BUREAU OF
RECLAMATION

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

Natural Resources Consulting Engineers, Inc.
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:

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

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:

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

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}).

$$\mathrm{ETc} = \mathrm{Kco} * \mathrm{ETos} \qquad \text{or} \qquad \mathrm{ETc} = \mathrm{Kcr} * \mathrm{ETrs}$$

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$^{\text{TM}}$; 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$^{\text{TM}}$ 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$^{\text{TM}}$) 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$^{\text{TM}}$, 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$^{\text{TM}}$.
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

References
Agricultural Research Service (ARS). 2021. *Bushland ET Calculator*. Software. U.S. Department of Agriculture Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX. Available at: https://www.ars.usda.gov/research/software/?badid=1.
Allen, R.G. 2021. *Ref-ET*. Software. University of Idaho, Moscow, ID. Available at: https://www.uidaho.edu/cals/kimberly-research-and-extension-center/research/water-resources/ref-et-software. Accessed 3/4/2021.
Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. *Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements*. Irrigation and Drainage Paper No. 56. Food and Agricultural Organization of the United Nations, Rome. Available at: http://www.fao.org/3/x0490e/x0490e00.htm.
Allen, R.G., Tasumi, M., and R. Trezza. 2007. "Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC) - Model." *Journal of Irrigation and Drainage Engineering*. 113(4): https://doi.org/10.1061/(ASCE)0733-9437(2007)133:4(380).
American Society of Civil Engineers (ASCE). 2005. *The ASCE Standardized Reference Evapotranspiration Equation*. Prepared by the Task Committee on Standardization of Reference Evapotranspiration of the Environmental and Water Resources Institute of American Society of Civil Engineers, Reston, VA.
Anderson, M.C., C.M.U. Neale, F. Li, J.M. Norman, W.P. Kustas, H. Jayanthi, and J. Chávez. 2004. "Upscaling ground observations of vegetation water content, canopy height, and leaf area index during SMEX02 using aircraft and Landsat imagery." *Remote Sensing of Environment*. 92(4): 447-464. https://doi.org/10.1016/j.rse.2004.03.019.
Anderson, M.C., W.P. Kustas, J.G. Alfieri, C.R. Hain, J.H. Prueger, S.R. Evett, P.D. Colaizzi, T.A. Howell, and J.L. Chávez. 2012. "Mapping Daily Evapotranspiration at Landsat Spatial Scales During the BEAREX'08 Field Campaign." *Advances in Water Resources*. 50: 162-177. https://doi.org/10.1016/j.advwatres.2012.06.005.
Ayars, J.E., G.J. Hoffman, and D.L. Corwin. 2012. “Chapter 12: Leaching and Rootzone Salinity Control.” In: W.W. Wallender and K.K. Tanji, Eds. *Agricultural Salinity Assessment and Management*. 2nd Ed. ASCE Manuals and Reports on Engineering Practice No. 71. American Society of Civil Engineers, Reston, VA.
Baker, J.M. 2008. "Challenges and Cautions in Measuring Evapotranspiration.” *Southwest Hydrology*. 7(1). http://www.swhydro.arizona.edu/archive/V7_N1/.
Barker, J.B., T.E. Franz, D.M. Heeren, C.M.U. Neale, and J.D. Luck. 2017. “Soil Water Content Monitoring for Irrigation Management: A Geostatistical Analysis.” *Agricultural Water Management*. 188: 36-49. https://doi.org/10.1016/j.agwat.2017.03.024.
Barker, J.B., C.M.U. Neale, D.M. Heeren, A.E. Suyker. 2018. “Evaluation of a Hybrid Reflectance-Based Crop Coefficient and Energy Balance Evapotranspiration Model for Irrigation Management.” *Transactions of the ASABE*. 60(2): 533-548. https://doi.org/10.13031/trans.12311.
Bastiaanssen, W.G.M., M. Menenti, R.A. Feddes, and A.A.M. Holtslag. 1998. "A remote sensing surface energy balance algorithm for land (SEBAL). 1. Formulation." *Journal of Hydrology*. 212–213: 198-212. https://doi.org/10.1016/S0022-1694(98)00253-4.

References
Bausch, W.C. and C.M.U. Neale. 1987. "Crop Coefficients Derived from Reflectance Canopy Radiation: A Concept." *Transactions of the ASAE.* 30(3): 703-709. https://doi.org/10.13031/2013.30463.
Blaney, H. F. and Criddle, W.D. 1950. *Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data*. USDA SCS TP-96. United States Department of Agriculture, Washington DC.
Blaney, H. F. and Criddle, W.D. 1962. *Determining Consumptive Use and Irrigation Water Requirements*. USDA Agricultural Research Service Tech Bulletin 1275. United States Department of Agriculture, Washington DC.
Bowen, I. 1926. "The Ratio of Heat Losses by Conduction and by Evaporation from Any Water Surface." *Physical Review.* 27(6): 779-787. https://doi.org/10.1103/PhysRev.27.779.
Burba, G. and D. Anderson. 2010. *Brief Guide to Eddy Covariance Measurements.* LI-COR, Inc. Available at: https://www.licor.com/env/pdf/eddy_covariance/Brief_Intro_Eddy_Covariance.pdf.
Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D. L.A. Hardy, T.A. Howell, and D.E. Eisenhauer. 1997. "Irrigation Performances Measures: Efficiency and Uniformity." *Journal of Irrigation and Drainage Engineering.* 123(6). https://doi.org/10.1061/(ASCE)0733-9437(1997)123:6(423).
California Department of Water Resources (CDWR). 2005. *How much water has your crop used since your last irrigation?* California Department of Water Resources. Available at: https://cimis.water.ca.gov/Content/pdf/Crop_Coeffients.pdf.
California Department of Water Resources (CDWR). 2021. *CMIS: California Irrigation Management Information System*. California Department of Water Resources. Available at: https://water.ca.gov/Programs/Water-Use-And-Efficiency/Land-And-Water-Use/Agricultural-Water-Use-Models. Accessed 3/4/2021.
California Department of Water Resources (CDWR). 2021a. *Agricultural Water Use Models*. California Department of Water Resources. Retrieved from: https://cimis.water.ca.gov/Default.aspx. Accessed 3/4/2021.
California Department of Water Resources (CDWR). 2021b. *IWFM: Integrated Water Flow Model*. California Department of Water Resources. Retrieved from: https://water.ca.gov/Library/Modeling-and-Analysis/Modeling-Platforms/Integrated-Water-Flow-Model. Accessed 3/4/2021.
California Department of Water Resources (CDWR). 2021c. *ssj-calsimetaw*. Software. California Department of Water Resources. Available at: https://github.com/ssj-delta-cu/ssj-calsimetaw#readme. Accessed 3/4/2021.
Campos, I., C.MU. Neale, A.E. Suyker, T.J. Arkebauer, and I.Z. Gonçalves. 2017. “Reflectance-Based Crop Coefficients Redux: For Operational Evapotranspiration Estimates in the Age of High-Producing Hybrid Varieties.” *Agricultural Water Management.* 187: 140-153. https://doi.org/10.1016/j.agwat.2017.03.022.
Chávez, J., C.M.U. Neale, L.E. Hipps, J.H. Prueger, and W.P. Kustas. 2005. "Comparing Aircraft-Based Remotely Sensed Energy Balance Fluxes with Eddy Covariance Tower Data Using Heat Flux Source Area Functions." *Journal of Hydrometeorology.* 6(6): 923-940. https://doi.org/10.1175/JHM467.1.

References

Colaizzi, P.D., S.R. Evett, T.A. Howell, and J.A. Tolk. 2006. "Comparison of Five Models to Scale Daily Evapotranspiration from On-Time-of-Day Measurements." *Transactions of the ASABE.* 49(5): 1409-1417. https://doi.org/10.13031/2013.22056.

Colorado Water Conservation Board and Colorado Division of Water Resources (CWCB-CDWR). 2021. *StateCU.* Software. Colorado Water Conservation Board and Colorado Division of Water Resources. Retrieved from: https://cdss.colorado.gov/software/statecu. Accessed 3/4/2021.

Djaman, K. and S. Irmak. 2016. "Effects of Planting Date and Density on Plant Growth, Yield, Evapotranspiration, and Water Productivity of Subsurface Drip-Irrigated and Rainfed Maize. *Transactions of the ASABE.* 59(2): 1235-1256. https://doi.org/10.13031/trans.59.11169.

Doorenbos, J., A.H. Kassam, C.L.M Bentvelsen, V. Branscheid, J.M.G.A. Plusje, M. Smith, G.O. Uittenbogaard, and H.K. Van Der Wal. 1986. *Yield Response to Water*. Irrigation and Drainage Paper No. 33. Food and Agriculture Organization of the United Nations, Rome, Italy.

Elhaddad, A. and L.A. Garcia. 2011. "ReSET-Raster: Surface Energy Balance Model for Calculating Evapotranspiration Using a Raster Approach." *Journal of Irrigation and Drainage Engineering.* 137(4). https://doi.org/10.1061/(ASCE)IR.1943-4774.0000282.

English, M.J., K.H. Solomon, and G.J. Hoffman. 2002. A Paradigm Shift in Irrigation Management. *Journal of Irrigation and Drainage Engineering*, 128(5):267-277.

Evett, S.R., R.C. Schwartz, T.A. Howell, R.L. Baumhardt, and K.S. Copland. 2012b. "Can Weighing Lysimeter ET Represent Surrounding Field ET Well Enough to Test Flux Station Measurements of Daily and Sub-Daily ET?" *Advances in Water Resources.* 50:79-90. https://doi.org/10.1016/j.advwatres.2012.07.023.

Fisher, J.B., K.P. Tu, and D.D. Baldocchi. 2008. "Global estimates of the land–atmosphere water flux based on monthly AVHRR and ISLSCP-II data, validated at 16 FLUXNET sites." *Remote Sensing of Environment*. 112(3): 901-919. https://doi.org/10.1016/j.rse.2007.06.025.

Food and Agricultural Organization of the United Nations (FAO). 2021a. *CROPWAT.* Software. Food and Agricultural Organization of the United Nations, Rome. Available at: http://www.fao.org/land-water/databases-and-software/cropwat/en/. Accessed 3/4/2021.

Food and Agricultural Organization of the United Nations (FAO). 2021b. *ETo Calculator.* Software. Food and Agricultural Organization of the United Nations, Rome. Available at: http://www.fao.org/land-water/databases-and-software/eto-calculator/en/. Accessed 3/4/2021.

Geili, H.M.E. 2012. *Modeling Spatial Surface Energy Fluxes of Agricultural and Riparian Vegetation Using Remote Sensing.* P.H.D. Dissertation. Utah State University Department of Civil and Environmental Engineering. Available at: https://digitalcommons.usu.edu/etd/1165.

Geli, H.M.E., C.M.U. Neale, D. Watts, J. Osterberg, H.A.R. De Bruin, W. Kohsiek, R.T. Pack, and L.E. Hipps. 2012. "Scintillometer-Based Estimates of Sensible Heat Flux Using Lidar-Derived Surface Roughness." *Journal of Hydrometeorology*. 13(4): 1317–1331. https://doi.org/10.1175/JHM-D-11-085.1.

Grieve, C.M., S.R. Grattan, and E.V. Maas. 2012. "Chapter 13: Plant Salt Tolerance." In: W.W. Wallender and K.K. Tanji, Eds. *Agricultural Salinity Assessment and Management.* 2nd Ed. ASCE Manuals and Reports on Engineering Practice No. 71. American Society of Civil Engineers, Reston, VA.

References
Hardie, M. "Review of Novel and Emerging Proximal Soil Moisture Sensors for Use in Agriculture." *Sensors.* 20: 6934. https://doi.org/10.3390/s20236934.
Hargreaves, G. and Samani, Z. 1982. "Estimating Potential Evapotranspiration." *Journal of the Irrigation and Drainage Division* 108(3): 225-230. American Society of Civil Engineers, Reston VA.
Hargreaves, G.H. and Z.A. Samani. 1985. "Reference Crop Evapotranspiration from Temperature." *Applied Engineering in Agriculture* 1(2):96-99.
Henderson, D. C., & Sorensen, E. F. 1968. *Consumptive Irrigation Requirements of Selected Areas in New Mexico*. New Mexico State University, Las Cruces, NM.
Hill, R.W. 1994. *Consumptive Use of Irrigated Crops in Utah.* Utah Agricultural Experiment Station Research Report No. 145. Utah State University, Logan, UT. Available at: https://waterrights.utah.gov/docSys/v912/a912/a912044e.pdf.
Hill, R.W., R.J. Hanks, and J.L. Wright. 1999. *Crop Yield Models Adapted to Irrigation Scheduling Programs*. Utah Agricultural Research Experiment Station Research Report 99, Utah State University, Logan, UT.
Hill, R.W. and J.B. Barker. 2010. *Verification of Turfgrass Evapotranspiration in Utah.* Utah Agricultural Experiment Station Research Report No. 211. Utah State University, Logan, UT.
Huete, A.R. 1988. "A Soil-Adjusted Vegetation Index (SAVI)." *Remote Sensing of Environment.* 25(3): 295-309. https://doi.org/10.1016/0034-4257(88)90106-x.
Hydroinnova. 2011. *Soil Moisture.* Hydroinnova, LLC, Albuquerque, NM. Retrieved from: http://hydroinnova.com/ps_soil.html#overview. Accessed: 2/3/2021.
Idso, S.B., R.D. Jackson, P.J. Pinter, R.J. Reginato, J.L. Hatfield. 1981. "Normalizing the stress-degree-day parameter for environmental variability." *Agricultural Meteorology*. 24: 45-55. https://doi.org/10.1016/0002-1571(81)90032-7.
Irmak, S. and A. Irmak. 2005. "Performance of Frequency-Domain Reflectometer, Capacitance, and Psuedo-Transit Time-Based Soil Water Content Probes in Four Coarse-Textured Soils." *Applied Engineering in Agriculture*. 21(6): 999-1008. https://doi.org/ 10.13031/2013.20035.
Itenfisu, D. R.L. Elliott, R.G. Allen, and I.A. Walter. 2003. "Comparison of Reference Evapotranspiration Calculations as Part of the ASCE Standardization Effort." *Journal of Irrigation and Drainage Engineering.* 129 (6):440-448.
Jackson, R.D., S.B. Idso, R.J. Reginato, and P.J. Pinter. 1981. "Canopy temperature as a crop water stress indicator." *Water Resources Research*. 17(4): 1133– 1138. https://doi.org/10.1029/WR017i004p01133.
Jensen, M. E. 1993. "Evaluating Effective Rainfall in CVWD." In S. M. Jones, C. M. Burt, A. J. Clemmens, M. E. Jensen, J. M. Lord, & K. H. Solomon, *Water Use Assessment, Coachella Valley Water District and Imperial Irrigation District* (p. Appendix 3). U.S. Bureau of Reclamation. Boulder City, NV.
Jensen, M.E. 1998. *Coefficients for Vegetative Evapotranspiration and Open-Water Evaporation for the Lower Colorado River Accounting System.* Available from the U.S. Bureau of Reclamation Boulder Canyon Operations Office. Boulder City, NV.

References

Jensen, M.E. 2003. *Vegetative and Open Water Coefficients for the Lower Colorado River Accounting System (LCRAS) Addendum to the 1998 Report.* Available from the U.S. Bureau of Reclamation Boulder Canyon Operations Office. Boulder City, NV.

Jensen, M.E., R.D. Burman, and R.G. Allen (ed). 1990. *Evapotranspiration and Irrigation Water Requirements*. ASCE Manuals and Reports on Engineering Practice No. 70, New York, 332 p. American Society of Civil Engineers, Reston, VA.

Jin, Y., J.T. Randerson, and M.L. Goulden. 2011. "Continental-Scale Net Radiation and Evapotranspiration Estimated Using MODIS Satellite Observations." *Remote Sensing of Environment.* 115(9): 2302-2319. https://doi.org/10.1016/j.rse.2011.04.031.

Kipp and Zonen. 2015. *Instruction Manual: LAS MkII Scintillometer.* Kipp and Zonen B.V., Delft, The Netherlands. Available at: https://www.kippzonen.com/Product/193/LAS-MkII-Scintillometer#.YBmMSXJICUk.

Lewis, C.S. 2021. *GridET.* Software. Utah State University and Utah Division of Water Resources. Retrieved from: https://github.com/claytonscottlewis/GridET. Accessed, 3/4/2021.

Ley, Thomas W. 2012. “Using the ASCE Standardized Reference Evapotranspiration Equation to Determine Crop Evapotranspiration.” Proceedings paper prepared for: “Evapotranspiration.: Determination of Consumptive Use in Water Rights Proceedings”, 4th Course of the Technical and Engineering Program Series, Continuing Legal Education, Colorado Bar Association, Denver CO. October.

Li-Cor. 2020. *Eddy Covariance Systems.* Li-Cor Biosciences, Lincoln, NE. Retrieved from: https://www.licor.com/env/products/eddy_covariance/. Accessed 12/28/2020.

Louie, M.J., P.M. Shelby, J.S., Smesrud, L.O., Gatchell, and J.S., Selker, J.S. 2000. "Field evaluation of passive capillary samplers for estimating groundwater recharge." *Water Resources Research.* 36(9): 2407-2416. https://doi.org/10.1029/2000WR900135.

Mancosu, N., Spano, D., Orang, M., Sarreshteh, S., Snyder, R.L. 2015. "SIMETAW# - a Model for Agriculture Water Demand Planning." *Water Resources Management.* 30: 541-557. https://doi.org/10.1007/s11269-015-1176-7.

Martin, E.C. and D.C. Slack. 2003. *Arizona Irrigation Scheduling System (AZSCHED)*. University of Arizona, Tucson, AZ. Retrieved from: https://cals.arizona.edu/crop/irrigation/azsched/azsched.html. Accessed: 12/30/2020.

Monteith, J.L. 1965. “Evaporation and environment.” In G.E.Fogg (edit.) *Symposium of the Society for Experimental Biology, The State and Movement of Water in Living Organisms*, 19: 205-234. Academic Press, Inc. NY.

Nagler, P.L. C.J. Jarchow, and E.P. Glenn. 2018. "Remote Sensing Vegetation Index Methods to Evaluate Changes in Greenness and Evapotranspiration in Riparian Vegetation in Response to the Minute 319 Environmental Pulse Flow to Mexico." *Proceedings of the International Association of Hydrological Sciences*. 380: 45-54. https://doi.org/10.5194/piahs-380-45-2018.

References

Natural Resources Consulting Engineers and Jacobs Engineering Group (NRCE and Jacobs). 2021. *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. Bureau of Reclamation. Available at: https://lcrbpilotstudy.com.

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.

Natural Resources Conservation Service (NRCS). 2021. *Irrigation Water Requirements – Penman-Monteith Method (IWRpm).* Software. U.S. Department of Agriculture Natural Resources Conservation Service. Retrieved from: https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/irrigation/?cid=stelprdb1044890. Accessed 3/4/2021.

Neale, C.M.U., H.M.E. Geli, W.P. Kustas, J.G. Alfieri, P.H. Gowda, S.R. Evett, J.H. Prueger, L.E. Hipps, W.P. Dulaney, J.L. Chávez, A.N. French, and T.A. Howell. 2012. "Soil water content estimation using a remote sensing based hybrid evapotranspiration modeling approach." *Advances in Water Resources*. 50: 152-161. https://doi.org/10.1016/j.advwatres.2012.10.008.

Norman, J.M., W.P. Kustas, and K.S. Humes. 1995. "Source Approach for Estimating Soil and Vegetation Energy Fluxes in Observations of Directional Radiometric Surface Temperature." *Agricultural and Forest Meteorology*. 77(3–4): 263-293. https://doi.org/10.1016/0168-1923(95)02265-Y.

Orang, M.N., R.L. Snyder, G. Shu, Q.J. Hart, S. Sarreshteh, M. Falk, D. Beaudette, S. Hayes, and S. Eching. 2013. "California Simulation of Evapotranspiration of Applied Water and Agricultural Energy Use in California." *Journal of Integrative Agriculture*. 12(8): 1371-1388. https://doi.org/10.1016/S2095-3119(13)60742-X.

Penman, H.L. 1948. "Natural Evaporation from Open Water, Bare Soil, and Grass." *Proceedings of the Royal Society of London* A193:120-146.

Rouse, J.W., R.H. Haas, J.A. Schell, D.W. Deering, and J.C. Harlan. 1974. *Monitoring the Vernal Advancement and Retrogradation (Greenwave Effect) of Natural Vegetation*. Texas A & M University Remote Sensing Center. Available at: https://ntrs.nasa.gov/search.jsp?R=19740022555.

Saxton, K.E. 2017. *SPAW: Soil-Plant-Atmosphere-Water Field and Pond Hydrology.* Unites States Department of Agriculture Agricultural Research Service and Washington State University. Available at: https://hrsl.ba.ars.usda.gov/SPAW/Index.htm.

Schmid, W. and R.T. Hanson. 2009. *The Farm Process Version 2 (FMP2) for MODFLOW-2005 – Modifications and Upgrades to FMP1.* U.S. Geological Survey, Reston, VA. Available at: https://pubs.usgs.gov/tm/tm6a32/pdf/tm6a32.pdf.

Senay, G.B., S. Bohms, R.K, Singh, P.H., Gowda, N.M, Velpuri, H., Alemu, and J.P., Verdin. 2013. "Operational Evapotranspiration Mapping Using Remote Sensing and Weather Datasets: A New Parameterization for the SSEB Approach." *Journal of the American Water Resources Association*. 49(3): 577– 591. https://doi.org/10.1111/jawr.12057.

Sharma, V. 2019. *Soil Moisture Sensors for Irrigation Scheduling.* University of Minnesota Extension, St. Paul, MN. Retrieved from: https://extension.umn.edu/irrigation/soil-moisture-sensors-irrigation-scheduling. Accessed 2/3/2021.

References
Sharma, K., S. Irmak, and M.S. Kukal. “Propagation of Soil Moisture Sensing Uncertainty into Estimation of Total Soil Water, Evapotranspiration and Irrigation Decision-Making.” *Agricultural Water Management.* 243: 106454. https://doi.org/10.1016/j.agwat.2020.106454.
Smeal, D., M.K. O’Neill, and R.N. Arnold. 2005. “Forage Production of Cool Season Pasture Grasses as Related to Irrigation.” *Agricultural Water Management*, 76(2005): 224-236. https://doi.org/10.1016/j.agwat.2005.01.014.
Snyder, R.L., D. Spano, and K.T. Paw U. 1996. "Surface renewal analysis for sensible and latent heat flux density." *Boundary-Layer Meteorology*. 77: 249–266. https://doi.org/10.1007/BF00123527.
Snyder, R.L., M. Orang, S. Geng, and J.C. Matyac. 2006. *Final Report: Delta Evapotranspiration of Applied Water (DETAW) Version 1.0*. California Department of Water Resources and University of California, Davis Department of Air, Land and Water Resources.
Snyder, R.L. C. Pedras, A. Montazar, J.M. Henry, and D. Ackley. “Advances in ET-Based Landscape Irrigation Management.” *Agricultural Water Resources.* 147: 187-197. https://doi.org/10.1016/j.agwat.2014.07.024.
Soil Conservation Service (SCS). 1992. "Chapter 2: Irrigation Water Requirements." in *National Engineering Handbook* Part 523. U.S. Department of Agriculture Soil Conservation Service. Available at: https://www.wcc.nrcs.usda.gov/ftpref/wntsc/waterMgt/irrigation/NEH15/ch2.pdf.
Soil Conservation Service (SCS). 1970. *Irrigation Water Requirements*. Technical Release No. 21. Soil Conservation Service Engineering Division. United States Department of Agriculture, Washington DC.
Taghveaian, S. 2011. *Water and Energy Balance of a Riparian and Agricultural Ecosystem Along the Lower Colorado River.* Ph.D. Dissertation Utah State University Department of Civil and Environmental Engineering, Logan, UT. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1956&context=etd
Thomas, T. 2015. *Three-Dimensional Wind Speed and Flux Measurements Over a Rain-Fed Soybean Field Using Orthogonal and on-Orthogonal Sonic Anemometer Designs*. M.S. Thesis, University of Nebraska-Lincoln. Available at: https://digitalcommons.unl.edu/natresdiss/128/.
Tule Technologies. 2020. *Your 24/7 Automated Irrigation Advisor.* Tule Technologies, Inc., California. Retrieved from: https://www.tuletechnologies.com/sense. Accessed 12/28/2020.
U.S. Bureau of Reclamation (Reclamation). 1997-2018. *Lower Colorado River Accounting System Calendar Years 1996-2002, Lower Colorado River Accounting System Evapotranspiration Calculations Calendar Year 2003, Lower Colorado River Accounting System Evapotranspiration and Evaporation Calculations Calendar Years 2004-2008, Estimates of Evapotranspiration and Evaporation Along the Lower Colorado River Calendar Years 2009-2010,* and *Lower Colorado River Annual Summary of Evapotranspiration and Evaporation Calendar Years 2011-2014.* U.S. Bureau of Reclamation Lower Colorado Region Boulder Canyon Operations Office. Available at: https://www.usbr.gov/lc/region/g4000/wtracct.html.
U.S. Bureau of Reclamation (Reclamation). 2012. *Colorado River Basin Water Supply and Demand Study.* U.S. Bureau of Reclamation. Available at: https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/index.html.

References

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/Phase1Report.html.

U.S. Bureau of Reclamation (Reclamation). 2019. *Pilot System Conservation Program (Pilot Program).* U.S. Bureau of Reclamation. Retrieved from: https://www.usbr.gov/lc/region/programs/PilotSysConsProg/pilotsystem.html. Accessed 1/4/2021.

U.S. Bureau of Reclamation (Reclamation). 2021. *ET-Demands.* Software. U.S. Bureau of Reclamation and R.G. Allen, University of Idaho, Kimberly Research and Extension Center, Kimberly Idaho. Retrieved from: https://et-demands.readthedocs.io/en/master/introduction.html. Accessed 3/4/2021.

U.S. Geological Survey (USGS). 2019. *Landsat 8 (L8) Data Users Handbook.* USGS, Reston, VA. Available at: https://prd-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/atoms/files/LSDS-1574_L8_Data_Users_Handbook-v5.0.pdf.

University of Arizona (UA). 2021. AZMET: *The Arizona Meteorological Network.* University of Arizona, Tucson, AZ. Retrieved from: https://cals.arizona.edu/azmet/. Accessed 2/2/2021.

University of California Cooperative Extension (UC Extension). 1994. *Using Reference Evapotranspiration (ETo) and Crop Coefficients to Estimate Crop Evapotranspiration (ETc) for Agronomic Crops, Grasses, and Vegetable Crops.* University of California Cooperative Extension. Available at: https://cimis.water.ca.gov/Content/PDF/21427-KcAgronomicGrassandVeg.pdf.

White, W.N. 1932. *A Method of Estimating Ground-Water Supplies Based on Discharge by Plands and Evaporation from Soil: Results of Investigations in Escalante, Utah.* Water Supply Paper 659-A. U.S. Geological Survey. U.S. Government Printing Office, Washington, D.C. https://doi.org/10.3133/wsp659A

Zotarelli, L. M. Dukes, and M. Paranhos. 2016. *Minimum Number of Soil Moisture Sensors for Monitoring and Irrigation Purposes.* HS1222. University of Florida Institute of Food and Agricultural Sciences Extension Service, Gainesville, FL. Available at: https://edis.ifas.ufl.edu/pdffiles/HS/HS122200.pdf.