environmental and recreational flows.

In the study, it was determined that no one sector can provide solutions for ensuring long-term sustainability. To respond to future challenges, diligent planning is required to find adaptable solutions that build resiliency and apply a wide variety of ideas at local, state, regional, and Basin-wide levels. Central to this process are partnerships and the recognition that future actions must be done collaboratively by relying on the inclusive stakeholder process conducted successfully in the Basin Study.

The Agricultural Water Conservation, Productivity, & Transfers Workgroup objectives were to:

- Quantify historical trends in agricultural conservation and transfers of Colorado River water (both inside and outside of the Basin).
- Document agricultural water conservation programs that have been successful to date. Fifteen case studies were examined as examples of ongoing or planned projects (eight of the case studies were located in the Lower Basin).
- Identify existing future plans for these types of activities and estimate what potential savings could come from these existing plans.

The workgroup documented the following findings:

- Types of water conservation measures and the extent of implementation vary extensively among producers and geographies depending on water supply portfolios, climate, crop mix, and available funding.

- Many agricultural conservation advances have been achieved as part of a variety of Federal, state, and local stakeholder programs working toward mutually beneficial solutions.

- Agricultural producers have implemented a wide range of conservation and efficiency measures and have often increased productivity as a result.

- Increases in "on-farm efficiency" result in more uniform application of water and may improve productivity, but may not result in consumptive use reduction, and the potential for water savings varies by location (e.g., in or out of the hydrologic basin).

- Opportunities exist for additional agricultural water conservation, transfers, and productivity enhancements, but may become more difficult and costly as they are implemented.

- Data gaps and reporting variations—including variations in the methods used to quantify agricultural water conservation savings—make analysis of agricultural water use difficult.

Pilot Study Scope, Schedule, and Milestones

Tom Ley, Senior Supervising Engineer with NRCE Inc., provided an overview of the proposed Pilot Study Scope, Schedule, and Milestones in order to inform the workshop participants and solicit feedback on any suggested refinements. The major scope items include:

- Review relevant previous/on-going efforts in order to avoid duplication.
- Conduct a literature review of agricultural water conservation activities.
- Focus on activities in the LCRB with an emphasis on quantification methodologies.
- Identify LCRB case studies for potential analysis.
- Conduct site visits/interviews for selected case studies.
- Document the conservation activity implemented and the quantification method(s) used to estimate conserved water.
- Compare the estimate of conserved water with Reclamation's methods and calculations.
- Assess opportunities to improve the quantification method(s).
- Document efforts throughout process.

During the second day of the workshop, the following topics were reviewed in detail to confirm alignment of the remaining major scope items with expectations:

General Considerations

Input and feedback from all interested parties is critical and valued. Project participants are encouraged to provide leads for the literature review as well as information on conservation activities they have applied and tested or that are part of current and on-going efforts to improve efficiency/conserve water. A project website has been created for the Pilot Study: https://LCRBPilotStudy.com/. Project participants can post comments, ask questions, and upload/download project reports and other documents.

This study will focus on conservation measures that include both consumptive use reductions (e.g. fallowing, deficit irrigation, crop mix changes, etc.) and efficiency improvements (on-farm irrigation improvements, and conveyance system improvements).

In order to fully characterize water conservation, it is essential to perform a water balance-- the inflows, outflows, and change of storage for a given system. Each component of the water balance (inflows, uses that remove water from the system, or return flows) are identified, characterized, measured, or estimated. The ultimate fate and disposition of the return flows (losses due to inefficiencies) are important factors in determining if there is a water savings or not. Accurate quantification requires that the water balance be performed prior to any efficiency improvement to understand the baseline condition.

Consumptive use reductions occur at the farm field level. Similar to efficiency improvements, accurate measurement or estimation of actual consumptive use under pre-intervention conditions is necessary. Quantification methods must consider measuring or estimating actual consumptive use versus potential consumptive use to avoid overstating consumptive use savings.

Tasks 3 and 4 – Literature Review

A review of academic and technical literature (studies, research, reports, journals) will be conducted to determine what agricultural water conservation technologies are being implemented and what methodologies are being used to quantify conservation in the LCRB, including:

- Full-year agricultural cropland fallowing
- Seasonal or partial-year cropland fallowing
- Deficit irrigation
- Switching crops or crop rotations requiring less irrigation water
- Irrigation methodology conversions

The literature review effort will focus on information, data, reports, research, and results since the completion of the Basin Study and the Moving Forward Effort. Literature addressing conservation activities and topics applied in the Lower Basin will be prioritized.

Task 5 – Workshop 2

A list of recent or on-going irrigation water conservation efforts that could serve as potential case studies will be identified using information from the project participants and the literature review effort.

The case studies to be evaluated as part of this study will be selected through a collaborative workshop process (Workshop #2) with the project participants. Potential considerations in selecting case studies include:

- Representation of a diversity of agricultural conservation activities (to the extent possible)
- Representation of a diversity of water savings quantification methods (to the extent possible)
- Representation of a diversity of geographies within the LCRB (to the extent possible)

Tasks 6 and 7 – Case Study Investigations

The following data and information will be documented for each case study through site visits and interviews:

- The conservation activity that was/is being implemented
- The water savings quantification methodologies and approaches utilized
- The observed results, findings, constraints and limitations of the conservation activity
- Any unanticipated consequences and lessons learned
- The final outcome(s) of the quantification of consumptive use savings or water use efficiency
- A comparison of the quantification with Reclamation's methods and calculations
- Recommendations for improving quantification methods

Task 8 – Workshop 3

A third workshop (Workshop #3) will be held with the project participants. The purpose of this workshop will be to present and discuss the results of the case studies and the proposed Pilot Study recommendations.

No significant scope refinements were suggested by the workshop participants. It was noted that, where possible, the study should highlight the success of agricultural efficiency improvements in the LCRB, the impacts of conservation on productivity, and non-consumptive use benefits.

The proposed project schedule is shown in *Figure 3*.

Figure 3 Proposed Project Schedule

LCRB Pilot Study Performance Schedule	Qtr 3 2020	Qtr 4 2020	Qtr 1 2021	Qtr 2 2021	Qtr 3 2021	Qtr 4 2021
Task 1 – Project Administration (by Reclamation)						
Task 2 – Workshop 1 – Scope Refinement & Case Study Definition	9/25		1/4			
Task 3 – Literature Review of Seasonal Fallowing, Deficit Irrigation & Irrigation Conversion Activities		11/16	1/15			
Task 4 – Review and Summarize Seasonal Fallowing, Deficit Irrigation & Irrigation Conversion		11/16		4/4		
Task 5 – Workshop 2 – Case Study Definitions & Selection			1/15	5/23		
Task 6 – Site Visits & Interviews				5/23 5/30		
Task 7 – Case Studies & Technical Reviews				5/30	9/9	
Task 8 – Workshop 3 – Draft Review of Case Studies					7/29	11/13

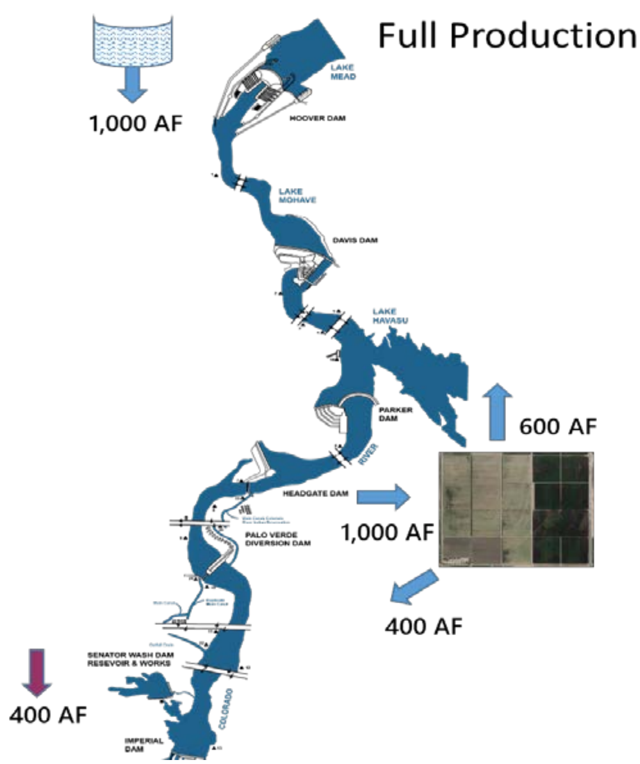
Key milestones are as follows:

- Workshop 1 – November 9-10, 2020
- Milestone 1: Draft Technical Memorandum 1 – Project Definition and Summary of Workshop #1 – December 2020
- Milestone 2: Draft Technical Memorandum 2 – Summary of Significant Findings from Literature Review & Recent/Current Activities in the Lower Basin – February 2021
- Workshop 2 – March 2021
- Milestone 3: Draft Technical Memorandum 3 – Summary of Case Study Definition, Site Selection & Evaluation Process – April 2021
- Site Visits/Interviews – May 2021
- Milestone 4: Draft Report – Case Studies and Technical Reviews – August 2021
- Workshop 3 – September 2021
- Milestone 5: Final Report –November 2021
- Presentation at CRWUA – December 2021

Conservation Measures and Quantification of Consumptive Use in Colorado River Water Accounting

Jeremy Dodds, Water Conservation and Accounting Group Manager with Reclamation, provided an overview of Reclamation's consumptive use water accounting methodology and how it relates to conservation measures. Pursuant to 1964 U.S. Supreme Court Decree (Consolidated in 2006), Reclamation is required to account for Colorado River water use including providing an official record of mainstream diversions, returns and consumptive uses, and the annual Colorado River Accounting & Water Use Report.

Figure 4 Consumptive Use Calculation Example



The fundamental premise of the methodology is that conservation activities must result in a measurable reduction in mainstream Colorado River consumptive use. Examples of conservation activities include:

- Fallowing (seasonal or full-year)
- On-farm efficiency improvements (e.g. drip irrigation, tailwater return systems, center pivot)
- Delivery system improvements (e.g. seepage recovery, canal lining)

Jeremy provided examples (see *Figure 4*) of consumptive use calculations for various activities (full production, fallowing, efficiency improvements, and exported water) to demonstrate the impact on conservation savings quantification. He also highlighted that various quantification methods are currently used in the Lower Basin due to the uniqueness of each water user and that historically water users have proposed the method to be utilized to Reclamation.

Case Study Definition and Approach

To lead the workshop participants in a discussion of the case study definition and approach process, Tom Ley provided the following working definition of a case study (emphasis added)[1]:

> An applied research method involving an *up-close, in-depth, and detailed examination of a particular phenomenon*, like a person, group, or situation. The phenomenon is studied and analyzed in detail and *solutions or interpretations are presented to provide a deeper understanding* of a complex topic or assists in *gaining experience about a certain historical situation*.

Defining the Phenomenon

The first step in the case study definition and approach process is to define the phenomenon. The phenomena to be examined through this study are the agricultural water conservation technologies being implemented and the methodologies being used to quantify conservation in the LCRB.

Detailed Examination of the Phenomenon

These phenomena will be studied and analyzed in detail through both the literature review and case study process. The literature review will identify recent water conservation quantification methodologies and approaches under various relevant conservation measures, and annotated bibliographies will be developed. Potential recent/current case studies will be identified by project participants. Case studies will be selected for evaluation through a collaborative workshop process with the goals of representing of a diversity of agricultural conservation activities, water savings quantification methods, and geographies within the LCRB (to the extent possible).

Solutions/Interpretations to Provide a Deeper Understanding

Pertinent data and information will be collected through site visits and interviews and analyzed for each case study. In addition, an assessment of opportunities to improve or enhance quantification methods will be conducted and recommendations will be provided. The results of this effort will be documented in technical memoranda and a final report and will be shared with the project participants through collaborative workshops throughout the process.

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[1] Paraphrased from: Stephanie Glen. "Case Studies: Case Study Definition and Steps" From StatisticsHowTo.com: Elementary Statistics for the rest of us! https://www.statisticshowto.com/case-studies/

Workshop Participant Perspectives

A facilitated discussion was held among the workshop participants in order to solicit insights to better inform the study process. The following questions were asked of the group:

- What actions have led to successful collaboration in previous Reclamation studies?
- What would be the ideal outcome of the Pilot Study for the various participants?
- Are there concerns about participating in this study? If so, what can be done to address/minimize the concerns?

A participant inquired how Reclamation and the non-Federal funding partners will use the results of this study. The following responses were provided:

- From Reclamation's standpoint, this effort will benefit everyone by promoting a common understanding and better quantification of agricultural conservation savings. However, this study will not make other quantification methods "unusable" even if they are not identified as "best".
- SNWA indicated that the benefit of this study is obtaining, documenting, and sharing information (the collective experience) and identifying the best methods for quantification.
- MWD agreed with SNWA's sentiment of identifying best methods/practices.
- CAWCD added that the study addresses the need for transparency between project partners, could help answer questions of quantitative benefit posed by Upper Basin, and helps document the success of efficiency efforts in the Lower Basin.

A participant commented that incentives to improve water efficiency vary across the basin and need to be developed. For example, CRIT is focused on canal lining and re-regulation of reservoirs. Incentives to implement these projects are currently not available to CRIT.

A participant asked what the definition of conservation is for this study. Reclamation indicated that conservation of applied water and actual water use will both be considered. CAWCD added that the definition should relate to water use reductions that can be tracked by water levels in Lake Mead, which will be largely geography dependent. The participant agreed that the conservation definition should consider both applied water and consumptive use.

A member of the consultant team asked the group how this study could be best crafted to benefit agricultural districts. A participant expressed concern about salinity and desertification, and that even moderate deficit irrigation reduces crop yield, and results in declining productivity. Agricultural producers would be more willing to conserve but need to be compensated for lost crop productivity. This is different than other conservation practices which do not necessarily result in crop yield loss.

Reclamation reiterated that Reclamation would like to hear about any concerns with the study as soon as possible.

Appendix: Workshop 1 Presentation Slides

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Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

Workshop #1

November 9-10, 2020

Agenda – Day 1

- Welcome and Introductions
- Pilot Study Overview and Objectives
- Overview of Previous Planning Studies
- Overview of Pilot Study-Scope, Schedule and Milestones
- Workshop Participant Perspectives
- Wrap-up and Preview of Day 2

Welcome/Introductions

Project Team Organization

Funding Partners

- Bureau of Reclamation
- Central Arizona Water Conservation District
- Metropolitan Water District of Southern California
- Southern Nevada Water Authority

Participants

- Agricultural Districts
- Tribes
- State Agencies
- Non-Governmental Organizations

Consulting Team

- Natural Resources Consulting Engineers
- Jacobs Engineering Group

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Pilot Study Overview and Objectives

Background

- The 2012 Colorado River Basin Supply and Demand Study identified strategies to address the evolving supply-demand imbalance
- The subsequent Moving Forward effort identified quantification of agricultural conservation water savings as a challenge
- In 2019, Reclamation began funding a new activity under the Basin Study Program called Water Management Options Pilots
  - The goal is to identify solutions to water management issues by building on completed basin studies
- Reclamation and partners awarded funding for proposal for pilot study to quantify agricultural water conservation and demand management methodologies for the Lower Colorado River Basin

Pilot Study Objectives

- Explore methods currently in use to quantify agricultural water conservation
- Evaluate methods for consistency and accuracy with Reclamation's Lower Colorado River water accounting methods
- Recommend approaches to improve methods of quantifying agricultural water conservation in the Lower Basin
- Evaluate case studies using a combination of research and applied science
- Participant input and feedback is critical to the success of the Study

What this Study is Not

- This is not a policy study
- Participation is not mandatory
- Not an attempt to change accounting practices
- Not a hypothetical analysis of potential future application or savings
- Not a water use/efficiency audit

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Overview of Previous Planning Studies

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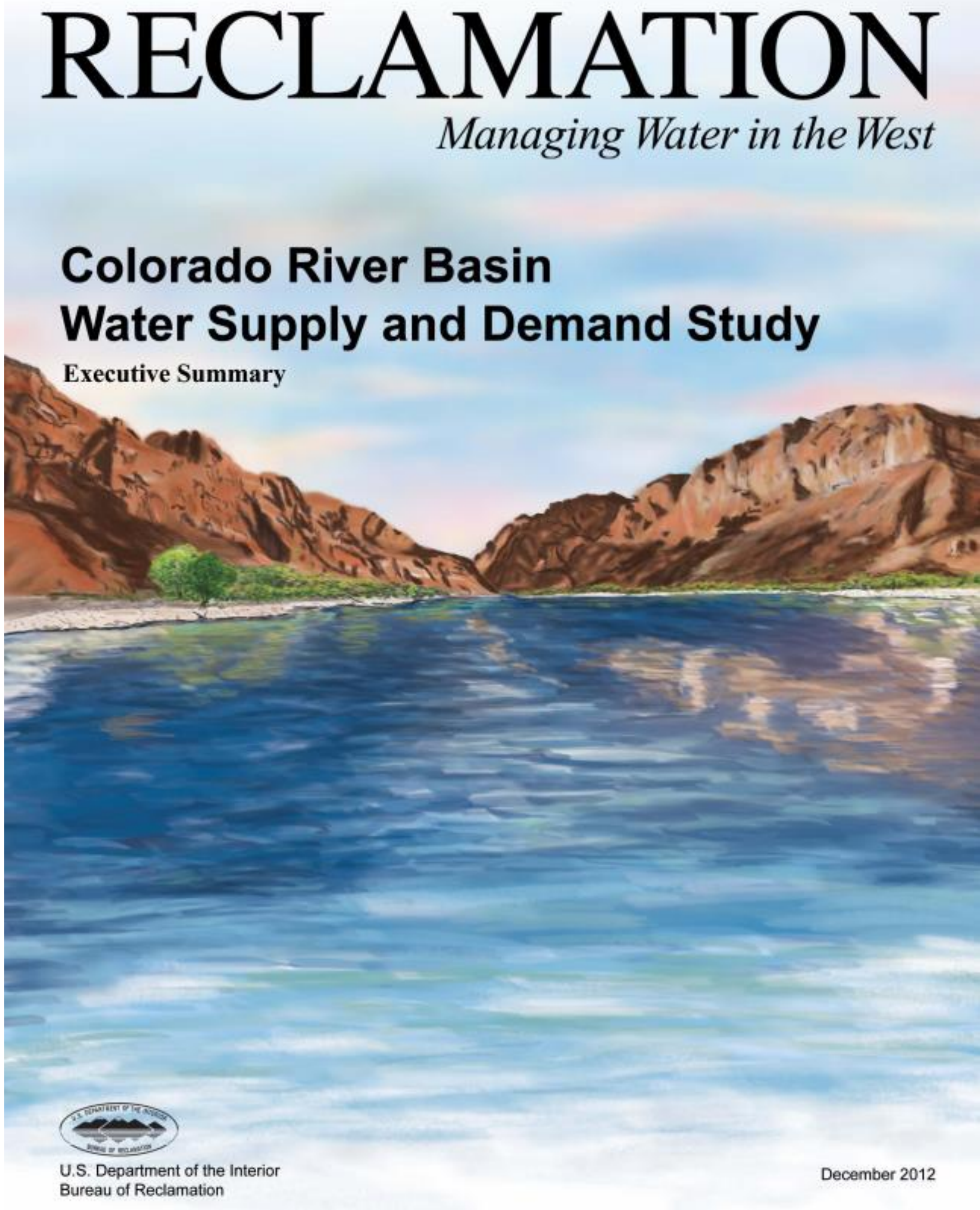
Colorado River Basin Water Supply and Demand Study

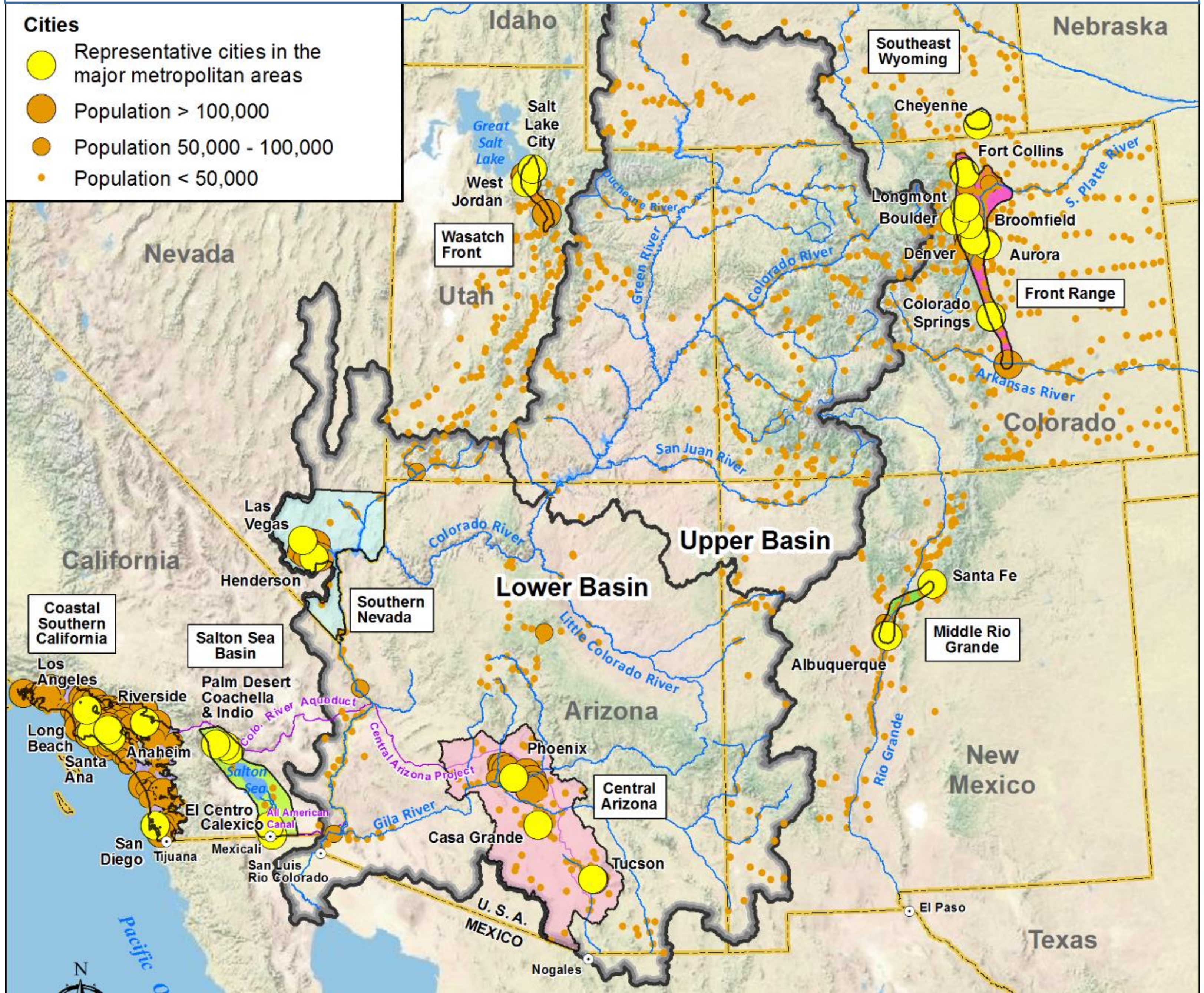
Integrated, Long-Term Planning in the Face of Uncertainty



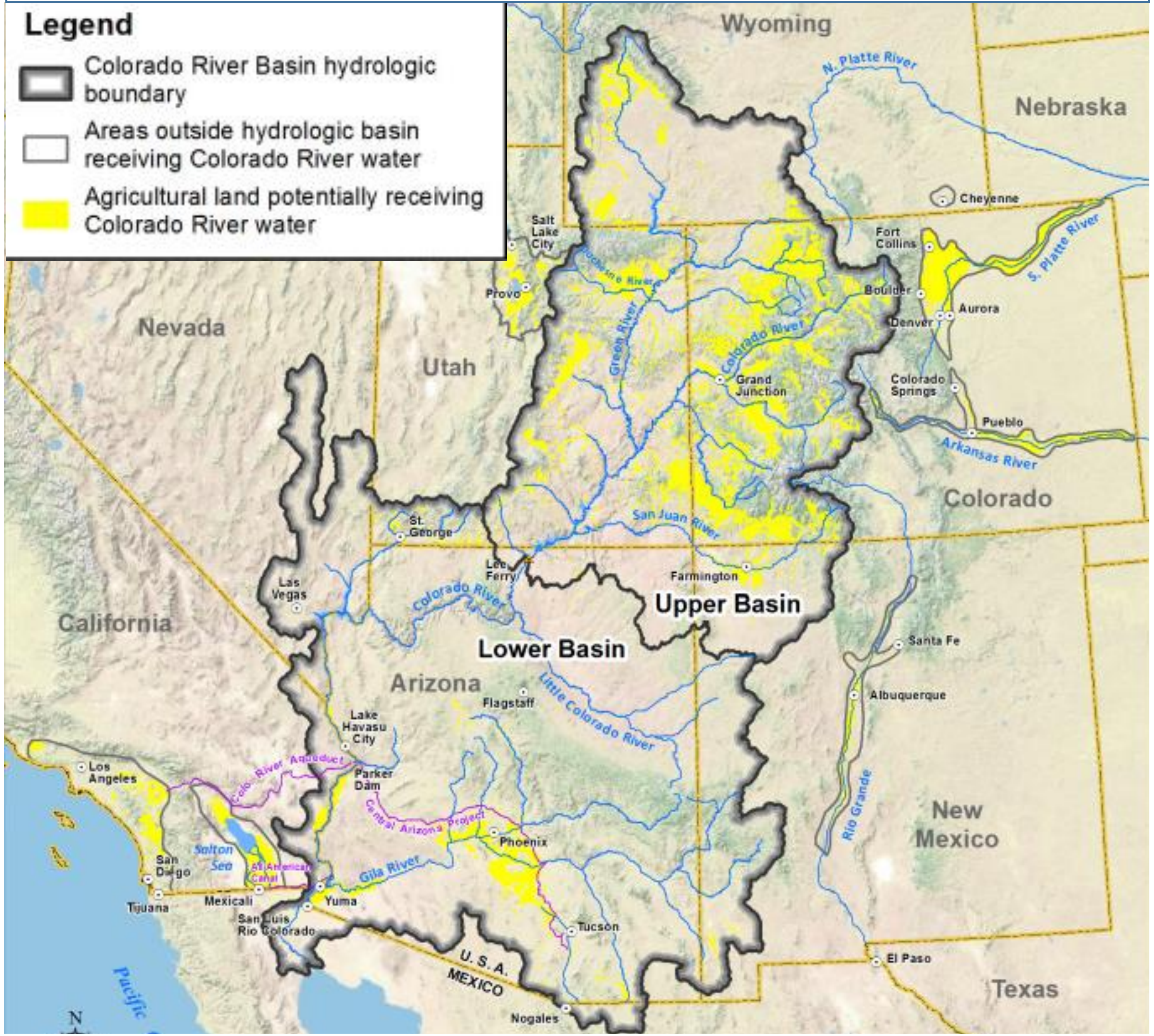
Colorado River Basin Water Supply and Demand Study (2012)

- Study Objective
  - Assess future water supply and demand imbalances over next 50 years
  - Develop and evaluate opportunities for resolving imbalances
- Study conducted by Reclamation and the Basin States in collaboration with stakeholders throughout the Basin
- A planning study – did not result in any decisions, but provided the technical foundation for future activities

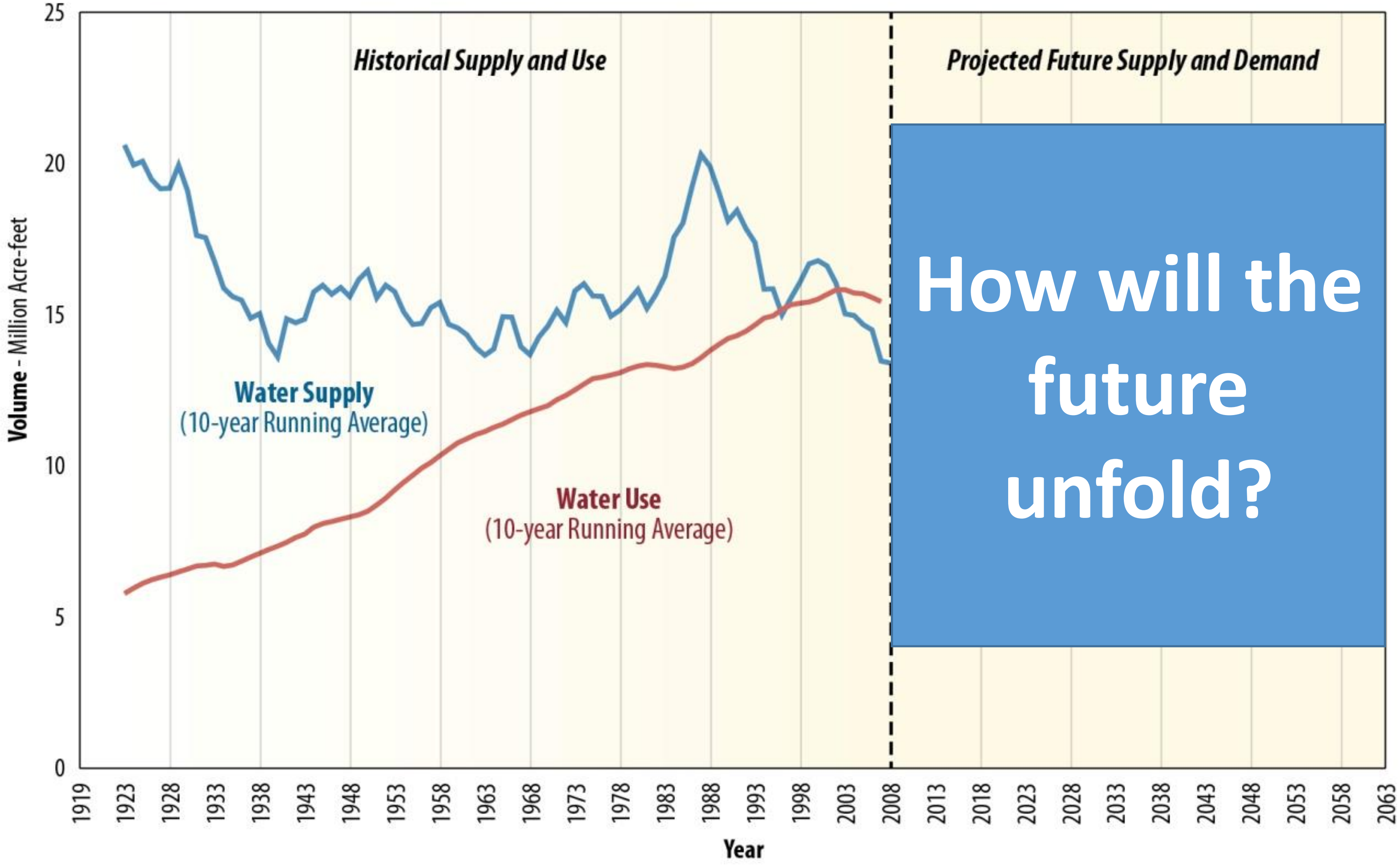
Colorado River Basin and Major US Metropolitan Areas



Colorado River Basin and U.S. Agricultural Areas

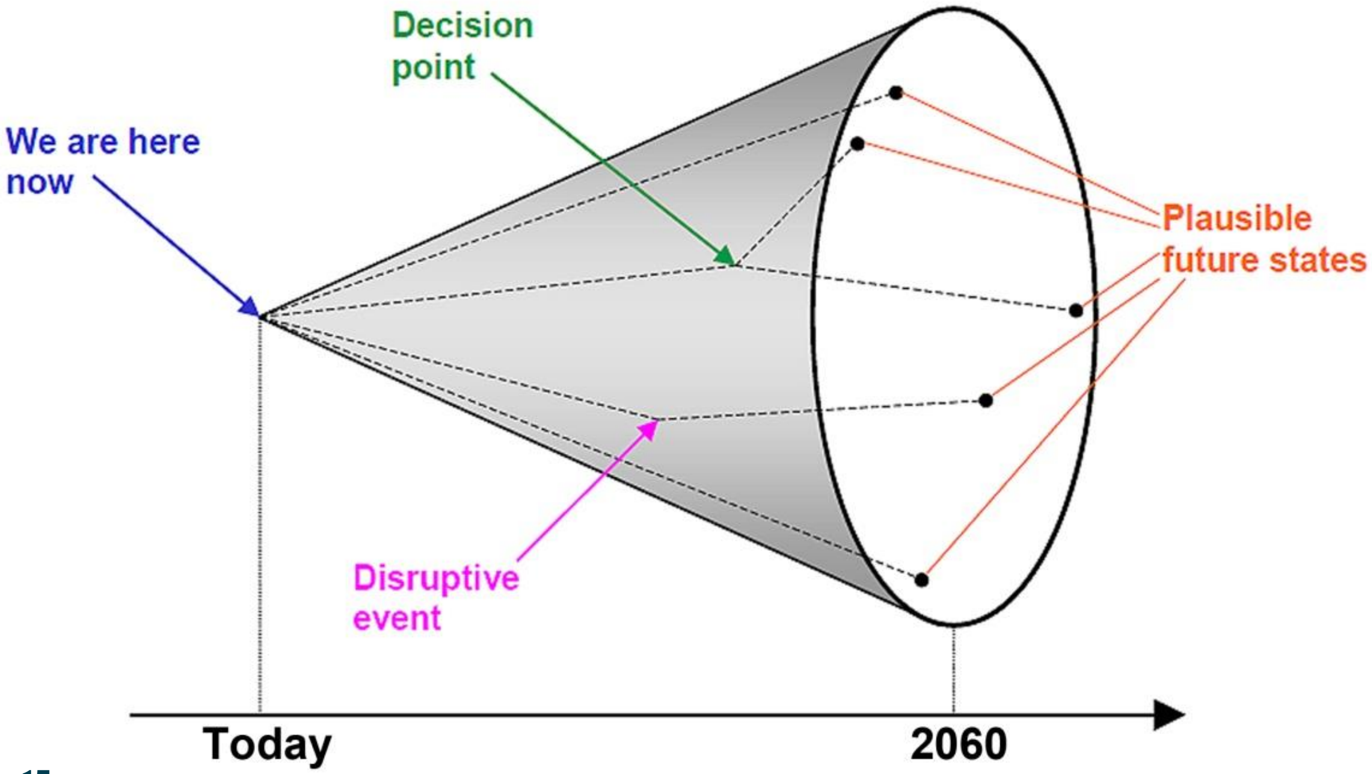


Colorado River Basin Study: The Challenge



Scenario Planning: Addressing an Uncertain Future

- The path of major influences on the Colorado River system is uncertain and cannot be represented by a single view



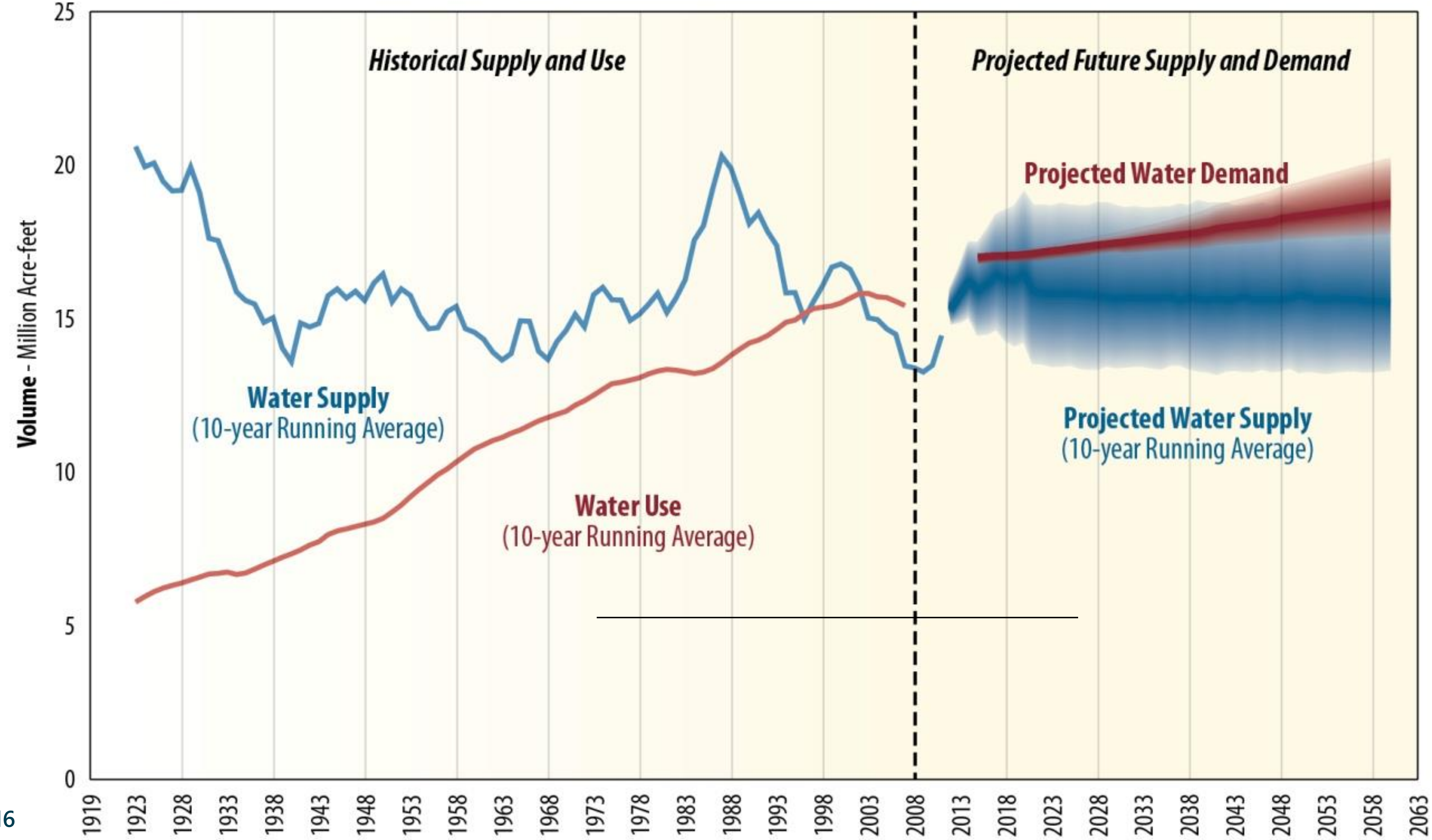
Water Supply Scenarios

- Observed Resampled
- Paleo Resampled
- Paleo Conditioned
- Downscaled GCM Projected

Water Demand Scenarios

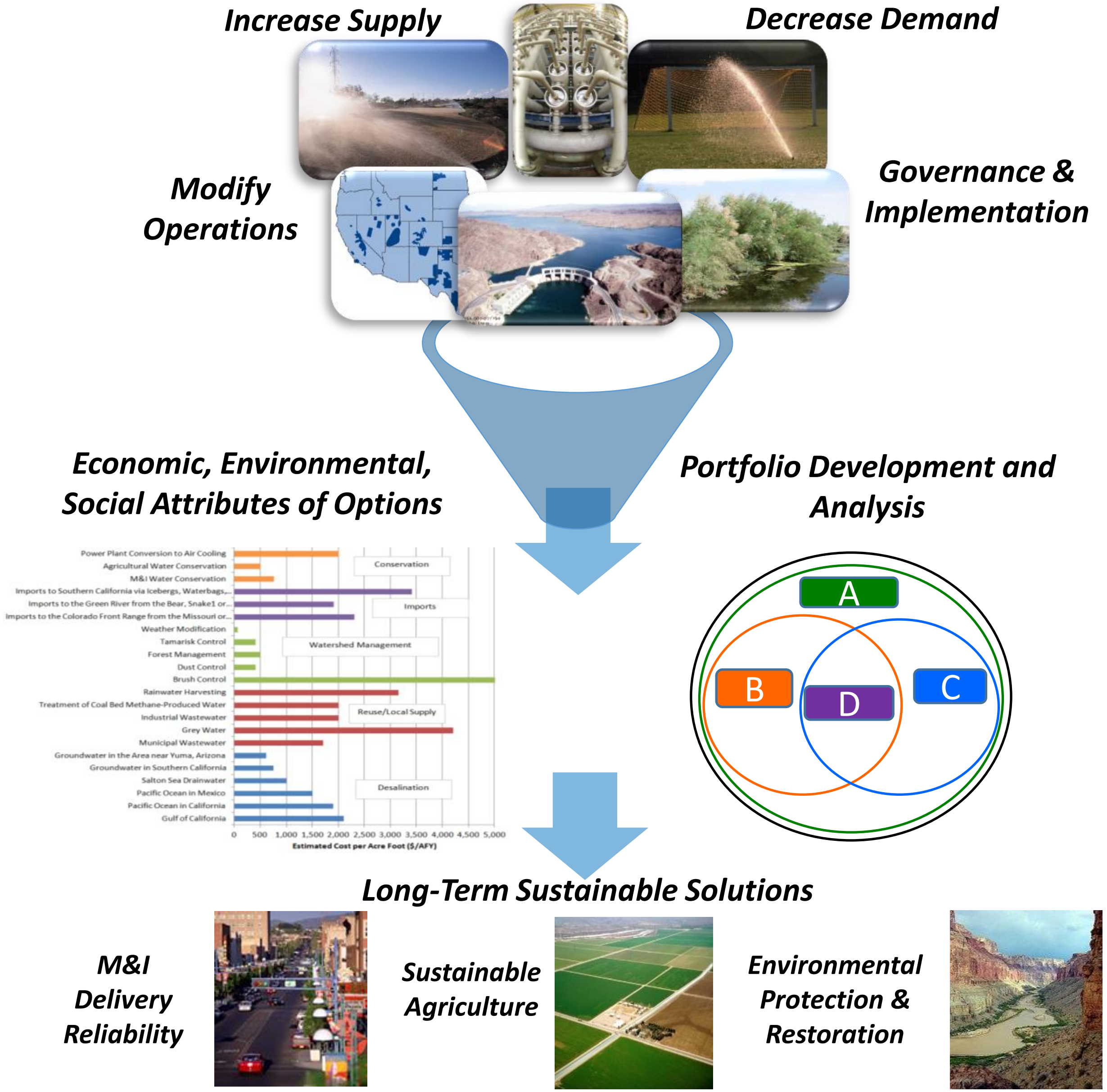
- Current Projected
- Slow Growth
- Rapid Growth
- Enhanced Environment

Potential for Significant Future Imbalances Exists



Analysis of Options and Strategies

- Broad assessment of options to address long-term reliability
- Multiple criteria evaluation and decision analysis
- Water management portfolio development and analysis
- Strategies for long-term sustainable solutions

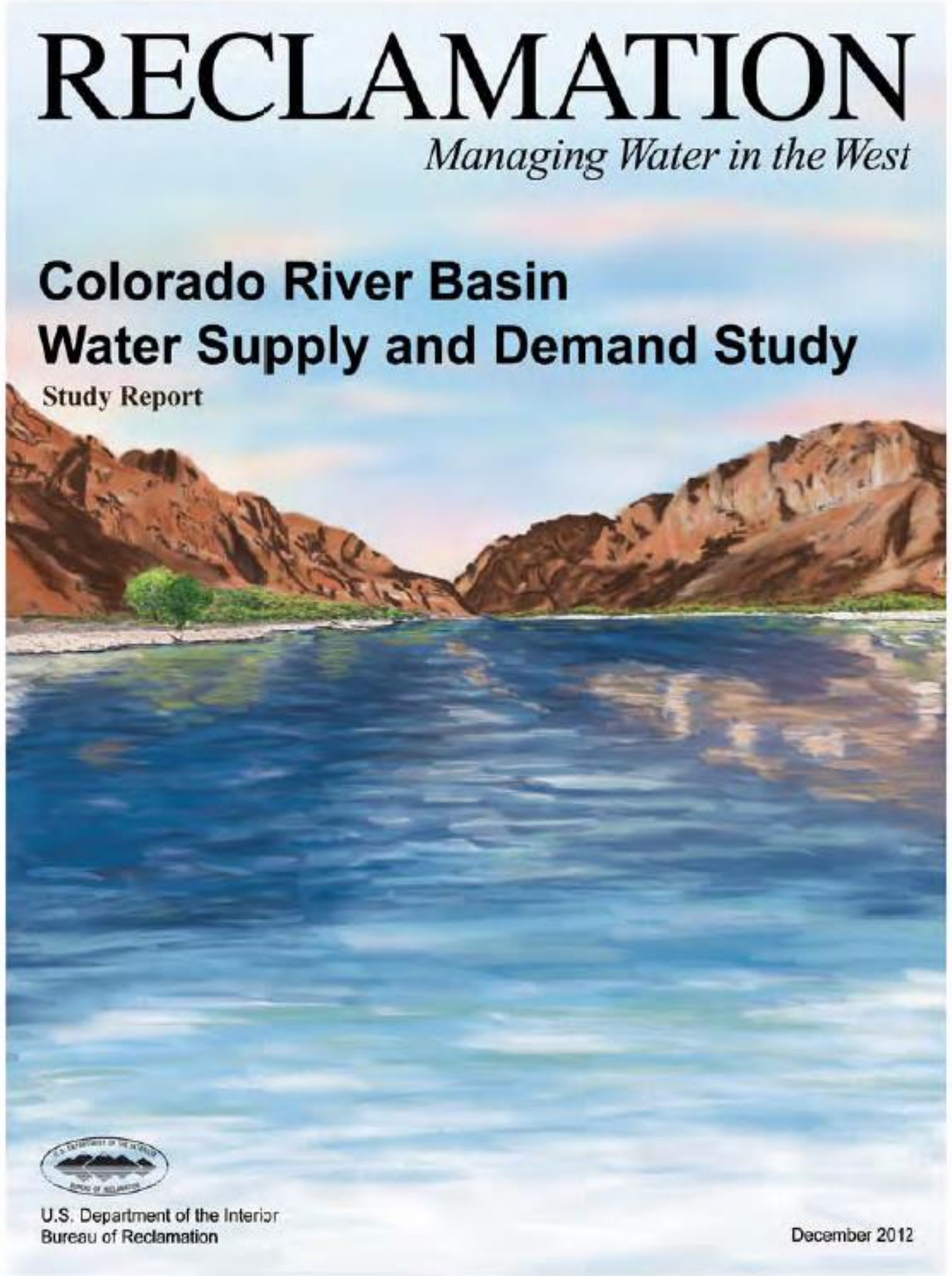


Agricultural Options Identified in Basin Study

- Nine options were submitted and classified into 6 categories
  - Advanced irrigation scheduling
  - Deficit irrigation
  - On-farm irrigation system improvements
  - Controlled environment agriculture
  - Conveyance system efficiency improvements
  - Fallowing of irrigated lands
- Estimated potential Colorado River water savings

Study Summary

- The system is vulnerable if we do nothing
- Action greatly reduces that vulnerability and makes the system more resilient, but does not eliminate vulnerability
- In the near term, all portfolios show that water conservation and reuse are cost-effective ways to reduce vulnerability



http://www.usbr.gov/lc/region/programs/crbstudy.html

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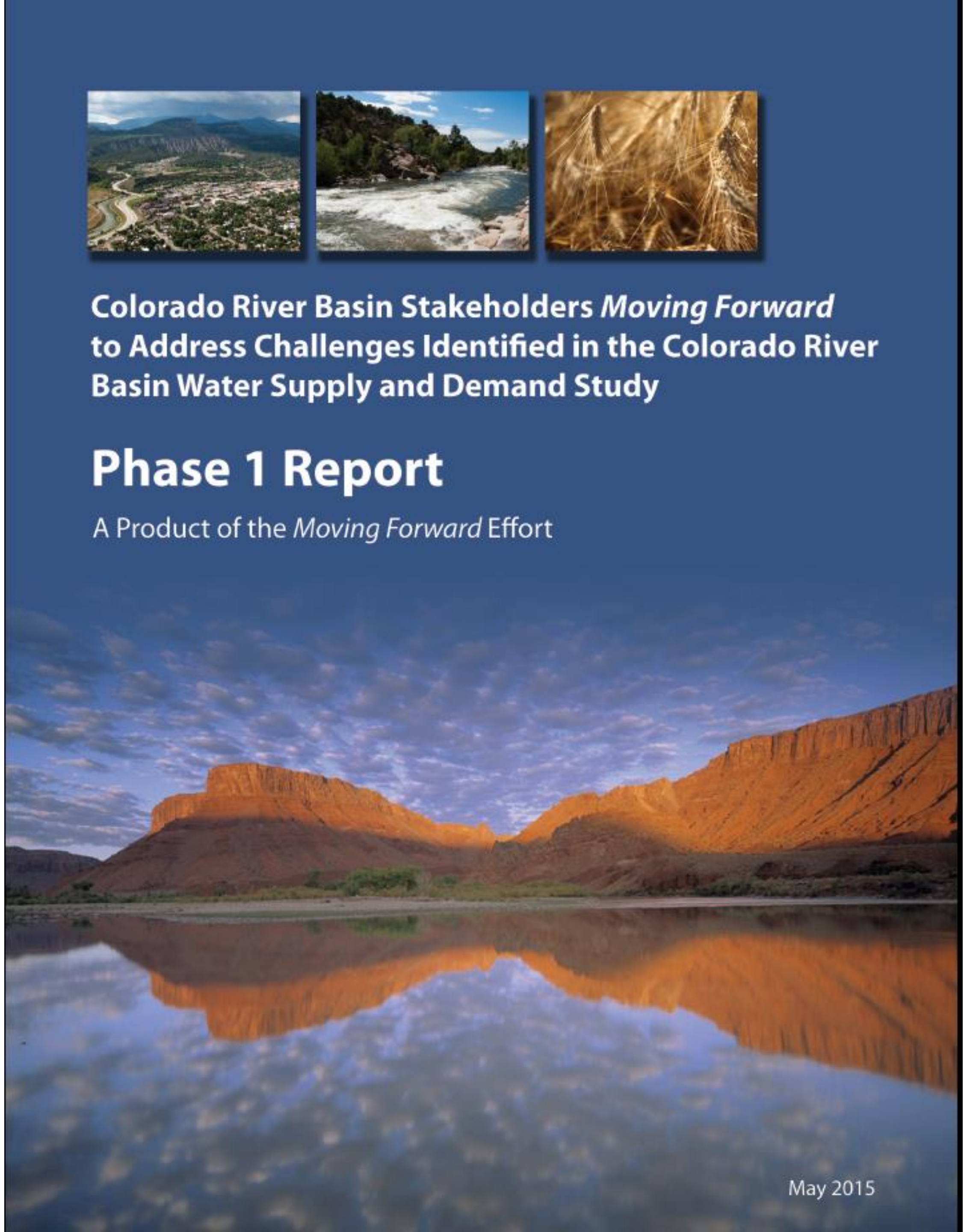
Moving Forward Effort (2015)

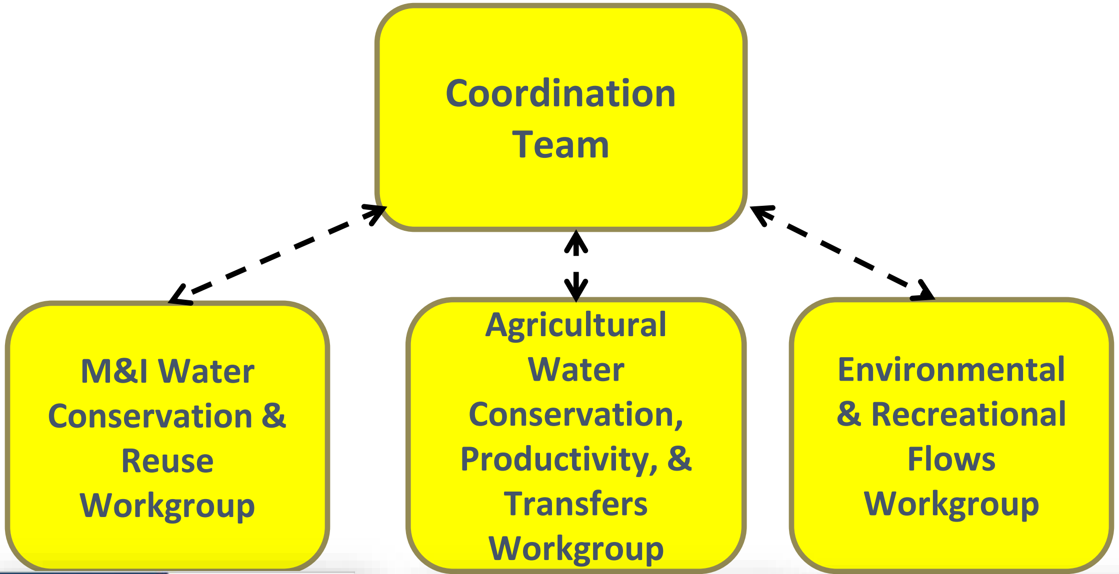
Building from the Basin Water Supply and Demand Study

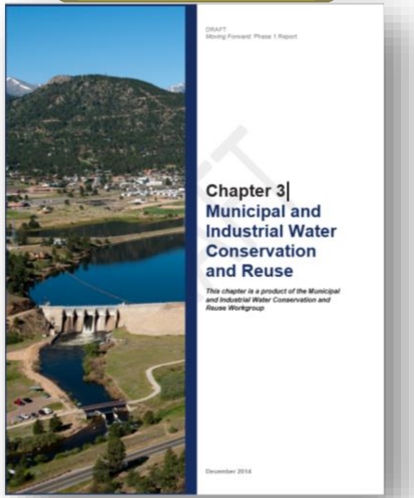


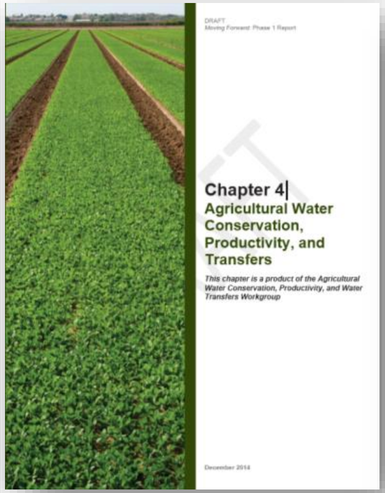
Moving Forward Effort

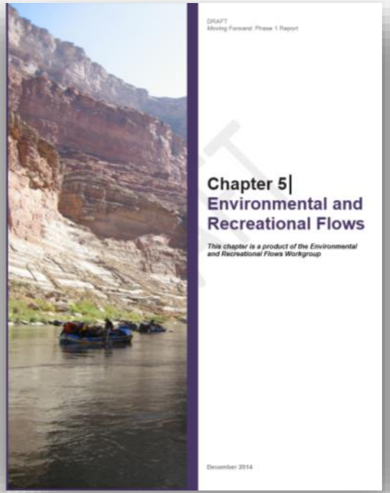
"…all that rely on the Colorado are taking initial steps — *working together* — to identify positive solutions that can be implemented to meet the challenges ahead."

- Initiated in May 2013 and consisted of the formation of three multi-stakeholder groups
- Expanded to an even broader stakeholder group with the necessary expertise to explore specific topics identified in the Study and Phase 1
- More detailed analysis and discussion than was considered in the Basin Study

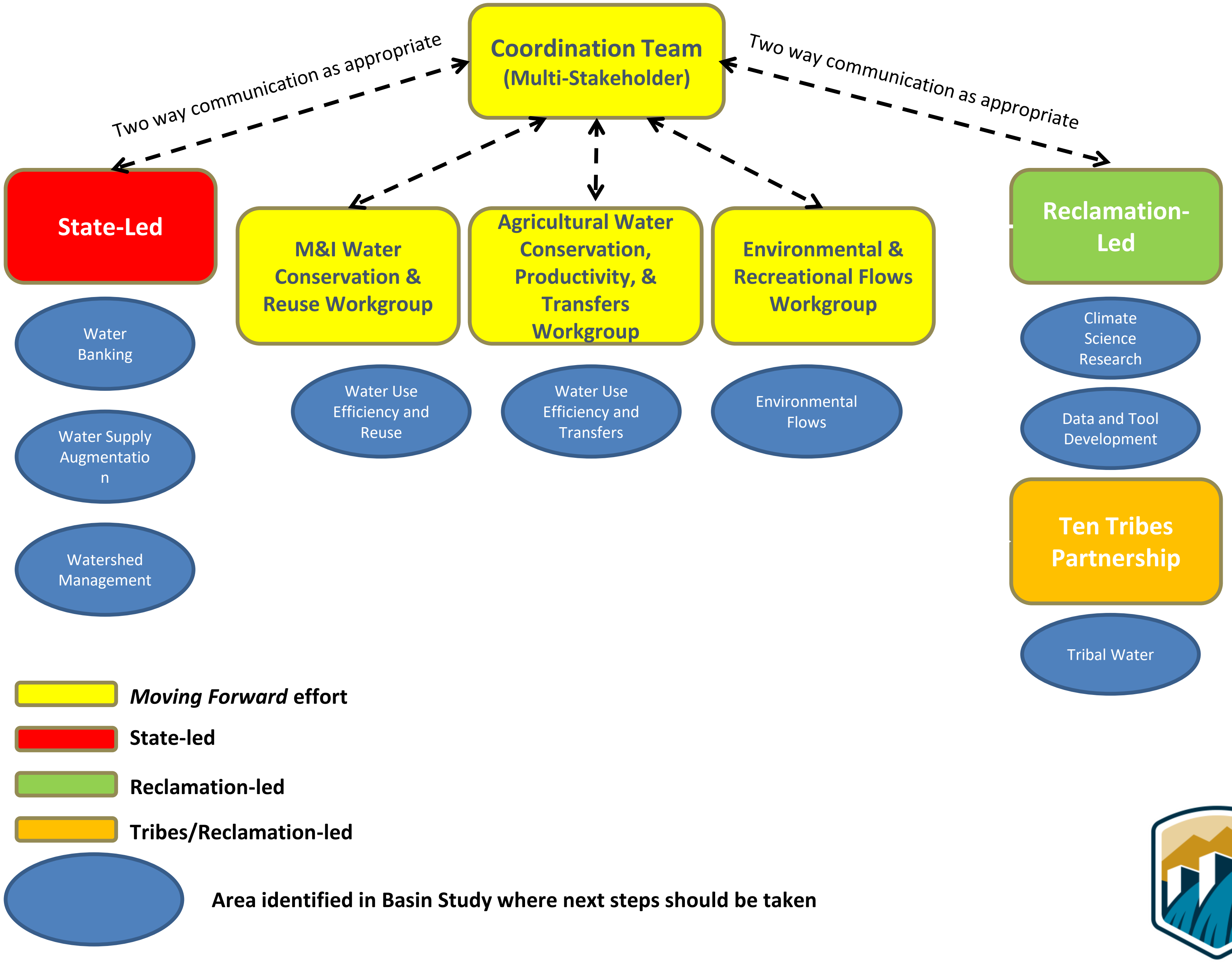






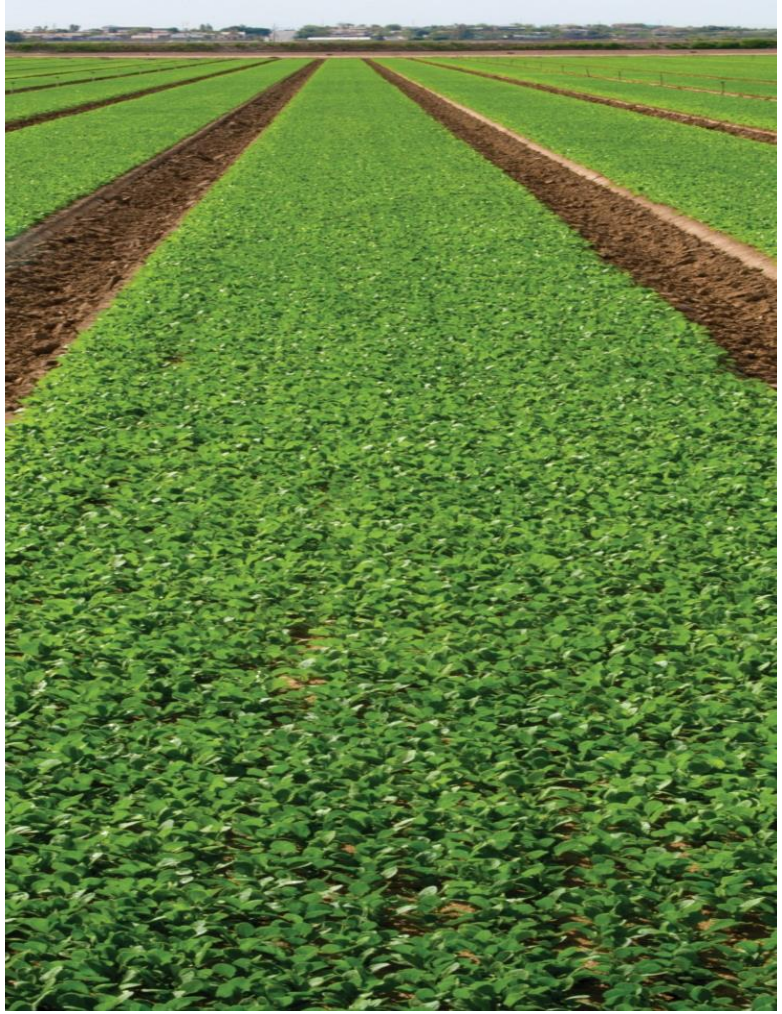


Workgroups Part of Broader Next Steps Effort



Agricultural Options Identified in Basin Study

- Co-Chairs – Colorado State University, IID, BOR
- Workgroup tasks:
  - Quantify historical trends in agricultural conservation and transfers of Colorado River water (both inside and outside of the Basin)
  - Document agricultural water conservation programs that have been successful to date
  - Identify existing future plans for these types of activities, and estimate what potential savings could come from these existing plans
- Challenges – concern about preservation of agricultural productivity



Colorado River Agriculture Acreage & Climate

Irrigated Acreage

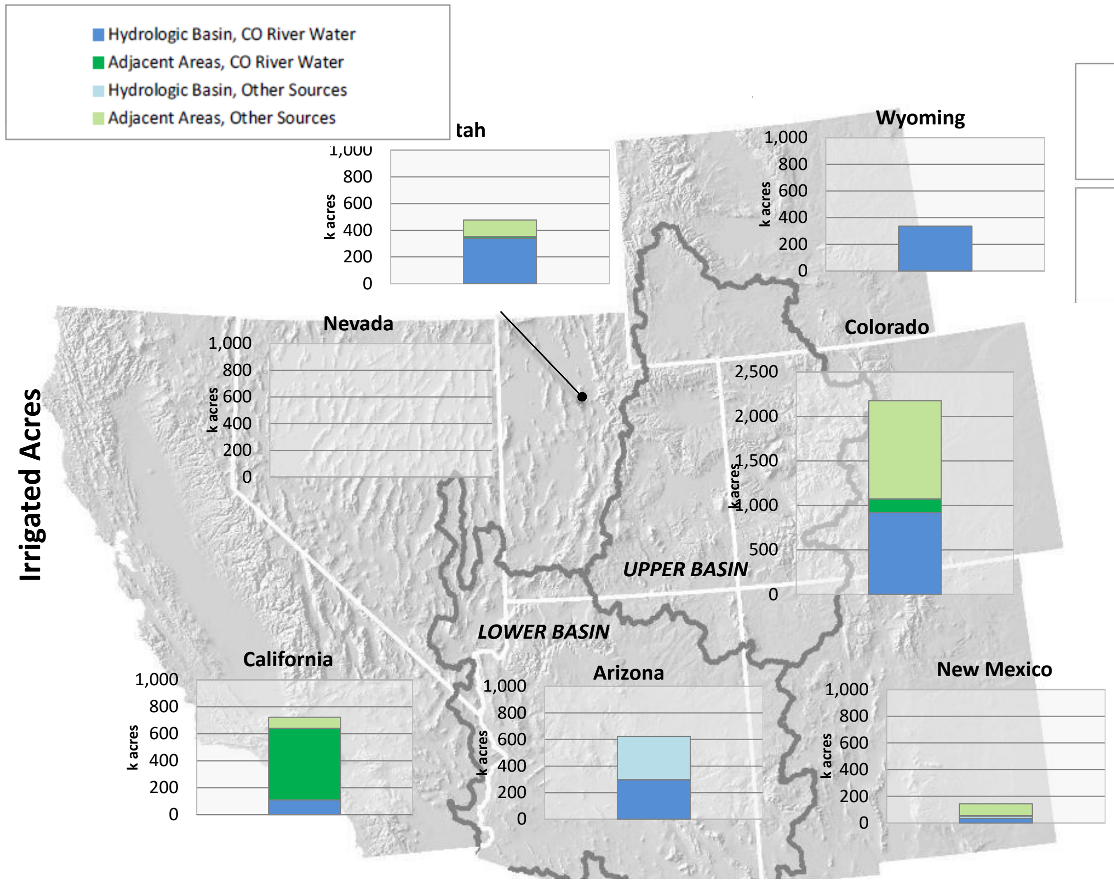


Figure 4-3. Agricultural Production Acreage and Water Supply Source

Climate

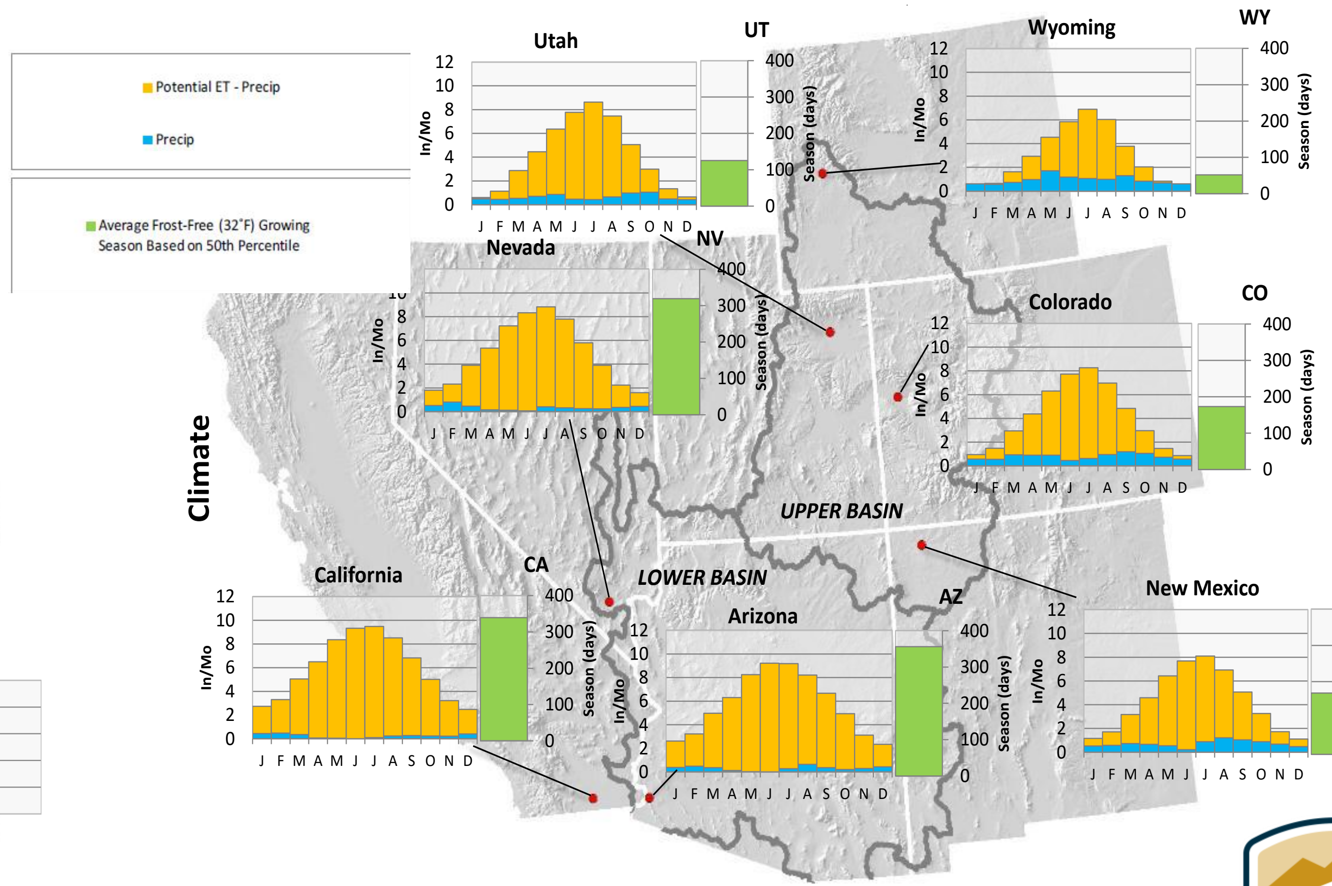


Figure 4-4. Climate Information by State

Colorado River Agriculture Crops and Sales

Crop Type

Crop Type

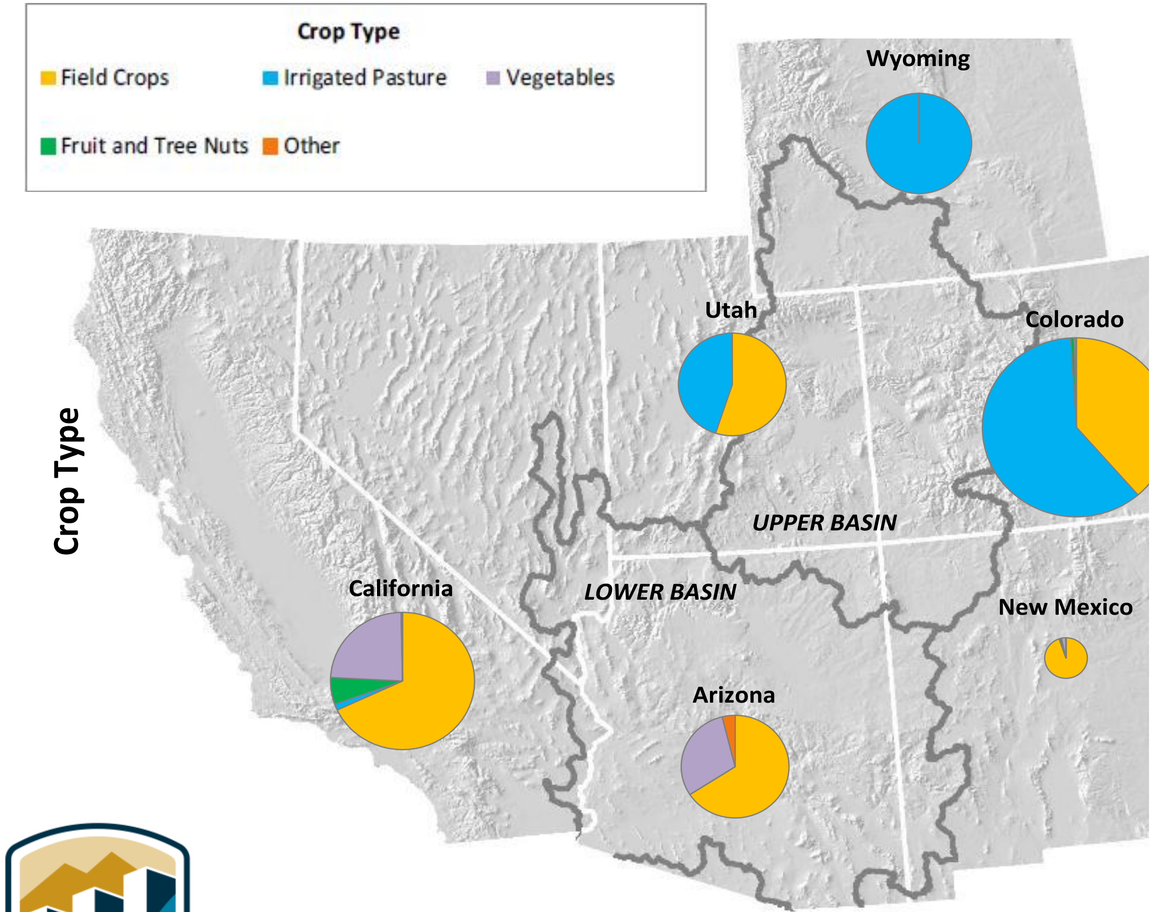


Figure 4-5. Crop Types by State

Agricultural Sales

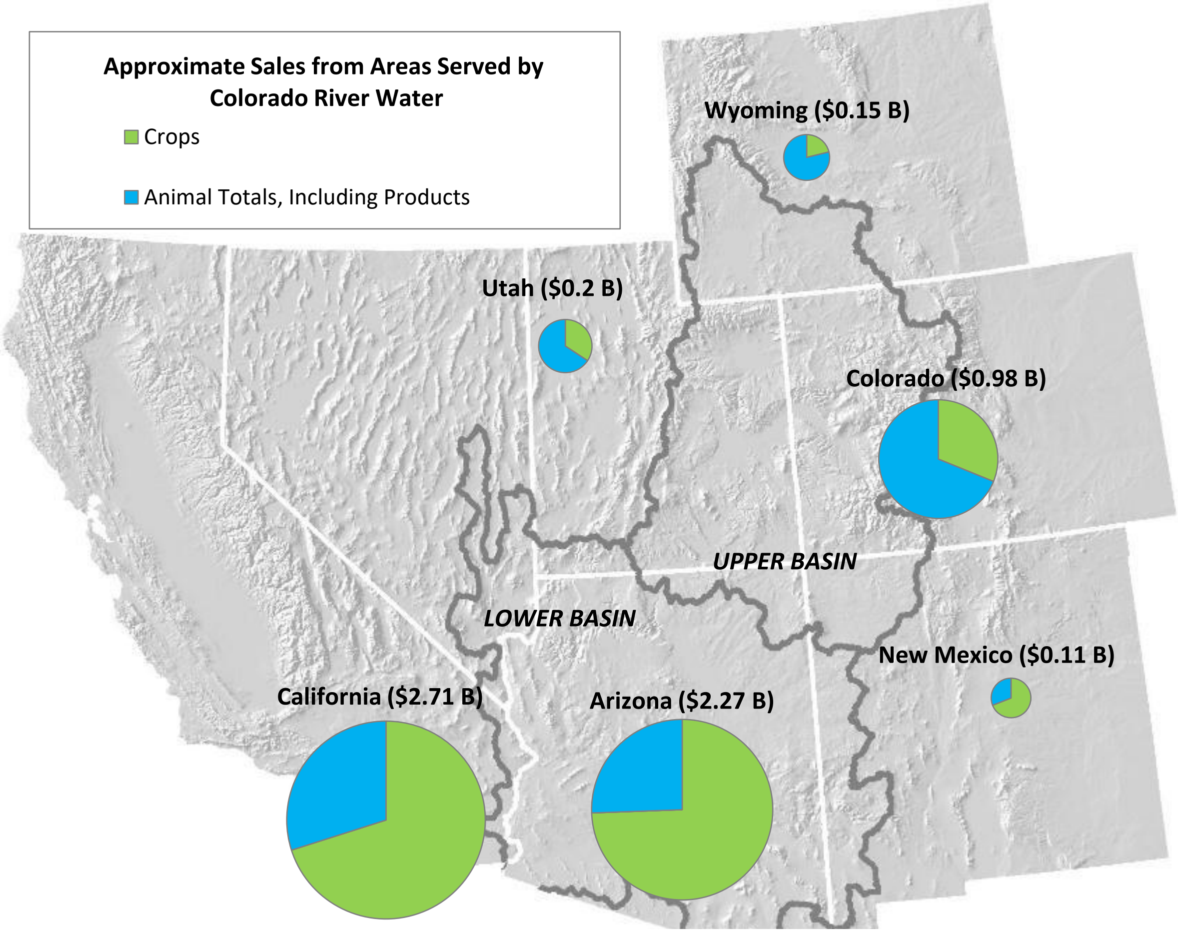


Figure 4-2. Agricultural Sales that Rely on Colorado River System Water

Agriculture Productivity in the Basin

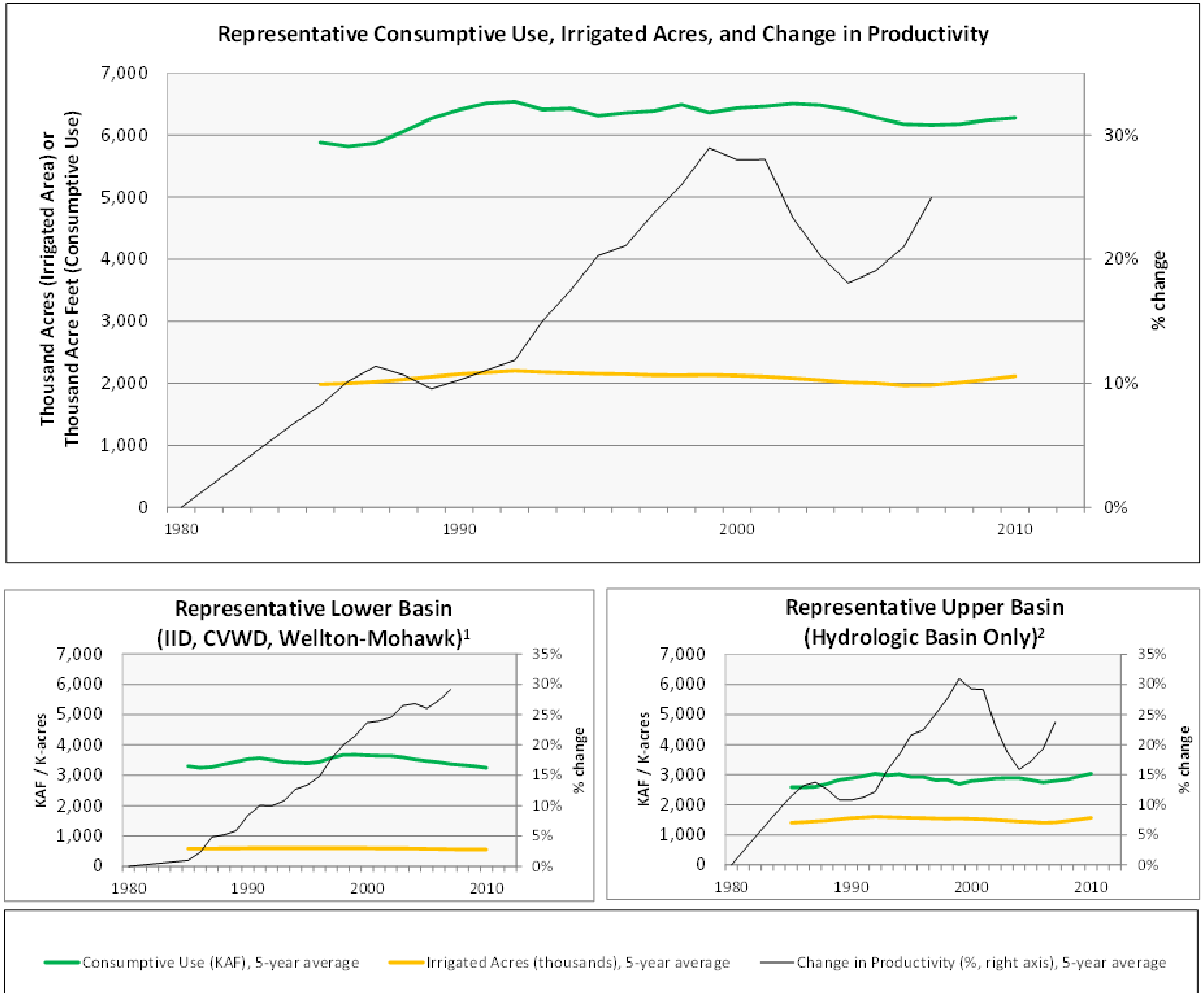
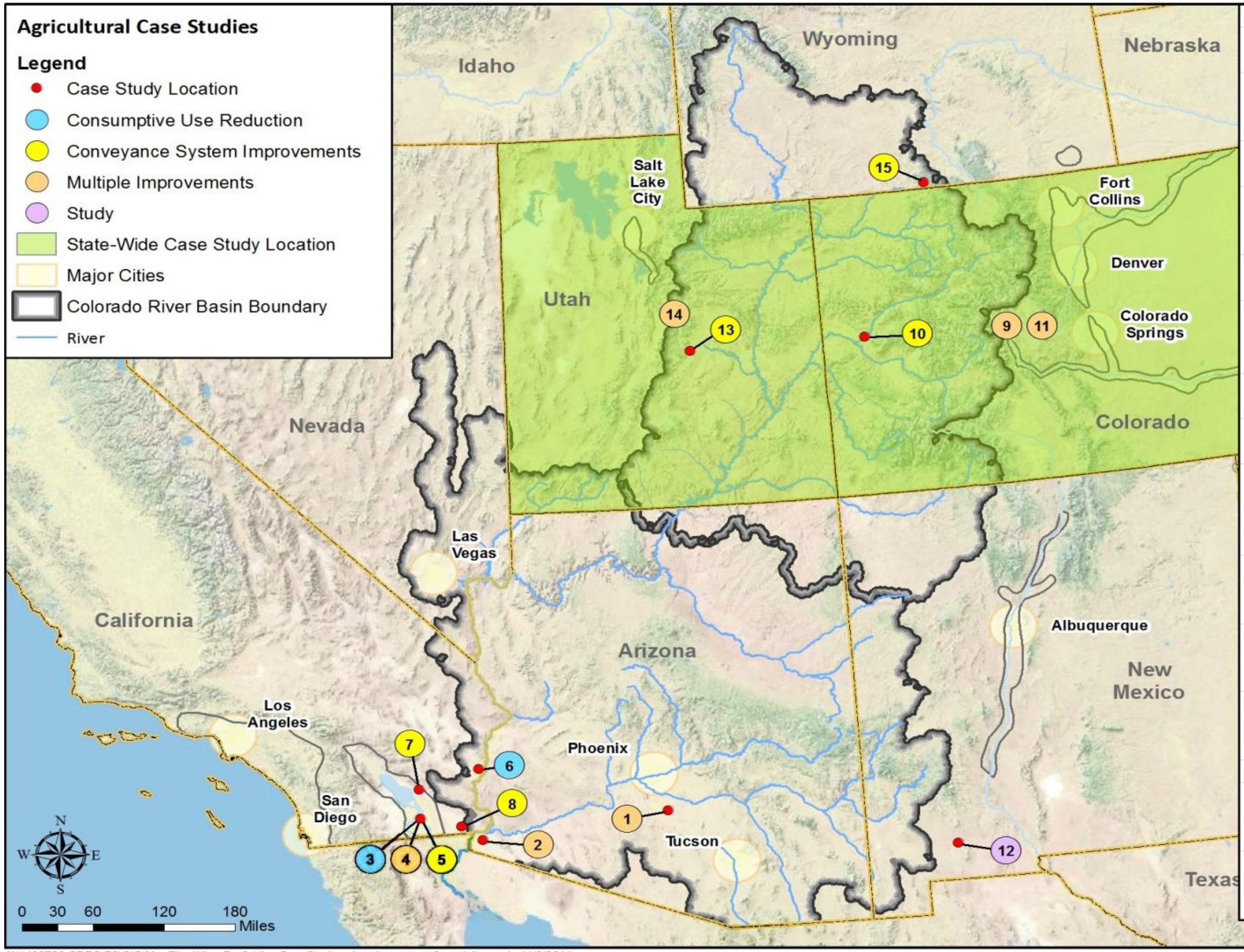


Figure 4-7. Acreage and Consumptive Use of Colorado River Water Compared to Change in Productivity

Case Studies

- Workgroup identified 15 case studies as examples of ongoing or planned projects
- 8 case studies in the Lower Basin



W:\480790 CRBS P2\GIS\MapFiles\Kim_Drafts\Ag_CaseStudies_Landscape_rev9.mxd lheyerda 11/6/2014

ID	Case Study
1	CAP Irrigation Districts
2	Yuma Area Efficiency Improvements
3	IID Fallowing and Transfer Program
4	IID & MWD Conservation Program
5	IID Seepage Recovery Program
6	PVID & MWD Forbearance and Fallowing Program
7	Coachella Canal Lining Project
8	All American Canal lining
9	Alternative Agricultural Water Transfer Methods Grants
10	Canal System Improvement Project
11	Colorado River Water Bank Feasibility Study
12	Investigation of Drip Irrigation Consumptive Use
13	Ferron Project
14	Revolving Construction Loan Funding Program
15	West Fork of Battle Creek Reservoir

Case Studies Suggest Considerable Conservation and Efficiency Improvements

- Available data demonstrate that producers have implemented a wide range of conservation and efficiency measures and often increased productivity as a result

TABLE 4-4
Summary of Select Agricultural Conservation Programs with Quantified Acres and Water Savings

Type	Acres	Annual Water Savings[1] (KAFY)	Unit cost ($ per AFY)[2]
Conveyance System Improvements	N/A	456	20–150
On-Farm Efficiency Improvements	362,227	124	285
Consumptive Use Reduction	73,601	400	30–246
Total		980	
Transfers	N/A	650	

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Potential Opportunities

Opportunity 1: Increase and/or maintain productivity through more efficient on-farm activities.

Opportunity 2: Reduce losses and improve operational efficiency through improved conveyance infrastructure.

Opportunity 3: Pursue flexibility associated with strategic consumptive use reductions.

Opportunity 4: Enhance and use mechanisms to facilitate flexible water management

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Potential Opportunities (cont'd)

Opportunity 5: Encourage efficient water management through conservation planning and reporting, data management, and tools development.

Opportunity 6: Foster efficient agricultural water use through sustainable funding and incentive programs.

Opportunity 7: Increase or maintain productivity and improve water management through soil health

Workgroup Key Findings and Messages

- Data gaps and reporting variations make analysis of agricultural water use difficult.
- Increases in on-farm efficiency result in more uniform application of water and may improve productivity, but may not result in consumptive use reduction, and the potential for water savings varies by location (e.g. in or out of the hydrologic basin).
- Water use per acre has remained relatively constant historically while productivity has increased Basin-wide by about 25 percent since 1980.
- Types of water conservation measures and the extent of implementation vary extensively among producers and geographies depending on water supply portfolios, climate, crop mix, and available funding.

Workgroup Key Findings and Messages (cont'd)

- Many of the advances in agricultural conservation have been achieved as part of programs with a variety of federal, state, and local stakeholders working toward mutually beneficial solutions.
- Available data demonstrate that producers have implemented a wide range of conservation and efficiency measures and often increased productivity as a result.
- Agricultural producers will continue to increase the efficiency of water use as feasible. Feasibility depends on location, crops, economic, and other considerations. These efforts may play a role in improving reliability for agricultural producers and building flexibility for meeting additional demand.
- Opportunities exist for additional agricultural water conservation, transfers, and productivity enhancements, but may become more difficult and costly as they are implemented.

Role of Water Savings Pilot Study in Relation to Past and Current Efforts

Progression of Past/Current Efforts

Colorado River Basin Study (2012)	The Basin Study documented the basin-wide water supply-demand imbalance and identified agricultural water use efficiency and transfers as areas where next steps should be taken (among others).
Moving Forward Study (2015)	The Agricultural Conservation, Productivity, and Transfers workgroup identified opportunities for potential future actions and considerations of those actions. Accurate quantification of agricultural conservation savings was identified as a concern.
Conservation Programs (2007-present)	Implementation of proposed pilot projects, such as ICS and the System Conservation Pilot Program. Several program projects were agricultural consumptive use reduction and on-farm efficiency projects.
Ag Water Savings Pilot Study (2020)	Assess current quantification practices and potentially inform future concepts and opportunities through the review of recent/current literature and evaluation of existing case studies.

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Pilot Study – Scope, Schedule, and Milestones

Scope Overview

- Review relevant previous/on-going efforts
  - Avoid duplication
- Refine Pilot Study scope—an exploration of quantification methods
- Conduct literature review of agricultural water conservation
- Focus on activities in the LCRB with an emphasis on quantification methodologies
  - Full-year and seasonal (partial year) fallowing
  - Deficit irrigation
  - Irrigation conversion
  - Crop mix changes
  - Other
- Identify potential case studies in the LCRB

Scope Overview

- Conduct site visits/interviews for selected case studies
  - Conservation activity implemented
  - Quantification method(s) used to estimate conserved water
  - Comparison with Reclamation’s methods and calculations
  - Assessment of opportunities to improve the quantification method(s)
- Document efforts throughout process
- Prepare draft and final reports
- Geographic scope – LCRB (in the US) and the areas in Arizona and California outside the physiographic boundary of the Lower Basin that are supplied with imported Colorado River water

Pilot Study Schedule

LCRB Pilot Study Performance Schedule	Qtr 3 2020	Qtr 4 2020	Qtr 1 2021	Qtr 2 2021	Qtr 3 2021	Qtr 4 2021
Task 1 – Project Administration (by Reclamation)						
Task 2 – Workshop 1 – Scope Refinement & Case Study Definition	9/25		1/4			
Task 3 – Literature Review of Seasonal Fallowing, Deficit Irrigation & Irrigation Conversion Activities		11/16	1/15			
Task 4 – Review and Summarize Seasonal Fallowing, Deficit Irrigation & Irrigation Conversion		11/16		4/4		
Task 5 – Workshop 2 – Case Study Definitions & Selection		1/15		5/23		
Task 6 – Site Visits & Interviews				5/23 5/30		
Task 7 – Case Studies & Technical Reviews				5/30	9/9	
Task 8 – Workshop 3 – Draft Review of Case Studies				7/29		11/13

Pilot Study Milestones

- Workshop 1 – November 9-10, 2020
- Milestone 1: Technical Memorandum 1 – Summary of Refined Scope & Case Study Definition – Draft for Review – Early December 2020
- Milestone 2: Technical Memorandum 2 – Summary of Significant Findings from Literature Review & Recent/Current Activities in the Lower Basin – Draft for Review Late February 2021
- Workshop 2 – Mid-March 2021
- Milestone 3: Technical Memorandum 3 – Summary of Case Study Definition, Site Selection & Evaluation Process – Draft for Review Late April 2021
- Site Visits/Interviews – Late May 2021
- Milestone 4: Draft Report – Case Studies and Technical Reviews– Draft for Rev Mid-August 2021

Pilot Study Milestones (cont'd)

- Workshop 3 – Early September 2021
- Milestone 5: Pilot Study Final Report – Draft for Review Mid to Late October 2021
- Pilot Study Final Report – Mid November 2021
- Presentation at CRWUA – December 2021

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Workshop Participant Perspectives

Day 1 Wrap-up and Preview of Day 2

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Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

Workshop #1

November 9-10, 2020

Agenda – Day 2

- Brief Review of Day 1
- Pilot Study Scope Refinement
- Conservation Measures and Quantification of Consumptive Use in Colorado River Water Accounting
- Case Study Definition and Approach
- Wrap-up and Next Steps

Review of Day 1

BUREAU OF RECLAMATION

Pilot Study Scope Refinement – Discussion and Feedback

Pilot Study Scope Refinement

- Conservation actions
- Available literature – studies, reports
- Recent, on-going and planned efforts
- Data and information sharing

Conservation Actions

- *Basin Study* – options organized into 6 categories "…agricultural water conservation mechanisms consisted of advanced irrigation scheduling, deficit irrigation, on-farm irrigation system improvements, controlled environment agriculture, conveyance system efficiency improvements, and fallowing of irrigated lands"
- *Moving Forward* Ag Water Conservation Workgroup focused on four topics:
  - Consumptive use reductions
  - On-farm efficiencies
  - Conveyance system improvements
  - Water transfers

Conservation Actions (continued)

"Types of water conservation measures and the extent of implementation vary extensively among producers and geographies depending on water supply portfolios, climate, crop mix, and available funding"

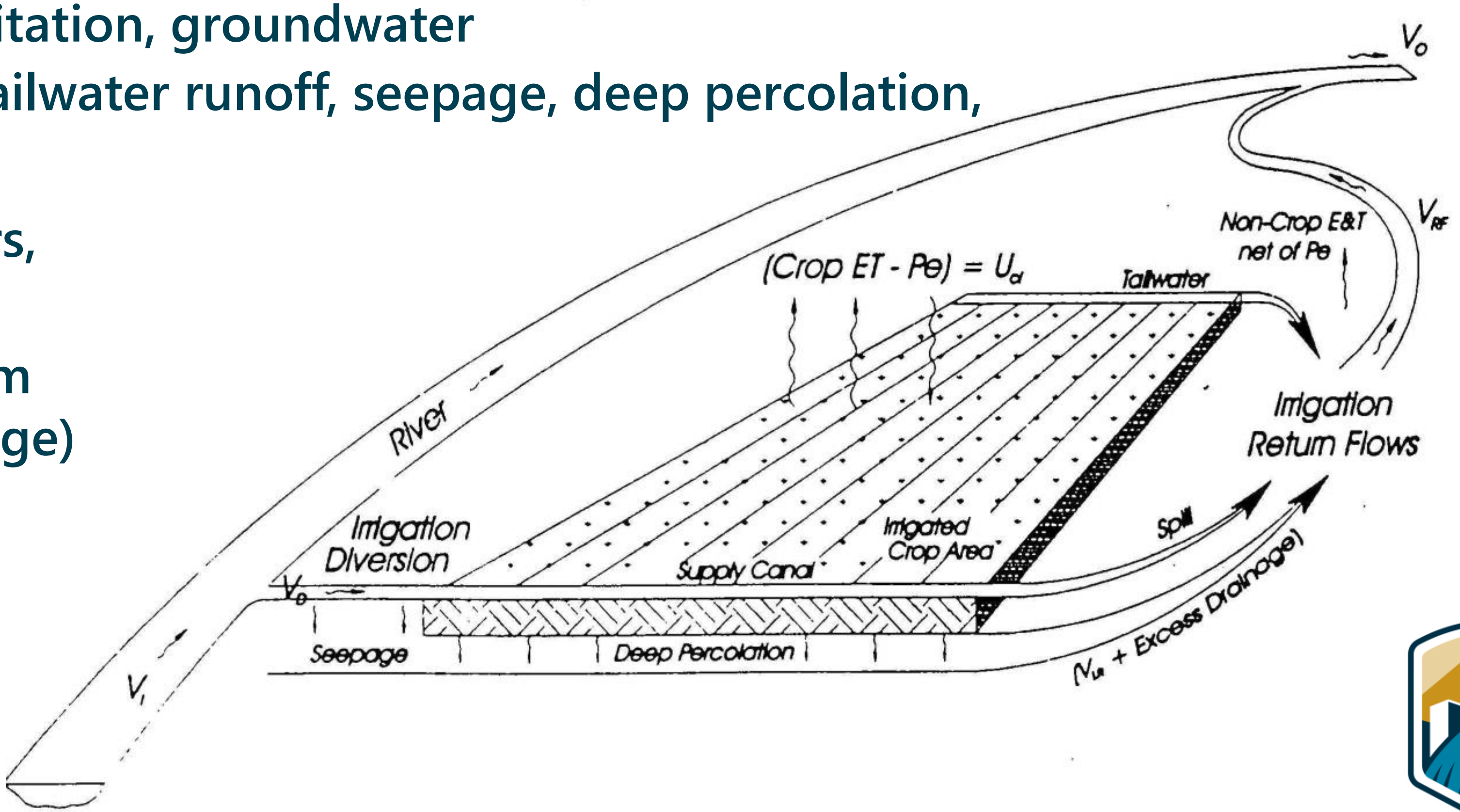
-Moving Forward Phase 1 Report

Efficiency Analyses and Estimation of Conserved Water

Water budget/ water balance analyses

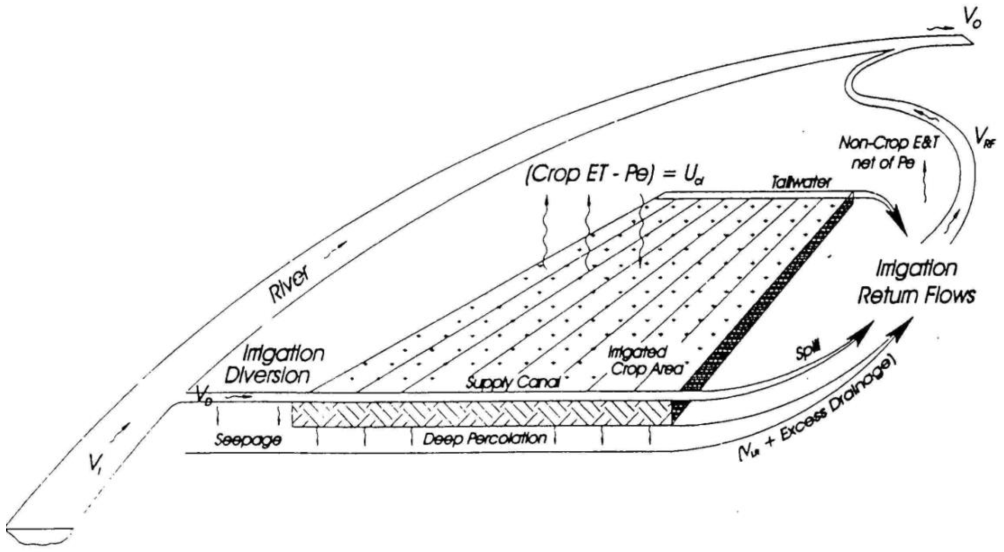
Inflows - Outflows ± ΔStorage = 0

- Water budget/ water balance analyses
  - Inflows→ diversions, precipitation, groundwater
  - Outflows→ crop ET, spills, tailwater runoff, seepage, deep percolation, groundwater
  - Storage→ surface reservoirs, soil water
  - Conveyance/delivery system level (losses to spills, seepage)
  - Farm system level (deep percolation, tailwater runoff)
  - Crop ET



Efficiency Analyses and Estimation of Conserved Water (continued)

- Overall Efficiency =
  Crop ET ÷ Total Diversions
- Conveyance Efficiency =
  Total Farm Deliveries ÷ Total Diversions
- On-farm Efficiency =
  Crop ET ÷ Total Farm Deliveries



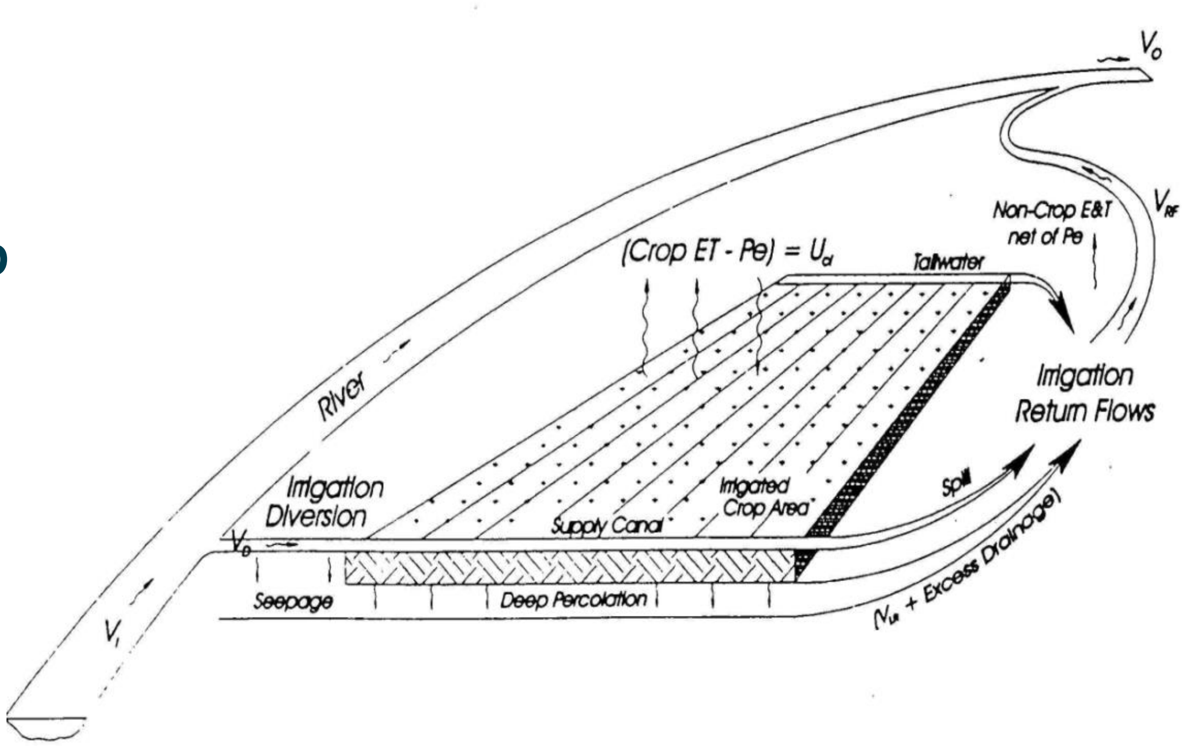
- Identify where water is going, how much is going there, and when
- Identify potential improvements and how much water can be saved
  - Varies from location to location across the project
  - Varies during the season or during the year
  - May vary from year to year (dry years, wet years, climate change)

Efficiency Analyses and Estimation of Conserved Water (continued)

- Efficiency Improvements
  - Conveyance/Delivery System
    - Re-regulation to capture and use operational spills
    - Lining or replacement with pipe to reduce canal seepage losses
  - On-farm System
    - Irrigation method conversion to reduce on-farm losses – tailwater runoff, deep percolation, evaporation
    - Improve on-farm water management – tools and instrumentation to help with decisons of when to irrigate and how much needs to be applied
  - Drainage System
    - Capture and re-use drain water (quality is acceptable)
    - Reduce non-beneficial plant water use (assuming desirable habitat is not destroyed)
- Water losses (return flows) are reduced thereby allowing less water to be diverted and applied while meeting same level of crop demand

Consumptive Use Reduction and Estimation of Conserved Water

- Demand reduction
  - Fallowing – permanent, temporary, rotational, seasonal
  - Switch to lower water use crops or crop mix
  - Deficit irrigation
- Occurs on-farm at the field level
- Requires estimation of associated diversion reduction based on:
  - On-farm efficiency
  - Conveyance efficiency



Literature Review

- Review of academic and technical literature – studies, reports, journals
- Consumptive use quantification methodologies and approaches to quantification of water conserved
  - Full-year agricultural cropland fallowing
  - Seasonal or partial-year cropland fallowing
  - Deficit irrigation
  - Switching crops or crop rotations to alternate crops requiring less irrigation water
  - Irrigation methodology conversions

Literature Review (continued)

- The water conservation methodologies drive the literature review
- Focus on information, data, reports, and results since the completion of the Basin Study and the Moving Forward Phase 1 report
- Prioritize literature addressing conservation activities and topics applied in the Lower Basin
- Document all literature reviewed and prepare an annotated bibliography

Recent, On-going, and Planned Efforts

- Review irrigation water conservation efforts in the Lower Basin
- Document the conservation activity
- Document the quantification methodologies and approaches
- Observed results, findings, constraints and limitations of the activity
- Unanticipated consequences… lessons learned
- What was the final outcome(s) of the quantification of consumptive use savings
- Recommendations for improving quantification methods
- Other factors – accuracy, cost, effectiveness…

Data and Information Sharing

- Input and feedback from all interested parties is critical and valued
- We want to know about your ideas and experiences

- Pilot Study website:

https://LCRBPilotStudy.com/

-Post comments

-Ask questions

-Upload/download project reports and other documents

BUREAU OF RECLAMATION

Conservation Measures and Quantification of Consumptive Use in Colorado River Water Accounting

Colorado River Water Accounting

- The Secretary of the Interior serves as Water Master for the Lower Colorado River
- Pursuant to 1964 U.S. Supreme Court Decree (Consolidated in 2006) Reclamation is required to account for Colorado River water use
  - Official record of mainstream diversions, returns & consumptive uses
  - Colorado River Accounting & Water Use Report

Decree Definitions

- Diversions: Colorado River Water diverted from the mainstream, including underground pumping
- Returns: Return flow of such water to the stream as is available for consumptive use in the United States or in satisfaction of the 1944 Mexican Treaty obligation
- Consumptive Use: "…diversions from the stream less such return flow thereto as is available for consumptive use in the United States or in satisfaction of the Mexican Treaty obligation"
  - Consumptive Use = Diversions – Returns

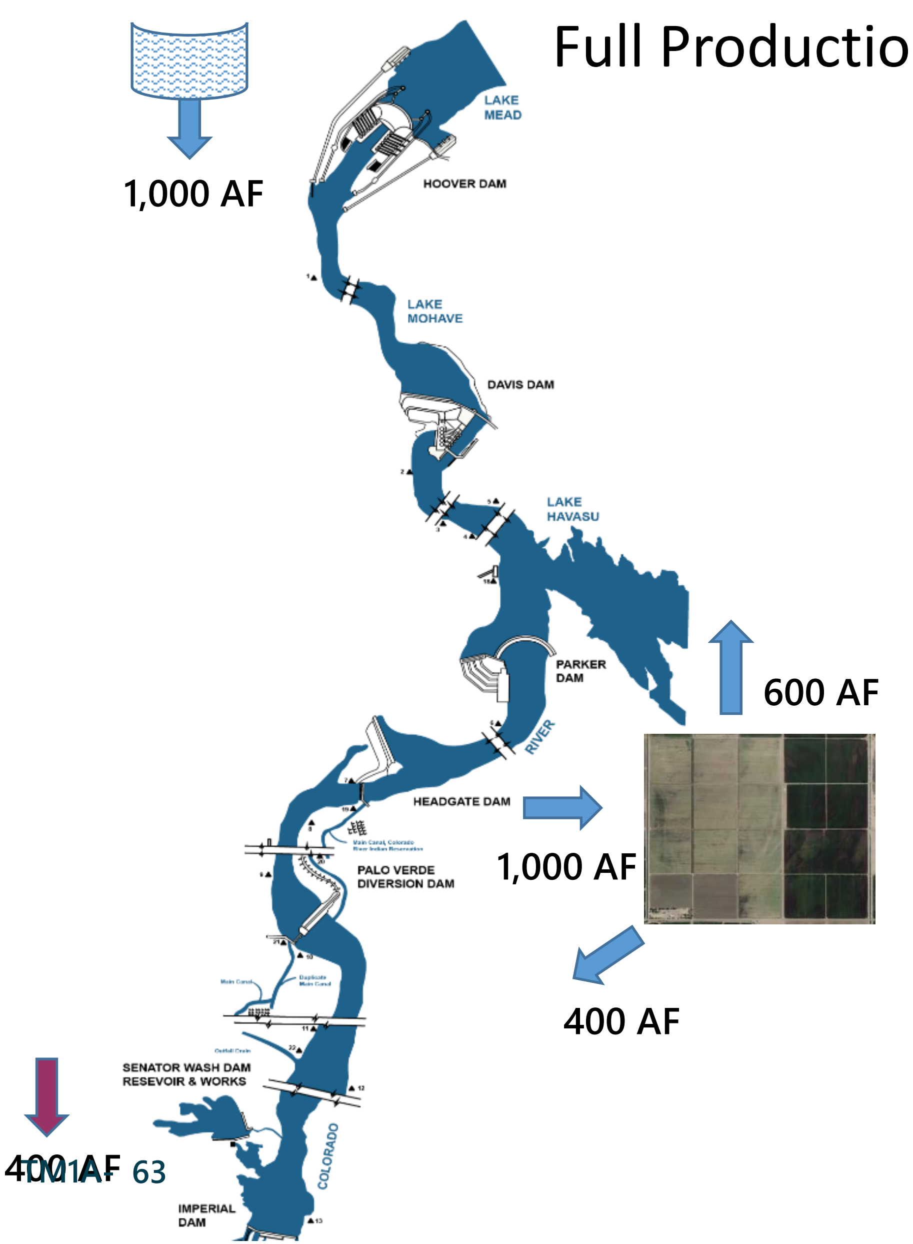
Fundamental Principle of Conservation

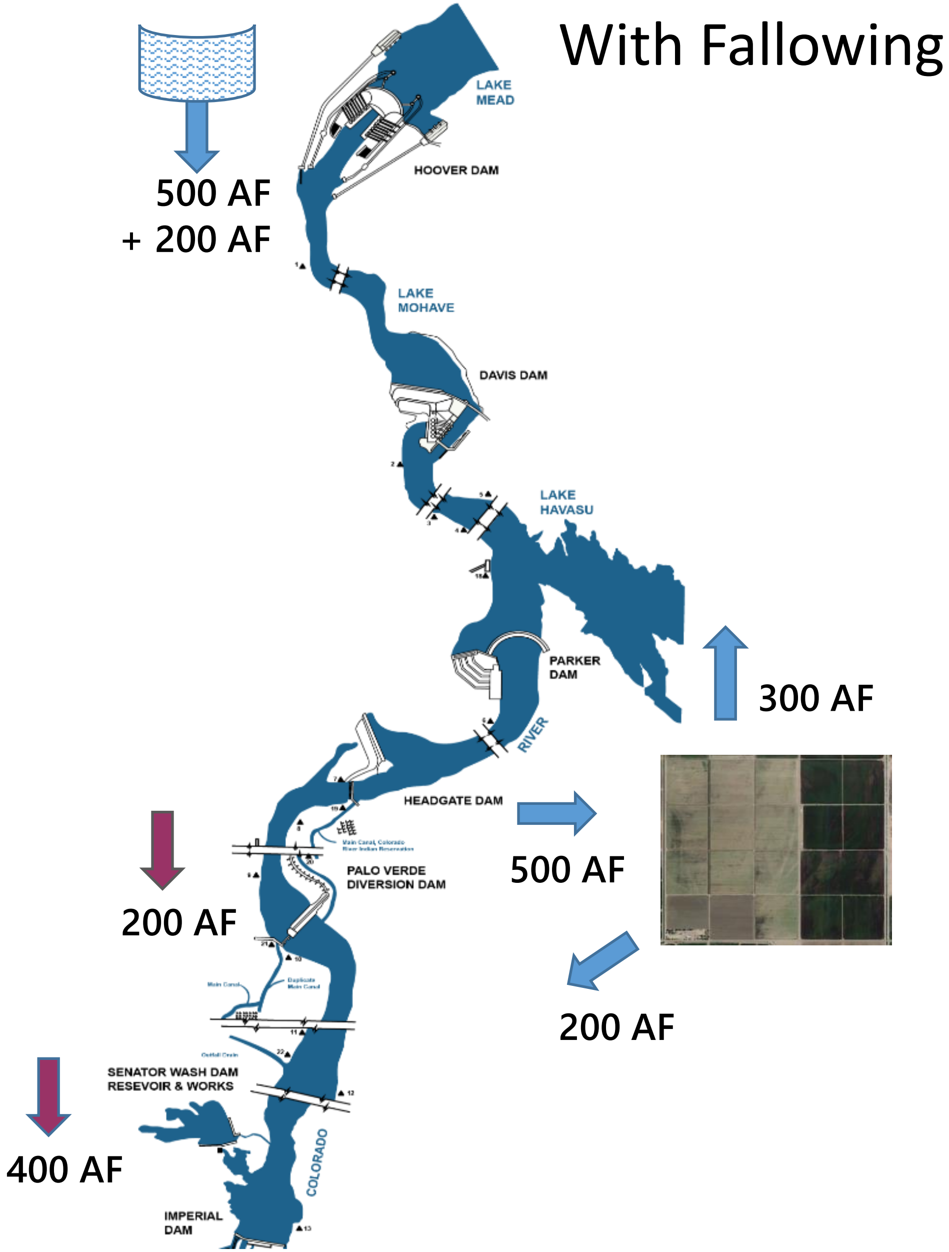
- Must be a measurable reduction in mainstream Colorado River consumptive use
  - Potential for water savings varies by location (for example, in or out of the hydrologic basin)

Conservation Measures Implemented in the Lower Basin

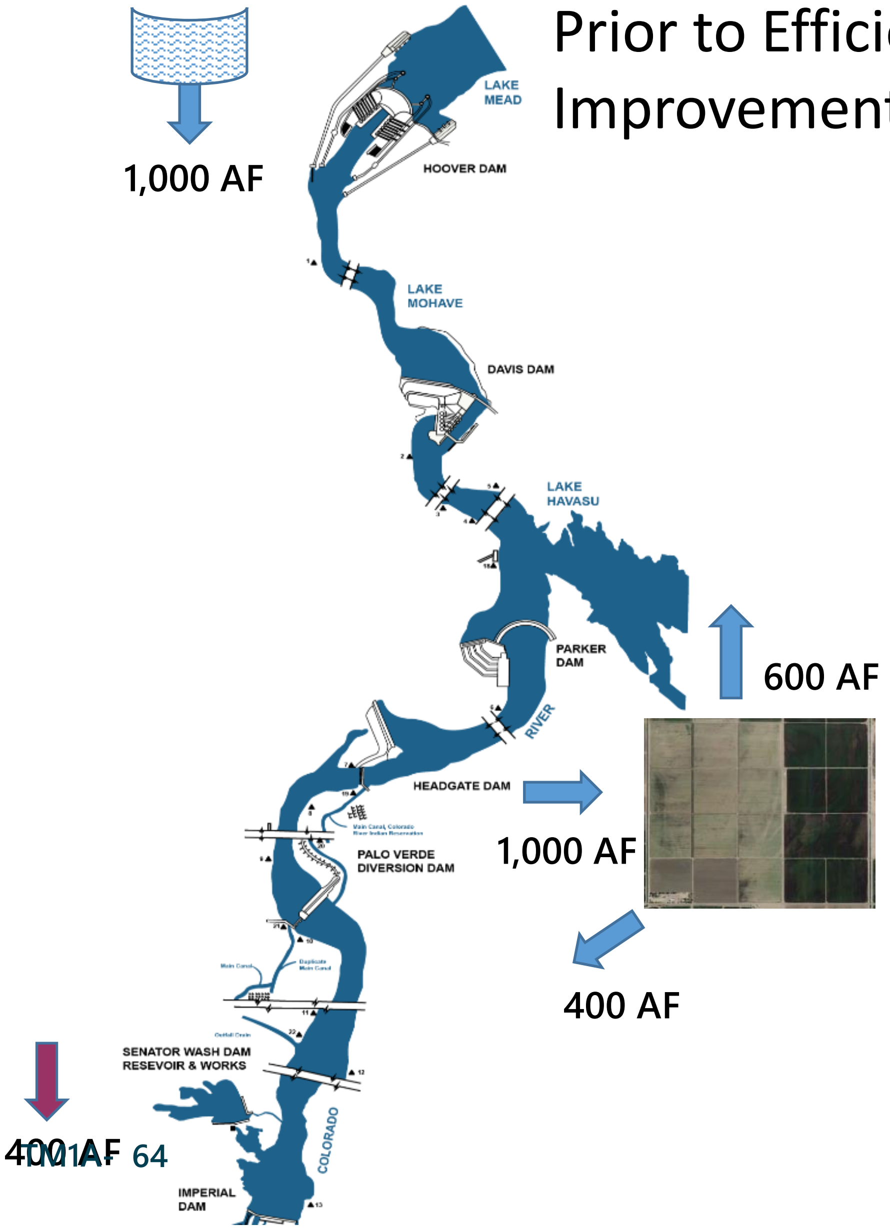
- Fallowing
  - Seasonal/Full-Year
- On-Farm Efficiency
  - Drip Irrigation
  - Tailwater Return Systems
  - Center Pivot
- Delivery System Improvements
- Seepage Recovery
- Canal Lining

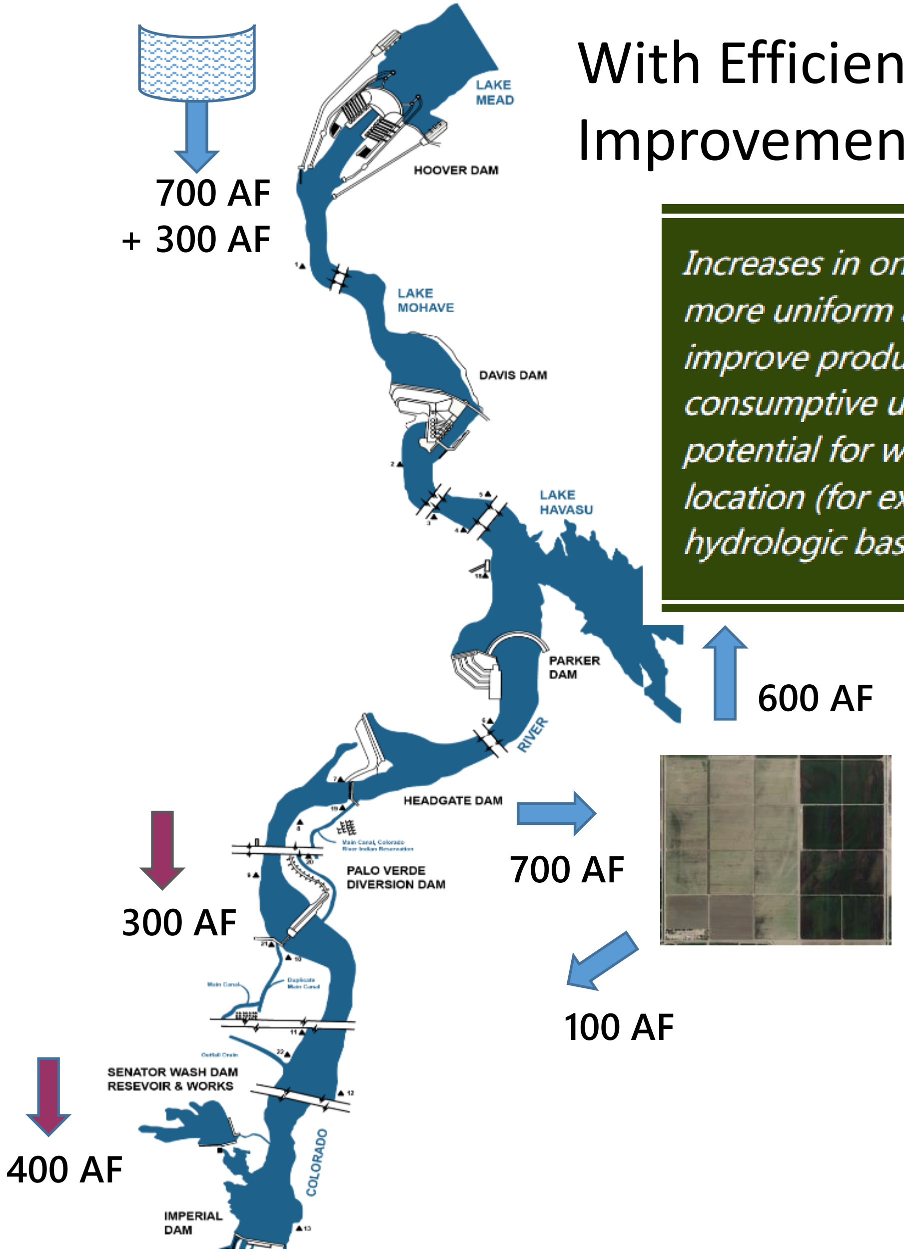
Consumptive Use Examples - Fallowing





Consumptive Use Examples – Efficiency

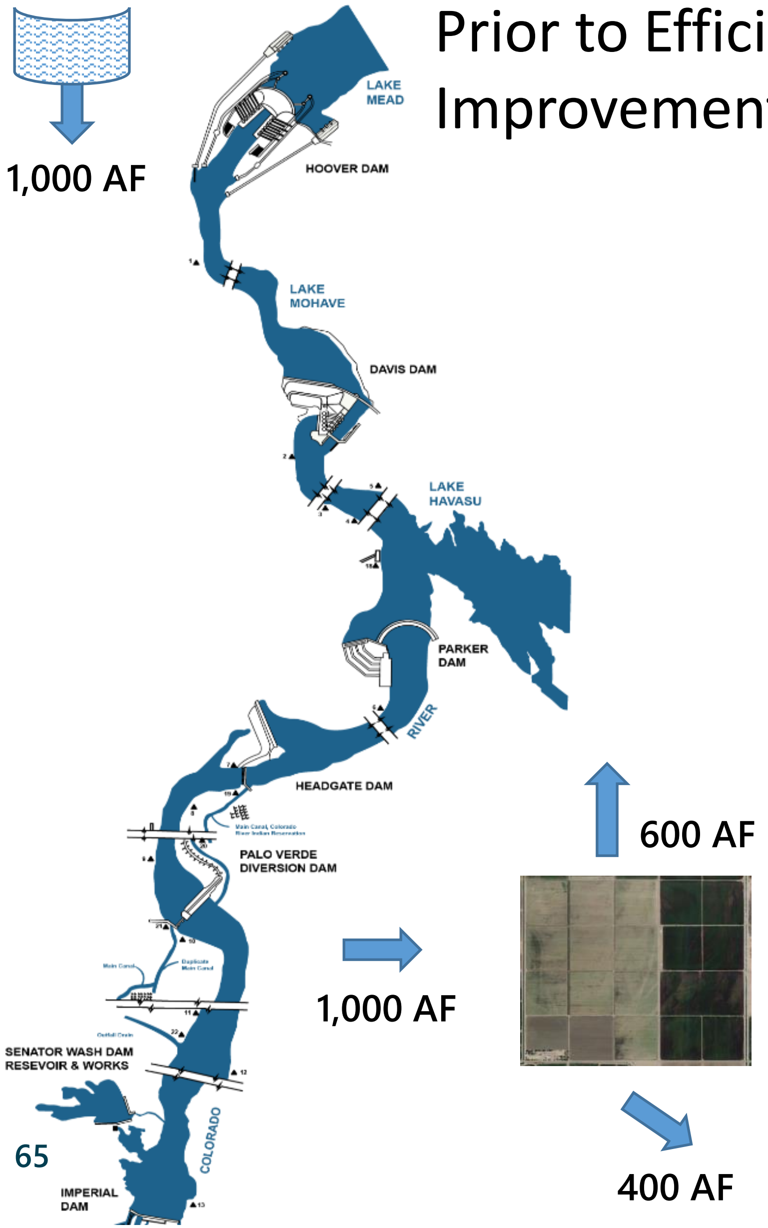




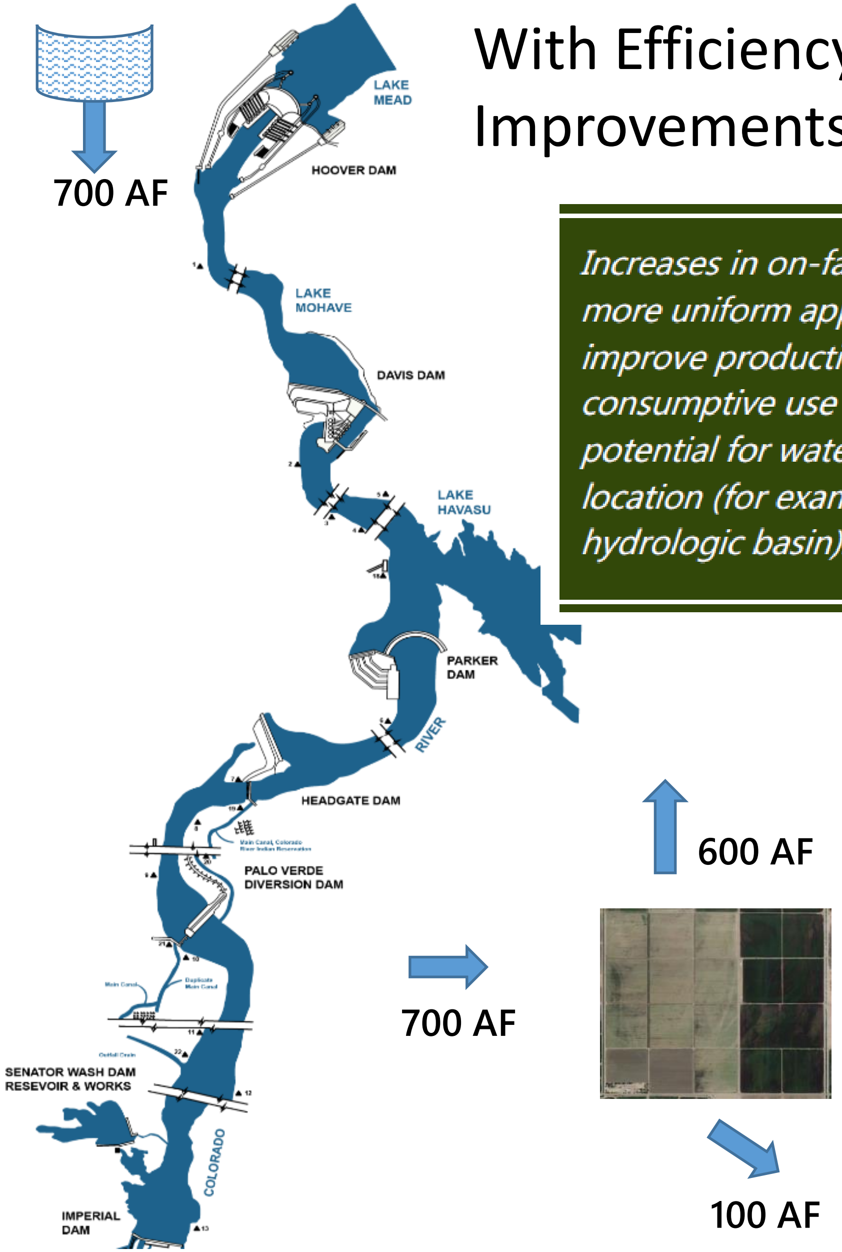
Increases in on-farm efficiency result in more uniform application of water and may improve productivity but may not result in consumptive use reduction, and the potential for water savings varies by location (for example, in or out of the hydrologic basin).

Consumptive Use Examples – Exported Water

Prior to Efficiency Improvements



With Efficiency Improvements



Increases in on-farm efficiency result in more uniform application of water and may improve productivity but may not result in consumptive use reduction, and the potential for water savings varies by location (for example, in or out of the hydrologic basin).

Lower Basin Programs Administered by Reclamation

- Inadvertent Overrun and Payback Policy (IOPP)
  - Requires water users to payback overruns to the system through extraordinary conservation
    - 583 KAF paid back since initiation of the IOPP
- Intentionally Created Surplus (ICS)
  - Provides water users ability to store conserved water in Lake Mead for future delivery
    - Total ICS stored in Lake Mead was 2.3 MAF at end of CY 2019
- Pilot System Conservation Program (PSCP)
  - Funding provided for extraordinary conservation yielding water stored in Lake Mead as System Water
    - 165 KAF of created through CY 2019

Quantification Methods Used in the Lower Basin

- Quantification methods are unique to each water user
  - User proposes method to Reclamation
- Fallowing quantification methods include:
  - District average
    - Historical or actual year
  - Field specific
    - Water delivery records
    - ET estimates

Fallowed Field in Imperial Valley

Summary

- Consumptive Use = Diversions – Returns
- Conservation measures must result in a measurable reduction in mainstream Colorado River consumptive use
  - Potential for water savings varies by location (for example, in or out of the hydrologic basin)
- Various quantification methods are currently used in the Lower Basin

Case Study Definition and Approach

Working Definition of Case Study

- An applied research method involving an up-close, in-depth, and detailed examination of a particular phenomenon, like a person, group, or situation
- The phenomenon is studied and analyzed in detail and solutions or interpretations are presented … provides a deeper understanding of a complex topic or assists in gaining experience about a certain historical situation

Paraphrased from: Stephanie Glen. "Case Studies: Case Study Definition and Steps" From StatisticsHowTo.com: Elementary Statistics for the rest of us! https://www.statisticshowto.com/case-studies/

Case Study Steps

- Determine the research question and carefully define it…
  - What agricultural water conservation technologies are being implemented and what methodologies are being used to quantify conservation in the Lower Colorado River Basin
- Choose the cases and state how data is to be gathered and which techniques for analysis will be used…
  - Which conservation activities will be focused on and where
    - Review of recent/current activities
    - Literature review

Case Study Identification Approach

- Potential case studies identified by project team and participants
- Through a collaborative workshop process, determine:
  - Agricultural conservation method(s) utilized
  - Locations in the LCRB
  - Quantification method employed
  - Available data/information
- Develop consensus recommendations for the case studies to be evaluated

Case Study Steps (continued)

- Prepare to collect the data…
  - Workshop to identify and recommend case studies
    - Opportunities, constraints, limitations
    - Sites
    - Evaluation process
- Collect the data…
  - Site visits and interviews – site specific perspectives on the impacts (positive and negative) of the identified activities, as well as limitations or constraints on quantification methods, and opportunities for improvements

Case Study Steps (continued)

- Analyze the data…
  - Technical review of the quantification methods used
  - Relationship with the quantification of consumptive use and Reclamation's Decree Accounting in the Lower Basin
  - Review and compare the applied quantification methods to the approaches identified in the literature review.
  - Provide an assessment of opportunities to improve or enhance quantification methods
- Report results…
  - Prepare draft report and review with participants at final workshop
  - Prepare final report

Wrap-up and Next Steps

Technical Memorandum 2 – Summary of Significant Findings from Literature Review and Recent/Current Activities in the Lower Basin

Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

U.S. Department of the Interior March 2021

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Technical Memorandum 2 – Summary of Significant Findings from Literature Review and Recent/Current Activities in the Lower Basin

Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

prepared by

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Jacobs Engineering Group Inc.

Cover Photo: United States Bureau of Reclamation

Contents

Page

List of Tables

Project Definition

The Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin Pilot Study (Pilot Study) is a logical next step in the long-standing commitment of United States Bureau of Reclamation (Reclamation) and the Lower Colorado River Basin (LCRB, Lower Basin) stakeholders to ensure the resiliency, reliability, and sustainability of the Colorado River. The objective of this study is to work collaboratively with a diversity of stakeholders to explore the methods used to quantify consumptive use (CU) for certain agricultural water conservation activities in the Lower Basin, including the relationship of those quantification methods to Reclamation's Lower Colorado River Decree Accounting, and to recommend approaches to improve agricultural water conservation quantification methods.

The Pilot Study commenced with a workshop (Workshop #1) held remotely November 9 and 10, 2020. The workshop included a summary of the 2012 *Colorado River Basin Supply and Demand Study* (Reclamation, 2012) and the 2015 *Colorado River Basin Stakeholders Moving Forward to Address Challenges Identified in the Colorado River Basin Water Supply and Demand Study* (Reclamation, 2015) reports. The workshop also provided an opportunity for stakeholders and participants to provide input regarding scope refinement for the Pilot Study. A summary of Workshop #1 and the refined project scope were provided in *Technical Memorandum 1 – Project Definition and Summary of Workshop #1*, herein referred to as TM1 (NRCE and Jacobs, 2021).

Introduction

This technical memorandum (TM2) is the second step in the Pilot Study effort and provides documentation of methods used to quantify CU reductions from agricultural irrigation conservation measures in the LCRB and elsewhere. This documentation effort was divided into two portions: 1) a review of scientific literature and other sources to identify CU quantification methods, and 2) a more detailed review of specific conservation activities within the LCRB and associated CU quantification methods.

Overview of Literature Review

The literature reviewed included scientific journals, project reports, regional publications, reference books, etc. The focus of the review was documentation and evaluation of CU quantification methods. The review was particularly focused on literature for studies within the LCRB and the Lower Basin states. However, literature from adjacent regions, the western U.S., and some international literature was also reviewed. Greater consideration was typically given to literature within the LCRB, with decreasing priority or focus the further a study location was from the LCRB.

The literature reviewed included documentation of specific CU quantification methods, application of such methods, and comparisons between methods. Some of the literature reviewed focused on certain conservation activities rather than CU quantification. These sources were considered to be of secondary importance. As part of the literature review, an annotated bibliography was prepared documenting references that were reviewed in greater detail (Table B-1).

Overview of Recent Activities in the Lower Basin

For more than two decades there has been significant agricultural water conservation activity and investment in irrigation systems to improve efficiencies in the LCRB. This section provides a review of specific conservation measures and associated CU quantification methods for a handful of projects within the LCRB for which readily accessible information was available. Five specific agricultural irrigation water conservation projects located in Arizona and California were selected as examples for this review. The review included a summary of the project conservation measures as well as the CU methods used.

Background and Key Definitions

Definitions and background concerning specific conservation activities and CU quantification methods considered in this Pilot Study are provided in the following subsections.

Conservation Activities

For the present study, water conservation was defined as any activity that reduces CU from the mainstream of the Colorado River and focused primarily on the following four conservation methods:

- Deficit irrigation
- On-farm irrigation system conversion
- Seasonal fallowing
- Crop rotations/alternative cropping

Other conservation methods that were considered include (but are not limited to):

- District/distribution system conveyance system (efficiency) improvements (upstream of the farm turnout or diversion)
- On-farm conveyance system (efficiency) improvements (downstream of the farm turnout or diversion)
- Advanced irrigation scheduling

These latter activities were reviewed to a lesser extent than the prior four. In addition to the conservation methods noted above, crop productivity implications of all conservation methods were considered where information was available since this is an important decision factor for growers engaging in irrigation water conservation efforts.

It is prudent here to define the term *irrigation efficiency* as it relates to conservation. Although there can be several different measures of irrigation efficiency within different parts of an irrigation distribution and application system (Burt, et al. 1997), system or district level irrigation efficiency is considered for the purpose of this study. Irrigation efficiency at the system or district level is a measure of the amount of water beneficially used by a crop relative to the amount of water that was diverted. Inefficiencies include water seepage or deep percolation, surface water runoff, operation spills, and evaporation. Improvements in irrigation efficiency may or may not result in a reduction in CU depending upon the type of improvement made (e.g., see TM1; see also Ward and Pulido-

Velazquez, 2008) and, in the context of the LCRB, depending on whether the improvements were for on the Colorado mainstream or off-mainstream projects (TM1). Therefore, whether or not an efficiency improvement should be considered a conservation measure is location dependent. It is noted, however, that some on-mainstream efficiency improvements may result in reduced CU (e.g., in the case of reduced evaporation as a result of piping a canal), or reduced water contribution to non-beneficial riparian vegetation CU (e.g., tamarisk and phragmite removal) regardless of their location (on-mainstream vs. off-mainstream).

Quantification Methods

Evapotranspiration (ET) is the combined process of evaporation of water from the soil surface and other wet surfaces (wetted foliage, etc.) and transpiration by vegetation. In the evaporation process, free water on the evaporating surface changes state from liquid to vapor and is removed from the evaporating surface. In the transpiration process, water that is absorbed by the plant's root system and moved to the above ground vegetative surfaces is vaporized in intercellular spaces of the plant tissue. This water vapor is exchanged with the atmosphere and is controlled by plant stomata. Evaporation and transpiration occur simultaneously; as a result, there is no easy way to distinguish between the two processes. When the crop is small, water is primarily lost by soil evaporation. Once the crop is more developed and completely covers the soil, water is primarily lost by transpiration. The terms crop evapotranspiration (ET_c) and crop CU are often used interchangeably. Crop consumptive use may, in some cases, be slightly greater in magnitude as it includes any water removed from the field contained in plant tissues at harvest time. Typically, however, this is a very small percentage of total water lost in the ET process.

It is common for literature on CU quantification to focus on quantification of ET. This is because, ET is water that leaves a basin and is not available for downstream or downgradient uses. For the purposes of the present study, it is also helpful to consider CU to be the portion of ET derived from applied irrigation water (ET_{aw}) as opposed to ET derived from precipitation (e.g., Orang, et al., 2013; Simons et al., 2020; Allen et al., 1997). This is also termed the net irrigation water requirement (NIR), which is evapotranspiration less effective precipitation (where effective precipitation is that portion of total precipitation that effectively meets crop demand).

Reclamation prepares an annual report of diversions, measured and unmeasured return flows, and consumptive use by each water user diverting Colorado River water in the Lower Basin per the requirements of the Consolidated Decree of the U.S. Supreme Court in *Arizona v California* (547 U.S. 150 (2006)). This report is known as the Decree Accounting Report or Water Accounting Report. In the case of on-mainstream diversion and use where return flows eventually re-enter the Colorado River at some downstream location, CU is computed as the Diversions minus Return Flows (Reclamation, 2020; TM1). In cases where water is diverted and exported from the Colorado River Basin, CU equals the total portion of the diversion that leaves the basin, (i.e., no mainstream return flows).

The differences between on-mainstream and off-mainstream diversions mentioned above is important to understand because in the latter case, a simple properly sited flow measurement can capture CU but in the former case, it may be necessary to quantify ET, in particular ET_{aw}. Most methods for quantifying CU detailed herein relate to quantifying total ET. Quantification of ET_{aw} often requires additional measurements and or modeling exercises to partition ET into the various source terms.

The ET quantification methods described in the literature review include the primary methods used in both research and practical settings. Methods currently limited to research settings typically require more data, more expertise in application, more time or monetary resources, or some combination of these than do methods more suited to practical settings.

Primary methods for quantifying ET can be characterized into several categories (e.g., Shuttleworth, 2008; UDNR, 2020).

- Water balances
  - Soil water balances and field-level water balances
  - Project-level water balances
  - Delivery and other flow measurements
- Micrometeorology
  - Eddy covariance
  - Bowen ratio energy balance
  - Surface renewal
  - Scintillometry
- Lysimetry
- Reference evapotranspiration/crop coefficient modeling and spatial crop surveys
- Remote sensing evapotranspiration modeling
  - Reflectance-/Vegetation-Index-based methods
  - Energy balance models/thermal methods
- Other (micro-lysimeters, sap flow, etc.)
- Combined methods

As previously mentioned, it is often necessary to quantify not only ET but ET_{aw} (e.g., Simons et al., 2020), which includes, among other things, quantification of precipitation. It is also important to identify a means of comparing CU in areas with conservation to what the CU would have been without conservation (e.g., Allen and Torres-Rua, 2020).

Significant Findings of Quantification Literature Review

As mentioned, the literature review included sources from scientific journals, project reports, regional publications, reference books, etc. The focus of the review was the documentation and evaluation of CU quantification methods, rather than individual study results, except where those results related to the performance of a method. In some cases, the literature included comparisons between methods, though such information was not always available. The literature review has been organized by quantification method, with some literature appearing in multiple subsections and some methods, subsequently, being discussed in comparison with others.

Water Balances

The discussion of water balances provided below has been organized into three sections: 1) Soil water balances and field-level water balances, 2) project-level water balances, and 3) delivery and other flow measurements.

Soil Water Balances and Field-Level Water Balances

A common method for quantifying CU in research studies is to perform a soil water balance, typically at a field- or plot-level. In a soil water balance, a control unit must be defined. A control volume is a volume (in this case of bulk soil) for which inflows, outflows, and changes in storage are quantified. In a soil water balance, the soil root zone or some deeper reaching zone is typically considered to be the control volume of interest (e.g., Jensen and Allen, 2016). Water inflows and outflows are quantified and also the change in soil water content in the root zone. Water inflows include irrigation (*I*), precipitation (*P*), surface run-on (*ROn*), subsurface lateral (horizontal) inflow (*LIn*), and contributions from groundwater through capillary rise (*CR*) or direct root extraction from the saturated zone (RE_{GW}) resulting from rootzones extending into the saturated zone (e.g., Jensen and Allen, 2016). Water outflows include ET, surface runoff (*RO*), deep percolation (*DP*), and subsurface lateral outflow (*LOut*) (e.g., Jensen and Allen, 2016). The complete soil water balance is frequently defined in terms of soil water storage (*S*) (e.g., Jensen and Allen, 2016) and can represented as:

$$S_i = S_{i-1} + P_i + ROn_i + LIn_i + CR_i + (RE_{GW})_i - ET_i - RO_i - DP_i - LOut_i$$

where the subscript *i* represents the time step of interest, with *i*-1 being the previous time step. To simplify the analysis, assumptions are often made regarding some of the inflows and outflows, requiring careful site selection and water management (e.g., Evett et al., 2012b; Jensen and Allen, 2016). Typically, subsurface lateral flows are disregarded. Surface run-on, too, is typically disregarded. Under certain circumstances runoff too may be disregarded, but it may also be estimated through modeling (e.g., Djaman and Irmak, 2016). If the water table is far below the root zone, direct contributions of groundwater can be disregarded. If the soil water content is maintained at a sufficiently dry content and soil water content measurements are made below the rooting depth, then an assumption of zero deep percolation can be verified (Evett et al., 2012b). Under these conditions, the soil water balance can be performed by measuring applied irrigation, precipitation, and soil water content (used to quantify *S*) throughout the root zone and solved for ET e.g.:

$$ET_i = S_{i-1} - S_i + P_i - RO_i$$

It should be noted that the assumption of zero deep percolation may not be reasonable in many applications within the LCRB because of the necessity of salt leaching. Salt leaching is the practice of applying irrigation water above the amount necessary to replenish the root zone soil water with the express purpose of moving salts out of the crop root zone (e.g., Ayars et al., 2012). This is necessary, because as irrigation water with some dissolved salts is applied to a field, ET processes result in a concentrating of salt in the root zone. Without leaching, this can become toxic to plants and reduce yield (Greive et al., 2012). If leaching is necessary, or *DP* is otherwise unavoidable during a water balance computation period, the associated *DP* must be quantified. For example, Barker et al. (2018) did this by running a water balance including an ET model between soil water measurements to estimate *DP*. Irmak and Djaman (2016) also computed *DP* using a water balance.

It is important to measure the soil water content with sufficient accuracy and precision. Therefore, not all soil water sensing technologies are well suited for these purposes (Evett et al., 2012a). Common soil water sensing technologies include:

- Capacitance sensors, which are among the least expensive of electronic sensors for soil water content (Sharma, 2019), may not be sufficiently accurate for field soil water balance estimations (Evett et al., 2012a). Such sensors often give a reading on a relative scale and may require site calibration to convert the reading to water content on a depth of water per unit depth of soil (Sharma, 2019). Such a conversion is necessary to determine depth or volume of water extracted from the soil profile as ET or CU.

- Time-domain reflectometry (TDR) measures soil water content and tends to be among the most accurate of electronic sensors (Evett et al., 2012a; Sharma, 2019), and may not require local calibration but can be more expensive (Sharma, 2019).

- Frequency-domain and pseudo transit time sensors measure soil water content, but are not true TDR sensors, and likely require local calibration (Irmak and Irmak, 2005).

- Neutron probe is a highly accurate means of measuring soil water content (at depths greater than about 15-20 cm (6-9 inches). Neutrons exit the soil into the atmosphere at shallower depths and as a result, the probe's calibration is not usable. Special calibrations can be prepared for the surface layer but are typically less reliable. Neutron probes have both safety and regulatory concerns, are expensive, and require a human to take the measurements (Jensen and Allen, 2016; Sharma, 2016; Evett et al., 2012a).

- Gravimetric soil sampling involves collecting and weighing wet soil samples, drying the samples under prescribed standard conditions, and then re-weighing the samples. It is subject to soil variability, time, sample collection effort, and expense among other things (e.g., Jensen and Allen, 2016; Evett et al., 2012a). Gravimetric sampling requires the soil water content by weight to be converted to a depth or volume basis in order to determine depth or volume of water extracted from the soil profile as ET or CU.

- Matric potential measurements use a tensiometer or granular matrix block. While these can be inexpensive, they may require local calibration (Sharma, 2019). Since they measure soil water matric potential (tension) rather than water content, must be converted to a depth or volume basis in order to determine depth or volume of water extracted from the soil profile as ET or CU.

In research settings, soil water content measurement by neutron attenuation (neutron probe) or TDR are typically the preferred methods (Evett et al., 2012a; Chávez et al, 2012). Evett et al. (2012a) reported that capacitance sensors were not sufficiently accurate for water balance purpose. Sharma et al. (2019) found several types of electronic sensors, including TDR required local calibration. It is also important to understand that a single measurement location in a field is likely insufficient (Zotarelli, et al. 2016; Barker et al., 2017). The sensors described above could be considered point sensors and require multiple measurements be made spatially and with depth over the field of interest. Some other methods that exist are cosmic ray probes, which measures soil water content over a relatively large area, but only at shallow depths (e.g., Hardie, 2020; Hydroinova, 2020); and electromagnetic surveys, which measure soil apparent electrical conductivity, but can be used for soil water content measurement, though this is difficult (Hardie, 2020).

For the point soil profile water sensors, it is common to make measurements at regular intervals, e.g., the center of each foot below ground surface. For water balance purposes, volumetric water content is the necessary measurement. Volumetric water content has units of volume of water per volume of bulk soil and can be thought of as the fraction of the total soil volume that is water. When computing soil water storage (S) for a water balance, each sensor or measurement in a profile is assumed to represent a certain depth range of soil (in the current example, that would be one vertical foot of soil). Thus, S would be the sum of all measurements in a profile at a given time multiplied by each measurement's respective depth (each multiplied by one foot of soil, in this case).

Soil water balances have been used to quantify CU for different conservation measures. Iniesta et al. (2008) used a water balance based upon neutron probe measurements to quantify ET in deficit-irrigated pistachio in California. Orloff (2003) reported the use of a soil water balance for deficit-irrigated alfalfa in the Klamath Basin and Sacramento Valley of California. Stewart et al. (2011) used a soil water balance to quantify ET for deficit-irrigated almonds in the Sacramento Valley of CA.

An accurate soil water balance can also serve as a standard for validating other quantification methods. For example, Chávez et al. (2012) used a soil water balance to validate ET measured using remote sensing techniques.

Often field-scale water balances are computed using customized tools following methods presented in Jensen and Allen, 2016 and Allen et al, 1998. However, some packaged software programs are available that compute some aspects of field water balances such as the Soil-Plant-Atmosphere-Water (SPAW) model (Saxton, 2017).

Project-Level Water Balances

Project-level water balances follow the same principles as a field-level water balance, though the inputs and outputs and assumptions may vary. Project-level water balances also vary in size and methodology. For example, Allen et al. (2005) used a surface water inflow and outflow balance to quantify ET for the Imperial Irrigation District (IID) in southern California. They describe the soil conditions with depth underlying the IID as having a high percentage of clay with very low hydraulic conductivity. This results in any deep percolation of applied irrigation water being forced to move laterally to surface drains and "only very small amounts of deep percolation leave the project directly as subsurface flows" (Allen et al. 2005). This allowed disregarding subsurface flows in the water balance without introducing large errors. Taghvaeian and Neale (2011) computed a water balance for the Palo Verde Irrigation District (PVID) in southern California and compared it to a remote-sensing-based ET model (SEBAL; Bastiaanssen et al., 1998). As was demonstrated for field- or plot-level soil water balances, Taghvaeian and Neale (2011) used a water balance for PVID as a comparison method and found it was within 1.4% of the remote-sensing-based method.

The most notable project-level water balance method for the LCRB is that employed in Reclamation's decree accounting or water accounting methods. In this method, for on-mainstream diversions and return flows, as described above, CU is equal to total diversions less total return flows (e.g., Reclamation, 2020). This is a simplification of the full water balance methodology, whereby quantifying or estimating CU then requires the measurement of diversions and surface return flows and estimation of surface return flows (if not measured) and estimation of subsurface return flows (e.g., Reclamation, 2020, Jensen 1998, 2003). It should be noted in this case that the CU estimated by this approach includes free water surface evaporation and consumptive use by non-agricultural vegetation.

Delivery and Other Flow Measurements

Delivery measurements may include farm or field turn-out flow measurements, diversion flow measurements, or flow measurement at some other appropriate location in the irrigation system (e.g., this may be near the basin boundary for a transbasin diversion). Flow measurements are beneficial in quantifying losses in delivery systems (e.g., Green, 2020), though this may be of most benefit for off-mainstream projects. For on-mainstream projects, diversion and delivery measurements are needed in combination with other quantification methods. Delivery measurements alone are insufficient for quantifying ET or ET_{aw} because they cannot account for unused return flows However, reductions in gross diversion or delivery may still be of interest and can be beneficial to report as was done in the review by Udall and Peterson (2017d) for the Colorado River Basin and by many researchers including Montazar et al. (2020).

Lysimetry

Lysimetry is a method of quantifying ET based upon the principles of a water balance. In lysimetry, lysimeters (tanks or containers containing a control volume of soil) are employed to facilitate the control and measurement of inflows and outflows from the soil volume. Lysimeters can be considered to be of two basic types: 1) weighing lysimeters, and 2) other lysimeters (Jensen and Allen, 2016). Weighing lysimeters include a means of weighing the lysimeter tank and, thus, quantify ET by way of the change in weight per unit of time. Well designed and managed weighing lysimeters allow for accurate measurement of the change in soil water content and are considered the most accurate method for measuring ET (Jensen and Allen, 2016). Application of weighing lysimeters has included comparisons of irrigation methods (e.g., Umair et al., 2019).

Other types of lysimeters also exist (Jensen and Allen, 2016), including simple tanks from which drainage can be measured (e.g., Hill and Barker, 2011), to buried wick lysimeters (Louie et al, 2000). However, weighing lysimeters are typically the only type of lysimeter capable of measuring ET within sufficient accuracy for conservation verification. Regardless of the type, lysimeters are usually limited to research settings because of their high construction, operation, and maintenance costs. For example, the care necessary in implementing a weighing lysimeter can be observed in the extensive efforts necessary to outfit lysimeters with subsurface drip irrigation in Texas by Evett et al. (2018).

Of final note is the scale of measurement of lysimeters, which, strictly speaking, is the size of the lysimeter, e.g., ~one square yard to several square yards. However, under proper siting and management, particularly with respect to the extent and moisture status of surrounding vegetation, lysimeter measurement may be considered representative of a larger area (Evett et al., 2012b).

Micrometeorology

ET is an energy-controlled process requiring the conversion of available radiation energy (sunshine) and sensible energy (heat contained in the air) into latent energy (energy stored in water vapor molecules). The energy balance at the crop surface includes all major sources and consumers of energy.

Micrometeorology is a class of methods that rely on specific, typically high frequency, measurements of wind, temperature, and/or humidity as a means of quantifying portions of the surface energy balance. For the purposes of ET measurement, micrometeorological techniques are used to quantify latent heat flux (*LE*; the energy used in the evaporation of water; Jensen and Allen, 2016). ET is computed as:

$$ET = \frac{LE}{\lambda \rho_w}$$

where λ is the latent heat of vaporization and ρ_w is the density of water (Jensen and Allen, 2016). In micrometeorology, *LE* is estimated either directly, or by quantifying other energy flux measurements to obtain *LE* through solving a simplified energy balance (Jensen and Allen, 2016):

$$LE = R_n - G - H$$

where R_n is net electromagnetic radiation at ground surface/vegetation surface, *G* is the flux of energy into or out of the ground (heating or cooling of the soil), and *H* is sensible heat flux (heating or cooling of the air). The energy balance is attractive in its simplicity. Net radiation and soil heat flux can be directly measured, however, measurement of sensible heat flux (*H*) is complex and not easily obtained. As well, only vertical fluxes are considered, and the net rate at which energy is transferred horizontally, known as advection, is ignored. Thus, in some respects, this approach can only be applied to large, extensive surfaces of homogeneous (type and moisture status) vegetation. Aerodynamic processes for removing and transporting water vapor away from evapotranspiring surfaces as well as for transporting warmer, drier air from upwind regions to these surfaces must be considered.

The two primary methods of micrometeorology are the eddy covariance (or correlation) and the Bowen ratio energy balance methods (Jensen and Allen, 2016; Shuttleworth, 2008). Two other micrometeorological methods, surface renewal (Snyder et al, 1996) and scintillometers, are also briefly presented below. Additional discussion and evaluation of micrometeorological methods for applicability to CU measurement can be found in UDNR (2020). The various methods differ in the specific means of quantifying *H* and/or *LE*. However, all micrometeorological methods are impacted by air movement (wind) and are thus sensitive to some area extending upwind of the measurement location. This area is dependent upon the wind speed and measurement height, among other things, but typically is in the range of hundreds of yards for eddy covariance, Bowen ratio, and surface renewal methods (though surface renewal measurements can be made for smaller areas, Snyder et al., 2015). For scintillometers, the length of the measurement path is also a consideration (e.g., Geli, 2012).

Eddy Covariance

The eddy covariance method is accomplished by making high frequency measurements of vertical wind speed, air temperature, and air water content. The basic idea is that ET results in an upward flux of water vapor. Wind is made of eddies, or swirls, so that at a given point in the air at any instant in time air may be moving upward or downward or have little vertical component, depending on the part of an eddy that is being measured. If upward moving wind has greater water content than downward moving wind, this represents a net upward water flux or ET. Therefore, water vapor movement or flux can be measured by correlating fluctuations in water vapor concentration measurements in the air with fluctuations in vertical wind speed and *LE* can be computed as:

$$LE = \frac{K\rho}{P_{atm}}\left(\overline{w'e'}\right)$$

where *K* is a constant combining the latent heat of vaporization and the ratio of the molecular weight or water to the molecular weight of air, ρ is the density of air, P_{atm} is atmospheric pressure, and w' and e' are the fluctuations (or deviations from the mean) of vertical wind speed and vapor pressure, respectively, with the quantity $\overline{w'e'}$ being the covariance of the two (Burba and Anderson, 2010). Similary, *H* may be computed as:

$$H = c_p\rho\left(\overline{w'T'}\right)$$

where c_p is the specific heat of air and T' is the deviation of air temperature from the mean, with the covariance with vertical wind speed fluctuations again computed (Burba and Anderson, 2010). Jensen and Allen (2016) provide a good, brief description of the eddy covariance method along with pros and cons and Burba and Anderson (2010) provide a discussion of the inherent assumptions.

The eddy covariance method has the benefit of being able, when coupled with R_n and *G* measurements, to measure all major components of the surface energy balance. Eddy covariance is widely used and generally considered to be one of the best methods of quantifying ET. Major challenges associated with the eddy covariance method include the extensive effort typically required to maintain the field equipment, process the data, and the care necessary to avoid measuring ET of surrounding surfaces (Jensen and Allen, 2016). Jensen and Allen (2016) provide a good summary of the pros and cons of the eddy covariance method. However, recent developments have improved the method (e.g., Thomas, 2015) and automated processing is becoming available (Li-Cor, 2020).

Bowen Ratio Energy Balance

The Bowen ratio energy balance method is based on partitioning the available energy (R_n - *G*) into *H* and *LE* using the ratio of H/LE named for a method of measuring that ratio originally reported by Bowen (1926), see Jensen and Allen (2016). This is accomplished by making measurements of air temperature (*T*) and vapor pressure (*e*) at two known heights (*z*) above the surface and maintaining the assumption of Bowen (1926) regarding the behavior of heat and vapor transport (Jensen and Allen, 2016). Thus, H/LE may be determined as:

$$\beta = \frac{H}{LE} = \gamma\left(\frac{T_2 - T_1}{e_2 - e_1}\right)(z_2 - z_1)l$$

where β is the Bowen ratio, γ is the psychrometric constant, subscripts 1, and 2, represent the two elevations, and l is the adiabatic lapse rate (e.g., Jensen and Allen, 2016). In practice, *LE* is then computed as:

$$LE = \left(\frac{R_n - G}{1 + \beta}\right)$$

Jensen and Allen (2016) and Baker (2008) provide good summaries of the pros and cons of the Bowen ratio method.

Surface Renewal

The surface renewal method is based upon characterizing air temperature in the air as it is affected by the surface using the equation:

$$H' = \rho c_p \left(\frac{\partial T}{\partial t}\right) z$$

where $\partial T/\partial t$ represents the changing in air temperature with time, z is a measurement height, and *H* is represented as *H'*. which is an approximation of *H*, which traditionally has required calibration with an eddy covariance system (Snyder et al., 1996; Spano et al., 1997). The quantity $\partial T/\partial t$ is estimated by quantifying what are termed temperature ramps (Snyder et al., 1996), which describe the magnitude and duration of temperature changes. The method requires relatively little equipment (e.g., a thermocouple for temperature measurement, but only measures *H*. Thus, *LE* is found using the energy balance by measuring R_n and *G* also solving for *LE*:

$$LE = R_n - G - H$$

The method was largely developed at the University of California Davis and has been used for numerous ET studies in California (e.g., Hanson et al., 2007; Medellín-Azuara et al., 2018; Montazar et al., 2020, 2018). As mentioned, the traditional methods of quantifying ET with surface renewal have traditionally required calibration to measurements from an eddy covariance system (Snyder et al., 1996). While stand-alone surface renewal systems are now available for irrigation scheduling support service (Tule Technologies, 2020), these are typically employed without direct measurements of R_n and *G* on site, which limits the accuracy for CU and conservation quantification.

Scintillometry

Scintillometry is another micrometeorological method, which can be used to quantify ET over a larger area than is typical of the other micrometeorology methods described above (Shuttleworth, 2008). Scintillometers measure the effects on light as it passes through the air, particularly those effects caused by changes in refraction caused primarily by temperature and humidity called scintillations (Kipp and Zonen, 2015). A scintillometer detects these scintillations from a beam of light emitted by one part of the instrument and detected by another some distance (e.g., one kilometer away) (Kipp and Zonen, 2015). When coupled with air temperature, humidity, and wind speed measurements, the method can be used, following common theories employed in micrometeorology, to estimate *H* (Kipp and Zonen, 2015). This can then be used to find *LE* using the energy balance (Kipp and Zoenn, 2015):

$$LE = R_n - G - H$$

The method has been used in the LCRB. For example, Geli et al. (2012) quantified riparian ET in the Cibola National Wildlife Refuge using this method. Due to the expense of the equipment, this method is typically limited to research applications.

Applications of Micrometeorology

Micrometeorological techniques have been used extensively to quantify ET including for conservation measures relevant to the present study. For example, Cuenca et al. (2013) used the Bowen ratio method and remote sensing to quantify ET for seasonal forbearance of irrigation in pasture in the Klamath Basin of Oregon. Hanson et al. (2007) used both eddy covariance and surface renewal techniques to quantify a reduction in ET for deficit irrigated alfalfa in California. Medellín-Azuara et al. (2018) used both eddy covariance and surface renewal to quantify ET in the Sacramento-San Joaquin Delta of California. Montazar et al. (2020) employed eddy covariance and surface renewal to quantify ET in conventionally irrigated and deficit irrigated fields in PVID.

Often micrometeorological techniques are used to validate other means of estimating ET. For example, Medellín-Azuara et al. (2018) used both eddy covariance and surface renewal in comparison with several ET models.

Reference Evapotranspiration/Crop Coefficient and Spatial Crop Surveys

Many factors affect evaporation and transpiration. In an irrigated crop environment, the primary factors are weather parameters, crop type and characteristics, water and crop management, and environmental conditions. The primary weather parameters affecting ET are total solar radiation, air temperature, humidity, and wind speed.

Crop factors affecting ET include crop type and variety. These factors determine the crop structure and height, which in turn, can determine or affect the crop's stomatal control and surface resistance to water loss, and the aerodynamic roughness of the crop surface affecting mechanical transport of vapor from the crop surfaces, or aerodynamic resistance. Crop growth stage and the level of vegetative cover that develops over time affect both surface resistance and aerodynamic resistance over time. Differences in crop surface reflectivity of sunshine energy affects energy absorption and use. Crop rooting characteristics define the depth and density of crop rooting and thereby, the volume of available soil water that a plant or crop can uptake and use.

There is an extensive volume of research literature which discusses effects of irrigation management, crop cultural practices, and environmental conditions on crop ET. Factors which impact or reduce plant water availability from optimal conditions and cause water stress to the plant have an impact on photosynthetic efficiency and thus vegetative development. This leads to reduced ET rates. Such factors include irrigation water supply and availability; poor irrigation distribution uniformity; soil layers (plow layers) that limit plant root development; and the salinity of the irrigation water, the soil water, and the soil, all of which may cause induced water stress to a crop due to the increased energy necessary to extract soil water. Factors affecting plant growth such as poor soil fertility, limited application of fertilizers, plant disease and pest pressure, and poor soil management practices can limit crop growth and development, and thus reduce ET.

A common approach to estimating crop ET in practice is to use an ET equation or model that incorporates both climate and crop information. There are numerous ET equations that have been developed in the western US and worldwide. These methods range from simple empirical equations requiring minimal climate and crop data to physically-based methods requiring considerable climate and crop data. To review all of these is beyond the scope of this memorandum and only a few of the more commonly used methods are reviewed here. A detailed review of many such equations and an intercomparison of their ET estimating accuracy with lysimeter-measured ET is provided in Jensen et al. (1990).

Blaney-Criddle Method

The original Blaney-Criddle and the modified SCS Blaney-Criddle method are both empirical equations requiring only location data (latitude) and air temperature and crop information to estimate crop CU. While it is included in this section, it is not a reference ET/crop coefficient method.

The original Blaney-Criddle equation (Blaney and Criddle, 1950; 1962) uses the following equation to calculate crop consumptive use:

$$U=KF$$

where:

U	= seasonal crop consumptive use
K	= seasonal consumptive use coefficient (varies with crop)
F	= climate factor

$$F=[(T)(P)/100]$$

T	= mean monthly air temperature
P	= mean monthly percentage of annual daylight hours based on the latitude of the area under study and time of year

The distinctive feature of the original Blaney-Criddle method is that the consumptive use coefficient (K) remains constant throughout the frost-free growing period. A different consumptive use coefficient is used for that part of a crop's growing season that occurs before the last spring frost or past the first fall frost. Crop parameters used in the original Blaney-Criddle method were originally developed in New Mexico. (*Consumptive Irrigation Requirements of Selected Irrigated Areas in New Mexico* (Henderson and Sorenson, 1968). The consumptive-use coefficients (*K*) vary by crop type and time of season: before, during, and after the frost-free period. Local planting dates and growing season lengths are also required.

In an effort to increase the applicability of the original Blaney-Criddle equation to areas having different growing seasons and different crop growth rates than the areas of New Mexico where the original work was performed, the USDA SCS modified and published what has become known as the modified SCS Blaney-Criddle equation (SCS BC) (USDA SCS, 1970):

$$u = f\ k_c\ k_t$$

where:

u = monthly crop consumptive use (inches)

f = monthly climate factor

$$f = [(T)(P)/100]$$

T = mean monthly air temperature (°F)

P = monthly percentage of annual daylight hours based on the latitude of the area under study and time of year

k_c = monthly crop growth stage coefficient

k_t = climatic coefficient related to the mean air temperature, calculated as:

$$k_t = 0.0173t - 0.314 \text{ (subject to minimum } k_t = 0.3 \text{ for } T < 36°F)$$

The primary modifications are the addition of both the monthly crop growth stage coefficient (as opposed to the constant seasonal value) and a climate coefficient based on air temperature. Crop parameters for the modified SCS Blaney-Criddle method are given in USDA SCS (1970), which provides updates and modifications to the crop parameters used in the original Blaney-Criddle method. USDA SCS (1970) provides crop growth stage curves for various crops both as monthly coefficients and based on a percentage of the growing season duration.

An obvious attractive feature or the original Blaney-Criddle and modified SCS Blaney-Criddle methods are their simplicity and needing only monthly air temperature as a climate data input, which is widely available with many locations having long periods of record. However, Jensen et al. (1990) found the modified SCS Blaney-Criddle method underestimated average peak monthly ET by 14% in arid locations and overestimated average peak monthly ET by 20% in humid locations. It was found to underestimate seasonal ET by 16% in arid locations and overestimate seasonal ET by 17% in humid locations. The modified SCS Blaney-Criddle method ranked 15th out the 19 methods at both arid and humid locations when comparing monthly ET estimates to lysimeter measured monthly ET. Due to these limitations, it is recommended the Blaney Criddle methods should be calibrated against more accurate physically based ET models.

Crop Coefficient-Reference Evapotranspiration Methods

In this approach, ET is modeled using what is known as reference ET (ET_{ref}); Jensen and Allen, 2016). ET_{ref} is computed from weather/climate data and represents the ET from a specified green, well-watered, hypothetical vegetated surface. Reference crop evapotranspiration is more dependent on weather and climate conditions and less dependent on crop characteristics, and therefore represents the evaporative power of the atmosphere at specific locations, elevations, and times during the year.

Crop evapotranspiration (ET_c) is defined as the evapotranspiration rate from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under given climatic conditions (Allen et al., 1998). To model crop ET (ET_c) from ET_{ref}, a dimensionless crop coefficient (K_c) is employed. Thus, this approach is often termed the two-step approach-- ET_{ref} is computed first using a reference ET equation, and second, crop ET is computed by applying the appropriate crop coefficient. The reference ET-crop coefficient method is widely used due to its simplicity, reproducibility, relatively good accuracy, and transportability among locations and climates.

In the following subsections, crop ET based on two different reference ET equations is reviewed:

- The American Society of Civil Engineers (ASCE) standardized (Penman-Monteith) reference evapotranspiration (ASCE Standardized Reference ET) equation (ASCE, 2005)
- Hargreaves-Samani (HS) equation (Hargreaves and Samani, 1982; 1985)

Both the ASCE Standardized Reference ET and HS equations are crop coefficient-reference evapotranspiration methods. Following this, a discussion and review of crop coefficients used in this approach is given.

The ASCE Penman-Monteith Equation

In 1948, Howard Penman published what has become the well-known Penman combination equation. Penman (1948) defined the latent heat flux as a combination of the energy balance and an aerodynamic vapor transfer process. Over many years, many researchers, including Penman himself, refined the Penman combination equation. Details of this evolution are beyond the scope of this memo but are given in (Jensen et al. 1990). Monteith (1965) combined a logarithmic eddy diffusion function and bulk surface resistance (or canopy resistance) to formulate a physically-based version of the Penman equation: the Penman-Monteith equation. The ASCE Penman-Monteith equation (Jensen et al. 1990) is:

$$ET_{ref} = \frac{\left(\frac{\Delta\ (R_n - G) + K_{time}\ \rho a\ cp\ \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\ \left(1 + \frac{r_s}{r_a}\right)}\right)}{\lambda}$$

where:

ET_{ref} = reference evapotranspiration [mm d-1 or mm h-1],
R_n = net radiation [MJ m-2 d-1 or MJ m-2 h-1],
G = soil heat flux [MJ m-2 d-1 or MJ m-2 h-1],
$(e_s - e_a)$ = vapor pressure deficit of the air [kPa],
e_s = saturation vapor pressure of the air [kPa],
e_a = actual vapor pressure of the air [kPa],
ρ_a = mean air density at constant pressure [kg m-3],
c_p = specific heat of the air [MJ kg-1 oC-1],
Δ = slope of the saturation vapor pressure temperature relationship [kPa oC-1],
γ = psychrometric constant [kPa oC-1],
r_s = (bulk) surface resistance [s m-1],
r_a = aerodynamic resistance [s m-1],
λ = latent heat of vaporization, [MJ kg-1],
K_{time} = units conversion, equal to 86,400 s d-1 for ET in mm d-1 and equal to 3600 s h-1 for ET in mm h-1.

The aerodynamic resistance to water vapor flux, r_a, is a function of wind speed and crop canopy parameters such as crop height and roughness. The bulk surface resistance, r_s, is dependent on crop specific parameters such as light penetration and stomatal resistance, and environmental parameters such as radiation and vapor pressure deficit. The Penman-Monteith formulation as given above along with several standard equations for computing some of the parameters/variables is known as the ASCE "full form" Penman-Monteith equation. In this formulation, and with specific values of parameters for either a grass reference surface, or an alfalfa reference surface, the Penman-Monteith equation provides reference ET, which is the ET rate of an extensive, actively growing green surface of grass or alfalfa of uniform height, not short of water, pest and disease free, and completely shading the ground. Note that this equation may be used to directly compute the ET of any crop if crop characteristics affecting the bulk surface resistance of the crop and the aerodynamic resistance of the crop can be specified.

Jensen et al. (1990) evaluated 19 different ET estimating methods against carefully screened lysimeter data from 11 worldwide locations representing a range of climatic (arid to humid) conditions. The ASCE Penman-Monteith method was found to be most accurate and consistent across all climates on both monthly and daily basis.

The ASCE Standardized Reference Evapotranspiration Equation

Much of the following discussion of the ASCE Standardized Reference ET equation is adapted from Ley (2012).

In 1999, the Irrigation Association requested the ASCE EWRI ET in Irrigation and Hydrology Technical Committee to develop a benchmark reference ET equation with an objective of standardizing calculation procedures. A task committee was formed to act on this request. The task committee established several criteria for the selection of the equation (ASCE, 2005):

- The equation must be understandable.
- Whether monthly, daily, or hourly data are used, the equation must be defensible, in that it will provide a precise, reliable measure of evaporative demand.
- The equation should be a derivation of methods that have been accepted by the science and engineering communities such as those methods described in Jensen et al. (1990), and Allen et al. (1998) among others.
- Simplification of an accepted method to enhance its implementation and ease of calculations by users without significant loss of accuracy is desirable.
- The equation should have the capability to use data from the numerous weather networks, which currently measure daily and hourly radiation, humidity, temperature, and wind speed.
- The equation must be based on (or traceable to) measured or experimental data. Specifically, the user of the equation should be able to relate the equation to a known reference crop, evaporative index, or hypothetical surface.
- Sums of hourly calculated ET should closely approximate daily computed ET values.

Given these criteria, the task committee developed the ASCE Standardized Reference ET equation below (ASCE, 2005). The standardized reference equation is derived from the ASCE "full form" Penman-Monteith equation. It provides reference evapotranspiration estimates for two different hypothetical reference surfaces: reference ET for a hypothetical short crop (similar to grass) having an approximate height of 0.12 meters, and reference ET for a hypothetical tall crop (similar to alfalfa) having an approximate height of 0.50 meters. By specifying these two common reference crops, the task committee was able to simplify and reduce calculations for aerodynamic and surface resistances and present a single equation with two different constants that depend on the reference crop and time step. Additional simplifications were made by specifying constants values for some parameters and calculation equations and procedures for some variables, thereby "standardizing" the computation process.

$$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

where:

ET_{sz} = standardized reference crop evapotranspiration for short (ET_{os}) or tall (ET_{rs}) surfaces (mm d-1 for daily time steps or mm h-1 for hourly time steps),
R_n = calculated net radiation at the crop surface (MJ m-2 d-1for daily time steps or MJ m-2 h-1 for hourly time steps),
G = soil heat flux density at the soil surface (MJ m-2 d-1 for daily time steps or MJ m-2 h-1 for hourly time steps),
T = mean daily or hourly air temperature at 1.5 to 2.5-m height (°C),
u_2 = mean daily or hourly wind speed at 2-m height (m s-1),
e_s = saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature,
e_a = mean actual vapor pressure at 1.5 to 2.5-m height (kPa),
Δ = slope of the saturation vapor pressure-temperature curve (kPa °C-1),
λ = psychrometric constant (kPa °C-1)

The constants C_n and C_d change with the time step and aerodynamic roughness of the short or tall (reference) surface. C_n and C_d were derived by simplifying several terms within the ASCE Penman-Monteith equation.

The ASCE Standardized Reference ET equation is a physically-based approach accounting for energy available for evaporation and aerodynamic transport of moisture away from the evaporating surface. Because of this physically-based formulation, it requires detailed weather measurements including air temperature, relative humidity, incoming total solar radiation, and wind speed. Given high quality input weather data that are representative of the irrigated area(s) in question, both the "full form" ASCE Penman-Monteith equation and the ASCE Standardized Reference ET equation have been shown to have consistently high, if not the best, predictive accuracy when compared to lysimeter measurements of reference crop ET over a wide range of climatic conditions ((Jensen et al., 1990; ASCE EWRI, 2005; Itenfisu et al., 2003).

Hargreaves-Samani Equation

When solar radiation data, relative humidity, or wind speed data are missing, an alternative equation for estimating reference evapotranspiration was proposed by Hargreaves and Samani (1982; 1985). The 1985 HS equation for grass reference evapotranspiration is:

$$ET_0 = 0.0023(T_{mean} + 17.8)(T_{max} - T_{\min})^{0.5} R_a$$

where:

ET_o	= grass reference evapotranspiration
T_{mean}	= average air temperature
T_{max}	= maximum temperature
T_{min}	= minimum temperature
R_a	= extraterrestrial radiation

This method requires only air temperature as a climate or weather data input. Extraterrestrial radiation is estimated as a function of latitude and day of the year. Because wind speed is not explicitly included in the HS equation, this method has been found to underpredict in windy, high advection conditions.

Crop Coefficients

The reference crop evapotranspiration is developed to provide a reference to which ET from other crops can be related so that the ET of a specific crop can be estimated without defining a separate ET level for each crop and stage of growth. Under this approach, reference crop evapotranspiration is multiplied by a crop coefficient for a specific crop to estimate ET_c:

$$ET_c = K_c ET_{ref}$$

The crop coefficient, K_c, represents a specific crop and stage of growth condition (e.g., Jensen and Allen, 2016). Kc is typically a value that changes with crop type, crop condition, and crop growth stage. It can also be climate-specific (Jensen and Allen, 2016) a point stressed by Periera et al. (2021a,b). Crop coefficients are determined under controlled research conditions by relating the measured crop evapotranspiration (such as by lysimetry) to the calculated reference evapotranspiration. In the crop coefficient approach, the difference in the crop evapotranspiration of a specific crop relative to the reference crop is accounted for by the crop coefficient.

The type and variety of a crop affects ET_c even though the crops may have identical environmental conditions. These crop dependent variations in ET_c are caused by differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover, and crop rooting characteristics. The characteristics of a crop such as its albedo, crop height, aerodynamic properties, and physiological properties, are all contributing factors that determine the value of the crop coefficient. Plants that have closer spacings and taller canopy height and roughness will have numerically larger crop coefficient (K_c) values. Plants with large leaf resistances that have leaves with stomata on only the lower side of the leaves such as citrus and deciduous fruit trees, the K_c values are smaller.

Unlike the reference crop, which has a hypothetical fixed height, the ground cover, leaf area, and height of an agricultural crop changes as the crop grows. The crop evapotranspiration also varies as it develops into maturity because of these physiological changes. Consequently, the crop coefficient, K_c, varies accordingly over the growing period.

One simple K_c methodology has been adopted by the Food and Agricultural Organization (FAO) of the United Nations and is presented in FAO Irrigation and Drainage Paper No. 56 (FAO-56; Allen et al. 1998). In this methodology, the K_c is represented by a time-based piecewise linear function. A crop's growing period may be divided into four growth stages: the initial period, the crop development period, the midseason period, and the late season period. A crop coefficient curve based on methods presented in Allen et al. (1998) and consisting of four straight lines is developed to model the four major growth stages in a specific crop.

The initial growth stage covers the period from planting date to approximately 10% ground cover and has a duration (in days) denoted as L_{ini}. $K_{c\ ini}$ represents the initial K_c value just after planting of annuals or shortly after the initiation of new leaves for perennials.

The crop development stage starts from 10% ground cover and ends when the crop has reached effective full cover. During the crop development stage, K_c increases from $K_{c\ ini}$, at the beginning of rapid plant development, to a maximum threshold, $K_{c\ mid}$, at or near the peak of plant development. It is then followed by the mid-season stage which begins at effective full cover and continues to the start of maturity and has duration (in days) denoted as L_{mid}. The crop continues to grow at a relatively constant K_c mid-level until it reaches the beginning of the late season when leaves begin to age and dry up.

The late season stage covers the period from beginning of crop maturity to harvest and has duration (in days) denoted as L_{late}. K_c decreases to a point represented by $K_{c\ end}$, which is the end of the growing period. The value of K_c end is very much influenced by the crop and water management practices during the crop's late season stage. If the crop is frequently irrigated until the crop is harvested fresh, the $K_{c\ end}$ value will be high, but if the crop is allowed to dry out before harvesting, the $K_{c\ end}$ value will be low.

For example, if ET_{ref} was 0.30 inches per day in mid-season, the crop coefficient has a value of 1.20, then ET_c would be 0.30 inches per day × 1.20 = 0.36 inches per day.

This is the single crop coefficient approach, in which crop coefficients that vary by time and growth stage are used to represent the combined effects of soil evaporation and crop transpiration rate through the growing season.

The K_c may also be computed from component coefficients specifically representing crop transpiration and soil evaporation separately, in what is known as a dual crop coefficient method, which is typically represented as (Jensen and Allen, 2016):

$$K_c = K_{cb}K_s + K_e$$

where K_{cb} is the basal crop coefficient (representing transpiration), K_s is the crop water stress coefficient, and K_e is the soil evaporation coefficient. Incorporated soil evaporation and/or crop water stress typically requires modeling a soil water balance (Jensen and Allen, 2016).

As noted, the ASCE Standardized Reference ET equation is a reference crop ET method. Calculation of crop evapotranspiration (ET_c) requires the selection of K_c for use with the standardized reference evapotranspiration (ET_{os} or ET_{rs}).

ETc = Kco * ETos   or   ETc = Kcr * ETrs

Where the subscript "o" refers to short crop reference ET and crop coefficient and the subscript "r" refers to tall crop reference ET and crop coefficient.

The HS equation provides grass reference ET and thus only crop coefficients developed for use with grass (or short crop) reference ET should be used with this method.

K_c values that have been developed for many crops and land covers are reported in standard sources on the subject including Jensen and Allen (2016) and FAO-56 (see also, Periera et al., 2021a,b). Care must be taken by the user regarding the source of the K_c used, including the climate and management conditions for which it was developed and also for the type of ET_{ref} (both equation used and whether it is tall or short reference, e.g., K_c values in FAO-56 are for short (grass) reference and Jensen and Allen, 2016, has values for both tall and short reference). For details on much of the state of the practice on employing this type of ET modeling, see Jensen and Allen, 2016.

Standard Conditions vs. Non-Standard Conditions

The crop coefficients discussed in the previous section were typically developed in relation to measured crop ET under well-managed, well-watered conditions. Crop ET computed in the two-step method using such crop coefficients represents the crop ET under what are designated standard conditions and represents the upper limit of crop ET under pristine conditions. This is sometimes also referred to as "potential" crop ET. Allen et al.(1998) describe crop evapotranspiration under standard conditions as "evapotranspiration from excellently managed, large, well-watered fields that achieve full production under the given climate conditions…" while they describe crop evapotranspiration under non-standard conditions as "the real or actual crop evapotranspiration that results from non-optimal conditions, such as the presence of pests and diseases, soil salinity, low soil fertility, water shortage or waterlogging" All of which are factors that may reduce crop growth, or plant populations, and thereby reduce evapotranspiration rates below that under standard conditions. It is generally agreed a water stress coefficient can be applied as one approach to compute crop evapotranspiration when there is water stress or water shortage. When or how to make corrections for the other factors discussed is less certain. In addition to tables or other published literature, K_c values may also be derived from remote sensing data (e.g., Calera et al., 2017) to take local crop production and irrigation water management considerations into account.

As discussed above, the crop coefficient-reference ET approach produces crop ET under non-stressed, or near-ideal, conditions. This results from K_c factors typically being developed in research fields for full production non-stressed conditions. When considering field production of crops, ideal non-stressed conditions are rarely achieved over the entirety of large irrigation service areas, thus CU can be overestimated with this approach unless corrections are employed to consider water supply limitations and/or local soil/crop limitations (e.g., Jensen and Allen, 2016).

The K_c method has been the subject of much research and refinement over time (e.g., Jensen and Allen, 2016). This is demonstrated by recently published updates to the FAO-56 K_c values by Pereira et al. (2021a,b). However, Periera et al. (2021a,b) argue that since the new K_c factors they reported were typically similar to previously published ones (FAO-56), their review and analysis support the applicability of using the FAO-56 K_c (e.g., Periera et al., 2021b). In addition to improving K_c values, the methodology has been adapted for automated application to large areas as reported by Allen et al. (2020). Their adaptations including modeled crop initiation using heat units (growing-degree-days) and growing-degree-days -based K_c temporal progression modeling (see also Jensen and Allen, 2016).

Using the ET_{ref} and K_c methodology has been widely promoted by states, land grant universities, and Reclamation for irrigation scheduling. This is in part because the method is relatively simple to employ, particularly if weather stations with the necessary measurements are available. For example, programs operated within the LCRB, the State of California operates the California Irrigation Management Information System (CIMIS; CDWR, 2020) and provides resources to irrigation managers regarding ET and K_c estimation (CDWR, 2005; UC Extension, 1994). Similarly, the University of Arizona manages the Arizona Meteorological Network (AZMET; UA, 2021) and has the Arizona Irrigation Scheduling System (AZSCHED; Martin and Slack, 2003).

There is an important distinction between use of the ET_{ref} and K_c methodology for irrigation scheduling and use of the method for large area and/or basin scale water balances. The ET_{ref} and K_c methodology is the standard practice for irrigation scheduling and is supported by the fact that most producers have a goal of achieving peak crop production represented by the "potential" ET_c. For the purpose of large area and/or basin scale water balances however, it is the field scale actual ET_c that needs to be measured or estimated and corrections are often needed to account for field scale reductions in actual ET_c from the potential ET_c. The remainder of this section is focused on large scale applications of the ET_{ref} and K_c methodology.

Forms of this methodology have been used extensively including throughout the Lower Basin states (e.g., Reclamation, 1997-2019; Lin and Sandoval-Solis, 2013; French et al., 2018). Most notable for the present analysis is the use of K_c methods in Reclamation's Lower Colorado River Annual Summary of Evapotranspiration and Evaporation (LCRAS) reports (formerly Lower Colorado River Accounting System reports). In these reports, Reclamation provides "estimates of annual agricultural, riparian vegetation, and open water acreages and water uses along the lower Colorado River from Hoover Dam to the Southerly International Boundary with Mexico" (https://www.usbr.gov/lc/region/g4000/wtraccttypes.html). Methods for K_c estimation and daily K_c values for multiple crops and segments of the LCRB are detailed in Jensen (1998), Jensen (2003), and in annual reports.

Multiple studies have been performed in the LCRB for which the K_c method was compared with other means of quantifying ET (e.g., French et al., 2018; Elhaddad and Garcia, 2014; Clark et al., 2008). French et al. (2018) employed the K_c methodology along with remote-sensing-based models at the Central Arizona Irrigation and Drainage District (CAIDD). In their study, the K_c method following FAO-56 resulted in less ET than the average of the three remote sensing models for wheat (14% less) and cotton (1% less). However, for cotton, the ET from the K_c method was nearer to the mean ET across the remote sensing models than was the ET from any one of the remote sensing models.

While French et al. (2018) found the K_c method to produce lower ET estimates than other methods, others have found the opposite. Allen et al. (2005) found that the dual K_c method produced 8% greater ET than did a water balance at IID and they attributed the difference to the K_c basically representing potential conditions, that is that the crops were actually experiencing stress(es) not captured in the K_c method. Elhaddad and Garcia (2014) compared ET computed using the K_c method with a remote sensing model (ReSET-Raster; Elhaddad and Garcia, 2011), and found that the K_c method overestimated ET as compared to the remote sensing method. They computed potential ET_c using reference ET computed using local CIMIS weather station data and crop coefficients developed for Reclamation's LCRAS program (Jensen, 1998; and Jensen, 2003. Across PVID, the average ratio of actual ET to potential ET_c found was 0.86. For major crops (alfalfa, Bermuda grass, wheat) prevalent in PVID, the ratio of remote sensing ET to K_c ET was 0.86 for alfalfa; 0.70 to 0.84 for Bermuda grass; and 0.95 for wheat and other small grains.

Similarly, Clark et al. (2008) compared K_c-based ET (FAO-56, dual K_c) with a remote-sensing ET model (SEBAL; Bastiaanssen et al., 1998). The results were presented as ratios of actual (SEBAL) ET to potential (i.e., K_c) ET_c. Across IID, the average ratio of actual (remote sensing) ET to potential (K_c) ET_c found was 0.85. For different crops (alfalfa, Bermuda grass, wheat) and irrigation methods (graded border and graded furrow) the IID remote sensing ET to K_c ET ratio was 0.83 to 0.87 for graded border and graded furrow irrigation of mature alfalfa and new alfalfa on all soil types; 0.79 for graded border irrigation of mature Bermuda on all soil types; and 0.85 for graded border irrigation of wheat on all soil types.

Medellín-Azuara et al. (2018) compared several ET models including a K_c method based upon gridded weather data (California Simulation of Evapotranspiration of Applied Water; CalSIMETAW) and one that was calibrated to ET from the remote sensing model SEBAL (Bastiaanssen et al., 1998). This latter model is called the Delta Evapotranspiration of Applied Water (DETAW; Snyder et al., 2006) model and it is specific to the Sacramento-San Joaquin Delta area (Medellín-Azuara et al., 2018). Medellín-Azuara et al. (2018) found that both models resulted in a mean bias error (the average of differences between two methods) of about 0.04 inches/day in comparison to surface renewal and eddy covariance measurements. However, the two performed similarly to a mean of several models, including the two models in questions and some remote sensing models, for most months of the study. There were some statistically significant differences particularly for pasture. Medellín-Azuara et al. (2018) also made use of spatial crop surveys. Identifying crops to be modeled is an important component of K_c methods (e.g., Jensen and Allen, 2016). Identifying crops to be modeled can be important for remote sensing-based methods also e.g., Neale et al., 2012.)

Remote Sensing Evapotranspiration Modeling

Remote sensing incorporates various methods of indirectly measuring or estimating properties of a surface by measuring electromagnetic emissions or reflections from the surface. The benefit of remote sensing is that no contact with the surface is necessary. In the context of irrigation and ET, remote sensing is typically referring to the measurement of reflected solar radiation, reflected microwave radiation, or emitted thermal radiation from the soil/crop surface (e.g., Alvino and Marino, 2017; Jensen and Allen, 2016). Remote sensing measurements are typically limited to specific bands of the electromagnetic spectrum that are selected for specific application. Remote sensors may be cameras or imaging or non-imaging radiometers (e.g., Alvino and Marino, 2017). These sensors may be mounted on aircraft, including unpiloted aircraft, or satellites (Alvino and Marino, 2017). For the present discussion, proximal sensing (using sensors near the plant, e.g., infrared thermometers) is also included as a remote sensing method (see Alvino and Marino, 2017) because the general science is similar.

Remote sensing ET methods have been demonstrated to be accurate. For example, Karimi and Bastiaanssen (2015) reviewed literature and reported that ET could be accurately modeled from remote sensing data with an average error of about ±5% (across the models considered). Remote sensing models have also been promoted specifically for quantifying CU for water conservation forbearance programs (Colby et al., 2014).

Reflectance-/Vegetation-Based Methods

Shortwave reflectance is of particular interest for the purposes of ET estimation because it can be used to estimate a number of biophysical properties (e.g., Alvino and Marino, 2017; Anderson et al. 2004). These estimates are typically based upon vegetation indices, dimensionless indices based upon reflectance from multiple shortwave electromagnetic bands. Most well-known of all vegetation indices is the Normalized Difference Vegetation Index (NDVI; e.g., Rouse et al., 1974), which is based upon surface reflectance in the visible red band and invisible near infrared band (*NIR*):

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

or the Soil Adjusted Vegetation Index (SAVI; Huete et al., 1988):

$$SAVI = \frac{(NIR - RED)(1 + L)}{NIR + RED + L}$$

The simple intent of something like the NDVI or SAVI is to have a measurable (and possibly transferable) index that is sensitive to leaf area (Anderson et al. 2004) or even yield (Campos et al., 2018; Bugdayci, 2020). These parameters may then be included in various types of ET models. For example, direct Penman-Monteith methods (Calera et al., 2017) and surface energy balance models.

Models that rely primarily upon vegetation indices include direct Penman-Moteith Methods and methods that derive K_c values (e.g., Bausch and Neale, 1987) or otherwise scale ET_{ref} based upon the vegetation index (as is the case with the Beer-Lambert extinction-type method used by Nagler et al., 2018). As noted by UDNR (2000) and Calera et al. (2017). A limitation of reflectance-/vegetation-based methods is that they do not respond to water stress as well as energy balance methods may. Reflectance-based methods alone do not capture the effects of stress, except as it impacts vegetation growth or greenness particularly of leaf area (UDNR, 2000). With reflectance-based methods, water stress may be modeled through a water balance, like FAO-56; though this may be subject to error (Neale et al., 2012).

Researchers have also developed direct relationships, often simple linear relationships, between the NDVI and other vegetation indices and K_c values (Bausch and Neale, 1987; Calera et al., 2017):

$$K_{cb} = mVI + b$$

where m and b are regression coefficients and VI represents a vegetation index (e.g., Caleral et al., 2017; Barker et al., 2017). The benefit of these methods over traditional K_c methods is that the vegetation index can be used to determine the magnitude and temporal progression of the K_c, taking out some of the judgement necessary in traditional K_c methods. Furthermore, spatial variation in K_c may be represented and the effects of some crop stresses that reduce plant leaf area may be accounted for. The reflectance-based K_c methodology represents likely the simplest means of estimating ET with remote sensing, though relationships used to estimate K_c from remote sensing are hardly standard (Calera et al., 2017). Reflectance-based K_c methods have been used to quantify ET in the Lower Basin states, for example, French et al. (2018) used this and other remote sensing methods in the CAIDD. The K_c method typically resulted in less than the mean ET from the remote sensing models for wheat and alfalfa, but greater for cotton. They discuss that the reflectance-based K_c method may not perform well for deficit irrigation conditions. For this method to track crop water stress, it may be necessary to run a soil water balance, which can be subject to error (see Geli et al., 2012). Medellín-Azuara et al. (2018) compared ET from several methodologies, including a reflectance-based K_c method, the Satellite Irrigation Management Support System (SIMS), by the National Aeronautics and Space Administration (NASA). They found the SIMS method performed near the mean of all models in their study. The insensitivity of the SIMS model to some deficit irrigation conditions was acknowledged by authors of Appendix G of Medellín-Azuara et al. (2018). The SIMS model seemed to generally overestimate ET as compared to surface renewal and eddy covariance methods.

Reflectance-based K_c methods have the benefit, in the context of the present study, of incorporating the spatial-scale of historically collected satellite remotely sensed imagery (e.g., a Landsat satellite tile is roughly 100 miles wide with a ground resolution of 30 m, USGS, 2019). Another benefit of the method is that while, satellite imagery may sometimes be relatively sparce temporally (e.g., Landsat satellites return every 16 days, USGS, 2019), vegetation indices or derived Kc curves can be interpolated or even extrapolated in time. For example, Campos et al. (2017) presented such a methodology for corn and soybean and Barker et al. (2018) refined it for near-real-time application.

Energy Balance Models and Thermal Infrared Methods

While reflectance-based models may generally be the simplest of remote-sensing-based ET methods, energy balance methods are likely the most widely accepted methods for accurate estimation of ET over large land surfaces. Energy balance models use remote sensing inputs to simulate and solve the surface energy balance, described earlier. Energy balance methods are typically based upon thermography (thermal infrared imaging) or thermal sensing and use a variety of methods to estimate sensible heat flux (H) and then solve for latent heat flux (LE) through the energy balance or solve the two simultaneously. Some relatively well know remote sensing energy balance models include: the Atmosphere-Land Exchange Inverse model (ALEXI) and its disaggregation methodology (DisALEXI; e.g., Anderson et al., 2012), Mapping Evapotranspiration with Internalize Calibration (METRIC™; Allen et al., 2007), Operational Simplified Surface Energy Balance (SSEBop; Senay et al., 2013), the raster version of Remote Sensing of Evapotranspiration (ReSET-Raster; Elhaddad and Garcia, 2011), Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen, et al., 1998), the Two-Source Energy Balance (TSEB, Norman et al., 1995), and versions of the Priestly-Taylor method (Jin et al., 2011; Fisher et al., 2008). These methods vary in formulation, complication, input data required, necessary skill, and applicability (e.g., Medellín-Azuara et al., 2018; Avino and Merino, 2017).

While generally more complicated than reflectance-based methods, energy balance methods have the advantage of modeling what can be termed "actual" ET, including water stress (Alvino and Merino, 2017), while reflectance-based methods may generally provide "potential" ET_c, assuming well-watered conditions (Calera et al., 2017). It should be noted that while the term "reflectance-based" has been used here to differentiate from energy balance methods, energy balance models typically require crop biophysical parameters modeled from reflectance data (e.g., Barker et al., 2018). One challenge with energy balance methods is that they typically produce ET estimates for an instant in time when imagery is available and must use some method to scale the ET in time (e.g., Colaizzi et al., 2006; Calera et al., 2017). Satellite imagery may also be infrequent, for example, Landsat satellite imagery is available only once every 16 days for many areas and may be rendered unusable because of cloud cover.

A number of energy balance remote sensing methods have been employed in the LCRB and elsewhere in the Lower Basin States. For example, French et al., (2018) compared METRIC™, TSEB, and reflectance-based K_c factors at CAIDD. METRIC™ estimated ET was less than the mean of the three models, while TSEB ET was greater than the mean. As mentioned, Elhaddad and Garcia (2014) applied ReSET-Raster in PVID and found that ET using this method was less than estimated using ET_{ref} and crop specific K_c factors. Semmens et al. (2015) modeled grape ET in the Central Valley of California using ALEXI/DisALEXI.

Remote sensing has also been used to quantify CU from conservation efforts in the Upper Colorado River Basin by Allen and Torres-Rua (2018). They used METRIC™ to quantify ET for deficit irrigated pasture fields as part of the Upper Basin Deficit Irrigation Pilot Program. The method allowed them to observe that CU reductions were, in general, relatively small for the deficit irrigated fields. METRIC™ ET estimates for a past year were also used to estimate CU reductions for the System Conservation Pilot Program agreements in Wyoming (UCRC and Wilson Water, 2018).

It is common to validate remote sensing models with micrometeorological data. Cuenca et al. (2013) compared METRIC™ ET to Bowen ratio ET in Oregon. The METRIC™ ET was less than 3% greater than the Bowen ratio ET. Medellín-Azuara et al. (2018) compared three energy balance remote sensing methods (ALEXI/DisALEXI, METRIC™ (executed in two ways), and an Optimized Priestley-Taylor (Jin et al, 2011) along with the SIMS model and some non-remote-sensing models in the Sacrament-San Joaquin Delta of California. They compared results with micrometeorology measurements (surface renewal/eddy covariance) measurements. For days with satellite imagery, the ALEXI/DisALEXI model best matched the ground measurements (mean bias error = 0.13 millimeters per day [mm/d]). METRIC™ and SIMS had greater ET than did the ground measurements (mean bias 1.29 mm/d to 2.62 mm/d) and the Priestley Taylor method was less than the ground measurements (-0.19 mm/d).

Some of the major challenges with remote sensing ET estimation are the time and expertise required for some of the modeling (see Medellín-Azuara et al., 2018). However, this may become less of an issue in the future as resources like the OpenET project become publicly available and accessible on the internet. OpenET is a collaborative remote-sensing-based ET modeling project for which ET products will be produced from multiple remote sensing models including ALEXI/DisALEXI, METRIC™, SEBAL, SIMS, and SSEBop (OpenET, 2020). OpenET aims to automate the ET calculation effort with the help of custom algorithms and a cloud computing infrastructure, thereby making these complicated techniques easily accessed by non-technical audiences. Moreover, with OpenET, individual models can be used to generate ensemble ET estimates that can be used to identify variability (OpenET, 2020, Medellín-Azuara et al., 2018). This may be particularly helpful when ground-based methods are not available.

In addition to energy balance ET models from thermal imagery, thermography or other thermal infrared measurements may be used to estimate crop water status or use stress indices, such as the Crop Water Stress Index (CWSI; Jackson et al., 1981 and Idso et al., 1981; Chávez, 2015, Chávez et al., 2012). Chávez et al. (2012) used the CWSI to estimate ET and compared it to a remote sensing energy balance model by Chávez et al. (2005) for corn and to a water balance using neutron probe and TDR. However, this methodology was based upon proximal infrared thermometry and use in quantifying CU for large areas would need to be demonstrated.

Other Methods

There are other methods for quantifying ET, which were not the focus of the present study. Most notably are methods that may be considered partial methods, i.e., they quantify only part of ET (Shuttleworth, 2008). These include micro-lysimetry (for quantifying soil evaporation), sap flow measurement (for quantifying plant transpiration), and plant water interception measurements (for quantifying interception and evaporation from plants) (Shuttleworth, 2008). Another method described by Shuttleworth (2008) is a less-conventional remote sensing method for ET quantification, the use of light detection and ranging (LIDAR).

Crop modeling has also been used to quantify water use in deficit irrigation (e.g., Zhang et al., 2018). However, these methods likely have primary value in management and the practicality of using such methods for quantifying CU for irrigation conservation measures on a large scale would need to be demonstrated before being considered adoptable in practice.

Another method that has been employed in the LCRB is the White (1932) method, which relies upon groundwater elevation observations (Taghvaeian, 2011). However, as Taghvaeian points out, this method neglects CU from the unsaturated zone. Irrigated agriculture is typically managed specifically to maintain unsaturated conditions within the plant root zone. Therefore, while conditions may exist where the method is appropriate (e.g., White, 1932 included natural vegetation and agriculture in his study), this method is likely to be of most use in monitoring CU from natural systems. It is acknowledged that natural systems may be affected by irrigation conservation measures on local groundwater levels. Taghvaeian (2011) found the method compared favorably with a version of SEBAL for Tamarisk in the LCRB.

Irrigation Contribution to Consumptive Use

Typically, ET measurements and modeling do not differentiate between ET derived from precipitation and ET_{aw}. Different means of accounting for precipitation include running a soil water balance, such as that described in Jensen and Allen (2016) or using empirical means to estimate effective precipitation (SCS, 1992), among others. Reclamation's LCRAS program uses a flat monthly multiplier approach to estimate effective precipitation as given by Jensen (1993). Comparative measurement of representative fully irrigated and non-irrigated or deficit-irrigated fields can also be used to estimate ET_{aw} (Cuenca et al, 2013). Simons et al. (2020) presented a method for partitioning ET (in their case, modeled with SSEBop) using what is known as the Budyko hypothesis. It is important to account for reuse when considering conservation measures. In any case, accurate precipitation datasets and estimation of contributions to ET aside from applied irrigation water are necessary to quantify ET_{aw}. Allen et al. (1997) also discussed these principles and stated that for regional water management, determination of the consumed fraction and reusable fraction is much more relevant than irrigation efficiency. They state that water use should be expressed in terms of 1) the fraction of water consumed, 2) the fraction that is rendered unavailable to other users, and 3) the fraction that is returned to the hydrologic system for reuse.

Accuracy and Error Estimation

There are some general considerations regarding ET methodologies. For ET measurement methodologies (e.g., water balance, lysimetry, micrometeorology), Allen et al. (2011a) have reported that these considerations include the accuracy of measurements and understanding the sources of error. Allen et al. (2011b) suggested methods of documenting ET measurement conditions to aid with evaluating and using the data.

Available Software

While ET and CU are often computed using private models or software developed by professionals for their own work, publicly available software packages for some of the methods or models mentioned in the previous sections have been developed. These programs are typically developed by government agencies or researchers. While not comprehensive, some publicly available models are listed in *Table 1*.

It is important for users of ET or CU programs to understand the development, assumptions, and formulations of such models. It is also important to consider the expertise and experience of the program developer(s). It is not uncommon for errors to exist in any computer model, and care should be particularly paid to formulations and parameterizations of utilities not developed by experts in the field of ET and CU quantification. It is also important to understand the purpose of the model, as an ET subroutine in a larger model may not require the same accuracy for the parent model's purpose as would a model developed specifically to model ET.

Table 1 Sample List of Some Publicly Available Consumptive Use Software Programs

Model*	Reference	Description
Bushland ET Calculator	ARS (2021)	ASCE Standardized ET_{ref} calculation
California Simulation of Evapotranspiration of Applied Water (Cal-SIMETAW)	CDWR (2021a,c); Appx. C of Medellin-Azuara et al. (2018).	ET_{ref} and K_c water balance modeling
Consumptive Use Program PLUS (CUP+)	CDWR (2021a)	ET_{ref} and K_c water balance modeling
CROPWAT	FAO (2021a)	ET_{ref} and K_c modeling
ET-Demands	Reclamation (2021)	ET_{ref} and K_c water balance modeling
ETo Calculator	FAO (2021b)	ET_{ref} calculation
Farm Process (plug in to MODFLOW groundwater simulation software)	Schmid (2009)	ET_{ref} and K_c modeling subroutine of a groundwater flow model
GridET	Lewis (2021)	Spatial ET_{ref} and K_c modeling
Integrated Demand Calculator (IDC; a component of the Integrated Water Flow Model, IWFM)	CDWR (2021b)	ET_{ref} and K_c modeling subroutine of a hydrologic model
Irrigation Water Requirements - Penman-Monteith (IWRpm)	NRCS (2021)	ET_{ref} and K_c modeling
Ref-ET	Allen (2021)	Multiple ET_{ref} methods calculation

Simulation of Evapotranspiration of Applied Water (SIMETAW)	CDWR (2021a)	ET_{ref} and K_c water balance modeling
Soil-Plant-Atmosphere-Water Field and Pond Hydrology (SPAW)	Saxton (2017)	ET_{ref} and K_c water balance modeling
StateCU	CWCB-CDWR (2021)	ET_{ref} and K_c water balance modeling

*This is a sample list of some publicly available models, it is not comprehensive, Inclusion or exclusion of a model does not represent endorsement or lack thereof. Users should investigate model formulations, parameterizations, and beware of possible modeling or coding errors.

Comparisons and Consumptive Use Differences

Quantifying CU is only one step in quantifying CU changes from implementing conservation efforts. It is also necessary to estimate what CU would be in the absence of the conservation measure. Allen and Torres-Rua (2018) explored three methods for making this comparison: 1) comparing CU from a field with a conservation measure to CU from neighboring fields that were not part of that conservation measure; 2) comparing CU from a field with a conservation measure to CU from the same field in previous years; and 3) computing the ratio CU/ET_{ref} (basically a K_c) for the field in a year without the conservation measure and multiplying that ratio by the ET_{ref} in the conservation year to estimate the non-conservation CU. There are pros and cons to each of these methods and Allen and Torres-Rua (2018) provided a good discussion of these. For example, for Method 1, the implicit assumption is that the field under conservation would have similar CU to the selected neighboring fields; this assumption may or may not be the case and is dependent upon a number of crop, soil, location, and management factors. For Method 2, the assumption is similar to Method 1, but the assumption is in time as opposed to space. Climate, crop condition, possibly the crop itself, and management may change in time (see also PVID et al., 2020). For Method 3, the assumption is that the ratio of CU/ ET_{ref} would be the same from year-to-year. If the crop, crop condition, and crop management have been similar, then this method is perhaps the best of the three. Some models have also been developed specifically for standardizing the estimation of ET_{aw} such as SIMETAW (Mancosu et al, 2015).

Udall and Peterson (2017d) discussed similar methodologies for quantifying differences in CU for alternative cropping, i.e., comparing ET between the water conserving crop or crop mix and the mix to be replaced. Similar methods to those described have been employed by PVID et al. (2020) and a discussion of the assumptions implicit with their methodology is described in the Section: Palo Verde Irrigation District Forbearance and Fallowing Program of this memo.

Finally, it is noteworthy to mention that the previous year(s) selected for comparison impact the final results. For example, do the previous year(s) capture the type of crop that would have been grown on the field(s) under normal conditions? What were the weather conditions during the included years (dry vs. wet years)? Additional considerations are provided in the Palo Verde Irrigation District Forbearance and Fallowing Program section of this memo. For example, PVID et al. (2020) assumed that the CU for fallowed fields would be similar to non-fallowed fields in the same year. However, they also compared this value to typical CU for means of three, five, and twelve previous years with certain years deliberately included or excluded from these means.

Crop Yield Considerations

Crop yield has been shown to be closely linked to CU and has been the subject of extensive research to develop crop production functions defining these relationship (Doorenbos et al, 1986). Crop yield is an important consideration for irrigation water conservation projects for two reasons: 1) Growers need to understand the potential impact to crop yields when making irrigation water conservation decisions; and 2) Crop yield can be used to provide independent checks against crop CU estimates (e.g., Hill et al., 2011).

For growers considering deficit irrigation or changing crops to continue production with lower applied water amounts, crop yield considerations can be especially important. For some crops, such as pasture grass forage, different species can have substantially different yield response to the same amount of applied irrigation water and CU (Smeal et al, 2005) creating an opportunity to maximize the yield per unit water consumed within a limited water supply. Understanding the crop yield impacts resulting from intentional deficit irrigation can also allow growers to optimize economic returns and in some cases, produce higher net profit with reduced water consumption (English et al, 2002). Another factor affecting crop yield relating to irrigation is salinity leaching (e.g., Ayars et al., 2012; Grieve et al., 2012). For example, under deficit irrigation, it may still be necessary at some time in the season to apply sufficient water to leach salts.

When using crop yield for independent checks against crop CU, there are limitations to the types of crops and limitations to the accuracy of yield to CU estimates. For example, while fruiting and grain crops can have dramatically different yield response to plant water stress and CU at different stages of crop growth, vegetative forage crops such as alfalfa have more linear yield response to plant water stress and CU (Doorenbos et al, 1986). Within the CRB and particularly in Utah there has been substantial research to define the yield to CU relationship of alfalfa (Hill et al, 1999). This study and related work documented higher crop water productivity (yield to CU ratios) for early alfalfa cuttings and diminishing crop water productivity for later season cuttings during hotter weather. However, for seasonal average crop water productivity, they documented a seasonal mean productivity of 0.186 ton/acre per inch of crop transpiration or 5.4 inches of crop transpiration per tons/acre of alfalfa yield over research sites in Utah and Idaho. These results would suggest a crop transpiration of approximately 43.2 inches for an alfalfa field with 8 ton/acre of production. Additional corrections for evaporation losses are required to estimate total CU impacts. However, these types of relationships along with recorded crop yield information can be helpful in providing cross-checks against CU estimates over conservation program areas. As mentioned, researchers have developed methods of estimating yield using remote sensing data (Campos et al., 2018; Bugdayci, 2020). It is also possible that such methods may be of benefit in the context of validating CU estimates.

Additional Conservation Measure and Consumptive Use Literature

In addition to the sources cited above, the literature reviewed contained a number of reports and articles specifically addressing certain conservation measures or reviewing multiple quantification measures. Those specifically addressing certain conservation measures include:

- Deficit irrigation (Fereres and Soriano, 2006; Rudnick et al., 2018; Samani and Skaggs, 2006; Udall and Peterson, 2017a,b; Barber et al., 2020; Trout et al., 2020);

- On-farm irrigation system conversion (Samani and Skaggs, 2006; Udall and Peterson, 2017a,e; Akhbari and Smith, 2016; Green et al., 2020; Barber et al., 2020; TWDB, 2003);
- Seasonal fallowing (Udall and Peterson, 2017 a,c);
- Crop rotations/alternative cropping (Udall and Peterson, 2017 a,d);
- District/distribution and/or on-farm irrigation conveyance and efficiency improvements (CSU, 2013; Samani and Skaggs, 2006; Udall and Peterson, 2017a,e); and
- Advanced irrigation scheduling (Samani and Skaggs, 2006; Barber et al., 2020; TWDB, 2003).

Significant Findings of Current/Recent Conservation Activities

For more than two decades there has been significant agricultural water conservation activity and investment in irrigation systems to improve efficiencies in the LCRB. Along with the review of scientific literature, reports, etc., a review was made of several current or recent conservation activities in the LCRB for which readily accessible information was available. This included a review of the CU quantification methods used in those studies. Five specific agricultural irrigation water conservation projects located in Arizona and California were selected as examples including:

- Colorado River Indian Tribes Fallowing Program
- Palo Verde Irrigation District Forbearance and Fallowing Program
- Palo Verde Deficit Irrigation Studies
- Yuma County Agriculture Water Coalition
- Yuma Mesa Irrigation and Drainage District

Colorado River Indian Tribes Fallowing Program

The Colorado River Indian Reservation was created in 1865 by the Federal Government for the Indians of the Colorado River and its tributaries. Initially, these were the Mohave and Chemehuevi people, but Hopi and Navajo people were relocated to the Reservation in 1945. The Mohave, Chemehuevi, Hopi, and Navajo Tribes are, collectively, the Colorado River Indian Tribes (CRIT). The Colorado River Indian Reservation is located on both sides of the Colorado River in western Arizona and eastern California, with most of the land in Arizona. The Colorado River Irrigation Project, a federal irrigation project, is operated by the Bureau of Indian Affairs, serves approximately 80,000 acres of irrigated farmland, and is located entirely within CRIT's Arizona lands. Small parcels on the Reservation (both Arizona and California) receive water by direct pumping from the Colorado River.

Program Summary

Starting in 2016 and continuing to present, the CRIT have participated in system conservation (SC) programs to create conserved water for storage in Lake Mead. These include the Pilot System Conservation Program (PSCP) established by Reclamation, the Central Arizona Water Conservation District (CAWCD), the Metropolitan Water District of Southern California (MWD), the Southern Nevada Water Authority (SNWA), and Denver Water (Reclamation, 2019), and CRIT's three-year system conservation (SC) agreement with Reclamation, the Arizona Department of Water Resources (ADWR) and CAWCD under the State of Arizona's Drought Contingency Plan (AZ DCP). See *Table 2* below for a summary of these water conservation activities. Conserved water in each case has consisted of CU reductions due to temporary fallowing of irrigated cropland on CRIT's Arizona lands. In all instances, except for the creation of extraordinary conservation-intentionally created surplus (EC-ICS), CRIT has been compensated for its CU reductions under the various system conservation programs it has participated in.

Quantification Methods

The net consumptive use (net CU) reductions realized in each of CRIT's agreements under the PSCP and the AZ DCP were rigorously developed. The same methodology has been used in each of the water conservation activities shown in *Table 2*. NRCE (2019) includes details of CRIT's fallowing program for calendar year 2020 under the system conservation agreement in Arizona and is an example of the approach used in other years.

In its first proposal to the Pilot System Conservation program, CRIT proposed to quantify CU reductions due to fallowing of irrigated cropland by computing the average crop ET for the previous 5-year period on the farm unit to be fallowed. CRIT has continued to use this 5-year average calculation in succeeding fallowing contracts, although contract terms in this regard have been slightly relaxed such that parcels being fallowed are required to have been in active irrigated crop production for four of the previous five years prior to being included in a program. On each farm unit, the cropping patterns—meaning the crop type and acreage—for the previous five years were determined by field surveys conducted by the CRIT Water Resources Department and entered into a geographic information system (GIS) database allowing mapping and determination of net irrigated area of each crop.

Table 2 Summary of CRIT Water Conservation by Fallowing of Irrigated Cropland (2016 – Present)

Program	Farm	Dates	Fallowed Acreage (ac)	Net Consumptive Use Reduction		Diversion Reduction
				AFY/ac	AF	AF
Pilot SCP-Phase 2	Kudu Farm	Oct 1, 2016-Sep 30, 2018	1,591	5.39	17,144	30,772
Pilot SCP-Phase 3	MTA Farm	Oct 1, 2018-Sep 30, 2019	1,884	5.70	10,697	19,932
Pilot SCP- Phase 3	Quail Mesa	Jan 1, 2019-Dec 31, 2019	3,705	4.72	17,488	32,996
AZ DCP System Conservation	Multiple	Jan 1, 2020-Dec 31, 2020	10,786	4.98	53,736	100,623
AZ DCP System Conservation	Multiple	Jan 1, 2021-Dec 31, 2021	10,826	5.05	54,685	103,078
AZ DCP System Conservation	Multiple	Jan 1, 2022-Dec 31, 2022	TBD			

Note: Under CRIT's DCP System Conservation Agreement during 2020-2022, any net consumptive use reduction in excess of 50,000 acre-feet (AF) is not compensated but is credited to CRIT's intentionally created surplus (ICS) accoun

The ET of each crop was computed using the K_c – ET_{ref} approach. In this method, ET_{ref} was computed using ASCE's standardized reference evapotranspiration equation (Jensen and Allen, 2016) and daily weather data collected at one or more local AZMET electronic weather stations operated by the University of Arizona (UA, 2020). Daily K_c values developed by Jensen (1998, 2003) were taken from Reclamation's LCRAS for the Parker Valley. Daily ET_c is the product of ET_{ref} and the K_c for that day.

This method results in daily ET_c estimates for crops growing under ideal, pristine conditions and not short of water, and in some cases, has been termed "potential" ET_c. Jensen (1998, 2003) recognized that alfalfa ET_c by this method was higher than local estimates and attributed the differences to water and other stresses, delayed removal of hay bales, and other factors, and applied a factor of 0.85 to the alfalfa hay coefficients to obtain more realistic estimates of actual alfalfa ET in the LCRB. Jensen did not adjust K_c values for other crops. CRIT used the results from two regional remote sensing studies to estimate actual crop ET (Clark et al., 2008 at IID; El Haddad and Garcia, 2014 at PVID). The ratios of actual crop ET from remote sensing to the "potential" crop ET determined by the Kc-ETref approach were used to adjust potential crop ET_c estimates to be representative of actual crop ET. This was done to avoid overstating the actual CU reductions due to temporary fallowing.

The net crop CU was computed by subtracting the effective precipitation from the crop ET estimates. Effective precipitation was computed using the same method as used in Reclamation's Evapotranspiration and Evaporation (LCRAS) methodology. The net crop CU (acre feet per acre [AF/ac]) was multiplied by the acreage for each crop and then an average weighted net CU was computed for the acres fallowed on each farm unit across all years and crops. This average net crop CU was then multiplied by the maximum number of acres irrigated in the four or five years evaluated to determine the total crop CU reduction due to fallowing.

The total crop CU reduction and project irrigation efficiency are then used to determine a diversion reduction at the main canal diversion at Headgate Rock Dam. The diversion reduction is factored into CRIT's annual water order (and/or an amendment to the water order) and is considered integral to the overall quantification and verification of CRIT's responsibilities under the implementation agreements.

During the fallowing period, both CRIT and Reclamation perform various types of checks to verify fields in the program remain in fallowed condition and that any green vegetation (weeds or other plants) growth due to rain is promptly controlled. Two to three times during the annual fallowing period CRIT has conducted field checks of all fallowed parcels, which includes on-site photo documentation, checks of locked headgates and of delivery lateral closures. CRIT also has collected Landsat 8 satellite imagery and processed surface reflectance bands 5, 4, and 3 to create false color infrared images in which shades of red color represent green vegetation. Deeper red color indicates healthy well-watered green vegetation (irrigated crops) while lighter reds indicate sparse vegetation and/or water stressed vegetation. Browns, tans, and light grays to dark grays represent dead vegetation, lack of vegetation, and bare soils. Reclamation performs a similar remote sensing process to develop maps of normalized difference vegetation index, which has been shown to be closely correlated with the degree of green vegetative cover on the land surface.

Palo Verde Irrigation District Forbearance and Fallowing Program

In 2004, MWD and PVID landowners entered into a 35-year agreement wherein MWD pays for land to be fallowed in PVID (e.g., MWD, 2019; Exhibit 1). The forborne water is then made available for use by MWD on a direct acre-foot for acre-foot basis (MWD, 2019).

Program Summary

Documentation of the program is publicly available (e.g., MWD, 2019). MWD has included this forbearance program as part of their plan to provide intentionally created surplus (ICS) in the LCRB storage system (MWD, 2019). The amount of land under the forbearance program is allowed to fluctuate between nine and 35 percent, as determined by MWD. This land is not permanently taken out of production as it is periodically (in one to five years) put back into production. The total area of PVID is about 104,485 acres in the Palo Verde Valley plus an additional 26,800 acres of nearby lands (PVID et al., 2020). The forbearance program is for lands in the Palo Verde Valley only (MWD, 2109). Maximum limits have been placed on the amount of land fallowed.

Each year MWD submits documentation of the program to Reclamation. The present review is focused on Calendar Year 2019, the most recent on record at the time of writing. For the 2019 forbearance plan, MWD (2019) estimated that 49,301 acre-feet of water could be conserved by fallowing 10,379 acres based upon a historical estimated CU of 4.75 AF/ac per year.

Quantification Methods

The methods used to quantify CU reductions from the PVID forbearance and fallowing program included three basic components: 1) verification of fallowing practice, 2) estimating CU, and 3) determining CU reduction for fallowed lands. These methods are detailed for 2019 in PVID et al. (2020).

Verification of fallowed land is an essential component of estimating CU reductions. Verification is done through a site visit by MWD for each field included in the forbearance program at the start of fallowing (MWD, 2019). Reclamation also performs a verification of a sampling of the fields, which was planned to be 5% of the fallowed area in 2019 (MWD, 2019).

With the fallowed area known, it is necessary to quantify CU. PVID et al. (2020) used four methods for estimating CU. Three of the methods were using historical CU data for 12, five, and three previous years, respectively. These years excluded periods when a fallowing program had been in place. In this, they quantified CU using measured diversions and return flows and estimates of unmeasured return flows that were not measured from Reclamation's decree accounting data. They also subtracted deliveries to the lands outside of the Palo Verde Valley (Palo Verde Mesa lands). They then effectively divided the average monthly CU by the average annual irrigated acreage during that period, which was assumed to be the reduced CU rate for lands fallowed each respective month in 2019. This resulted in an estimated 47,211 acre-feet of forborne water.

A similar method was used looking at only five previous years, resulting in an estimated 49,286 acre-feet of forborne water. Likewise, the analysis was done for a three-year period resulting in an estimated 52,192 acre-feet of forborne water.

For the fourth method, CU was obtained from the Reclamation's decree accounting report for 2019 (Reclamation, 2020). The CU was reduced by subtracting CU from ecological and riparian areas (i.e., the Palo Verde Ecological Reserve, the Dennis Underwood Conservation Area, and upstream of the Palo Verde Diversion Dam). Again, deliveries to the Palo Verde Mesa lands were subtracted. The resulting estimated CU reduction was 44,477 acre-feet. This total was less than all three historical methods and was selected as the final quantity for the report. Note that it was unclear in PVID et al. (2020) whether the CU from the ecological and riparian areas was subtracted from the historical method analyses.

As is evident from the CU discussion, the method used to translate estimated CU into CU reductions for fallowed fields was to assume that fallowed lands would have had similar CU as the rest of PVID during the various analysis periods. Implicit in this methodology are assumptions of soil, management, and crop similarities.

Of particular note, is the assumption that fallow fields would replace the average crop mix (or at least average CU) of the district, rather than replacing specific crops in a rotation (e.g., fallow instead of lower value rotation crops). MWD (2019) and PVID et al. (2020) acknowledged this type of uncertainty and therefore provided projected CU estimates with that understanding. It may also be important to consider carryover effects, e.g., if fallowed or deficit irrigated fields are rotated throughout a district or service area, then the practice may mine water that is then replenished at the end of the practice. This is one reason why quantifying ET, even over fallowed fields, may be necessary in CU quantification in some situations.

Palo Verde Deficit Irrigation Studies

In late 2019 and early 2020, a deficit irrigation experiment in four fields in PVID was conducted by researchers at the University of California, Davis (UC Davis) and the U.S. Department of Agriculture Agricultural Research Service (Montazar et al., 2020). The project was detailed in a peer reviewed journal by Montazar et al. (2020) and is summarized here.

Project Summary

The project was conducted in four surface irrigated alfalfa fields in PVID planted in late 2018. The fields were paired by irrigation method (two were border irrigated and two were furrow irrigated) and by treatment. Each field included a section (or multiple sections) irrigated per the grower's convention. For the two border irrigated fields, deficit irrigation treatments were applied by avoiding irrigation for three and two events in late summer, respectively. For the two furrow irrigated fields, two deficit irrigation treatments were applied by avoiding irrigation for two events and one event in late summer, respectively.

Quantification Methods

To quantify CU, the research team quantified applied irrigation water and ET. They quantified ET using eddy covariance and surface renewal in the grower irrigation method treatments and used surface renewal systems from Tule Technologies (e.g., Tule Technologies, 2020) for the deficit irrigation treatments. They reported ET for the grower method treatments only and found a corresponding computed crop coefficient to be less than some published values. They also computed irrigation and ET water productivity based upon yield measurements. They demonstrated reduced applied water from deficit irrigation but did not test this statistically. Yields were reported to be possibly less than full irrigation. Differences in water productivity were not tested statistically but using productivity as a comparison metric is important when considering deficit irrigation. The authors suggested deficit irrigation as a means to reduce summer irrigation use, which could be offset by irrigating more in the early season to bank soil water. The use of commercially available surface renewal systems may be viable for small projects or for validation.

Yuma County Agriculture Water Coalition

In 2015, the Yuma County Agriculture Water Coalition (YCAWC) studied the agriculture and water use near Yuma, Arizona (YCAWC, 2015). The article "A Case Study in Efficiency – Agriculture and Water Use in the Yuma, Arizona Area" reviewed the history and water management of agriculture in the area around Yuma and concluded that agriculture water use efficiency has improved over time in the Yuma area. Computerization, automation, and real-time optimization have helped to increase on-farm application efficiency.

Program Summary

The Yuma Project of Reclamation was authorized in 1904 and provides water from the Colorado River to irrigate about 68,000 acres of land near the towns of Yuma, Somerton, and Gadsden as well as Bard and Winterhaven, California (Frisvold et al, 2018). This area is one of the most productive agricultural areas in the United States. Overtime, growers switched from perennial and summer-centric crops production to winter-centric, multi-crop systems and quickly realized that traditional approaches to crop irrigation had to be modified in order to address the challenges of irrigating large acreages of shallow-rooted vegetables (Frisvold et al, 2018). As a result, the growers adopted alternative irrigation practices.

Between 1970 and 2010, agriculture production changed dramatically in Yuma. During the 1970's growers mainly focused on perennial crops such as alfalfa and citrus, or warm season crops such as cotton and sorghum. However, since this time a nearly six-fold increase in vegetable production has occurred.

Quantification Methods

The YCAWC case study did not utilize specific quantification methods to calculate conserved water or foregone consumptive use. Instead, the case study detailed a history of productive agriculture, increasing crop yields, and reduced deliveries. Infrastructure improvements (e.g. canal lining, mechanical land-leveling) driven by the switch to a multi-cropped system were identified as the biggest contributors to reduced monthly diversion. Multi-crop systems fallow land in mid-summer to late summer by design, which aligns with the high evaporative demand months for the Yuma area. The case study was careful to point out that infrastructure improvements such as canal lining may improve system operations, but they do not necessarily result in less consumptive use or increased water in the Colorado River.

The case study also found that ET_o and ET_c have remained relatively unchanged outside of typical variability resulting from year-to-year differences in weather. However, the water use efficiency in terms of crop weight per acre per inch of ET_c has significantly improved over the period of 1970 to

2010. For example, head lettuce water use efficiency increased from approximately 1,300 to 2,700 pounds per acre-inch from 1970 to 2010.

Yuma Mesa Irrigation and Drainage District

In 2013, a voluntary Pilot Fallowing and Forbearance Program Agreement (Pilot Fallowing Program) was established between Yuma Mesa Irrigation and Drainage District (YMIDD) and the Central Arizona Groundwater Replenishment District (CAGRD), which is a department within the Central Arizona Water Conservation District (CAWCD). The primary objective of the Pilot Fallowing Program was to demonstrate through a "proof of concept" exercise a rigorous methodology for the quantification of forgone consumptive water use resulting from fallowing lands within the YMIDD service area to inform the viability of a long-term, larger-scale fallowing program (YMIDD, 2017).

Program Summary

The Pilot Fallowing Program was comprised of up to two three-year cycles, the first from 2014 through 2016 and the second from 2017 through 2019; however, the second cycle was not implemented. Qualified land had to meet certain requirements related to enrolled acreage, production history, and landownership. Participation was limited to a maximum of 1,500 enrolled acres. A summary of results for the first cycle period are shown in below in *Table 3*. Total compensation payments made to YMIDD totaled more than $3.3 million during the first cycle and included costs associated with spring and fall acreage verification, lost revenue (non-use of excess water), and administration.

Table 3 Summary of YMIDD Pilot Fallow Program (2014 – 2016)

Year	Enrolled Acres	Unit Consumptive Use (AF/ac)	Conserved Water (AF)[1]
2014	1,406	4.86	6,827
2015	1,411	5.09	7,180
2016	1,401	5.36	7,509

[1]Includes removal of special water use such as dust control and tree removal.

Quantification Methods

Quantification of forgone consumptive water use was based on the approach and results established in the technical memorandum, "YMIDD Crop Mapping and Consumptive Use Estimation (YMIDD, 2015). This memorandum documented field-scale cropping system delineation and consumptive use estimates of conserved water based on spatial crop surveys and application of reference evapotranspiration (ET_o) and adjusted crop coefficients. Other factors considered as part of this quantification included crop productions assumptions, irrigation efficiency assumptions, and evaporative losses within the irrigation system

The spatial crop survey included a combination of satellite/aerial imagery and "ground-truthing". A baseline crop acreage was established for 2014 and then previous years (2010-2013) were estimated by employing a reverse chronological change analysis. Crop types were delineated, and in the case of citrus crops, age was also documented (young, mature, declining). Acres within the YMIDD that were enrolled in the Pilot Fallowing Program were dominated by alfalfa and declining citrus, approximately 51% and 36% of enrolled acres, respectively.

ET_o was based on data collected from 2010 through 2013 at the Yuma South station via the Arizona Meteorological Network (AZMET). While AZMET stations do report and calculate ET_o it was determined that an adjustment was needed in order to utilize the selected and standard reference evapotranspiration methodology, Penman-Monteith. Crop coefficients were largely based on FAO 56 (Allen et al, 1998). Additional sources for crop coefficients were relied on as well; however, the crop types associated with these sources make a relatively small percentage of the Pilot Fallowing Program's enrolled acres.

Table 4 summarizes the quantification results of the 2010 to 2013 study period which served as the foundation for quantification of conserved water for the Pilot Fallowing Program's first cycle (2014-2016).

Table 4 2014 Consumptive Use Calculated Using the Crop Distribution for 2011, 2012, and 2013

Program	2011 Crop Distribution		2012 Crop Distribution		2013 Crop Distribution		Average
	Acres	2014 CU (ac-ft)	Acres	2014 CU (ac-ft)	Acres	2014 CU (ac-ft)	CU (ac-ft)
Alfalfa	577	3,177	660	3,633	716	3,945	3,627
Dates	9	53	9	53	9	53	53
Declining Citrus	387	1,820	424	1,995	501	2,356	2,081
Mature Citrus	304	1,407	217	1,002	135	625	1,023
Small Grains	52	1,01	--	--	11	21	62
Sudan Grass	40	1,47	--	--	--	--	148
Young Citrus	17	56	8	26	8	26	36
Total		**6,761**		**6,710**		**7,026**	**6,832**

References

References have been organized and summarized in a series of tables included in Appendix A: References Summary Table and Appendix B: Reference List. In the former, key references have been summarized using a matrix for ease in identifying relevant sources regarding specific conservation measures or quantification methods (*Table A-1*). The full and formal reference list has been organized into three tables in Appendix B: Reference List: *Table B-1*, which is an annotated bibliography of primary or notable sources, *Table B-2*, which is a list of the references for the current/recent conservation activities, and *Table B-3*, which contains the other references cited herein.

Appendix A: References Summary Table

A summary matrix was prepared (*Table A-1*) as an aide in identifying literature from the annotated bibliography (*Table B-1*).

Table A-1 *Reference Summary Matrix*

Reference Number	Author(s) Last Name	Year	Quantification Method	Deficit Irrigation	Irrigation Conversion	Seasonal Fallowing	Crop Rotation	Conveyance System Improvements	Advanced Irrigation Scheduling	Crop Productivity	Water Conservation
101	Akhbari	2016									■
102	Allen	2018	1,5	■							
103	Allen	2020	4								
104	Allen	2011	1,3,5,6								
105	Allen	2011	1,2,3,4,5,6								
106	Allen	2005	1, 4								■
107	Allen	1997	6								■
108	Alvino	2017	5						■		■
109	Barber	2020	1, 5	■							
110	Bugdayci	2020		■							
111	Calera	2017	5								
112	Campos	2018	5								
113	Chavez	2012	1,5	■							
114	Colby	2014	4,5	■	■	■	■				
115	CSU	2015	6		■						
116	CSU	2013									
117	Cuenca	2013	2,5			■					
118	Clark	2008	4,5		■		■				■
119	Elhaddad	2014	4,5								■
120	Evett	2018	3								
121	Evett	2012a	1								
122	Fereres	2006		■						■	■
123	French	2018	4,5	■							
124	Green	2020			■						
125	Hanson	2007	2	■							
126	Iniesta	2008	1	■							
127	Jensen	2016	1,2,3,4,5								
128	Karimi	2015	5								■
129	Lin	2013	4							■	

Reference Number	Author(s) Last Name	Year	Quantification Method	Deficit Irrigation	Irrigation Conversion	Seasonal Fallowing	Crop Rotation	Conveyance System Improvements	Advanced Irrigation Scheduling	Crop Productivity	Water Conservation
130	Medellin-Azuara	2018	2, 4, 5			■	■				
131	Montazar	2020	2, 4	■							
132	Montazar	2018	2		■						
133	Open ET	2020	5								
134	Orloff	2003	1	■						■	■
135a/ 135b	Pereira; Pereira	2020	4								
136	Rudnick	2017		■							
137	Samani	2008		■	■			■	■		■
138	Semmens	2016	5								■
139a/ 139b	Shuttleworth; Baker	2008	1,2,5								
140	Simons	2020	5								
141	Stewart	2011	1	■							
142	Taghvaeian	2011	1,5								
143	Texas Water Development Board	2003	1,4		■						■
144	Trout	2020	1	■							
145	Trout	2018	4								
146	UCRC	2018	1,4,5	■		■					
147	Udall	2017		■	■	■	■				■
148	Udall	2017	4	■							■
149	Udall	2017	1,4			■	■				■
150	Udall	2017					■				■
151	Udall	2017			■						■
152	UDWR	2020	1,2,5								
153	Umair	2019	3		■						
154	USBR	2019									
155	Ward	2008			■						■

Quantification Method Key:
- 1-Water Balance
- 2-Micrometeorology
- 3-Lysimetry
- 4-Reference Evapotranspiration/Crop Coefficient Modeling
- 5-Remote Sensing Evapotranspiration Modeling
- 6-Other

Appendix B: Reference List

The references cited in this memo have been organized into three tables, all included in this appendix. The first, *Table B-1*, is an annotated bibliography of primary or notable sources. The second, *Table B-2*, is a list of the references for the current/recent conservation activities. The third, *Table B-3*, contains the other references cited herein.

Table B-1 Annotated Bibliography for Primary Sources

101	Akhbari, M. and Smith, M. 2016. "Case Studies Outlining Challenges and Opportunities for Agricultural Water Conservation in the Colorado River Basin." Retrieved from: http://www.cwi.colostate.edu/publications/SR/27.pdf. Accessed December 16, 2020.
Summary	The reference produced 78 case studies that highlights various ways that diverted water has been managed over time. These examples illustrate the sociological, economic, and legal challenges that must be overcome in order to conserve ag water.
Findings	These studies can be used by entities to develop water conservation programs. Framework can be developed to demonstrate how agricultural water management organizations can use available technology to improve infrastructure and management to benefit improve operations and conserve water.
Method(s)	None specifically.

102	Allen, L.N. and A.F. Torres-Rua. 2018. *Verification of Water Conservation from Deficit Irrigation Pilot Projects in the Upper Colorado River Basin: Findings and Recommendations*. Utah State University, Logan, UT.
Summary	The main objective of this study was to verify reductions in consumptive water use from deficit irrigation using a Landsat-based energy balance model for crop evapotranspiration. The study fields were pilot program pasture fields in Wyoming and Colorado.
Findings	The study showed that most pilot project fields had very little consumptive water use reductions from deficit irrigation. The low reductions occurred because after irrigation stopped, plants continued using available soil water, precipitation, and there were also contributions from groundwater in areas with a high-water table. The estimated water conservation based on reduced consumptive use can be as high as 238 mm (9.4 inches) to none. Of greatest interest is the quantification method, the METRIC™ model. This provided a scientifically rigorous method of ET analysis. Of equal interest to the remote-sensing-based modeling was the methods of comparing consumptive use. They looked at comparing a given field under deficit irrigation with neighboring fields that were not part of the pilot program. They looked at comparing a field under the pilot program against the same field in non-pilot program years. Most interestingly, they compared ET in a non-pilot program year with reference ET to estimate non-deficit conditions of the field during the pilot program period. They described the assumptions inherent with each method. They could have looked at more years for the third option. Third method considered to have notable benefits. Recommended validation with a soil water balance.
Method(s)	Remote sensing (energy balance; METRIC™) comparing field to itself in other years and other in the same year.

103	Allen, R.G., C.W. Robinson, J. Huntington, J.L. Wright, and A. Kilic. 2020. "Applying the FAO-56 Method for Irrigation Water Requirements over Large Areas of the Western U.S." *Transactions of the ASABE*. 63(6): 2059-2081. https://doi.org/10.13031/trans.13933.
Summary	Describes efforts to model crop water use using reference ET and K_c in portions of the western U.S. including the Colorado River Basin.
Findings	Methods were considered transferable over large areas.
Method(s)	Reference ET and K_c.

104	Allen, R.G. 2011a. "Evapotranspiration Information Reporting: I. Factors Governing Measurement Accuracy." December 16, 2020. https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1834&context=usdaarsfacpub or https://doi.org/10.1016/j.agwat.2010.12.015
Summary	Basic principles of ET measuring systems are reviewed and causes of common error and biases endemic to systems are discussed. Recommendations are given for reducing error in ET retrievals.
Findings	Reporting of data containing measurement biases causes substantial confusion and impedance to the advancement of ET models and in the establishment of irrigation water requirements, and translates into substantial economic losses caused by misinformed water management.
Method(s)	Micrometeorology, lysimetry, water balance, remote sensing ET.

105	Allen, R.G. 2011b. "Evapotranspiration Information Reporting: II. Recommended Documentation." December 16, 2020. https://doi.org/10.1016/j.agwat.2010.12.016
Summary	Suggestions are given for documentation describing the primary types of ET measuring systems including recommended independent testing.
Findings	Beneficial documentations should include a description of the vegetation, its aerodynamic fetch, water management and background soil moisture, types of equipment and calibration checks, photographs of the measured vegetation/equipment combinations, and independent assessments of measured ET using models or other means. Documentation and assessment should also include a description of all weather recording equipment and parameters.
Method(s)	Micrometeorology, lysimetry, water balance, remote sensing ET.

106	Allen, R.G., A.J. Clemmens, C.M. Burt, K. Solomon, and T. O'Halloran. 2005. "Accuracy of Predictions of Project-wide Evapotranspiration using Crop Coefficients and Reference Evapotranspiration." *Journal of Irrigation and Drainage Engineering*, Volume 131 Issue 1, February. https://doi.org/10.1061/(ASCE)0733-9437(2005)131:1(24).
Summary	Crop evapotranspiration estimated using the dual crop coefficient-reference ET method was compared to crop evapotranspiration computed as the residual of inflows and outflows in a surface water balance on Imperial Irrigation District (IID) in southern California over a 7-year period. The hydrogeologic setting of IID allowed for subsurface flows to effectively be neglected without introducing too much error in the surface water balance.
Findings	The authors reported an eight percent over prediction of project crop water use by the crop coefficient-reference ET methodology compared to the crop water use estimated from the water balance. Crops were not in pristine growth conditions due to water stress, insect and disease pressure, soil fertility and salinity issues, etc. Estimates of actual crop ET using the crop coefficient-reference ET method were obtained by applying a constant 6% reduction to all crops, months, and years. Additional reductions were applied dependent on crop, time of year to obtain a match of CU estimates by the two methods used.
Method(s)	Surface water balance, Reference ET and K_c.

107	Allen, Richard G. and Willardson, Lyman S. 1997. "Water Conservation Questions and Definitions from a Hydrologic Perspective." December 14, 2020. https://www.irrigation.org/IA/FileUploads/IA/Resources/TechnicalPapers/2003/WaterConservationDefinitionsFromAHydrologicPerspective.pdf.
Summary	Water conservation programs should fundamentally be evaluated in the context that the only real loss of water from an irrigation project is by the process of evaporation from open water surfaces, evaporation from moist soil and transpiration from vegetation. Hydrologic concepts that can help planners and manager establish the context and impact of individual conservation programs in the near and long term are discussed.
Findings	For regional water management, determination of the consumed fraction and reusable fraction is much more relevant than irrigation efficiency. The quantity impact of a given use should be expressed in terms of (a) the fraction of water it directly consumes, (b) the fraction that is rendered unavailable to other users, and (c) the fraction that is returned to the hydrologic system for reuse.
Method(s)	High level equations.

108	Alvino, A. and S. Marino. 2017. "Remote Sensing for Irrigation of Horticultural Crops." *Horticulturae*. 3(40). https://doi.org/10.3390/horticulturae3020040.
Summary	Review of some remote sensing methods, sensors, and platforms. The former include satellite, aircraft, unmanned aircraft, and proximal. Sensors include shortwave reflectance, thermal infrared, and microwave.
Findings	Models include energy balance: SEBAL, METRICTM, ReSET, etc.; reflectance-based methods including: K_c, direct Penman-Monteith, hyperspectral analysis for partitioning, etc., CWSI.
Method(s)	Remote sensing ET (many models).

109	Barber, Michael. et al. 2020. *Literature Review of Current & Upcoming Irrigation Technologies and Practices Applicable to Utah*. Available at: https://water.utah.gov/wp-content/uploads/2020/11/Final-Report-11-25-2-LiteratureReviewofCurrentUpcomingIrrigationTechnologiesandPracticesApplicabletoUtah.pdf.
Summary	This document examines the historical, current, and upcoming irrigation technologies and practices applicable to Utah and in particular, technologies in relation to water losses based on permanent versus temporary losses that could go into groundwater recharge or lagged stream return flows. Twelve strategies for reducing agriculture water demand were examined including deficit irrigation with and without water spreading, conservation tillage, LEPA/LESA, ET-based irrigation scheduling, mobile drip irrigation, soil moisture monitoring (own and rent), tillage to reduce runoff, irrigation automation, variable speed irrigation and variable zone irrigation.
Findings	Deficit irrigation with water spreading and conservation tillage are the only options investigated where irrigators would make money. The other ten options resulted in some additional cost to the irrigator. LEPA, ET-based irrigation scheduling and mobile drip irrigation have the potential to be adopted in water short areas; however, financial incentives for implementation could me modest. A summary of costs per acre per year for each technology and the estimated water conserved is provided in the report.
Method(s)	Soil water measurement and balance, remote sensing ET.

110	Bugdayci, I.B. 2020. *Effects of Short Season Irrigation on Pasture Yield and Predicting Yield with Sentinel-2 Satellite*. M.S. Thesis. Civil and Environmental Engineering Department, Utah State University, Logan, UT. Available at: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=9063&context=etd.
Summary	Modeled pasture yield under full- and deficit irrigation treatments using remote sensing. Yield estimates are important for decision making.
Findings	Vegetation index was accurate for predicting yield.
Method(s)	None.

111	Calera, A., I. Campos, A. Osann, G. D'Urso, and M. Menenti, M. 2017. "Remote Sensing for Crop Water Management: From ET Modeling to Services for the End Users." *Sensors (Basel, Switzerland)*, 17(5): 1104. https://doi.org/10.3390/s17051104.
Summary	Review of methods used for remote sensing of ET, including energy balance methods, vegetation index K_c, direct Penman-Monteith methods, and combined methods.
Findings	Energy balance methods represent a snap-shot in time, which is then extrapolated. Reflectance-based methods may have difficulty representing water stressed conditions or require soil and root information.
Method(s)	Remote sensing.

112	Campos, I., C.M.U. Neale, T.J. Arkebauer, A.E. Suyker, and I.Z. Gonçalves. 2018. "Water Productivity and Crop Yield: A Simplified Remote Sensing Driven Operational Approach." *Agricultural and Forest Meteorology*. 249: 501-511. https://doi.org/10.1016/j.agrformet.2017.07.018.
Summary	Corn and soybean yield was modeled using remote sensing vegetation indices for irrigated and rainfed conditions in Nebraska. The value is in quantifying yield.
Findings	Reflectance-based methods can provide accurate estimates of yield.
Method(s)	Remote sensing (vegetation indices for yield).

113	Chavez, J.L, S Taghvaeian, and T.J. Trout. 2012. "Evaluating Remote Sensing-based Crop Water use Monitoring Methods Using Soil Moisture Sensors." 2012 ASABE Annual International Meeting. https://doi.org/10.13031/2013.41797.
Summary	Looked at using the CWSI to determine ET. Verified with soil water balance.
Findings	Model errors were considered small. Though error was apparently greater for deficit irrigation than for full irrigation.
Method(s)	Proximal sensing (CWSI), soil water content measurement (neutron probe and TDR), remote sensing energy balance.

114	Colby, B., L. Jones, M. O'Donnell. 2014. "Supply Reliability Under Climate Change: Forbearance Agreements and Measurement of Water Conserved." In: K. Easter, Q. Huang, Eds. *Water Markets for the 21st Century. Global Issues in Water Policy* v. 11. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-9081-9_4.
Summary	Book chapter about temporary conservation programs, water shortages, and climate change. Provides discussion of consumptive use methods.
Findings	Accuracy and affordability of consumptive use quantification is critical for temporary conservation programs. Remote sensing methods for identifying land cover, and ET are promising but do require human resources. For fallowing, observations of fallow conditions may be sufficient.
Method(s)	Remote sensing (energy balance and Reflectance-based K_c); remote sensing landcover identification; Reference ET and K_c; irrigation measurements, soil water measurement.

115	Chavez, J.L. 2015. "Monitoring Crop Water Use and Stress to Inform Irrigation." *Colorado Water*. November/December 2015, CSU Water Center. December 22, 2020. https://watercenter.colostate.edu/colorado-water-archive/.
Summary	A research team conducted water use and water stress surveys and held a field day presenting irrigation monitoring and techniques. Commercially available IRT guns were compared to temperatures collected with the research grade sensor.
Findings	Results indicate that the CWSI method is a viable way of monitoring corn water stress and use. In general, handheld IRT gun sensors were developed for indoor use, and when used outdoors for extended periods of time they heat up and yield erroneous temperature readings.
Method(s)	Infrared thermometers, weather station.

116	Colorado State University (CSU). 2013. *Addressing Water for Agriculture in the Colorado River Basin.* Colorado State University. Retrieved from: http://www.crbagwater.colostate.edu/addressingag/about.shtml. Accessed: January 11, 2021.
Summary	Researchers at the seven land grant universities of the Colorado River Basin utilized a USDA grant to reach out to Colorado River Basin agricultural producers and water managers through interviews, a survey, and GIS mapping to find out about pressures on ag water in their area.
Findings	The pressures include drought, urban expansion, regulations, groundwater availability, tribal rights, ag land fragmentation, and increasing age of farmers. Farmers are creating storage projects, improving delivery systems, selling water, water sharing, water leases, and water banking.
Method(s)	None.

117	Cuenca, R.H., S.P. Ciotti, and Y. Hagimoto. 2013. "Application of Landsat to Evaluate Effects of Irrigation Forbearance." *Remote Sensing*, 2013, 5, 3776-3802; https://doi.org/10.3390/rs5083776.
Summary	Summary of ground based and remote sensing energy balance estimates of actual ET over irrigated and non-irrigated grass pasture in the Wood River Valley of the Klamath Basin.
Findings	The cumulative difference in ET over a 152 growing season evaluation period was 9.8 inches between irrigated and non-irrigate pasture. Non-irrigated pasture ET was 19.6 inches showing continued depletion of shallow groundwater even with irrigation forbearance.
Method(s)	Micrometeorology (Bowen ratio energy balance) and remote sensing energy balance using METRIC.

118	Clark, B., J. Eckhardt, J. Keller, and G. Davids. 2008. "Imperial Irrigation District Efficiency Conservation Definite Plan: On-Farm Conservation Opportunities and Costs. In Urbanization of Irrigated Land and Water Transfer." *Proc. of the USCID Water Management Conference*, May 2008, Scottsdale AZ.
Summary	The authors reported the results of comparisons of actual ET (as determined by remote sensing energy balance methods) to potential ET (as determined by the crop coefficient-reference ET approach) for several different combinations of soils, on-farm irrigation method, and crop types, found on Imperial Irrigation District (IID). In this case, the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen, 1998) and Landsat satellite imagery with 30 m thermal resolution for water year 1998 was used to estimate actual ET. Potential ET was estimated using the dual crop coefficient approach presented in Allen et al. (1998).
Findings	The results were presented as ratios of actual ET to potential ET. Across IID the average ratio of actual ET to potential ET found was 0.85. For crops (alfalfa, Bermuda grass, wheat) and irrigation methods (graded border and graded furrow) prevalent on the CRIP, the IID energy balance ET / K_c ET ratio was 0.83 to 0.87 for graded border and graded furrow irrigation of mature alfalfa and new alfalfa on all soil types; 0.79 for graded border irrigation of mature Bermuda on all soil types; 0.85 for graded border irrigation of wheat on all soil types.
Method(s)	Actual ET estimated using remote sensing energy balance using SEBAL. Potential ET was estimated using the dual crop coefficient approach presented in FAO-56 (Allen et al. 1998).

119	Elhaddad, A. and L. Garcia 2014. "Using a Surface Energy Balance Model (ReSET-Raster) to Estimate Seasonal Crop Water Use for Large Agricultural Areas: Case Study of the Palo Verde Irrigation District." *Journal of Irrigation and Drainage Engineering*. 140(10):05014006. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000716.
Summary	The authors reported the results of comparisons of actual ET (as determined by remote sensing energy balance methods) to potential ET (as determined by the crop coefficient-reference ET approach) for several different crop types, found on Palo Verde Irrigation District (PVID). In this case, actual ET was estimated using the ReSET Raster method (Elhaddad and Garcia, 2008) and Landsat 7 satellite imagery with 30 m thermal resolution for calendar year 2002. Potential ET was estimated using methods employed by the Reclamation in the Lower Colorado River Accounting System (LCRAS) (Reclamation, 1997-2019; Jensen, 1998; Jensen, 2003).
Findings	Across PVID, the average ratio of actual ET to potential ET found was 0.86. For crops (alfalfa, Bermuda grass, wheat) prevalent on the CRIP, the PVID remote sensing ET / K_c ET ratio was 0.86 for alfalfa; 0.70 to 0.84 for Bermuda grass; 0.95 for wheat and other small grains.
Method(s)	Actual ET estimated using remote sensing energy balance using ReSET. Potential ET was estimated using methods employed by Reclamation in the Lower Colorado River Accounting System (LCRAS) (Reclamation, 1997-2019; Jensen, 1998; Jensen, 2003).

120	Evett, S.R., G.W. Marek, P.D., Colaizzi, B.B. Ruthardt, and K.S. Copeland. 2018. "A Subsurface Drip Irrigation System for Weighing Lysimetry." *Applied Engineering in Agriculture*. 34(1):213-214. https://doi.org/10.13031/aea.12597.
Summary	A drip irrigation system was installed in some large, relatively renowned lysimeters in northern Texas.
Findings	Demonstrates the effort of accurate lysimetry, the only direct method for measuring ET. Describes the difficulty of this method when trying to quantify ET for drip irrigation.
Method(s)	Lysimetry.

121	Evett, S.R., R.C. Schwartz, J.J. Casanova, and L.K. Heng. 2012a. "Soil Water Sensing for Water Balance, ET and WUE." *Agricultural Water Management*. 104: 1-9. https://doi.org/10.1016/j.agwat.2011.12.002.
Summary	Demonstrates the care, specific conditions, and effort of a scientifically accurate soil water balance study. Review based on article abstract.
Findings	Neutron probe and TDR are preferred methods. Capacitance sensors may not be sufficiently accurate for water balance purposes.
Method(s)	Soil water content measurement and balance.

122	Fereres, E. and M.A. Soriano. 2006. "Deficit Irrigation for Reducing Agricultural Water Use." *Journal of Experimental Botany*. 58(2): 147-159. https://doi.org/10.1093/jxb/erl165.
Summary	A review of deficit irrigation as it relates to reducing water consumption for biomass production and for irrigation of annual and perennial crops.
Findings	Water productivity, yield per unit of water used in ET, increases under deficit irrigation for many crops; however, it is not known whether deficit irrigation can be used over long time periods.
Method(s)	

123	French, A.N., D.J. Hunsaker, L. Bounoua, A. Karnieli, W.E. Luckett, and R. Strand. 2018. "Remote Sensing of Evapotranspiration over the Central Arizona Irrigation and Drainage District." *Agronomy*. 8(12): 278. https://doi.org/10.3390/agronomy8120278.
Summary	Remote-sensing-based ET study for the CAIDD. Promote the idea of ensemble ET, specifically mentioning Open ET.
Findings	Remote sensing models had less than 20% variation in ET as compared to the mean of the three models. Reference ET and K_c methods also varied from the model mean. Vegetation indices may not be best for quantifying ET in deficit irrigation.
Method(s)	Remote sensing (energy balance: METRICTM, TSEB; reflectance-based K_c); Reference ET and crop coefficients.

124	Green, A. et al. 2020. “Case Study of Emery County Real-time Monitoring and Control System Implementation.” December 14, 2020. https://water.utah.gov/wp-content/uploads/2020/04/Final-Case-Study-of-Emery-County-Agriculture-Water-Quantification-System-Implementation.1-2.pdf.
Summary	This article summarizes a case study in Emery County, Utah where a network of flow measurement structures and Real-time Monitoring and Control System was implemented. The case study discusses the drivers, methods, costs, benefits, and lessons learned.
Findings	Three quantifiable benefits found are 1) additional water delivered to take-outs at the farm, 2) reduced conveyance efficiency losses and salt loading, 3) reduced annual irrigation diversions from creeks to the canal systems.
Method(s)	

125	Hanson, B., D. Putnam, and R. Snyder. 2007. "Deficit Irrigation of Alfalfa as a Strategy for Providing Water for Water-Short Areas." *Agricultural Water Management*. 93(1–2): 73-80. https://doi.org/10.1016/j.agwat.2007.06.009.
Summary	Alfalfa water use and yield experiment in California. Used energy flux stations to quantify ET. Review based on article abstract.
Findings	Found that both ET and yield were less for deficit irrigation than for full irrigation.
Method(s)	Micrometeorology (eddy covariance and surface renewal).

126	Iniesta, F., L. Testi, D.A. Goldhamer, and E. Fereres. 2008."Quantifying Reductions in Consumptive Water Use Under Regulated Deficit Irrigation in Pistachio (Pistacia vera L.)." *Agricultural Water Management*. 95(7): 877-886. https://doi.org/10.1016/j.agwat.2008.01.013.
Summary	Evapotranspiration study in pistachio in Madera, CA. Review based on article abstract.
Findings	Both transpiration and evaporation decreased in deficit irrigation as compared to full irrigation. The decrease in ET extended after deficit irrigation ceased.
Method(s)	Soil water content measurement and balance (neutron probe).

127	Jensen, M.E. and R.G. Allen. 2016. *Evaporation, Evapotranspiration, and Irrigation Water Requirements*. ASCE Manuals and Reports on Engineering Practice No. 70. 2nd Ed. American Society of Civil Engineers. Reston, VA.
Summary	This manual is the gold standard regarding the physics of evaporation and transpiration. It is an excellent, comprehensive treatment of the topic and provides guidance for developing practical, accurate methods of estimating ET.
Findings	Along with the 1990 1st edition and the 2005 ASCE Task Committee report on the standardized Ref-ET Equation, the 2nd edition of Manual 70 provides excellent guidance on methods of direct measurement of ET (lysimetry, solution of the full energy balance using remote sensing and of estimating methods based on climate and micrometeorology methods.
Method(s)	All

128	Karimi, P. and W.G.M. Bastiaanssen. 2015. "Spatial Evapotranspiration, Rainfall and Land Use Data in Water Accounting - Part 1: Review of the Accuracy of the Remote Sensing Data." *Hydrology and Earth System Sciences*. 19: 507-532. https://doi.org/doi:10.5194/hess-19-507-2015.
Summary	This paper reviews the reliability of remote sensing algorithms to accurately determine the spatial distribution of actual evapotranspiration, rainfall, and land use.
Findings	By using remote sensing, the absolute values of evapotranspiration can be estimated with an overall accuracy of 95% and rainfall with an overall absolute accuracy of 82%. Land use can be identified with an overall accuracy of 85%. While not always perfect at all spatial and temporal scales, seasonally accumulated actual evapotranspiration maps can be used with confidence in water accounting and hydrological modeling.
Method(s)	Remote sensing.

129	Lin, V., S. Sandoval-Solis, B.A. Lane, and J.M. Rodriguez. 2013. "Potential Water Savings Through Improved Irrigation Efficiency in Pajaro Valley, California." December 14, 2020. http://watermanagement.ucdavis.edu/files/5313/8116/1627/UC_Davis_-_Water_Savings_In_Pajaro_Valley.pdf.
Summary	This report evaluates a water conservation project in Pajaro Valley, California and the economic impact on the growers. This project estimates the potential water savings by applying an interview campaign with growers, an evapotranspiration consultation with experts and statistical analysis of the collected data. Applied water and crop ET were compared in this study.
Findings	An estimated savings of 4,600 to 5,100 acre-feet per year could be achieved through water conservation; however, there was a decrease in revenue ranging from $862,000 to $951,000.
Method(s)	Reference ET and K_c; well production and land use to calculate water applied.

130	Medellin-Azuara, J., K.T. Paw U, Y. Jin, and J. Lund. 2018. *A Comparative Study for Estimating Crop Evapotranspiration in the Sacramento-San Joaquin Delta*. University of California Davis Center for Watershed Sciences. Available at: https://watershed.ucdavis.edu/project/delta-et.
Summary	Compared models against the mean of all models and against flux station measurements. This was a cooperative effort with extensive instrumentation and modeling. The need for further research and improvements supports the concept that these types of studies require refinement and on-going efforts. Collaboration is seen as important for improving accuracy and "transparency."
Findings	Most models did were not statistically significantly different than the mean of models for most months. However, some differences that were not statistically significant, were practically significant. Crop coefficient methods were significantly different than flux station ET. Remote-sensing ET estimates were mostly not significantly different than flux stations. Remote sensing ET was greater for fallow than flux measurements, but the flux dataset was limited in time and did not include low elevation areas. Remote sensing was stated to potentially decrease "self-reporting" efforts and as to be "cost-effective."
Method(s)	Remote sensing ET (energy balance: ALEXI/DisALEXI, METRIC^{TM}, Optimized Priestley-Taylor; reflectance-based crop coefficient: SIMS); micrometeorology (eddy covariance, surface renewal); crop coefficient (using gridded weather data and using point weather data calibrated to SEBAL).

131	Montazar, A., O. Bachie, D. Corwin, and D. Putnam. 2020. "Feasibility of Moderate Deficit Irrigation as a Water Conservation Tool." *Agronomy*. 10(11): 1640. https://doi.org/10.3390/agronomy10111640.
Summary	Deficit irrigation study in Palo Verde Valley, CA. Not clear if surface renewal ET in deficit plots was used in final analyses.
Findings	Reduced water application varied notably.
Method(s)	Micrometeorology (eddy covariance and surface renewal), proximal sensing (CWSI), soil water potential measurement, applied water.

132	Montazar, A., K. Bali, D. Zaccaria, and D. Putnam. 2018. "Viability of Subsurface Drip Irrigation for Alfalfa Production in the Low Desert of California." 2018 ASABE Annual International Meeting. https://doi.org/10.13031/aim.201800415.
Summary	Subsurface drip irrigation and surface irrigation in Palo Verde Valley, CA. Project was not replicated (one field of each irrigation method).
Findings	SDI had greater ET and greater yield than flood. Increased irrigation adequacy was a cause. Productivity increased, so more yield per unit ET was a result.
Method(s)	Micrometeorology (eddy covariance and surface renewal).

133	OpenET. 2020. *Frequently Asked Questions*. OpenET Available at: https://openetdata.org/faq.pdf.
Summary	Multi-model remote sensing ET dataset for western U.S. To be made available in 2021.
Findings	A tailored ensemble modeling approach is promoted to provide more accurate results.
Method(s)	Remote sensing (energy balance: ALEXI/DisALEXI, METRICTM, Priestley-Taylor, SEBAL, SSEBop; reflectance-based crop coefficient: SIMS).

134	Orloff, Steve. (2003). "Controlled Deficit Irrigation of Alfalfa: Opportunities and Pitfalls." December 15, 2020. https://ucanr.edu/sites/adi/files/204411.pdf.
Summary	Large-scale field trials were performed in the Klamath Basin and Sacramento Valley in 2003 to evaluate the effects of early-season irrigation cut-off (deficit irrigation) on yield, forage quality, stand persistence and economics.
Findings	Severe yield loss when irrigation was halted in late summer in some cases; however, little to no stand loss in these trials. Preliminary results suggest that the concept of temporary voluntary water transfers from alfalfa for other uses may have merit.
Method(s)	Soil water content measurement.

135a/ 135b	Pereira, L.S., P. Paredes, D.J. Hunsaker, R. López-Urrea, and Z. Mohammadi Shad. 2021a. "Standard Single and Basal Crop Coefficients for Field Crops. Updates and Advances to the FAO56 Crop Water Requirements Method." Agricultural Water Management. 243: 106466. https://doi.org/10.1016/j.agwat.2020.106466; and Pereira, L.S., P. Paredes, R. Lopez-Urrea, D.J. Hunsaker, M Mota, and Z.M. Shadi. 2021b. "Standard Single and Basal Crop Coefficients for Vegetable Crops, an Update of FAO56 Crop Water Requirements Approach." *Agricultural Water Management*. 243: 106196. https://doi.org/10.1016/j.agwat.2020.106196.
Summary	These are paired papers. Large review of crop coefficient research and recommendation of a revised set of crop coefficients for many crops. Includes many references to ET studies.
Findings	They reported K_c for many crops. They express the accuracy of applicability of using K_c to compute ET.
Method(s)	Reference ET and K_c.

136	Rudnick, D., S. Irmak, C. Ray, J. Schneekloth, M. Schipanski, I. Kisekka, A. Schlegel, J. Auilar, D. Rogers, D. Mitchell, C. West, T. Marek, Q. Xue, W. Xu, and D. Porter. 2018. "Deficit Irrigation Management of Corn in the High Plains: A Review." 2017 Central Plains Irrigation Conference. https://www.ksre.k-state.edu/irrigate/oow/p17/Rudnick17.pdf.
Summary	Provides description of deficit irrigation projects throughout the Plains. A useful source of additional literature.
Findings	a notable drought year.
Method(s)	Not specified.

137	Samani, Z. and R.K. Skaggs. 2006. "The Multiple Personalities of Water Conservation." *Water Policy.* 10(3): 265-294. https://www.researchgate.net/profile/Rhonda_Skaggs/publication/228425854_The_multiple_personalities_of_water_conservation/links/0a85e52e950bce9111000000.pdf or https://doi.org/10.2166/wp.2008.154.
Summary	This paper examines the water conservation impacts of drip irrigation, irrigation scheduling and canal lining in the context of hydrological assumptions that are used to promote these technologies. The potential of these technologies to sustain and increase crop evapotranspiration in deficit irrigation is discussed.
Findings	Drip irrigation and irrigation scheduling may actually result in increased consumptive use. Canal lining may make delivery more efficient but at the cost of depleting water from the basin-wide hydrologic system.
Method(s)	

138	Semmens, K.A., M.C. Anderson, W.P. Kustas, F. Gao, J.G. Alfieri, L. McKee, J.H. Prueger, C.R. Hain, C. Cammalleri, Y. Yang, T. Xia, L. Sanchez, M. Mar Alsina, and M. Vélez. 2016. "Monitoring daily evapotranspiration over two California vineyards using Landsat 8 in a multi-sensor data fusion approach." *Remote Sensing of Environment*. 185: 155-170. https://doi.org/10.1016/j.rse.2015.10.025.
Summary	The utility of a multi-scale system for monitoring ET as applied over two vineyard sites near Lodi, California during the 2013 growing season into the 2014 drought is evaluated. The system employs a multi-sensor satellite data fusion methodology combined with a multi-scale ET retrieval algorithm to compute daily ET.
Findings	Multi-sensor remote sensing observations provide a unique means for monitoring crop water use and soil moisture at field scales over extended growing regions and may have value in supporting operational water management decisions.
Method(s)	Remote sensing ET (ALEXI/DisALEXI).

139a/ 139b	Shuttleworth, W.J. 2008. "Evapotranspiration Measurement Methods." *Southwest Hydrology*. 7(1). http://www.swhydro.arizona.edu/archive/V7_N1/; and Baker, J.M. 2008. "Challenges and Cautions in Measuring Evapotranspiration." *Southwest Hydrology*. 7(1). http://www.swhydro.arizona.edu/archive/V7_N1/.
Summary	Two articles in the same publication. One provides a summary, though not quite comprehensive, of methods for quantifying ET. The other describes difficulties with lysimetry and two micrometeorology methods.
Findings	Methods include micrometeorology, remote sensing, water balance, and measuring only ET components.
Method(s)	Remote sensing, micrometeorology, water balance, etc.

140	Simons, G.W.H., W.G.M. Bastiaanssen, M.J.M. Cheema, B. Ahmad, and W.W. Immerzeel. 2020. "A Novel Method to Quantify Consumed Fractions and Non-Consumptive Use of Irrigation Water: Application to the Indus Basin Irrigation System of Pakistan." *Agricultural Water Management*. 236:106174. https://doi.org/10.1016/j.agwat.2020.106174.
Summary	Quantified consumptive use in India. Discussed the challenges with efficiency projects. Divide ET into irrigation and precipitation components. Describe a method for quantifying contributions to ET other than precipitation and surface water diversions.
Findings	Water reuse can make quantification tricky. Method for dividing consumptive use between precipitation and irrigation is of note.
Method(s)	Remote sensing (energy balance: SSEBop).

141	Stewart, W.C., A. Fulton, W.H. Krueger, B.D. Lampinen, and K.A. Shackel. 2011. "Regulated Deficit Irrigation Reduces Water Use of Almonds Without Affecting Yield." *California Agriculture*. 65(2):90-95. https://doi.org/10.3733/ca.v065n02p90.
Summary	Multi-year deficit irrigation study in an almond orchard in Sacramento Valley, CA. Soil water content measurements were not replicated.
Findings	Irrigation and ET reductions from deficit irrigation. Yield differences were not significant.
Method(s)	Soil water balance.

142	Taghvaeian, S. and C.M.U. Neale. 2011. "Water balance of irrigated areas: a remote sensing approach." *Hydrologic Processes*. 25(26): 4132-4141. https://doi.org/10.1002/hyp.8371.
Summary	The authors provide a thorough review of challenges in performing water balances on large irrigation schemes and present results of several studies. They then introduce remote sensing as a potential means for estimating actual crop water use on large irrigation districts and discuss a few of the methods in use worldwide and in the western US, i.e., SEBAL and METRIC™.
Findings	For the year 2008, the authors performed a Palo Verde Irrigation District (PVID) District-wide water balance with spatially averaged ET estimated as the residual of the water balance and compared the result with Remote Sensing of ET using SEBAL model. Ground based weather data (CIMIS station) and precipitation were used. The instantaneous SEBAL ET estimates were upscaled to daily values using the fraction of reference ET method. Total ET from water balance (1268 mm) was found to be 1.4% less than SEBAL estimated ET (1286mm).
Method(s)	Water balance, remote sensing of ET (SEBAL).

143	Texas Water Development Board (TWDB). 2003. "Agricultural Water Conservation Practices." December 15, 2020.
Summary	This brochure outlines various agricultural water efficiency measures and explains how they can help save water, energy, money and possibly increase crop yields.
Findings	Not necessarily any finding as this is a brochure that discusses efficient water management practices that can be implemented.
Method(s)	Soil water content measurement, reference ET and K_c noted but not in regard to quantifying.

144	Trout, T.J., T.A. Howell, M.J. English, D.L. Martin. (2020). "Deficit Irrigation Strategies for the Western U.S." *Transactions of the ASABE*. 63(6): 1813-1825. https://doi.org/10.13031/trans.14114.
Summary	This article discussed managing deficit irrigation in which the manager is aware of water supply limitations and value and has flexibility to adjust irrigated area. The article considered two constraints, water supply is adequate but expensive and limited by volume due to legal limitations.
Findings	The analyses determined that potential benefits of deficit irrigation are greatest when water is expensive, irrigation efficiency is low, the water supply is flexible, and rainfed production is not economically viable. Deficit irrigation will become more important as irrigation water supplies continue to decline in the future.
Method(s)	Water balance.

145	Zhang, Y, N. Hansen, T. Trout, D. Nielsen, and K. Paustian. 2018. "Modeling Deficit Irrigation of Maize with the DayCent Model." *Agronomy Journal*. 110(5):1754-1764. https://doi.org/10.2134/agronj2017.10.0585.
Summary	Used crop model to simulate water use for deficit irrigated maize. Example of this type of method in research. Review based on article abstract.
Findings	Model simulated ET well.
Method(s)	Crop modeling.

146	Upper Colorado River Commission and The Wilson Water Group (UCRC and Wilson Water). 2018. *Colorado River System Conservation Pilot Program in the Upper Colorado River Basin Final Report.* Available at: http://ucrcommission.com/RepDoc/SCPPDocuments/2018_SCPP_FUBRD.pdf and http://www.ucrcommission.com/RepDoc/SCPPDocuments/2018_SCPP_RUFinal.pdf.
Summary	Final report of the Upper Basin pilot conservation program funded by municipal water users in the Colorado River Basin. Used historical estimates of ET using METRIC or Blaney-Criddle to estimate consumptive use reductions beforehand. Reduced potential consumptive use reductions based on estimated insufficient water supplies. Implemented simple water content modeling to account for carryover soil water.
Findings	The existence of historical crop water use and cropping patterns is helpful in conservation planning. Estimates of reduced consumptive use were less than projected before implementation. Making quantification resources available to irrigators is important. They acknowledged the possible contribution of carryover soil water content to ET during conservation that could subsequently increase irrigation requirements later. They described pros and cons of using historical average ET estimates. Quantification methods have economic implications. Estimates of "actual" consumptive use reductions sometimes differed from the historical means.
Method(s)	Remote sensing ET (METRIC^{TM} for a previous year); Blaney-Criddle; simple soil water content modeling; Reference ET and K_c.

147	Udall, Brad and Greg Peterson. 2017a. "Part 1 of 5. Executive Summary." in *Agricultural Water Conservation in the Colorado River Basin: Alternatives to Permanent Fallowing Research Synthesis and Outreach Workshops*. Colorado State University Colorado Water Institute, Fort Collins, CO. Available at: http://www.crbagwater.colostate.edu/files/CWI_Completion_Report232_Part1.pdf.
Summary	This is the Executive Summary for CWI Completion Report No.232, a five-part report providing a literature review and observations of case studies for water conservation via deficit irrigation of alfalfa and other forages, rotational fallowing, crop switching and efficiency improvement activities. Not constrained to just CRB.
Findings	This is the executive summary of the overall study.
Method(s)	Not discussed.

148	Udall, Brad and Greg Peterson. 2017b. "Part 2 of 5. Deficit Irrigation of Alfalfa and Other Forages in the Colorado River Basin: A Literature Review and Case Studies." in *Agricultural Water Conservation in the Colorado River Basin: Alternatives to Permanent Fallowing Research Synthesis and Outreach Workshops*. Colorado State University Colorado Water Institute, Fort Collins, CO. Available at: http://www.crbagwater.colostate.edu/files/CWI_Completion_Report232_Part2.pdf.
Summary	This is part 2 of CWI Completion Report No.232 (see no. 54). It focuses on and provides a literature review and case studies of deficit irrigation of alfalfa and other forages. Extensive review of alfalfa production, agronomic factors, markets and uses. Defines different approaches to deficit irrigation. Focus on alfalfa because of its large consumptive use relative to other crops and extensive acreage in production in the western US.
Findings	Alfalfa will go dormant under excess water stress or cutoff, allowing it to survive reduced irrigation but with a loss of economic yield. Has a deep tap root that allows uptake from deep soil profiles and helps keeps the stand alive. Grass hay will also go dormant under reduced irrigation but has a shallow rooting system and the stand may die from lack of water. Extensive review of the significant relationship between alfalfa ET and yield. Best yields obtained in cooler early spring to early summer periods and less so during hottest summer and early fall months. Many theoretical studies but few actual case studies.
Method(s)	Reference ET and K_c, reduced diversions.

149	Udall, Brad and Greg Peterson. 2017c. "Part 3 of 5. Rotational Fallowing in the Colorado River Basin: A Literature Review and Case Studies." in *Agricultural Water Conservation in the Colorado River Basin: Alternatives to Permanent Fallowing Research Synthesis and Outreach Workshops*. Colorado State University Colorado Water Institute, Fort Collins, CO. Available at: http://www.crbagwater.colostate.edu/files/CWI_Completion_Report232_Part3.pdf.
Summary	This is part 3 of CWI Completion Report No.232 (see no. 54). It focuses on and provides a literature review and case studies of rotational fallowing as a water conservation activity. A good overview of fallowing benefits and costs.
Findings	Reviews of the 2004 long term PVID-MWD fallowing program; three 1998 IID-SDWCA fallowing; the 2016 BARD-MWD fallowing; the YMIDD fallowing projects; and ag to urban and ag to environmental transfers. There are very few details regarding quantification methods. Need to go to the original cases study documentation to find this.
Method(s)	Reference ET and K_c; water balance and headgate diversion reduction.

150	Udall, Brad and Greg Peterson. 2017d. "Part 4 of 5. Crop Switching in the Colorado River Basin: A Literature Review and Case Studies." in *Agricultural Water Conservation in the Colorado River Basin: Alternatives to Permanent Fallowing Research Synthesis and Outreach Workshops*. Colorado State University Colorado Water Institute, Fort Collins, CO. Available at: http://www.crbagwater.colostate.edu/files/CWI_Completion_Report232_Part4.pdf.
Summary	This is part 4 of CWI Completion Report No.232 (see no. 54). It focuses on and provides a literature review and case studies of crop switching as a water conservation activity. There have been extensive proposals regarding crop switching, but many lack complete consideration of the full economic, market, and physical tradeoffs. Crop switching must consider local and regional infrastructure support systems and market needs for the alternative crop(s).
Findings	Growers must be able to easily and economically adapt their on-farm production system to the new crop(s). Climate, soils, water quality, labor availability, knowledge are all factors that must be considered. Describes the Yuma area long term transition from field crops to vegetables and generally reduced diversion rates. Some of the reduced diversion due to crop mix changes and some due to irrigation efficiency improvements.
Method(s)	CU savings can be quantified as the difference in ET of the existing crop (or crop mix) and the ET of the replacement crop (or crop mix). Not much detail provided.

151	Udall, Brad and Greg Peterson. 2017e. "Part 5 of 5. Irrigation Efficiency and Water Conservation in the Colorado River Basin: A Literature Review and Case Studies." in *Agricultural Water Conservation in the Colorado River Basin: Alternatives to Permanent Fallowing Research Synthesis and Outreach Workshops*. Colorado State University Colorado Water Institute, Fort Collins, CO. Available at: http://www.crbagwater.colostate.edu/files/CWI_Completion_Report232_Part5.pdf.
Summary	This is part 5 of CWI Completion Report No.232 (see no. 54). It focuses on defining and discussing differences between water conservation (consumptive use reduction) and water savings that result from irrigation efficiency improvements (canal lining, irrigation conversion, etc.) which allow reduced diversions. Efficiency improvements may maintain or possibly may increase consumptive use. Importance of understanding impacts of efficiency improvements on return flows stressed. Good review of water balances and efficiency improvements at farm level, district level and basin level and impacts on return flows.
Findings	Good review and discussion of relevant definitions and concepts. Discusses irrigation efficiency improvement measures at all levels of an irrigation system. Provides overview of multiple case studies of efficiency improvement projects in the CRB. Details on quantification of savings found under these case studies are very general in nature and require review of the case study documentation.
Method(s)	Details not provided, but the multiple case studies referenced in general used one or more of the methods listed.

152	Utah Department of Natural Resources (UDNR). 2020. “Depletion Accounting for Irrigation Water Rights in Utah.” December 14, 2020. https://water.utah.gov/wp-content/uploads/2020/06/2020AgDepletionMethodsReport_FINAL.pdf.
Summary	The main objective of this study was to evaluate and identify the most practical, effective, and defensible means of measuring and accounting for actual depletion in Utah and to recommend methodologies to be validated for use in Utah via a pilot program.
Findings	A recommended layered approach including remote sensing methods for field scale to basin scale depletion assessment, ground-based methods for field scale depletion reporting and ground-based methods for field scale depletion validation was identified as the most effective depletion accounting method and will be used in a case study for validation in 2021-2022.
Method(s)	Remote sensing (Automated OpenET platform and METRIC with manual operation), soil moisture balance method, field water balance with flow measurements, and eddy covariance method.

153	Umair, M., T. Hussain, H. Jiang, A. Ahmad, J. Yao, Y. Qi, Y. Zhang, L. Min, and Y. Shen. 2019. "Water-Saving Potential of Subsurface Drip Irrigation for Winter Wheat." *Sustainability*. 11(10): 2978. https://doi.org/10.3390/su11102978.
Summary	Used very small lysimeters to compare irrigation methods.
Findings	ET was less in flood than drip or SDI. However, grain yield was greater in flood irrigated.
Method(s)	Lysimetry.

154	U.S. Bureau of Reclamation (Reclamation). 2020. *Colorado River Accounting and Water Use Report: Arizona, California, and Nevada; Calendar Year 2019*. U.S. Bureau of Reclamation. Available at: https://www.usbr.gov/lc/region/g4000/4200Rpts/DecreeRpt/2019/2019.pdf; Other years available at: https://www.usbr.gov/lc/region/g4000/wtracct.html.
Summary	This is the water accounting report for the LCRB for 2019. Similar reports are available for other years. This report is essentially a results report, methods are in other documents.
Findings	The report is essentially the results of the accounting for 2019.
Method(s)	Multiple.

155	Ward, F.A. and M. Pulido-Velazquez. 2008. "Water Conservation in Irrigation Can Increase Water Use." *Proceedings of the National Academy of Sciences of the United States of America.* 105(47):18215-18220. https://doi.org/10.1073/pnas.0805554105.
Summary	This article presents results of an integrated basin-scale analysis linking biophysical, hydrologic, agronomic, economic, policy and institutional dimensions of the Upper Rio Grande Basin. It analyzes a series of water conservation policies for their effect on water used in irrigation and on water conserved.
Findings	Water conservation subsidies are unlikely to reduce agricultural water depletions and programs subsidizing irrigation efficiency are likely to reduce water supplies available for downstream, environmental, and future uses. Reducing water scarcity requires accurate measurement of water use at different scales, including better estimates of return flows and ET. It also requires defining water rights, water transfers, water use, and water accounting overall in water depletions rather than water applications.
Method(s)	

Table B-2 References for Current/Recent Conservation Activities

Ref. No.	Reference
201a	Yuma County Agriculture Water Coalition (YCAWCA). 2015. *A Case Study in Efficiency – Agriculture and Water Use in the Yuma, Arizona Area*. February 2015. Yuma County Agriculture Water Coalition. Available at: https://www.agwateryuma.com/wp-content/uploads/2018/02/ACaseStudyInEfficiency.pdf.
201b	Frisvold, G., C. Sanchez, N. Gollehon, S. Megdal, and P. Brown. 2018. "Evaluating Gravity-Flow Irrigation with Lessons from Yuma, Arizona, USA." *Sustainability*. 10(5):1548. https://doi.org/10.3390/su10051548.
202a	Metropolitan Water District of Southern California (MWD). 2019. *Revised Plan for the Creation of Extraordinary Conservation Intentionally Created Surplus During Calendar Year 2019*. Metropolitan Water District of California. Available at: https://www.usbr.gov/lc/region/g4000/4200Rpts/DecreeRpt/2019/27.pdf.
202b	Palo Verde Irrigation District, The Metropolitan Water District of Southern California, and U.S. Bureau of Reclamation (PVID, MWD, and USBR). 2020. *Calendar Year 2019 Fallowed Land Verification Report: PVID/MWD Forbearance and Fallowing Program*. Available at: https://www.usbr.gov/lc/region/g4000/4200Rpts/DecreeRpt/2019/27.pdf.
203 (also 133)	Montazar, A., O. Bachie, D. Corwin, and D. Putnam. 2020. "Feasibility of Moderate Deficit Irrigation as a Water Conservation Tool." *Agronomy*. 10(11): 1640. https://doi.org/10.3390/agronomy10111640.
204a	Yuma Mesa Irrigation Drainage District (YMIDD) /Central Arizona Water Conservation District (CAWCD). 2017. *Pilot Fallowing and Forbearance Program: 2014-2016 Summary Report*. Yuma Mesa Irrigation Drainage District
204b	Yuma Mesa Irrigation Drainage District. 2015. *Crop Mapping and Consumptive Use Estimation*. Yuma Mesa Irrigation Drainage District
205a	Natural Resources Consulting Engineers (NRCE). 2019. *Exhibit A CY2020--Proposed Lands for Compensated System Conservation Program (SCP) and Extraordinary Conservation Intentionally Created Surplus (EC ICS)*. Natural Resources Consulting Engineers, Inc., Fort Collins, CO.

Table B-3 Additional Literature Review References

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Technical Memorandum 3 – Summary of Case Study Definitions, Site Selection, and Evaluation Process

Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Technical Memorandum 3 – Summary of Case Study Definitions, Site Selection, and Evaluation Process

Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

prepared by

Natural Resources Consulting Engineers, Inc.
Jacobs Engineering Group Inc.

Cover Photo: United States Bureau of Reclamation

Contents

List of Tables

List of Figures

Project Definition

The Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin Pilot Study (Pilot Study) is a logical next step in the long-standing commitment of United States Bureau of Reclamation (Reclamation) and the Lower Colorado River Basin (LCRB, Lower Basin) stakeholders to ensure the resiliency, reliability, and sustainability of the Colorado River. The objective of this study is to work collaboratively with a diversity of stakeholders to explore the current methods used to quantify certain agricultural water conservation activities in the Lower Basin, including the relationship of those quantification methods to the Lower Basin consumptive use accounting, and to recommend approaches to improve agricultural water conservation quantification methods.

Project Activities

The Pilot Study commenced with a workshop (Workshop #1) held remotely November 9 and 10, 2020. The workshop included a summary of the *Colorado River Basin Supply and Demand Study* (Reclamation, 2012) and the *Colorado River Basin Stakeholders Moving Forward to Address Challenges Identified in the Colorado River Basin Water Supply and Demand Study* (Reclamation, 2015) reports. The workshop also provided an opportunity for stakeholders and participants to provide input regarding scope refinement for the Pilot Study. A summary of Workshop #1 and the refined project scope were provided in *Technical Memorandum 1 – Project Definition and Summary of Workshop #1*, herein referred to as TM1 (NRCE and Jacobs, 2021a).

The second step in the Pilot Study effort was to perform a review of scientific and technical literature, project reports, regional publications, reference books and other sources to document methods used to quantify consumptive use (CU) reductions from agricultural irrigation conservation measures in the LCRB and elsewhere (e.g., full-year agricultural cropland fallowing, seasonal or partial-year cropland fallowing, deficit irrigation, switching crops or crop rotations to alternate crops requiring less irrigation water, irrigation methodology conversions, and similar topics). This study effort was divided into two portions: 1) a review of scientific literature and other sources to identify CU quantification methods, and 2) an overview of select conservation activities within the LCRB and associated CU quantification methods. This effort resulted in *Technical Memorandum 2 – Summary of Significant Findings from Literature Review and Recent/Current Activities in the Lower Basin* referred to as TM2 (NRCE and Jacobs, 2021b).

TM2 was made available for review and comment by participants prior to Workshop #2. Workshop #2 was held remotely on March 2, 2021. A copy of the presentation slides is included in the Appendix. The primary purposes of Workshop #2 were to:

- Provide a summary of the literature review documented in TM2,
- Present a review of some recent and on-going agricultural water conservation activities in the LCRB documented in TM2,
- Identify relevant case study opportunities in the LCRB in which specific conservation activities and/or methods of quantifying CU reductions could be reviewed in depth,
- Present a framework for categorizing case study opportunities considering location, type of conservation activity, and quantification methodology, and

- Seek input from workshop participants on any constraints or limitations regarding case studies and the site selection evaluation process

The purpose of this technical memorandum (TM3) is to document the results of Workshop #2 and the case study selection process.

Workshop #2 Participants

Over 50 people participated in Workshop #2. *Table 1* is a list of the workshop attendees.

Table 1 Workshop #2 Participants

Funding Partners			
Reclamation Dan Bunk Jeremy Dodds John Shields Amber Cunningham Nancy DiDonato Nohemi Olbert	**Central Arizona Water Conservation District** Chuck Cullom Deanna Ikeya	**Metropolitan Water District of Southern California** Bill Hasencamp Aaron Mead Larry Lai Noosha Razavian Jessica Arm Kira Alonzo Laura Lamdin David Bradshaw Ed Smith	**Southern Nevada Water Authority** Seth Shanahan Casey Collins

Agricultural Districts/Cities				
Imperial Irrigation District Dylan Mohamed Ben Brock	**Palo Verde Irrigation District** Ned Hyduke Andrew Slagan Bert Bell	**Mohave Valley Irrigation and Drainage District** Kerri Hatz Michael Pearce Vince Vasquez	**Coachella Valley Water District** Robert Cheng Ivory Reyburn	**Bard Water District** Nicholas Bahr

Tribal Representatives			
Bureau of Indian Affairs Jonathan Cody Denni Shields Cherry Bustos Gary Colvin	**Fort McDowell Yavapai Nation** Gerry Walker	**Colorado River Indian Tribes** Devin Heaps Angie Ingram Margaret Vick	**Gila River Indian Community** Jason Hauter
Navajo Nation Jason John	**Cocopah Tribe** Michael Smith	**Quechan Tribe** Jay Weiner	**Tohono O'odham Nation** Selso Villegas

State Agencies				
Arizona Department of Water Resources Bret Esslin	**Colorado River Board of California** Rich Juricich	**University of California Cooperative Extension** Ali Montazar	**San Juan Water Commission** Aaron Chavez	**Colorado River Commission of Nevada** Warren Turkett

Consultants/Attorneys/Other			
NRCE Tom Ley Ryan McBride Burdette Barker	**Jacobs** Lela Perkins Chris Kurtz Jason Smesrud	**Noble Law** Wade Noble Meghan Scott	Marissa Johnson

Agricultural Conservation Measures

This study focuses on agricultural water conservation measures that include both crop water use reductions and efficiency improvements. The distinction between these two categories of conservation measures was fully discussed in TM1 and TM2, and while there can be overlap, the distinction generally is dependent upon the where the conservation measure is implemented. CU reductions in which there is some type of change in crop water use (e.g. fallowing, deficit irrigation, crop mix changes, etc.) applies to both on-mainstream (of the Colorado River) diversions and uses, and to off-mainstream (i.e., transbasin or out of basin) diversions and uses. CU reductions due to efficiency improvements (e.g., conversion of on-farm irrigation systems to more efficient methods, canal lining, operational spill reduction, system automation, etc.), however, do not result in a CU reduction for on-mainstream diversions and uses. In contrast, efficiency improvements made under off-mainstream diversions and uses do result in CU reductions for the off-mainstream diversion.

CU reductions due to reductions in crop water use occur predominantly at the farm field level. Accurate measurement or estimation of CU savings can, among other approaches, require comparing CU from a field with a conservation measure to CU from neighboring fields that were not part of that conservation measure, or comparing CU from a field with a conservation measure to CU from the same field in previous years.

Efficiency improvements may be made at the conveyance/delivery system level and at the farm level. Often a water balance at the project level or sub-system level where improvements are implemented is necessary. The water balance must be performed prior to any efficiency improvement (to establish the baseline condition) and post-improvement (to quantify changes). Each component of the water balance (inflows, outflows, uses that remove water from the system, and changes in storage) is identified, characterized, measured, or estimated. As discussed above, efficiency improvements may or may not result in a CU reduction.

Information from TM2 was presented during Workshop #2 regarding the following agricultural water conservation measures:

- Deficit irrigation,
- On-farm irrigation system conversion,
- Seasonal fallowing,
- Crop rotation/alternative cropping,
- District/distribution system (efficiency) improvements,
- On-farm conveyance system (efficiency) improvements, and
- Advanced irrigation scheduling.

Methods to Quantify Consumptive Use

The primary focus of this Pilot Study is methods used to quantify CU reductions associated with different water conservation measures. The following methods to quantify CU were discussed in TM2 and highlighted during Workshop #2:

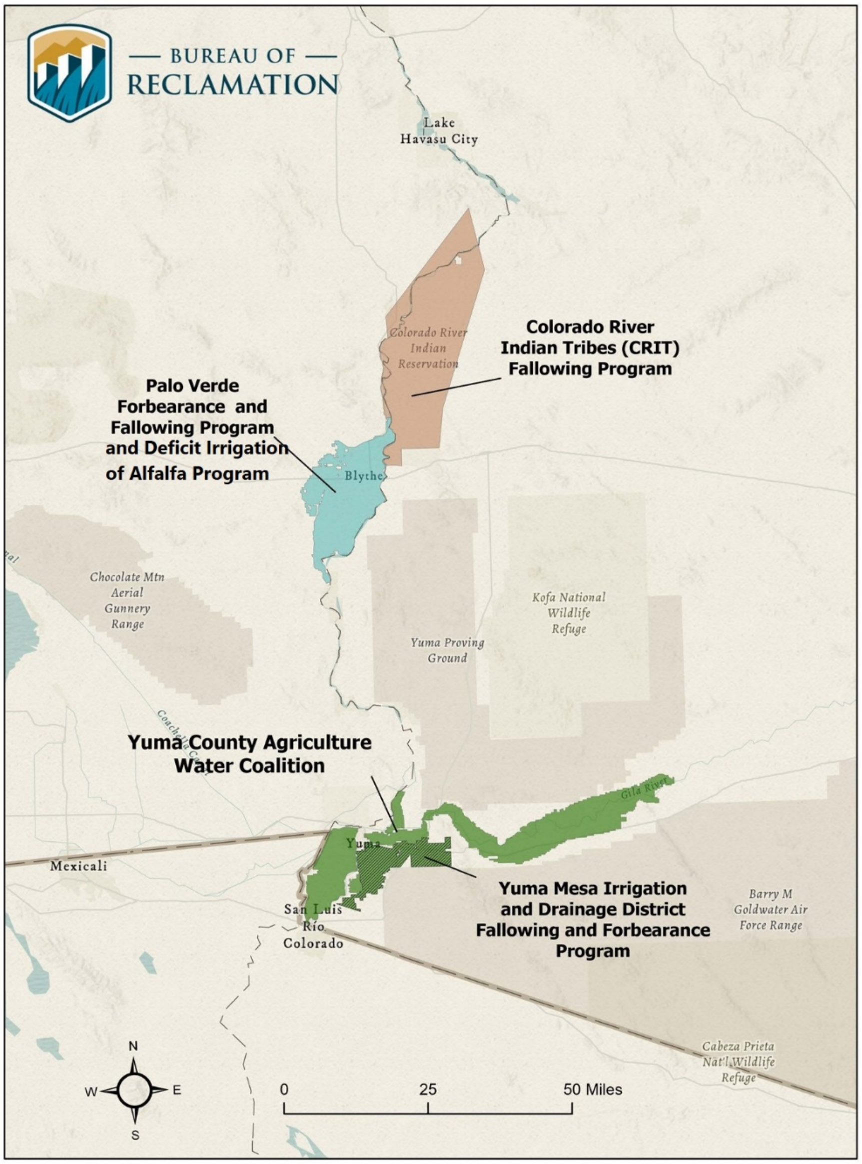
- Water balance,
- Lysimetry,
- Micrometeorology,
- Reference evapotranspiration, and
- Remote sensing.

Selected Current/Ongoing Conservation Activities

In addition to general conservation measures and CU quantification methods, the following current/ongoing conservation activities that were highlighted in TM2 and shown in *Figure 1* were reviewed during Workshop #2:

- Colorado River Indian Tribes (CRIT) Fallowing Program,
- Yuma County Agriculture Water Coalition Study,
- Yuma Mesa Irrigation Drainage District (YMIDD) Fallowing and Forbearance Program,
- Palo Verde Irrigation District (PVID) Forbearance and Fallowing Program, and
- PVID Deficit Irrigation Program.

Figure 1 Selected Current/Ongoing Conservation Activity Locations



Case Study Identification and Selection

The purpose of the case study analysis in this Pilot Study is:

- To gain knowledge from actual implemented (recent, current, or on-going) agricultural water conservation efforts in the LCRB regarding methods and approaches used to quantify water conserved; and
- To relate the results of conservation activities to quantification of CU under Reclamation's Decree Accounting.

Case Study Framework

A framework was developed to assist the identification of case study opportunities and final case study site selection. Considerations (to the extent possible) included representing:

- The geographical diversity within the LCRB,
- A diversity of agricultural conservation activities, and
- A diversity of water savings quantification methods.

Ideally, this framework would allow for selection of a set of case studies that are representative of agricultural water conservation activities in the LCRB.

Locations

Preferably, case study opportunities would represent both geographic diversity across the Lower Basin—all three lower basin States—Arizona, California, and Nevada; as well as projects that include both on-mainstream and off-mainstream water users. Quantification of CU in the latter situation depends on the fate of return flows. For on-mainstream projects, Reclamation has defined CU as diversions minus return flows, while for off-mainstream diversions, CU is equal to the diversion less any losses (or returns) that occur prior to water leaving the Colorado River drainage.

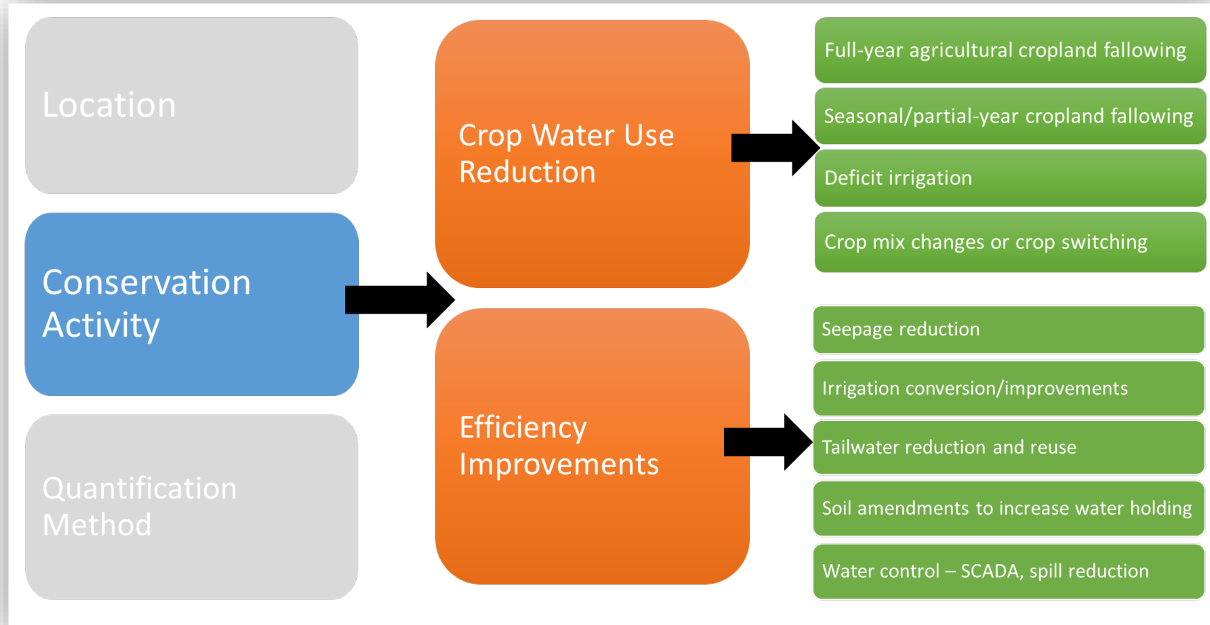
Conservation Activities

As discussed previously, there are two general categories of conservation activities under consideration: crop water use reductions and efficiency improvements. Both of these categories can be divided into sub-categories of irrigated agriculture water conservation activities, as shown in *Figure 2*.

As mentioned previously, whether or not a water conservation activity results in a CU reduction for the mainstream of Colorado River can be location dependent. For example, conservation activities that reduce crop water use generally may result in Colorado River CU reductions regardless of where the project is located. However, efficiency improvements, whereby the losses that occur during conveyance and application of water are reduced, as discussed above, may or may not result in CU reduction of Colorado River water.

- In the case of off-mainstream diversions, water savings from efficiency improvements (e.g., water savings from converting from flood irrigation to drip irrigation) do result in CU savings of mainstream Colorado River water. The entity or agency diverting and using the water can use the saved water for their purposes without increasing their Colorado River diversions.
- In the case of on-mainstream diversion and use, however, while the efficiency improvements still do reduce losses, most on-mainstream water users cannot use such savings because the water saved is system water and there is no net change in the available Colorado River water.

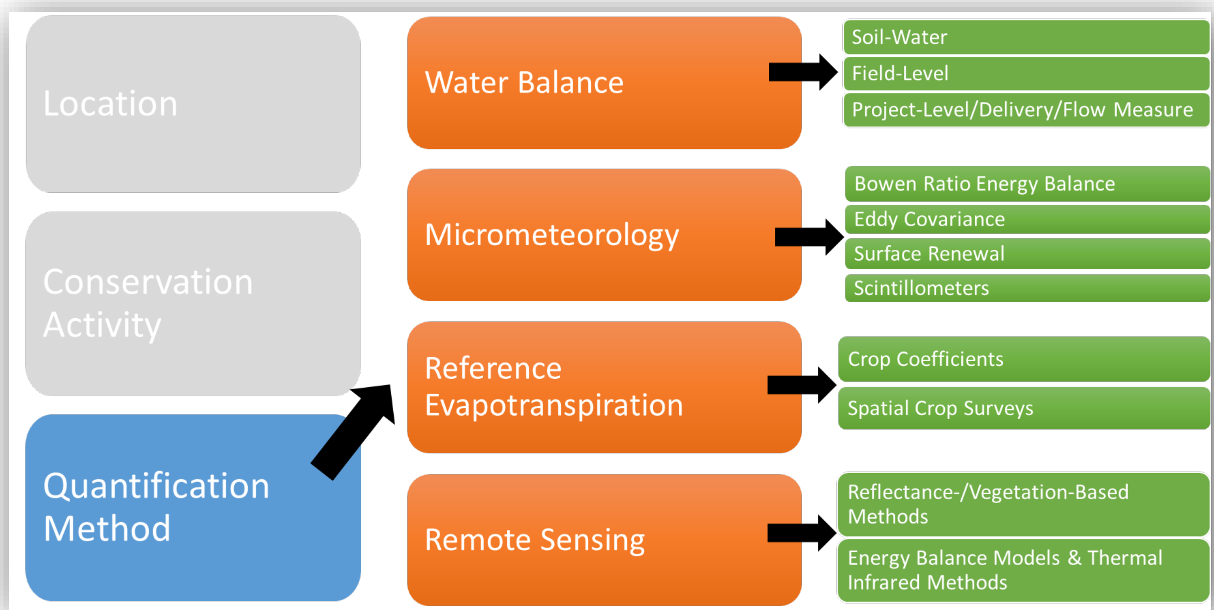
Figure 2 Case Study Framework – Types of Conservation Activities



Quantification Methods

As discussed previously, CU quantification methods were reviewed in detail and presented in TM2. The general categories of methods reviewed included water balance, micrometeorology, reference evapotranspiration, and remotes-sensing-based models. As shown in *Figure 3*, these categories can be divided into sub-categories as well.

Figure 3 Case Study Framework – Quantification Methods



Application of the Case Study Framework and Discussion of Recent Activities

Deficit irrigated alfalfa. Photo credit: A. Montazar, used with permission.

During Workshop #2, Mr. Ned Hyduke of PVID introduced Dr. Ali Montazar of University of California Agriculture and Natural Resources (UCANR). Dr. Montazar delivered a presentation of a current and on-going study of "moderate" deficit irrigation of alfalfa within PVID in California (Montazar et al., 2020). The case study framework discussed above was applied to this particular conservation activity as an example.

Other Workshop #2 participants were invited to provide short descriptions regarding conservation activities of the entities they represent:

- Mr. Michael Pearce spoke on behalf of the Mohave Valley Irrigation and Drainage District's (MVIDD's) fallowing program.
- Mr. Nick Bahr of Bard Water District (Bard) and Ms. Noosha Razavian of the Metropolitan Water District of California (MWD), spoke on behalf of the MWD/Bard Water District seasonal fallowing project.
- Mr. Devin Heaps of CRIT spoke briefly on behalf of CRIT regarding participation in the study.

Potential Case Studies

Table 2 is a matrix of the potential case studies that were identified along with the case study framework conditions they would satisfy. As shown, these potential case studies cover a range of the framework-defined conditions. Ideally, selected case studies would represent a cross-section of the different quantification methodologies. Case studies from sites where the same conservation activity has been implemented, but with different quantification methods, were also considered appropriate. It is important to note that *Table 2* is a list of identified current/recent programs and does not imply agreement by the organization to participate as a case study. Each of these potential case studies is described briefly below.

Table 2 Matrix of Potential Case Studies

Potential Case Study	Location		Conservation Activity					Quantification Method			
	On-/Off Mainstream	State	Deficit Irrigation	Irrigation Conversion	Fallowing	Crop Modification	Efficiency Improvements	Water Balance	Micrometeorology	Reference ET	Remote Sensing
PVID Forbearance and Fallowing Program	On-Mainstream	CA			X			X			
PVID Moderate Deficit Irrigation of Alfalfa Program	On-Mainstream	CA	X					X	X	X	
CRIT Fallowing Program	On-Mainstream	AZ			X			X		X	
MVIDD Fallowing Program	On-Mainstream	AZ			X			X		X	
Bard Water District Seasonal Fallowing Program	On-Mainstream	CA			X			X			
MSIDD Efficiency Improvements	Off-Mainstream	AZ					X				
CAIDD Efficiency Improvements	Off-Mainstream	AZ					X				
GRIC System Modernization	Off-Mainstream	AZ					X	X			
California Agriculture Extension On-farm Irrigation Studies	Off-Mainstream	CA		X			X		X	X	

Palo Verde Irrigation District Forbearance and Fallowing Program

In 2004, MWD and PVID landowners entered into a 35-year agreement wherein MWD pays for land to be fallowed in PVID's service area (MWD, 2019a). The forborne water is then made available for use by MWD on a direct acre-foot for acre-foot basis. The amount of land under the forbearance program is allowed to fluctuate between nine and 35 percent, as determined by MWD. Any participating land is not fallowed for more than five years at a time. Maximum limits have been placed on the amount of land fallowed. The methods used to quantify CU reductions from the PVID forbearance and fallowing program include three basic components: 1) verifying of fallowing practice, 2) estimating average CU for fields under cultivation in PVID, and 3) determining CU reduction for fallowed lands. CU is quantified over various historical periods using measured diversions and return flows and estimates of unmeasured return flows from Reclamation's decree accounting data. The method used to translate estimated average CU for fields under cultivation into CU reductions for fallowed fields includes the assumption that fallowed lands would have had similar CU as the rest of PVID during the various analysis periods. See TM2 for more information.

Palo Verde Irrigation District Moderate Deficit Irrigation of Alfalfa Program

In 2019 and 2020, a deficit irrigation experiment in four fields in PVID was conducted by researchers at the UCANR, the University of California, Davis (UC Davis), and the U.S. Department of Agriculture Agricultural Research Service (Montazar et al., 2020). The project was conducted in four surface irrigated alfalfa fields in PVID planted in late 2018. The fields were paired by irrigation method (two were border irrigated and two were furrow irrigated) and by irrigation treatment. Each field included a section (or multiple sections) irrigated per the grower's convention. For the two furrow irrigated fields, deficit irrigation treatments were implemented by avoiding irrigation for three and two events in the summer in what the researchers call "moderate" deficit irrigation (Montazar et al., 2020). For the two border irrigated fields, two deficit irrigation treatments were implemented by avoiding irrigation for two events and one event in the summer. To quantify CU, the research team quantified applied irrigation water and ET. They quantified ET using eddy covariance and surface renewal methods in the grower irrigation treatments and used surface renewal systems from Tule Technologies for the deficit irrigation treatments. See TM2 for more information.

Colorado River Indian Tribes Fallowing Program

The Colorado River Indian Reservation is located on both sides of the Colorado River in western Arizona and eastern California, with most of the land in Arizona. Starting in 2016 and continuing to present, CRIT has participated in system conservation programs to create conserved water for storage in Lake Mead. These programs include the Pilot System Conservation Program (PSCP) established by Reclamation, the Central Arizona Water Conservation District (CAWCD), MWD, the Southern Nevada Water Authority (SNWA), and Denver Water (Reclamation, 2019); and CRIT's three-year system conservation agreement with Reclamation, the Arizona Department of Water Resources (ADWR) and CAWCD under the State of Arizona's Drought Contingency Plan. Conserved water in each case has consisted of CU reductions due to temporary fallowing of irrigated cropland on CRIT's Arizona lands. Field tracts in the temporary fallowing program are required to have been in irrigated cropping four of the previous five years, and no fields will be fallowed for periods longer than five years. CRIT has been compensated for its CU reductions under the various system conservation programs in which it has participated. CRIT quantified CU reductions due to fallowing of irrigated cropland by computing the average crop ET using the reference ET/crop coefficient method for the previous five-year period on the farm unit to be fallowed. See TM2 for more information.

Mohave Valley Irrigation and Drainage District Fallowing Program

MVIDD is conserving Colorado River water by fallowing MVIDD agriculture land that has a recent history of irrigation. An enrollment process was created whereby participating farmers voluntarily agreed to limit or alter the planting of crops on land that had been verified as actively cultivated in three of the then most recent five years. To make participation equitably available, the minimum fallowed area was 10 acres. The cropping history for each participating farm for the five-year period 2015-2019 was evaluated using satellite (Landsat) and aerial (National Agricultural Imagery Program, NAIP) imagery (MVIDD, 2019; Land-IQ, 2019). Cropscape, a National Agriculture Statistics Service remote sensing program, was also used. Crop CU for each of the previous five years was determined by using reference evapotranspiration computed using operational weather data collected at Arizona Meteorological Network (AZMET) electronic weather stations located in the Mohave Valley area. Crop coefficients for computing crop ET were adapted from Allen et al. (1998) and consultation with University of California, Davis faculty (Land-IQ, 2019).

Bard Water District Seasonal Fallowing Program

The Bard Water District is currently in a seasonal fallowing program in cooperation with MWD for 2020 – 2026 (MWD, 2019). In this program, MWD pays growers to not grow crops from April – July (Businesswire, 2019). MWD pays for this conservation (Businesswire, 2019). The program allows growers to continue growing "higher-value" winter crops (MWD, 2019b). Quantification of CU savings during this seasonal fallowing has been estimated (post facto) using Reclamation's decree accounting monthly reported diversions, return flows, and consumptive use for the Bard Water District and for the Yuma Project Reservation Division (J. Shields, communication, May 2021). CU (acre-foot per acre basis) during each of the four months of seasonal fallowing was determined for the Bard's total irrigable acres less the acres in the fallowing program. These monthly unit CU values were then multiplied by the acres fallowed to estimate total water savings. MWD uses the conserved water for diversion or Lake Mead storage (Businesswire, 2019). The program is reported to provide 6,000 acre-feet per year of water to MWD (MWD, 2019b).

Maricopa Stanfield Irrigation and Drainage District and Central Arizona Irrigation and Drainage District Efficiency Improvements

Maricopa Stanfield Irrigation and Drainage District (MSIDD) and Central Arizona Irrigation and Drainage District (CAIDD) are located in central Arizona. Significant investments to improve the irrigation delivery system and service and to improve on-farm irrigation efficiency have been implemented by both MSIDD and CAIDD over the past 30 years (HDR, 2013). The districts have invested extensively in improvements to their irrigation conveyance and delivery systems (canal lining and extensive system automation and control via supervisory control and data acquisition (SCADA) implementation and monitoring. A study of agricultural water efficiency for the Central Arizona Project (CAP) service area reported that MSIDD and CAIDD have delivery system losses and spills "…of less than 3%..." annually as result of these improvements (HDR, 2013). This same study reports the districts have also adopted on-farm irrigation methods with minimum irrigation efficiency of 80% for most farms.

Gila River Indian Community Irrigation System Modernization

The concept of the Pima-Maricopa Irrigation Project (PMIP) was developed as part of the Gila River Indian Community's (GRIC's) *1985 Master Plan for Land and Water Use* (Franzoy Corey, 1985; GRIC and EcoPlan, 1997). P-MIP is a large irrigation water delivery and distribution system that was planned to serve about 146,000 acres of land on the Reservation. P-MIP includes "rehabilitat[ion]" of existing irrigation infrastructure of the San Carlos Irrigation Project, which serves about 50,500 acres on the Reservation; and also service to other areas of the Reservation (GRIC and EcoPlan, 1997). P-MIP was planned to convey about 173,000 acre-feet per year (AF/yr) of CAP water, plus Gila River water, groundwater, Salt River water, reclaimed wastewater, and other sources (GRIC and EcoPlan, 1997). Project construction began in 1998 and continues through present (P-MIP, communication, 2021). Significant investment has been made in lined canals, pipelines, check structures, turnouts, and state of the art SCADA for water regulation and control, monitoring and measurement (P-MIP, communication, 2021).

California Agriculture Extension On-farm Irrigation Studies

Dr. Aliasghar Montazar, University of California Cooperative Extension Adviser in Imperial, Riverside, and San Diego Counties, and his associates have been collecting crop CU data in commercial production fields under different on-farm irrigation methods in the Imperial Valley of California. These studies have included comparisons of various combinations of comparisons of surface irrigation (flood or furrow), sprinkler (including linear move sprinklers) and drip (including subsurface drip irrigation). Studies have included several commonly grown crops in the area, e.g., sugarbeet, onion, alfalfa, carrot, spinach, and lettuce. Many of the studies have been multi-year efforts and include two to three years of data collection. The research has been conducted in the fields of cooperating growers and, thus, represents production-level scale. The data include crop evapotranspiration measurements and resulting crop coefficients, farm delivery records, crop yield, etc. (A. Montazar, communication, 2021).

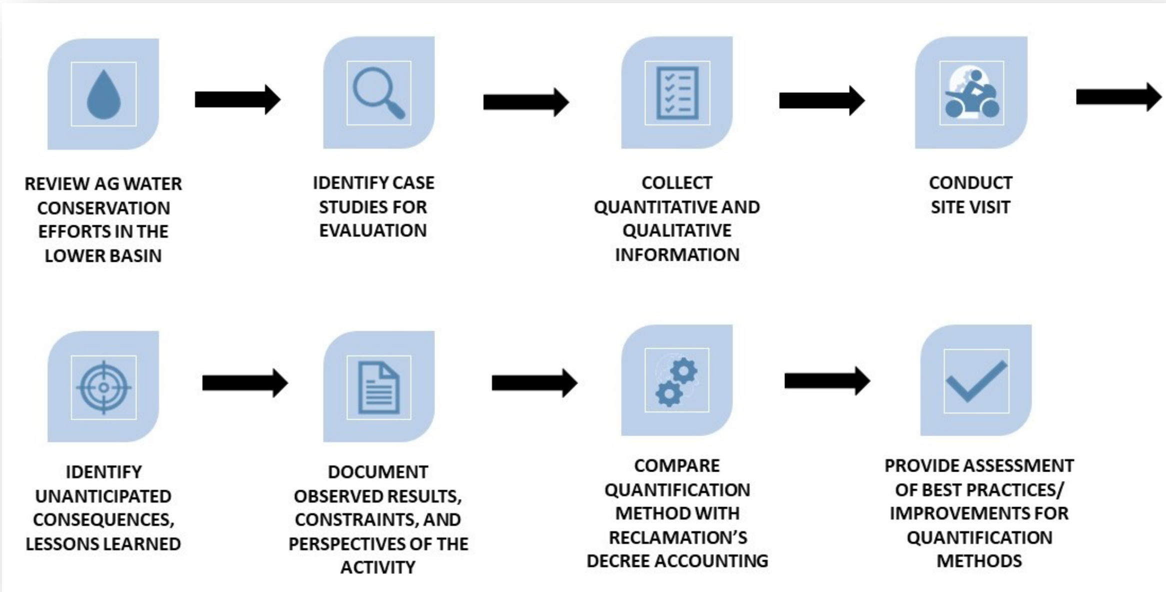
Case Study Evaluation Process

The case studies were evaluated with the goal of gaining knowledge on quantification methods and approaches. The envisioned process for carrying out each case study is shown in *Figure 4* and described below.

The case study process will include the following efforts:

- Site visits, in-person if possible, remote if necessary due to COVID-19,
- Interviews with case study participants,
- Reviews of documentation, reports, etc. relating to the conservation project and quantification methods,
- Identification of what did and did not yield desirable results with the project and quantification methods,
- Identification of what the participants would like to have done different and why,
- Determination of how the applied quantification approaches compare with the quantification approaches identified in TM2,
- Determination of whether a particular conservation activity and quantification approach could provide valuable information for application in other situations,
- Consideration of the accuracy of methods used in the project:
    - How well does the method quantify water savings/efficiency?
    - Characterization of the estimated water savings relative to the potential error limits of the quantification method,
- Consideration of costs of implementation (administrative, equipment, data collection, and analysis cost),
- Determination of whether or not the quantification method is conceptually complicated or difficult to implement,
- Determination of whether or not the conservation activity yielded expected conservation results,
- Determination of how widely the quantification method is currently used,
- Identification of the relationship of the conservation activity and quantification method to the Reclamation Decree Accounting—is there measurable reduction in mainstream Colorado River CU?
- Assessment of opportunities for improvement of the quantification method(s).

Figure 4 Case Study Evaluation Steps



The following constraints and limitations were specified or identified for the Pilot Study:

- This Pilot Study is not an exercise to promote or condemn any particular method or approach; rather the intent is to learn from what was done and to receive feedback from the implementing entities on what could be improved,
- The COVID-19 pandemic must be considered and participants may not want to host a large traveling group, and
- Use of the case study information and results will not negatively impact the case study participants.

Conclusions and Recommendations

Based on a review of the potential case studies and discussions with representatives from the potential participating organizations, the following six case studies were selected for evaluation as part of this effort:

- GRIC Irrigation System Modernization
- Bard Fallowing Program
- PVID Forbearance and Fallowing Program
- PVID Moderate Deficit Irrigation of Alfalfa Program
- CRIT Fallowing Program
- MVIDD Fallowing Program

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Appendix: Workshop 2 Presentation Slides

BUREAU OF RECLAMATION

Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

Workshop #2

March 2, 2021

Welcome/Introductions

Workshop #2 Agenda

- Welcome and Introductions
- Pilot Study Overview
- Technical Memorandum 2 Results and Summary
- Presentation on PVID Deficit Irrigation Study
- Case Study Framework (with PVID Deficit Irrigation Study as an Application Example)
- Project Sharing Opportunities
- Wrap-up and Next Steps

Pilot Study Overview

Pilot Study Objectives

- Participants' input and feedback is critical to the success of the Study
- Explore current methods to quantify agricultural water conservation
- Evaluate methods for consistency with Reclamation's Lower Colorado River water accounting methodology
- Evaluate case studies using both research and applied science
- Recommend approaches to improve methods of quantifying Lower Basin agricultural water conservation

Pilot Study Schedule

Workshop 1

Workshop 2

Site Visits/Interviews

Workshop 3

Pilot Study Final Report

Nov 2020

Feb 2021

Mar 2021

Apr 2021

May 2021

Aug 2021

Sep 2021

Oct 2021

Nov 2021

Dec 2021

Milestone 1: Technical Memorandum 1 – Summary of Refined Scope & Case Study Definition

Milestone 2: Technical Memorandum 2 – Summary of Significant Findings from Literature Review & Recent/Current Activities in the Lower Basin

Milestone 3: Technical Memorandum 3 – Summary of Case Study Definition, Site Selection & Evaluation Process

Milestone 4: Draft Report – Case Studies and Technical Reviews

Milestone 5: Pilot Study Final Report

Presentation at CRWUA

BUREAU OF RECLAMATION

Technical Memorandum 2 Results and Summary

www.lcrbpilotstudy.com

Technical Memorandum 2

1) A review of scientific literature and other sources to identify consumptive use (CU) quantification methods

2) A review of a several example conservation activities within the LCRB and the associated CU quantification methods which have readily accessible information

Literature Review

- Academic and technical literature – studies, reports, journals
- Documentation and evaluation of CU quantification methods
- Focus on LCRB and adjacent regions, some literature from other areas
- Including literature since *Moving Forward* report
- Annotated bibliography

Conservation Measures

Primary

- Deficit irrigation
- On-farm irrigation system conversion
- Seasonal fallowing
- Crop rotation/alternative cropping

Other

- District/distribution system (efficiency) improvements
- On-farm conveyance system (efficiency) improvements
- Advanced irrigation scheduling

What is CU?

In Reclamation's Decree Accounting, CU is defined as diverted water less return flows to the Colorado River

Focuses on quantification of evapotranspiration

Portion of ET derived from applied irrigation water

CU of water for transbasin diversions is the total portion of the diversion that leaves the basin

Methods to Quantify CU

- Water Balance
- Lysimetry
- Micrometeorology
- Reference Evapotranspiration
- Remote Sensing

USDA-FSA NAIP Imagery, 2019, Yuma Co., AZ

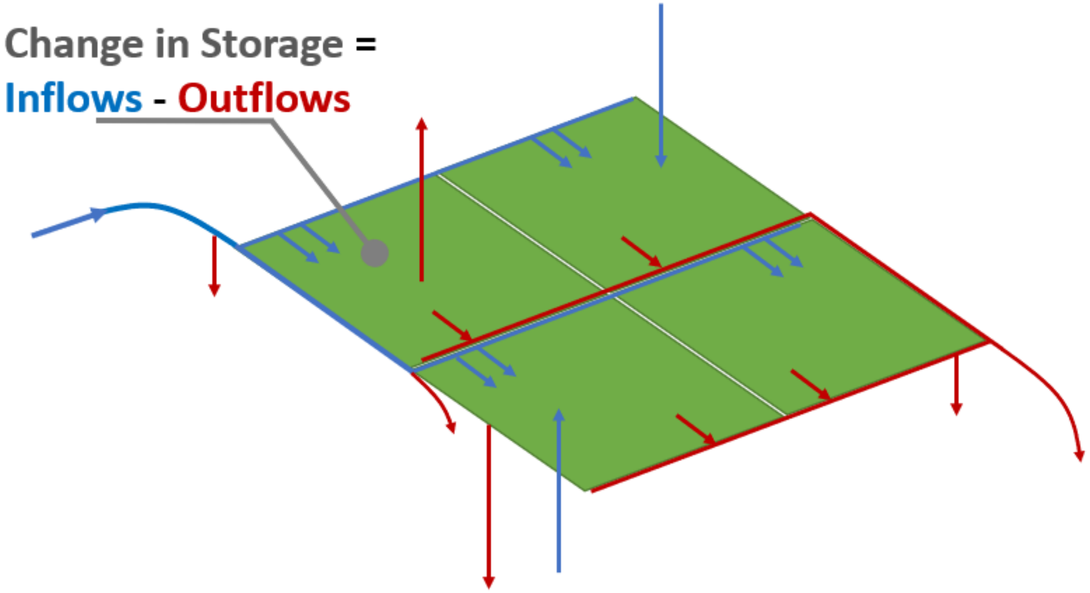
Eddy Covariance Station, USDA ARS Conservation and Production Research Laboratory, Bushland TX. Photo courtesy of Tom Ley.

Water Balance

Soil water balances and field-level water balances

Project-level water balances

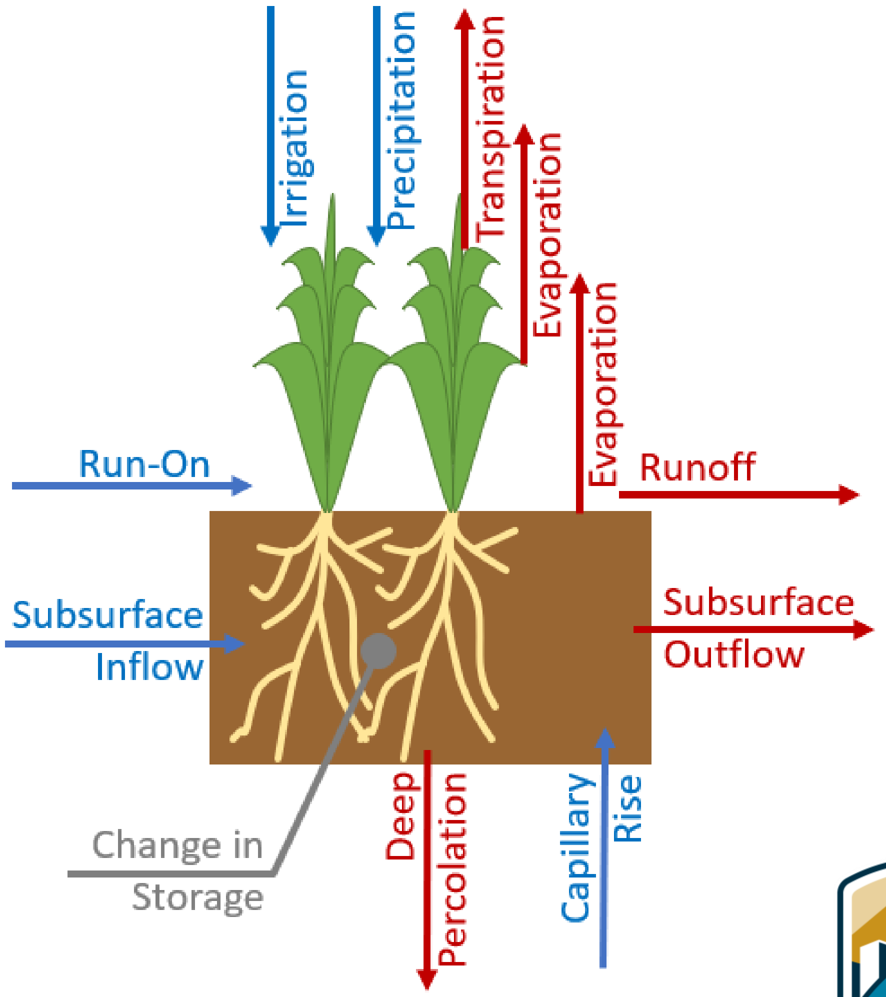
Delivery and other flow measurements



Soil Water Balances and Field-Level Water Balances

Must simplify water balance (site conditions/management must fit assumptions)

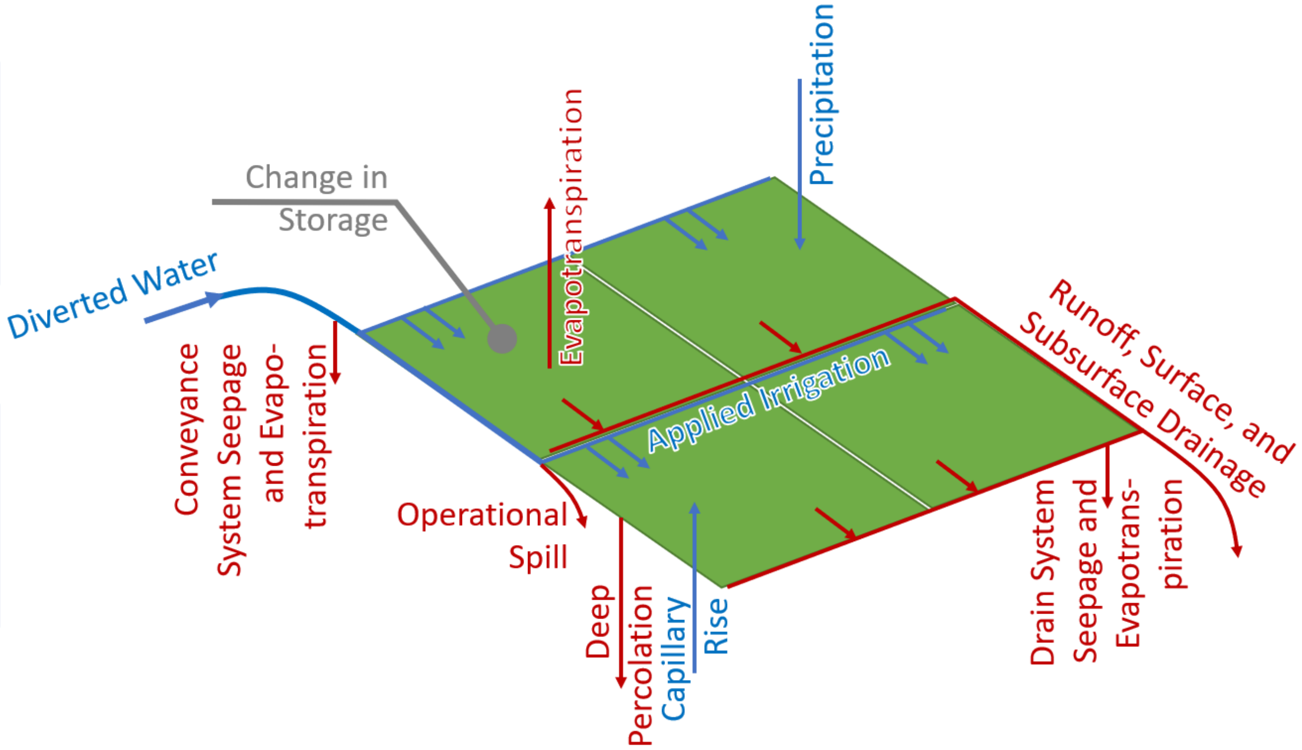
Soil water (soil moisture) sensing



Project-Level Water Balances, Delivery and other Flow Measurements

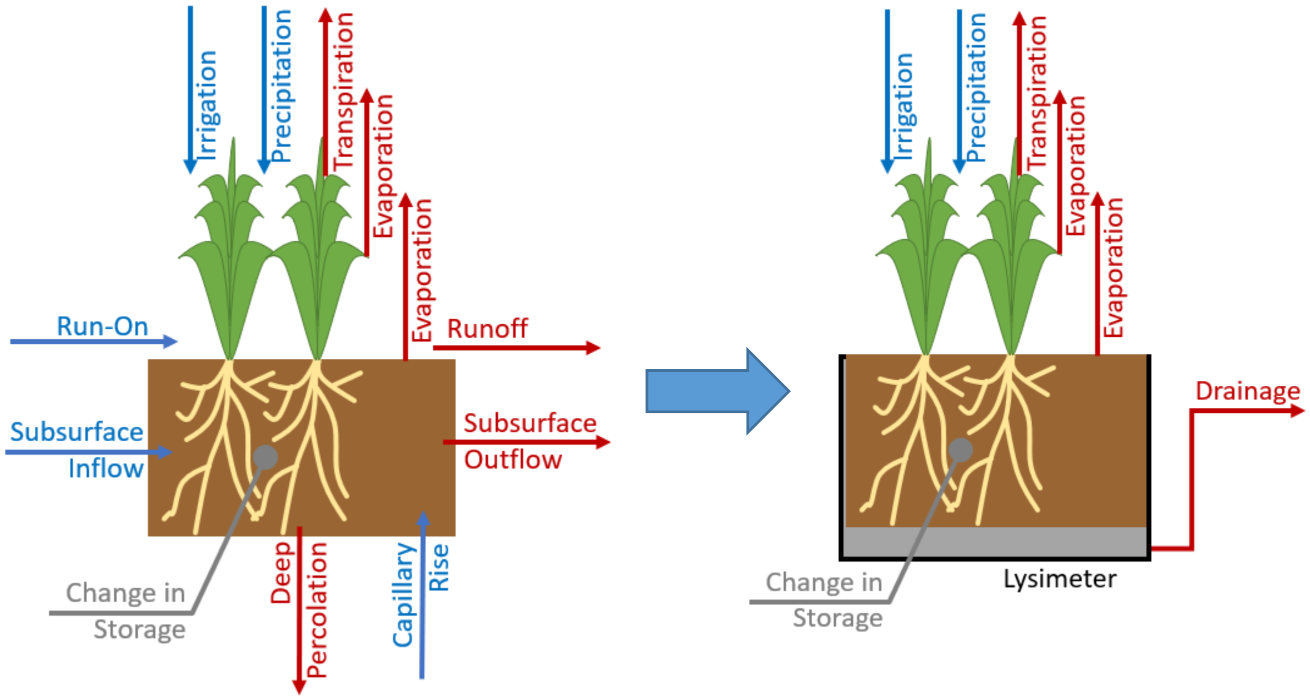
Must simplify water balance

Site conditions/management must fit assumptions



Lysimetry

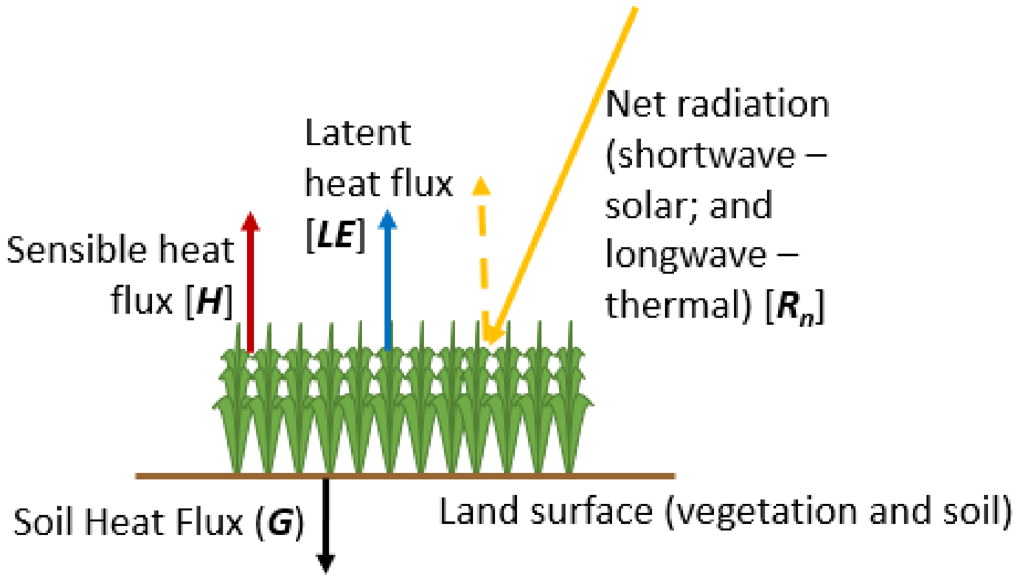
- Weighing lysimeters
- Drainage and other lysimeters
- Can be a highly accurate method
- Resource intensive
- Limited to research studies



3m x 3m weighing lysimeter with monolithic core at USDA ARS Conservation and Production Research Laboratory, Bushland TX. Photo courtesy of Tom Ley.

Micrometeorology

- Eddy covariance
- Bowen ratio energy balance method
- Surface renewal method
- Scintillometers



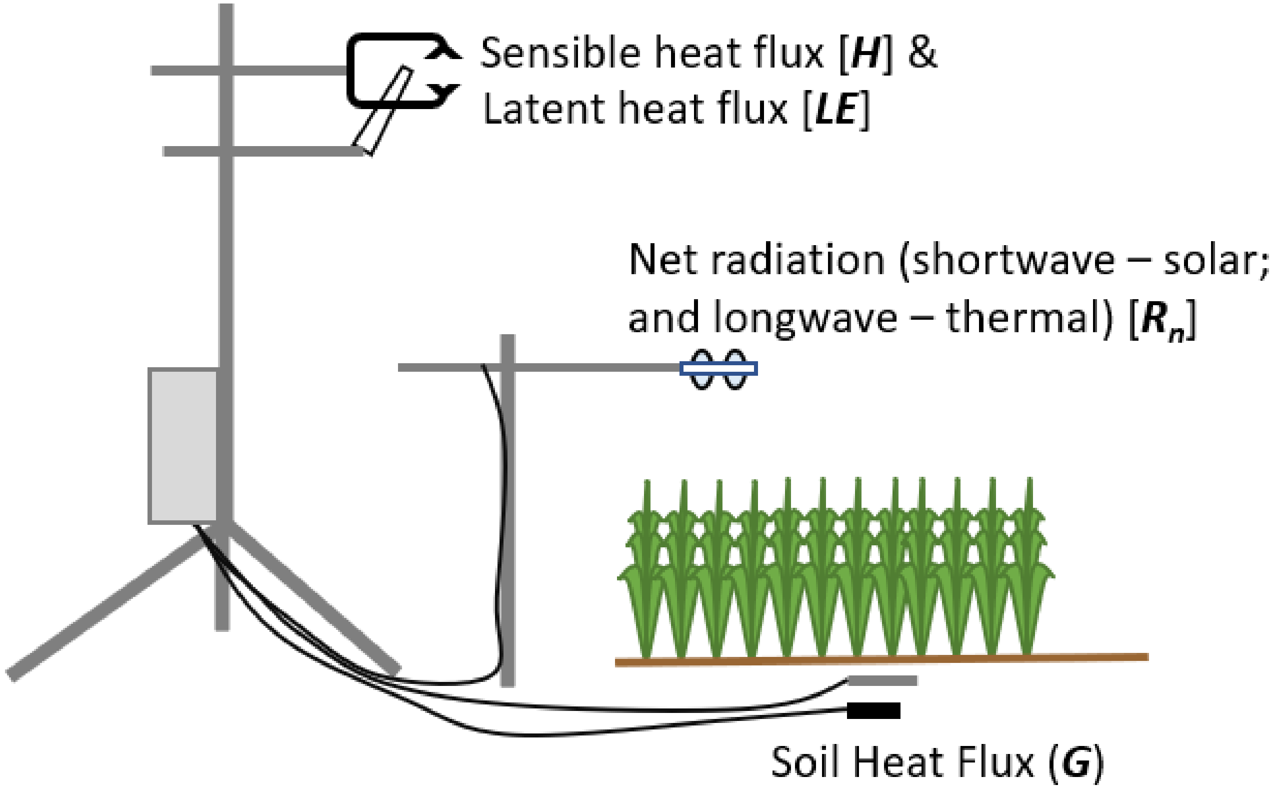
$$LE = R_n - G - H$$

$$ET = \frac{LE}{\lambda \rho_w}$$

Eddy Covariance

- Field-scale
- Widely used
- High operation requirements

Eddy Covariance Station, USDA ARS Conservation and Production Research Laboratory, Bushland TX. Photo courtesy of Tom Ley.

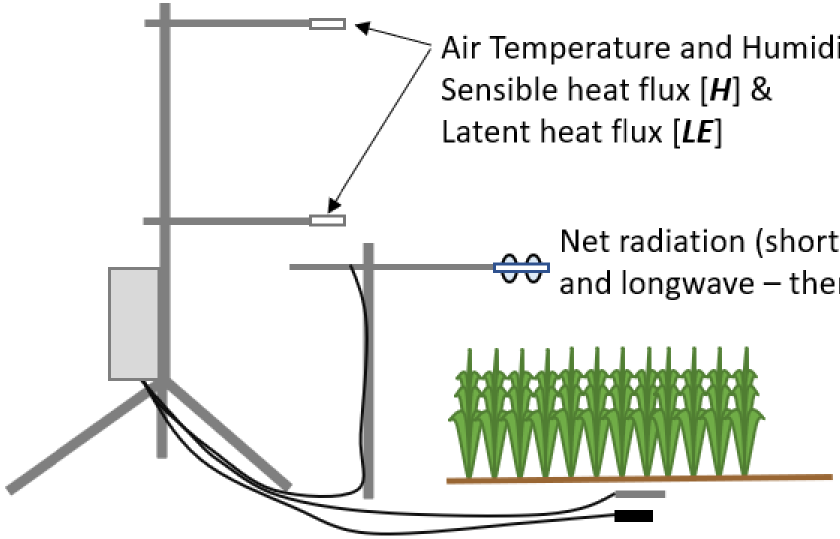


Bowen Ratio Energy Balance

Field-scale

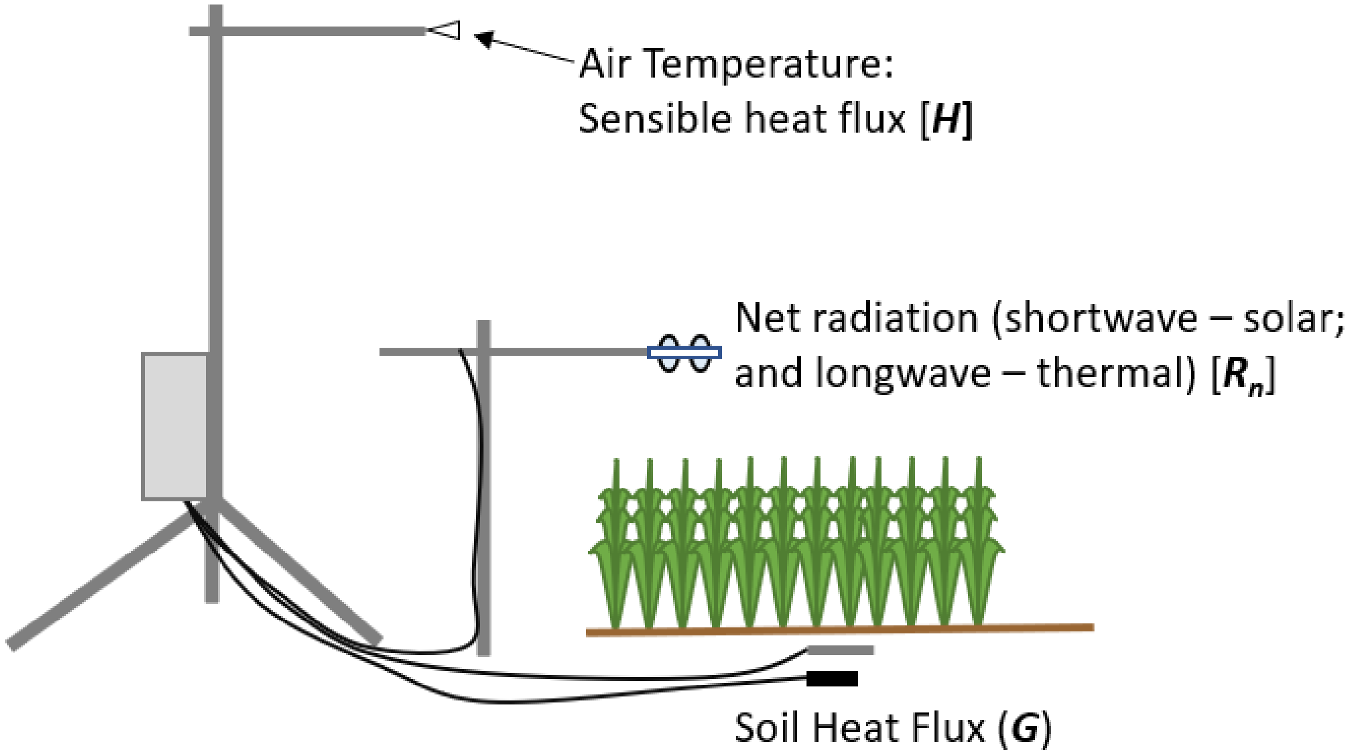
Moderately-high operational requirements

Bowen Ratio Station, USDA ARS Conservation and Production Research Laboratory, Bushland TX. Photo courtesy of Tom Ley.



Surface Renewal Energy Balance Method

- Field-scale and smaller
- Latent heat flux through energy balance
- Moderately-high operational requirements



$$LE = R_n - G - H$$

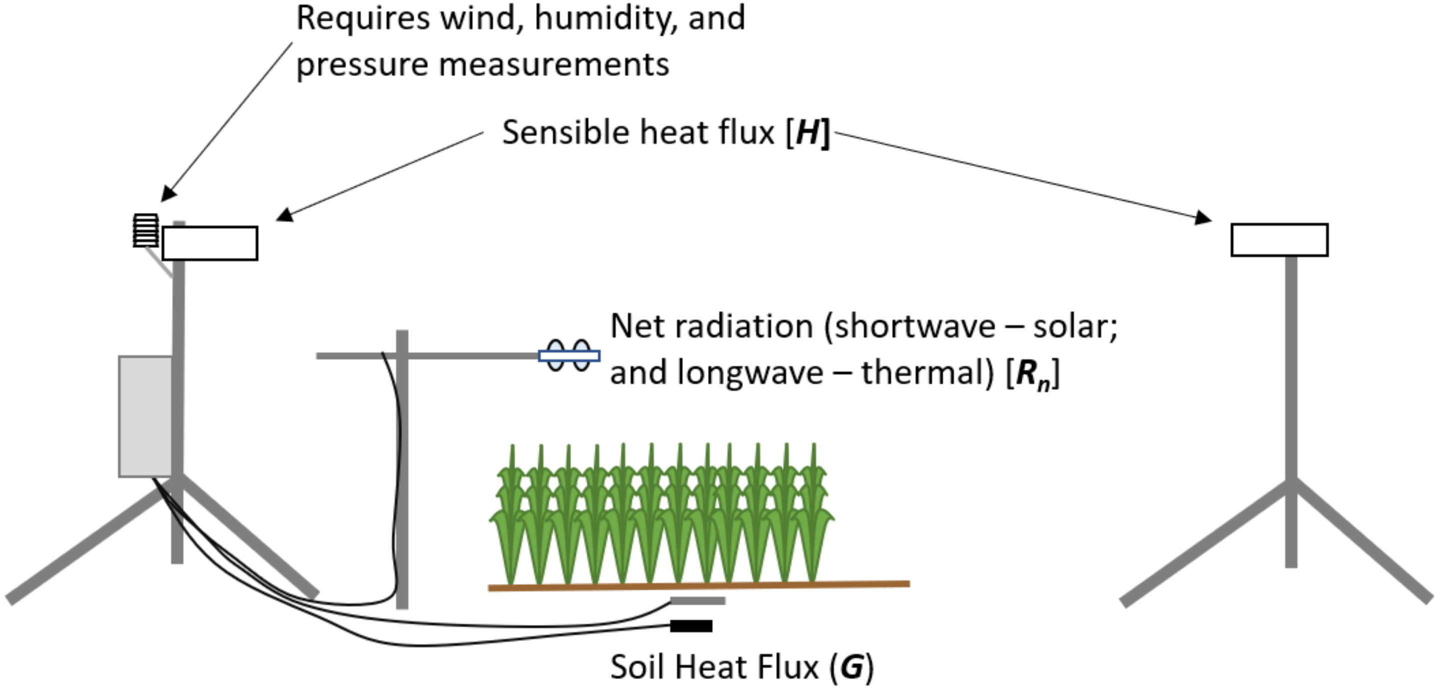
Scintillometry

Multiple-field-scale

LE through energy balance

Expensive and limited to research

https://en.wikipedia.org/wiki/Scintillometer

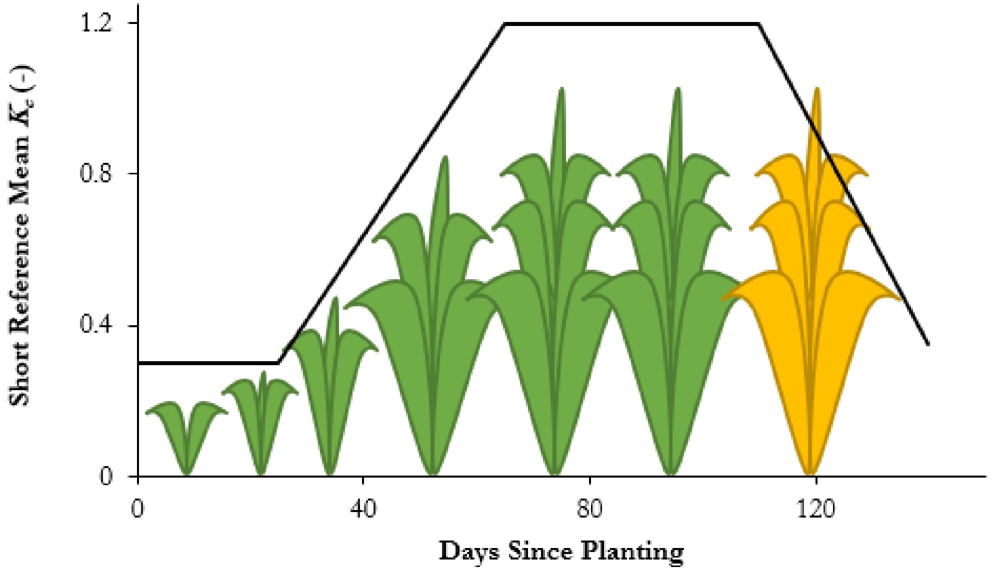


Based on: https://www.kippzonen.com/Product/193/LAS-MkII-Scintillometer#.YBmMSXJlCUk; https://www.kippzonen.com/Product/193/LAS-MkII-Scintillometer#.YCQY83JlCUk; https://www.kippzonen.com/Product/194/LAS-MkII-ET-System

$$LE = R_n - G - H$$

Reference Evapotranspiration

- Crop Coefficient
- Spatial Crop Surveys



Based on Allen et al. (1998) and Jensen and Allen (2016).

Automated agricultural weather station, Bushland, TX. Photo courtesy of Tom Ley.

$$ET_c = K_c ET_{ref}$$

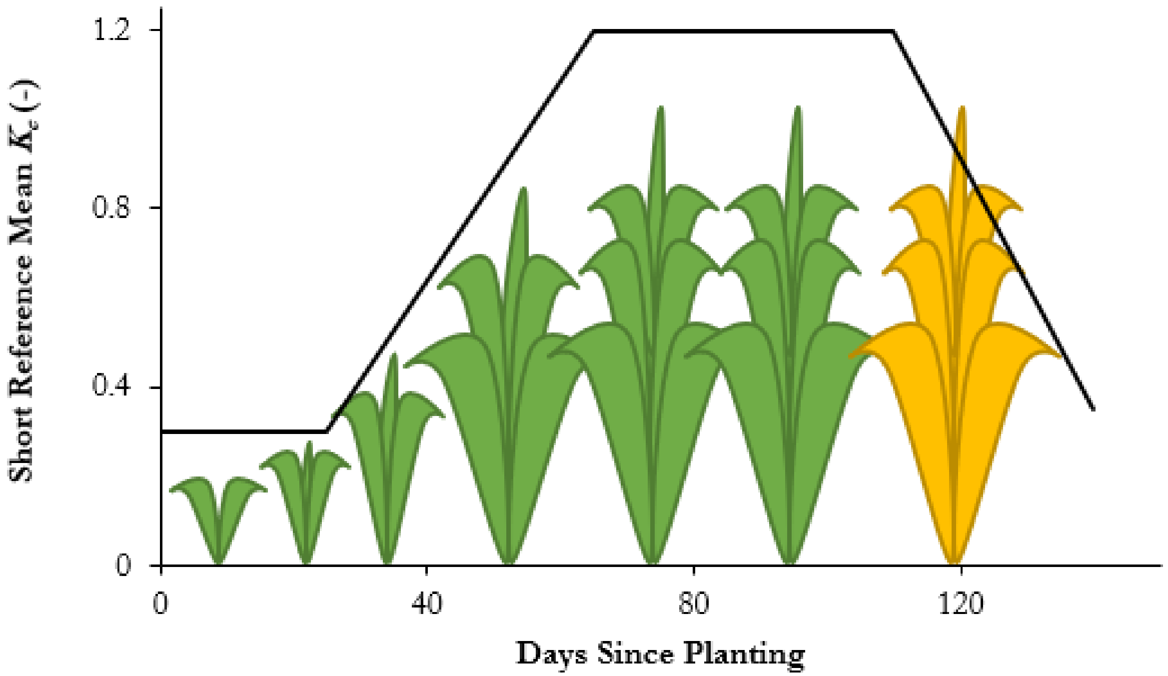
Reference Evapotranspiration

Reference methods (ASCE Standardized Reference Evapotranspiration Equation, ASCE, 2005)

“Potential” vs. actual ET or standard vs. non-standard conditions

Dual vs. single crop coefficient

Based on Allen et al. (1998) and Jensen and Allen (2016).



$$ET_c = K_c ET_{ref}$$

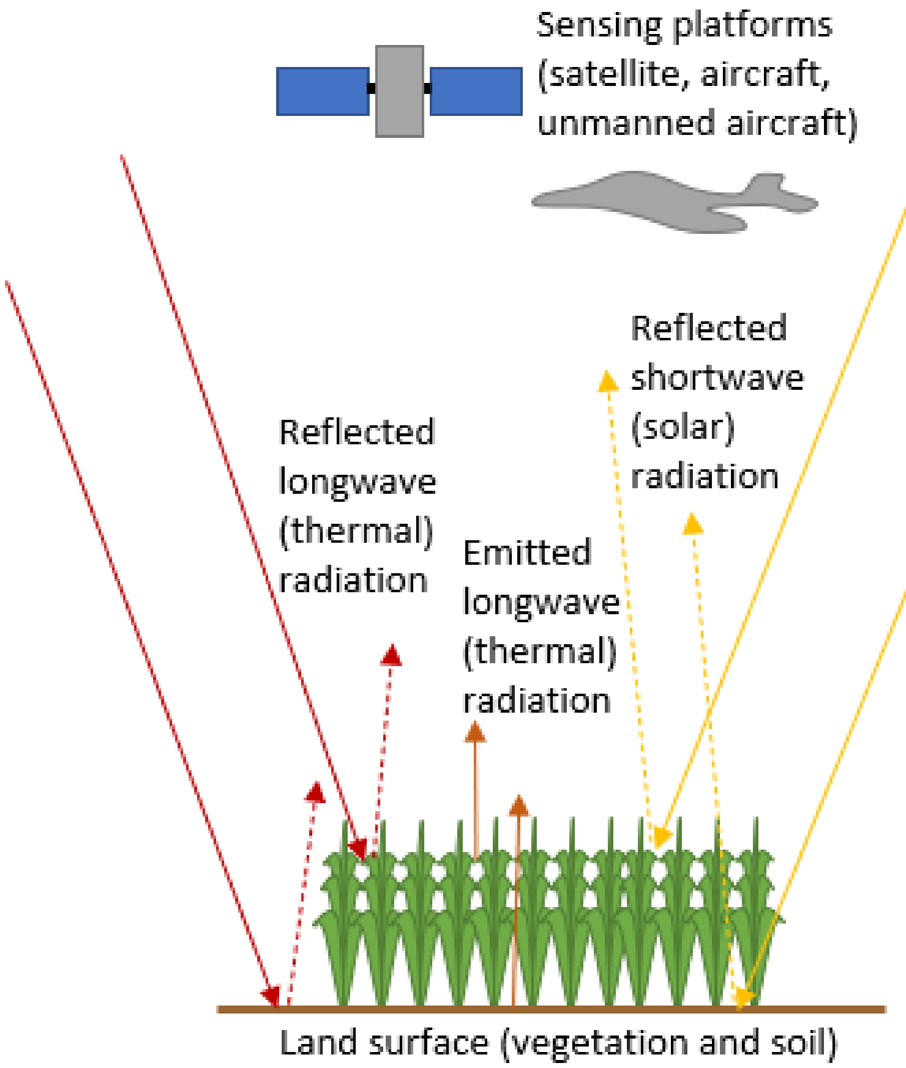
$$K_c = K_{cb} K_s + K_e$$

Based on Allen et al. (1998) and Jensen and Allen (2016).

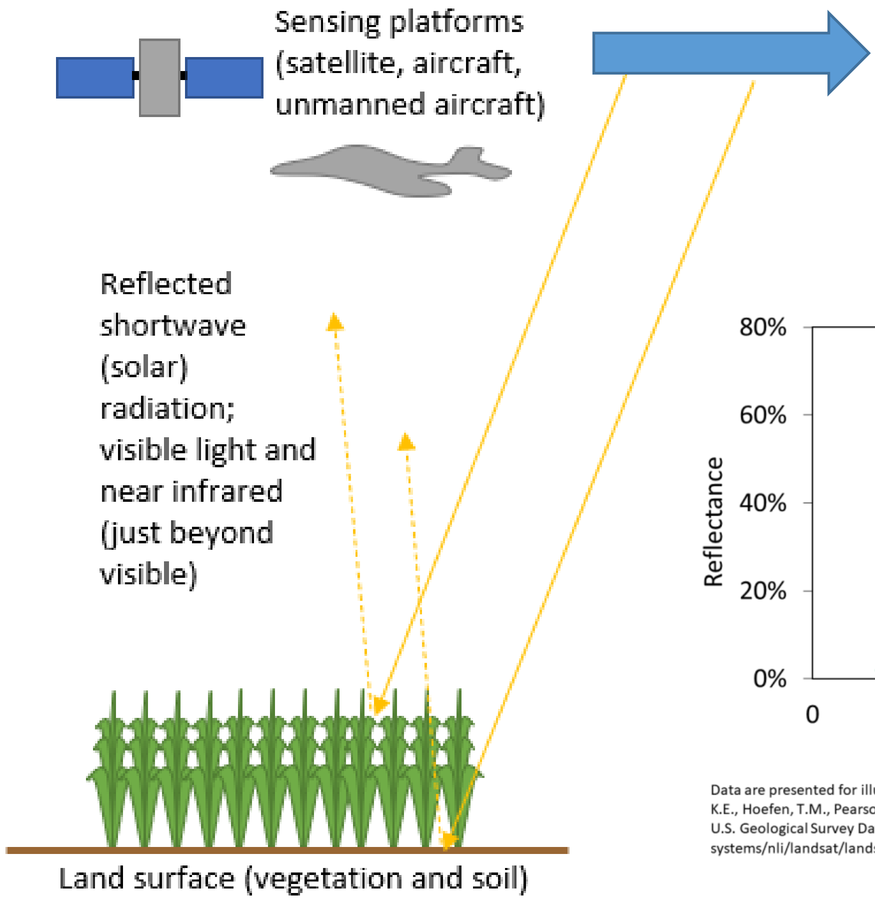
Remote Sensing Evapotranspiration Modeling

Reflectance-/Vegetation-Based Methods

Energy Balance Models and Thermal Infrared Methods

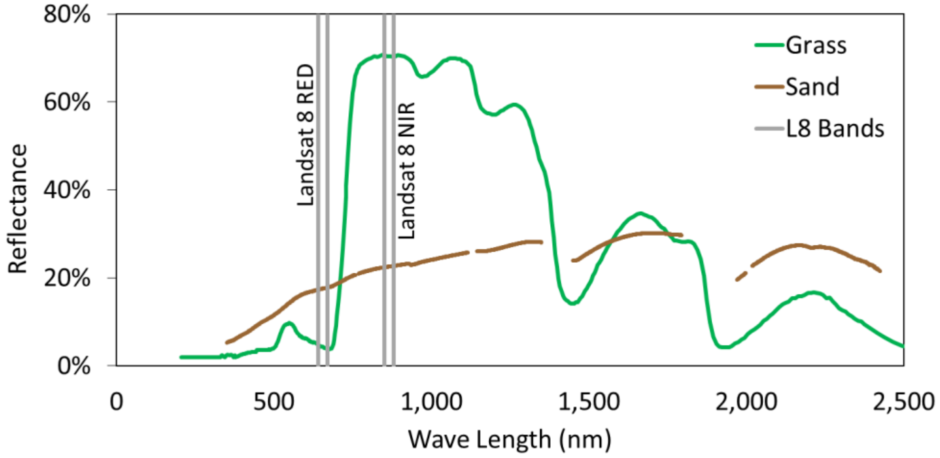


Remote Sensing Reflectance-/Vegetation-Based Methods

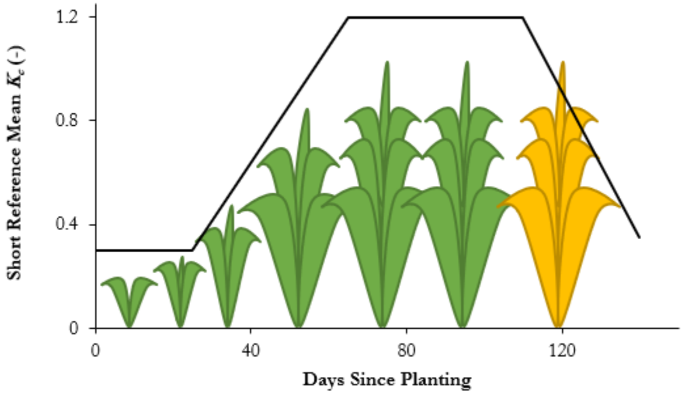


USDA-FSA NAIP Imagery, 2019, Yuma Co., AZ

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

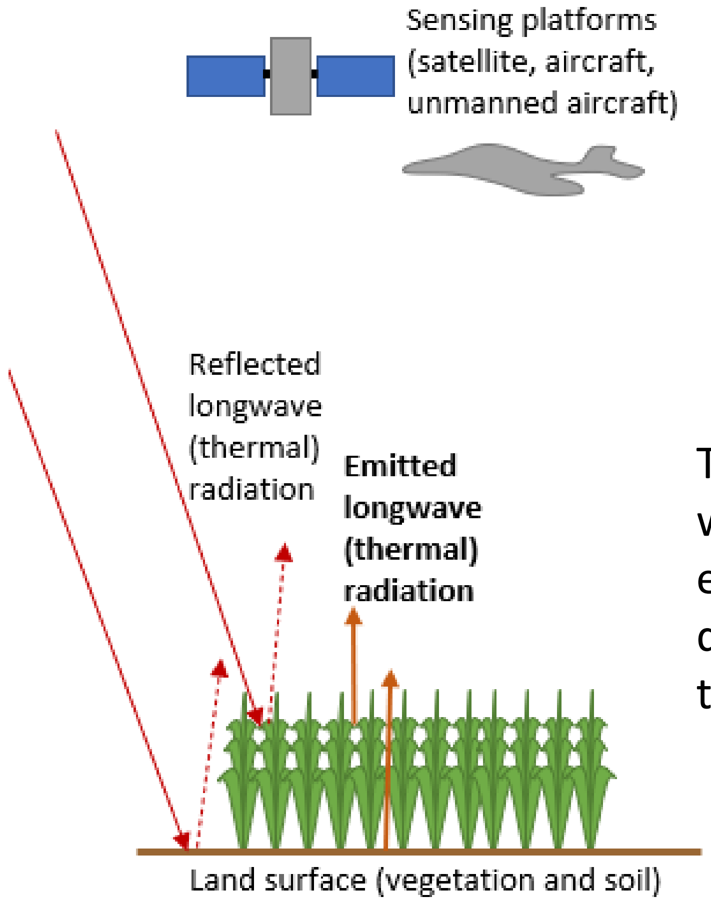


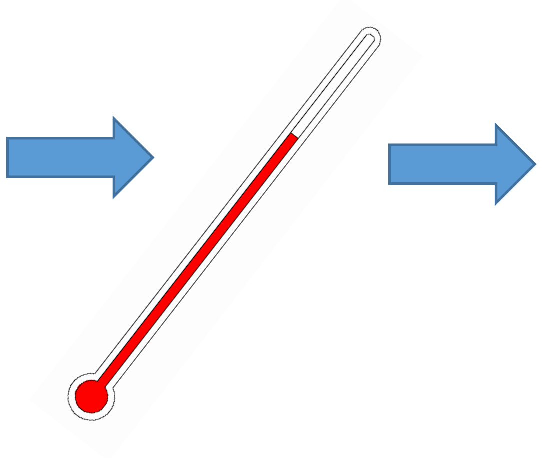
Data are presented for illustrative purposes and may not be comparable. Reflectance data from: Kokaly, R.F., Clark, R.N., Swayze, G.A., Livo, K.E., Hoefen, T.M., Pearson, N.C., Wise, R.A., Benzel, W.M., Lowers, H.A., Driscoll, R.L., and Klein, A.J., 2017, USGS Spectral Library Version 7: U.S. Geological Survey Data Series 1035, 61 p., https://doi.org/10.3133/ds1035. Landsat 8 bands from: https://www.usgs.gov/core-science-systems/nli/landsat/landsat-8?qt-science_support_page_related_con=0#qt-science_support_page_related_con



Based on Allen et al. (1998) and Jensen and Allen (2016).

Remote Sensing Energy Balance Modeling and Thermal Infrared Methods





The amount and wavelengths of radiation emitted by a surface are dependent upon the temperature of the surface

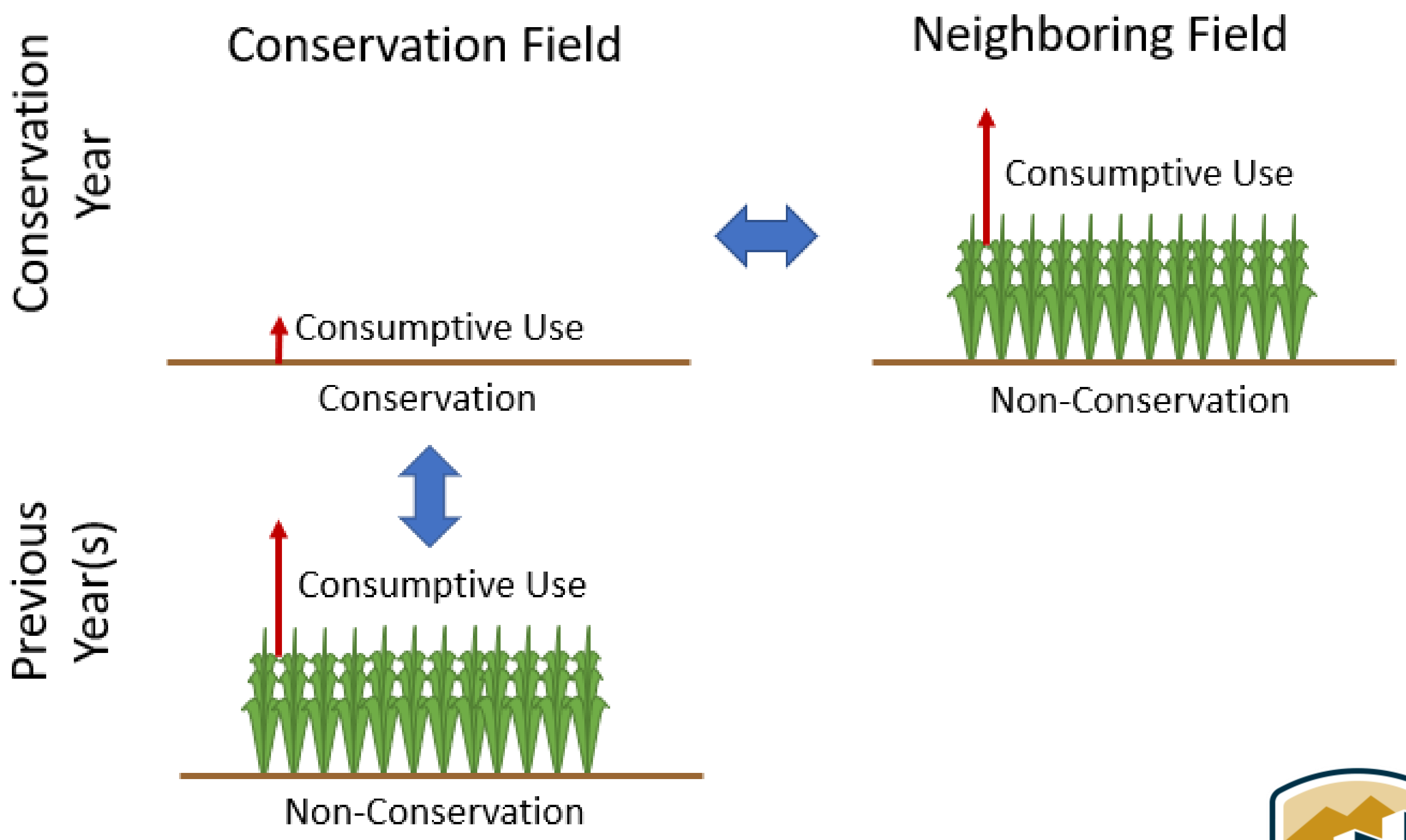
$$LE = R_n - G - H$$

- Land surface temperature is used to model sensible heat flux (H); latent heat flux (LE) is solved using the energy balance or concurrently with H
- Models differ largely in the methods of making use of the land surface temperature to compute energy fluxes
- Temporal scaling

Quantifying Differences in Consumptive Use

Methods for estimating consumptive use differences for conservation practices

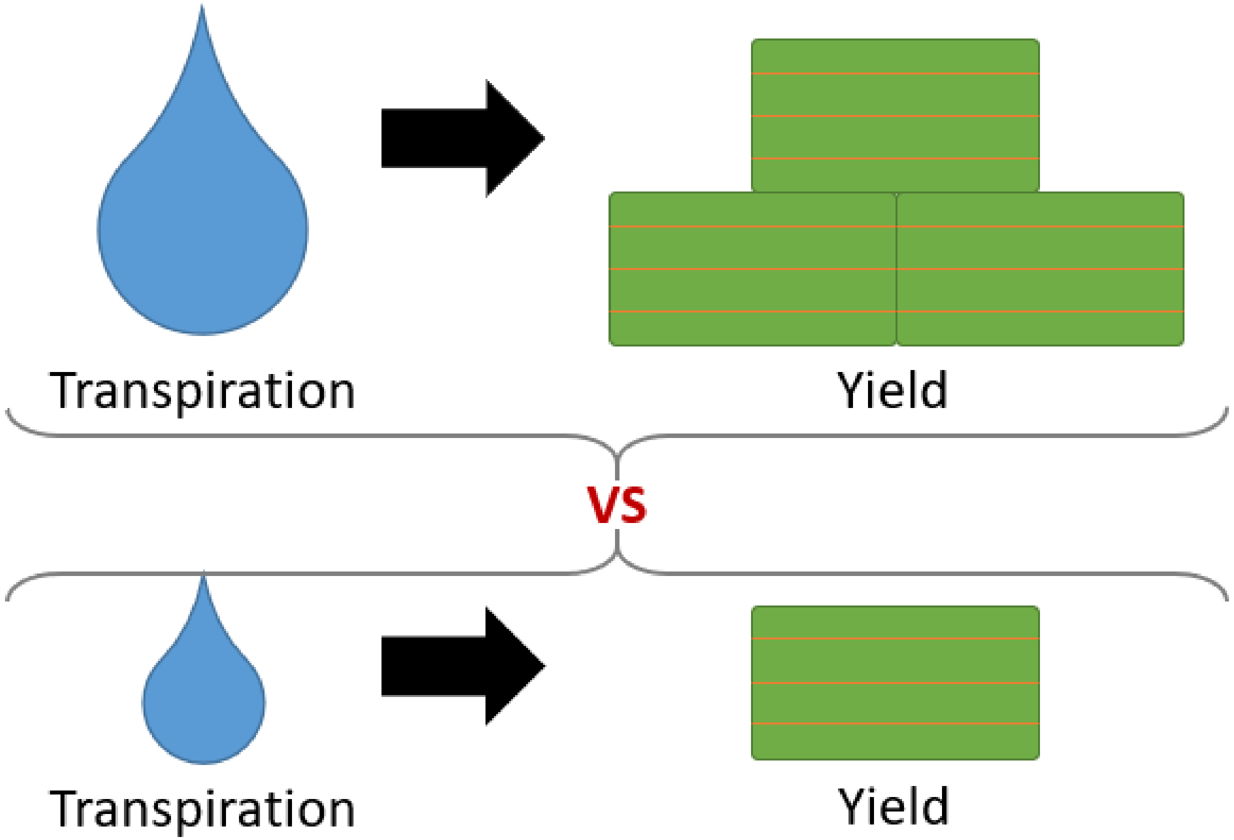
Comparisons of conservation vs. non-conservation



Yield Considerations

Impact of conservation on yield

Yield is related to consumptive use



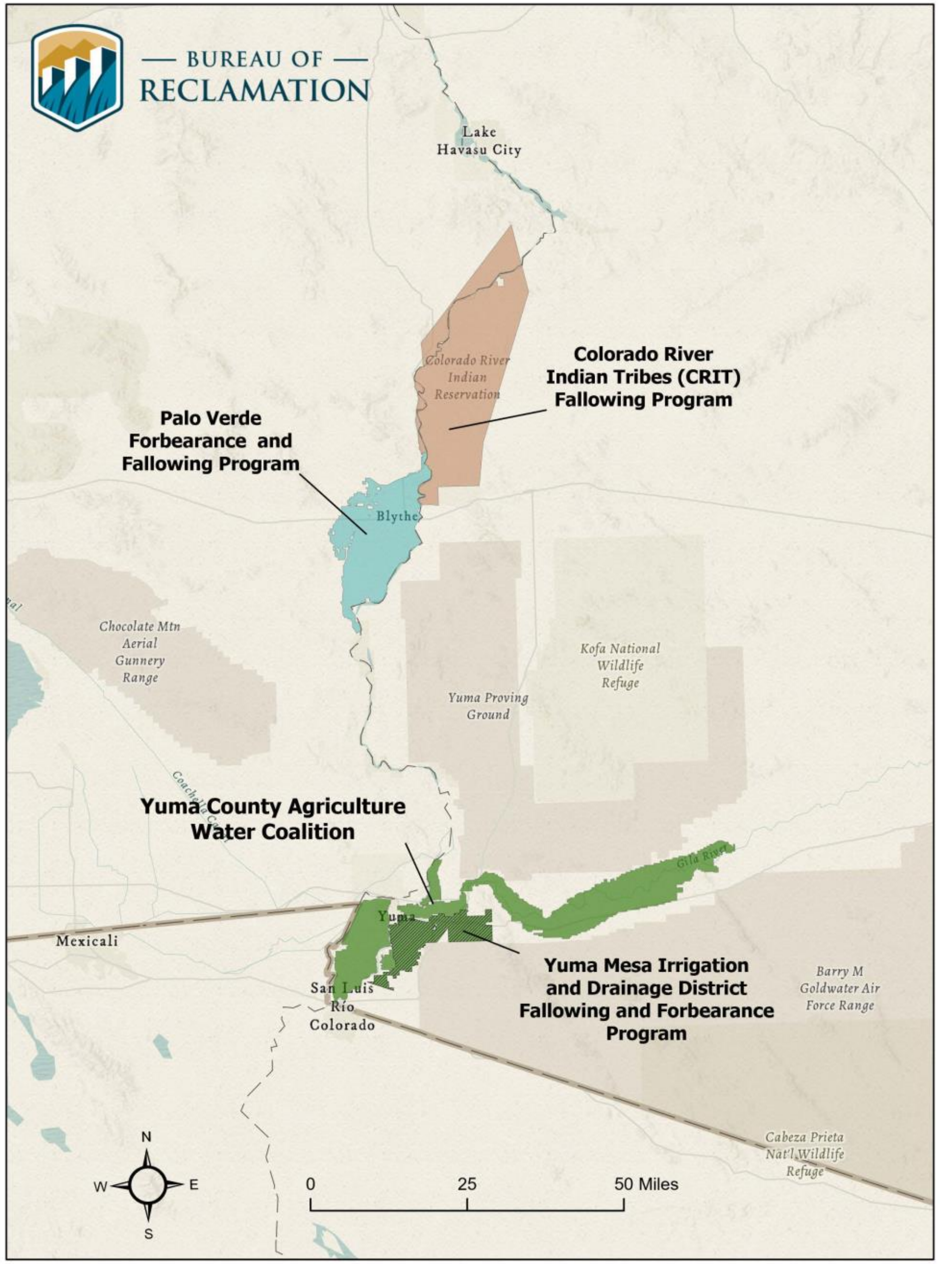
Findings from Current/Recent Conservation Activities

Ag Water Conservation in the LCRB

- Significant activity and experience across the LCRB over the past 20+ years
- Extensive investment in irrigation system improvements at the conveyance/delivery system and on-farm irrigation system levels
- Several recent conservation efforts with readily accessible information were selected as examples for review

Reviewed Conservation Activities

- Colorado River Indian Tribes (CRIT) Fallowing Program
- Yuma County Agriculture Water Coalition Study
- Yuma Mesa Irrigation Drainage District Fallowing and Forbearance Program
- Palo Verde Forbearance and Fallowing Program
- Palo Verde Deficit Irrigation Program



CRIT Fallowing Program

Program Summary

- 2016 – present
- CU reduction due to fallowing computed as average ET of crops produced on the parcel during at least 4 of previous 5 years
- Fallowing verification checks
- Satellite imagery analyses—NDVI and false color infrared

Quantification Method

- Crop coefficient/reference ET/spatial crop surveys
- ASCE Standardized Reference ET Equation
- AZMET electronic weather stations
- Crop coefficients from Reclamation LCRAS Program

CRIT Water Conservation by Fallowing

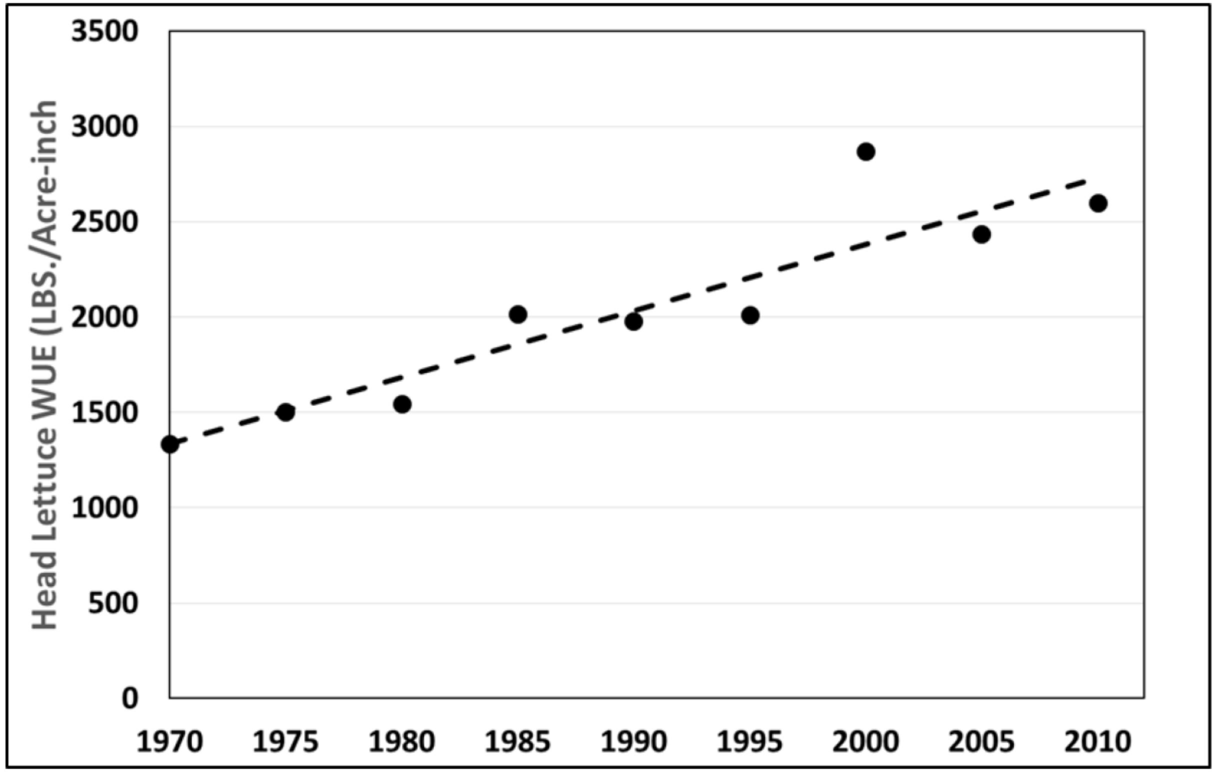
Program	Farm	Dates	Fallowed Acreage (ac)	Net Consumptive Use Reduction		Diversion Reduction
				AFY/ac	AF	AF
Pilot SCP-Phase 2	Kudu Farm	Oct 1, 2016 - Sep 30, 2018	1,591	5.39	17,144	30,772
Pilot SCP-Phase 3	MTA Farm	Oct 1, 2018 - Sep 30, 2019	1,884	5.70	10,697	19,932
Pilot SCP- Phase 3	Quail Mesa	Jan 1, 2019 - Dec 31, 2019	3,705	4.72	17,488	32,996
AZ DCP System Conservation	Multiple	Jan 1, 2020 - Dec 31, 2020	10,786	4.98	53,736	100,623
AZ DCP System Conservation	Multiple	Jan 1, 2021 - Dec 31, 2021	10,826	5.05	54,685	103,078
AZ DCP System Conservation	Multiple	Jan 1, 2022 - Dec 31, 2022	TBD			

Note: CRIT ICS Creation through fallowing during CY 2019 totaled 6,274 AF, but is not included here.
Under CRIT's DCP System Conservation Agreement during 2020-2022, any net consumptive use reduction in excess of 50,000 acre-feet (AF) is not compensated but is credited to CRIT's intentionally created surplus (ICS) account.

Yuma County Agriculture Water Coalition

Program Summary

- 2015 study
- Reviewed history/water management
- Crops changed from perennial crops to vegetable production
- Growers adopted alternative irrigation practices
- Increased crop yield



https://doi.org/10.3390/su10051548; http://creativecommons.org/licenses/by/4.0/

YMIDD Pilot Fallowing and Forbearance Program

Program Summary

- 2014 – 2016
- Agreement with CAGRD
- Spatial crop surveys
- Reference evapotranspiration
- Crop coefficients

Summary of Pilot Fallow Program (2014 – 2016)			
Year	Enrolled Acres	Unit Consumptive Use (AF/ac)	Conserved Water (AF)[1]
2014	1,406	4.86	6,827
2015	1,411	5.09	7,180
2016	1,401	5.36	7,509

[1]Includes removal of special water use such as dust control and tree removal

http://www.cap-az.com/documents/meetings/2018-09-20/1716-2.0_WEB FINAL_Information Brief_Fallowing Programs Report.pdf

Palo Verde Forbearance & Fallowing Program

Program Summary

- Started in 2005, 35-year agreement between MWD and PVID & contracts w/ individual farmers
- Average farmland in production = 91,400 acres
- 7% - 28% fallowed annually
- Temporary fallowing (no acre fallowed >5 years w/out rotation back into production)
- Reclamation's LCRB accounting consumptive use
- Comparison of fallow fields to other fields in PVID

From: https://www.usbr.gov/lc/region/g4000/4200Rpts/DecreeRpt/2019/27.pdf

http://www.mwdh2o.com/PDF_NewsRoom/6.4.2_Water_Reliability_Palo_Verde.pdf; https://www.usbr.gov/lc/region/g4000/4200Rpts/DecreeRpts/DecreeRpt/2019/27.pdf

PVID Deficit Irrigation Project Overview

BUREAU OF RECLAMATION

Case Study Framework

Case Study Considerations

Location

Conservation Activity

Quantification Method

Case Study Considerations

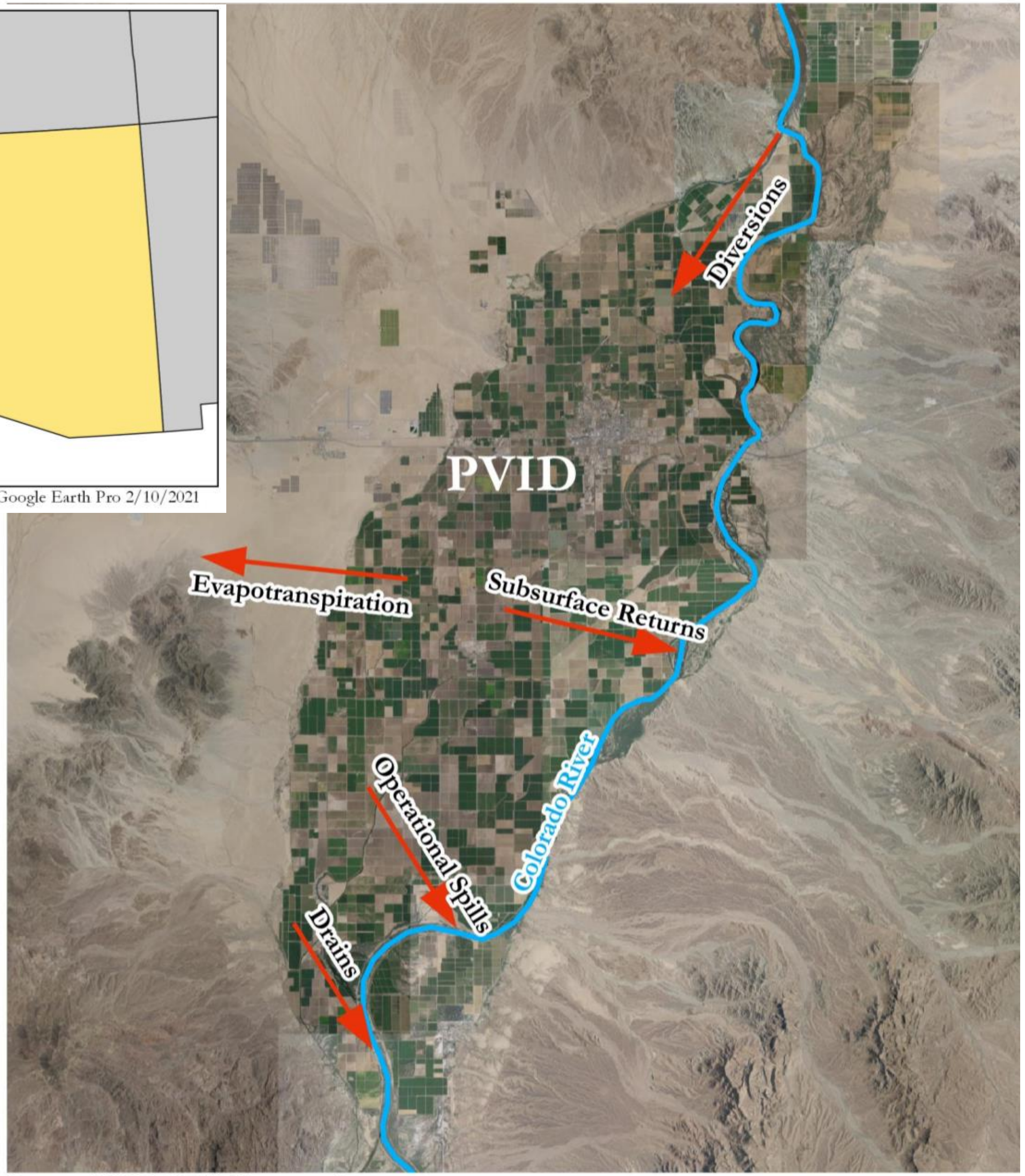
Location → Geographical; On-river/Transbasin

Conservation Activity

Quantification Method

PVID Location: Palo Verde Valley, On-River

Sources: U.S. Census Bureau TIGER 2018; Google Earth Pro 2/10/2021



Source: USGS (2017) Basemap Imagery

Case Study Considerations

- Location
- **Conservation Activity**
  - Consumptive Use (CU) Reduction
    - Full-year agricultural cropland fallowing
    - Seasonal/partial-year cropland fallowing
    - Deficit irrigation
    - Crop mix changes or crop switching
  - Efficiency Improvements
    - Seepage reduction
    - Irrigation conversion/improvements
    - Tailwater reduction and reuse
    - Soil amendments to increase water holding
    - Water control – SCADA, spill reduction
- Quantification Method

PVID Conservation Activity: CU Reduction, Deficit Irrigation

- Deficit irrigation 1 (D1): Eliminate three irrigation events in summer harvest cycles (Jul – Sept)
- Deficit irrigation 2 (D2): Eliminate two irrigation events in summer harvest cycles (Aug – Sept)
- Deficit irrigation 3 (D3): Eliminate one irrigation event in summer harvest cycles (Aug – Sept)

Case Study Considerations

Location

Conservation Activity

Quantification Method

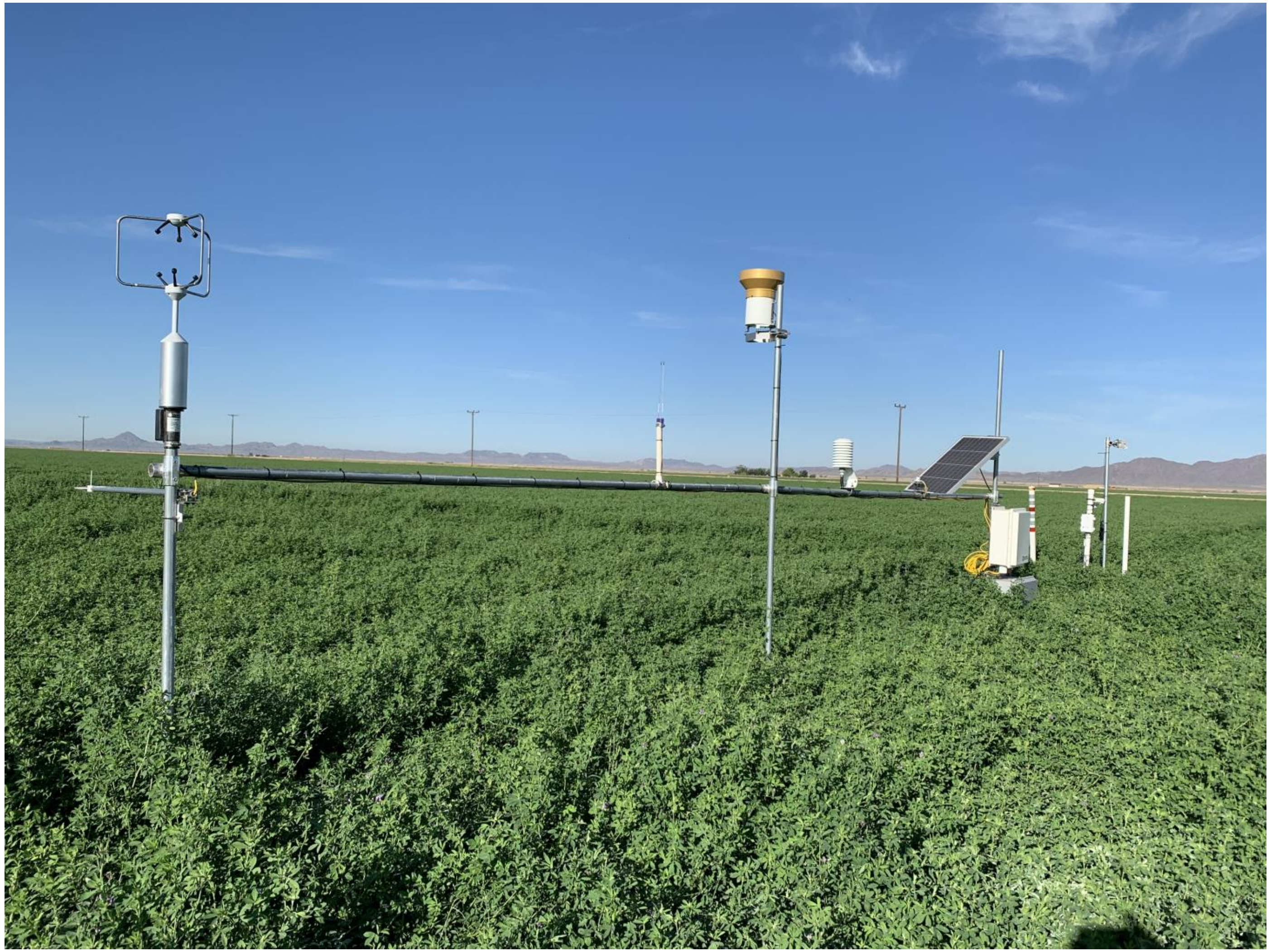
Water Balance
- Soil-Water
- Field-Level
- Project-Level/Delivery/Flow Measure

Micrometeorology
- Bowen Ratio Energy Balance
- Eddy Covariance
- Surface Renewal
- Scintillometers

Reference Evapotranspiration
- Crop Coefficients
- Spatial Crop Surveys

Remote Sensing
- Reflectance-/Vegetation-Based Methods
- Energy Balance Models & Thermal Infrared Methods

PVID Quantification Method: Micrometeorology (Surface Renewal & Eddy Covariance)



Case Study Evaluation Steps

1. REVIEW AG WATER CONSERVATION EFFORTS IN THE LOWER BASIN →
2. IDENTIFY CASE STUDIES FOR EVALUATION →
3. COLLECT QUANTITATIVE AND QUALITATIVE INFORMATION →
4. CONDUCT SITE VISIT →
5. IDENTIFY UNANTICIPATED CONSEQUENCES, LESSONS LEARNED →
6. DOCUMENT OBSERVED RESULTS, CONSTRAINTS, AND PERSPECTIVES OF THE ACTIVITY →
7. COMPARE QUANTIFICATION METHOD WITH RECLAMATION'S DECREE ACCOUNTING →
8. PROVIDE ASSESSMENT OF BEST PRACTICES/ IMPROVEMENTS FOR QUANTIFICATION METHODS

Matrix of Potential Case Studies

Potential Case Studies	Location		Conservation Activity					Quantification Method			
	State	On-river/ Transbasin	Deficit Irrigation	Irrigation Conversion	Fallowing	Crop Modification	Efficiency Improvements	Water Balance	Micrometeorology	Reference ET	Remote Sensing
PVID/MWD Forbearance and Fallowing Program	CA	On-river			X			X			
PVID Partial Year Deficit Irrigation of Alfalfa Program	CA	On-river	X					X	X	X	
CRIT Fallowing Program	AZ	On-river			X			X		X	
Mohave Valley IDD Fallowing Program	AZ	On-river			X			X		X	
Bard Water District Seasonal Fallowing Program	CA	On-river			X			X			
Central Arizona IDD	AZ	Transbasin					X				
Maricopa-Stanfield IDD	AZ	Transbasin					X				

Project Sharing Opportunities

Wrap-up and Next Steps

Pilot Study Schedule

Workshop 1

Workshop 2

Site Visits/Interviews

Workshop 3

Pilot Study Final Report

Nov 2020

Feb 2021

Mar 2021

Apr 2021

May 2021

Aug 2021

Sep 2021

Oct 2021

Nov 2021

Dec 2021

Milestone 1: Technical Memorandum 1 – Summary of Refined Scope & Case Study Definition

Milestone 2: Technical Memorandum 2 – Summary of Significant Findings from Literature Review & Recent/Current Activities in the Lower Basin

Milestone 3: Technical Memorandum 3 – Summary of Case Study Definition, Site Selection & Evaluation Process

Milestone 4: Draft Report – Case Studies and Technical Reviews

Milestone 5: Pilot Study Final Report

Presentation at CRWUA

Technical Memorandum 4 – Case Study Evaluations

Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

U.S. Department of the Interior September 2021

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Technical Memorandum 4 – Case Study Evaluations

Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

prepared by

Natural Resources Consulting Engineers, Inc.
Jacobs Engineering Group Inc.

Cover Photo: United States Bureau of Reclamation

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- Ryan Seiler, Grower
- Grant Chaffin, Grower
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- Paula Hayden, PVID Fallow Coordinator
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- Tommy Drennan, Councilman
- J.D. Fisher, Councilman
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- Kerri Hatz, MVIDD General Manager
- Charles (Chip) Sherrill, Chairman
- Vince Vasquez, Board Director
- Michael Pearce, MVIDD Legal Counsel
- Chris Stall, Land IQ, Consultant

Contents

List of Tables

List of Figures

Project Definition

The Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin Pilot Study (Pilot Study) is a logical next step in the long-standing commitment of United States Bureau of Reclamation (Reclamation) and the Lower Colorado River Basin (LCRB, Lower Basin) stakeholders to ensure the resiliency, reliability, and sustainability of the Colorado River. The objective of this study was to work collaboratively with a diversity of stakeholders to explore the current methods used to quantify agricultural water conservation activities in the Lower Basin, including the relationship of those quantification methods to the Lower Basin consumptive use (CU) accounting, and to recommend approaches to improve agricultural water conservation quantification methods.

Project Activities

The Pilot Study commenced with a workshop (Workshop #1) held remotely November 9 and 10, 2020. The workshop included a summary of the *Colorado River Basin Supply and Demand Study* (Reclamation, 2012) and the *Colorado River Basin Stakeholders Moving Forward to Address Challenges Identified in the Colorado River Basin Water Supply and Demand Study* (Reclamation, 2015) reports. The workshop also provided an opportunity for stakeholders and participants to provide input regarding scope refinement for the Pilot Study. A summary of Workshop #1 and the refined project scope were provided in *Technical Memorandum 1 – Project Definition and Summary of Workshop #1*, herein referred to as TM1 (NRCE and Jacobs, 2021a).

The second step in the Pilot Study effort was to perform a review of scientific and technical literature, project reports, regional publications, reference books and other sources to document methods used to quantify CU reductions from agricultural irrigation conservation measures in the LCRB and elsewhere (e.g., full-year agricultural cropland fallowing, seasonal or partial-year cropland fallowing, deficit irrigation, switching crops or crop rotations to alternate crops requiring less irrigation water, irrigation methodology conversions, and similar topics). This documentation effort was divided into two portions: 1) a review of scientific literature and other sources to identify CU quantification methods, and 2) an overview of select conservation activities within the LCRB and associated CU quantification methods. This effort resulted in *Technical Memorandum 2 – Summary of Significant Findings from Literature Review and Recent/Current Activities in the Lower Basin* referred to as TM2 (NRCE and Jacobs, 2021b). TM2 includes general descriptions and discussions of quantification methods that are subsequently included in the present memorandum.

TM2 was made available for review and comment by participants prior to Workshop #2. That workshop was held remotely on March 2, 2021. During the workshop the reviews of literature and on-going agricultural water conservation activities in the LCRB documented in TM2 were presented. The workshop was also used as a platform to identify and discuss relevant case study opportunities in the LCRB for specific conservation activities and/or methods of quantifying CU reductions. A framework for categorizing case study opportunities was presented and input from workshop participants was sought regarding constraints and limitations for the case studies and the site selection. The results of Workshop #2 and the case study selection process were documented in *Technical Memorandum 3 – Summary of Case Study Definitions, Site Selection, and Evaluation Process* (TM3; NRCE and Jacobs, 2021c).

The purpose of the present technical memorandum (TM4) is to document the case study site visits, data obtained, and evaluations made, and to present recommendations for future agricultural water conservation programs. TM4 was made available for review and comment by participants prior to Workshop #3. Workshop #3 was held remotely on September 22, 2021. The primary objectives of the Workshop were to present the findings documented in TM4 and seek feedback from workshop participants regarding the information and any additional insights gleaned from other conservation efforts.

Case Studies Selected for Evaluation

Based on a review of the potential case studies and the interest in participating expressed by representatives from the potential participating organizations, the following six case studies were selected for evaluation as part of this effort:

- Gila River Indian Community (GRIC) Irrigation System Modernization
- Bard Water District (Bard) Seasonal Fallowing Program
- Palo Verde Irrigation District (PVID) Forbearance and Fallowing Program
- PVID Partial-Year Deficit Irrigation of Alfalfa Program
- Colorado River Indian Tribes (CRIT) Fallowing Program
- Mohave Valley Irrigation and Drainage District (MVIDD) Fallowing Program

These studies were selected from among the available choices to represent a variety of conservation activities, quantification methods, and project locations (shown in *Figure 1*) and are described in TM3. As discussed in TM3, the case studies were evaluated with the goal of gaining knowledge on CU quantification methods and approaches. The case study evaluation process included:

- In-person field visits
- Interviews with case study participants
- Review of documentation relating to the conservation project(s) and quantification methods
- Identification of the relationship of the conservation activity and quantification method to Reclamation's Colorado River Decree Accounting (Decree Accounting)[1], where applicable
- Identification of challenges and lessons learned
- Consideration of the accuracy of methods used in the project
- Consideration of costs and complexity of program implementation
- Assessment of opportunities for improvement of the quantification method(s)

The results of the case study evaluations are presented in the following sections named for the respective case studies. The information presented in this technical memorandum includes the input from the many individuals who participated in the case study discussions (see Acknowledgements at the beginning of the document). Some of these communications are cited; while a number of them are not, they are hereby acknowledged.

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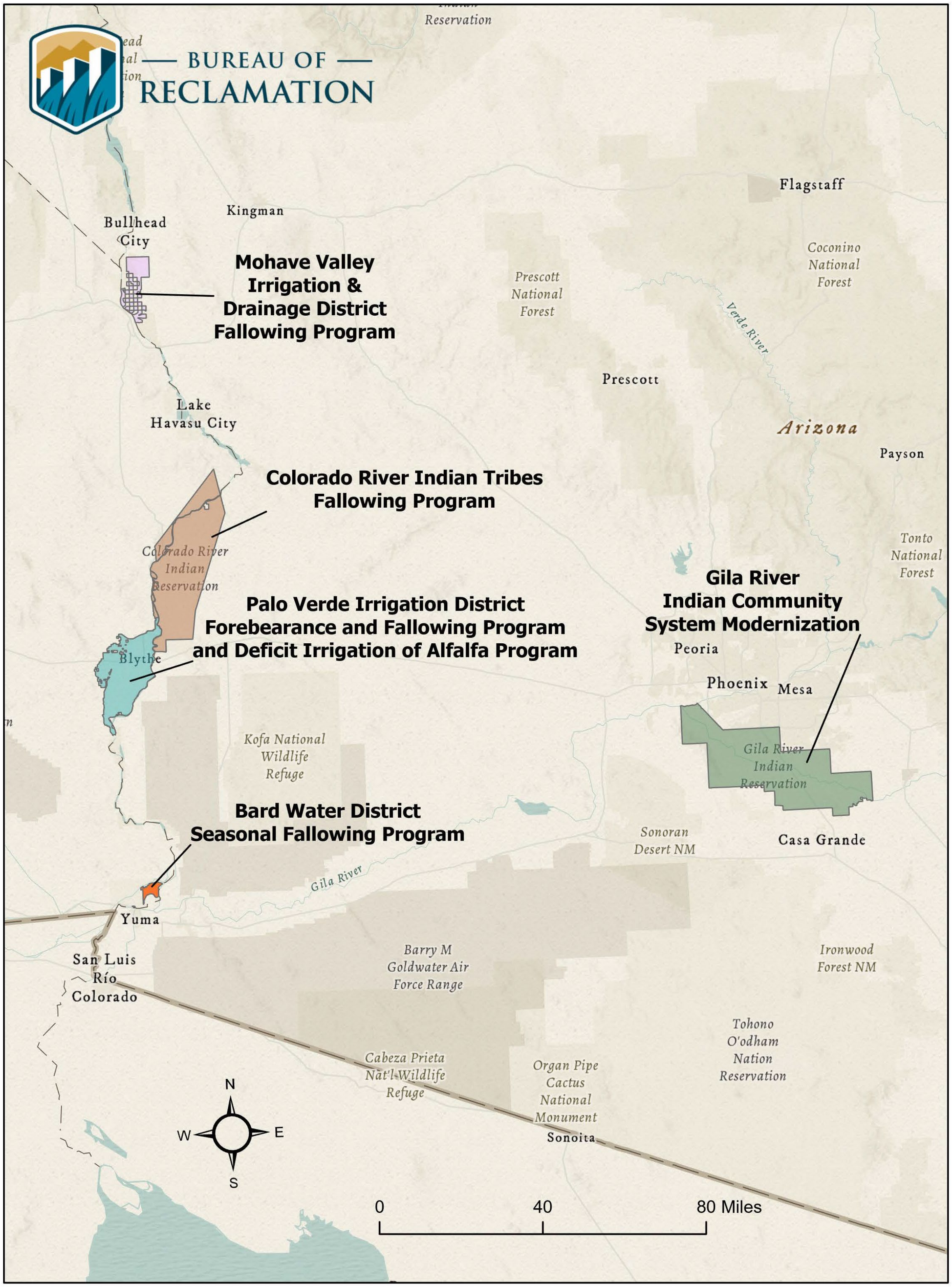
[1] *Colorado River Accounting and Water User Report: Arizona, California and Nevada* published annually in accordance with Article V of the Consolidated Decree of the United States Supreme Court in Arizona *v.* California, 547 U.S. 150 (2006).

Figure 1 Map of the Project Locations of the Six Case Studies



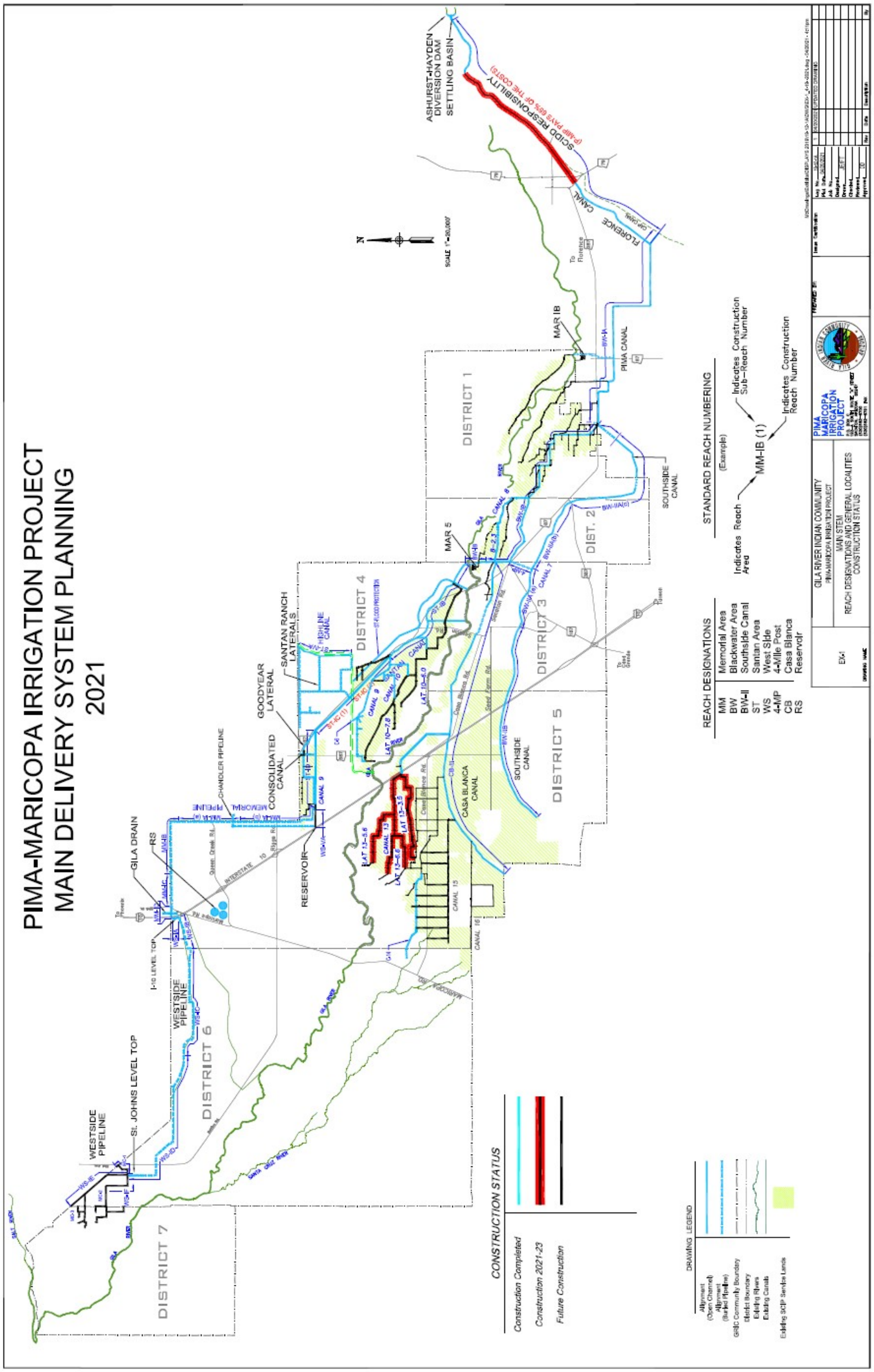
Gila River Indian Community Irrigation System Modernization

The Gila River Indian Community (GRIC, Community) is located just south of Phoenix in Central Arizona (*Figure 1*); and is home to the Akimel O'otham (Pima) and Pee-Posh (Maricopa) tribes. Growers in the Community raise alfalfa, cotton, small grains, and silage corn, among other crops (BIA, 2021).

The Community has been undertaking an extensive rehabilitation, rebuild, and expansion of existing irrigation infrastructure on and/or serving the Gila River Indian Reservation. This effort, which is referred to as the Pima-Maricopa Irrigation Project (P-MIP), was developed as part of GRIC's 1985 *Master Plan Report for Land and Water Use* (Franzoy Corey, 1985; GRIC and EcoPlan, 1997). P-MIP specifically refers to the capital improvement project for the irrigation system (*Figure 2*). The P-MIP irrigation water delivery and distribution system is planned to serve up to 146,300 total acres of land on the Reservation (GRIC and EcoPlan, 1997) and includes the rehabilitation and reconstruction of existing irrigation infrastructure within BIA's San Carlos Irrigation Project (SCIP) service area and areas in the northern and western portions of the Reservation located outside of the SCIP service area. The service area of the SCIP Indian Works (SCIP-IW) is 50,000 acres of land on the Reservation. The total project area that the P-MIP system may serve includes up to an additional 96,300 acres of new development. In connection with P-MIP, GRIC is also in the process of transferring operation and maintenance (O&M) responsibilities for the SCIP-IW division from BIA to a GRIC entity, the Gila River Indian Irrigation and Drainage District (GRIIDD), which will include O&M of all of the P-MIP system within the Reservation boundary.

The P-MIP system is being constructed to deliver all of the Community's 311,800 acre-feet per year (AFY) of Central Arizona Project (CAP) water. Additional water sources for P-MIP include: the Gila River (the source for the SCIP project), groundwater, the Salt River Project (SRP), the Roosevelt Water Conservation District (RWCD), and reclaimed municipal water from the cities of Chandler and Mesa. P-MIP improvements started in 1998 outside of the SCIP service area under the Community's Master Repayment Contract. Construction within the SCIP service area began in earnest in 2010 when consistent and reliable funding for the project became available as a result of the Arizona Water Settlements Act (AWSA), a water rights settlement between GRIC, the United States, and some 34 state parties (P-MIP, communication, August 19,2021). Construction is slated for completion in 2030. The project includes rehabilitation, modernization, and construction of canals, pipelines, turnouts, and measurement and control structures. The project will also include an extensive supervisory control and data acquisition (SCADA) system.

Figure 2   Map of the Pima-Maricopa Irrigation Project (Courtesy of the Pima-Maricopa Irrigation Project).



Technical Analysis

A technical analysis of the GRIC irrigation system modernization case study including a description of the conservation activities and quantification methods is presented in the following subsections.

Description of Conservation Activities

P-MIP includes a suite of system improvement activities. The goal of P-MIP is three-fold:

- Make efficient use of the portfolio of water supplies provided to GRIC through a complex array of sovereign rights, decrees, water rights settlements, and exchange agreements.
- Enhance and sustain a reliable irrigation system, and
- Modernize the GRIIDD system for the benefit of the Community. P-MIP infrastructure improvements led to the formation of GRIIDD and the corresponding transfer of O&M responsibilities from BIA SCIP-IW.

The above-mentioned improvement activities are described in the following subsections.

Additional Water Sources

P-MIP is served by multiple water sources, which increase the supply resiliency and allow the system to adequately serve water users and expand GRIC's irrigated area. The original primary source of the SCIP system is Coolidge Dam, which impounds water in San Carlos Reservoir. This reservoir is on the Gila River but has historically been an inconsistent and erratic water supply. For example, the Reservoir has reached full capacity in only five years[2]. The reservoir has a limited supply much of the time and it is not uncommon for it to be depleted early in the irrigation season according to a case study participant. For example, the reservoir was empty on April 7, 2021 and had impounded only 14,258 acre-feet (AF) as of August 17, 2021.

Because of the unreliable nature of the Gila River water source and the desire of the Community to increase irrigated agriculture, GRIC has pursued additional water sources. The combination of all these water sources adds operational complexity to the system. The P-MIP infrastructure and SCADA improvements, in concert with the consolidated O&M responsibilities of GRIIDD are necessary to improve the efficient use and management of the system's relatively large number of water sources.

Infrastructure Improvements

P-MIP includes extensive system rehabilitation and additional infrastructure construction. These improvements include measures to improve water delivery management and to reduce system losses and spills through:

- Reconstruction of all main canals and most laterals
- Concrete lining of all main canals and most laterals
- Construction of pipelines and siphons

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[2] As cited in *San Carlos Apache Tribe v. United States, 272 F. Supp. 2d 860* (2003). United States District Court for the District of Arizona. No. CV 99-255 TUC DCB. July 9, 2003. Available at: https://cite.case.law/f-supp-2d/272/860/#p867. Both the BIA and P-MIP indicated three fills, which differed in included years, none of which were after the 2003 order, just cited.

- Construction or reconstruction of check and drop structures

All reconstructed canals have been designed to provide sufficient head to serve adjacent fields. The canals have also all been designed to have the same uniform bed-slope.

Some highlighted major improvements include:

- Construction of the concrete-lined Florence Canal, to replace the present, unlined, Florence-Casa Grande Canal, which carries Gila River water to both tribal and non-Indian users. This is a shared project between P-MIP and the non-Indian users and is currently under construction.
- Concrete lining of the Pima Canal, which is the primary canal entering the Reservation and includes the Pima Feeder Canal which delivers CAP water to the Community (*Figure 3*).
- Reconstruction of the Casa Blanca Canal. This is a major canal serving much of the GRIC irrigated area. The Casa Blanca Canal was originally constructed by modifying an existing waterway, the Little Gila River. Reconstruction has included raising and realigning the canal, concrete lining, and construction of control structures (*Figure 4*). The capacity of the reconstructed canal is 350 cubic feet per second (cfs) at its head and 75 cfs near its tail.
- Extensive reconstruction and lining of canal laterals, including the Southside Canal (425 cfs down to 75 cfs), the Santan Canal (700 cfs) and new construction that includes over 24 miles of reinforced concrete pipe (108-inch diameter down to 54-inch diameter) in the Memorial and Westside areas.

P-MIP improvements are for the canal conveyance system only, they do not include any on-farm improvements including farm ditch reconstruction. However, P-MIP improvements do include turnouts with measurement capabilities to serve farms and the reconstruction of any farm ditches that must be moved to facilitate P-MIP infrastructure. This includes moving farm ditches that are within the P-MIP rights-of-way so that they are outside of the rights-of-way.

Figure 3 Photos of the Lined Pima Canal (Left) and of the Pima Canal Including a Portion of the Casa Blanca Canal Headworks and Well Discharge (Right) (Credit: L. Perkins, May 24, 2021).

Water Measurement and Automation

Historically, the SCIP system had a limited number of water measurement sites and records were often in hardcopy (SCIP, communication, June 30, 2021). These measurements were made using staff gauge readings and sedimentation could have affected these measurements according to communications from the BIA. The P-MIP improvements include an extensive monitoring network, with automated measurement structures placed at the heads of canals and throughout the system (*Figure 4*), though not necessarily at all spill sites. The improvements also include measurements of all source waters including installation of flow meters on all supply wells (*Figure 5*). The new measurement devices are all presently equipped with telemetry or will be in time. This facilitates real-time observation of system conditions and electronic data storage and retrieval.

Figure 4 Photo of an Automated Drop Control Structure on the Reconstructed Casa Blanca Canal (Left; Credit: B. Barker, May 24, 2021); and Photo of the Casa Blanca Canal Headworks and Unlined Pima Canal Before Improvements (Right; Courtesy of David DeJong, 2006).

Figure 5 Photo of an Irrigation Supply Well for the Pima Canal with a Flow Meter Installed in the Discharge Pipe (Credit: B. Barker, May 24, 2021).

The system improvements also include automated gates, which are incorporated, along with the measurement structures, into a full SCADA system. While the SCADA system is not fully completed at present, real-time observation and control operations are conducted from an interim location. A dedicated central monitoring and control building has been constructed for the project and will be used in the future.

The improved management made possible by the SCADA system will enable the system operators to better match supply with demand. However, even without an operational SCADA system, some of this benefit has already been realized. For example, the Casa Blanca Canal, which is a primary canal on the Reservation, and which does not yet have operating SCADA, historically spilled into a "sump" at its tail (some of which water could be pumped and reused). As a result of the canal reconstruction, lining, measurement, and operation, spills from that canal are notably less than in the past[3].

P-MIP does not include extensive measurements of drain (surface or subsurface) discharge; though, one drain does have discharge measurement (BIA, 2021). However, in the context of the Decree Accounting, drain discharge in this case is not considered a return flow to the Colorado River system because it does not flow as surface water to the Colorado River and any possible subsurface connection to the river or the Colorado River Alluvial Aquifer is considered negligible. Accordingly, P-MIP drain water is not considered in the CU quantification, because P-MIP is an off-mainstream (of the Colorado River) system.

Consolidated Management

GRIC is also implementing organizational changes in connection with the infrastructure improvements of P-MIP in the formation of GRIIDD. While this is an administrative activity, it has relevance for future system efficiency and conservation. This change will result in a single organization, GRIIDD, being responsible for all of the O&M responsibilities of the P-MIP system within the Reservation. Presently, both GRIC and BIA share responsibilities for the system. Consolidation of O&M responsibilities will facilitate a streamlining of communication and system response. The simplification of the system management will better allow the operators to match supply with demand, thus reducing the risk of operational spills or inadequate supplies, which may result from communication lags. These benefits will particularly be possible once the full SCADA system is operational. After this management transfer, BIA will continue to operate the portions of the system that are upstream of the Reservation and that serve both GRIC and non-Indian users. This includes operation of Coolidge Dam. The process of transferring O&M responsibilities to GRIIDD will be completed in late 2022.

Additional Conservation Measures

In addition to the P-MIP and GRIIDD conservation measures, on-farm improvements have been undertaken by some P-MIP water users. A specific example is that a notable number of users have taken advantage of the U.S. Department of Agriculture Natural Resources Conservation Service's (NRCS's) Environmental Quality Incentives Program (EQIP) to improve farm fields. These efforts have included laser grading and field ditch and pipeline improvements for surface irrigated fields.[4] In total from 2006 to 2020, 78 fields were improved under this program covering a total of about 1,813 acres (*Table 1*). According to the BIA, in general, this has resulted in shorter application times

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[3] According to BIA (2021), there is one other location within the P-MIP service area that no longer has spills; and there are also three locations that currently do spill within P-MIP, though spills are infrequent for one of them.

[4] Most of the irrigation in the P-MIP service area is surface irrigation, with about 1,051 acres within the SCIP-IW service area and 2,199 acres outside of the SCIP-IW service area in center pivots (P-MIP, communication, August 19, 2021).

per irrigation event, which may be evidence of less applied water and consequently greater application efficiencies (e.g., less deep percolation).

Table 1 Summary of Total Areas of Fields Served by the Pima-Maricopa Irrigation Project that Received U.S. Department of Agriculture Natural Resources Conservation Service's Environmental Quality Incentives Program (EQIP) Funded Improvements (GRIIDD, 2021).

Year	Improved Area (acres)	Year	Improved Area (acres)	Year	Improved Area (acres)
2006	46.0	2011	61.7	2016	62.2
2007	320.9	2012	27.6	2017	94.6
2008	692.4	2013	0.0	2018	0.0
2009	142.6	2014	68.1	2019	87.5
2010	10.1	2015	44.2	2020	154.9
Grand Total (acres)					**1,812.8**

CU Quantification Methods

The change in CU (ΔCU) from the system improvements was quantified using variations of a project-level water balance (TM2). The P-MIP system can be considered an off-mainstream water user in relation to the Colorado River since return flows do not make it to the mainstream of the Colorado River. Therefore, under the Decree Accounting definition of CU as diversions less return flows, CU for P-MIP is equivalent to diversion because there are no return flows to the Colorado River mainstream[5]. Therefore, ΔCU resulting from efficiency improvements can be quantified by comparing diversion records before and after the improvements, assuming all else is equal.

There are a few challenges with applying the principle of CU equaling diversion to quantify ΔCU for P-MIP. The first challenge is that, based on the site visit discussion with P-MIP, GRIIDD, and SCIP personnel and the fact that the P-MIP build-out is not completed, it was decided that ΔCU would be evaluated for sub-areas of the P-MIP. A second challenge is that the particular ΔCU of interest for the present study is that relating to the infrastructure and management efforts of P-MIP and GRIIDD as compared to those relating to grower practices. A third challenge is that the system service area has changed and is intended to change along with the P-MIP improvements. A final difficulty is that historical records of irrigated area, diversions, and flows are not as extensive nor as easily processed or analyzed as the flow records after the infrastructure improvements. Such conditions, which are certainly not unique to P-MIP, pose a direct challenge to quantifying ΔCU.

To address the first challenge, it was necessary to consider ΔCU in partial terms. This could be done based on the supply water inflow to the area in question (Q_{In}), which would be some value less than the equivalent diversion at the water source(s) serving that area. For subareas that have other service areas downstream, it is necessary to subtract the supply water that flows past the area of interest (Q_{Out}), which value does not include spills or drainage. Thus:

$$CU = Q_{In} - Q_{Out}$$

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[5] Of the various water sources for P-MIP, only CAP water is included in the Decree Accounting and that water is accounted as having no return flows (e.g., Reclamation, 2021a).

In order to assess the impact of irrigation conveyance system improvements on CU, it is helpful to consider conveyance system losses (L_{Conv}), which can be defined as:

$$L_{Conv} = Q_{In} - Q_{Out} - F$$

where F is water delivered to farm turnouts in the area of interest (*Figure 6*). It is also helpful to compute the application efficiency (E_{Conv}), which can be defined as:

$$E_{Conv} = \frac{F}{Q_{In} - Q_{Out}} = 1 - \frac{L_{Conv}}{Q_{In} - Q_{Out}}$$

Because the service area of the irrigation system has changed from year to year, it is helpful to consider CU and L_{Conv} on a per-acre basis:

$$\frac{CU}{A_{Irr}} = \frac{Q_{In} - Q_{Out}}{A_{Irr}}$$

and

$$\frac{L_{Conv}}{A_{Irr}} = \frac{Q_{In} - Q_{Out} - F}{A_{Irr}}$$

where A_{Irr} is the area irrigated, which would be the area listed in the "then being irrigated" (TBI) acreage tracked by the Gila Water Commissioner (OGWC; 2021), which is intended to be only cropland that is irrigated[6].

The final ΔCU comparison is then:

$$\frac{\Delta CU}{A_{Irr}} = \frac{Q_{In}^{Before} - Q_{Out}^{Before}}{A_{Irr}^{Before}} - \frac{Q_{In}^{After} - Q_{Out}^{After}}{A_{Irr}^{After}}$$

where the superscripts *After* and *Before* are relative to the improvements. The final change in conveyance losses (ΔL_{Conv}) comparison is:

$$\frac{\Delta L_{Conv}}{A_{Irr}} = \frac{Q_{In}^{Before} - Q_{Out}^{Before} - F^{Before}}{A_{Irr}^{Before}} - \frac{Q_{In}^{After} - Q_{Out}^{After} - F^{After}}{A_{Irr}^{After}}$$

Changes in E_{Conv} can be made without dividing by A_{Irr}.

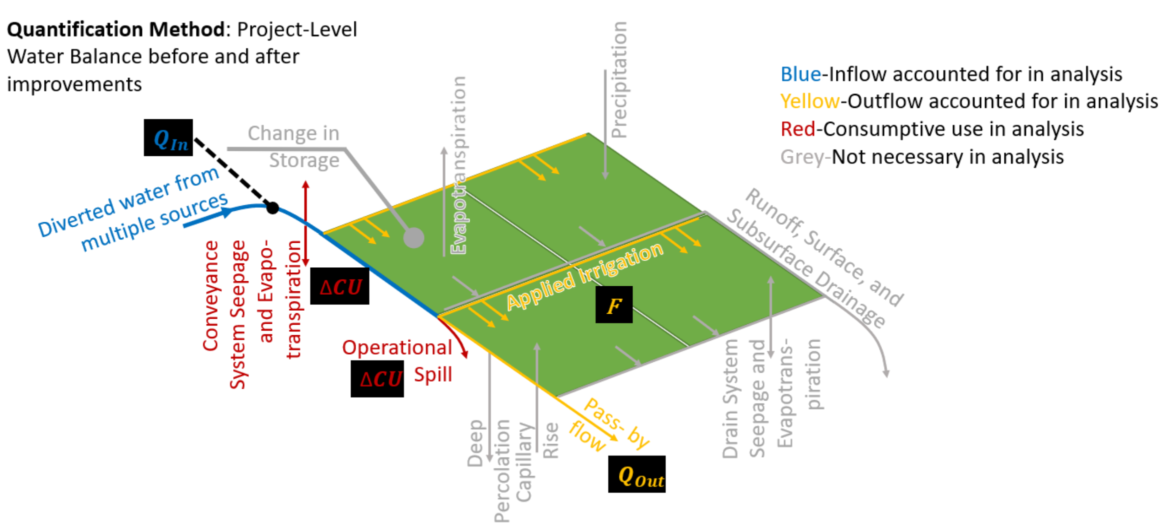
As mentioned, the ΔCU analysis was for subareas of the entire P-MIP system. The first and largest subarea was for the 50,000-acre SCIP-IW service area on Community lands starting at the Reservation boundary (this subarea is referred to as the Full System for simplicity). There are other GRIC lands served by P-MIP that are under GRIIDD that were not included. The system

[6] In the past, TBI acreage was computed as a percentage (85%-90%) of the leased area. However, in the "last two years," according to BIA (communication, August 31, 2021), the TBI acreage was delineated using a geographical information system (GIS) and was found to be about 85%-90% "in most cases."

improvements have not yet been completed for the Full System, therefore, the analysis was also performed for the Division 1 subarea, known as the Blackwater Area, for which improvements are complete. These improvements include the lining of the Pima Canal and a reconfiguration of secondary canals in the area to serve as laterals off the Pima, thus reducing the conveyance distance in unlined canals (*Figure 7*; *Figure 8*; BIA, communication, August 27, 2021). The comparisons were performed for the years 2010 and 2011, which were before many of the system improvements and 2019 and 2020, which were after many improvements.

For both studied areas, Q_{In} does not represent the system diversion, but rather the supply at the head of the respective service area, which is the Pima Canal at the Reservation boundary for the Full System and the heads of respective laterals for the Blackwater Area. Q_{In} also included any additional sources downstream of these locations (i.e., groundwater). In 2010 and 2011, there was some groundwater pumped into the laterals in the Blackwater Area, but in 2019 and 2020, groundwater in that area was only pumped into the Pima. For 2010 and 2011, half of the groundwater pumping in the Blackwater Area was assumed to contribute to the laterals in the area and half was assumed to discharge into the Pima. In 2019 and 2020, there were also some farm turnouts served directly from the Pima in the Blackwater Area, which was not the case in 2010 and 2011. Using the Reservation boundary as the starting point was selected because of the presence of flow measurement at that location and because the said location captures the effects of notable improvements, including some of the Pima Canal lining and, in the case of the Full System, the reconstruction of the Casa Blanca Canal. Notable improvements not included are the portion of the Pima Canal upstream of the Reservation boundary (fully improved and concrete lined with new checks and control structures) and the new Florence Canal, which is not yet completed, and which is located upstream of the Reservation boundary[7].

Figure 6 Simplified Representation of the Project-Level Water Balance Approach for Quantifying CU Reductions for the Pima-Maricopa Irrigation Project Infrastructure.



$$\frac{\Delta CU}{A_{Irr}} = \frac{Q_{In}^{Before} - Q_{Out}^{Before}}{A_{Irr}^{Before}} - \frac{Q_{In}^{After} - Q_{Out}^{After}}{A_{Irr}^{After}} \qquad \frac{\Delta L_{Conv}}{A_{Irr}} = \frac{Q_{In}^{Before} - Q_{Out}^{Before} - F^{Before}}{A_{Irr}^{Before}} - \frac{Q_{In}^{After} - Q_{Out}^{After} - F^{After}}{A_{Irr}^{After}}$$

[7] It is known that there are significant seepage losses of water between Coolidge Dam and the Reservation, some of which will be reduced by the Florence Canal project. All CAP water is conveyed in the Pima Canal. Gila River diversions will still be subject to losses in the Gila River between Coolidge Dam and the Ashurst-Hayden Diversion Dam.

The Q_{Out} would differ for the two studied areas. For the Blackwater Area, Q_{Out} would be the outflow from lateral canals back into the Pima Canal in 2010 and 2011. There was no Q_{Out} from the Blackwater area in 2019 and 2020 because there was no longer any return to the Pima. For the Full System, Q_{Out} would be zero in all cases because, according to a communication from the BIA, no SCIP-IW water was delivered to the GRIIDD managed portion of P-MIP in the study years, and operational spill is considered CU for this project. Therefore, the $\Delta CU/A_{Irr}$ for the Full System was computed as:

$$\frac{\Delta CU}{A_{Irr}} = \frac{Q_{In}^{Before}}{A_{Irr}^{Before}} - \frac{Q_{In}^{After}}{A_{Irr}^{After}}$$

and $\Delta L_{Conv}/A_{Irr}$ was computed as:

$$\frac{\Delta L_{Conv}}{A_{Irr}} = \frac{Q_{In}^{Before} - F^{Before}}{A_{Irr}^{Before}} - \frac{Q_{In}^{After} - F^{After}}{A_{Irr}^{After}}$$

Figure 7 Simplified Representation of the Pima-Maricopa Irrigation Project Infrastructure (Blue Lines), Gila River Indian Community, San Carlos Irrigation Project Indian Works Service Area (Full System Area), and the Blackwater Area (Derived from Figure 2 and BIA Communication).

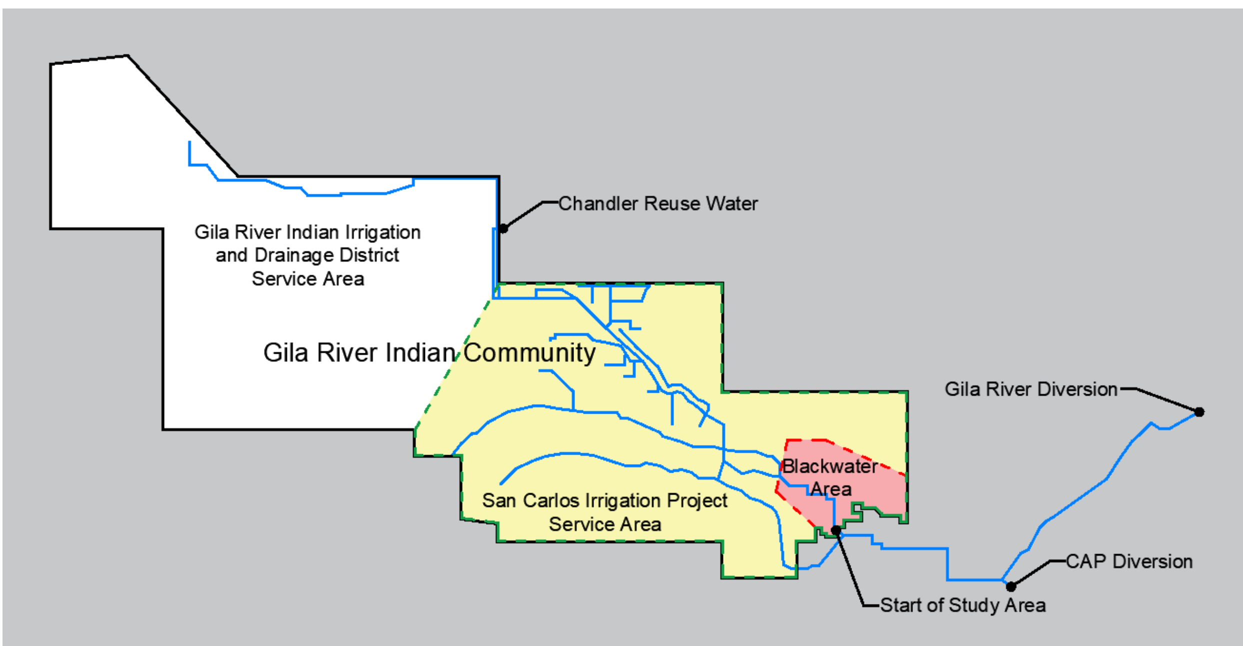


Figure 8 Photo of a Field in the Blackwater Area (Credit: B. Barker, May 24, 2021).

CU Results

Supply and service area data were provided by BIA SCIP staff for the Full System starting at the Reservation boundary. Improvements are ongoing for the full project, therefore supply and service area data were also provided for the Blackwater Area (*Figure 2*; *Figure 7*), for which improvements are complete. The Full System was about 24,800 irrigated acres in 2010-2011, effectively before any P-MIP improvements within the SCIP-IW system (*Table 2*). The service area was about 17,200 irrigated acres in 2019-2020, which was after many improvements. The total CU/A_{Irr} varied notably between the two years before the P-MIP improvements; being 8.7 AF per acre (AF/ac) in 2010 and 6.9 AF/ac in 2011. However, the total F/A_{Irr} was similar for both years (about 4.7 AF/ac). The estimated L_{Conv} was about 4.0 AF/ac in 2010 and 2.2 AF/ac in 2011. The estimated E_{Conv} for the portions of the system on the Reservation varied accordingly from about 54% in 2010 to 69% in 2011. Since this was prior to most of the system improvements, the difference may be a result of management practices.

After the improvements were made, the CU/A_{Irr} for the Full System was about 8.3 AF/ac in 2019 and 10.3 AF/ac in 2020. The total F/A_{Irr} was about 5.7 AF/ac in 2019 and 6.0 AF/ac in 2020. The estimated L_{Conv} was about 2.6 AF/ac in 2019 and 4.3 AF/ac in 2020. Both the $\Delta CU/A_{Irr}$ and $\Delta L_{Conv}/A_{Irr}$ were negative (indicating an increase in both CU/A_{Irr} and L_{Conv}/A_{Irr} for the Full System from 2010 and 2011 to 2019 and 2020). On average, $\Delta CU/A_{Irr}$ was -1.5 AF/ac for an increase in CU/A_{Irr} of about 19% from 2010-2011 to 2019-2020. The $\Delta L_{Conv}/A_{Irr}$ was about -0.33 AF/ac representing an increase of about 11% in L_{Conv}/A_{Irr} from 2010- 2011 to 2019-2020. These increases could be a result of the decreased farmed area, changes in cropping practices, changes in on-farm irrigation management, increased irrigation adequacy of farm deliveries (if deliveries were insufficient prior to improvements), and/or improved measurement accuracy. The E_{Conv} for the Full System was about 69% in 2019 and 58% in 2021, or about 2.6 percentage points greater, on average, than in 2010-2011, prior to the improvements. These differences are subject to the data quality and completeness[8], analysis assumptions, and partial build-out nature of the project.

The ΔCU values for the Full System were compared to the ΔCU for the Blackwater Area, for which P-MIP improvements have been completed. The Blackwater Area is about 1,400 acres in size

[8] There was "major concern" from SCIP regarding the 2010 and 2011 "data quality" including the irrigated acreage.

(*Table 3*). The total CU/A_{Irr} for the Blackwater Area was about 9.4 AF/ac in 2010 and 11.0 AF/ac in 2011. This is compared to about 4.4 AF/ac for both 2019 and 2020. On average, the $\Delta CU/A_{Irr}$ was 5.8 AF/ac, or about a 57% decrease from 2010-2011 to 2019- 2020. In contrast to the full system, the F/A_{Irr} was similar before and after the improvements were made. In 2010, F/A_{Irr} in the Blackwater Area was about 3.8 AF/ac, and in 2011, it was 3.9 AF/ac. In 2019, the total water turned out to farms was about 3.8 AF/ac and in 2010 it was 3.5 AF/ac. The combined effect of these changes in F/A_{Irr} and the $\Delta CU/A_{Irr}$ was that L_{Conv}/A_{Irr} was reduced from about 5.6 AF/ac and 7.2 AF/ac in 2010 and 2011, respectively to 0.6 AF/ac and 0.9 AF/ac in 2019 and 2020, respectively. The resulting $\Delta L_{Conv}/A_{Irr}$ was about 5.6 AF/ac, on average, or a decrease of about 88%.

The E_{Conv} for the Blackwater Area was estimated to be about 41% in 2010 and 35% in 2011. This increased notably after the improvements to 86% in 2019 and 79% in 2020, for an improvement of about 45 percentage points, on average (*Table 3*). This apparently clear improvement is subject to the methods and assumptions used in the analysis (*Table 2*). However, with this caveat in mind, the efficiency improvement for the Blackwater Area is much greater than observed for the full system.

Table 2 Summary of Water Use for the Pima-Maricopa Irrigation Project (P-MIP) Service Area within the Gila River Indian Community Before and After P-MIP Improvements (Full System; Data Provided by BIA).

Year	Irrigated Area[1]	Total Water Supplied (Q_{In}-Q_{Out}=CU)[2]		Total Water to Farms (F)[3]		Conveyance Losses (L_{Conv})		Efficiency[4] (E_{Conv})
	(acre)	(AF	(AF/ac)	(AF)	(AF/ac)	(AF)	(AF/ac)	
Before P-MIP Improvements[5]								
2010	24,782	216,526	8.74	116,825	4.71	99,701	4.02	54.0%
2011	24,857	171,473	6.90	117,572	4.73	53,901	2.17	68.6%
Average	24,819	193,999	7.82	117,198	4.72	76,801	3.10	60.4%
After P-MIP Improvements for Casa Blanca and Pima Canals[5]								
2019	17,188	141,837	8.25	97,746	5.69	44,091	2.57	68.9%
2020	17,250	177,435	10.29	103,454	6.00	73,981	4.29	58.3%
Average	17,219	159,636	9.27	100,600	5.84	59,036	3.43	63.0%
Before - After (AF/ac)[6]		$\Delta F/A_{Irr}$	**-1.45**	$\Delta CU/A_{Irr}$	**-1.12**	$\Delta L_{Conv}/A_{Irr}$	**-0.33**	**-2.61%**
Before - After (%)[6]		$\Delta F/A_{Irr}$	**-18.6%**	$\Delta CU/A_{Irr}$	**-23.7%**	$\Delta L_{Conv}/A_{Irr}$	**-10.7%**	**-4.32%**

[1]Then being irrigated" area (see OGWC, 2021), which is intended to only be irrigated crop area.

[2]Total supply is gross supply in the Pima Canal at the Community boundary plus the gross supply from all other water sources that enter the system downstream of that location. This, therefore, is not a total gross diversion value, because it does not account for losses upstream of the Community boundary. Quantities are based upon flow measurement records. This includes Gila River water, SRP, reclaimed municipal water, and groundwater. CAP water was only included in the 2019 and 2020 values, because data were not available for 2010 and 2011 (SCIP, communication August 27, 2021).

[3]Total farm-turnout water is the net delivered water used in the analysis. Based upon water orders, nominal delivery flow estimates and duration.

[4]Conveyance efficiency for the respective subarea computed as Total Water Turned Out to Farms/Total Water Supplied to Area.

[5]Before P-MIP improvements means before any P-MIP infrastructure improvements. After P-MIP improvements means after the lining of the Pima Canal and the reconstruction of the Casa Blanca Canal and some of the laterals in the Casa Blanca system. There were also some on-farm improvements during this time (e.g., *Table 1*).

[6]Before P-MIP improvements minus after P-MIP improvements. The percentage change = (before – after)/before.

The difference in E_{Conv} before and after the system improvements is apparent, as is the difference in E_{Conv} when considered at different spatial scales. It should be remembered that the E_{Conv} values that are presented here are not relative to the diversion works, but to the Reservation boundary and that additional system losses occur upstream of the areas included in this analysis. However, according to P-MIP, CAP losses are expected to be small since the ditch is concrete lined.

The differences between the Full System and Blackwater Area results are evidence both of the impact of the relative completeness of the improvements and of the study area scale. The relative completion of the improvements is represented because the Full System, while benefitting from major improvements like the Casa Blanca and Pima Canals, is incomplete; while improvements for the Blackwater Area, which is upstream of the Casa Blanca Canal, are complete. The Blackwater Area is also smaller than the Full System and is located at the head end of the Full System. Therefore, the distance that water must travel in canals to serve the average farm turnout in the Blackwater Area is shorter than for the Full System. This shorter travel time will tend to reduce conveyance losses. Therefore, the Blackwater area is expected to have greater E_{Conv}, on average, than the Full System.

Table 3 Summary of Water Use for the Blackwater Area Before and After Pima-Maricopa Irrigation Project Improvements (Data Provided by BIA).

Year	Irrigated Area[1]	Total Water Supplied (Q_{In}-Q_{Out}=CU)[2]		Total Water to Farms (F)[3]		Conveyance Losses (L_{Conv})		Efficiency[4] (E_{Conv})
	(acres)	(AF)	(AF/ac)	(AF)	(AF/ac)	(AF)	(AF/ac)	
Before P-MIP Improvements[5]								
2010	1,405	13,180	9.38	5,344	3.80	7,836	5.58	40.5%
2011	1,398	15,430	11.03	5,406	3.87	10,024	7.17	35.0%
Average	1,402	14,305	10.21	5,375	3.83	8,930	6.37	37.6%
After P-MIP Improvements[5]								
2019	1,255	5,539	4.42	4,776	3.81	763	0.61	86.2%
2020	1,074	4,702	4.38	3,723	3.47	979	0.91	79.2%
Average	1,165	5,120	4.40	4,250	3.64	871	0.76	83.0%
Before - After (AF/ac)[6]		**$\Delta F/A_{Irr}$**	**5.81**	**$\Delta CU/A_{Irr}$**	**0.20**	**$\Delta L_{Conv}/A_{Irr}$**	**5.61**	**-45.42%**
Before - After (%)[6]		**$\Delta F/A_{Irr}$**	**56.9%**	**$\Delta CU/A_{Irr}$**	**5.2%**	**$\Delta L_{Conv}/A_{Irr}$**	**88.1%**	**-120.88%**

[1]Then being irrigated" area (see OGWC, 2021), which is intended to only be irrigated crop area.

[2]Total supply is for the heads of canals and laterals serving the Blackwater Area (plus groundwater pumping and minus returns to the Pima from Canals 3 and 4 in 2010 and 2011). This, therefore, is not a total gross diversion value. Quantities are based upon flow measurement records. In 2010 and 2011, Well discharge records did not specify whether wells discharged into canals serving just the Blackwater Area or the Pima Canal, which primarily conveyed water past the Area. The full discharge for two of the wells in the Area plus half of the discharge from all other wells were assumed not to be available for the Blackwater Area (SCIP, communication, August 17, 2021).

[3]Based upon water orders, nominal delivery flow estimates and duration.

[4]Conveyance efficiency for the respective subarea computed as Total Water Turned Out to Farms/Total Water Supplied to Area.

[5]Before P-MIP improvements means before any P-MIP infrastructure improvements in the Blackwater area. After P-MIP improvements means after the improvements. There may also have some on-farm improvements during this time (e.g., *Table 4*).

[6]Before P-MIP improvements minus after P-MIP improvements. The percentage is a percentage of the before P-MIP improvements conditions.

Anecdotal Evidence of CU Reduction

Prior to the present case study, the ΔCU had not previously been computed for the P-MIP improvements. However, evidence of the combined benefits of the P-MIP and on-farm improvements have been observed in the form of decreased water order durations as mentioned by a BIA SCIP representative during the site visit.

Discussion of Method Assumptions

The method used to quantify *ΔCU* does not represent the *ΔCU* for the entirety of P-MIP in terms of estimated differences in total diversion. In addition to this caveat, some assumptions relating to the methods and other implications of the conservation efforts were discussed above. Further discussions of method assumptions are provided in this section.

Assumption 1: *ΔCU* for periods with differing service areas can be represented using the ratio of *ΔCU* to "then being irrigated" land.

This assumption is reasonable, as a means of comparing conditions before and after major changes in irrigated area as in the case of P-MIP. From the perspective of GRIC, an increase in irrigated area is beneficial to the Community and therefore, the amount of water applied per acre irrigated is a valuable metric of system efficiency. Even more complete measures of efficiency would be in terms of crop yield or crop value.

However, system losses may not be proportional to the TBI acreage. This concept is discussed in further detail in the Bard Water District case study discussion. Further, this method of comparison includes the inherent assumption that the cropping patterns and irrigation water requirements were similar, for the average TBI acre, before and after the improvements were made and that the fraction of land that was double-cropped was also similar. These considerations are described in the discussion of Assumption 2 below.

Additionally, P-MIP includes multiple types of system improvements and the administrative changes with the O&M responsibilities of GRIIDD make it difficult or impossible to attribute *ΔCU* to specific actions. Only the aggregate effects can be evaluated.

Assumption 2: *ΔCU* resulting from efficiency improvements can be quantified by comparing diversion records before and after the improvements, assuming all else is equal.

The assumption that all else is equal after an efficiency improvement may- or may not- be accurate in practice. This is because *ΔCU* is still dependent upon the crops grown[9], crop timing, the area irrigated, and the irrigation water users' demand[10]. All of these things may change from season-to-season. This challenge is analogous to the situation faced in quantifying *ΔCU* for fallowed fields in some of the other case studies. This difficulty is further compounded by the addition of water sources and the expansion of the service area. It is also possible that lands served by the improved system are now more adequately supplied than they were previously, a condition which could result in increased CU.

Assumption 3: The diversion and delivery records in 2010 and 2011 were comparable to those in 2019 and 2020.

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[9] Crop reports were not available for 2010 and 2011, therefore, further discussion of cropping pattern differences was not possible.

[10] Changes in irrigation water demand may result from weather conditions, irrigation timing, or changes in on-farm efficiency, among other things. However, grower irrigation practices may also be tied to tradition or other factors and may not be well represented by crop evapotranspiration or other quantifiable conditions.

This assumption was known to not be fully satisfied because of the general increase in data availability, detail, and accuracy in 2019-2020 versus 2010-2011. For example, in 2010 and 2011, CAP delivery data were missing for the full system. For the Blackwater Area in 2010 and 2011, the disposition of well discharge was not documented; therefore, it was assumed that half of the well discharge was into laterals serving the Blackwater Area and half into the Pima Canal. The uncertainty associated with such an assumption is apparent. These deficiencies have been addressed and were not challenges for 2019 and 2020. However, the completeness of historical records, even those that are only a decade old, is a challenge for quantifying the benefits of conveyance system improvements.

Assumption 4: ΔCU can be represented by subareas of the total system.

This assumption is apparent with the inclusion of the Blackwater Area analysis. However, the Full System analysis is also a subdivision of the total system because the analysis only includes the system downstream of the GRIC Reservation boundary. This location is downstream of the diversion and, thus does not include losses in the system upstream of the boundary. Therefore, some portions of total ΔCU are not included. This includes not only the ΔCU associated with upstream improvements, but also the dependence of upstream losses on the downstream improvements. This is because system losses upstream of a given improvement may be dependent upon that improvement. The improvement may have affected the total diversion and losses would, in-turn, be dependent upon the diversion. Therefore, considering only downstream portions of the system does not provide a complete representation of ΔCU. The impact is difficult to assess, because it is related to the total diversion of Gila River water and also CAP water and the relative fraction of additional water sources within the Reservation.

Despite the stated limitations regarding the use of system subdivision to quantify ΔCU, the methods used are useful for assessing any ΔCU directly resulting from the system improvements in the areas studied. Caution should be used in this type of method for comparison when evaluating either volumetric ΔCU or changes in system conveyance efficiencies.

Assumption 5: For the anecdotal evidence of ΔCU: the change in duration of the irrigation turns is indicative of ΔCU.

Irrigation applications consist of both an applied flow of water and a duration of application. A reduced duration of a water turnout can be evidence of one or more of the following: 1) an increased flow at the farm turnout resulting from reduced canal losses, 2) increased flow at the farm turnout not resulting from reduced canal losses, 3) increased on-farm efficiency resulting in a lower irrigation water requirement, and 4) decreases in crop water requirements resulting from a change in crop type or variety, or changes in meteorological conditions (atmospheric demand).

It is evident that not all of these causes may be evidence of irrigation system conveyance or application efficiency improvements. However, it is expected that a widespread presence of reduced water turnout durations would more likely be evidence of widespread changes, of which the P-MIP improvements are the most evident.

Assumption 6: The mean of two years before improvements and two years after improvements is sufficient for computing ΔCU.

The CU, L_{Conv}, and E_{Conv} were all characterized for two years before P-MIP improvements and for the most recent two years as of the analysis to capture the effects of P-MIP improvements up to the time of the analysis. However, it is evident that considerable interannual variability exists in CU and L_{Conv}, making it difficult to separate conservation effects from the typical interannual noise. The selection was a practicality decided upon during the site visit. However, it generally could be considered that the more years prior to- and following improvements the better the quantification could be characterized.

The P-MIP system improvements have been comprehensive, multifaceted, and concurrent with other changes in the system including those to management and source water. This makes it difficult to attribute changes in efficiency to any one particular activity. For example, is canal lining a primary activity contributing to changes in efficiency? Is canal reconfiguration? Is increased automation and remote control? Is increased source reliability? This is a universal challenge for any project that includes multiple activities. To completely associate the activity with the corresponding change in efficiency would require performing only one activity at a time so that before and after comparisons could be made, which is obviously impractical for a major system rehabilitation and improvement project.

Considerations for Multiple-Source Systems

The P-MIP system includes multiple water sources, only one of which, CAP, is directly associated with the Colorado River mainstream[11]. In a mixed system, water conservation may be considered on the whole, as it is herein, or individually for each water source. For example, there may be specific incentive or need to prioritize conservation efforts for one source above another. When considering only one particular source, shifting water use to other supplies may be accounted as conservation, with CU for that source decreasing even if CU increases commensurately for other sources. It may also be necessary to ensure CU reductions for a given source without increasing CU from other sources. It should also be acknowledged that the conveyance efficiency between any one given source and the portion of the service area that it contributes to may differ from the efficiency between source and service area for other sources. For example, Gila River diversions must be conveyed to the Community through an extensive canal system to reach the average field. Conversely, a well located near the tail of the system will discharge into a canal relatively near the average field that it serves. This is even evident based on the different estimated efficiencies presented by GRIC and EcoPlan (1997) for Gila River water and CAP water under a scenario with no P-MIP improvements.

Reflections

The P-MIP system is complex, with multiple water sources, combined system improvements and expansions, and multiple types of system or administrative modifications. There are many lessons that can be learned from the P-MIP experience. One such lesson is regarding the feasibility of the project. P-MIP is a comparatively large project that has been made possible by the reliable and consistent funding associated with the Arizona Water Settlements Act (Public Law 108-451--December 10, 2004) and the GRIC Water Rights Settlement contained in Title II therein. Such funding has allowed for the extensive design, planning, and construction of the project.

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[11] Some of the municipal reclaim water may ultimately originate from CAP also.

GRIC has a commitment to pursue development and implementation of system improvements as a means of providing a resilient, reliable, and efficient irrigation system to serve GRIC's interests now and into the future.

In addition to the funding and infrastructure, the changes in system management, including the reduction in the number of organizations involved with the system O&M, provide not only increased water conveyance and use efficiency, but also potential efficiencies in administrative effort and expense.

For all of the possible and realized management and infrastructure benefits of the system, quantifying certain benefits, e.g., changes in CU, can be challenging. This is because the improvements include the addition of measurements and/or databases that were not available pre-improvement. Thus, CU for the improved system may be determined with accuracy and relatively little effort, but the pre-improvement conditions may be difficult or impossible to assess. This is somewhat of a universal challenge likely experienced by many water service providers.

Another observation relative to the system improvements concerns the interdependence of water sources and other systems. BIA (2021) provided anecdotal evidence of apparent decreased groundwater recharge from the canals now that they have been lined. This may indicate, as would be expected, that some of the groundwater that has historically been pumped into the system has been a recovery of seepage losses from the canals and that increasing efficiency may reduce another down-gradient water source. In this case, the responsible and affected parties may be the same. The Community has, however, begun on-Reservation recharge in an effort to balance groundwater extraction with groundwater recharge.

Finally, a consideration for improved assessment would be to conduct a *post facto* analysis of historical satellite images to model seasonal evapotranspiration (ET) representative of pre- and post-conservation measures. With this information, total modeled ET divided by total water supplies could be used as a composite metric for system-wide irrigation efficiency.

Bard Water District Seasonal Fallowing Program

Bard Water District (Bard) is located in southeastern California. The Bard Water District is part of the Yuma Project Reservation Division. The Reservation Division includes two subunits, which are the Bard Unit and the Indian Unit. The Indian Unit is comprised of Quechan Tribal lands, while the Bard Unit is comprised of non-Indian lands (*Figure 9*). Bard Water District serves both units, but in the present context will refer to specifically the Bard Unit. The Bard Unit serves about 7,120 acres of land (Bard, 2021).

Figure 9 Map of the Bard Water District (http://mwdh2o.granicus.com/MetaViewer.php?view_id=7&clip_id=1595&meta_id=43649).

Only the Bard Unit is participating in the seasonal fallowing program. The Bard seasonal fallowing program has been going, in different forms, since 2016. Bard first participated in a seasonal fallowing pilot program with the Metropolitan Water District of Southern California (MWD) in 2016 and 2017. Bard then participated in a pilot seasonal fallowing program with Reclamation for the 2018 and 2019 growing seasons and is now in a longer duration program with MWD for 2020 – 2026. The discussion herein will focus on the present program with MWD. Participating growers do not grow or harvest crops or irrigate fields from fallowed land during summer months (e.g., April 1 through July 31). Thus, this program is a seasonal (partial-year) fallowing program, enabling growers to grow crops during the rest of the year. MWD uses the conserved water for diversion or Lake Mead storage (Businesswire, 2019).

The maximum fallowable land each year is 3,000 acres (MWD, 2019a). The fallowing agreements are between MWD the respective grower, and the district. MWD pays each grower a flat rate based upon the area fallowed (each fallowed area must be 10 contiguous acres or greater), not water conserved. MWD also pays Bard a flat rate to cover administrative costs (25% of the MWD payment for the fallowed land) and a per-acre rate that is to be used for district infrastructure improvements. The latter, among other things, was beneficial in obtaining the consent of growers not participating in the program.

Technical Analysis

A technical analysis of the Bard seasonal fallowing case study is presented in the following sections.

CU Quantification Methods

Reductions in CU, resulting from fallowing, are estimated using the principles of a project-level water balance (TM2). These estimates are based on Reclamation's Decree Accounting (e.g., Reclamation, 2021a; MWD, 2021a).

The CU estimates for the Bard seasonal fallowing program are based upon Reclamation's Decree Accounting (e.g., Reclamation, 2021a) for the YPRD (MWD, 2021a), which includes both the Bard Unit and the Indian Unit of the YPRD. In the Decree Accounting, diversions, unmeasured return flows, and a portion of the measured return flows are reported by Unit. However, large fractions of the total return flows are measured in a shared drain and are, thus, not divided between the two units. These measured flows are referred to as "unassigned" returns (Reclamation, 2021a).

In the CU estimates for the Bard fallowing program, the unassigned returns are divided between the two irrigation units based on the total fraction of measured and unmeasured returns for each unit as:

$$R_{Tot}^{Bard} = R_{Meas}^{Bard} + R_{Unmeas}^{Bard} + R_{Meas}^{Unassigned}\left(\frac{R_{Meas}^{Bard} + R_{Unmeas}^{Bard}}{R_{Meas}^{Bard} + R_{Unmeas}^{Bard} + R_{Meas}^{Indian} + R_{Unmeas}^{Indian}}\right)$$

where *R* is return flows, the superscripts refer to the unit to which the flows were assigned and the subscripts *Tot*, *Meas*, and *Unmeas* represent total, measured, and unmeasured, respectively. Following the Decree Accounting, CU is then computed as:

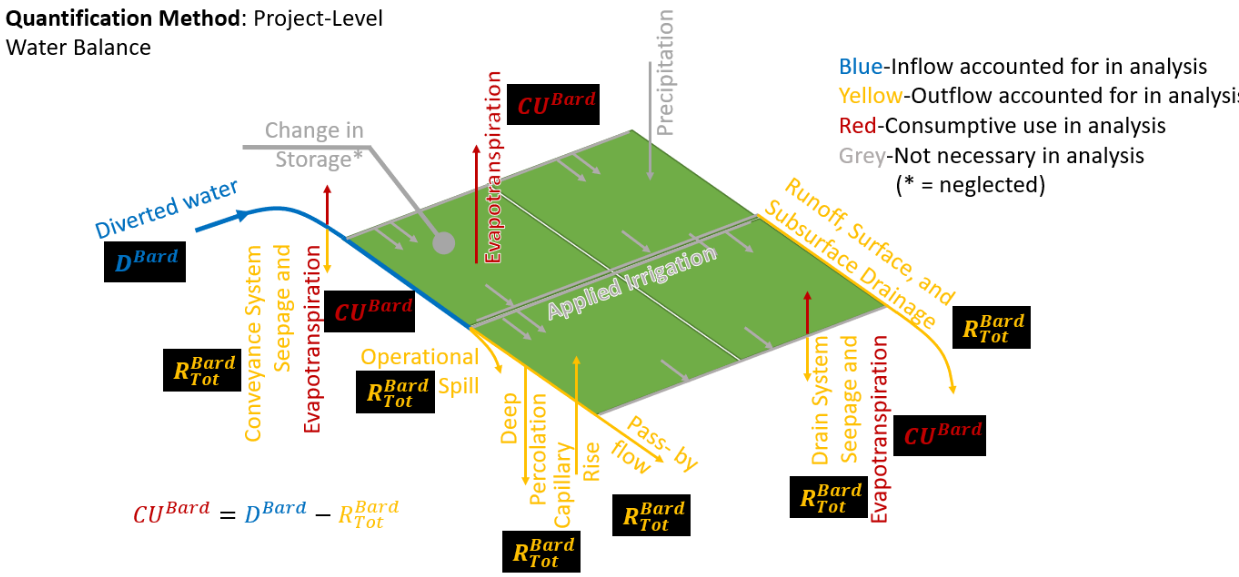
$$CU^{Bard} = D^{Bard} - R_{Tot}^{Bard}$$

where *D* is diversion, and subscripts and superscripts were as previously defined (see also *Figure 10*). The ΔCU for fallowing can then be computed as:

$$\Delta CU = A_{Fallow}^{Bard}\left(\frac{CU^{Bard}}{A_{Irr}^{Bard}}\right)$$

where A_{Fallow}^{Bard} is the fallowed area in the Bard Unit, A_{Irr}^{Bard} is the irrigable area of the Bard Unit (i.e., area that *could* be irrigated, excluding fallowed area) during the fallow period, and the ratio (CU^{Bard}/A_{Irr}^{Bard}) may be referred to as the consumptive use factor. A mean water savings factor is calculated for the fallowing period based on historical data, and the final ΔCU is calculated as the mean consumptive use factor multiplied by the April – August fallowed area. For example, for 2020, the five-year mean CU^{Bard}/A_{Irr}^{Bard} for 2016 – 2020 was multiplied by the 2020 A_{Fallow}^{Bard} to compute ΔCU.

Figure 10 Simplified Representation of the Project-Level Water Balance Approach for Quantifying Consumptive Use Reductions for the Bard Water District Seasonal Fallowing Program.



Fallowed Land Delineation Methods

Another important aspect of the CU quantification for the Bard seasonal fallowing program is the delineation of irrigated lands. This delineation is done by MWD personnel. The areas used to represent the irrigable land both participating in and not participating in the fallowing program (A^{Bard}_{Fallow} and A^{Bard}_{Irr}, respectively) are mapped to exclude roadways, ditches, and other non-farmed areas (according to MWD, ca. May 25, 2021). This likely represents the most time-consuming task in this CU quantification method.

Example CU Results

Two of the benefits of this methodology are: 1) it is tied to the Decree Accounting methods, and 2) it is relatively simple to execute (e.g., MWD, 2021a). The series of calculations necessary to compute the consumptive use factor for a given year can easily be done in a spreadsheet and displayed in a table (*Table 4*). For 2020, an area weighted, five-year average consumptive use factor was used to compute ΔCU (*Table 5*). The mean consumptive use factor was 2.21 AF/ac and the total ΔCU was 6,075 AF.

Table 4 Consumptive Use Factor Estimates for the Bard Water District Seasonal Fallowing Program, 2020.

Description	Apr	May	Jun	Jul	Aug	Total
Diversions, Bard Unit (AF)[1]	3,393	3,599	3,277	2,774	3,325	16,368
Returns, Measured, Assigned to Bard Unit (AF)[1]	29	14	49	41	60	193
Returns, Unmeasured, Assigned to Bard Unit (AF)[1]	567	601	547	463	555	2,733
Returns, Measured, Assigned to Indian Unit (AF)[1]	108	46	108	70	128	460
Returns, Unmeasured, Assigned to Indian Unit (AF)[1]	1,077	990	670	456	680	3,873
Bard Unit Fraction of Unassigned Returns[2]	0.33	0.37	0.43	0.49	0.43	0.40
Returns, Measured, Unassigned, Both Units (AF)[1]	2,146	2,545	2,522	1,997	1,906	11,116
Returns, Measured, Unassigned, Bard Unit (AF)[2]	718	948	1,094	977	824	4,561
Returns, Total, Bard Unit (AF)[2]	1,314	1,563	1,690	1,481	1,439	7,487
Consumptive Use, Bard Unit (AF)[2]	2,079	2,036	1,587	1,293	1,886	8,881
Irrigable Area, Bard Unit (ac)[2]	3,823	3,823	3,823	3,823	3,823	3,823
Consumptive Use Factor, Bard Unit (AF/ac)[2]	0.54	0.53	0.42	0.34	0.49	2.32
Fallowed Area, Bard Unit (ac)[2]	2,749	2,749	2,749	2,749	2,749	2,749
Consumptive Use Reduction, Fallow, Bard Unit (AF)[2]	1,495	1,464	1,141	930	1,356	6,385

[1]Source: Reclamation (2021a)
[2]Taken from, or based upon, MWD (2021a).

Table 5 Consumptive Use Reduction (ΔCU) Estimates for the Bard Water District Seasonal Fallowing Program, 2020 (MWD, 2021a).

Year	Area Fallowed (acres)	Reported CU Factor (AF/ac)
2016	509	1.87
2017	1,641	2.32
2018	973	1.99
2019	1,984	2.14
2020	2,749	2.32
Area-Weighted Mean	1,571	2.21
------------- 2020 ΔCU -------------		
2020 Fallowed Area (ac)		2,749
2020 ΔCU (AF)		6,075

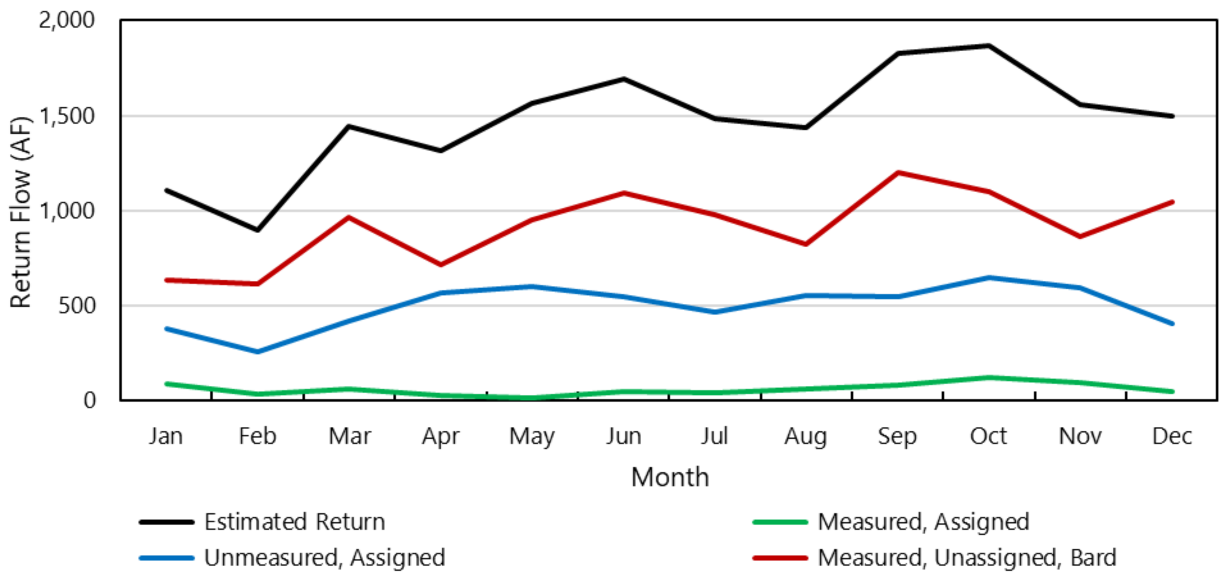
Discussion of Method Assumptions

The ΔCU method includes several assumptions, which are either explicit or implicit in the method. The primary assumptions are discussed below.

Assumption 1: The unassigned return flows are proportional to the total assigned return flows for the two respective units.

The need for this assumption is apparent. It is necessary, for the purposes of the seasonal fallowing program CU quantification, to attribute a fraction of those unassigned flows to the Bard Unit. Some possible options for estimating the Bard Unit portion of the unassigned flow include basing the proration on respective diversions, measured return flows, measured and unmeasured return flows (the method selected by MWD), and service areas. The impact of this assumption is not trivial because the unassigned return flows make up the majority of the estimated returns for the Bard Unit (*Figure 11*).

Figure 11 Estimated Return Flows for the Bard Unit, 2020 (Reclamation, 2021a; MWD, 2021a).

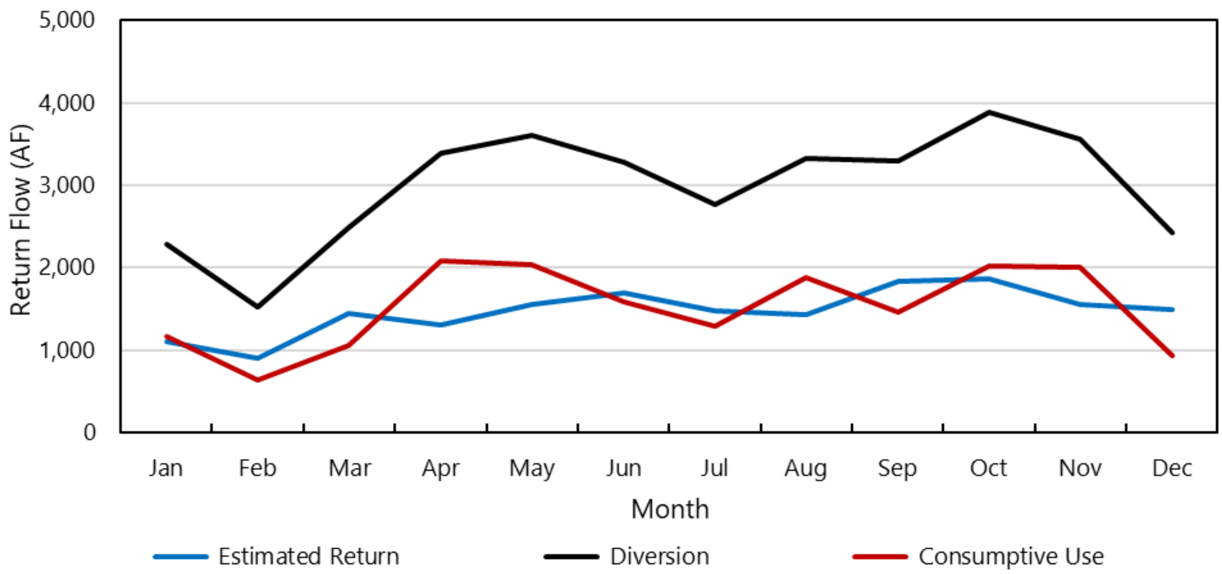


Assumption 2: There is no effective lag in the return flows.

This assumption is implicit in using return flows estimated for the same reporting period as the diversion flows. In reality, it takes water some time to travel through the irrigation system and then return to the river. The amount of time involved could be quite short, in the case of spills back to the river from the canal system, or it could be longer for some drainage water. This is because drainage water must percolate below the root zone and then flow laterally though soil to a drain or the river. Thus, some fraction of the return flows will have originated from pre-fallowing diversions and conversely, some water from diversions during the fallow period will be expected to return to the river post-fallowing.

For the measured returns, the duration of the lags and the associated impact would be difficult, if not impossible, to fully assess. Furthermore, neglecting these lags is inherent in the Decree Accounting methodology. For the unmeasured return, the effect of lag is essentially accounted for because return flows are computed as a fraction of the diversion (17% of the diversion for the Bard Unit throughout the year; Reclamation, 2021a). This is, of course, assuming that the estimated fraction of unmeasured return flow is accurate for each month, and, in this case, that it is consistent throughout the year. Based on a plot of estimated diversions, returns, and CU, for the Bard Unit in 2020 there is possible, but not clear, visual evidence of some return flow lag (*Figure 12*). This possible evidence is the difference between the timing of relative peaks in the diversion and return flow curves. However, if such a lag exists, as might be expected, the evidence is not strong. As with other assumptions, this is a practical solution to a theoretically complicated problem.

Figure 12 2020 Estimated Diversion, Return Flows, and Consumptive Use for the Bard Unit, 2020 (Reclamation, 2021a; MWD, 2021a).



Assumption 3: The *ΔCU* for the fallow fields is proportional to the Bard Unit-wide CU divided by the area irrigated during the fallow period.

This assumption includes the concept that the crops, or at least CU, would be similar in the fallow fields, if irrigated, as it was in the non-fallowed areas of the Bard Unit. In this assumption, any evaporation from the fallowed fields is neglected.

A common difficulty in quantifying *ΔCU* for any conservation activity is estimating what the CU would have been if the activity had not been practiced. The difficulty associated with this is partly addressed by aggregating the conservation for all of the fallowed fields together, rather than speculating what *ΔCU* would be for each, individually. However, it is impossible to know what growers would have done had they not fallowed. For example, growers may specifically elect to fallow instead of planting certain low-return crops. Or they may elect to fallow instead of growing crops that increase the difficulty of land preparation (seedbed preparation) for the winter cash crop season, as was related by one grower during the site visit.

Furthermore, the Bard Unit has a notable fraction of land that is used to produce permanent crops. These areas are not likely to be fallowed. Thus, these areas would not be representative of the *ΔCU* for the fallowed land. To illustrate this point, a total of 1,528 acres in the Bard Unit were reported to be planted to permanent crops (dates and citrus), with the majority of that area (1,499 acres) being dates (*Table 6;* Bard, 2021). The total irrigable area of the unit was reported to be 6,899 acres (Bard, 2021). Thus, about 22% of the Unit's irrigated land was estimated to be in permanent crops in 2020. The total irrigable area used by MWD when computing *ΔCU* was 6,572 acres with about 2,749 acres fallowed in 2020. This left about 3,823 acres of land (58%) not being fallowed. If 22% of the irrigable land in the unit was permanent crops and 58% of the land was not fallowed, then about 38% (22% × 100% ÷ 58% = 38%) of the non-fallowed land was in permanent crops.

The actual impact of the permanent crops on the ΔCU is dampened when CU, not acreage is considered. To illustrate this point, estimates of crop ET (ET_c) were made using the reference ET and crop coefficient method using methods similar to the *Lower Colorado River Annual Summary of Evapotranspiration and Evaporation* (e.g., Reclamation, 2019b; *Table 7*). Short crop reference ET (ET_o), computed using the American Society of Civil Engineers Standardized Reference Evapotranspiration Equation (ASCE, 2005), was obtained for the Arizona Meteorological Network (AZMET; UA, 2021) used in Reclamation (2019b)[12]. The ET_o was then averaged across the three sites as in Reclamation (2019b). Crop coefficients were obtained from Jensen (2003). For crops assumed to be summer crops, the areal-weighted average ET_c was 33.9 inches for April – August if permanent crops were included and 29.2 inches if permanent crops were excluded (*Table 7*). Thus, the effect of permanent crops on ET_c was a (33.9 inches – 29.2 inches) / 29.2 inches × 100% = 16% increase. The exact effect for the Bard Unit may differ from this illustration. Addressing the effect of the permanent crops would require some means of estimating ΔCU only for irrigated fields that did not have permanent crops.

Table 6 Cropped Areas from Bard Unit Crop Report, 2020.

Crop	Area (acres)	Season
Bok Choi	5	Winter
Broccoli	1,751	Winter
Cabbage	9	Winter
Cauliflower	984	Winter
Celery	496	Winter
Cilantro	51	Winter
Citrus	29	Summer
Cotton	819	Summer
Dates	1,499	Summer
Fennel	38	Winter
Greens (Kale)	185	Winter
Lettuce	4,035	Winter
Onion (Dry)	197	Winter
Other Forage (Napa)	55	Winter
Other Hay (Sudan)	970	Summer
Pasture	67	Summer
Spinach	135	Winter
Sugar Beet	22	Summer
Watermelon	117	Summer
Wheat	1,421	Summer
Total Bard Unit Area	7,120	---
Total Irrigable Area	6,899	---

Source (including crop titles): Bard (2020).

[12] These stations were Yuma North Gila, Yuma South, and Yuma Valley.

Table 7 Illustrative Crop Evapotranspiration Estimates for Crops Grown in the Bard Unit, April 1 – August 31, 2020 to Demonstrate the Potential Impact of Permanent Crop Evapotranspiration on Consumptive Use Estimates.

Reported Crop[1]	**Cotton**	**Other Hay (Sudan)**	**Pasture**	**Sugar Beet**	**Water-melon**	**Wheat**	**Citrus[3]**	**Dates[3]**	**Total or Average**	**Total or Average Excluding Permanent Crops**
Modeled Crop[2]	**Cotton**	**Sudan Hay**	**Bermuda …**	**Sugar Beet**	**Melon, Spring**	**Small Grains[4]**	**Citrus, Mature**	**Dates**		
Area (acres)	*819*	*970*	*67*	*22*	*117*	*1,421*	*29*	*1,499*	4,944	3,416
Month	**Estimated Crop ET (inches)**									
April	4.0	6.5	2.9	1.7	6.6	7.4	2.9	6.7		
May	3.5	8.7	7.2	6.3	7.9	6.0	5.1	8.6		
June	6.6	10.8	8.1	0.0	0.0	0.0	5.5	9.4		
July	10.2	11.8	8.8	0.0	0.0	0.0	5.9	10.1		
August	11.5	10.9	8.5	0.0	0.0	0.0	5.8	9.9		
Total	35.8	48.7	35.5	8.0	14.6	13.4	25.2	44.7	**33.9**	**29.2**

[1]Source: Bard (2020)
[2]Source: Jensen (2003)
[4]Permanent crop.
[3]The crop coefficient curve was temporally scaled and shifted based upon reported experimental planting and harvest dates in Ottman (2014).

Technically, there is some quantity of evaporation from the bare soil during the fallow period that would either increase the irrigation requirement or decrease the return flows at the end of the period. This ΔCU method neglects evaporation from the fields during the fallow period, or it is otherwise assumed that bare soil evaporation is accounted for. Any soil evaporation from the irrigated lands is accounted for in the Decree Accounting of CU. In computing ΔCU, the evaporation from rainfall is not important, because the ΔCU of interest is that derived from irrigation water and the Decree Accounting definition of CU is diversions less return flows. Therefore, the methodology implicitly accounts for precipitation on the irrigated lands. Furthermore, precipitation is small enough that it is generally negligible. For example, in 2020, there was a measured average of 0.4 inches of rainfall[13].

Of greater note than precipitation is the practice of irrigating the fallowed fields prior to fallowing in an effort to produce a soil crust to reduce wind erosion (*Figure 13*). Depending on the timing of this practice, the evaporation of water from this application may or may not be negligible during the fallow period. Growers also sometimes cultivate the fields in an effort to kill weeds that may contribute ET during the fallow period (*Figure 14*), though this practice is expected to have a negligible effect on total evaporation.

[13] This is averaged across the available records for the three previously cited AZMET stations and four National Oceanic and Atmospheric Administration (NOAA) climate stations used by Reclamation (2019) (NOAA, 2021a,b; UA, 2021). The NOAA stations were: Yuma MCAS, Yuma 13.8 ESE, Yuma Quartermaster Depot, and Yuma Proving Ground. This rainfall all effectively occurred between April 8 – April 11, 2020, inclusive. An average of <0.01 inches also was estimated for August 18, 2020 (precipitation was recorded at only one station for this event).

Figure 13   Photo of a Bard Fallowed Field with a Soil Crust (credit: B. Barker, May 25, 2021).

Figure 14   Photo of a Bard Fallowed Field Cultivated for Weed Control (credit: B. Barker, May 25, 2021).

Assumption 4: The reduction in ET from field ditches, canals, and drainage ditches resulting from fallowing is proportional to the fallowed land in comparison with the irrigated land.

It is also important to consider the assumption that the reduction in ET (incidental CU including in-ditch water evaporation, seepage, canal loss, and phreatophytes) from field ditches, canals, and drainage ditches resulting from fallowing) would be proportional to the area fallowed in relation to the irrigated area. This assumption would neglect any ET during the drying up of farm ditches and any service laterals that are not used during the fallow program. Under this assumption, the ET from the canal and drainage systems would be proportional to the area served, or to the water conveyed. This may not be entirely accurate as vegetative growth along many of the ditch banks may be similar with or without the fallowing program. Evaporation from the conveyed water itself and from the ditch banks may also not be proportional to the delivered volume of water, but evaporation is often considered a negligible conveyance loss.

Assumption 5: Any carry-over effects of fallowing on CU are negligible.

This assumption is directly related to the assumption that the CU from fallowed land and the associated ditches is negligible. This assumption is valid so long as evaporation from the fields and the dried-up ditches can be considered negligible during the fallow period.

Assumption 6: The CU of irrigated crops for a fallow period that includes partial calendar months (e.g., April 15 – August 15) can be represented by the CU estimated for the respective full calendar months (e.g., April 1 – August 31).

This assumption is only relevant for some years of the program. For example, in 2018, the fallow period was April 15 – August 15, but the CU computation period was April 1 – August 31 (*Table 8*). A similar condition is observed for 2020; however, the fallow period was full months (April 1 – July 31), but the CU computation period was April 1 – August 31. This assumption for some fallowing years, is likely a practicality of working with the Decree Accounting CU values, which are provided as monthly values (Reclamation, 2021a). For years like 2020, the assumption may be a carryover for consistency with other fallowing program years or in acknowledgment of prolonged lack of irrigation outside of the following period resulting from farming logistics. However, the difference could effectively add an additional month to the CU computation period (e.g., April 1 – August 31 vs. April 15 – August 15). This, of course, is assuming that there would be irrigation and ET in the non-fallowed fields during the entire additional included time; such may be the case only a portion of that time.

The effect of this assumption can be demonstrated by using the same analysis presented in *Table 7*, but with monthly summations based on the April 15 – August 15. This example analysis was performed for 2020 data for illustration. Based on this analysis, the ET_c for April 15 – August 15 may be roughly 80% of that for April 1 – August 31 (*Table 9*). Coincidentally, the length of time from April 15 – August 15, inclusive, is about 80% of the length of time from April 1 – August 31, inclusive. The actual impact of this assumption would depend upon the planting, growth, harvest, precipitation, and irrigation in the irrigated fields during the added CU-period, i.e., April 1 – April 14 and August 16 – August 31 in this example.

One possible method of adjusting ΔCU to approximate the fallowing period is to prorate the monthly ΔCU values based on the number of days of each respective month included in the actual fallowing period, where necessary. If this were done, the ΔCU would be less than that used by MWD (2021a) for all years except 2016 (*Table 9*).

For 2020, an area-weighted mean ΔCU for the different fallow years was used. However, the period included in the mean varied among years. If the mean were computed over the April 1 – July 1 period for all years (matching the 2020 fallowing period), then the ΔCU would be 0.33 to 0.40 AF/ac less than the value used by MWD (2021a), depending on whether an area-weighted mean or an arithmetic mean were used[14].

[14] See Footnote 6 in *Table 8*.

Table 8 Consumptive Use Reduction Compared with Fallowing Periods for the Bard Unit, 2016-2020.

Year	Fallow Period[1]	ΔCU Period[1]	Area Fallowed[1] (acres)	Reported ΔCU[1,2] (AF/ac)	Adjusted ΔCU[1,3] (AF/ac)	April 1 - July 31 ΔCU[1,4] (AF/ac)	April 1 - August 31 ΔCU[1,4] (AF/ac)
2016	April 1 – July 31	April 1 – July 31	509	1.87	1.87	1.87	2.03
2017-1[5]	March 15 – July 15	March 1 – July 31	752	2.06	1.71	---	---
2017-2[5]	April 15 – August 15	April 1 – August 31	889	1.89	1.46	---	---
2017 (for 5-year mean)[6]	---	March 1 – August 31	1,641	2.32	---	1.64	1.89
2018	April 15 – August 15	April 1 – August 31	973	1.99	1.52	1.71	1.99
2019	April 15 – August 15	April 1 – August 31	1,984	2.14	1.76	1.93	2.14
2020	April 1 – July 31	April 1 – August 31	2,749	2.32	1.83	1.83	2.32
Mean				2.13	---	1.80	2.08
Area-Weighted Mean				2.21[7]	---	1.80	2.13

[1]Taken from, or based upon, MWD (2021a).
[2]Value used by MWD (2021a).
[3]Adjusted to better match the CU period. For partial months, the value was prorated based on the number of days in the month included in the fallow period.
[4]*ΔCU* for the stated period, inclusive, for each year.
[5]2017-1 is the first fallow period in 2017, 2017-2 is the second fallow period in 2017, neither of these are included in the means.
[6]In computing the area-weighted mean, the total area of the two 2017 fallow periods was used even though that total area was only effectively fallowed during the overlapping periods fallowing period of April 15 - July 15.
[7]Value used by MWD (2021a), see also Reclamation (2021a).

Table 9 Illustrative Comparison of Crop Evapotranspiration Estimates for Crops Grown in the Bard Unit to Demonstrate the Impact of Computation Period on Consumptive Use Estimates April 1 – August 31 and April 15 – August 15, 2020.

Reported Crop[1]	Cotton	Other Hay (Sudan)	Pasture	Sugar Beet	Watermelon	Wheat	Citrus	Dates	Total	Total Excluding Permanent Crops
Modeled Crop[2]	**Cotton**	**Sudan Hay**	**Bermuda Grass (Seed)**	**Sugar Beet**	**Melon, Spring**	**Small Grains[3]**	**Citrus, Mature**	**Dates**		
Area (ac)	819	970	67	22	117	1,421	29	1,499	4,944	3,416
Computation Period: April 1 - August 31										
Month	**Estimated Crop ET (inches)**									
April	4.0	6.5	2.9	1.7	6.6	7.4	2.9	6.7		
May	3.5	8.7	7.2	6.3	7.9	6.0	5.1	8.6		
June	6.6	10.8	8.1	0.0	0.0	0.0	5.5	9.4		
July	10.2	11.8	8.8	0.0	0.0	0.0	5.9	10.1		
August	11.5	10.9	8.5	0.0	0.0	0.0	5.8	9.9		
Total	**35.8**	**48.7**	**35.5**	**8.0**	**14.6**	**13.4**	**25.2**	**44.7**	**33.9**	**29.2**
Computation Period: April 15 - August 15										
Month	**Estimated Crop ET (inches)**									
April	1.0	1.9	1.9	3.9	4.0	4.4	2.4	3.9		
May	3.5	8.7	7.2	6.3	7.9	6.0	5.1	8.6		
June	6.6	10.8	8.1	0.0	0.0	0.0	5.5	9.4		
July	10.2	11.8	8.8	0.0	0.0	0.0	5.9	10.1		
August	5.7	5.7	4.3	0.0	0.0	0.0	2.9	4.9		
Total	**27.0**	**38.9**	**30.2**	**10.2**	**11.9**	**10.4**	**21.8**	**36.9**	**27.1**	**22.9**
April 15 - August 15 Percent of April 1 - August 31									**80%**	**78%**

[1]Source: Bard (2020)
[2]Source: Jensen (2003)
[3]The crop coefficient curve was temporally scaled and shifted based upon reported experimental planting and harvest dates in Ottman (2014).

Assumption 7: The ΔCU is best represented by a mean of multiple years.

For the 2020 fallowing period, the ΔCU was computed as an area-weighted mean across the five years, then included in the various Bard fallowing periods (MWD, 2021a). One benefit of using an average, as opposed to the estimated ΔCU for the conservation year only, is that an average may better represent typical conditions and reduce the uncertainty involved with assumptions and measurements in any one year. Furthermore, it can be expected that the annual variability in ET for a given crop will not be too great (e.g., SCS, 1993). It is conversely possible that the methods used to estimate ΔCU for a given year are sufficiently accurate to be more representative than a mean across years.

The type of mean used is also important to consider. The mean used for the 2020 ΔCU estimates was a weighted mean based on fallowed area for each year.[15] This would put more numerical value on the ΔCU for years with more fallowed area. Thus, providing a mean ΔCU value that could be representative, if grower practices for the non-fallowed land are affected by the amount of land

[15] See Footnote 6 in *Table 8*.

fallowed. An alternative weighting could be to use the irrigated land as the weighting factor since it is the irrigated area that the CU used in computing ΔCU is based upon. It may also be reasonable to expect that the mean ΔCU (in terms of AF/ac) would better represent the typical CU of irrigated crops in the Bard Unit.

Finally, the varying length of the periods used in computing ΔCU have an impact on the results. For example, if a simple mean of ΔCU for the period April 1 – July 31 across the five years were used, the final ΔCU would be 1.80 AF/ac compared to the 2.13 AF per acre if varying periods are used for the calculations (*Table 8*).

Reflections

From the grower's perspective, fallowing can be considered like one of several potential crops in a crop rotation. The fallowing program can be logistically favorable for the timing of tillage operations for the winter vegetable crops, where a summer crop may constrain the amount of time available for such operations. Furthermore, growers may see benefits to fallowing land that is less productive, which in some cases may require additional irrigation diversion (not necessarily CU), and that seed, labor and other inputs associated with producing a summer crop may be marginally or not economically profitable (e.g., because of low mid-year grain prices).

The district itself has also experienced benefits from the Program. While the fallowing program adds more complexity and effort for district staff (which does receive some administrative funding from MWD as part of the program), it has been able to take advantage of the reduced water deliveries during the fallowing period. For example, Bard has been able to coordinate with growers to concentrate the fallowed land to certain areas to help facilitate improvement projects, like canal lining. The reduced demand during the fallowing program also can help logistically with implementation of improvement projects. One such project, the Five Gates Reconstruction Project, was in progress during the site visit on May 25, 2021 (*Figure 15*; *Figure 16*). This project involves the reconstruction of a major bifurcation near the head of the system.

Figure 15 Photo of Five Gates Reconstruction Project in the Bard Water District (credit: B. Barker, May 25, 2021).

Figure 16 Photo of a Fallowed Field Being Used as a Staging Area for the Five Gates Reconstruction Project (credit: B. Barker, May 25, 2021).

Finally, the program includes infrastructure improvement funds paid to Bard from MWD as an incentive for participation and to offset the reduction in excess water fees that Bard may have collected from growers who may have exceeded their standard delivery allotments had they not fallowed land.

One challenge for Bard relates to the software they use to track water orders. The software was not designed to accept a field being fallowed (or have no allowable deliveries). This has required software program modifications to facilitate the fallowing program.

In addition to the individual considerations of growers and the district, the program fills an important role from the standpoint of water leases. This is because the Bard Unit has an unquantified water right, meaning that the water users have the right to irrigate a certain amount of land, rather than a right to a specified volume of water. Therefore, the only means of leasing water to other users, e.g., MWD, is through a program where a conservation practice, like fallowing, is implemented and the ΔCU is used to quantify the amount of water that can be leased. Thus, as with other programs the accuracy of the ΔCU is of importance to all parties involved. To this end, MWD is presently developing a revised method for quantifying ΔCU for the program, which will include precipitation and estimates of ET (MWD, communication, May 25, 2021).

The amount of water conserved is also related to the size of the program. The current program is considered by some to be a good size to appropriately balance potential impacts on agronomics and the local economy. In addition, the payment for fallowing is important. The Bard Board of Directors, for example, pushed to have the payment from MWD to growers not be too great out of concern that too many growers would elect to fallow.

Palo Verde Irrigation District Forbearance and Fallowing Program

The Palo Verde Irrigation District (PVID) is located in southeastern California (*Figure 17*). PVID serves over 131,000 acres of land including most of which is in the Colorado River flood plain but roughly 27,000 acres are on the Palo Verde Mesa (PVID, 2021b). In 2004, MWD entered into a 35-year agreement with PVID and landowners within PVID's service area wherein MWD pays for valley land to be fallowed (MWD, 2019b). Annual payments to farmers vary in response to actual acreage fallowed. The forborne water is then made available for use by MWD on a direct acre-foot for acre-foot basis. The amount of land under the forbearance program is allowed to fluctuate between 9 and 35 percent, as determined by MWD (MWD, 2019b).

Participation in the program is voluntary and participants entered into a landowner agreement prior to the start of the program in 2004. Easements were acquired by MWD for the parcels included in the program. The land is fallowed for a minimum of one year and a maximum of five years at a time (MWD, 2019b). A minimum of five acres must be fallowed and portions of fields are allowed to be fallowed (*Figure 18*). Maximum limits have been placed on the amount of land fallowed in the program.

Figure 17 Map of the Palo Verde Irrigation District (Source: Environmental Impact Report for the Proposed Palo Verde Irrigation District Land Management, Crop Rotation, and Water Supply Program, PVID, 2002).

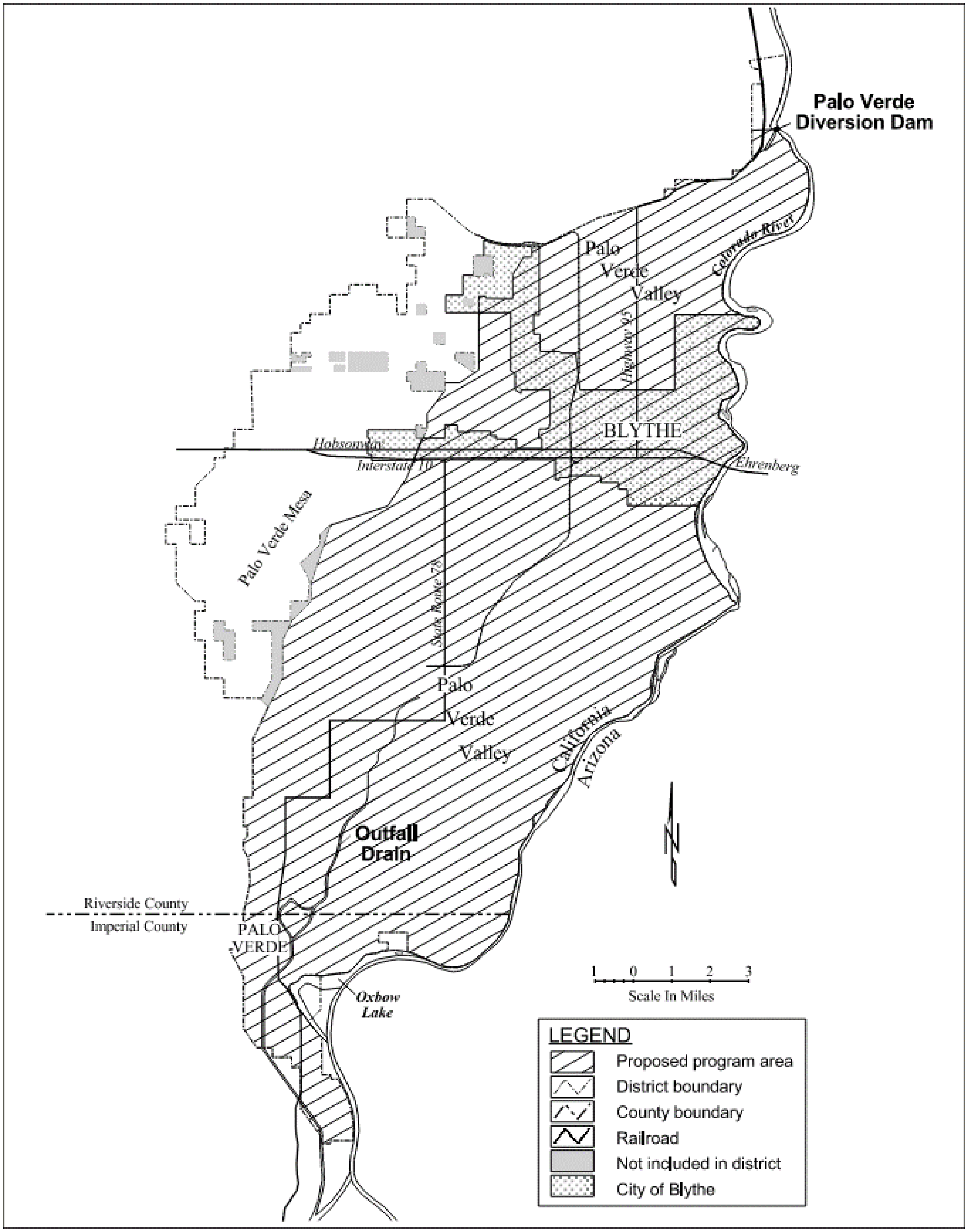


Figure 18 Photo of Partial-Field Fallowing at Palo Verde Irrigation District (credit: L. Perkins).

Technical Analysis

A technical analysis of the PVID forbearance and fallowing case study is presented in the following sections.

CU Quantification Methods

The methods used to quantify CU reductions from the PVID forbearance and fallowing program are based on a project-level water balance (TM2). These methods include three basic components: 1) verification of the fallowing practice, 2) estimation of the average CU for fields under cultivation in PVID, and 3) determination of the CU reduction for fallowed lands. CU is quantified over various historical periods using measured diversions, measured return flows, and estimates of unmeasured return flows from Reclamation's decree accounting data. The method used to translate estimated average CU for fields under cultivation into CU reductions for fallowed fields includes an assumption that fallowed lands would have had similar CU as the rest of PVID during the various analysis periods.

The CU estimates for the PVID fallowing program are based upon Reclamation's Decree Accounting (e.g., Reclamation, 2021a; *Figure 19*) for PVID (MWD, 2021b). The Decree Accounting CU for PVID includes CU from several areas that are aggregated together for accounting purposes. These areas include agricultural lands irrigated with water diverted at the Palo Verde Diversion Dam, agricultural areas receiving water "…pumped from the river…" (Pumped), the Palo Verde Ecological Reserve (PVER), the Palo Verde Ecological Reserve South (PVER-So), and the Dennis Underwood Conservation Area (DUCA) (Reclamation, 2021a; MWD, 2021b). The latter three are Lower Colorado River Multi-Species Conservation Program (LCR MSCP, or MSCP) units. The agricultural lands receiving water diverted from Palo Verde Diversion Dam can further be defined as "Valley lands," located in the Colorado River Valley, and "Mesa lands," which are above the valley (*Figure 17*; MWD, 2021b).

The fallowing program is only on lands that would be considered Valley lands. Therefore, the CU estimated for the fallowing program is estimated by subtracting out the CU for those areas outside of the Valley lands as (MWD, 2021b):

$$CU_{Valley} = CU_{Total} - CU_{Mesa} - CU_{Pumped} - CU_{PVER} - CU_{PVER-So} - CU_{DUCA}$$

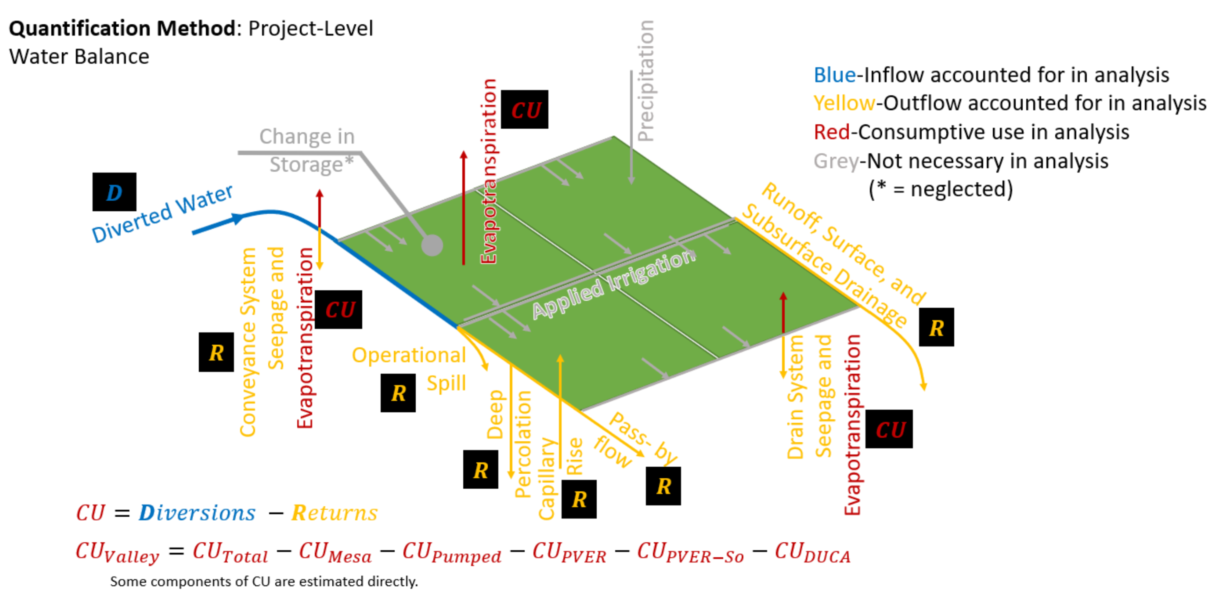
where the subscripts represent the respective CU component. The CU_{Total}, CU_{Pumped}, CU_{PVER}, $CU_{PVER\text{-}So}$, and CU_{DUCA} values are all provided by Reclamation (MWD, 2021b; Reclamation, 2021b). The CU estimates from Reclamation (2021b) are obtained from an academic journal article, Federal agency reports, a plan report (LCR MSCP, 2004), and sources to support assumptions made. Reclamation (2021b) opined that the assumptions made in these CU estimates were "conservative," in that the resulting CU was more likely to be overestimated than underestimated. In the case of CU_{Pumped}, the Blaney-Criddle Method is used to estimated ET (USGS, 2021a). CU_{Mesa} is assumed to be equal to the "…deliveries to the Mesa," from "…PVID records" (MWD, 2021b).

The CU reduction (ΔCU) for fallowing is effectively computed as:

$$\Delta CU = A_{Fallow}^{Toll}\left(\frac{CU_{Valley}}{A_{Irr}^{Toll}}\right)$$

where A is area, the superscript *Toll* indicates that the area is in terms of water toll acres (the area used in water assessments, which may differ from the net area irrigated), and the subscripts *Fallow* and *Irr* represent fallowed land and land irrigated, respectively. These calculations are performed on a monthly basis.

Figure 19 Simplified Representation of the Project-Level Water Balance Approach for Quantifying Consumptive Use Reductions for the Palo Verde Irrigation District Fallowing Program.



Fallowed Land Verification

As with other fallowing programs, the PVID fallowing program includes multiple verifications of fallowing practice. This verification includes the following tasks:

- Inspection of all fields in PVID's service area three times per year by PVID staff.
- Field verification by a representative of MWD that all participating fields are indeed fallowed.
- Field verification of a randomly selected five percent of the participating fields by Reclamation twice per year.
- Verification of field eligibility with each crop rotation.
- Maintenance of a spreadsheet by PVID to verify that the fallowed acreage balances on a daily basis.

In addition, the district's water order system flags fallowed fields so that no water orders are accepted, and no deliveries are allowed on fallowed fields.

Example CU Results

Two of the benefits of the quantification strategy used in this fallowing program are: 1) it is tied to the Reclamation Decree Accounting methods, and 2) it is relatively simple to execute (e.g., MWD, 2021b). The series of calculations necessary to compute ΔCU can easily be done in a spreadsheet (*Table 10*).

Table 10Consumptive Use Reduction Estimates for the Palo Verde Irrigation District Fallowing Program, 2020.

Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
D_{PVID} (AF)[1]	35,240	44,410	37,460	69,840	91,680	92,910	102,300	96,870	81,800	61,260	39,160	39,130	792,060
D_{Pumped} (AF)[1]	81	102	139	150	183	222	243	233	183	154	109	107	1,906
R_{Meas} (AF)[1]	26,815	27,098	28,533	28,760	33,629	33,423	35,360	36,741	36,162	36,116	32,101	31,371	386,109
R_{Unmeas} (AF)[1]	2,846	3,624	4,448	6,065	5,866	6,632	7,307	7,357	6,684	5,427	2,735	2,781	61,772
CU_{Total} (AF)[1]	5,660	13,790	4,618	35,165	52,368	53,077	59,876	53,005	39,137	19,871	4,433	5,085	346,085
CU_{PVER} (AF)[2]	189	224	367	477	941	993	976	593	527	397	245	182	6,111
CU_{DUCA} (AF)[2]	3	3	7	14	23	25	26	24	18	12	5	1	161
$CU_{PVER\text{-}So}$ (AF)[2]	0	0	1	4	6	6	6	6	5	3	1	0	38
CU_{Pumped} (AF)[2]	47	59	81	88	107	129	142	136	107	90	64	62	1,112
CU_{Mesa} (AF)[3]	1,027	1,035	706	1,176	1,211	1,268	1,299	1,632	1,789	1,632	1,250	1,351	15,376
CU_{Valley} (AF)[4]	4,394	12,469	3,456	33,406	50,080	50,656	57,427	50,614	36,691	17,737	2,868	3,489	323,287
A_{Irr} (ac)[4]	76,484	76,484	76484	76,484	76,484	76,484	76,484	76,484	76,484	76,484	76,484	76,484	76,484
Valley CU Factor (AF/ac)[4]	0.06	0.16	0.05	0.44	0.65	0.66	0.75	0.66	0.48	0.23	0.04	0.05	4.23
A_{Fallow} (ac)[4]	10,376	10,376	10,376	10,376	10,376	10,376	10,376	10,376	10,376	10,376	10,376	10,376	10,376
ΔCU (AF)[4]	596	1,692	469	4,532	6,794	6,872	7,791	6,866	4,978	2,406	389	473	43,858

[1]From Reclamation (2021a). *D* is diversion, *R* is return, *CU* is consumptive use, *PVID* is Palo Verde Diversion Dam, *Pumped* is "…pumped from River…," *Meas* is measured, *Unmeas* is unmeasured, and *Total* is total.
[2]From MWD (2021b), see also Reclamation (2021b). CU is consumptive use, *PVER* is Palo Verde Ecological Reserve, DUCA is Dennis Underwood Conservation Area, PVER-So is Palo Verde Ecological Reserve South.
[3]From MWD (2021b) based on Palo Verde Irrigation District delivery records. *Mesa* refers to Palo Verde Irrigation District Mesa lands.
[4]From or based upon MWD (2021b).

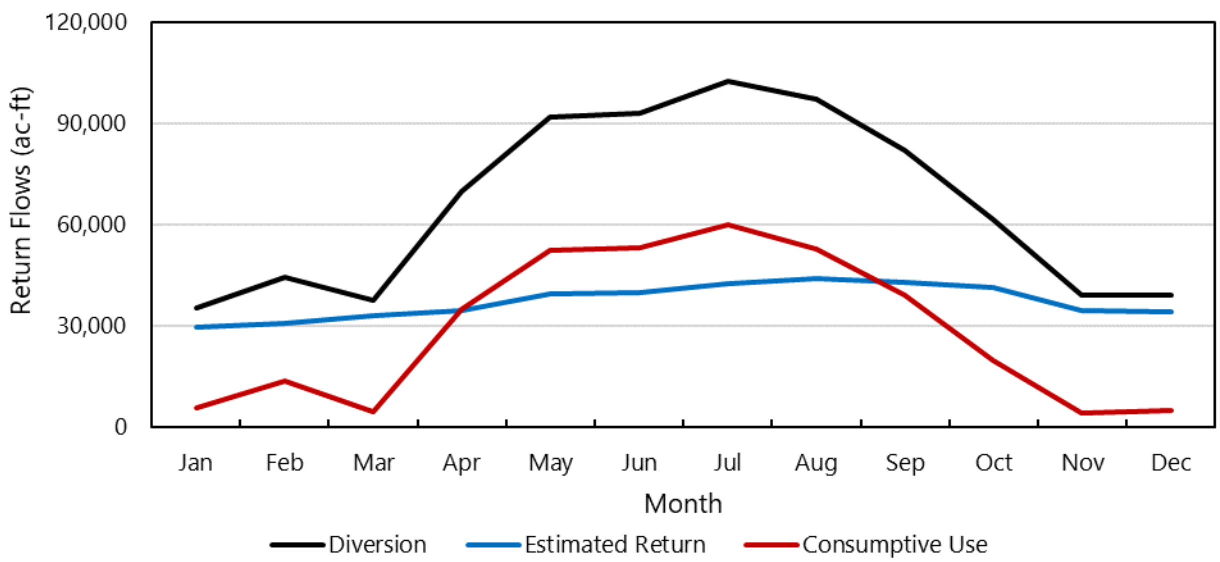
Discussion of Method Assumptions

The *ΔCU* method includes several assumptions, which are either explicit or implicit in the method. The primary assumptions are discussed below.

Assumption 1: There is no effective lag in the return flows.

This assumption was discussed previously in the *Discussion of Method Assumptions* section of the Bard Water District Seasonal Fallow Program case study analysis. Additional considerations for the PVID fallowing program are discussed here. For instance, the return flows from the PVER, PVER-South, DUCA, etc. are computed as diversion less estimated CU, the latter of which is estimated using methods described by Reclamation (2021b). This, of course, is assuming that the estimated fraction of unmeasured return flow is accurate for each month. Based on a plot of estimated diversions, returns, and CU for PVID in 2020, there is not clear, visual evidence of return flow lag, or lack of such lag (*Figure 20*). Because of the duration of the fallowing program (minimum one year per field), the effect of any lag may be dampened. As with other assumptions, this is a practical solution to a complicated problem.

Figure 20 Estimated Diversion, Return Flows, and Consumptive Use for PVID, 2020 (Reclamation, 2021a).



Assumption 2: The per-acre *ΔCU* for the fallow fields is similar to the CU for the Valley lands divided by the area irrigated during the fallow period.

This includes the assumption that crops, or at least CU, would be similar in the fallow fields, if irrigated, as it was in the non-fallowed areas of the Valley lands. Further discussion of this assumption has been provided in the *Discussion of Method Assumptions* section of the Bard Water District Seasonal Fallow Program case study analysis. Additional considerations for the PVID fallowing program are discussed here. For example, growers may also elect to fallow historically less productive land with challenging soils as communicated during the site visit.

For the PVID fallowing program, there is also the consideration of fallowable crops. Based on a crop report for 2020 from PVID (2021a), PVID served 94,057 total water toll acres in 2020

(*Table 11*). This included 2,054 acres of MSCP lands (e.g., PVER, PVER-So, and DUCA; CDFW, 2021; LCR MSCP, 2018, 2021a,b), 73 acres in fish ponds (likely related to the LCR MSCP), 3,436 acres of idle land, 10,796 acres of fallowed land, and 1,167 acres of permanent crops. The permanent crops included citrus, golf course, orchard, palm, and roses (PVID, 2021a). The 94,057 acres also includes the Mesa lands. According to PVID (2005) and Google (2021), it is apparent that the permanent crops are predominantly grown on the Mesa lands. Since the MSCP lands are accounted for by subtracting out CU_{PVER}, $CU_{PVER\text{-}So}$, and CU_{DUCA}, the associated MSCP land covers and fishponds can be neglected. This leaves a total of 90,763 water toll acres, if the 3,436 acres of "idle or diverted" land is also removed, the resulting area is 87,327 acres, which is not much greater than the total 86,860 water toll acres in the Valley lands from (MWD, 2021b). The difference could be related to possible non-permanent crops grown on Mesa lands (e.g., Google, 2021). Since it is apparent that the vast majority of the crops grown on the Valley lands are annual, and thus easily fallowed, the assumption that the crop mix would be similar on the fallowed lands, were they not fallowed, may be reasonable.

Table 11 Cropped Areas from Palo Verde Irrigation District Crop Report, 2020.

Description	Water Toll Acres		
	Gross Area	Adjustment for Double Cropping	Net Area
Field Crops, Annual	89,106	-15,997	73,109
Field Crops, Permanent	1,167	0	1,167
Vegetables	4,051	-2,781	1,270
Melons	2,167	-15	2,152
MSCP Habitat	2,054	0	2,054
Fish Ponds	73	0	73
Fallow	14,880	-4,084	10,796
Idle or Diverted	3,436	0	3,436
Total	116,934	-22,877	94,057

Source: PVID (2021a). Description names are directly from PVID (2021a) with exception of Annual and Permanent identifiers. MSCP is the Lower Colorado River Multi-Species Conservation Program.

Assumption 3: The reduction in ET from field ditches, canals, and drainage ditches resulting from fallowing is proportional to the fallowed land in comparison with the irrigated land in terms of water toll acres.

This assumption is discussed in the *Discussion of Method Assumptions* section of the Bard Water District Seasonal Fallow Program case study analysis.

Assumption 4: Water toll area is representative for use in per-acre CU quantification.

When computing per-acre CU, it is important to understand what acreage is being used. For the PVID program it is water toll acreage, or the acreage at which fields are assessed for water service. According to PVID, water toll acreage includes some non-cropped areas like access roads in the fields. This is somewhat different than the program's enrolled area, which was based on field delineations made relative to the California Environmental Quality Act and excludes some non-cropped areas (e.g., stack yards for hay). Furthermore, it is assumed that the water toll acreage is correct for all fields in the Valley lands (the water toll area for some PVID fields was known to be inaccurate in the past, based on communications from PVID and MWD representatives, May 26, 2021). The water toll area of the program fields was not reassessed prior to enrollment (i.e., for suspected errors). So, if any discrepancy exists between the field and water toll area, it is not accounted for in this quantification method.

Assumption 5: The CU from the fallowed fields (and possibly the irrigation and drainage ditches serving the fallowed land) is negligible.

This assumption is discussed in the *Discussion of Method Assumptions* section of the Bard Water District Seasonal Fallow Program case study analysis. However, a PVID-specific example is provided here. First, it should be recalled that in computing *ΔCU*, the evaporation from rainfall is not important, because the *ΔCU* of interest is that derived from irrigation water using the definition of Decree Accounting (*CU* is diversions less return flows). Furthermore, precipitation is small enough that it is generally negligible.

To illustrate this point, precipitation data were obtained for weathers stations used in Reclamation (2019b)[16]. The average annual precipitation for 2020 from the available records for the remaining stations was 2.6 inches, with a maximum daily value of about 0.6 inches. It is probable that all of this precipitation would be evaporated in the fallow fields. A portion of this precipitation would theoretically reduce irrigation water CU for the irrigated fields by about 2.6 inches either in the form of increased return flows or decreased irrigation application (plus any consumptive conveyance losses). Much of the portion of the 2.6 inches that did not offset irrigation water CU would likely be evaporated.

In addition, there would be some prolonged evaporation during the fallow period that would deplete soil water that had carried over from the previous irrigation season (Jensen and Allen, 2016), though this may be small in magnitude. The magnitude of evaporation would depend on the length of the fallow period, presence of crop residue, the soil water content at the initiation of fallowing, and field tillage operations including those used to kill weeds. The relative impact of any evaporation would be dampened the longer that a field were fallowed.

Assumption 6: The CU for the Mesa lands is equal to the water deliveries to the Mesa lands.

This assumption is basically that return flows are negligible from the Mesa lands. This would include an assumption that all irrigation inefficiencies related to those deliveries were consumptive. Because irrigation water is pumped to the Mesa lands (PVID, 2005), it is probable that conveyance losses (and the associated returns) between the PVID canals and those lands is negligible. Because the Mesa lands are predominantly permanent crops with pumped supply (PVID, 2005), it is possible that many of these crops are irrigated using sprinkler or drip irrigation. These Mesa lands likely have less return flows than the Valley lands based on these irrigation methods. However, a certain amount of deep percolation will be necessary for salt leaching. The water quality at the United States Geological Survey (USGS) station Colorado River Below Palo Verde Dam (No. 09429100) averaged about 0.95 deci-Siemens per meter between September 2020 and May 2021 (USGS, 2021b). Based on the commonly used leaching requirement equation of Rhodes (Suarez, 2012) and the salt sensitivities of lemons and oranges (Grieve et al., 2012), the leaching requirement could be as much as 15% - 17%

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[16] These included four NOAA climate stations (Ehrenberg, AZ, Blythe ASOS, CA, Blythe, CA, and Parker, AZ; NOAA, 2021a,b), two AZMET weather stations (Parker, and Parker #2; UA, 2021), and three California Irrigation Management Information System (CIMIS) stations (Blythe NE, Ripley, and Palo Verde II; CDWR, 2021). One of these stations (CIMIS Palo Verde II) had notably lower precipitation than the other stations and was, thus, excluded.

of applied irrigation water. Though notable, this is expected to be less than the deep percolation on the Valley lands based on a communication with A. Montazar (May 26, 2021). Because of distance, there is also expected to be a lag in the return of this leached water to the river that could be difficult to estimate.

General Accuracy of the CU Adjustments

The reductions made to the Decree Accounting CU so that it better represents Valley lands have varying levels of impact relative to the estimated CU_{Total} and CU_{Valley} (*Table 12*). For 2020, CU_{Valley} was about 93% of CU_{Total}. Therefore, the total adjustment for year 2020 was less than 7% of the CU_{Total}. Any uncertainty or error in the various adjustments would reasonably be less than the full magnitude of the respective adjustment. Therefore, any resulting error would be expected to be notably less than 7% of CU_{Total} and would probably be negligible. For example, if the leaching requirement adjustment of about 16%, as described in the previous paragraph, is multiplied by 4.4% (CU_{Mesa} relative to CU_{Total}), this would be about an 0.7% error relative to CU_{Total} (about an 0.8% error relative to CU_{Valley}). There are other uncertainties in measurements and estimates that are larger than this.

Table 12 Consumptive Use Adjustments for the Palo Verde Irrigation District, 2020.

Description		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
CU_{Total}[1]	(AF)	5,660	13,790	4,618	35,165	52,368	53,077	59,876	53,005	39,137	19,871	4,433	5,085	346,085
	% CU_{Total}	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
CU_{PVER}[2]	(AF)	189	224	367	477	941	993	976	593	527	397	245	182	6,111
	% CU_{Total}	3.3%	1.6%	7.9%	1.4%	1.8%	1.9%	1.6%	1.1%	1.3%	2.0%	5.5%	3.6%	1.8%
CU_{DUCA}[2]	(AF)	3	3	7	14	23	25	26	24	18	12	5	1	161
	% CU_{Total}	0.1%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%
$CU_{PVER\text{-}So}$[2]	(AF)	0	0	1	4	6	6	6	6	5	3	1	0	38
	% CU_{Total}	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CU_{Pumped}[2]	(AF)	47	59	81	88	107	129	142	136	107	90	64	62	1,112
	% CU_{Total}	0.8%	0.4%	1.8%	0.3%	0.2%	0.2%	0.2%	0.3%	0.3%	0.5%	1.4%	1.2%	0.3%
CU_{Mesa}[3]	(AF)	1,027	1,035	706	1,176	1,211	1,268	1,299	1,632	1,789	1,632	1,250	1,351	15,376
	% CU_{Total}	18.1%	7.5%	15.3%	3.3%	2.3%	2.4%	2.2%	3.1%	4.6%	8.2%	28.2%	26.6%	4.4%
CU_{Valley}[4]	(AF)	4,394	12,469	3,456	33,406	50,080	50,656	57,427	50,614	36,691	17,737	2,868	3,489	323,287
	% CU_{Total}	77.6%	90.4%	74.8%	95.0%	95.6%	95.4%	95.9%	95.5%	93.8%	89.3%	64.7%	68.6%	93.4%

[1]From Reclamation (2021a). *D* is diversion, *R* is return, *CU* is consumptive use, *PVID* is Palo Verde Dam, *Pumped* is "...pumped from river...," *Meas* is measured, *Unmeas* is unmeasured, and *Total* is total.

[2]From MWD (2021b), see also Reclamation (2019b). CU is consumptive use, *PVER* is Palo Verde Ecological Reserve, DUCA is Dennis Underwood Conservation Area, PVER-So is Palo Verde Ecological Reserve South.

[3]From MWD (2021b) based on Palo Verde Irrigation District delivery records. *Mesa* refers to Palo Verde Irrigation District Mesa lands.

[4]From or based upon MWD (2021b).

Reflections

Some of the notable benefits and challenges of the PVID program relate to the field areas that may be fallowed. From the grower's perspective, the fallowing program is designed to allow for a certain level of flexibility. This is because the PVID fallowing program allows for fractions of fields to be fallowed so long as fallowed areas are at least five contiguous acres. This allows growers to fallow portions of their fields that may be particularly problematic (e.g., because of soils, etc.). though there are some additional administrative efforts required by PVID to mark, measure, and maintain records on such sub-field areas.

A noted aspect of the program with regard to the fallowed area is that to help with fallowing enforcement, MWD required easements on some portion of the landowner's land equal to the land area of their commitment to the program. Thus, if a grower failed to comply with the fallowing call, MWD could legally forcibly fallow that area with the easement. This provision did require additional time, expenses, and effort to clear land titles at the onset of the program but was also viewed by some landowners as a benefit, as the cost for the title clean-up was borne by MWD.

In addition to the considerations relating to the program area, the program also requires a notable amount of local administrative effort. The effort is such that PVID has hired a full-time staff member to help MWD administer the program (MWD pays PVID for their administrative role to help manage the program).

Finally, it is notable that the PVID fallowing program fills an important role from the standpoint of water leases. This is because, like the Bard Water District, PVID has an unquantified water right. Meaning that the PVID water users have the right to irrigate a certain amount of land, rather than a right to a specified volume of water. Therefore, the only means of leasing water to other users, e.g., MWD, is through a program where a conservation practice, like fallowing, is implemented and the ΔCU is used to quantify the amount of water that can be leased. Thus, as with other programs, the accuracy of the ΔCU is of importance to all parties involved.

Palo Verde Irrigation District Moderate Deficit Irrigation of Alfalfa Program

In late 2018, a deficit irrigation experiment in PVID's service area was initiated by researchers with the University of California (UC) Division of Agriculture and Natural Resources, UC Davis, and the U.S. Department of Agriculture Agricultural Research Service (USDA ARS). The purpose of the study is to measure the impacts on applied irrigation water, CU, yield, yield quality, soil salinity, and alfalfa plant stand of what has been termed by the researchers as "moderate" deficit irrigation during the summer months (Montazar et al., 2020). The results for the first year or so of the study were published by Montazar et al. (2020), from which the information in the following two paragraphs were taken, unless otherwise cited.

The deficit irrigation strategy in the study is to eliminate one to three irrigation events during the summer (July – September). The number of irrigation events omitted depended upon the irrigation method (border or furrow) and treatment. The summer months were targeted because of the lower crop productivity and water use efficiency (crop production per unit water consumed) relative to other times of the year (A. Montazar, communication, May 26, 2021).

The project, which continues to late December 2021 (A. Montazar, communication, May 26, 2021), is being conducted in four surface irrigated alfalfa fields, which were planted late in 2018. The fields are paired by irrigation method (two border and two furrow, with examples shown in *Figure 21* and *Figure 22*, respectively). The treatments are tailored to the irrigation method. Border irrigation treatments include omitting one and two irrigations, respectively. Furrow irrigation treatments involve omitting two and three irrigations, respectively. There were more irrigations per season for furrow irrigation than border during the study period (Montazar et al., 2020). Each field also includes a section (or multiple sections) irrigated according to the grower's convention.

Figure 21 Photo of a Border Irrigated Study Field (credit, B. Barker).

Figure 22 Photo of a Furrow Irrigated Study Field (credit, L. Perkins).

Technical Analysis

A technical analysis of the PVID deficit irrigation case study is presented in the following sections.

CU Quantification Methods

The researchers are quantifying CU using micrometeorological techniques (TM2) for four study fields. Therefore, this case study differs from the other considered case studies in scope and CU method intensity. Where the other case studies include practical application of conservation measures at a district-level and ΔCU estimation methods based on available data, the PVID deficit irrigation study is a relatively small-scale (field-level) research project specifically using state-of-the-science methods to quantify ET (and thus CU).

CU is quantified as ET in this study using eddy covariance and surface renewal micrometeorological techniques without the need for a water balance analysis (*Figure 23*). These research-grade methods are subject to errors and uncertainties (as are all measurements of ET). These methods are based upon high-frequency meteorological measurements, rather than models, and for the purposes of the present discussion will be referred to as observation methods.[17] Eddy covariance is a common method for estimating ET. Surface renewal, which involves less equipment and less effort to analyze has traditionally been calibrated to eddy covariance sites (e.g., Snyder et al., 1996). Such is the case in the present study (A. Montazar, communication, May 26, 2021). An evaluation of these particular methods is not pursued here. A brief description of each was provided in TM2, which also includes pertinent literature with additional detail on each method.

In this deficit irrigation study, an eddy covariance system (consisting of a sonic anemometer, a net radiometer, and three soil heat flux plates) was installed in the area of each field treated according to the grower's irrigation convention, as shown in *Figure 24* (A. Montazar, communication, May 26, 2021). The systems do not include a gas analyzer or a hygrometer (to measure water vapor). ET is, therefore, computed using the energy balance (Montazar et al., 2020; TM2). These eddy covariance systems are also equipped with fine-wire thermocouples for surface renewal measurements. Paired with the eddy covariance systems are a suite of other sensors. These additional sensors are beneficial to the research, but not directly used for ET estimation, with the exception of a second surface renewal system. This second surface renewal system is a commercial product by Tule Technologies, Inc. These commercial surface renewal systems are also located in the individual deficit irrigation treatment areas and will be used by the researchers to quantify ET for the deficit treatments (A. Montazar, communication, May 26, 2021). The equipment in the grower-convention treatment areas will be used to develop surface renewal adjustments to be applied to the deficit irrigation surface renewal systems.

[17] These methods are not direct ET measurement methods, but rather are methods used to estimate ET based on meteorological measurements, atmospheric physics, and certain assumptions.

Figure 23 Simplified Representation of the Consumptive Use Quantification Approach for the Palo Verde Irrigation District Deficit Irrigation Project.

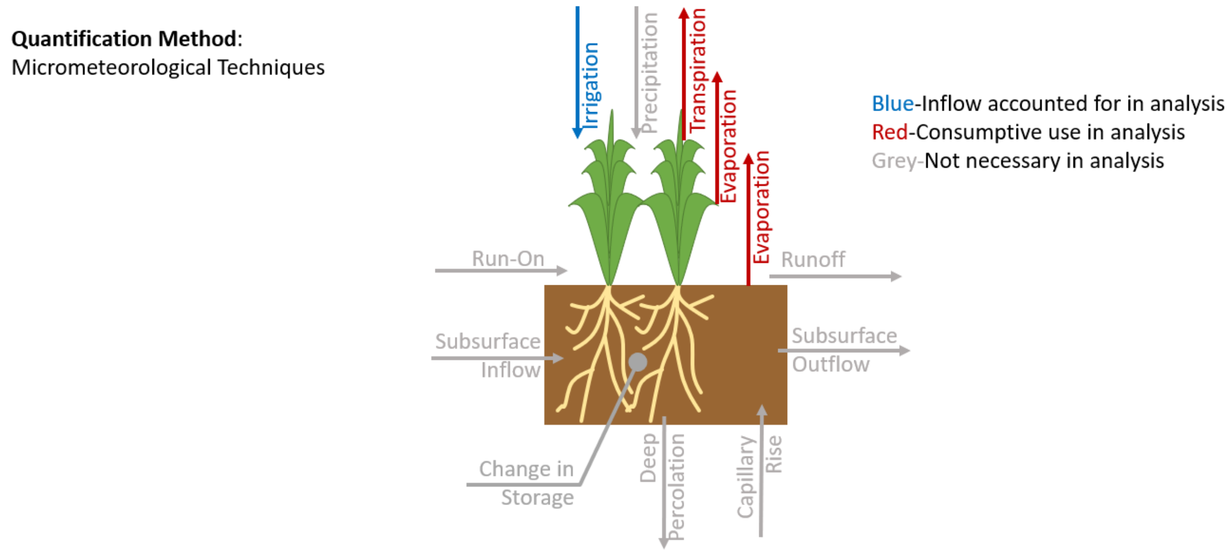


Figure 24 Photo of Eddy Covariance, Surface Renewal Systems and Other Monitoring Equipment (credit, B. Barker).

Applied Water Measurement Methods

A primary measure of water conservation being analyzed and reported by the researchers is the reduction in applied water. This is quantified using PVID records of farm turnout volumes for the study fields (A. Montazar, communication, May 26, 2021). According to a PVID staff member (May 26, 2021), PVID measures farm turnout deliveries at the turnout gate four times per day. The gates are fabricated by PVID and are uniform in dimension. The gates (or a representative gate) have been calibrated for orifice flow measurement.

Yield Measurements

Another primary measure of water conservation being analyzed and reported by the researchers is the change in yield resulting from the deficit irrigation treatments. Yield was measured by collecting samples within a sample frame from 12 locations in each treatment (Montazar et al., 2020). The purpose of these measurements is to relate the change in yield to the change in irrigation and ΔCU (A. Montazar, communication, May 26, 2021). However, as demonstrated in TM2, yield and ET are related, particularly for crops like alfalfa, where the yield is the crop's biomass. Therefore, changes in yield would be expected to be related to changes in CU.

Project End Products

In addition to the scientific knowledge regarding the impacts of this deficit irrigation method, the primary anticipated end product of the study will be an NRCS published conservation practice (A. Montazar, communication, May 26, 2021). This practice will include a mathematical function relating decreases in applied irrigation water (ΔI) from the deficit irrigation practice to impacts in yield (ΔY):

$$\Delta Y = f(\Delta I)$$

where the notation $f(\Delta I)$ simply indicates that ΔY is function of (or related to) ΔI, which function has not been published as of the writing of this document.

In addition to the yield impact vs. ΔI relationship, the relationship of ΔY to ΔCU will be published based on the research (A. Montazar, communication, May 26, 2021):

$$\Delta Y = f(\Delta CU)$$

Ultimately, it may be possible to approximate ΔCU based upon ΔI, but such a relationship would be specific to the irrigation practices of the grower, the soils, and other field conditions (alfalfa stand vigor, disease, and insect pressure, etc.) of each individual alfalfa field in PVID.

Replication and Statistics

One strength of this research study is the replication and possible application of statistical analyses to assess the difference in CU between treatments. It is unknown what statistical tests will be employed by the researchers in their final analyses but, depending on how treatments are defined, the researchers will have three or four replications for each imposed irrigation treatment. This replication and the possible statistical analyses are a benefit of this type of study. The other case studies, which are district-level in nature, do not lend themselves to the use of statistical analysis to test differences in CU. However, such is not practically necessary in those cases. Deficit irrigation, on the other hand, does not lend itself to the relatively simple water balance quantification methods that are employed, for example, in the fallowing cases. Therefore, statistical rigor is important in the development of ΔCU quantification methods for deficit irrigation. It should be acknowledged that, as with some other ET observation methods, micrometeorological measurements are relatively expensive to employ and the size of field plots necessary for this type of study are relatively large. Both of these factors affect the number of replications possible in this type of study.

Since the study is not finished and final statistical tests have not been performed nor provided by the researchers, no further discussion or example results are provided here regarding statistical measures of this case study.

Example CU Results

The full research datasets have not been fully collected or analyzed as of the writing of the present document. However, some initial results were published by Montazar et al. (2020) and other results were provided by A. Montazar for inclusion in this case study.

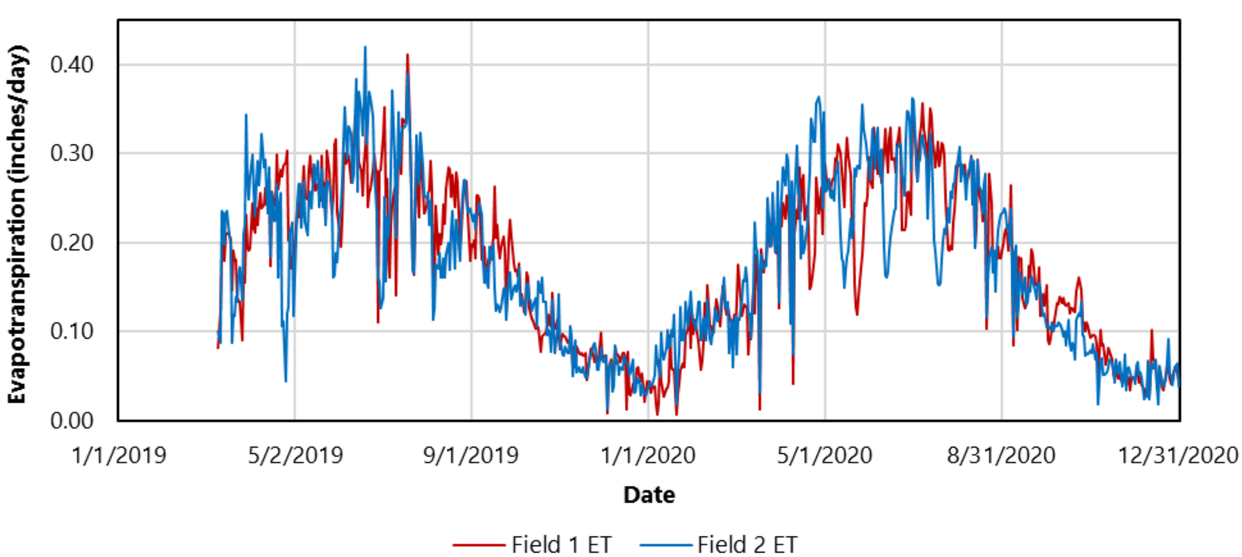
The researchers provided ET results for the grower-convention treatment for two irrigated fields (one furrow irrigated and one border irrigated). Data for the deficit irrigation treatments will be published by the researchers at a later date. Therefore, the present case study analysis does not include an analysis of ΔCU resulting from the conservation practice. However, anecdotally, A. Montazar communicated (May 26, 2021) that the magnitude of ΔCU had been observed to be about 1.8 to 2.0 inches (or 0.15 to 0.17 AF/ac) annually. This anecdotal result is not a final value and is presented for illustrative purposes only.

For the grower-convention irrigation treatment, daily observed ET (ET_{obs}) ranged from near zero to over 0.4 inches per day for the two fields over the period of March 11, 2019 – December 31, 2020 (*Figure 25*). Montazar et al. (2020) also reported ET_{obs} as a ratio of reference ET (ET_o)[18]. Such a ratio is instructive because it is similar to what is referred to as a crop coefficient (K_c) in the common reference ET/crop coefficient modeling method:

$$ET_c = ET_o K_c$$

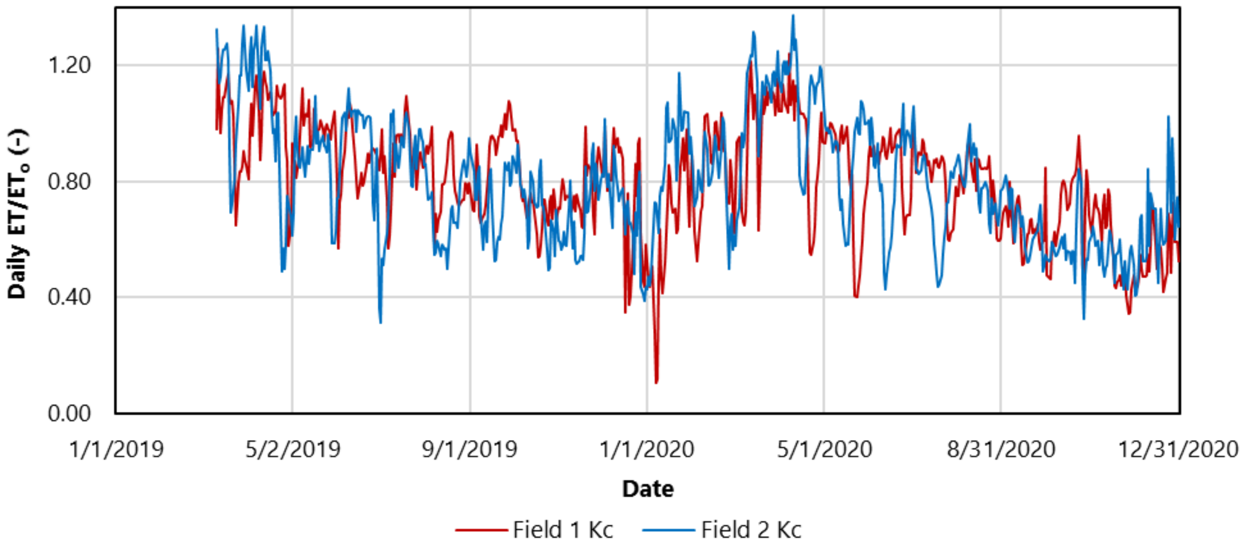
where ET_c is modeled crop ET (TM2; Jensen and Allen, 2016). Therefore, reporting ET_{obs}/ET_o allows for comparison with published K_c values. The latter typically represent conditions of minimal crop stress (TM2), and the former would include any effects of crop stress as discussed by Montazar et al. (2020). The researchers provided ET_{obs}/ET_o for 2019 and 2020. The ET_{obs}/ET_o values have seasonality, reaching their largest values in the spring months (*Figure 26*).

Figure 25 Daily Observed Evapotranspiration (ET) for the Grower Convention Irrigation Treatment for Two Research Fields for March 11, 2019 – December 31, 2020.



[18] Refer to TM2 for a discussion regarding reference ET.

Figure 26 Daily Observed Evapotranspiration (ET) Divided by Short Reference Evapotranspiration (ET_o) for the Grower Convention Irrigation Treatment for Two Research fields for March 11, 2019 – December 31, 2020.



K_c values for the Lower Colorado River Accounting System (LCRAS) were developed by Jensen (1998) and later refined by Jensen (2003). Jensen (1998), in acknowledgement of the fact that alfalfa ET may be less than represented by published K_c values[19], multiplied his alfalfa K_c values by 85% to better represent production field conditions. The later revisions by Jensen (2003) presumably maintained this type of adjustment but the revised alfalfa K_c values had greater peak magnitudes than those presented by Jensen (1998). Jensen's (2003) K_c values[20] for the "Parker-Palo Verde Area" were compared to the 2020 daily ET_{obs}/ET_o (*Figure 27*). The Jensen (2003) K_c magnitudes were similar to the observed values in the spring and early summer months but deviated from the observed in the later summer and fall (*Figure 27*). This observation is independent of the fact that the cutting periods used by Jensen (2003) differ from the observed cutting times in the study fields. It is apparent that both magnitude and K_c timing would need to be modified to better match the observations. Montazar et al. (2020) also discussed the fact that mean ET_{obs}/ET_o values for 2019 were also less than some published K_c values.

The total annual ET_{obs} for the grower-convention treatment in 2020 was about 61 inches in both fields (*Figure 28*). For comparison in the present discussion, Jensen's (2003) K_c values (*Figure 27*) were used to compute ET_c. In this computation, the average of available AZMET and CIMIS reported daily ET_o for stations used by Reclamation (2019b) in *Lower Colorado River Annual Summary of Evapotranspiration and Evaporation* were used (UA, 2021; CDWR, 2021). The calculated annual alfalfa ET_c for the area was estimated to be about 67 inches for 2020. This approximately 10% difference between the observed and modeled annual total ET can be used as an example of the obvious benefits of ET measurement methods over models. However, the expense, expertise, and effort required to make the observations make them impractical for many conditions outside of research.

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[19] Jensen's (2003) justification included the citation of Hill et al. (1983).

[20] The K_c for February 29, 2020 was assumed to be the same as February 28 and March 1 (which were equal), because the Jensen (2003) values were for a non-leap year.

Figure 27 Daily Crop Coefficients (Kc) from Jensen (2003) and from Observed Evapotranspiration Divided by Reference Evapotranspiration from Two Research Fields for 2020.

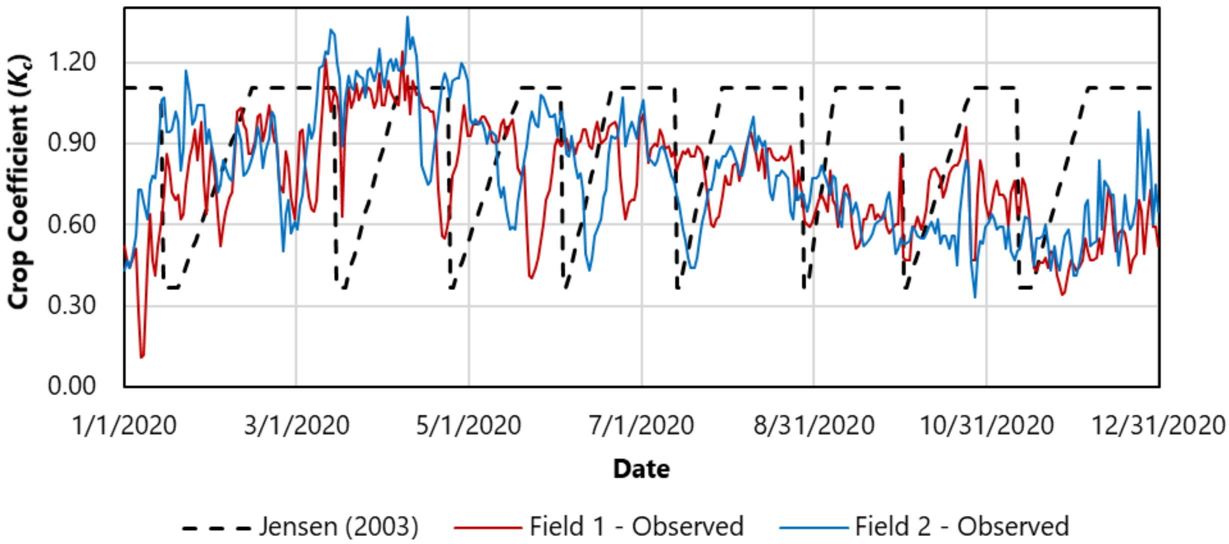
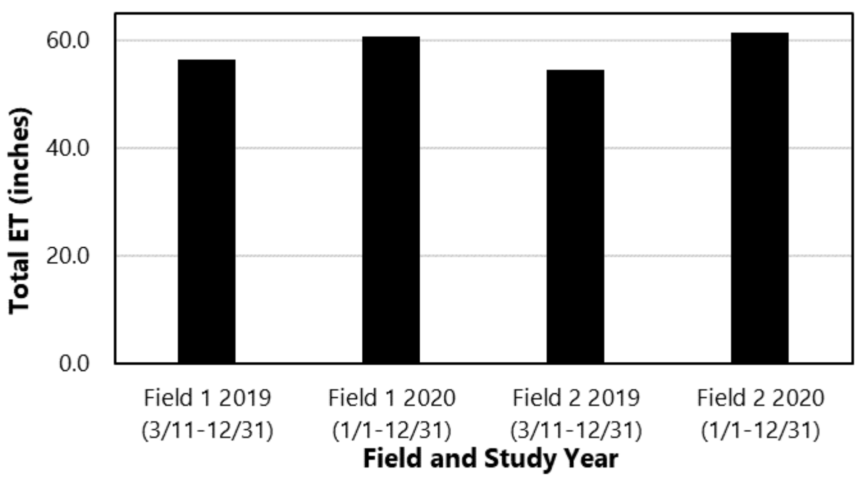


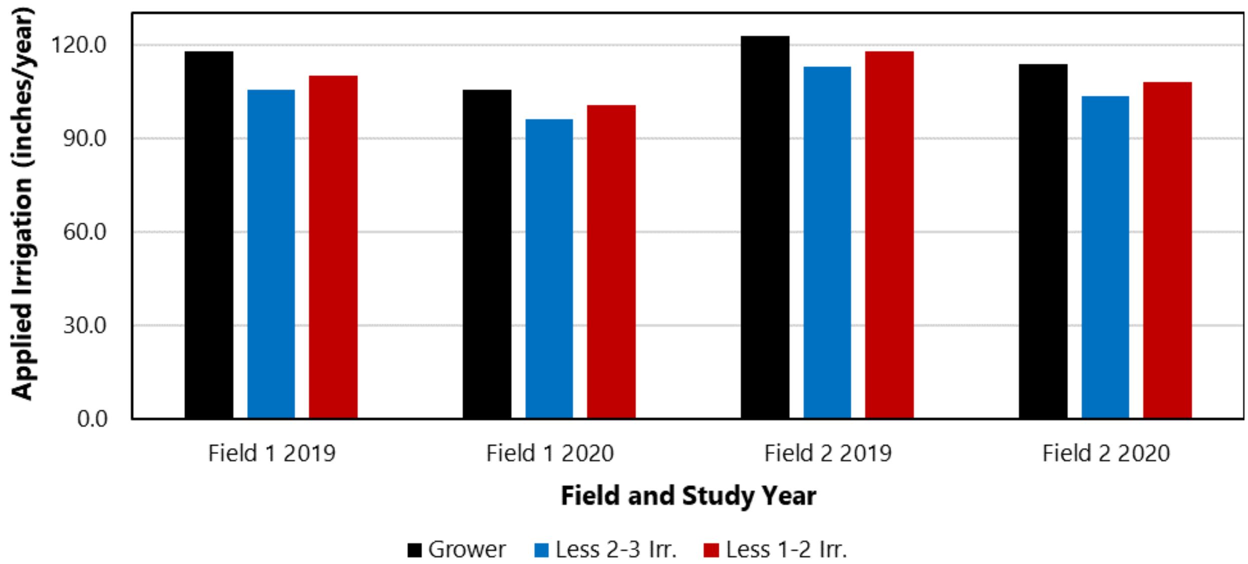
Figure 28 Total Observed Evapotranspiration (ET) for the Grower Convention Irrigation Treatment for Two Research Fields for a Partial Year in 2019 and all of 2020.



Applied Irrigation Water

As mentioned, the research study includes the quantification of reductions in applied irrigation water resulting from deficit irrigation. The reductions in irrigation water ranged from 4.6 to 12.5 inches less than the grower convention per season, depending on the year and season (*Figure 29*).

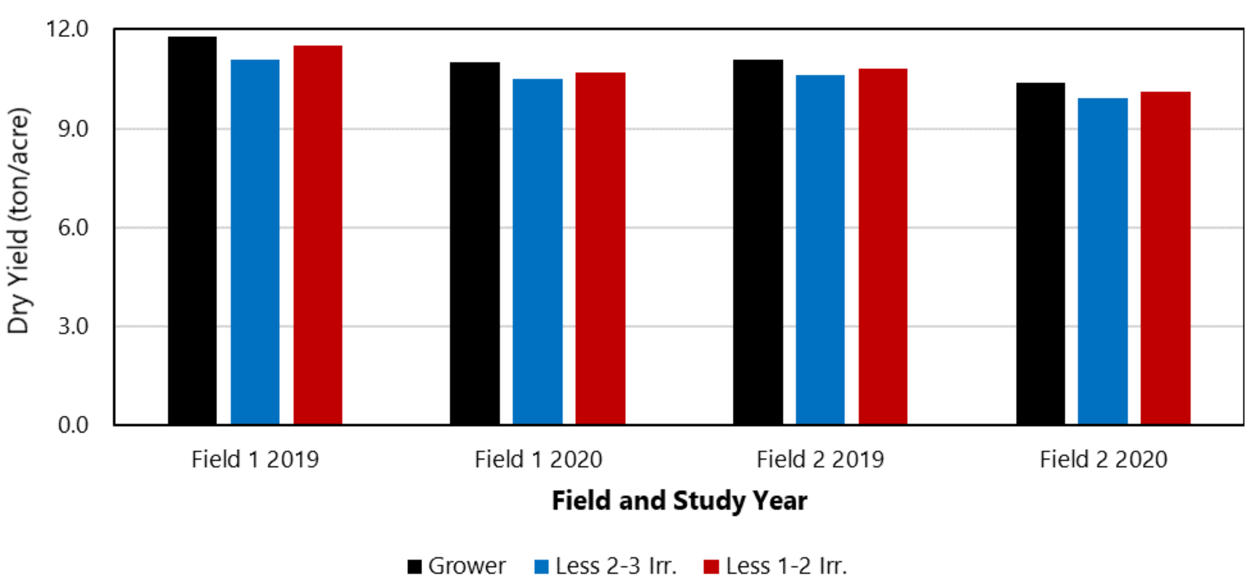
Figure 29 Seasonal Total Applied Irrigation Water for Study Treatments in Two Research Fields for 2019 and 2020.



Crop Yield

A final example result related to *ΔCU* from the study is the impact on yield. As expected, the crop yield appears, visually, to decrease with decreasing irrigation (*Figure 30*). However, it should be noted that the results as presented here do not include statistical tests of difference.

Figure 30   Seasonal Total Dry Yield for Study Treatments in Two Research Fields for 2019 and 2020.



Discussion of Method Assumptions

The *ΔCU* methods used include several assumptions based on the methods used. Some of these assumptions are discussed in the following paragraphs.

Assumption 1: Assumptions of the micrometeorological techniques.

All micrometeorological techniques include certain assumptions that enable the methods to be used to estimate energy fluxes (energy transfer rates per unit ground surface area) and subsequently ET. These assumptions may include the concept that energy transfer is vertical only, and in the case of eddy covariance, that the measurement is made in the proper layer of the atmosphere. It is beyond the scope of the present discussion to consider all of these assumptions. However, it is useful to address the fact that they exist and that, to varying extents, these assumptions impact the accuracy of the measurements. As the only truly more accepted methods for measuring ET include weighing lysimeters, which include vastly greater resources to install and operate, the assumptions and uncertainties associated with micrometeorological techniques are generally accepted by ET researchers.

Assumption 2: The measurement systems have adequate measurement footprints.

All micrometeorological techniques are sensitive to the effects of the land surface of some upwind area, known as a footprint or fetch. The measurement footprint is dependent upon the instrument height and wind speed and direction, among other things (Hsieh, 2000). In the case of the research study, the Tule Technologies surface renewal systems will have a smaller fetch distance than the eddy covariance system and the surface renewal measurements made with that system. This is because the Tule Technologies measurements are located much nearer to the ground. The treatment plots within the study fields are arranged as long strips, running the full field length in the direction of the irrigation application with a shorter dimension (~ 200 feet; A. Montazar, communication May 26, 2021) perpendicular to the irrigation direction (Montazar et al., 2020). It is expected that the fetch will be more sufficient when wind directions are generally parallel to the length of the plots than when wind directions are parallel to the width of the plots. However, because treatment differences are not expected to be large (per communication from A. Montazar, May 26, 2021), and since the measurements are more sensitive to areas relatively near the station than those further away, this may have a small effect. It is particularly expected the Tule Technologies systems will be more likely to have adequate fetch. The footprints are also expected to be shorter (nearer to the measurement station) when the alfalfa is tall than when it has recently been cut (Hsieh, 2000).

Assumption 3: The turnout gate measurements are representative.

The researchers used the PVID records of applied water for the research, rather than making an independent applied water measurement. This was done because the PVID measurements were deemed sufficiently accurate and also to avoid the contention that could arise should the researchers measure a slightly different application rate (A. Montazar, communication, May 26, 2021). This is a practical consideration, as the proposed deficit irrigation practice will likely be adopted by local growers in the near future. However, as with the other case studies, there can be a trade-off between practicality and accuracy.

For example, possible errors could exist if the gate itself or the flow conditions during application differ from those used during the calibration. It is also helpful to understand that any flow measurement will be subject to the precision and accuracy of the method. In this case, the water head measurement at the gate is subject to a certain precision that in turn affects the precision of the flow measurement. Finally, it is also possible that the flow conditions at the measurement times will not be representative of the flow conditions throughout the day. Taking four measurements per day is an attempt to address this concern.

General Observations

There could be some concern under a deficit irrigation program that the CU reductions may be reduced by the need for additional irrigation after resuming irrigation. This could occur in the case where the crop depleted the soil water during the no-irrigation period and then the grower applied additional water to ensure the soil water was replenished. Because the irrigation timing and duration for all treatments are based on the grower-convention part of the field, it is not expected that additional "make-up" water would be applied to the deficit irrigated treatments. Furthermore, it has been observed by A. Montazar (communication May 26, 2021) that there is typically some "overirrigation" during regular events such that it is unnecessary to apply additional water to compensate for extra depleted soil water during the deficit irrigation period.

It is also helpful here to discuss the general applicability of the results of this study. As mentioned, the results of this study will be in the form of functions relating ΔY to ΔI and ΔCU, respectively. It was also speculated above that these relationships could be used to relate ΔCU to ΔI. These relationships will have been developed under the irrigation practices and growing conditions (soils, climate, crop vigor, and health) of PVID and will best represent the study conditions. The researchers will be in the best position to recommend the application conditions of these results. The relationship between ΔY and ΔCU may be expected to be less location-dependent than the ΔY to ΔI relationship. Among other things, this is because the latter is dependent upon the application efficiency, which would vary from location to location and field to field. The ΔY and ΔCU relationship is basically a water use efficiency and may be transferable to areas with similar climate and growing practices. However, such relationships are dependent upon many factors and are still subject to limited transferability (Steduto et al., 2012).

Reflections

Since this case study is really a review of a research study, some of the lessons learned and reflections are different in nature than the other case studies. For example, the primary observation is that the quantification methods used in this study are essentially limited to research settings. The end product relationships (relating ΔY to ΔI and ΔCU), however, are intended for wider application. In such a program, the grower would record and report applied irrigation water quantities and changes in soil water measured by sensors (A. Montazar, communication May 26, 2021).

The applicability of this type of program and any ΔCU quantification relationship that may be developed are important because estimating ΔCU by district water balance or other methods used in the fallowing programs, is not a feasible approach for deficit irrigation. As mentioned, the ultimate end product of this research will be an NRCS conservation practice or guide.

Colorado River Indian Tribes Fallowing Program

The Colorado River Indian Reservation (CRIR) was created in 1865 by the Federal Government for the Indians of the Colorado River and its tributaries. Initially, these were the Mohave and Chemehuevi people, but Hopi and Navajo people were relocated to the Reservation in 1945. The Mohave, Chemehuevi, Hopi, and Navajo Tribes, are collectively, the CRIT. The CRIR is located on both sides of the Colorado River in western Arizona and eastern California, with most of the land in Arizona, as shown on *Figure 31*. The Colorado River Irrigation Project (CRIP), a federal irrigation project operated by BIA, serves approximately 80,000 acres of irrigated farmland, and is located entirely within CRIT's Arizona lands. Small CRIR parcels (in both Arizona and California) receive water by direct pumping from the Colorado River.

Starting in 2016 and continuing to present, CRIT have participated in system conservation (SC) programs to create conserved water for storage in Lake Mead. These include:

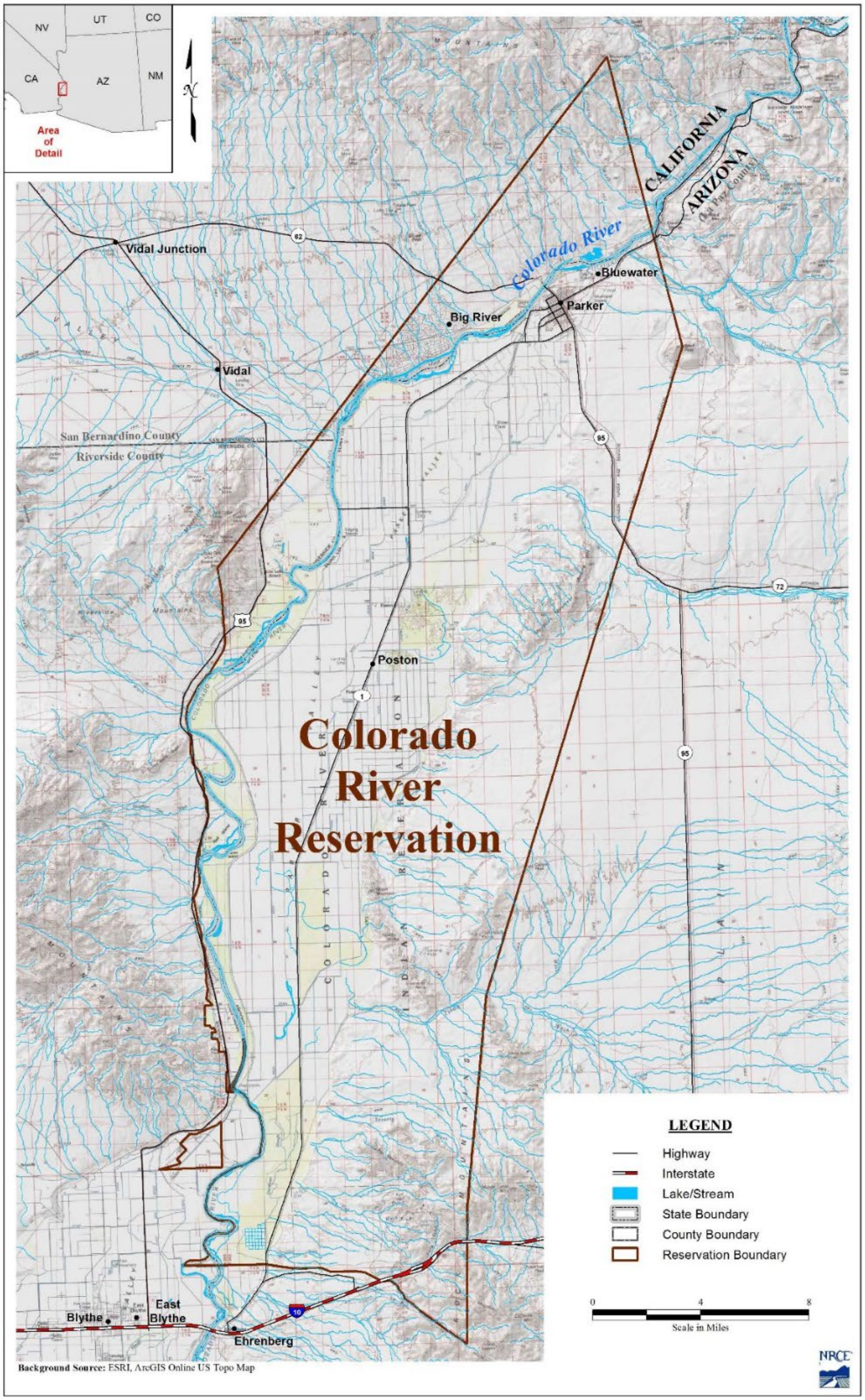
- The Pilot System Conservation Program (PSCP) established by Reclamation, the Central Arizona Water Conservation District (CAWCD), MWD, the Southern Nevada Water Authority (SNWA), and Denver Water[21] (later amended to include the Walton Family Foundation through the Environmental Defense Fund as a third-party contributor).

- CRIT's three-year (2020-2022) System Conservation Agreement (SC Agreement) with Reclamation, the Arizona Department of Water Resources (ADWR), and CAWCD under the State of Arizona's Drought Contingency Plan (DCP). Under this agreement, CRIT has agreed to create 50,000 AFY of CU savings to be stored in Lake Mead as system conservation water during each of the three years of the agreement. Any CU reduction in excess of the 50,000 AFY will be credited to CRIT as Extraordinary Conservation Intentionally Created Surplus (EC-ICS) and stored in CRIT's EC-ICS account in Lake Mead.

Conserved water in each case has consisted of CU reductions due to temporary fallowing of irrigated cropland on CRIT's Arizona lands. By the end of CRIT's current system conservation agreement (end of CY2022), CRIT will have created a total of 214,708 AF of CU savings for storage in Lake Mead. Of this amount, 195,329 AF will be system conservation water and 19,379 AF will be CRIT EC-ICS water. In all instances, except for the creation of EC-ICS, CRIT will have been compensated for its CU reductions under the various system conservation programs in which they have participated.

[21] https://www.usbr.gov/lc/region/programs/PilotSysConsProg/pilotsystem.html

Figure 31 Map of Colorado River Indian Reservation[22].



[22] Additional Sources: California Department of Forestry and Fire Protection, BIA, BLM, CRIT, Arizona State Land Department, Arizona Land Resources Information, USGS NHD, State of Arizona, U.S. Census Bureau, and/or State of California, California Spatial Information Library.

Technical Analysis

A technical analysis of the CRIT fallowing case study is presented in the following sections.

CU Quantification Methods

The primary method used to quantify changes in CU for the CRIT program is the reference evapotranspiration/crop coefficient method (TM2). In each of the water conservation activities in which CRIT has participated, the same methodology has been used to estimate crop CU. The following is summarized from pre-implementation reports provided by CRIT regarding their fallowing programs for system conservation and creation of EC-ICS during Calendar years 2020 and 2021 (NRCE, 2019; NRCE, 2020). *Figure 32* is a map of the CRIR and the locations of fallowed field parcels in the first year (2020) of the SC Agreement.

Field parcels being fallowed were required to have been in active irrigated crop production for at least four of the previous five years (study period) prior to being included in either program. In almost all instances, parcels fallowed had a full five-year irrigation and cropping history and the crop CU was estimated for the full five-year history. On each farm unit, the cropping patterns—meaning the crop type and acreage—for the previous five years were determined by field surveys conducted by the CRIT Water Resources Department[23] and entered into a geographic information system (GIS) database allowing spatially referenced mapping and determination of net irrigated area of each crop.

The ET of each crop was computed using the single (mean) crop coefficient-reference ET approach. In this method, reference ET was computed using the ASCE Standardized Reference Evapotranspiration Equation for short reference crop (ASCE, 2005; Jensen and Allen, 2016) and daily weather data collected at one or more local AZMET electronic weather stations operated by the University of Arizona (UA, 2021).

Daily crop coefficients developed by Jensen (1998, 2003) for Reclamation's LCRAS for the Parker Valley were used. Daily crop ET is computed as the product of reference ET and the crop coefficient for that day. Growing season durations of the various crops are implicit in the daily crop coefficients prepared by Jensen (1998, 2003) and were adopted for this analysis.

This method results in daily crop ET estimates for crops growing under ideal, pristine conditions and not short of water, and in some cases, has been termed "potential" crop ET (see TM2). Jensen (1998) recognized that alfalfa crop ET by this method was higher than local estimates and attributed the differences to water and other stresses, delayed baling and removal of hay bales, and other factors, and applied a factor of 0.85 to the alfalfa hay coefficients to obtain more realistic estimates of actual alfalfa ET in the LCRB. Jensen did not adjust crop coefficients for other crops. CRIT used the results from two regional studies that estimated actual crop ET by remote sensing (Clark et al., 2008 at Imperial Irrigation District (IID)); El Haddad and Garcia, 2014 at PVID) to adjust "potential" crop ET estimates from the crop coefficient-reference ET approach. This was done to avoid overstating the actual CU reductions due to temporary fallowing.

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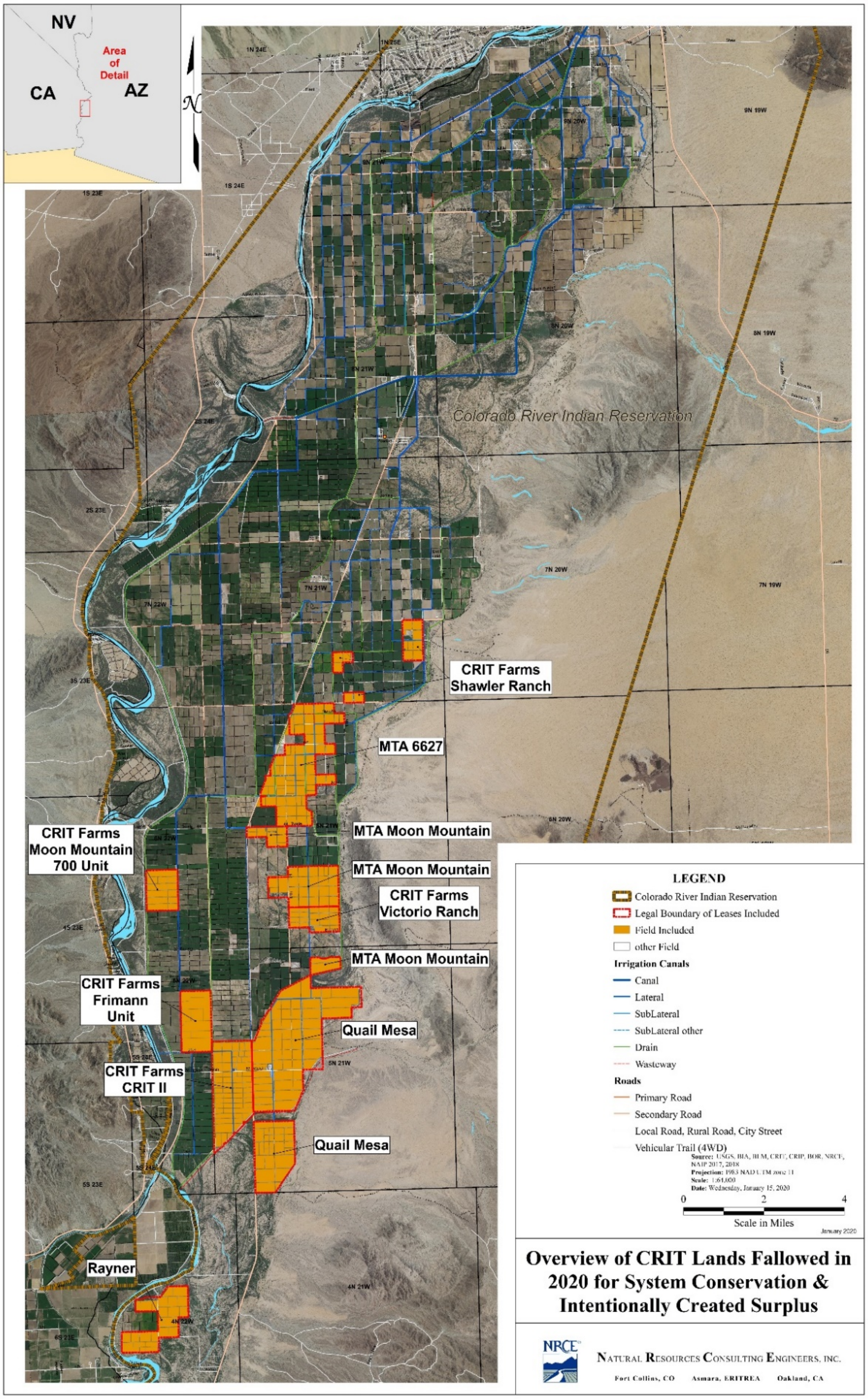
[23] With the exception of CRIT's first pilot system conservation implementation agreement when field crop survey data for 2013 were not available and the 2013 cropping pattern on the fallowed farm unit was estimated using the United States Department of Agriculture's (USDA's) National Agricultural Statistics Service Cropland Data Layer (CDL) (NASS, 2010-2015).

Figure 32 Map of Colorado River Indian Reservation and Location of Fallowed Parcels in 2020.



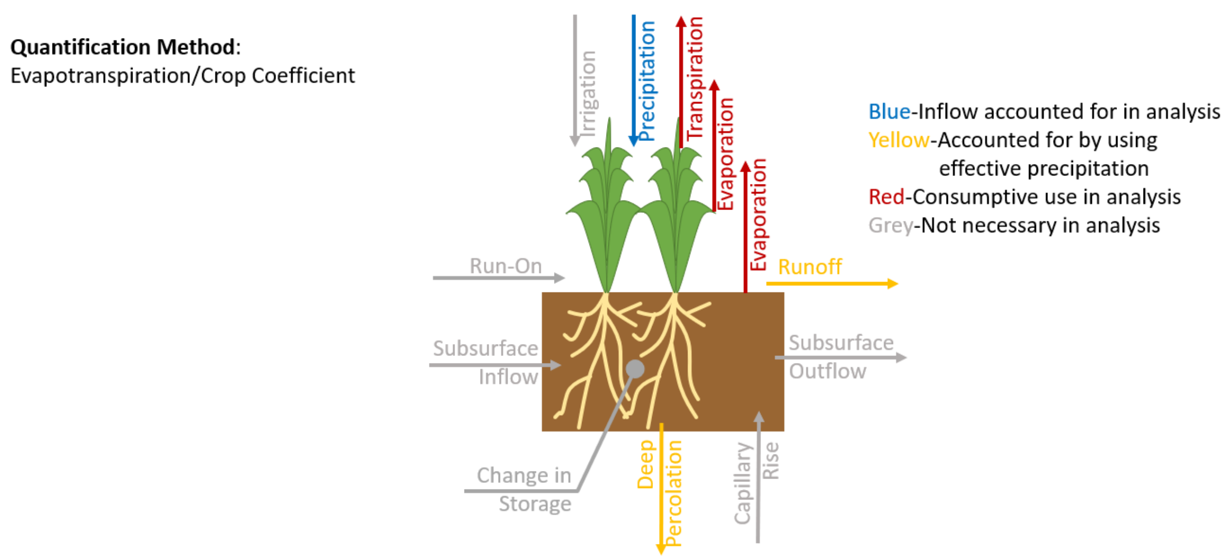
Net crop CU (of applied irrigation water) was computed by subtracting the effective precipitation (the portion of total precipitation that is effectively used by the crop in the ET process) from the crop ET estimates (e.g., *Figure 33*). Effective precipitation was computed using the same method as used in LCRAS, in which a region-specific flat monthly multiplier is applied to total precipitation to estimate effective precipitation (Jensen, 1993). As an example, average annual precipitation measured at the AZMET Parker No. 2 Station was 4.23 inches for the period: 2014-2019. Using the LCRAS method, effective precipitation on the Reservation is about 0.90 inches per year, or about 21 percent of average annual precipitation, for the 2014-2019 period at this location.

For each year of the study period analyzed, a weighted average net crop CU was determined for the farm unit based on acreages of the individual crop types on that unit and the net crop CU of each crop for that year. Using this result, an overall mean unit area net crop CU (in AF/ac) for the study period was determined for each farm unit. This study period average net crop CU was then multiplied by the maximum number of acres irrigated during the four or five years evaluated to determine the total crop CU reduction due to fallowing (ΔCU) as:

$$\Delta CU = A_{max} \times net\ CU_{unit\ area}^{mean}$$

where A_{max} is the maximum net irrigated crop area (in acres) during any year of the study period, and the net CU term is the study period mean unit area net crop CU. Computations were completed on a monthly basis and aggregated to annual totals.

Figure 33 Simplified Representation of the Consumptive Use Quantification Approach for the Colorado River Indian Tribes Fallowing Program.



Diversion Requirements

Under the SC Agreement, CRIT must determine an irrigation diversion requirement at Headgate Rock Dam corresponding to the crop CU reduction at each farm unit participating in the fallowing program. This was estimated by dividing the crop CU reduction by the estimated project irrigation efficiency (product of irrigation delivery system conveyance efficiency and on-farm application efficiency). For the purposes of these analyses, an overall project irrigation efficiency of 53.5% was applied (NRCE, 2017).

For any CU reduction designated as EC-ICS, the associated irrigation diversion is computed using the CU/Diversion ratio for the CRIP using data reported in the most recent published Reclamation Decree Accounting report (per the methodology designated in the Lower Colorado River Basin Drought Contingency Operations (LBOps) Intentionally Created Surplus (ICS) Exhibit S for CRIT.

SC Agreement Conditions

The CU on CRIT's Arizona lands is affected by many factors that are not within the control of the Tribes, including the number of acres planted by lessees, assignees, and allottees, and the crops planted. The SC Agreement required the following in an effort to make sure that a reduction in CU was realized and to limit the amount of water diverted for the Arizona CRIR lands:

- The total irrigated area on Arizona CRIR lands would not exceed 72,871 during the time of SC creation;
- CRIT would use 612,725 AFY as the baseline maximum diversion; and,
- The annual water order requests submitted by CRIT to BIA (under Title 43 Code of Federal Regulations Part 417) contain CRIT's Adjusted Maximum Diversion (which is to be computed as Baseline Diversion minus the required Reduced Diversion Amount, per the SC Agreement) for the year in question.

Irrigated Acreage

Irrigated crop acreage in 2020 was obtained from the annual CRIT Water Resources Department crop survey. The results of the 2020 crop survey are in *Table 13*, below. The total irrigated crop acreage in 2020 was 57,702 acres. The irrigated cropped acreage plus SC/EC-ICS program fallowed lands (10,786 acres) totaled 68,488 acres. This is less than the 72,871-acre limit for irrigated acreage during the SC agreement.

Table 13 Summary of Irrigated Cropland by Crop Type, Fallowed Acreage, and Idle Acreage on CRIT Reservation Lands in Arizona, CY2020.

Crop	Gross Acres
Alfalfa	43,981
Bermuda	2,956
Broccoli	261
Cotton	2,043
Garlic	--
Onion	122
Potato	1,865
Preserve	211
Sudan	2,828
Wheat	3,435
Total Irrigated Land in Production	**57,702**
Fallow (Project)	9,998
Fallow (Rayner)	788
Total Irrigated Land in Production plus SC/ICS Fallowing	**68,488**
Idle Land	7,723
Total	**76,211**

Reduced Diversions

CRIT's original and amended water orders for Colorado River water diversions to Reservation lands in Arizona called for a final 2020 diversion request of 509,390 AF by the CRIP, and a diversion request of 2,628 AF for "Other Diversions" that included direct pumping from the Colorado River and wells, making for a total diversion to CRIR Arizona lands of 512,018 AF. A diversion reduction of 100,706 AF associated with the ΔCU due to CY2020 fallowing was estimated (*Table 14*). The adjusted maximum diversion amount for CY2020 should thus be less than or equal to (612,725 – 100,706) 512,019 AF. The diversions, return flows, and CU for the CRIR in Arizona as reported in Reclamation's CY2020 Decree Accounting (Reclamation, 2021a) are contained in *Table 14*. CRIT's total diversion to its Arizona lands in 2020 was 459,026 AF, well less than the Adjusted Maximum Diversion amount and the amount requested of 512,018 AF.

CRIT's 2020 fallowing program met the conditions of the SC agreement to result in a measurable reduction of water use. Field verification by CRIT Water Resources Department, Reclamation, and ADWR supports that identified farm units were fallowed and did not receive irrigation water for all of CY2020.

Table 14 Record of Diversions, Returns, and Consumptive Use for CY 2020 by Colorado River Indian Reservation in Arizona.

Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Diversions at Headgate Rock Dam	17,500	30,270	11,150	47,220	57,730	56,080	59,550	57,450	40,820	28,190	23,090	27,900	456,950
Diversions Pumped from the Colorado River and Wells	122	115	129	146	235	225	247	237	200	175	136	109	2,076
Measured Returns	14,664	17,260	13,356	20,734	23,269	22,520	23,402	23,325	20,230	18,090	16,775	17,692	231,317
Unmeasured Returns	969	1,671	620	2,605	3,188	3,097	3,289	3,173	2,256	1,560	1,277	1,541	25,246
Consumptive Use	1,989	11,454	-2,697	24,027	31,508	30,688	33,106	31,189	18,534	8,715	5,174	8,776	202,463

Source: adapted from Reclamation (2021a)

Fallowed Land Verification

During the fallowing period, in order to ensure that any vegetation remaining on the fallowed lands does not consumptively use Colorado River water by drawing water from the Colorado River aquifer, CRIT is required to control and eradicate any green vegetation growth. Weed control is performed using both tillage and chemical means. Records of weed control activity, including date, chemicals used, rates of application, tillage methods, etc. are prepared and maintained. CRIT agreed to provide Reclamation, ADWR, and other applicable entities, with information and updates, when requested, regarding the vegetation eradication program. Stubble from previous cropping is kept on field surfaces to the extent possible to reduce wind erosion (see *Figure 34* of fallowed fields with crop residue and *Figure 35* of a field without residue). CRIT has agreed to grant access to Reclamation and ADWR personnel to perform periodic on-site inspections to verify compliance.

Additionally, CRIT agreed to furnish and install padlocks to lock the farm gate turnouts to fields fallowed to the extent possible to do so. In the event that a turnout serves multiple fields of which not all are being fallowed, other practical mechanisms, including but not limited to, dirt berms in the portion of the irrigation ditch serving the fallowed field, or sealing the on-farm turnouts onto fallowed fields are used to assure that no water deliveries can be made onto the fallowed fields.

Figure 34 Photos of Surface Crop Residue in Fallowed Fields in the Colorado River Indian Tribes' Fallowing Program (Credit: Right: L. Perkins, Left: B. Barker, May 26, 2021).

Figure 35 Photo of Fallowed Field without Surface Residue in the Colorado River Indian Tribes' Fallowing Program (Credit: L. Perkins, May 26, 2021).

Example CU Results

Table 15 below is a summary of CRIT's fallowing in CY2020 under the SC Agreement and the resultant CU estimated reductions (NRCE, 2019). This table includes, for each of nine farm units that were fallowed in CY2020[24], the following:

- Net irrigated field area
- Average crop mix during the study period
- Average unit area net CU for the five-year study period
- Average annual net CU, or ΔCU, for the five-year study period

[24] All of these fields were under the operation of CRIT Farms, the Tribal farming enterprise.

Table 15 Summary of CRIT System Conservation and EC-ICS for CY2020.

Unit	Name	Time Period	Gross Acreage	Max. Net Irrigated Acreage	Ave. Cropping Pattern	Total Net Consumptive Use		Net Consumptive Use Proration		Diversion Reduction Proration		Total Diversion Reduction
						Average AF/ac	Annual AFY	System Conservation AFY	EC ICS AFY	System Conservation * AFY	EC ICS** AFY	Annual AFY
6627	**MTA Farms**	2014-18	1,957.6	1,884.0	80% alfalfa 20% Sudan grass	5.39	10,157	9,450.7	706.2	17,664.8	1,502.6	19,167
6808	**Quail Mesa**	2014-18	3,999.7	3,704.6	58% alfalfa 4% small grain 6% Bermuda (grass hay) 11% Sudan 21% Miscellaneous (onion, garlic, corn, potato)	4.89	18,130	16,869.7	1,260.6	31,532.2	2,682.1	34,214
6693	**MTA Farms**	2014-18	1,343.6	1,183.9	64% alfalfa 1% cotton 6% small grain 13% Bermuda (grass hay) 14% Sudan 21% Miscellaneous (onion, garlic, corn,	4.97	5,886	5,476.3	409.2	10,236.1	870.7	11,107
CRIT Farms	**Victorio**	2014-18	424.7	406.8	60% alfalfa 5% cotton 17% small grain 12% Bermuda (grass hay) 5% Sudan	4.61	1,877	1,746.5	130.5	3,264.4	277.7	3,542
CRIT Farms	**Frimann**	2014-18	674.7	674.7	52% alfalfa 26% cotton 18% small grain 4% Sudan	4.37	2,951	2,745.4	205.2	5,131.7	436.5	5,568
CRIT Farms	**CRIT II**	2014-18	1,265.8	1,238.7	73% alfalfa 19% cotton 6% small grain 2% Miscellaneous (onion, garlic, corn, potato)	5.04	6,247	5,812.4	434.3	10,864.4	924.1	11,788
CRIT Farms	**MTA 700**	2014-18	484.3	465.8	86% alfalfa 7% cotton 7% Bermuda (grass hay)	5.50	2,562	2,383.8	178.1	4,455.7	379.0	4,835
CRIT Farms	**Shawler Ranch**	2014-18	454.9	439.5	69% alfalfa 30% cotton 2% Sudan	5.02	2,206	2,052.9	153.4	3,837.2	326.4	4,164
9035* **	**Rayner**	2013-17	870.7	788.0	52% alfalfa 32% cotton 12% Bermuda (grass hay) 4% Sudan	4.72	3,721	3,462	259	5,770	550.5	6,321
Totals			11,476.0	10,786.0			53,736	50,000	3,736	92,757	7,949	100,706

*System Conservation diversion reduction for Field Units served by the Project is based on Project overall average irrigation efficiency equal to 53.5%.

**ICS diversion reduction for all Units is based on Project CU/Diversion ratio of 0.470 for 2018 using methodology designated in the LBOps ICS Exhibit S for CRIT.

***Estimates in this table for 9035 are based on 2013-2017 USGS cropping data with the area under a linear move sprinkler system removed; System Conservation diversion reduction using an overall average irrigation efficiency for direct pumping from River equal to 60%

- Proration of *⊿CU* between SC and EC-ICS for each farm unit
- Proration of the associated diversion reduction between SC and EC-ICS for each farm unit
- Total diversion reduction on each farm

The last row of the table contains totals for CY2020. CRIT proposed to fallow a net irrigated field area of 10,786 acres to produce a total *⊿CU* of 53,736 AF (50,000 AF to SC and 3,736 AF to EC-ICS). The associated diversion reduction is a total of 100,706 AF.

Discussion of Method Assumptions

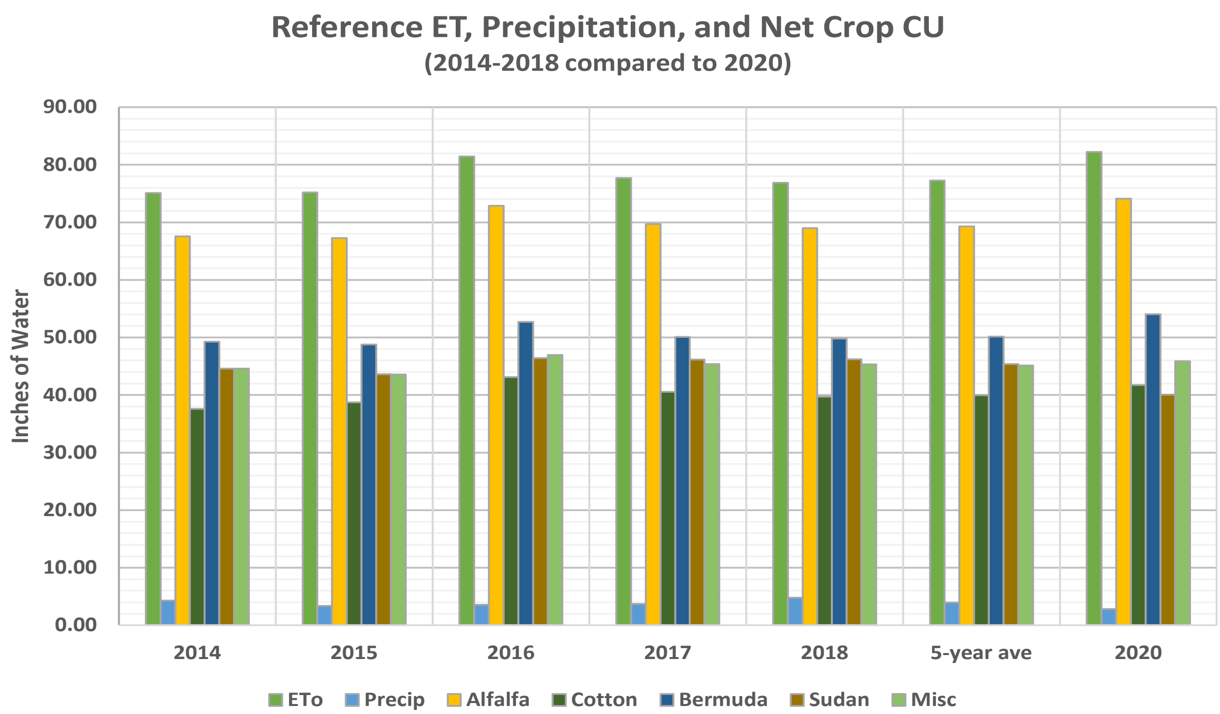
The *⊿CU* method includes several assumptions, which are either explicit or implicit in the method. The primary assumptions are discussed below.

Assumption 1: The four- or five-year study period average CU of crops grown on the fallowed fields is representative of the CU that would have occurred on the fallowed fields during the year or years of fallowing.

This assumption essentially has two parts—both the crop mix that would have been grown and the climate during the fallowing period are assumed to be represented by the crop mix and the climate of the study period used to determine *⊿CU*. Significant deviations in either of the cropping pattern or the climate of the fallowing period from the annual range of crops or climate occurring during the study period may result in either an over- or under-estimation of *⊿CU*. The crop mix that would have been present on the fallowed fields during the fallowing period is unknown. However, CRIT cropping is heavily dominated by perennial crops such as alfalfa and Bermuda grass hay, and the percentage of these crops across the Reservation has been relatively stable over the past 5-8 years, based on crop surveys prepared by the CRIT Water Resources Department.

Climate variability on a seasonal and annual basis does occur. Rather than evaluating each parameter, a comparison of the short crop reference ET, precipitation, and the net CU of the major crops allows assessment of whether there may be potential impacts from assuming the study period average climate condition is representative of the fallowing period climate. *Figure 36* is a graphical comparison of total annual reference ET, precipitation, and the net CU of alfalfa, cotton, small grains, Bermuda grass hay, Sudan grass, and miscellaneous winter crops for each year of the study period, the five-year average (2014-2018), and for the fallowing period (2020). Minor differences are observable, but in this instance are considered negligible. There may be other cases where a four- or five-year average is not considered representative of the fallowing period. In such instances, a normalizing factor such as the ratio of reference ET for the study period to that of the fallowing period could be computed and applied on a monthly basis to adjust the longer-term averages to the conditions of the fallowing period (e.g., Allen and Torres-Rua, 2018). Such adjustment would necessarily be *post facto* and would require flexibility in the terms and conditions of the SC agreement.

Figure 36 Comparison of Study Period (2014-2018) versus Fallowing Period (2020) Reference ET, Precipitation, and Net CU of Major Crops on the Colorado River Indian Reservation.



Assumption 2: The factors applied to reduce the computed "potential" crop ET to actual crop ET are reasonable and appropriate adjustments and result in actual crop ET that is representative of actual field conditions.

As discussed in TM2, it is well known that the crop coefficient-reference ET approach (whether single mean crop coefficient or dual crop coefficient) produces crop ET estimates considered to be "potential" crop ET because the crop coefficients used are typically developed under experiment station conditions whereby most stresses (water, pest, or disease) are carefully managed to minimize or eliminate the impacts of such stresses in crop water use. As noted above, Jensen (1998) recognized that alfalfa crop ET by this method was higher than local estimates and applied a factor of 0.85 to the alfalfa hay crop coefficients to obtain more realistic estimates of alfalfa ET in the LCRB. CRIT used the results of two relatively large-scale studies, one at PVID and one at IID to develop adjustment factors for other crops. The purpose of this effort was to avoid an overstatement of the actual *ΔCU*. A more rigorous evaluation of this approach, including a remote sensing ET modeling for CRIP lands, may be advisable.

Assumption 3: The CU from the fallowed fields (and possibly the irrigation and drainage ditches serving the fallowed land) is negligible.

This assumption is discussed in both the Bard Water District Seasonal Fallowing Program *Discussion of Method Assumptions* and the Palo Verde Irrigation District Forbearance and Fallowing Program *Discussion of Method Assumptions* sections.

Assumption 4: Any carryover effects of fallowing on CU are negligible.

This assumption is directly related to the assumption that the CU from fallowed land and the associated ditches is negligible (see the previous assumption). This assumption is valid so long as evaporation from the fields and the dried-up ditches can be considered negligible during the fallow period.

Reflections

A benefit of the approach taken to compute ΔCU under CRIT's fallowing program is the computation of crop CU and estimation of the associated diversion reduction prior to fallowing implementation. Also of benefit, is the fact that the computation methodology is independent of what is occurring on the remainder of the irrigated lands on the part of the Reservation in Arizona during the fallowing period. For each year of the study period analyzed, a weighted average net crop CU was determined for each farm unit based on acreages of the individual crop types on that unit and the net crop CU of each crop for that year. There were instances on some farm units during some years when fields on the unit may have been idle. These were not included in the calculated net crop CU for that unit for that year (i.e., both irrigated acres and CU on the idle parcel would be zero). The overall average net crop CU was calculated based only on the net irrigated and cropped acreage during the study period.

A potential drawback of the CRIT methodology that is very important to note, however, is that due care must be applied to develop crop CU estimates representative of the actual field conditions. This includes use of representative high-quality weather data, a state of the science crop ET estimating method (such as the single mean crop coefficient-reference ET method used that is based on ASCE's Standardized Reference ET Equation), accurate crop survey data, etc. The component of this due diligence that can and should be improved in the very near future is the cross-comparison of net crop CU under CRIT's methodology with actual crop ET estimates that will become available under the OpenET project (OpenET, 2021).

The comparison of the ΔCU under this methodology to Reclamation Decree Accounting requires a reasonably accurate assessment of irrigation efficiency to convert the ΔCU to an associated diversion amount. This diversion amount is actually the diversion reduction CRIT is required to show in its annual water order under terms of the SC Agreement, and as previously explained, is subtracted from the maximum baseline diversion to determine an adjusted maximum diversion amount. This maximum diversion amount is then directly comparable to Decree Accounting results. Parties to the agreement can track diversions monthly and annually to ensure there is a reduction in CRIT's diversions and water use due to the fallowing. The irrigation efficiency in this case is the ratio of net crop CU to total water diverted. All sources of the total CU other than net crop CU should be removed to the extent possible. The development of this ratio is most often accomplished with a water balance and requires extensive, high-quality data on crops, acres irrigated, water measurement at diversions, spills, drains, etc. This was accomplished at CRIT but there is considerable room for improvement of the data and the results. It is expected that as CRIT make water conservation improvements, the project irrigation efficiency will improve.

Other observations/lessons learned include:

- The maximum baseline diversion of 612,725 AF is approximately 50,000 AF less than CRIT's annual Colorado River water right allocation to CRIR lands in AZ of 662,402 AF. This condition was imposed in the agreement (among other conditions) to ensure that there would be a measurable reduction in CRIT's water use. The impact of not being able to draw upon this 50,000 AF was to cause CRIT Farms to idle additional land not in the fallowing agreement (of the 7,723 acres of idle land shown in *Table 13* above, approximately 3,990 acres were under CRIT Farms management and put into short term idle). CRIT Farms is adjusting its crop mix to lower water use crops to accommodate the restriction. However, access to divert and use the 50,000 AF imposed reduction would have alleviated CRIT Farms' need to perform additional short-term idling of irrigated cropland. CRIT's fallowing program performance has been demonstrated in 2020 and, so far, in 2021 with diversions and CU well less than what was actually proposed as can be verified in Reclamation annual Decree Accounting reports.

- The fallowing program at CRIT has focused on maximizing the CU yield from fallowing and thereby has focused on fallowing farm units with high percentages of alfalfa in the crop mix that are approaching the end of their useful stand life. Some of these units had multiple field parcels with glyphosate-resistant genetically modified (GMO) alfalfa. In fallowing such stands, CRIT management has found considerable extra diligence is required to eradicate the stand and keep the parcel free of green vegetation.

- In the development, implementation, and evaluation of its fallowing program, CRIT has had to work with multiple agencies to be successful: Reclamation, ADWR, CAWCD (the parties to the agreement); and BIA (at the national, regional, and local office levels, e.g., Colorado River Agency). There were multiple instances of delays with reviews, comments, and feedback due to the number of entities reviewing and agreeing to terms and conditions. There were also the inevitable communications breakdowns that resulted in misunderstandings and actions that negatively impacted the Tribes and their lessees.

- Recent studies commissioned by CRIT Tribal Council show there may be multiple opportunities to improve the overall irrigation efficiency of the Colorado River Irrigation Project (Franzoy, 2017; NRCE, 2017). Project irrigation efficiency is the combination of conveyance efficiency and on-farm efficiency. The Franzoy (2017) report refers to a systematic study of the Project, which provided details of infrastructure, e.g., leaky gates and check structures, eroded earthen canal prisms, and other large Project infrastructure, requiring significant capital investment to rehabilitate or replace. Improving such infrastructure will improve Project conveyance efficiency. The NRCE (2017) report presents the results of water balance analyses using Project data for the period June 2011-December 2015 to identify inefficiencies on the Project (at both the conveyance and on-farm levels) and opportunities for improving efficiency and conserving water. The Project has low on-farm efficiencies due to high seepage loss in on-farm ditches and a high volume of deep percolation losses of water applied to farm fields. On-farm improvements are the responsibility of the landowner or lessee. These delivery system and on-farm system inefficiencies have resulted in a Project efficiency of approximately 50%, meaning half of CRIT's diversions are returned to the River as Project return flows. CRIT has strong interest in addressing Project inefficiencies at both the delivery system and on-farm levels. CRIT's objectives are to make water available for expanded irrigation or alternate economic uses and benefits to the Tribes, while also maintaining an irrigated agriculture land base and a healthy environment along the Colorado River. To this end CRIT is using some of its compensated system conservation to fund improvements on the Project.

Mohave Valley Irrigation and Drainage District Fallowing Program

MVIDD is in western Arizona. The district is non-contiguous being positioned around lands of the Fort Mojave Indian Reservation (MVIDD, 2016; *Figure 37*). MVIDD's service area is about 31,500 acres with about 7,000 acres of farmland that can be irrigated and about 380 acres of golf course (MVIDD, 2016).

MVIDD's irrigation water is from wells in the Colorado River alluvial aquifer. MVIDD is comprised of individual farm-level conveyance systems, with wells discharging into lined head ditches (*Figure 38*), rather than a single, large, shared canal system.

In 2020, MVIDD began a fallowing program for system conservation (MVIDD, 2019). For this program, an enrollment process was created whereby participating farmers voluntarily enter into an agreement with MVIDD to fallow land that had been verified as actively cultivated in three or more of the five most recent years (MVIDD, 2020b). The fallowed areas or parcels are limited to 10 or more acres each (MVIDD, 2020b). Upper limits are specified for both the amount of land that can be irrigated and the total annual irrigation diversions for the district during the fallow periods. The proposed fallowed area was approximately 1,200 acres in 2020 and over 1,300 acres in 2021 (MVIDD, 2019, 2020b). The proposed system conservation volume was 6,137 AF in 2020 and 6,778 AF in 2021 (MVIDD, 2019, 2020b).

Figure 37   Map of the Mohave Valley Irrigation and Drainage District (Provided by MVIDD).

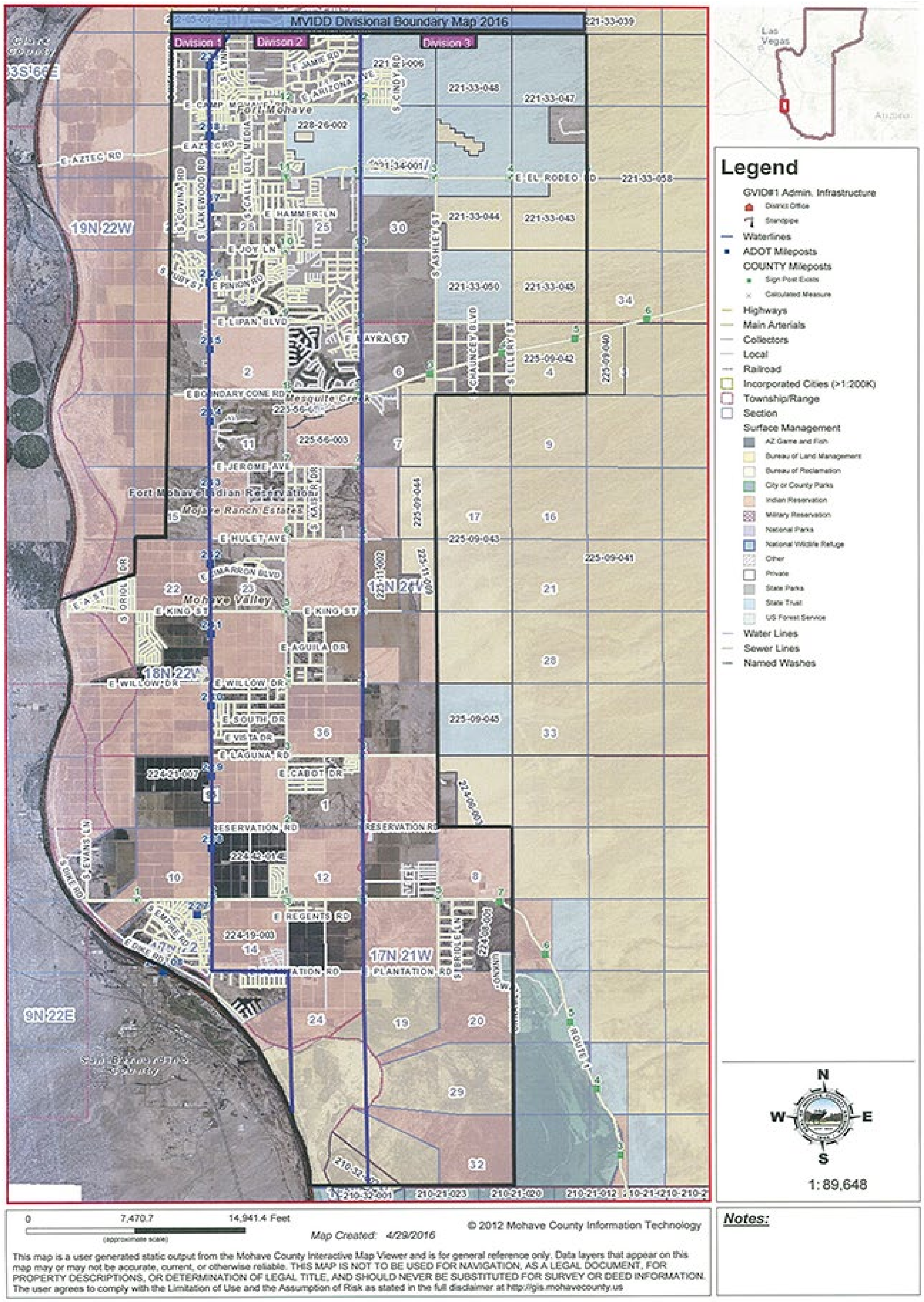


Figure 38 Photos of Irrigation Infrastructure in the Mohave Valley Irrigation District (credit: L. Perkins, May 27, 2021).

Technical Analysis

A technical analysis of the MVIDD fallowing case study is presented in the following sections.

CU Quantification Methods

The CU reduction estimates for the MVIDD fallowing program are estimated using the reference evapotranspiration/crop coefficient method and spatial crop surveys (Land IQ, 2020; see also TM2). MVIDD contracted with Land IQ (Sacramento, CA) to conduct the CU analysis.

Crop Surveys

Crop surveys were performed by Land IQ (2019, 2020) using a remote-sensing-based analysis for the five recent years (2014-2018 for 2020 and 2015-2019 for 2021). The surveys were performed only for fields that were intended to participate in the fallowing program (1,214 acres total in 2020[25] and 1,344 acres in 2021[26]). They used remote sensing techniques and both satellite imagery (Landsat) and aerial imagery (National Agricultural Imagery Program, NAIP) for the analysis. Care was taken to consider only irrigated areas. The geospatial Crop Data Layer from the National Agriculture Statistics Service (NASS) was used for validation (Land IQ, 2020; https://nassgeodata.gmu.edu/CropScape/). Land IQ (2020) reported the accuracy of their surveys to be better than 97% based on experience in California and provided justification that the accuracy at MVIDD was expected to be at least that based on the relatively few crops grown in the district.

Evapotranspiration and Crop Water Use Modeling

The ET modeling performed by Land IQ (2020) was done using the reference-ET-crop-coefficient method:

$$ET_c = ET_o K_c$$

[25] Later reduced to 1,196 acres (MVIDD, 2019).

[26] The program included 1,348 acres (MVIDD, 2020b).

where ET_c is modeled crop ET, ET_o is short reference ET, and K_c is used to represent a specific crop and crop growth conditions (TM2; Jensen and Allen, 2016). For this analysis, "quality control[led]" ET_o was obtained from the individual in charge of AZMET (Land IQ, 2019). They used mean ET_o for two to three AZMET stations in the Mohave Valley, depending on data availability. They obtained K_c values from a common source, the Food and Agriculture Organization of the United Nations Irrigation and Drainage Paper No. 56 (Allen et al., 1998) and from consultation from "…professors at University of California, Davis ([R.L.] Snyder, [communication], 2016)" (Land IQ, 2019).

CU was based on the ET of applied water (ET_{AW}), which was computed by subtracting effective precipitation, or that portion of precipitation that contributes to the crop water requirement (e.g., SCS, 1993). Effective precipitation was computed using a piecewise polynomial function and precipitation data from the same AZMET source as the ET_o (Land IQ, communication, September 2, 2021).

Reduction in CU

As with other fallowing programs, ΔCU was computed as the difference in CU quantified for crops (as represented by ET_{AW}) that may have been grown on the fields had they not been fallowed, as represented by the analysis described above (Land IQ, 2019, 2020). The fallowed fields were assumed to have zero CU. This was done for each participating landowner, with ET_{AW} or ΔCU for each year being computed as area weighted averages based on the crop surveys. Average ΔCU values were then computed across years for each grower and the five-year average ΔCU was totaled for the district.

Reduction in Diversion

The fallowing program has a limit on MVIDD diversions for irrigation, as described above (MVIDD, 2019, 2020b). To compute this, MVIDD used the mean total irrigation diversion for MVIDD from the Decree Accounting for 2014-2018 for 2020 and for 2016-2019[27] for 2021 (MVIDD, 2019, 2020b). These were 29,725 AF and 29,312 AF, respectively (MVIDD, 2019, 2020b). MVIDD (2019, 2020b) then subtracted a 7 AF/ac diversion allowance for each fallowed acre to obtain a diversion limit. For 2020, this was 29,725 AF – (1,196 ac × 7 AF/ac) = 21,353 AF. For 2021, this was 29,312 AF – (1,348.62 × 7 AF/ac) = 19,872 AF.

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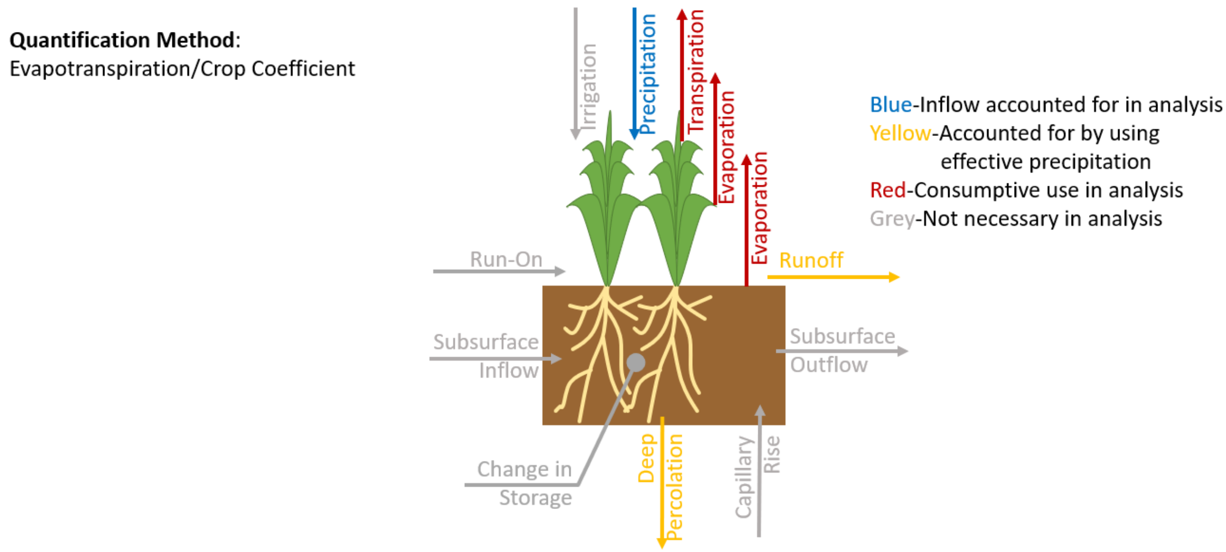
[27] The four years with the greatest diversion for MVIDD in Reclamation (2021a) from 2015-2019 (MVIDD, 2020b).

Figure 39 Simplified Representation of the Consumptive Use Quantification Approach for the Mohave Valley Irrigation and Drainage District Fallowing Project.



Example CU Results

Crop Surveys

The crops identified by Land IQ (2020) were alfalfa, other hay (including Bermuda), Sudan, and fallowed land, with alfalfa being the predominant crop (*Table 16*). The relative proportions of the various crops identified by Land IQ (2020) were similar to those reported in the 2019 and 2020 district crop reports (MVIDD, 2020a, 2021; *Table 17*).

Table 16 Summary of Crop Surveys for Fields to be Fallowed (Land IQ, 2019, 2020).

Crop Year	Program Year	Crop						
		Alfalfa	Alfalfa (Poor and Partial Year)	Other Hay (Including Bermuda)	Fallow	Sudan	Sudan Followed by Alfalfa	Total
		------- *Irrigated Area (acres)* -------						
2014	2020	1,162			19		34	1,214
2015	2020	1,123			19	36	36	1,214
	2021	1,118			154	36	36	1,344
2016	2020	1,161			19			1,180[1]
	2021	1,128		110	107			1,344
2017	2020	1,195		19				1,214
	2021	1,269		75				1,344
2018	2020	1,195		19				1,214
	2021	1,269		75				1,344
2019	2021	1,097	35	212				1,344

[1]Sum does not equal the full 2020 surveyed area of 1,214 acres.

Table 17 Summary of Mohave Valley Irrigation and Drainage District Crop Reports for 2019 (Before the Fallowing Program) and 2020 (First Year of the Fallowing Program) (MVIDD, 2020a, 2021).

Crop Year	Crop					
	Alfalfa	Other Hay (Including Bermuda and Ryegrass)	Hemp	Small Grain	Vegetables	Total
	------- *"Farmed" Area (acres)* -------					
2019	3,172	575			14	3,761
2020	2,215	436	51	394		3,095

Evapotranspiration and Crop Water Use

The modeled ET_C and ET_{AW} for the identified crops were computed and summarized as annual totals (Land IQ, 2020, 2021; *Table 18*). The computed ET_{AW} was similar in magnitude to ET_C as a result of the relatively small effective precipitation.

Table 18 Summary of Modeled Crop Evapotranspiration and Evapotranspiration from Applied Water for Mohave Valley Irrigation and Drainage District (Land IQ, 2020, 2021).

Crop Year	Crop			
	Alfalfa[1]	Other Hay (Including Bermuda)	Fallow	Sudan
	------- *Annual Crop Evapotranspiration (inches)* -------			
2014	62.1	62.3	0.0	37.0
2015	63.3	63.5	0.0	38.4
2016	62.8	62.7	0.0	38.3
2017	63.5	64.0	0.0	38.8
2018	66.6	67.0	0.0	41.3
2019	63.3	64.0	0.0	39.2
	------- *Annual Evapotranspiration from Applied Water (inches)* -------			
2014	59.6	59.8	0.0	35.1
2015	60.6	60.8	0.0	37.8
2016	59.6	59.5	0.0	35.6
2017	61.0	61.5	0.0	37.9
2018	65.0	65.5	0.0	40.9
2019	58.6	59.3	0.0	38.6

[1]Prorated when applied for partial years and reduced to 2/3 of this value for "poor" condition alfalfa.

Total Reduction in CU

The total ΔCU for the full program in MVIDD was estimated to be 6,137 AF for 1,196 acres of fallowed land in 2020 (MVIDD, 2019). Total ΔCU was estimated to be 6,778 AF for 1,349 acres of fallowed land in 2021 (MVIDD, 2020b).

Total Diversion

The total MVIDD agricultural irrigation diversion in the Decree Accounting for 2020 was 19,458 AF, which was 2,077 AF less than the limit of 21,535 AF described by MVIDD (2019). This is a difference of a little less than 10%.

Discussion of Assumptions

The *⊿CU* method includes several assumptions, which are either explicit or implicit in the method. Some of the primary assumptions are discussed below.

Assumption 1: The CU for the fallow fields, or at least the *⊿CU* for the fallow fields, would be similar to the CU in those same fields, on average, in five previous years.

This assumption is discussed in the *Discussion of Method Assumptions* section of the Colorado River Indian Tribes Fallowing Program case study. Two aspects of this assumption relating to MVIDD will be considered here. The first is that the crops that would be grown on the fallowed fields would be similar to those grown in previous years; the second is that other factors affecting CU would be the same in the fallowing year as the mean of the quantification years.

Regarding the crops grown, the surveyed crop mix was similar across many of the survey years in the fields to be fallowed (*Table 16*). The crop mix, based on MVIDD crop reports was similar in 2019, before the fallowing program, and 2020, a program year (*Table 17*). Though, there was about 445 acres (~14% of the reported area) of crop types not grown in 2019 that were grown in 2020. It is uncertain whether any of the program participants would have elected to grow crops that differed from their respective recent histories had they not fallowed their fields. Another consideration is the growth of alfalfa. Alfalfa is a perennial crop that is grown for several years before it is removed. Project participants may have strategically enrolled fields with aging alfalfa stands as opposed to randomly selecting fields to fallow regardless of the crop or stand age.

In addition to the crop mix considerations, other conditions may or may not have varied notably between the five-years used to estimate *⊿CU* and the fallowing year. These conditions include weather, pest pressure, and management, among others. For the present discussion, only weather is considered specifically. One benefit of using an average as opposed to the estimated *⊿CU* is that an average may better represent typical conditions and reduce the uncertainty involved with assumptions, measurement, and modeling methods in any one year. Furthermore, it can be expected that the annual variability in ET for a given crop will not be too great (e.g., SCS, 1993). Though *⊿CU* as being discussed here is actually ET less effective precipitation, the ET is of much greater magnitude than precipitation and, therefore, this justification has some merit. It is also possible, however, that the methods used to estimate *⊿CU* for a given year are sufficiently accurate to be more representative than a mean across years. Using the range of *⊿CU* (ET_{AW}) values presented in *Table 18*, alfalfa *⊿CU* ranged within -4% to +7% of the mean for 2014-2019. Similarly, the *⊿CU* for other hay ranged from – 3% to +7% of the mean, but Sudan *⊿CU* ranged from -7% to +9% of the mean. The actual *⊿CU* for 2020 could have been within or outside of this range (assuming the modeling method was accurate).

Assumption 2: The crop coefficients and effective precipitation methods used are representative of the conditions in MVIDD.

A difficulty in applying K_c values to quantify *⊿CU* is that published K_c values are often representative of crops under little stress in research conditions (e.g., TM2). This means that when applying published K_c values, the resulting ET_c will be an overestimate of actual production conditions unless adjustments are made. For example, Jensen (1998) reduced his recommended K_c values for alfalfa in the Lower Colorado River Basin by multiplying the values by 85% to account for production conditions. The reported actual K_c values in the PVID deficit irrigation case study are further evidence of the difference between research station and production field conditions; wherein the observed alfalfa K_c values were less even than Jensen's (2003) values used for LCRAS. This concept is further corroborated by the discussion in *Standard Conditions vs. Non-Standard Conditions* section of TM2.

Land IQ (2019, 2020) used K_c values based on communications from university faculty and from Allen et al. (1998), the latter of which, if properly adjusted for climate, would be considered "potential" values. Whether or not these values were reduced to represent actual conditions was not specified. For validation, Land IQ compared their results to the 2013 *Lower Colorado River Annual Summary of Evapotranspiration and Evaporation* (Reclamation, 2019a). Comparing ET_c or ET_{AW} estimates with other sources is good practice. It is noted that 2013 was outside of the years included in the Land IQ analysis but the 2014 analysis from Reclamation (2019b) was likely not available for the Land IQ (2019) analysis.

For the present discussion, the *Lower Colorado River Annual Summary of Evapotranspiration and Evaporation* or similarly named reports for 2010 – 2014 (Reclamation, 2014, 2016, 2018, 2019a,b) were considered for comparison (*Table 19*). As also observed by Land IQ (2019, 2020) for 2013, the alfalfa ET_{AW} from Reclamation was similar to that computed by Land IQ, about 64 inches per year versus about 61 inches per year, respectively. The difference may be caused by differences in ET_o, K_c, or effective precipitation, though the latter should be small (*Table 18*), particularly considering the differences observed for the overlapping analysis year, 2014. The difference for Sudan was a little greater in magnitude and proportion. The Land IQ ET_{AW} for Bermuda was notably greater than the estimate of Reclamation. However, according to Land IQ (communication, September 2, 2021), the difference is related to the "Bermuda grass growing season" being "incorrect in the past." It must be remembered that the comparisons in *Table 19* have little overlapping periods of record. Furthermore, with the exception of alfalfa, the Reclamation ET_{AW} values have not been reduced to represent production conditions. This comparison is an illustration of the differences that exist in methods, but in both cases a comparison to estimates of actual production field ET_{AW} would be beneficial.

Finally, regarding the impact of the effective precipitation methods used, it is important to consider the magnitude of precipitation in MVIDD. For example, in 2010 - 2019, there was an average of about 5.2 inches per year of precipitation averaged across the available records for the three AZMET stations and three NOAA climate stations[28] (NOAA, 2021a,b; UA, 2021; *Table 19*). For the one overlapping year in the Reclamation and Land IQ analyses, 2014, there was only 3.3 in. of precipitation. This was less than the difference between the ET_{AW} between the Land IQ (2019) and Reclamation (2019b) analyses. Effective precipitation is expected to be much less than the full quantity of precipitation (Jensen, 1993).

[28] The three AZMET stations were Mohave, Mohave 2, and Ft. Mohave, CA. The former two stations were used by Reclamation (2019) and all three by Land IQ (2019, 2020). The two NOAA stations were Bullhead City, AZ and Laughlin, NV and were used by Reclamation (2019b).

Table 19 Comparison of Crop Evapotranspiration of Applied Water for Select Crops for Mohave Valley Irrigation and Drainage District from Reclamation and Land IQ for 2010 – 2019.

Year	LCRAS ET_{AW} (in.)[1]			MVIDD ET_{AW} (in.)[2]			Precipitation[4] (in)
	Alfalfa	Bermuda/ Grass[3]	Sudan[3]	Alfalfa	Other Hay/ Bermuda	Sudan	
2010	62.0	53.3	40.7	--	--	--	9.4
2011	62.6	53.2	40.6	--	--	--	4.0
2012	65.4	55.7	41.8	--	--	--	6.8
2013	65.1	55.0	42.0	--	--	--	4.3
2014	63.6	54.6	41.6	59.6	59.8	35.1	3.3
2015	--	--	--	60.6	60.8	37.8	4.8
2016	--	--	--	59.6	59.5	35.6	4.9
2017	--	--	--	61.0	61.5	37.9	3.7
2018	--	--	--	65.0	65.5	40.9	2.5
2019	--	--	--	58.6	59.3	38.6	8.8
Average	63.7	54.4	41.3	60.7	61.1	37.7	5.2

[1]Source: Reclamation (2014, 2016, 2018, 2019a,b). Names similar to sources.
[2]Source: Land-IQ (2019, 2020). Names similar to sources.
[3]Jensen (1998) did not apply any reductions to the crop coefficients for Bermuda or Sudan and so too, the crop coefficients of Jensen (2003) would also not have this adjustment.
[4]Sources: AZMET Mohave, Mohave 2, and Ft. Mohave, CA stations (UA, 2021) and NOAA (2021) Bullhead, AZ and Laughlin, NV stations.
[4]The average for 2010 - 2014 was 5.5 in. and for 2014 - 2019 was 4.7 in.

Assumption 3: The CU from the fallowed fields and possibly the irrigation and drainage ditches serving the fallowed land is negligible.

This assumption is discussed in the *Discussion of Method Assumptions* sections of the other three fallowing case studies. Some additional commentary for MVIDD is provided here.

Because effective precipitation was subtracted from ET_c in computing ΔCU, the effect of precipitation on evaporation is technically accounted for. It has also been demonstrated that the total annual precipitation is relatively small (3.6 inches in 2020). Effective precipitation can be expected to be only a small portion of this (Jensen, 1993). It is reasonable to assume that deep percolation from precipitation is negligible. Given that the fields are leveled according to a site visit participant, it is likely that surface runoff is also negligible. Therefore, the fraction of precipitation that is not effective would likely be evaporated whether in an irrigated or a fallowed field.

Assumption 4: CU from conveyance ditches is negligible.

This assumption is that changes in CU occur only on irrigated land or that any other ΔCU is negligible. Technically, there is evaporation from field ditches, though the magnitude of the evaporation is expected to be small, and the wetted area of field ditches is also small compared to the minimum size of the fallowed fields (10 acres; MVIDD, 2019, 2020b). Furthermore, because the field ditches are concrete lined, the evaporation from the ditches will be essentially entirely from the water surface when the ditch is conveying water or during drying after an irrigation. Any evaporation or ET that may occur from ditch water that may leak through the turnout gates is prevented from entering the fallowed field by sealing the gates with silicone (*Figure 40*).

Figure 40 Photo of a Locked and Sealed Field Turnout Gate Serving a Fallowed Field in the Mohave Valley Irrigation District (credit: B. Barker, May 27, 2021).

Assumption 5: Any carry-over effects of fallowing on CU are negligible.

This assumption is directly related to the assumption that the CU from fallowed land and the associated ditches is negligible. This assumption is valid so long as evaporation from the fields and the dried-up ditches can be considered negligible during the fallow period.

Assumption 6: The diversion capacity of the fields can be represented by a set per-acre value.

To determine a maximum allowable annual diversion, MVIDD applied a per-acre diversion rate of 7 AFY/ac to all fallowed lands. This is convenient because it is the maximum irrigation duty allowed to irrigators in MVIDD (MVIDD, 2019, 2020b). Implicit in using this value is an assumed district-average combined conveyance and irrigation application efficiency. For example, in 2020, the total ΔCU was estimated to be 6,137 AF / 1,196 ac = 5.13 AF/ac (MVIDD, 2019). The total irrigation efficiencies would then be 5.13 AF/ac / 7 AF/ac × 100% = 73%. Similarly, for 2021, the total irrigation ΔCU would be 6,778 AF / 1,349 ac = 5.03 AF/ac (MVIDD, 2020b). The corresponding total irrigation efficiency would be 5.03 AF/ac / 7 AF/ac × 100% = 72%. It is expected that the conveyance efficiencies for the systems should be high because they are all short-run, concrete lined ditches (e.g., Brouwer et al., 1989). This still bespeaks a relatively high application efficiency for basin irrigated fields (compare to Brouwer et al., 1989). However, the turnouts, as shown in *Figure 40*, appear to typically have large flow capacities, possibly 10 – 20 cfs. Large turnout flow rates allow for relatively rapid movement of water across the field. This rapid distribution of water has the potential to result in relatively high application uniformity and consequently the potential for relatively high application efficiencies. Though, such may be possible as the fields are typically laser leveled according to a grower. The implication of an overestimated effective irrigation efficiency, if such existed, would be either an underestimate of the necessary diversion reduction or a possible overestimate of the ΔCU. The former is based on MVIDD administrative diversion limits. The latter has already been discussed. Conversely, the opposite implications would exist if the effective irrigation efficiency happened to be underestimated.

Reflections

The MVIDD fallowing program, as with the other case studies, has had both challenges and benefits. One challenge with the fallowing program is that it has been observed by a grower that participated in the site visit that the longer the fallowing duration, the more effort (and expense) is required when the field is brought into production again. This is reportedly largely related to the difficulty of cultivating the dry soil following fallowing. One effort to protect the fallowed fields in MVIDD is to leave crop stubble in the field to reduce wind erosion (*Figure 41*). One grower also expressed interest in the establishment of cover crops that could be killed without herbicide prior to the fallowing period for the soil stewardship value. This is because there is concern regarding the impact that applying chemicals during fallowing has on soil health.

The fallowing of a field is not seen entirely as a cost, as there may be some advantages that can be obtained from the program. For example, one of the participants pointed out that growers could use the fallowing period to convert fields from conventional production to organic production. However, this would require a move away from requirements to apply herbicide during the fallowing period to eliminate any vegetation. This is a three-year process that can have economic disadvantages because crops are grown without conventional inputs but cannot be certified organic. In addition to this, there was some expressed interest in developing a more tailored fallowing program by using seasonal fallowing.

In addition to some of the specific challenges and benefits of the program, there are concerns about the impact of other water users on the program's ΔCU. Specifically, there is still concern from some participants when idle land that is not in the program is brought back into irrigated production and, thus, could offset some of the ΔCU from the fallowing program. This is because at any given time and for various reasons, there is some land in MVIDD that is currently out of production. If this land were to be irrigated during the fallowing program, it could negate the conservation effects of the program.

Another concern with idle land was that if such land were enrolled in the program, it would not result in actual ΔCU relative to recent conditions. For this reason, fields had to be irrigated in three of five recent years to be included in the fallowing program.

Finally, it was reported that initial concerns regarding the fallowing program included socio-economic concerns and fear about loss of water entitlements. Education was key. This program is in the early stages of development and there is landowner interest in continued creative development and refinement of the system.

Figure 41 Photo of a Fallowed Field with Crop Stubble to Reduce Wind Erosion in the Mohave Valley Irrigation District (credit: B. Barker, May 27, 2021).

Synopsis and Recommendations

The six case studies presented in this technical memorandum include a variety of conservation activities, temporary fallowing, seasonal fallowing, deficit irrigation, and large-scale conveyance system improvements (*Table 20*). The reader may likewise benefit from a comparison of *Figure 6*, *Figure 7*, *Figure 10*, *Figure 19, Figure 23*, and *Figure 33*, which are simplified representations of the CU quantification methods for each respective case study. The CU, or ΔCU, methods applied in the different participating projects vary and are subject to available data and resources. There are pros and cons associated with each method for which commentary was primarily provided in the respective *Discussion of Method Assumptions* sections for the case studies. Many of the interconnected considerations and decisions related to the selection of a CU quantification method for the different conservation activities have been summarized in a decision tree (*Figure 42*).

The decision tree was developed in an attempt to condense the results and observations from the case studies into a single summary. While this simplified summarization is not comprehensive, it is helpful as an illustration of the very challenges that led to this Pilot Study effort. When viewing, or seeking to apply the tree, it is important to consider the following:

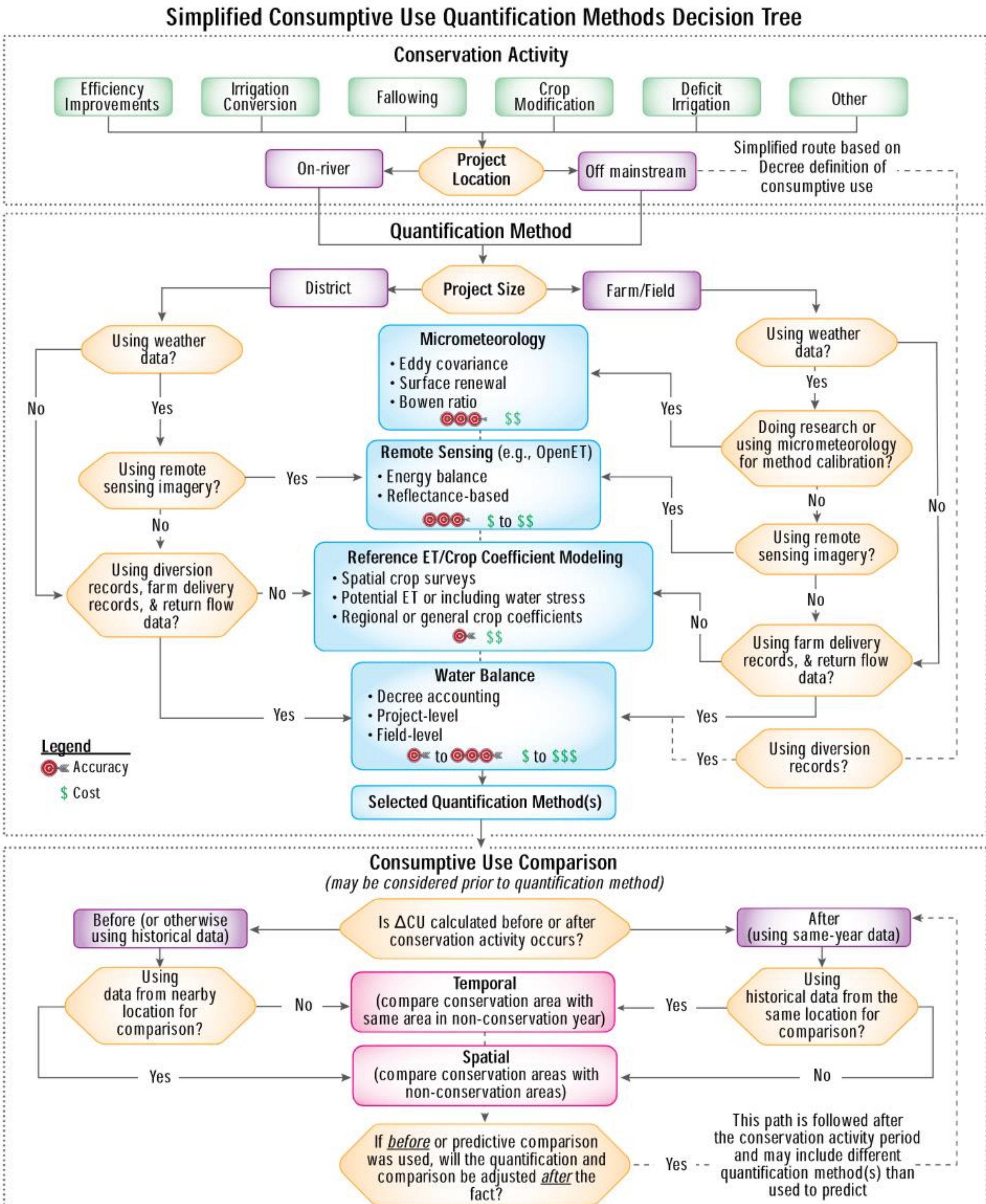
- The user must be aware of what options are practical or possible for each conservation activity. The decision tree is not the expert, it is a simplified summary based largely on the cases studied. As a future effort, the concepts from the tree could be combined with others into an electronic decision support tool that could be applied by users more directly.
- There is no single correct path for a given conservation method. Rather, the paths outlined in the tree represent things that practitioners should consider.
- Not all of the important decision factors are represented in the tree. Most notably, the decision tree does not include any direct references to non-technical aspects of a conservation agreement.
- Multiple CU quantification methods may be applied in a single study. For example, ET modeling methods could be used in conjunction or comparison with water balance methods.

Table 20 Summary of Case Study Conservation Measures and Consumptive Use Quantification Methods.

Potential Case Study	Location		Conservation Activity			Quantification Method			Comparison Method[1]		Time Period	
	On-/Off Mainstream	State	Deficit Irrigation	Fallowing	Efficiency Improvements	Water Balance	Micrometeorology	Reference ET	In Time	In Space	Single Year	Multi-Year Mean
GRIC System Modernization[2]	Off-Mainstream	AZ			•	•			•			•
Bard Water District Seasonal Fallowing Program[3]	On-Mainstream	CA		•		•				•		•
PVID Forbearance and Fallowing Program[3]	On-Mainstream	CA		•		•				•	•	•
PVID Moderate Deficit Irrigation Program[4]	On-Mainstream	CA	•			•	•	•		•		•
CRIT Fallowing Program[5]	On-Mainstream	AZ		•		•		•	•			•
MVIDD Fallowing Program[6]	On-Mainstream	AZ		•		•		•	•			•

[1]Method used to identify the change in consumptive use relative to conditions without the conservation method. The methods either compare the same area "in time" or effectively compare areas of conservation with areas not under conservation ("in space").
[2]Comparison on per-acre basis.
[3]Based on Decree Accounting Reports.
[4]Developing empirical relationship between irrigation deficit and yield.
[5]Specifically accounted for non-ideal growing conditions.
[6]Used remote sensing-based crop surveys.

Figure 42 Simplified Decision Tree for Selection of Consumptive Use Quantification Methods.



Notes:

This is a simplified representation based on the case study analyses, it is not a comprehensive guide for selecting quantification or comparison methods, though it may be helpful in identifying general technical considerations for method selection.

The logic steps are not absolute (e.g., micrometeorology is not strictly limited to field-scale research). In some instances, using multiple quantification or comparison methods may be more appropriate than just using one.

The effect of a comparison method is dependent upon similarity between the compared conditions (e.g., applying a comparison method for areas or time periods affected by water shortage).

- The decision statements on the tree are not necessarily absolute. For example, micrometeorology is not limited to field-level analyses or research applications. However, when applied practically, micrometeorology is likely to be paired with another CU technique (e.g., calibrating ET models).
- The effect of a comparison method is dependent upon similarity between the compared conditions. For example, this may be particularly a challenge when applying a comparison method for time periods when the comparison areas or times may be affected by water shortage. In such a case, the decision must be made whether to compare to water short conditions or non-water shortage conditions.

The tree can be applied to the case studies as follows:

- **GRIC Irrigation System Modernization:** This is an *Efficiency Improvement* project. This type of project requires some sort of *Water Balance*, be it a flow balance, or a ponding test, etc. to quantify CU. In this case, if there are no flow records, the practitioner would not use *Reference ET/Crop Coefficient Modeling* as the user should understand that that is not an applicable method. The CU comparison is done using data for the studied years, so the *After* timeframe would be selected with a *Temporal* comparison (comparing the same area in time).

- **Bard Seasonal Fallowing:** This is a *Fallowing* project applied at the *District* level. In the analysis, no weather data is being directly used in the quantification, nor is any remote sensing imagery. Flow data from the Decree Accounting report was utilized. This path correctly identified the *Water Balance* quantification method. The CU comparison is done using a combination of data for the studied years and previous (historical) years. So, really, both the *Before* and *After* timeframes apply with a *Spatial* comparison because the total fallowed area in the Unit is compared to the total irrigated area in the Unit.

- **PVID Forbearance and Fallowing:** This is similar to the Bard program, but the CU comparison is done separately using data for the studied year and data for previous (historical) years. Still, both the *Before* and *After* timeframes would be selected. The adjustment or "true-up" *After* the fact is also applied.

- **PVID Moderate Deficit Irrigation:** This is a *Deficit Irrigation* project applied at the *Field* level. In the analysis, weather data have been used, and it is a research project. *Micrometeorology* was correctly identified as the CU method. The comparison would be considered *After*-the-fact because data from the study years is used in quantification. The comparison would also be a *Spatial* comparison because the ΔCU is computed between plots. In future application, this comparison could be considered *Before* (i.e., predictive) when applied outside of the study itself.

- **CRIT Fallowing and MVIDD Fallowing:** These are *Fallowing* programs applied at the *District* level. However, the quantification could also be considered to be at the *Field* level. Weather data were used in the analysis, but remote sensing data were not used to estimate ET (remote sensing was used for crop identification for MVIDD) and micrometeorology was not used. Since flow records were not used for the CU directly, *Reference ET/Crop Coefficient Modeling* was correctly identified as the CU quantification method. The comparison was made using historical data from the same area in a predictive fashion (*Before* timeframe) and the comparison was temporal because CU for each participating field was compared with estimates of CU for past years from the same field. The CU comparison at CRIT was

> made *a priori* as one of the initial steps in the review and approval of CRIT's fallowing proposal by the respective parties to the fallowing agreement(s). This facilitated "up front" certainty in the process for the entity implementing the fallowing, for the entity funding the system conservation, and by the entity performing the accounting of water use.

One thing not fully captured in the decision tree is the full set of assumptions associated with each quantification method. Such assumptions are very situation dependent, as demonstrated in the case study discussions. For example, the Bard and PVID fallowing programs had similar CU methods, both based on the Decree Accounting reports. However, the two programs had a mix of similar and different assumptions. In an attempt to address some of the assumptions used in the two studies, including the shared assumption that the district-wide CU was representative of the fallowed ΔCU, the MVIDD and CRIT fallowing programs employed crop ET modeling. However, the methods used in these latter two programs also included certain qualifying assumptions, including some that were the same as for Bard and PVID and some additional ones as well.

One example of an assumption in the MVIDD and CRIT cases was the need to translate the CU estimates into diversion quantities for agreement purposes and comparison with the Decree Accounting. For CRIT this was done by using a universal irrigation efficiency. For MVIDD, the per-acre water duty was used. An additional assumption was that the modeled CU was an accurate representation of actual CU. This was a concern because the modeling methods used typically result in ET greater than realized for production conditions. A method that was applied in the CRIT analysis to address this concern was to adjust ET results downward based on results from remote sensing energy balance ET modeling studies in the region. More direct incorporation of remote sensing methods could be a logical next step in the progression of CU quantification methods (i.e., those used by PVID/Bard to those used by CRIT/MVIDD, and so forth).

Steps in this progression are cost dependent. For example, the quantification methods used by MVIDD and CRIT are likely more costly to employ than those used in the Bard and PVID programs because of the effort required (e.g., consultants were employed for both MVIDD and CRIT quantification efforts). Remote sensing methods are typically more expensive still. This is captured, in essence, by the accuracy and cost representations on in the decision tree. For each project, there is a practical balance between cost and accuracy.

One example of a trade-off between cost and accuracy is the employment of micrometeorological methods in the PVID deficit irrigation study. For example, these methods are not subject to the same assumptions that were included in the methods used for the fallowing programs (though there are theoretical and operation assumptions when using micrometeorology, TM2). Micrometeorological methods have the benefit of being directly sensitive to the conditions in the measurement locations. However, these methods themselves are research-grade and require expense, expertise, and effort that may not be reasonable in practice for all conservation programs. The challenge, then, for a study like the PVID deficit irrigation study is the generalization of the results. For example, that particular project will ultimately result in mathematical relationships that can be applied to estimate yield reduction from adopting the practice. The relationships, in turn, may also allow for the estimation of CU reductions. However, such relationships may need to be generalized using reference ET or by conducting a similar experiment in other areas of the LCRB to increase transferability.

In addition to the need to consider assumptions associated with the quantification methods, the user must also consider data availability. This again is not fully captured in the decision tree. For example, the GRIC project is an off-mainstream project, so, based on the Decree definition, CU = diversions, because there are no return flows to the Colorado River. Therefore, ΔCU could be quantified based on diversions (as represented using supply flows in the case study). However, there was a data availability challenge for historical (pre-improvement) flow records. This challenge is not unique to GRIC. It is common for data quality and availability to improve in time. For an efficiency project (especially off mainstream where CU is equal to diversions), it can be difficult or impossible to accurately estimate CU without flow measurements. For certain conservation activities (particularly on the Colorado mainstream), ET modeling techniques can be used to address the challenge resulting from a lack of certain measurements. However, even modeling methods require input data of some sort (e.g., weather data and cropping patterns).

Another related challenge faced in the GRIC case study was the comparability of before-and-after conditions to estimate ΔCU. This challenge is a universal difficulty in quantifying ΔCU. For the GRIC project, even without data record limitations, it is still necessary to make assumptions of similarity between years before and after the project improvements because factors other than the improvements may affect ΔCU. For the fallowing programs, these similarity assumptions were typically made in space (the fallowed fields would perform similarly to other fields in the area) though they were made in time also for MVIDD and CRIT (the fallowed fields would perform similarly to the same fields in the past). For the deficit irrigation study, the assumption of similarity will be in the applicability of the relationships developed at PVID, relating yield changes to ΔCU and to changes in irrigation application, to other areas of the LCRB.

The principle of similarity will always be necessary, since it is impossible to both implement and not implement a conservation activity in the same space and time. The assumption of similarity can be strengthened by including spatially and/or temporally accurate CU estimates. For example, by including remote-sensing-based ET models (RS-ET models). Such models are becoming increasingly affordable to implement and some RS-ET model output products are becoming publicly available (Open-ET, 2021). These products are subject to their own associated sets of assumptions and accuracies (TM2). However, they provide spatial estimates of actual crop ET, which can be of use in quantifying ΔCU. These products may also provide, as shared in a communication from the Arizona Department of Water Resources, a consistent methodology for estimating CU to be applied to projects in different areas.

One example of how remote sensing products could be used to improve ΔCU estimates, including supporting similarity assumptions, would be to analyze such products for a study area or district for years prior to any conservation program. A statistical analysis could be used to identify whether CU (and crop types) in fields that would later participate in the conservation program were significantly different than CU (and crop types) for fields that would not participate. If no difference is observed, the RS-ET models could be applied in years of conservation to quantify ΔCU based on comparison between the participating fields and non-participating fields. Using RS-ET models for comparisons in space was also applied in the Upper Colorado River Basin by Allen and Torres-Rua (2018).

A variation of the spatial RS-ET model analysis mentioned above would be to perform the same type of analysis but compare CU across several non-conservation years for fields that would participate in the conservation program. That is, perform the comparison in time. This would allow for identification of interannual variability in CU. The user could then use the mean CU for a determined number of non-conservation years in comparison with CU for one or more conservation years to estimate ΔCU. Using the ratio of CU to Reference ET could be used to assist in this comparison as was done by Allen and Torres-Rua (2018) in the Upper Colorado River Basin. Adaptation would be necessary for predictive analyses, such as MVIDD and CRIT provide.

The statistical analyses just described and the comparisons using reference ET to normalize comparisons could also be applied with adaptation to non-remote-sensing methods, like the water balance estimates of PVID and Bard. The RS-ET-model approaches described above could also be incorporated as either primary or secondary CU estimation methods. For example, the CU quantification for the CRIT fallowing program was adjusted based on the results of RS-ET modeling studies. However, incorporating longer period RS-ET model results and performing on-going analyses, including application during conservation periods could improve the CRIT methods. The inclusion of multiple CU estimation methods could benefit any of the projects considered herein, particularly the on-mainstream projects. RS-ET modeling could be used as a second or primary CU method for any of the projects. A second CU estimation method would not be limited to RS-ET models. For example, the reference-ET-based methods used for MVIDD and CRIT could be directly compared with the district-wide water balance approach used for Bard and PVID. When using multiple methods, invariably each method would result in a different estimate of *ΔCU*. However, having more than one estimate would allow the involved parties to investigate the causes of differences and decide which method(s) they would use ultimately use.

In addition to CU methods, the number of years included in an estimate of *ΔCU* is also important. For example, according to MWD, PVID estimates of CU are typically based on Decree Accounting results for the year in question. The Bard estimates of CU for 2020 also included the year in question, but it was incorporated in a mean with the four preceding years. For CRIT and MVIDD, the mean *ΔCU* was computed using up to five past years and for GRIC, two years prior to the improvements and two years after were used to characterize *ΔCU*.

These different periods of analysis were the result of several considerations. These considerations included the availability of data (e.g., only two years were available after improvements for GRIC). Another consideration was practicalities (e.g., the inclusion of two years prior to improvements for GRIC was a group decision made to keep the required effort reasonable, among other things). The analysis period was also dependent upon the project intent. For example, the PVID and Bard analyses were applied after-the-fact and so, including the data for the year of conservation was possible. However, the CRIT and MVIDD methods were designed to be used prior to the conservation activity. Therefore, a predictive estimate was needed and in both cases the mean of several past years was selected as the predictor. The benefit of using the current year's data for quantification for conservation activities like fallowing programs is evident. However, in cases where a forecast of the conservation activity is needed or in cases like GRIC's project, where the conservation activity provides a clear before-and-after type of condition, including multiple years in the analysis can provide a more robust estimate.

From a statistical standpoint, when using a mean across years as a predictor, the more years included, the better the prediction. This is subject to the condition that including more years does not mean including years with irrelevant crop, management, or irrigation practices and so forth (in general, the same considerations could be applied when comparisons are made in space). Where possible, efforts should be made to normalize data included in interannual or spatial means. For example, using reference ET, as described above, or by dividing estimates by irrigated area as in the GRIC and Bard cases and both PVID cases, or by excluding areas or times that have non-representative conditions. For example, if crops or irrigation methods changed 10 years ago, it may be inaccurate to extend an analysis back into that time. The discussion regarding permanent crop CU at Bard is another example. Including cropping patterns and other relevant practices in any temporal or spatial statistical analyses (e.g., as described in the recommendations for using RS-ET models above) can help identify periods or locations that should be excluded from CU quantification. Because a historical mean may differ from the actual conditions in a conservation year a prudent practice would be to include a correction using data for the conservation year after the conservation year is over. The PVID fallowing program is an example of this. The need for such an adjustment may be a collective decision of the various project parties.

In addition to technical considerations and improvements, it is important to consider the desires of the parties involved in a conservation activity. This includes the conserving parties and the beneficiary parties (e.g., funding parties or regulators). The varying interests will drive the type of quantification and comparison methods used and what is to be quantified. The selection of a comparison method and baseline for determining ΔCU is an example. Do the parties want an upfront (predictive) quantification, or should the quantification represent the conservation period? Or should the comparison be made upfront and corrected, or "trued-up" after the fact? Should the comparison be made in space (e.g., conservation field to neighboring fields), or in time (conservation period to non-conservation period), or both (e.g., the Bard method is implicitly both)? What periods or areas should be considered for a baseline? Should multiple baselines be used or multiple comparisons be made? For example, for CRIT and MVIDD, ΔCU is estimated, but a diversion reduction and corresponding diversion cap are also quantified as additional metrics of conservation.

Decisions on methods should be agreed upon collectively. Such processes should be transparent and should allow for adaptation and improvements as resources, technologies, etc. become available or the state of the science advances. When agreeing upon a set of quantification and comparison methods, it is important to acknowledge also that CU methods should be reviewed and changed as necessary. Agreements on quantification methods will likely be concurrent with other factors, payment, legal, etc. in a conservation program. Although not directly related to quantification, it is helpful to consider some of the lessons learned in the case study *Reflections* presented previously. For example, the ability of a district or participant to take advantage of a conservation program for purposes beyond water conservation (e.g., for system improvement construction at Bard, or the desire to use fallowing to transition to organic production at MVIDD). Conversely, negative impacts must also be considered like socio-economic impacts on communities, potential impact on other water resources (e.g., groundwater at GRIC), or the impact of the conservation practice on regular crop production (e.g., increased impact of chemical application on fallowed field soil health with time at MVIDD).

In closing, each of the studied cases have employed ΔCU methods that are in some way different than those applied by the others. The methods used vary in cost and expertise required to employ them and the availability of information. None of the ΔCU methods would be applicable in all cases and therefore, no "best" option is identified herein as multiple methods, or combinations may be equally valid, and cost and other non-technical factors must be considered. However, certain principles can be learned from each. The importance of data collection, e.g., regarding crops grown and grower practices, flow measurements, and weather, to name a few, is evident for all of the cases. Each of the ΔCU methods described has some advantage over the others, each could also benefit from refinement. The accuracy of quantification methods is important to all parties involved in a conservation program. The need to continue improving ΔCU methods, even for programs that seem highly developed or mature is important. For all cases, the ever-improving CU quantification methods, technology, and data products should be evaluated and incorporated in a continuous process. No ΔCU quantification methodology should be considered final or closed to improvement particularly as conditions (e.g., climate, infrastructure, political, management, cropping, irrigation methods), quantification and measurement technologies, and other information change.

Workshop #3 Participants

Almost 50 people participated in Workshop #3. *Table 21* is a list of the workshop attendees.

Table 21 Workshop #3 Participants

Funding Partners			
Reclamation Dan Bunk Jeremy Dodds John Shields Nohemi Olbert KayLee Nelson	**Central Arizona Water Conservation District** Deanna Ikeya	**Metropolitan Water District of Southern California** Bill Hasencamp Aaron Mead Larry Lai Michael Yu Nadia Hardjadinata	**Southern Nevada Water Authority** Seth Shanahan Casey Collins

Agricultural Districts/Cities				
Imperial Irrigation District Dylan Mohamed Ben Brock	**Yuma Mesa Irrigation and Drainage District** Mike Crowe	**Mohave Valley Irrigation and Drainage District** Kerri Hatz Michael Pearce Vince Vasquez	**Coachella Valley Water District** Robert Cheng	**Mojave Water Agency** Anna Garcia

Tribal Representatives				
Bureau of Indian Affairs Jonathan Cody Johnita Whiteman Cherry Bustos Gary Colvin Davetta Ameelyenah Catherine Wilson	**Fort Mojave Indian Tribe** Russell Ray	**Colorado River Indian Tribes** Guillermo Garcia Dillon Esquerra	**Ak-Chin Indian Community** Brenda Ball	**Quechan Tribe** Jay Weiner Frank Venegas

State Agencies				
Arizona Department of Water Resources Rabi Gyawali	**University of California Cooperative Extension** Ali Montazar	**Colorado Water Conservation Board** Michelle Garrison	**San Juan Water Commission** Aaron Chavez	**Colorado River Commission of Nevada** Warren Turkett

Consultants/Attorneys/Other				
NRCE Tom Ley Ryan McBride Burdette Barker	**Jacobs** Lela Perkins Chris Kurtz Armin Munevar	**Noble Law** Meghan Scott	**Moyes Sellers & Hendricks** Jason Moyes	**Pima-Maricopa Irrigation Project** David DeJong

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Appendix: Workshop 3 Presentation Slides

BUREAU OF RECLAMATION

Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin

Workshop #3

September 22, 2021

BUREAU OF RECLAMATION

Welcome/Introductions

Workshop #3 Agenda

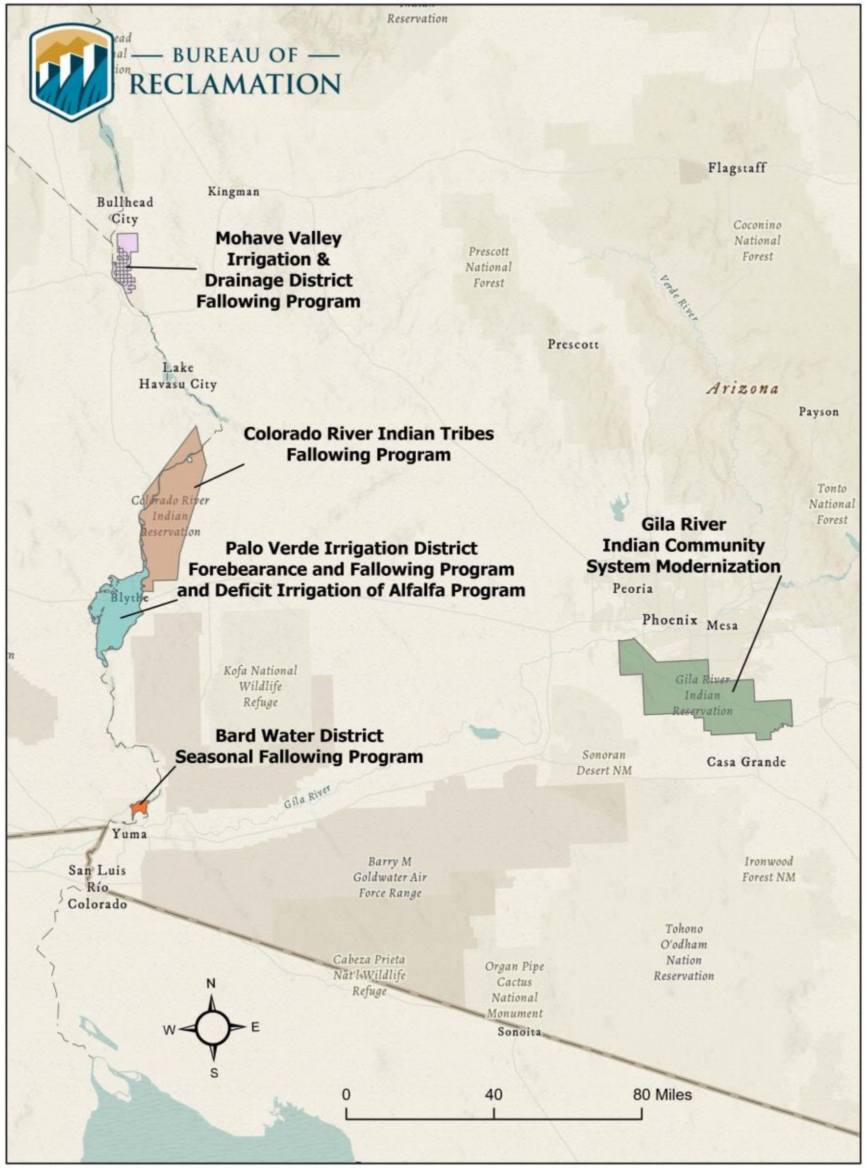
- Welcome and Introductions
- Background/Acknowledgements
- Case Study Summaries
- Decision Tree Summary
- Synopsis and Discussion
- Wrap-up and Next Steps

Background and Pilot Study Objectives

- The 2012 Basin Study identified strategies to address the evolving supply-demand imbalance
- The subsequent Moving Forward effort identified quantification of agricultural conservation water savings as a challenge
- Using case studies:
  - Explore methods currently in use to quantify agricultural water conservation
  - Evaluate methods for consistency and accuracy with Reclamation’s Lower Colorado River water accounting methods
  - Recommend approaches to improve methods of quantifying agricultural water conservation in the Lower Basin

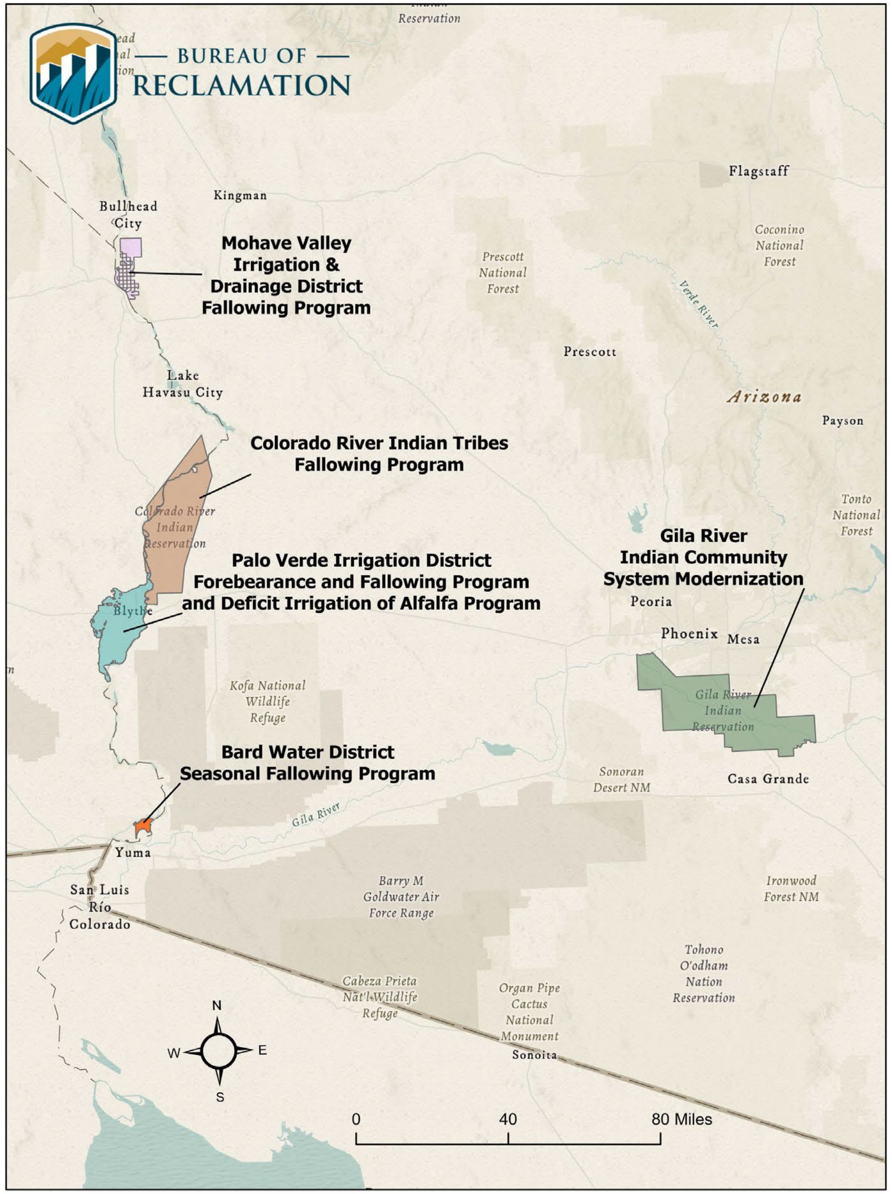
Case Studies Selected for Evaluation

- Gila River Indian Community System Modernization
- Bard Water District Seasonal Fallowing Program
- Palo Verde Irrigation District Forbearance and Fallowing Program
- PVID Partial Year Deficit Irrigation of Alfalfa Program
- Colorado River Indian Tribes Fallowing Program
- Mohave Valley Irrigation and Drainage District Fallowing Program



Case Studies Selected for Evaluation

Case Study	Location		Conservation Activity					Quantification Method			
	State	On-/ Off Mainstream	Deficit Irrigation	Irrigation Conversion	Fallowing	Crop Modification	Efficiency Improvements	Water Balance	Micrometeorology	Reference ET	Remote Sensing
PVID Forbearance and Fallowing Program	CA	On-Mainstream			X			X			
PVID Partial Year Deficit Irrigation of Alfalfa Program	CA	On-Mainstream	X					X	X	X	
CRIT Fallowing Program	AZ	On-Mainstream			X			X		X	
Mohave Valley IDD Fallowing Program	AZ	On-Mainstream			X			X		X	
Bard Water District Seasonal Fallowing Program	CA	On-Mainstream			X			X			
GRIC System Modernization	AZ	Off-Mainstream					X	X			



Case Study Evaluation Process

- In-person field visits and interviews
- Review of documentation
- Relationship of the conservation activity and quantification method to Reclamation’s Colorado River Decree Accounting
- Identification of challenges and lessons learned
- Consideration of the accuracy of methods used in the project
- Consideration of costs and complexity of program implementation
- Opportunities for improvement of the quantification method(s)

Acknowledgements

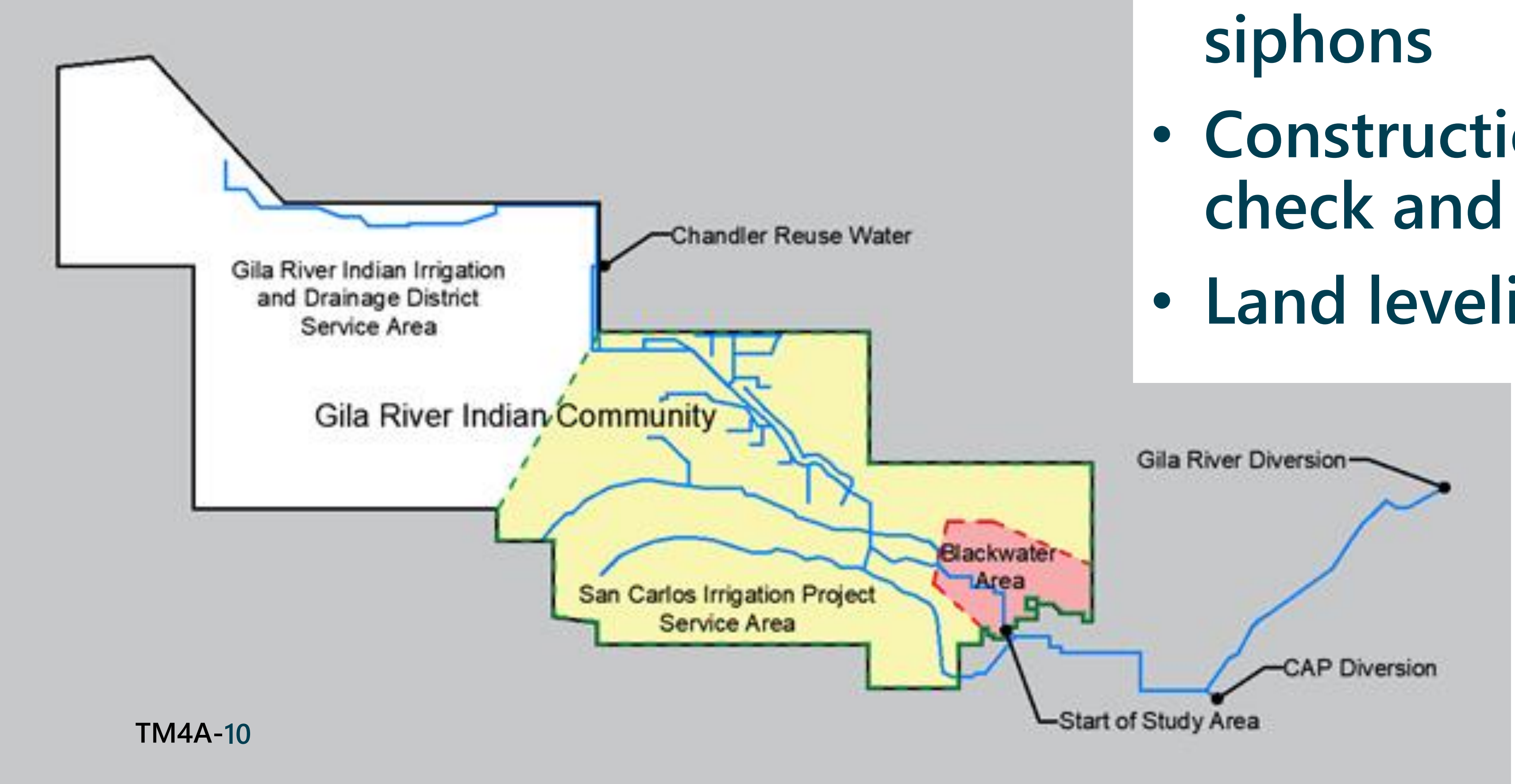
- Gila River Indian Community (GRIC)
  - David DeJong, Pima-Maricopa Irrigation Project (P-MIP) Director
  - Christopher Blackwater, Bureau of Indian Affairs (BIA)
  - Kyle Varvel, BIA
  - Bill Eden, P-MIP Senior Civil Engineer
  - Mark Moore, Gila River Irrigation and Drainage District (GRIDD)
  - Delbert Johnson, GRIDD
- Bard Water District (Bard)
  - Nick Bahr, Bard General Manager
  - Bill Scott, Board Director
  - Jerry Nakasawa, Board Vice President
  - Meghan Scott, Bard Legal Counsel
- Palo Verde Irrigation District (PVID)
  - Ned Hyduke, General Manager
  - JR Echard, Operations Manager
  - Jack Seiler, Board President
  - Ryan Seiler, Grower
  - Grant Chaffin, Grower
  - Kim Bishoff, District Controller
- Palo Verde Irrigation District (PVID) (cont'd)
  - Paula Hayden, PVID Fallow Coordinator
  - Ali Montazar, University of California
- Colorado River Indian Tribes (CRIT)
  - Amelia Flores, Chairwoman
  - Tommy Drennan, Councilman
  - J.D. Fisher, Councilman
  - Anisa Patch, Councilwoman
  - Devin Heaps, Water Resources Director
  - Guillermo Garcia, Hydrologist
  - Miguel Gonzales, CRIT Farms
  - Rebecca Loudbear, CRIT Attorney General
- Mohave Valley Irrigation and Drainage District (MVIDD)
  - Kerri Hatz, MVIDD General Manager
  - Charles (Chip) Sherrill, Chairman
  - Vince Vasquez, Board Director
  - Michael Pearce, MVIDD Legal Counsel
  - Chris Stall, Land IQ, Consultant

BUREAU OF RECLAMATION

Gila River Indian Community System Modernization

Pima-Maricopa Irrigation Project

- Goals: efficiency, reliability, modernization
- Reconstruction and concrete lining of all main canals and most laterals
- Reconstruction of pipelines and siphons
- Construction or reconstruction of check and drop structures
- Land leveling

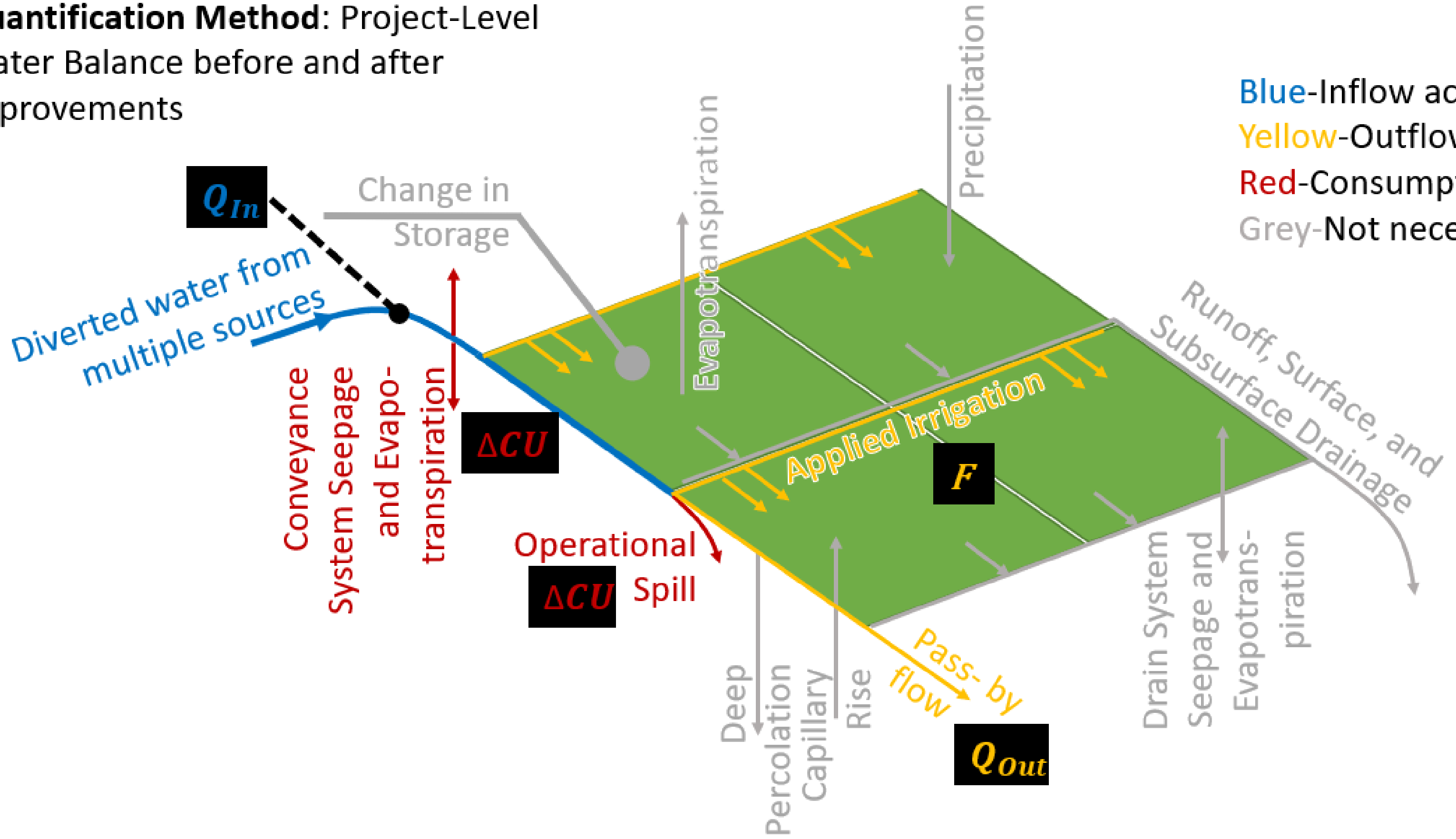


CU Quantification

Simplified Representation of the Project-Level Water Balance Approach for Quantifying Consumptive Use Reductions for the P-MIP Infrastructure

Quantification Method: Project-Level Water Balance before and after improvements

Blue-Inflow accounted for in analysis
Yellow-Outflow accounted for in analysis
Red-Consumptive use in analysis
Grey-Not necessary in analysis



$$\frac{\Delta CU}{A_{Irr}} = \frac{Q_{In}^{Before} - Q_{Out}^{Before}}{A_{Irr}^{Before}} - \frac{Q_{In}^{After} - Q_{Out}^{After}}{A_{Irr}^{After}}$$

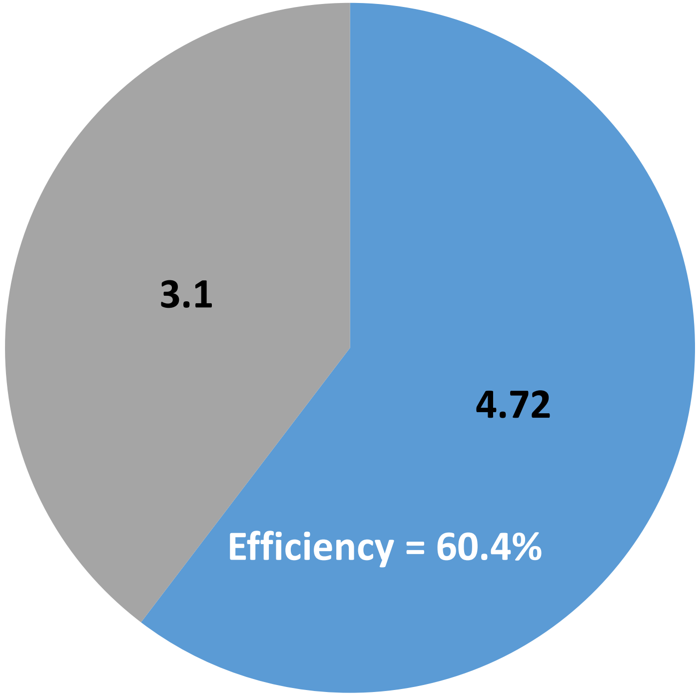
$$\frac{\Delta L_{Conv}}{A_{Irr}} = \frac{Q_{In}^{Before} - Q_{Out}^{Before} - F^{Before}}{A_{Irr}^{Before}} - \frac{Q_{In}^{After} - Q_{Out}^{After} - F^{After}}{A_{Irr}^{After}}$$

CU Quantification

- P-MIP system can be considered an off-river water user
- CU reduction can be quantified by comparing diversions records before and after improvements
- Since P-MIP build-out is not completed, it was decided that ΔCU would be evaluated for sub-areas of the P-MIP

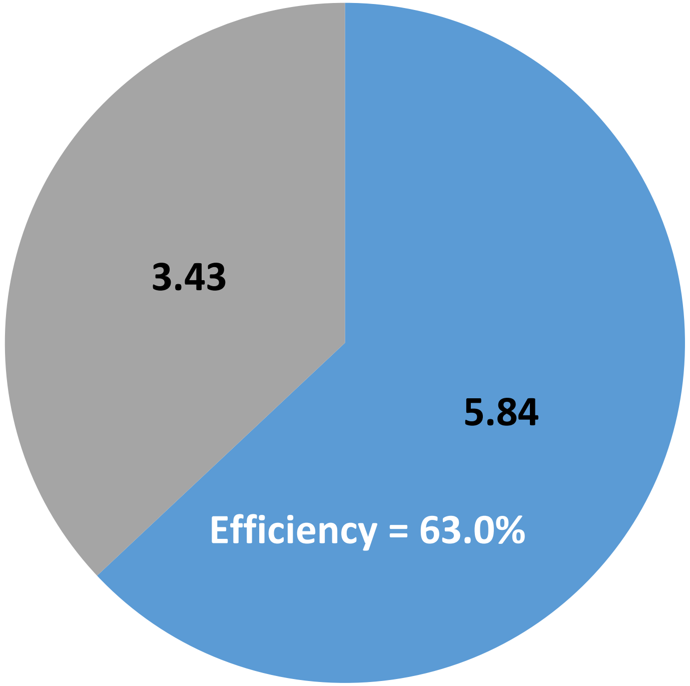
CU Results (P-MIP Service Area)

2010-2011 Average (Before Improvements)



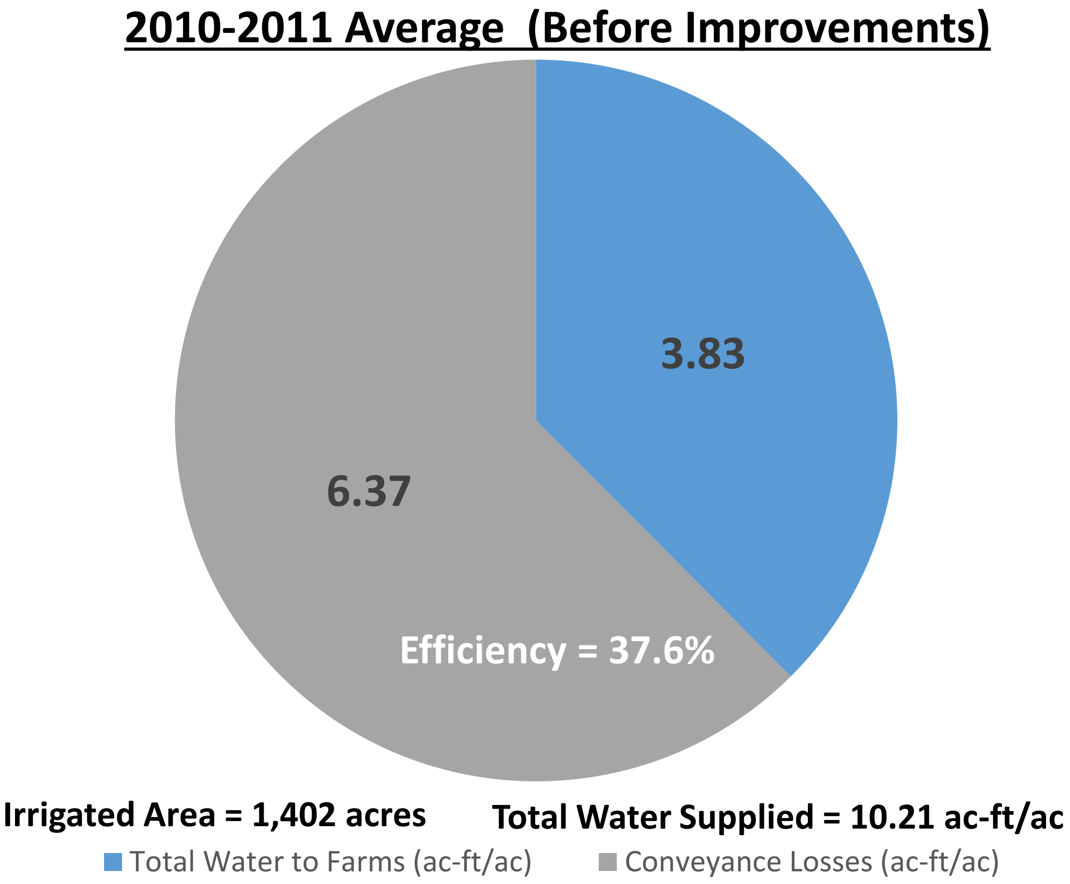
Irrigated Area = 24,819 acres **Total Water Supplied = 7.82 ac-ft/ac**

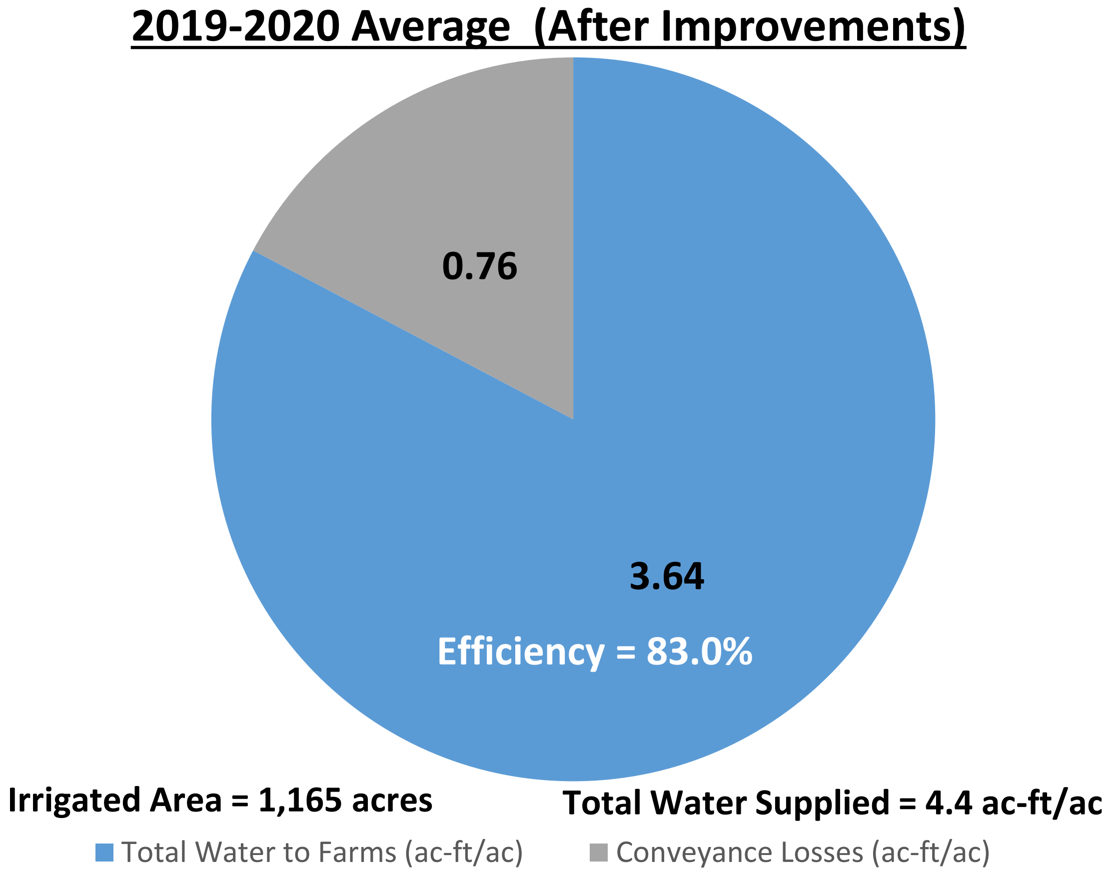
2019-2020 Average (After Improvements)



Irrigated Area = 17,219 acres **Total Water Supplied = 9.27 ac-ft/ac**

CU Results (Blackwater Area)





Reflections

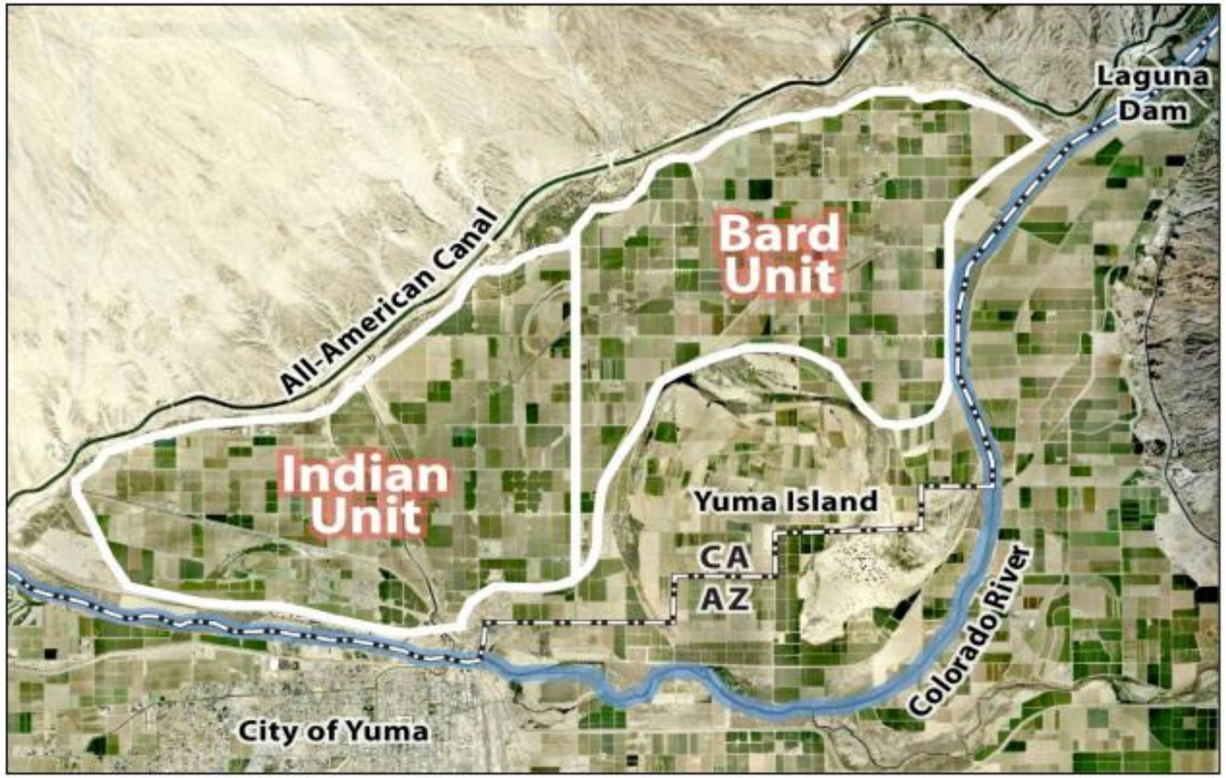
- P-MIP is a large project made possible by reliable and consistent funding
- GRIC is committed to providing a resilient, reliable and efficient irrigation system
- Changes in system management also provides potential efficiencies in administrative effort and expense
- Quantifying changes in CU is challenging due to lack of available pre-improvement data
- Anecdotal evidence of decreased groundwater recharge from the canals now that they have been lined

BUREAU OF RECLAMATION

Bard Water District Seasonal Fallowing Program

Bard Water District Seasonal Fallowing Program

- Applies only to Bard Unit from April 1 through July 31
- Up to 3,000 acres can be fallowed each year (minimum of 10 contiguous acres for each area)
- MWD pays each grower a flat rate based upon the area fallowed
- MWD covers administrative costs and a per-acre rate for district infrastructure improvements
- Conserved water available for use by MWD

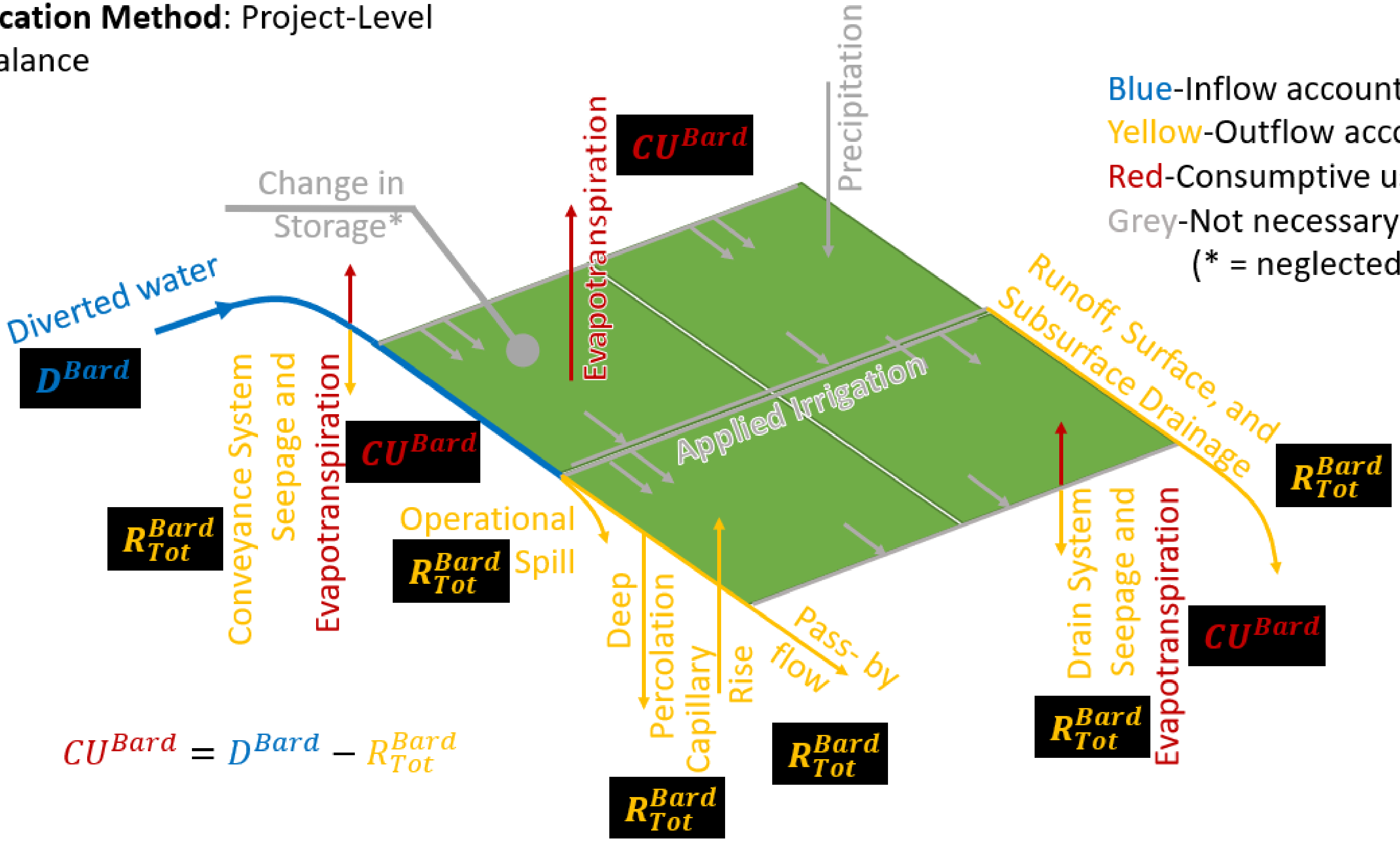


Map of Bard Water District

CU Quantification

Simplified Representation of the Project-Level Water Balance Approach for Quantifying Consumptive Use Reductions for the Bard Water District Seasonal Fallowing Program

Quantification Method: Project-Level Water Balance



Blue-Inflow accounted for in analysis
Yellow-Outflow accounted for in analysis
Red-Consumptive use in analysis
Grey-Not necessary in analysis
(* = neglected)

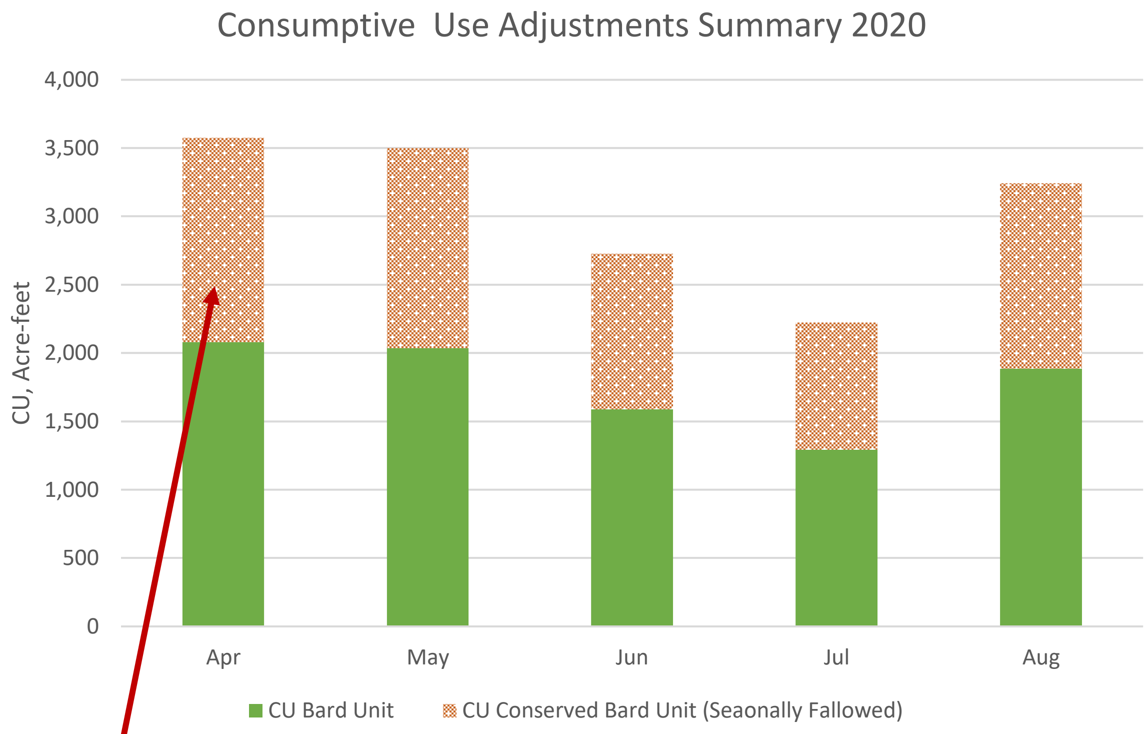
$$CU^{Bard} = D^{Bard} - R_{Tot}^{Bard}$$

CU Quantification

- *Δ*CU based upon Reclamation’s Decree Accounting
- Diversions, unmeasured return flows, and a portion of the measured return flows are reported by Unit
- Delineation of irrigated lands likely represents the most time-consuming task for CU quantification

CU Results

Year	Area Fallowed (acres)	Reported CU Factor (AF/ac)
2016	509	1.87
2017	1,641	2.32
2018	973	1.99
2019	1,984	2.14
2020	2,749	2.32
Area-Weighted Mean	1,571	2.21
------------- 2020 ΔCU -------------		
2020 Fallowed Area (ac)		2,749
2020 ΔCU (AF)		6,075



Conserved CU

Reflections

- From the grower's perspective, fallowing can be considered like one of several potential crops in a crop rotation
- Program can be logistically favorable
  - Timing
  - Less productive land
- Reduced water deliveries during the fallowing period can help facilitate improvement projects, like canal lining
- Software program modifications were required to facilitate the fallowing program
- The Bard Unit has an unquantified water right - a program is the only means of leasing water to other users

Reflections

- MWD is presently developing a revised method for quantifying ΔCU for the program, which will include precipitation and estimates of ET
- Accuracy of the ΔCU is of importance to all parties involved
- Current program is considered by some to be the "right" size to appropriately balance potential impacts on agronomics and the local economy

BUREAU OF RECLAMATION

Palo Verde Irrigation District Forbearance and Fallowing Program

TM4A-23

PVID Forbearance and Fallowing Program

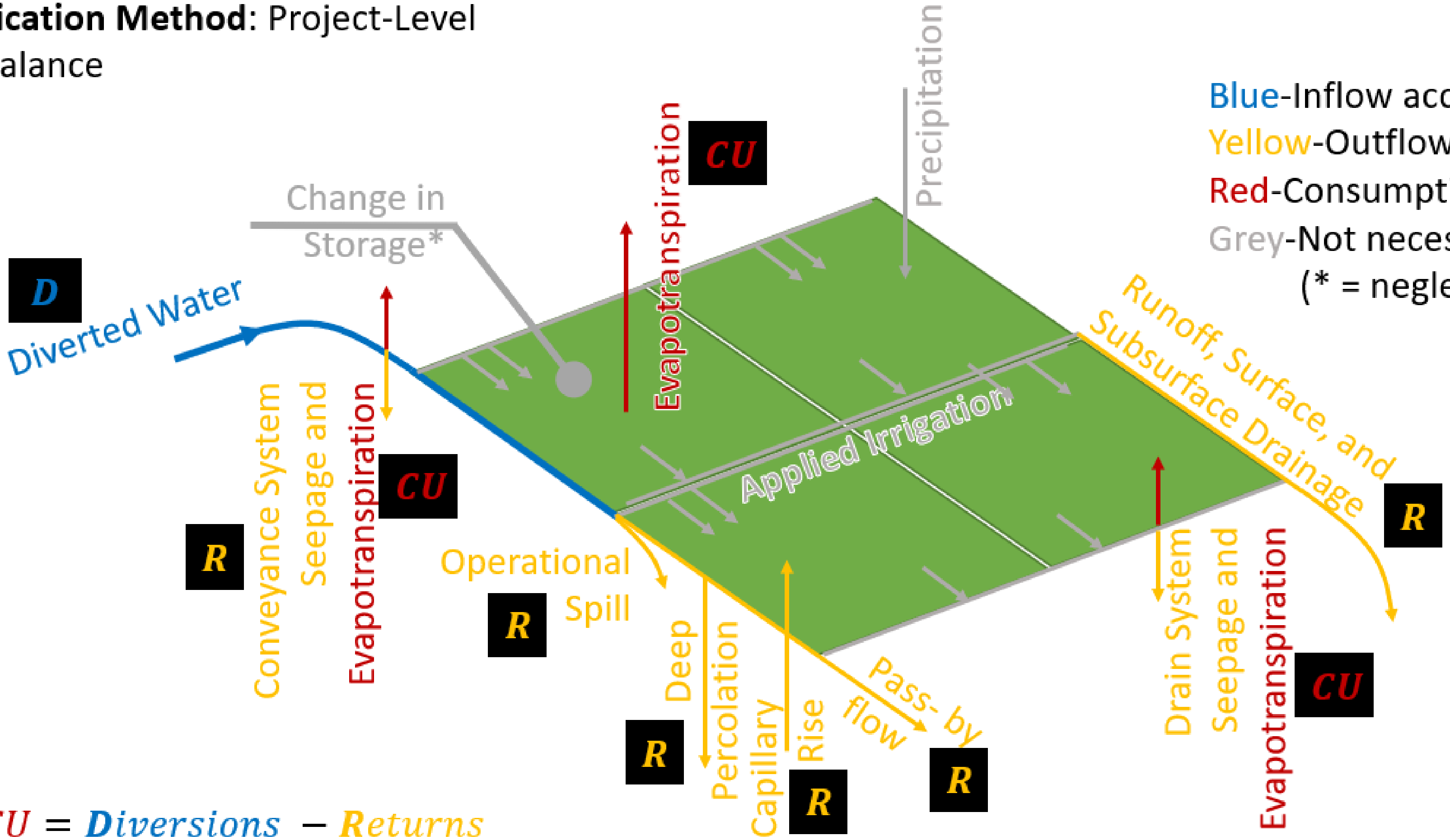
- Program began in 2004
- 35-year agreement with MWD
- Payments based on acreage fallowed
- $6M for local community improvement programs
- Conserved water available for use by MWD
- Amount of land in program each year is determined by MWD
- Minimum of 5 acres – portions of fields can be fallowed

CU Quantification

Simplified Representation of the Project-Level Water Balance Approach for Quantifying Consumptive Use Reductions for the PVID Fallowing Program

Quantification Method: Project-Level Water Balance

Blue-Inflow accounted for in analysis
Yellow-Outflow accounted for in analysis
Red-Consumptive use in analysis
Grey-Not necessary in analysis
(* = neglected)



$CU = Diversions - Returns$

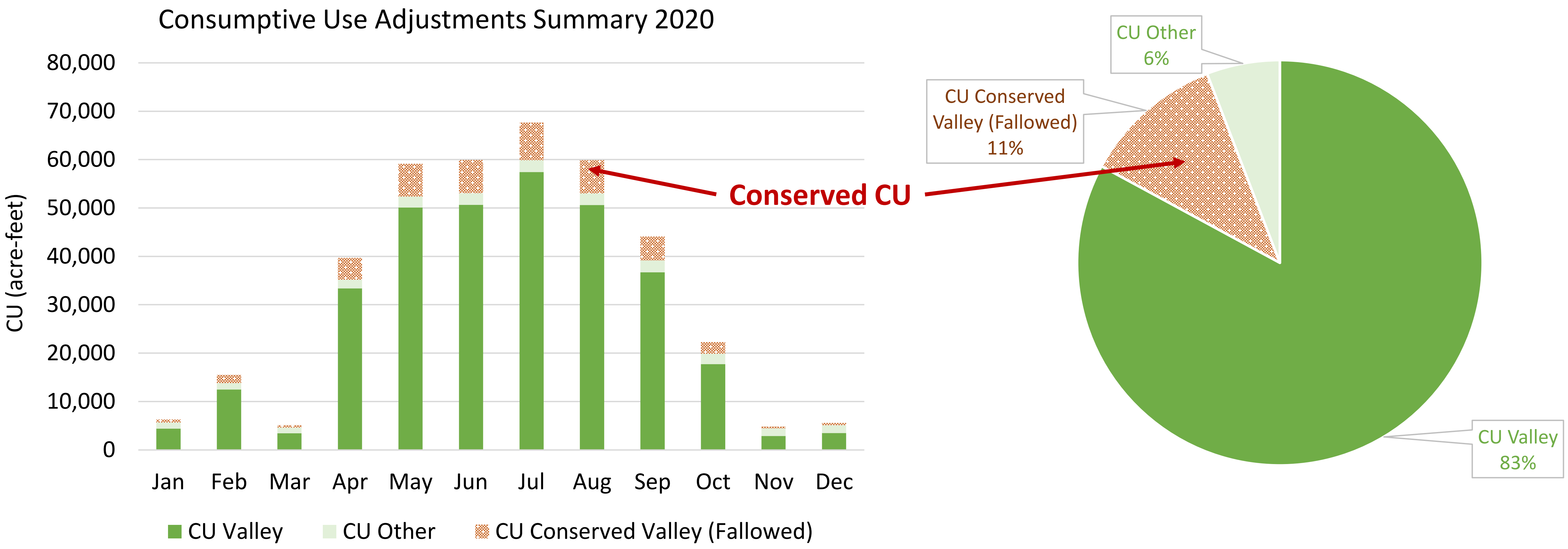
$CU_{Valley} = CU_{Total} - CU_{Mesa} - CU_{Pumped} - CU_{PVER} - CU_{PVER-So} - CU_{DUCA}$

Some components of CU are estimated directly.

CU Quantification

- ΔCU based upon Reclamation's Decree Accounting
- CU quantified over various historical periods using measured diversions, measured return flows, and estimates of unmeasured return flows
- Estimated by subtracting out CU of areas outside of the Valley

PVID Forbearance and Fallowing



Reflections

- Allows growers to fallow portions of their fields that may be particularly problematic
- MWD required an easement equal to the area committed to the program
- Program requires a notable amount of administrative effort
- Only means of leasing water to other users is through a program where a conservation practice, like fallowing, is implemented
- Accuracy of the ΔCU is of importance to all parties involved

BUREAU OF RECLAMATION

Palo Verde Irrigation District Partial Year Deficit Irrigation of Alfalfa Program

Partial Year Deficit Irrigation of Alfalfa Program

- Initiated by researchers with UC Agriculture and Natural Resources
- Purpose is to measure the impacts on applied irrigation water, CU, yield, yield quality, soil salinity, and alfalfa plant stand of “moderate” deficit irrigation during the summer months

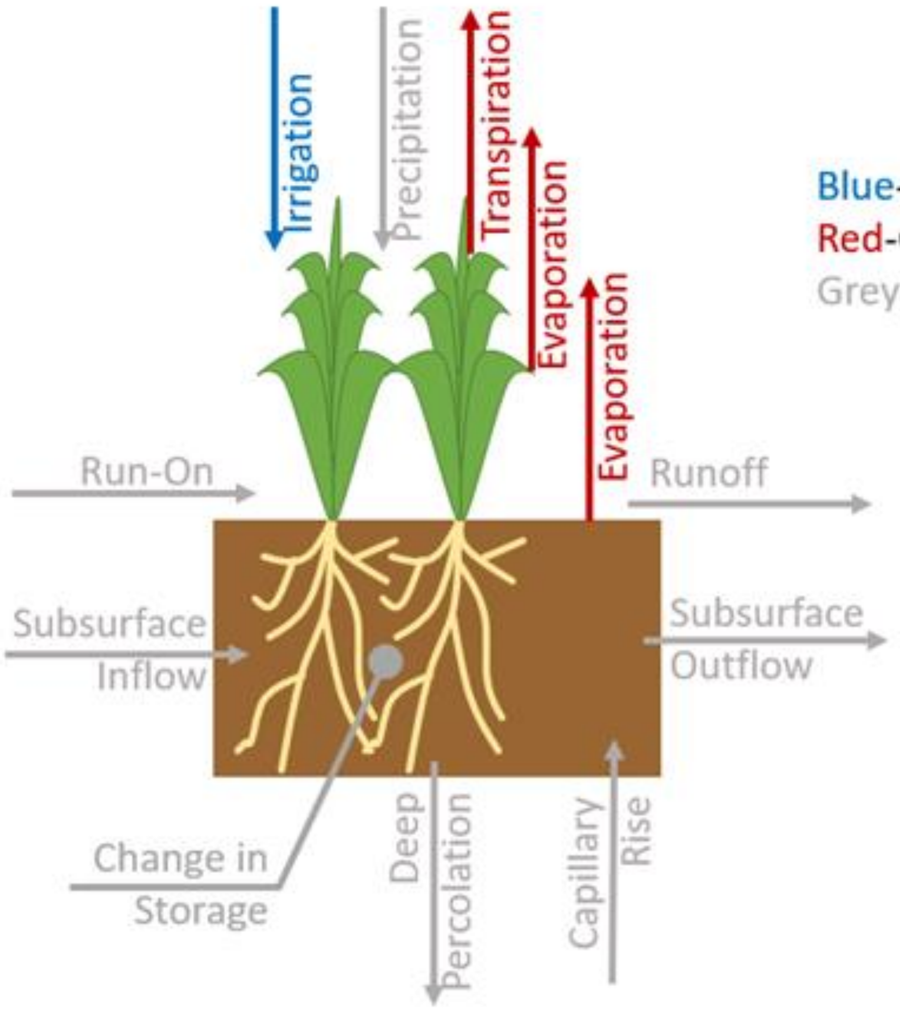
Partial Year Deficit Irrigation of Alfalfa Program

- Strategy is to eliminate one to three irrigation events during the summer (July – September), depending on the irrigation method (border or furrow) and treatment
- Summer months targeted because of the lower water use efficiency relative to other times of the year

CU Quantification

Simplified Representation of the Consumptive Use Quantification Approach for the Palo Verde Irrigation District Deficit Irrigation Project

Quantification Method:
Micrometeorological Techniques

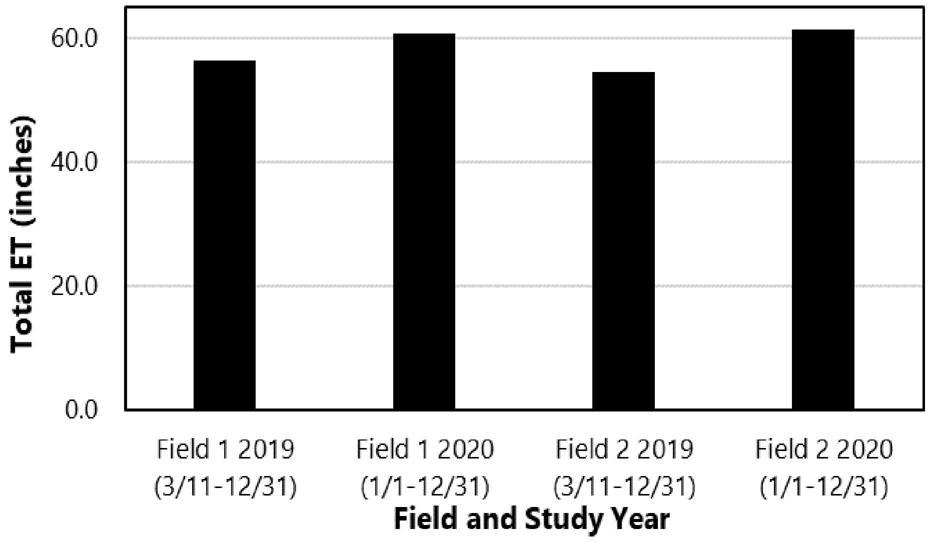


Blue-Inflow accounted for in analysis
Red-Consumptive use in analysis
Grey-Not necessary in analysis

CU Quantification

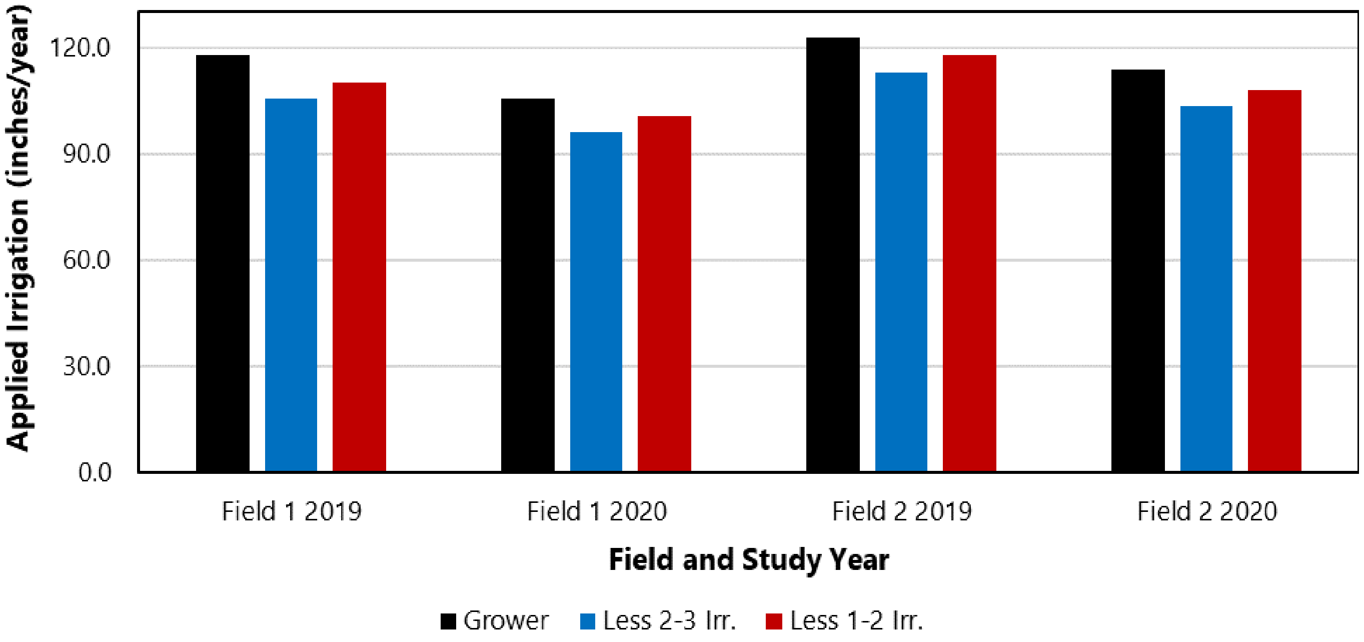
- CU is quantified as ET using eddy covariance and surface renewal micrometeorological techniques
- Primary measures of water conservation
  - Reduction in applied water
  - Change in yield
- Replication and possible statistical analyses

CU Results



Total Observed ET for the Grower Convention Irrigation Treatment for Two Research Fields for a Partial Year in 2019 and all of 2020

Seasonal Total Applied Irrigation Water for Study Treatments in Two Research Fields for 2019 and 2020



Reflections

- Quantification methods used in this study are limited to research settings
- Ultimate end-product of this research will be a NRCS conservation practice or guide

BUREAU OF RECLAMATION

Colorado River Indian Tribes Fallowing Program

CRIT Fallowing Program

- 3-year program (2020-2022)
- 50,000 AFY of CU savings to be stored in Lake Mead as system conservation water
- Any excess is credited and stored in CRIT's EC-ICS account in Lake Mead
- Conserved water due to temporary fallowing of irrigated cropland

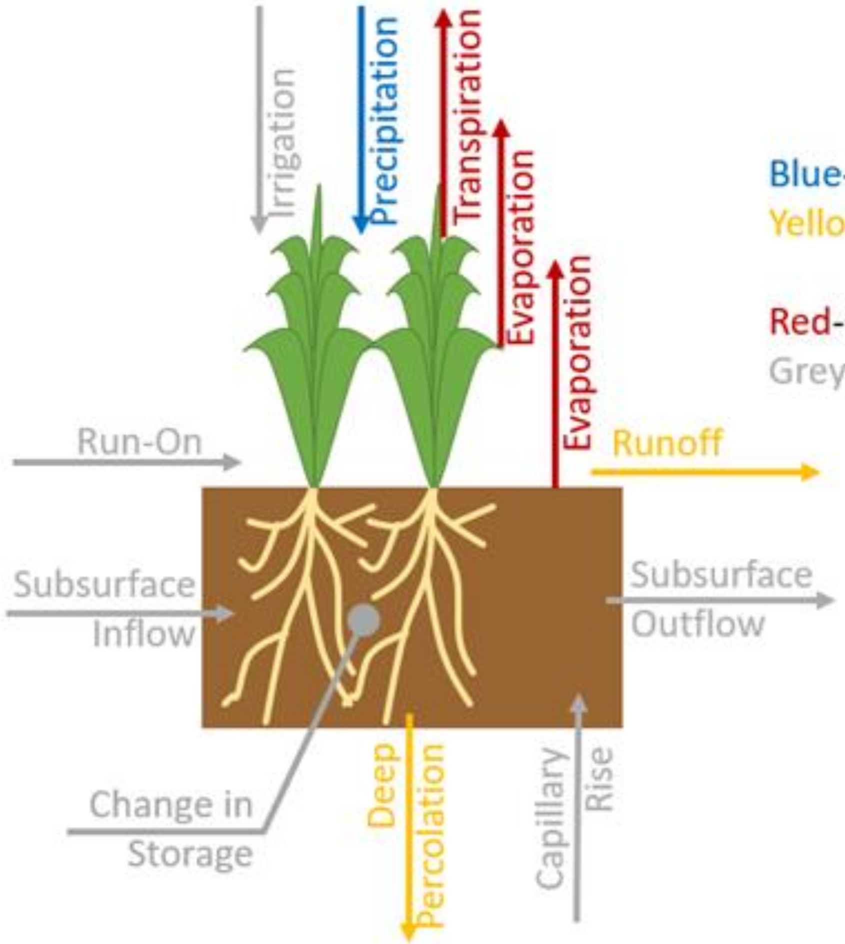
CRIT Fallowing Program

- Field parcels required to have been in active irrigated crop production for at least four of the previous five years
- Cropping patterns determined by field surveys
- Spatially referenced crop mapping system in GIS environment

CU Quantification

Simplified Representation of the Consumptive Use Quantification Approach for the CRIT Fallowing Program

Quantification Method:
Evapotranspiration/Crop Coefficient

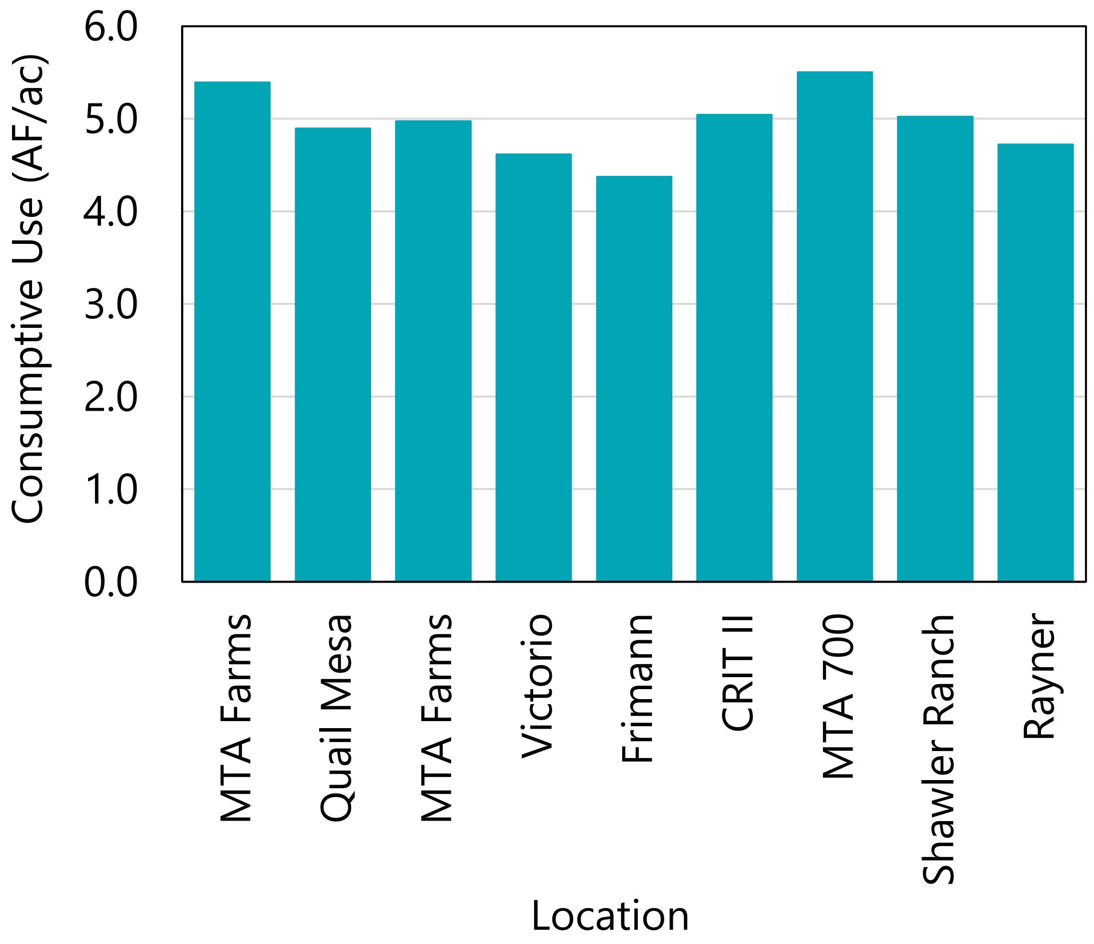


Blue-Inflow accounted for in analysis
Yellow-Accounted for by using effective precipitation
Red-Consumptive use in analysis
Grey-Not necessary in analysis

CU Quantification

- *Δ*CU based upon reference evapotranspiration/crop coefficient method
- ET of each crop was computed using the single (mean) crop coefficient-reference ET
- Daily crop coefficients for Reclamation's LCRAS for the Parker Valley were used
- Factors applied to account for "non-standard" growing conditions

CU Results



Year	Fallowed Land (acre)	Predicted Decrease		Maximum Diversion	
		Consumptive Use (ac-ft)	Diversion (ac-ft)	Predicted (ac-ft)	Decree Accounting (ac-ft)
2020	10,786	53,736	100,706	512,018	459,026

Reflections

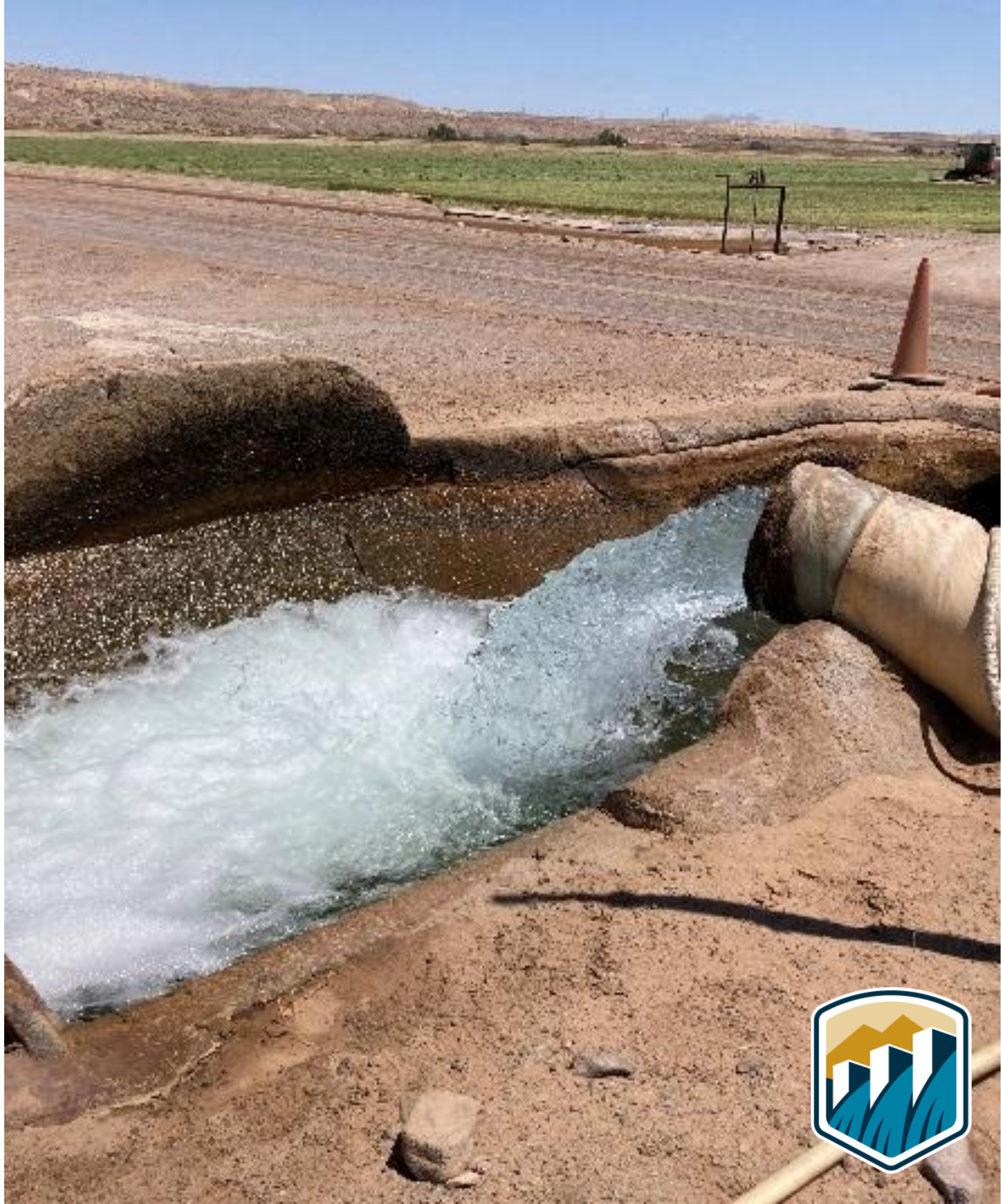
- Crop CU and estimation of the associated diversion reduction is computed prior to fallowing implementation and is independent of what is occurring on the remainder of the Reservation
- Care must be applied to develop crop CU estimates representative of the actual field conditions
- Comparison of the ΔCU to Reclamation Decree Accounting requires a reasonably accurate assessment of irrigation efficiency
- Agreement conditions caused CRIT Farms to idle additional land
- Extra diligence is required to eradicate GMO alfalfa stand and keep the parcel free of green vegetation
- Required coordination with multiple agencies resulted in delays and miscommunications

BUREAU OF RECLAMATION

Mohave Valley Irrigation and Drainage District Fallowing Program

MVIDD Fallowing Program

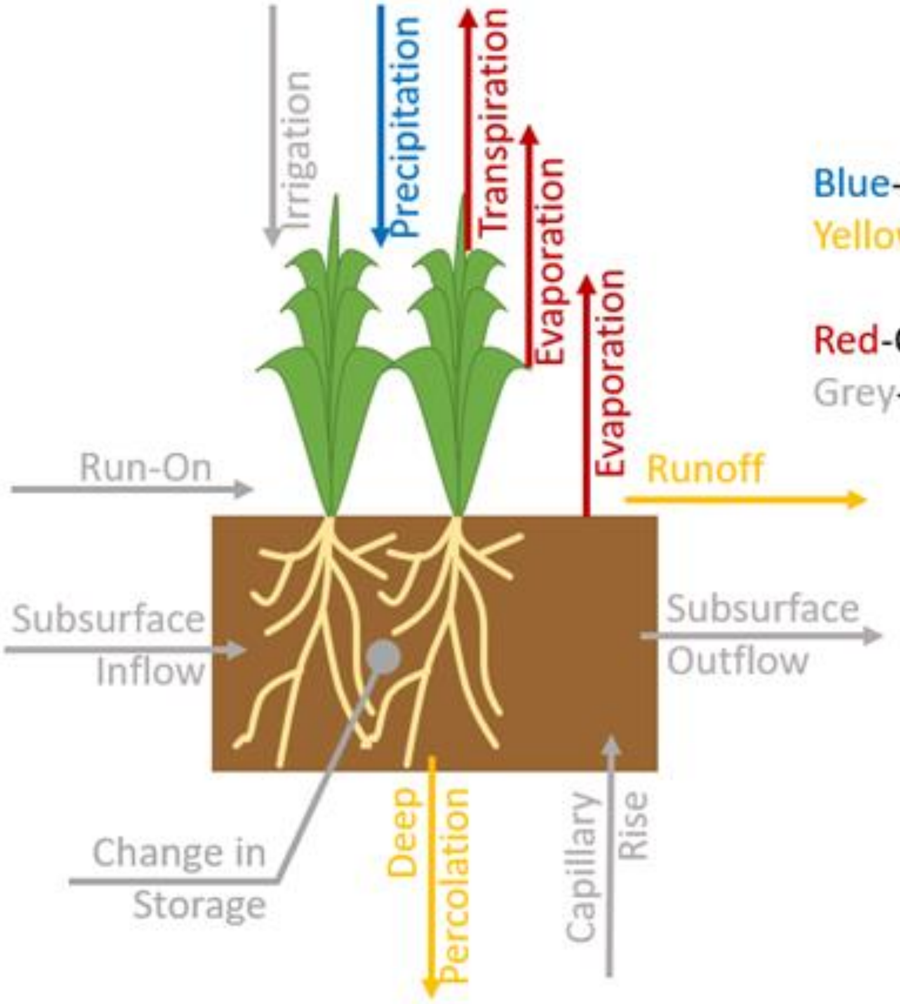
- MVIDD began a fallowing program in 2020 for System Conservation
- Land had to be actively cultivated in at least three of the five most recent years
- Minimum of 10 acres per participant
- Fallowed area was about 1,200 acres in 2020 and over 1,300 acres in 2021



CU Quantification

Simplified Representation of the Consumptive Use Quantification Approach for the MVIDD Fallowing Project

Quantification Method:
Evapotranspiration/Crop Coefficient

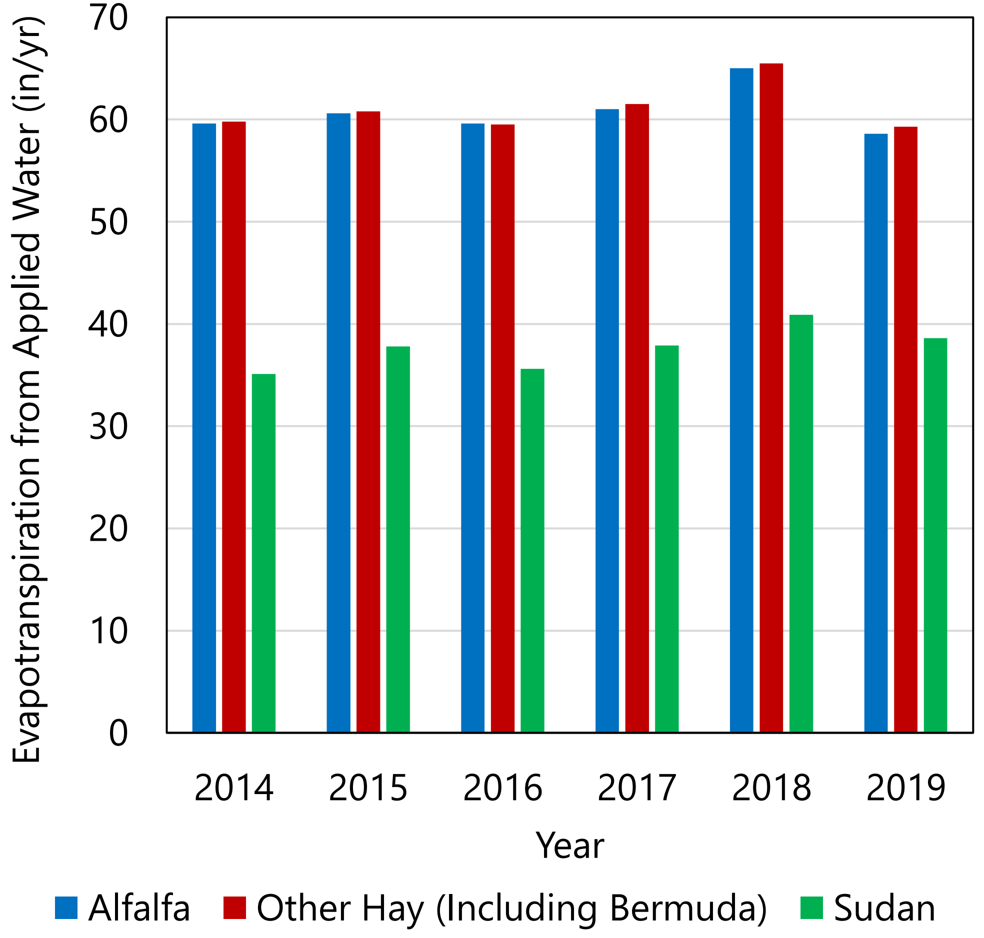


Blue-Inflow accounted for in analysis
Yellow-Accounted for by using effective precipitation
Red-Consumptive use in analysis
Grey-Not necessary in analysis

CU Quantification

- *Δ*CU based upon reference evapotranspiration/crop coefficient method and spatial crop surveys
- Estimated *Δ*CU:
  - *2020:* 6,137 AF on 1,196 acres of fallowed land (5.13 AF/ac)
  - *2021:* 6,778 AF on 1,349 acres of fallowed land (5.03 AF/ac)

CU Results



Year	Fallowed Land (acre)	Predicted Decrease		Maximum Diversion	
		Consumptive Use (ac-ft)	Diversion (ac-ft)	Predicted (ac-ft)	Decree Accounting (ac-ft)
2020	1,196	6,137	8,372	21,353	19,458
2021	1,349	6,778	9,440	19,872	---

Reflections

- The longer the fallowing duration, the more effort (and expense) is required to bring the field into production again
- Interest in the establishment of cover crops for soil stewardship value
- Growers could use the fallowing period to convert fields from conventional production to organic production
- Interest in a seasonal fallowing program
- Concerns about the impact of other water users on the program's ΔCU
- Initial socio-economic concerns and fear about loss of water – education was key

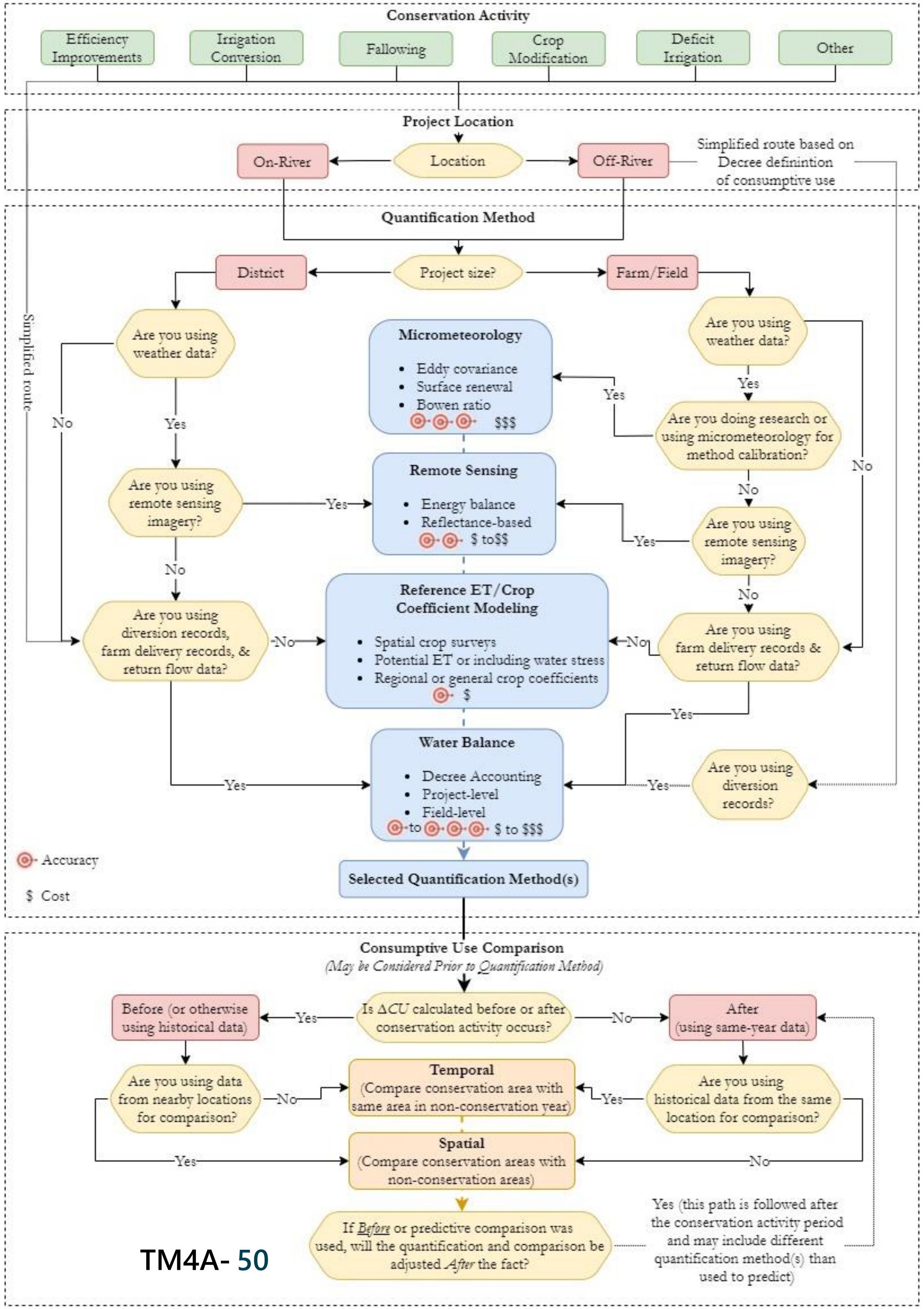
BUREAU OF RECLAMATION

Synopsis and Discussion

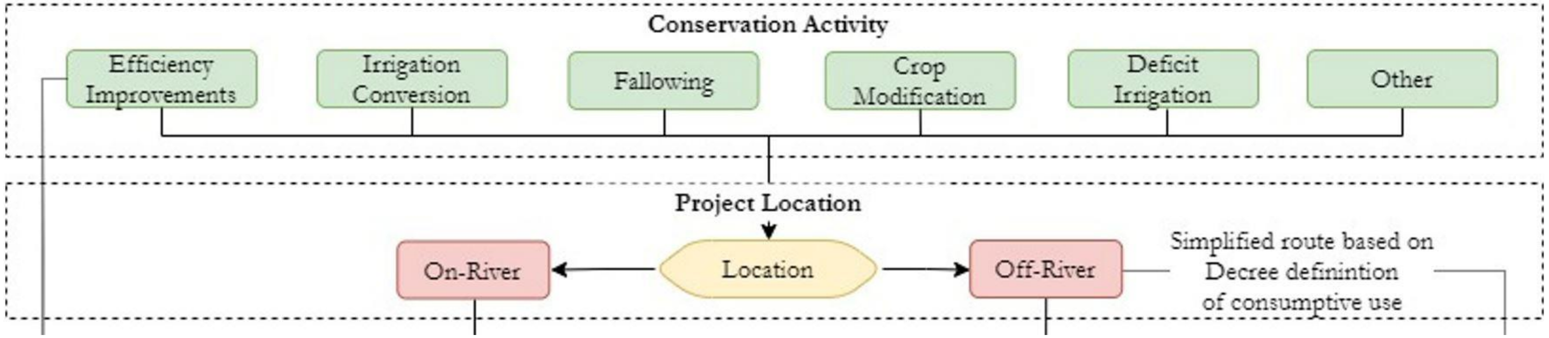
Case Study	Location		Conservation Activity			Quantification Method			Comparison Method[1]		Time-Period		Other Comment
	On-River/ Off Mainstem	State	Deficit Irrigation	Fallowing	Efficiency Improve-ments	Water Balance	Micromet-eorology	Reference ET	In Time	In Space	Single Year	Multi-Year Mean	
GRIC System Modernization	Off Mainstem	AZ			•	•			•			•	Comparison on per-acre basis
BWD Seasonal Fallowing	On-river	CA		•		•				•		•	Based on Decree Accounting reports
PVID Forbearance and Fallowing	On-river	CA		•		•				•	•	•	Based on Decree Accounting reports
PVID "Moderate" Deficit Irrigation	On-river	CA	•				•					•	Developing empirical relationship between irrigation deficit and yield
CRIT Fallowing	On-river	AZ		•				•	•			•	Specifically accounted for non-ideal growing conditions
MVIDD Fallowing	On-river	AZ		•				•	•			•	Used remote-sensing-based crop surveys

[1]Method used to identify the change in consumptive use relative to conditions without the conservation method. The methods either compare the same area (field or district) "in time" or effectively compare areas of conservation with areas not under conservation ("in space").

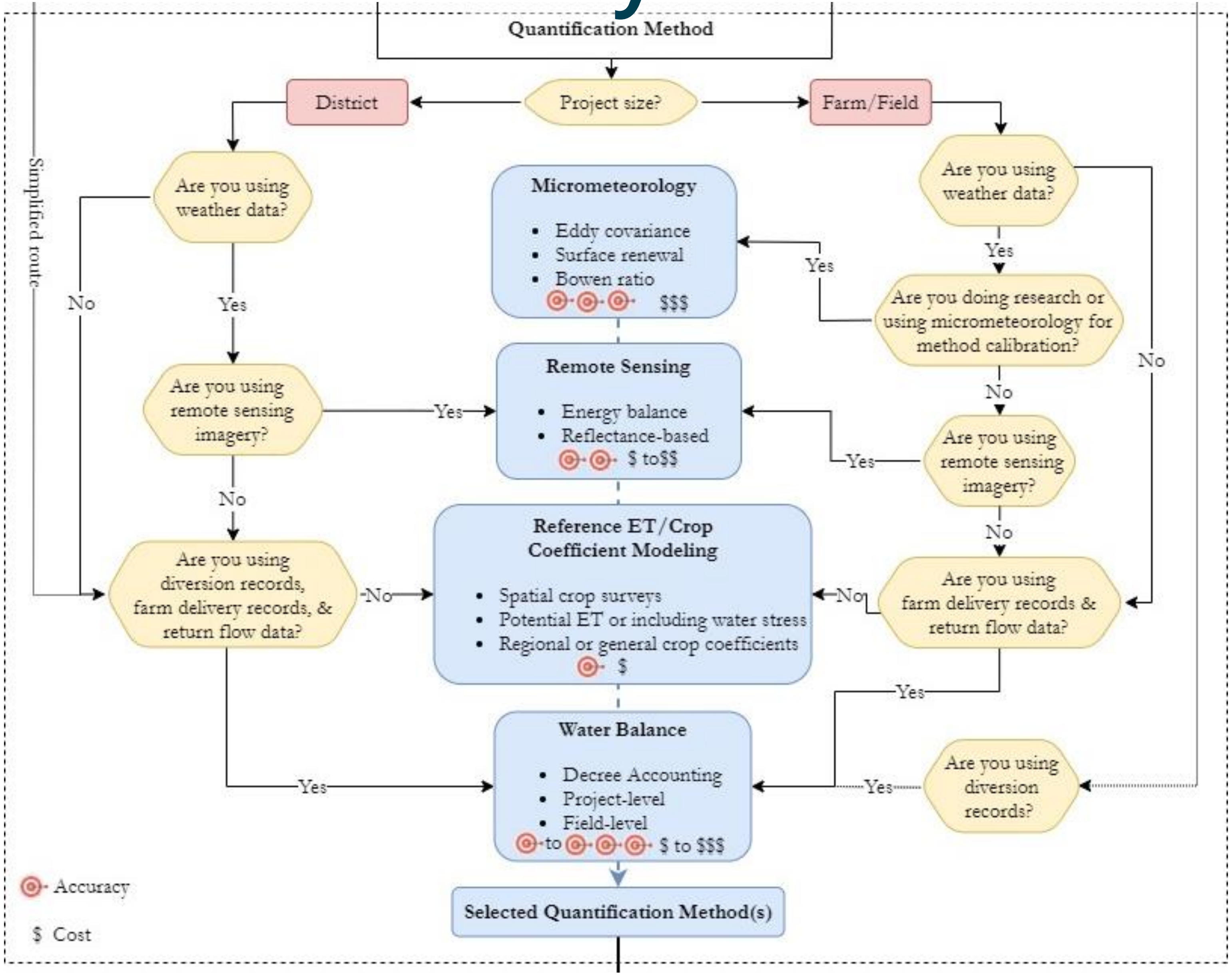
Decision Tree for Conservation Activities and Consumptive Use Quantification/ Comparison Methods



Decision Tree Summary



Decision Tree Summary



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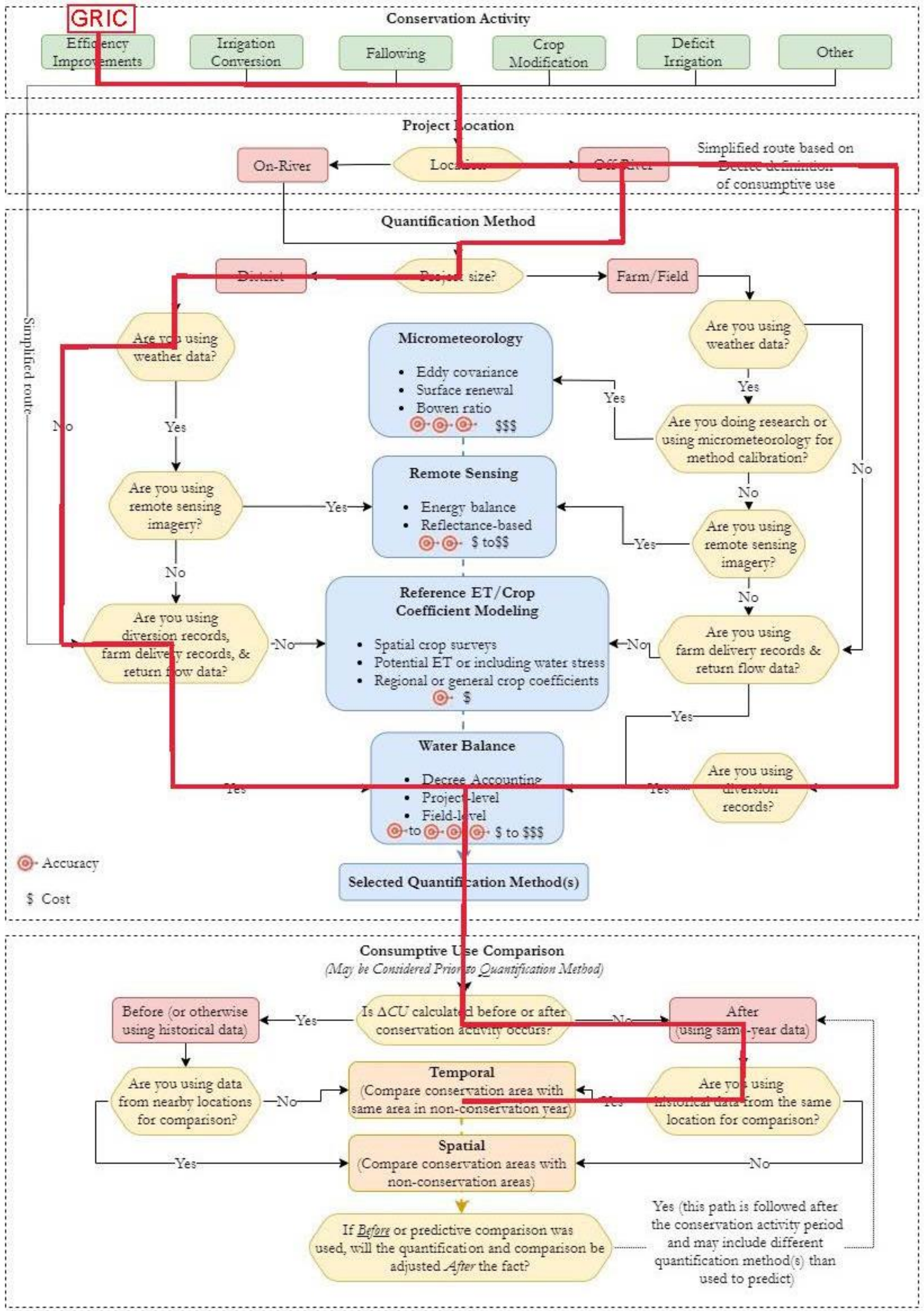

GRIC
Conservation Activity
Efficiency Improvements
Irrigation Conversion
Fallowing
Crop Modification
Deficit Irrigation
Other
Project Location
On-River
Location
Off-River
Simplified route based on Decree definition of consumptive use
Quantification Method
District
Project size?
Farm/Field
Simplified route
Are you using weather data?
Yes
No
Are you using remote sensing imagery?
Are you using diversion records, farm delivery records, & return flow data?
Micrometeorology
• Eddy covariance
• Surface renewal
• Bowen ratio
$$$
Remote Sensing
• Energy balance
• Reflectance-based
$ to$$
Reference ET/Crop Coefficient Modeling
• Spatial crop surveys
• Potential ET or including water stress
• Regional or general crop coefficients
$
Water Balance
• Decree Accounting
• Project-level
• Field-level
to
$ to $$$
Are you doing research or using micrometeorology for method calibration?
Are you using farm delivery records & return flow data?
Are you using diversion records?
Accuracy
$ Cost
Selected Quantification Method(s)
Consumptive Use Comparison
(May be Considered Prior to Quantification Method)
Before (or otherwise using historical data)
Is ΔCU calculated before or after conservation activity occurs?
After (using same-year data)
Are you using data from nearby locations for comparison?
Temporal
(Compare conservation area with same area in non-conservation year)
Are you using historical data from the same location for comparison?
Spatial
(Compare conservation areas with non-conservation areas)
If Before or predictive comparison was used, will the quantification and comparison be adjusted After the fact?
Yes (this path is followed after the conservation activity period and may include different quantification method(s) than used to predict)

Quantification Synopsis

- Balance between cost and accuracy
- Availability of data
- Quantification/comparison time period(s)
- Similarity of comparisons (in time, in space, in data)
- Relationship to Decree Accounting
- More than one method may be equally valid
- Need for continual quantification improvement
- Baseline considerations
- Upfront certainty versus true-up accounting

Wrap-up and Next Steps

Pilot Study Schedule

Workshop 1

Workshop 2

Site Visits/Interviews

Workshop 3

Pilot Study Final Report

Nov 2020

Feb 2021

Mar 2021

Apr 2021

May 2021

Aug 2021

Sep 2021

Oct 2021

Nov 2021

Dec 2021

Milestone 1: Technical Memorandum 1 – Summary of Refined Scope & Case Study Definition

Milestone 2: Technical Memorandum 2 – Summary of Significant Findings from Literature Review & Recent/Current Activities in the Lower Basin

Milestone 3: Technical Memorandum 3 – Summary of Case Study Definition, Site Selection & Evaluation Process

Milestone 4: Technical Memorandum 4 – Case Study Evaluations

Milestone 5: Pilot Study Executive Summary

Presentation at CRWUA


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TM4A-57