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Quantitative Assessments of Water and Salt Balance for Cropping Systems in the Lower Colorado River Region

A report for the
Yuma County Agriculture Water Coalition

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USDA/Arizona Department of Agriculture Specialty Crop Block Grant Program

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Arizona Grain Research and Promotion Council

Arizona Iceberg Lettuce Research Council

Arizona Citrus Research Council

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3 Foreword

In 2015, the Yuma County Agriculture Water Coalition (YCAWC) released a report titled "A Case Study in Efficiency - Agriculture and Water Use in the Yuma, Arizona Area." The YCAWC is a coalition of water delivery jurisdictions near Yuma. Members include seven irrigation water delivery entities: North Gila Irrigation and Drainage District (NGIDD), Yuma Irrigation District (YID), Yuma Mesa Irrigation and Drainage District (YMIDD), Unit B Irrigation and Drainage District (Unit B), Wellton-Mohawk Irrigation and Drainage District (WMIDD), Yuma County Water Users' Association (YCWUA), and Bard Water District (BWD) - see map on page 48.

The 2015 case study included contributions from the seven irrigation water delivery entities in Yuma County, the United States Bureau of Reclamation (USBR), the Arizona Department of Water Resources, and the University of Arizona (UArizona). The existing status of the irrigation conveyance system and changes in cropping systems and agricultural water management practices over the past five decades were summarized. While the report highlighted the resulting enhanced water use efficiencies at the district and farm level, it also identified the need for additional research. The additional information needed included updated crop water consumptive use and more quantitative data on the beneficial use of water for salt management.

In an effort to address these additional research areas, and to identify potential strategies for further agricultural water management improvements, the YCAWC supplied seed funding commitments in 2016 to the Yuma Center of Excellence for Desert Agriculture (YCEDA). YCEDA is a public-private partnership whereby the desert agriculture industry supports research efforts to proactively address their pressing problems. These funds were used to support research conducted by scientists at UArizona and the Arid Land Agricultural Research Center (ALARC), a USDA-ARS facility. It was hoped that YCEDA, UArizona, and ALARC would in turn seek additional funding partners to augment funds provided by the YCAWC. That was successfully accomplished on a significant scale. Partners included the USBR, two National Aeronautics and Space Administration (NASA) organizations - NASA Jet Propulsion Laboratory (NASA JPL) and NASA Goddard Space Flight Center (NASA GSFC), the USDA/Arizona Department of Agriculture Specialty Crop Block Grant Program, Cotton Incorporated, the Arizona Iceberg Lettuce Research Council, the Arizona Grain Research and Promotion Council, the Arizona Citrus Research Council, and several in-house funding programs within the UArizona and USDA-ARS ALARC.

Paul Brierley and his team at YCEDA provided project support and coordination among multiple funding partners and the scientific team. Dr. Charles Sanchez of the UArizona and Dr. Andrew French of

USDA-ARS ALARC led the scientific team participating in this project. Their team included scientific personnel recruited for this project, such as postdoctoral research associates and research technicians. It also included cooperating scientists within the UArizona, USDA-ARS ALARC, the USDA-ARS United States Salinity Laboratory (USDA-ARS USSL), the University of California, Riverside, and NASA.

In addition to summarizing consumptive crop water use and quantifying the beneficial applications of water for salt management, this report helps address needs by our funding partners. The USBR, our largest contributor, requires updated crop coefficients for their Lower Colorado River Accounting System (LCRAS). Evapotranspiration (ET) observations obtained from this study will help them update those coefficients. Other contributors, including commodity groups, the USDA/Arizona Department of Agriculture Specialty Crop Block Grant Program, USBR, and NASA, wished to improve irrigation science and remote sensing technologies. This report introduces advances to these and provides scientific findings important for the deployment for an irrigation and soil management app, DesertAgWISE.

Seasonal irrigation application efficiencies were found to be 80-90% for most Yuma-area vegetable cropping systems.

4 Executive Summary

Studies were initiated in 2016 to track water and salt balance across the significant cropping systems within the irrigation jurisdictions of the Yuma area of the Lower Colorado River Region. Crop evapotranspiration (ETc) was measured in 14 major crops throughout multiple cropping seasons on commercial farming operations using eddy covariance (ECV) and other methodologies. Weather data from nearby Arizona Meteorological Network (AZMET) stations were collected and Penman-Monteith reference evapotranspiration for grass (ETos) values compiled. Satellite and drone imageries were compiled and processed for multiple vegetation indices as potential aids in tracking crop growth and water demand. Salinity was monitored by electromagnetic conductance (EM38) surveys augmented by soil sampling and laboratory analyses.

Measurements of ETc, irrigation, and rainfall show that seasonal application efficiencies (AE) are 80-90% for most Yuma-area vegetable and spring-summer rotational cropping systems. These data indicate that in-season leaching fractions are generally below the leaching fraction of 20% typically required for salt balance with Colorado River water in salt-sensitive vegetable cropping systems. This conclusion is corroborated by direct measurements of soil salt balance which consistently showed net increases in salinity over the cropping season. Furthermore, most spring and summer crops grown in rotation with the cool season vegetables, such as grains or melons, also resulted in net seasonal salt loading. The practice of summer fallow was also net salt loading due to capillary rise of the more saline shallow groundwater to soil evaporation.

The data show that these cropping systems are not sustainable without additional leaching to mitigate salt accumulation. Deferring this leaching to pre-irrigation outside of the cropping season, as currently practiced, is a beneficial use of water. This allows for precise amounts of required leaching and increases the efficiency of in-season nitrogen (N) and pesticide management. The compiled database of water and salt observations is a robust and validated collection that will be a resource for future cropping and water management decisions and is being used to develop an irrigation and soil salinity management mobile app, DesertAgWISE, for growers to optimize required irrigation for crop use and leaching. The database will also contribute to improvements in water accounting methods used by the USBR.

Salt management is of paramount importance to sustainability in the arid agricultural areas of Arizona. Over 70% of all production sites showed a salinity increase during the crop production cycle demonstrating the frequent need for a pre-season leaching irrigation for sustainability.

5 Introduction

In arid regions, almost all agricultural crop water requirements come from irrigation. Irrigation water is applied to replace water lost from the crop rooting zone by transpiration through the crop leaf canopy, evaporation from the soil surface, and percolation below the rooting zone, before physiological stress occurs. The combined loss of water from the rooting zone by transpiration and evaporation is crop consumptive use or crop evapotranspiration (ETc).

Water Required for Crop Growth

The most comprehensive database of water use of major crops grown in Arizona was generated by Erie et al. (1982). Erie and coauthors estimated crop water use by measuring soil water depletion in the crop rooting zone with temporal soil sampling and gravimetric water determinations. This approach assumes that after a certain soil moisture tension, drainage becomes minimal. This was the best method available at the time, but the assumption is sometimes inaccurate. In reality, water continues to move in response to energy gradients, and there are uncertainties as to whether reductions in soil moisture in the crop rooting zones are due to evapotranspiration loss or continued drainage. Fortuitously, for the medium texture soils with deep water tables in Central Arizona where Erie did this work, errors in ETc estimates to drainage were likely minimal. More recent studies by USDA and others in Central Arizona on crop ETc of cotton (Hunsaker et al., 2005), wheat (Hunsaker et al., 2007), and alfalfa (Hunsaker et al., 2002) also generally confirmed data obtained by Erie et al. (1982). Perhaps the greater limitation to the database of Erie et al. (1982) is that the data are over five decades old and do not represent current cropping varieties and practices which have evolved over the past half century. Additionally, the agricultural industry in Arizona currently includes several commodities that were not grown in Erie's time and data do not exist as part of this database.

Another source for crop ETc estimates is FAO-56 (Allen et al., 1998). The authors of this document compiled ETc data from around the world and provided a protocol to estimate crop ETc from growing period, crop coefficients (Kc) characteristic to each growing period, and reference evaporation (ETos). ETos is calculated from local weather data using the Penman-Monteith approach. The Kc values are specific by crop type and local climate and are determined experimentally from the ratio of measured ETc to ETos. While the Allen et al. database is comprehensive and robust, it was compiled from areas around the world and was intended as a starting point, not as a substitute for locally calibrated data.

A third source for crop ETc is a modification of FAO-56: it is provided by the USBR, as part of their Lower Colorado River Annual Summary of Evapotranspiration and Evaporation (LCRAS) system (USBR, 2023).

Whereas FAO-56 aligns crop coefficients with growth period by days, LCRAS estimates crop acreage and growth period using satellite imagery.

Considering all three methods, ETc data for the complex multiple cropping systems in the Yuma area irrigation districts did not adequately capture Yuma's crop water use. While the methodologies were sound, all had shortcomings: the data were several decades old, collected on farms remote from Yuma, relied upon generalized coefficients not specific to current Yuma crops, and thus may not be representative. Furthermore, while irrigation AE were estimated from hydrological modeling (Sanchez et al., 2008), actual estimates of ETc relative to water applied were lacking.

Water Required for Salt Management

Beyond the water required for ETc, there are other beneficial uses of water. These include land preparation, residue decomposition, germination, irrigation to address distribution uniformity issues, frost control, and salt management. Salt management is of paramount importance to sustainability in the arid agricultural areas of Arizona. Soil minerals, irrigation water (CRBSCF, 2020), and groundwater (ADEQ, 1995; Dickinson, 2006) in the floodplain districts near Yuma contain salts that accumulate in the fine textured soils. Without management, salt concentrations would become detrimental to growing crops (Sanchez and Silvertooth, 1996). When YCAWC's first report was released in 2015, the impacts of current irrigation practices on salt balance were not well known, and management criteria for maximizing water AE while maintaining salt balance and sustainability were lacking. The objectives of these studies initiated in 2016 were to quantitatively track water use and salt balance across typical crop production systems and rotations in the Yuma area.

The general effects of bulk soil salinity in the soil solution are osmotic (Sanchez and Silvertooth, 1996). Essentially, a high salt concentration in the plant-rooting zone impedes the plants' ability to take up water from the soil solution. Plants often counter this gradient by osmotic adjustment. This adjustment may include increasing their internal solute concentration through the production of organic acids or by accumulating salts. However, this process requires energy that would typically be used for plant growth, resulting in yield reduction (Rains, 1987).

Salt concentrations can be expressed in terms of total dissolved solids (TDS). However, because determination of TDS is a tedious analysis, practitioners often use electrical conductivity (EC) of solutions, which are highly correlated to TDS (Rhoades, 1996). The electrical conductivity of irrigation water (EC_{iw}) is measured directly. The salinity of soil is typically assessed using the conduction of the saturated paste extract (EC_e).

Tolerances to salinity have been established for most economically important crops (Ayers and Westcot, 1994; Maas, 1990). Tolerances to soil salinity are typically expressed by defining a threshold, up to which

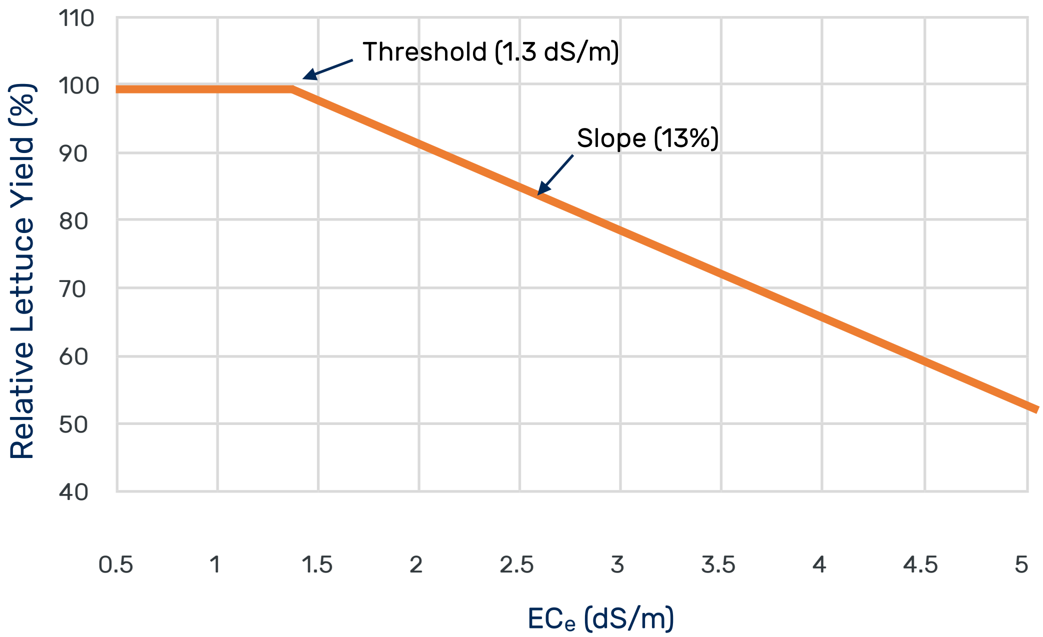


Figure 1. Relationship between soil salinity (EC_e) and lettuce yield (adapted from Ayers and Westcot (1994) and Maas (1990)).

point no negative impact occurs, and a slope, that characterizes the relationship by which crop yields decrease within increasing soil salinity:

$$Yr = 100-b\,(EC_e-a)$$

where Yr is relative yield, a is the salinity threshold expressed in dS/m, b is the slope expressed % yield reduction per dS/m, and EC_e is the mean electrical conductivity of a saturated paste extract. The relationship for lettuce is shown in Figure 1.

Some level of excess irrigation beyond ETc must be applied to leach salts below the crop root zone. Effective leaching is especially important in this region because many of the high-value vegetable crops are sensitive to salinity (Sanchez and Silvertooth, 1996). The relative amount of that excess is the leaching fraction (LF). Based on a steady state mass balance assumption, LF is quantified by the ratio of irrigation and drainage water salt concentrations. Measuring these concentrations is laborious, but obtaining LF can be greatly simplified by using water electrical conductivities of the two components. Salt concentrations are linearly related to conductivity over the range of interest. LF values obtained this way are defined:

$$LF = EC_{iw}/EC_{dw}$$

where EC_{iw} denotes the electrical conductivity of irrigation water and EC_{dw} the electrical conductivity of drainage water. The excess amount of water required to avoid detrimental salt accumulation is the leaching requirement (LR). Starting from the LF relationship, Rhoades (1974) found that that crop specific LR can be better determined from the electrical conductivities of the irrigation water and the plant salt tolerance (EC_e; Maas and Hoffman, 1977; Maas, 1990; Ayers and Westcot, 1994):

$$LR = EC_{iw}/(5EC_e - EC_{iw})$$

The total required leaching depth (RLD) can then be calculated by:

$$RLD = ETc \times (LR/(1 - LR))$$

Steady state assumptions ignore salt uptake by plants, precipitation and dissolution reactions of carbonates in the root zone. Ignoring plant uptake results in insignificant errors because the amount of salt taken up by plants is small relative to the total salt concentration in the rooting zone. On the other hand, precipitation and dissolution reactions should not be ignored when water high in bicarbonate is used for irrigation. In these cases, transient modeling might be needed to avoid over-estimated leaching requirements (Corwin et al., 2007). Currently, the steady state method remains the best approach for field practitioners since the input data for transient models are not available across a wide range of soil types.

The leaching requirement in complex cropping systems is aimed toward the most salt-sensitive crop in the rotation. For the floodplain irrigation districts in the Yuma area this is lettuce, with a leaching requirement of 20%, because it is irrigated with Colorado River water. For economic and environmental reasons, the required leaching for salt management is deferred to an off-season pre-irrigation. This has enabled better weed and disease management and reduced non-point source pollution from improved in-season management of nitrogen fertilizers, soil herbicides, and soil insecticides.

6 Methods

Studies were conducted in production field sites from 2016 through 2023. Over this period, field sites were established in all water management jurisdictions in the Yuma area with focus on the vegetable cropping and rotational systems in YCWUA, YID, NGIDD, WMIDD, and BWD (Figure 2, page 14). Due to double cropping of the irrigated area, approximately 260,000 acres of cool season vegetable crops and spring-summer rotational crops were produced (Table 1). The majority of the alfalfa in these five units was produced in the WMIDD. The remaining alfalfa produced in Yuma County is primarily produced in the YMIDD and Unit B (not shown). Studies on alfalfa and citrus are ongoing. A few studies were also conducted at sites outside the Yuma growing area due to opportunities for accessing certain crops and requests by commodity funding partners.

Table 1. Percentage of total cropped area in the flood plain irrigation management units.[a]

Crop	Acreage (%)
Lettuce (all types)[b]	44
Durum Wheat	16
Sudan Grass	12
Alfalfa	8
Spinach	7
Cotton	5
Broccoli	4
Cauliflower	2
Cantaloupe	1
Other Brassica[c]	< 1
Watermelon	< 1
Celery	< 1
Other Vegetables[d]	< 1
Other Grain[e]	< 1
Citrus	< 1
Dates	< 1

[a] This includes Bard Water District (BWD) and Reservation Unit, Yuma County Water Users Association (YCWUA), North Gila Irrigation and Drainage District (NGIDD), Yuma Irrigation District (YID), and Wellton-Mohawk Irrigation and Drainage District (WMIDD). Sources of data included USDA Agricultural Statistics and the United States Bureau of Reclamation satellite survey data collected as part of LCRAS.

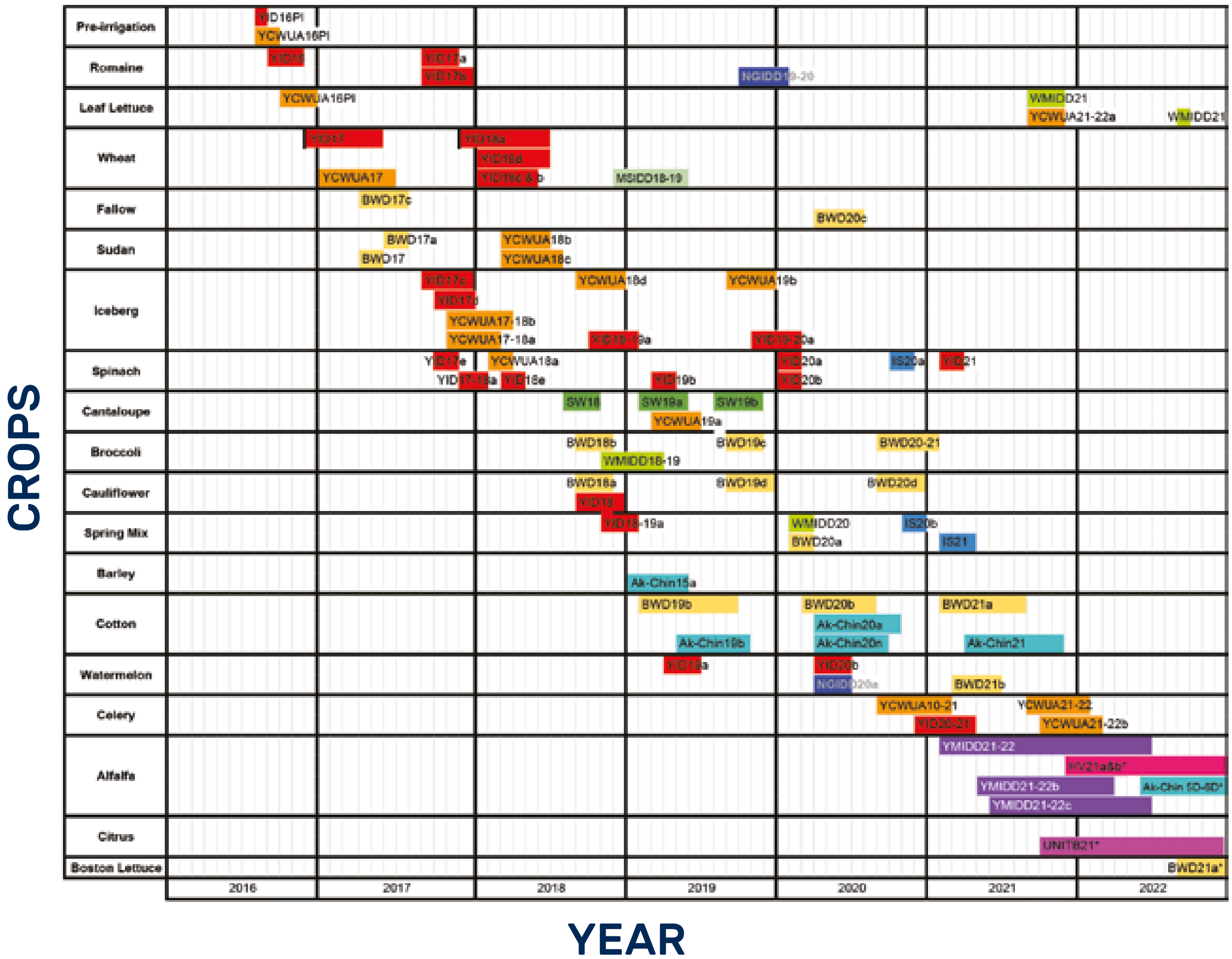
[b] This includes iceberg, romaine, leaf, Boston, and spring mix.

[c] This includes bok choy, Napa cabbage, and kale.

[d] This includes all other vegetables such as parsley, cilantro, etc.

[e] This includes corn and sorghum.

EDDY COVARIANCE DEPLOYMENTS



Each site label consists of an irrigation district code, two-digit year, and deployment sequence characters. PI denotes pre-irrigation. Lower case letters denote sequential sites. An * denotes ongoing data collection.

YID	Yuma Irrigation District	Ak-Chin	Ak-Chin
YCWUA	Yuma County Water Users' Association	NGIDD	North Gila Irrigation District
BWD	Bard Water District	IS	Island
SW	Sidewinder Ranch	YMIDD	Yuma Mesa Irrigation & Drainage District
WMIDD	Wellton-Mohawk Irrigation & Drainage District	UNITB	Unit B
MSIDD	Maricopa Stanfield Irrigation & Drainage District	HV	Harquahala Valley Irrigation District

Figure 2. Eddy covariance deployments by cropping system and date across study period.

Crops evaluated included: all lettuce types, broccoli, cauliflower, celery, spinach, spring mix, durum wheat, Sudan grass, cotton, cantaloupe, and watermelon. Additionally, summer fallow systems for two sites in the BWD were studied. Evaluations with alfalfa and lemons are ongoing as of the writing of this report. A total of 94 field site deployments occurred between Fall 2016 and Fall 2023.

Crop Evapotranspiration (ETc)

The quantification of crop water budgets and irrigation application efficiencies requires accurate methods of measuring ETc. The soil moisture depletion method used by Erie et al. (1982) would not be appropriate in the Yuma area due to the prevalence of fine textured soils and high water tables within the floodplain districts. Methodologies were evaluated including large aperture scintillometry, surface renewal analysis, and sap flow. For reasons of logistics, accuracy, and reliability, eddy covariance (ECV) was the predominant methodology. Examples of ECV deployments are shown in Figure 3.

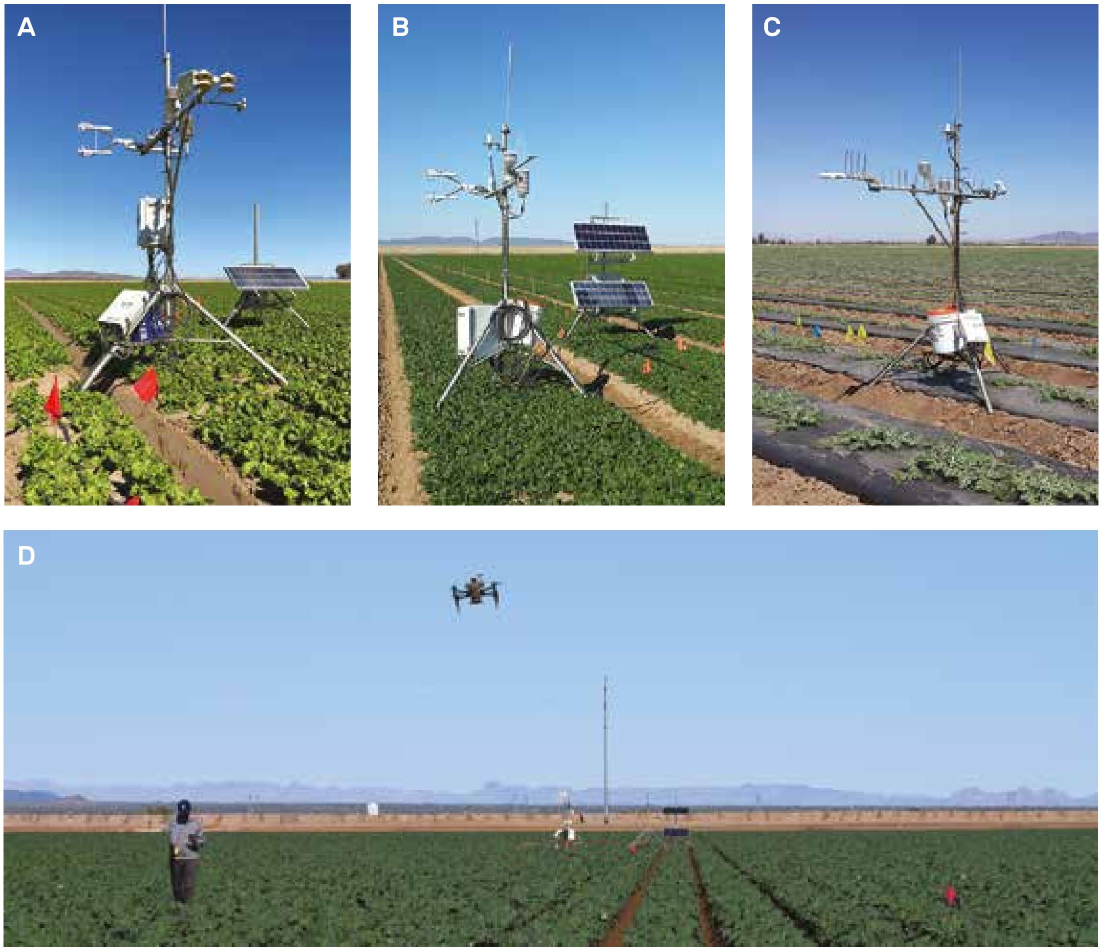


Figure 3. Eddy covariance deployments. Iceberg lettuce in YCWUA (A), Spinach in YID (B), Watermelons in NGIDD (C), Broccoli in WMIDD (D).

ECV obtains ETc by measuring incoming and outgoing energy fluxes over the cropped landscape. It measures four energy flux components: net radiation (R_n), ground heat flux (G), sensible heat flux (H), and latent heat flux (LE). R_n represents absorbed solar and infrared radiation, G is heat transported into the soil, H is turbulent heat above the crop due to air temperature gradients, and LE is latent heat energy due to ETc. While ETc can be estimated from only the LE component, accurate estimates require collecting all four components. ECV data values are reported in energy flux units (W/m^2), with water-specific quantities also reported as depths over time (e.g., mm/day).

Each ECV system requires sensors, one or more data loggers, power supplies, and mechanical support (Figure 4, page 17). Sensors measure 11 variables: air temperature, humidity, wind speed, wind direction, water vapor concentration, carbon dioxide (CO_2) concentration, soil moisture, soil heat flux, incoming and outgoing solar and infrared radiation. Wind and water fluxes are measured at 20 Hz. Data loggers collect, analyze, and store analog and digital signals from the sensors. In some cases, they are connected to a cellphone modem for transmitting synopses of data and system health information to one of the base offices. However, high-resolution data downloads require site visits to offload the data. Power supplies consist of 12-volt batteries, voltage regulators, grounding rods, and solar panels. Mechanical supports include tripods, masts, lightning rods, anchors, and guy wires to ensure the sensors, loggers, and power supplies remain accurately aligned in all weather conditions.

This project was initiated in Fall 2016 with two ECV systems. Nine systems were being utilized as of 2023. In cropped fields, the systems were installed at planting and removed immediately before harvest. In fallow fields, the systems were installed before fallow initiation and removed at fallow termination. A field crew maintained the systems continuously and was available to move the systems out of the way for field operations such as cultivation, fertilization, and pesticide application. On a subset of the sites, systems remained in the same fields over multiple cropping systems.

Water Inputs

Irrigation water amounts applied to all fields were measured. For sprinkler irrigation systems, in-line meters and both automatic/manual rain gauges were used. Manual gauges were used to collect water for salinity analysis because the automatic gauges do not retain the water. For surface irrigation, meters at the canal gates were used when they were available (YID and some BWD sites). Where meters at the gate were not available (most other sites), water deliveries were calculated from measurements of water velocity, water depth, irrigation times, and ditch geometry during each irrigation event. For drip irrigation, meters were used where available. Where not available, irrigation depths were estimated using irrigation time coupled with drip tape output ratings.

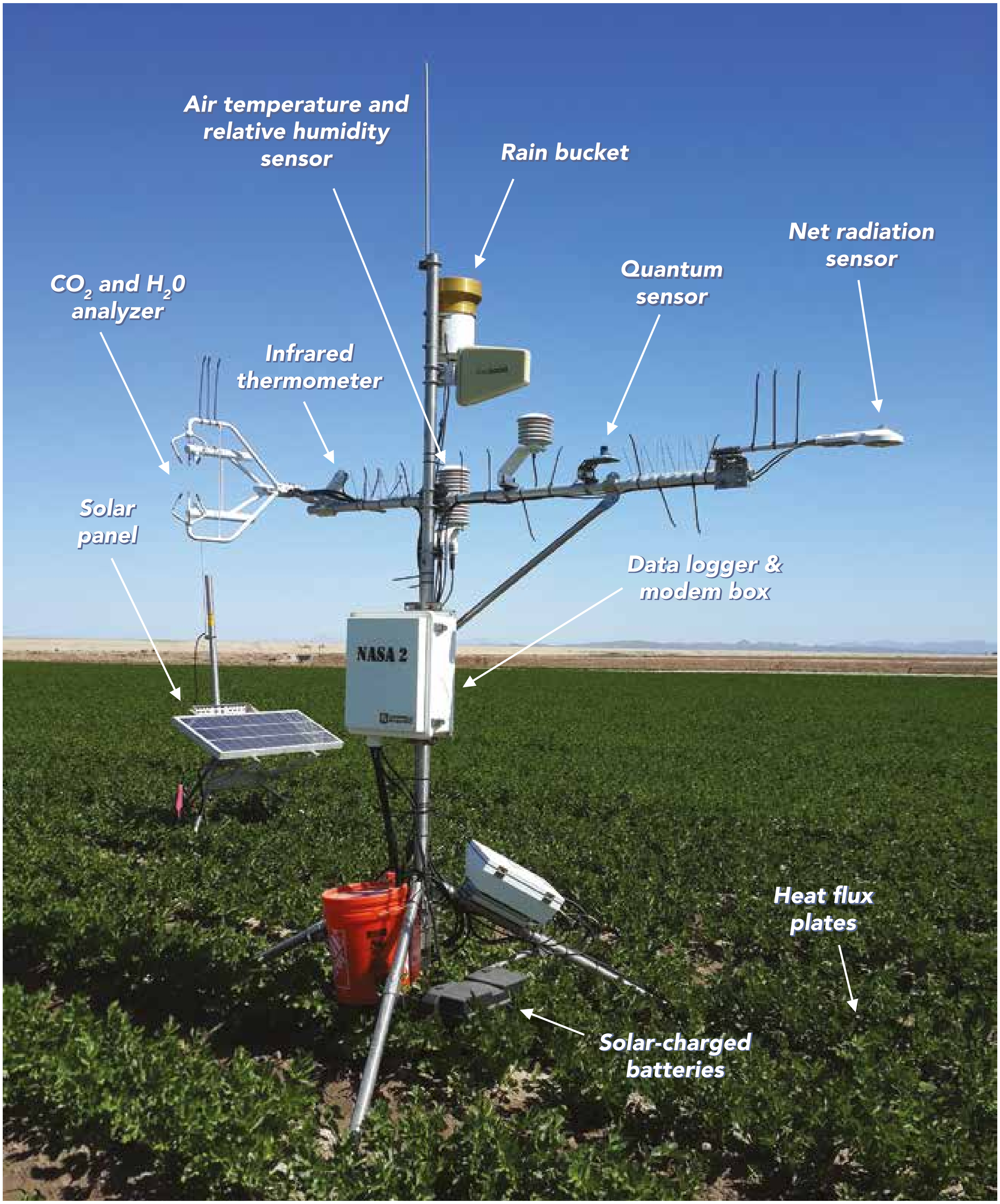


Figure 4. Eddy covariance system with sensors, data loggers, modem, power supply, and mounting hardware labeled.

Soil Moisture

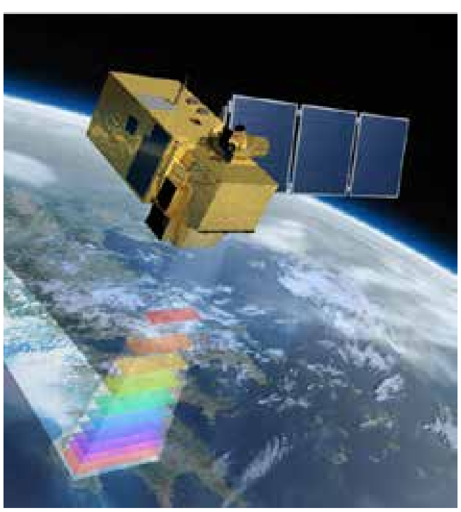
Soil moisture measurements in fields were determined gravimetrically and by capacitance/frequency domain sensors. Soil moisture within the ECV deployments was determined using time domain reflectometry sensors.

Weather Data

UArizona AZMET stations and on-site ECV observations provided the needed weather data. Data streams at hourly intervals, including ETos, and heat units (HU), were taken from the AZMET weather network. In most cases, the AZMET station nearest to each field study location was used. Some water managers, notably the USBR (LCRAS), use weather data and crop coefficients to estimate crop water use following FAO-56 protocols (Allen et al., 1998). Crop coefficients relate ETos calculated from weather data to ETc by growth stage. The direct measurement of ETc from ECV stations provided data to update crop coefficients. Resulting Kc values fulfill the objectives for the USBR funding contribution and assist commodity contributors interested in the development of DesertAgWISE, an irrigation and soil salinity management mobile app.

Satellite Imagery

Satellite imagery from multiple sources was used to verify and extend crop growth and water use data. Landsat 8 (https://www.nasa.gov/mission_pages/landsat/launch/index.html) and Sentinel 2 (www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-2) imagery provided vegetation indices to map planting, crop growth stages, crop uniformity, and harvest activity every 3-5 days with 10-30 m (30-100 ft) resolution (Figure 5). Normalized Difference Vegetation Index (NDVI) were used to



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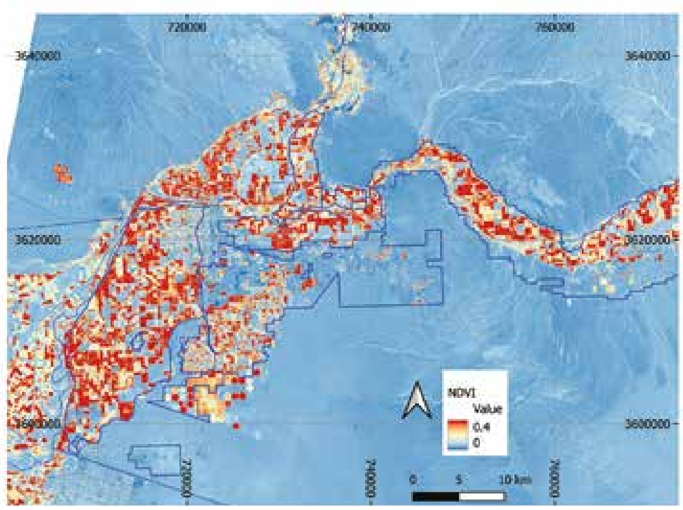


B

Figure 5. Sentinel 2 satellite (A, copyright European Space Agency-ESA) and NDVI Yuma image (B).

adjust ET-based crop coefficients, correlate HU data with crop maturity, assist with water use forecasting, and improve water use accounting for all Yuma irrigation districts. Emerging remote sensing tools were also used to improve detection and estimation of plant growth and water use. These included drone-imaged fields to measure fractional vegetative cover (Figure 6A) and to calibrate remotely sensed indices (Figure 6B). Satellite-based NDVI and crop coefficients were used to estimate crop areas and corresponding daily water use (e.g. lettuce, Figure 6C). Collections of thermal infrared data from the ECOSTRESS sensor (Figure 6D; https://ecostress.jpl.nasa.gov/) are being used to monitor land surface temperatures and verify water/energy balance models and have been part of the project's collaboration with NASA. Satellite-based radar imagery from Sentinel 1 (Figure 6E; https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-1/data-products) were collected

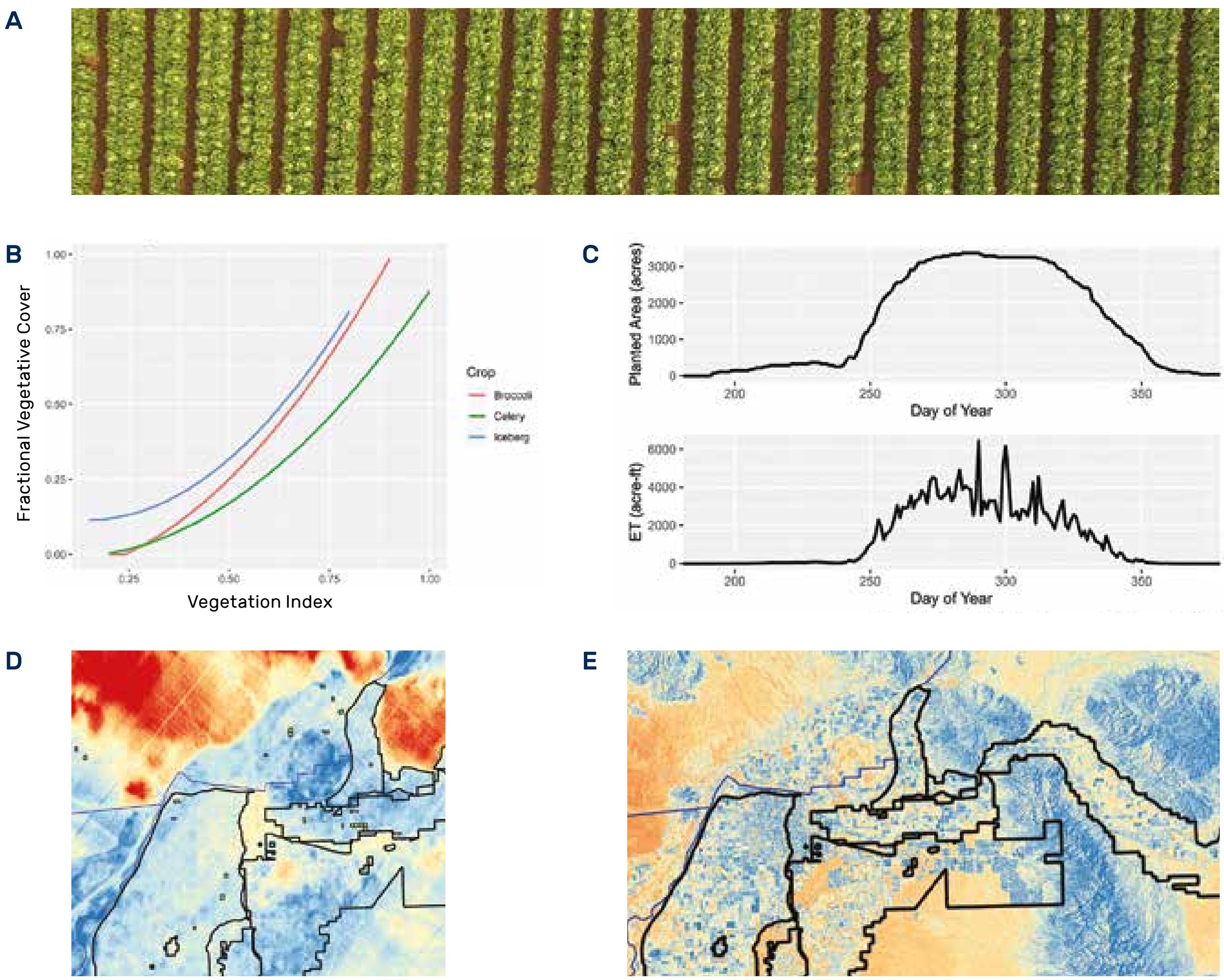


Figure 6. Remote sensing observations over lettuce (A), fractional cover from vegetation indices (B), area planted and evapotranspiration (C), lands surface temperature from ECOSTRESS (D), and soil moisture and irrigation detection using Sentinel 1 radar data (E).

to estimate soil wetness and detect early season irrigation events. Commercial, high spatial resolution 1 m (3 ft) Planet data (https://www.planet.com) were used to precisely locate field boundaries and calibrate fractional vegetative cover with vegetation indices. These data were initially collected to address the USBR deliverables but will ultimately have utility in scheduling as the DesertAgWISE app capabilities are expanded.

Salinity Monitoring

As with ETc measurements, redundant methodologies were initially deployed. On a smaller scale, sensors and data loggers measured soil moisture and bulk conductance (salinity) at multiple depths. These sensors enabled tracking of salinity with depth and within cropping beds. On a larger scale, electromagnetic conductance surveys (EM38) were used. Both were validated with soil sampling. In the first year, it was found that EM38 methods, augmented with soil sampling, were sufficiently adequate. Therefore, this approach was used going forward.

Fields were surveyed using a Dual-dipole EM38 meter (Geonics Limited, Mississauga, Ontario, Canada) mounted on a mobilized assessment platform with an integrated sub-meter accuracy Global Positioning System (GPS), with all survey and GPS position data logged into an on-board portable computer (Figure 7).

Figure 7. EM38 pre-plant conductance survey.

In baseline surveys, EM38 signal data were collected once every two seconds within transects spaced 10-20 m apart, typically generating from 1000-5000 survey positions per field. Transect spacing and the total number of survey positions depended on the field size. These data were analyzed using the ESAP software package (https://www.ars.usda.gov/pacific-west-area/riverside-ca/agricultural-water-efficiency-and-salinity-research-unit/docs/model/esap-model/) and the spatial response surface sampling algorithm in the ESAP-RSSD program. At each sampling location, a single 1.2 m soil core was extracted using automated soil auguring equipment and split into four depth-specific 30 cm samples. The soil samples collected from each core were bagged, labeled, and subsequently used for chemical and physical analyses. Subsets of all soil samples were oven-dried to determine soil moisture content. The remainder of the soil samples were air-dried prior to laboratory analysis. After obtaining saturated paste extracts from all soil samples, we determined electrical conductivity (EC_e) and cation/anion quantities for calcium (Ca^{+2}), magnesium, (Mg^{+2}), sodium (Na^{+}), potassium (K^{+}), chloride (Cl^{-}), sulfate (SO_4^{-2}), nitrate (NO^{-}_3), and bicarbonate (HCO_3^{-}) by ion chromatography. The chloride analyses were used as another indicator of leaching as it is more conservative, and less likely to be involved in precipitation/dissolution reaction in carbonate soil systems. The Ca^{+2}, Mg^{+2}, and Na^{+}, and HCO_3^{-} were used to calculate an adjusted sodium adsorption ratio (SAR). The cation and anion data were also used with a speciation program (MINTEQ 3A2; https://www.epa.gov/ceam/minteqa2-equilibrium-speciation-model) to gain a preliminary understanding of the chemistry of soil reactions and potential for salt precipitation with respect to these salinity ions.

While it was our objective to track salt balance on most of the ECV deployment sites, occasionally the grower land preparation and planting schedule did not allow for a time window sufficient to complete the EM38 surveys and soils sampling. Therefore, approximately 80% of the water balance sites have accompanying salt balance data.

The project was initiated in 2016 with two ECV systems. By 2023, nine systems were being utilized. A field crew continuously maintained the systems and moved them out of the way for field operations.

7 Results

Water Use, Seasonal ETc, and Water Application Efficiency

Most vegetable crops in the region are established by sprinklers as a means of climate modification. In a previous report (YCAWC, 2015), it was noted that conversion from furrow irrigation to sprinkler irrigation for stand establishment resulted in significant water savings (well over 300 mm or 12 ac-in). As part of these studies, water use in the stand establishment operation was tracked more closely. These data show that it typically takes a 24-30 hour run time to refill the top 30 cm (12 in) soil profile with water (Figure 8).

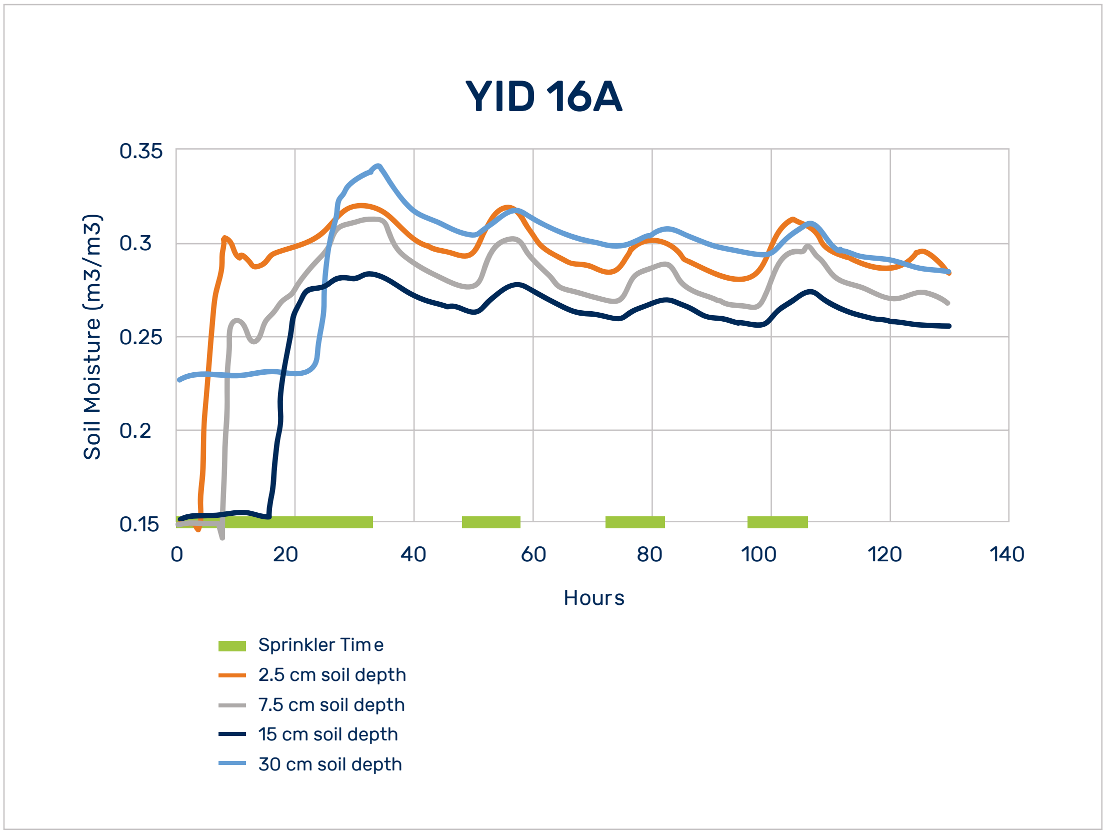


Figure 8. Water redistribution in the surface soil during sprinkler stand establishment.

Thereafter, sprinklers are only turned on for a few hours (5-8) each day to keep the surface moist until germination. After germination and emergence, the sprinklers are removed from the field and subsequent irrigations are by furrow. These studies were performed across multiple water jurisdictions, and typically less than 175 mm (7 in) of water is used for stand establishment (Tables 2A (SI Units) and 2B (English Units)). Beyond refilling the root zone and water lost to evaporation during the sprinkler event, leaching fractions were minimal. This will be addressed in more detail later in the report when salt balance is discussed.

Table 2A (SI Units). Water balance during sprinkler irrigation stand establishment of lettuce.

Site	Soil Deficit	Sprinkler Events	Total Run Time	Total Water Applied	Evaporation	Water Received
	mm	#	hours	mm	mm	mm
YID 16A	86	4	64	173	46	128
YID 16B	89	4	60	170	47	122
WMIDD 16A	87	5	54	154	43	111
WMIDD 16B	79	6	54	185	55	131
WMIDD 16C	77	5	44	137	29	108
BWD 16	103	6	56	142	53	89

Table 2B (English Units). Water balance during sprinkler irrigation stand establishment of lettuce.

Site	Soil Deficit	Sprinkler Events	Total Run Time	Total Water Applied	Evaporation	Water Received
	inches	#	hours	inches	inches	inches
YID 16A	3.4	4	64	6.8	1.8	5.0
YID 16B	3.5	4	60	6.7	1.9	4.8
WMIDD 16A	3.4	5	54	6.1	1.7	4.4
WMIDD 16B	3.1	6	54	7.3	2.2	5.2
WMIDD 16C	3.0	5	44	5.4	1.1	4.3
BWD 16	4.1	6	56	5.6	2.1	3.5

YID - Yuma Irrigation District
WMIDD - Wellton-Mohawk Irrigation and Drainage District
BWD - Bard Water District

Total seasonal water use was measured for all crops in these studies. The data collected for all crops are typified by that shown for iceberg lettuce, broccoli, celery, wheat, and cotton in Figures 9-13 (pages 25-27). The ETc was measured by ECV, data to calculate ETos and growing degree days were downloaded from nearby AZMET weather stations, irrigation and rainfall volumes were measured and recorded, and NDVI, or other indices, were processed from satellite data streams.

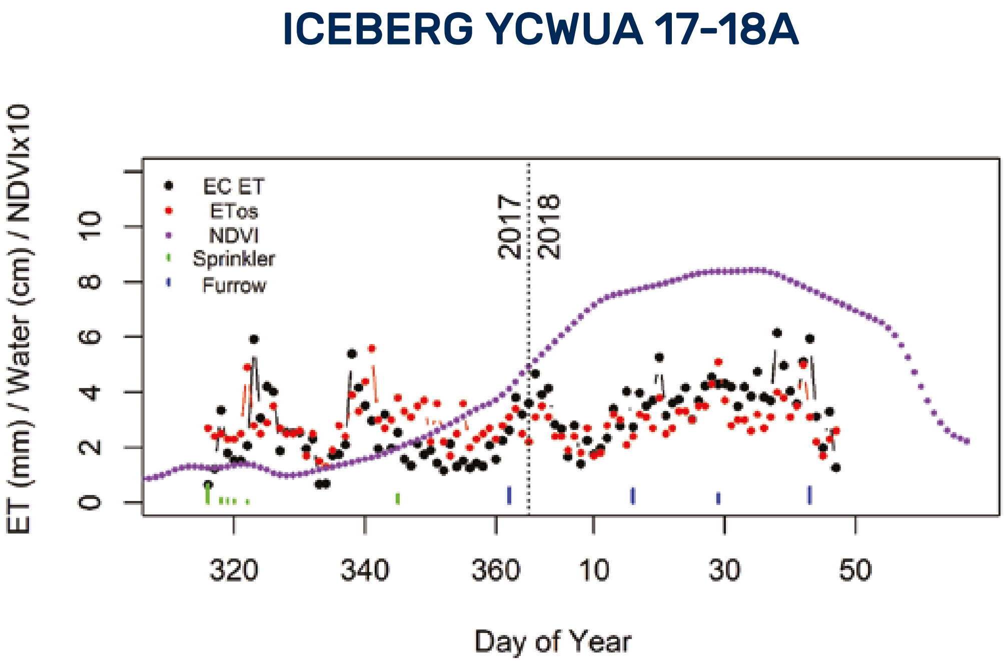


Figure 9. Water fluxes, reference evapotranspiration (ETos), and NDVI for iceberg site YCWUA 17-18a. Measured crop evapotranspiration (ETc) by eddy covariance (black), closely tracks ETos (red dots). Irrigation events are shown along the bottom (sprinkler: green, furrow: blue). Vegetation cover is tracked by satellite-generated NDVI (purple).

BROCCOLI WMIDD 18-19

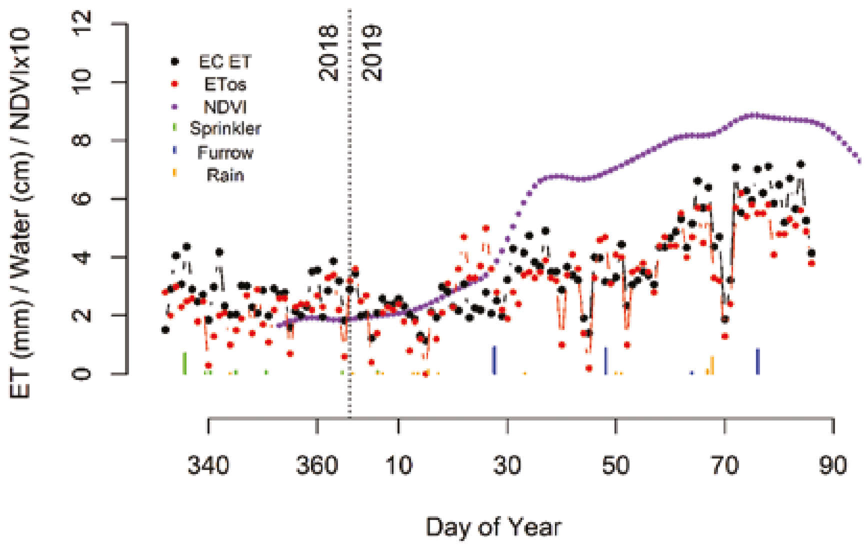


Figure 10. Water fluxes, reference evapotranspiration (ETos), and NDVI for broccoli site WMIDD 18-19. Measured crop evapotranspiration (ETc) by eddy covariance (black), closely tracks ETos (red dots). Irrigation events are shown along the bottom (sprinkler: green, furrow: blue, rain: orange). Vegetation cover is tracked by satellite-generated NDVI (purple).

CELERY YCWUA 21-22B

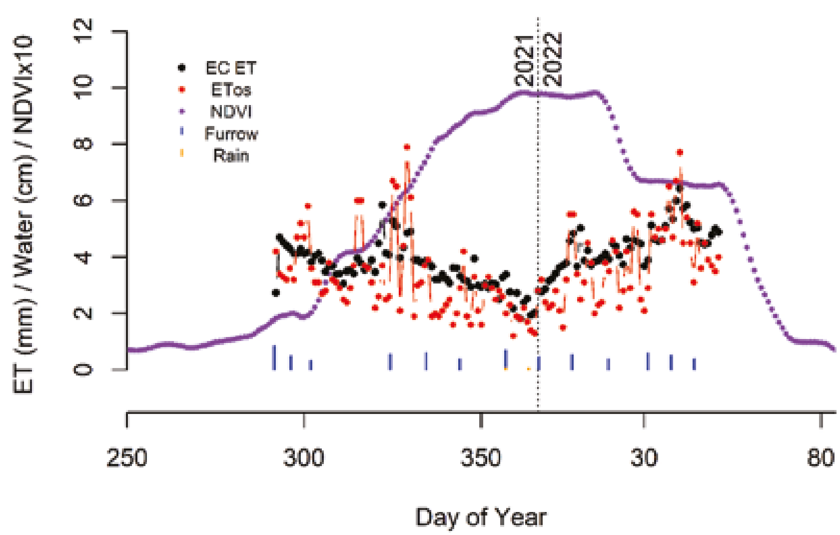


Figure 11. Water fluxes, reference evapotranspiration (ETos), and NDVI for celery site YCWUA 20-21b. Measured crop evapotranspiration (ETc) by eddy covariance (black), closely tracks ETos (red dots), which decreases to end-of-year, then begins to increase. Irrigation events are shown along the bottom (furrow: blue, rain: orange). Vegetation cover, tracked by satellite-generated NDVI (purple), denotes maximum cover at the new year.

WHEAT YID 17

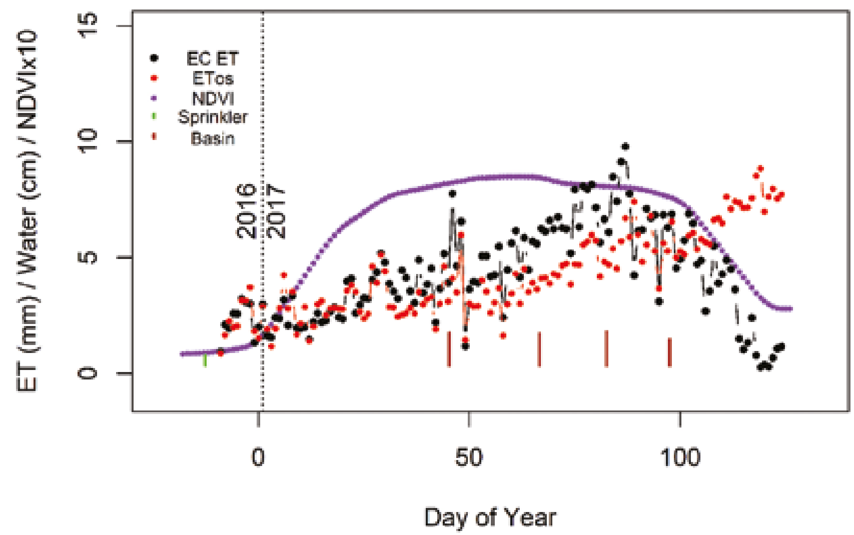


Figure 12. Water fluxes, reference evapotranspiration (ETos), and NDVI for wheat site YID 17. Measured crop evapotranspiration (ETc) by eddy covariance (black), closely tracks ETos (red dots). Irrigation events are shown along the bottom (sprinkler: green, basin: brown). Vegetation cover is tracked by satellite-generated NDVI (purple).

COTTON BWD 20B

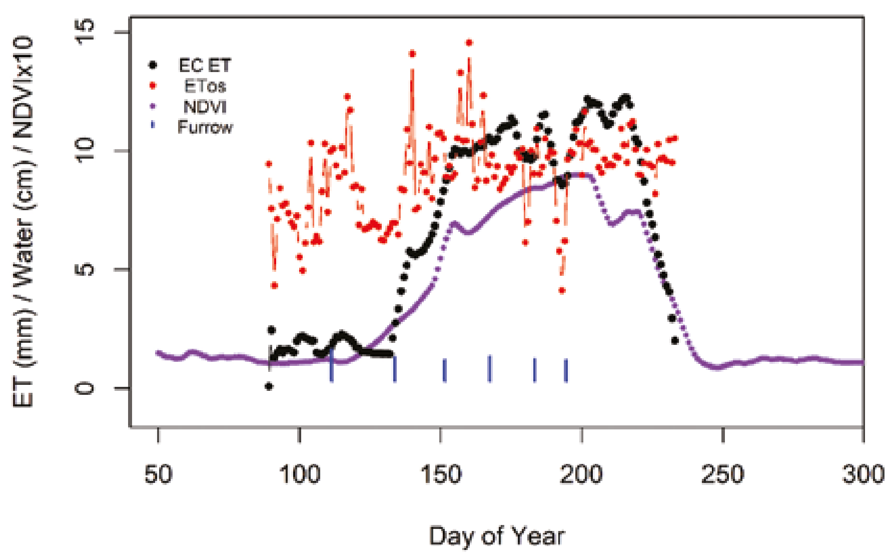


Figure 13. Water fluxes, reference evapotranspiration (ETos), and NDVI for cotton site BWD 20B. Measured crop evapotranspiration (ETc) by eddy covariance (black), closely tracks ETos (red dots). Irrigation events are shown along the bottom (furrow: blue). Vegetation cover is tracked by satellite-generated NDVI (purple).

A summary of crop ETc for major production systems in the Yuma region is shown in Tables 3A and 3B (pages 30-31). The average ETc for furrow irrigated iceberg and romaine lettuce are 271 mm and 287 mm (10.7 ac-in and 11.3 ac-in), respectively. Variation among sites was 8% for iceberg lettuce and 13% for romaine lettuce. Some of this variation is explained by the length of the growing season. For example, iceberg lettuce planted in September (YID 17C; approximately a 70-day crop) had approximately 27 mm (1.1 ac-in) less ETc than lettuce planted in October (YID 17D; 84-day crop) on the same farm. Because transpiration is closely tied to carbon assimilation (Cowan, 1982), higher seasonal ETc for longer growing periods is likely associated with more opportunity time for soil evaporation losses. However, variations in soil conditions and management are contributing factors. The measured average ETc values for iceberg lettuce are approximately 50 mm (2 ac-in) higher than those reported by Erie et al. (1982). This higher ETc value is likely due to the fact that lettuce yields per unit area have doubled (YCAWC, 2015) since Erie and coauthors did their work. Measured average seasonal water AE were 76% for iceberg lettuce and 87% for romaine. However, it should be noted that our calculated efficiency included all water received (irrigation and rainfall). While rainfall before an irrigation event would typically delay irrigation time, the effect of rainfall shortly after an irrigation event is not predictable and would often result in an unplanned leaching fraction, thereby lowering calculated seasonal AE. For crops having ETc less than 300 mm (12 ac-in), rainfall can impact calculated AE. Four of the eight iceberg lettuce sites had significant rainfall (20-45 mm, about 1-2 in) during the season. If these sites are excluded from the average, seasonal AE becomes 85%. In contrast, the iceberg sites with above average rainfall had an average AE of 66%, but this would occur infrequently. Overall, iceberg and romaine sites showed a similar pattern in water use and the average AE of these combined was 81%, including the sites with above-average rainfall. The average ETc for leaf lettuce was 213 mm (8.4 ac-in) and AE was 81%.

Similar to lettuce systems, broccoli and cauliflower are established by sprinklers and irrigated by furrow after germination. The average ETc for broccoli and cauliflower were 361 mm (14.2 ac-in) and 409 mm (16.1 ac-in), respectively. These values are less than the value of 500 mm (19.7 ac-in) for broccoli and 472 mm (18.6 ac-in) for cauliflower reported by Erie et al. (1982). The Erie values are based on growing periods of 170 days for broccoli and 140 days for cauliflower and are 40-50 days longer than current practice. In these studies, growing periods for broccoli ranged from 70 days for an early September planting to 122 days for a late November planting. Cauliflower was only transplanted in the fall, therefore its growing period ranged from 85-99 days. The lower ETc values measured in these studies are attributed to shorter growing periods compared to Erie et al. (1982). In-season AE for these crops averaged about 85%. Rainfall on broccoli and cauliflower experiments ranged from less than 1 mm (trace) to 40 mm (1.6 in). Because these crops have seasonal ETc about 35% higher than lettuce, rainfall had less noticeable impacts on seasonal AE.

For sites irrigated by sprinklers for the entirety of the growing season, AE values were especially high. Sprinklers enable water application near ETc replacement. At the one site where romaine lettuce was sprinkler irrigated all season, water received was close to crop ETc. In these evaluations, Boston lettuce was also irrigated season-long by sprinklers. ETc for Boston lettuce was 185 mm (7.3 ac-in) and AE was 81%. Baby spinach and spring mix were also irrigated season long with sprinklers. ETc for these crops was less than 130 mm (5.1 ac-in), and average AE were generally high. The variation in water received on these two crops was largely driven by variation in rainfall, since modest rain is significant for a crop with less than 130 mm (5.1 ac-in) ETc. However, beyond salt management (addressed later), one needs to be concerned with irrigation distribution uniformity. Distribution uniformity was characterized using two metrics: the low quartile (DU), which measures localized extreme negative deviations from the average applied, and Christiansen's Index (Burt et al., 1997), which measures the mean deviation from the average amount of water applied. Although solid set sprinkler irrigation systems used in the area are very well engineered and potentially provide uniform irrigation (Zerihun et al., 2014; Zerihun and Sanchez, 2014), the variation in frequency, speed, and direction of wind in Yuma can significantly distort wetting patterns (Brown et al., 1995), and one should not anticipate average distribution uniformities exceeding 85% (Figure 14). With the generally very high AE obtained for spinach, and typical seasonal distribution uniformities, it is likely that portions of fields were sometimes under irrigated.

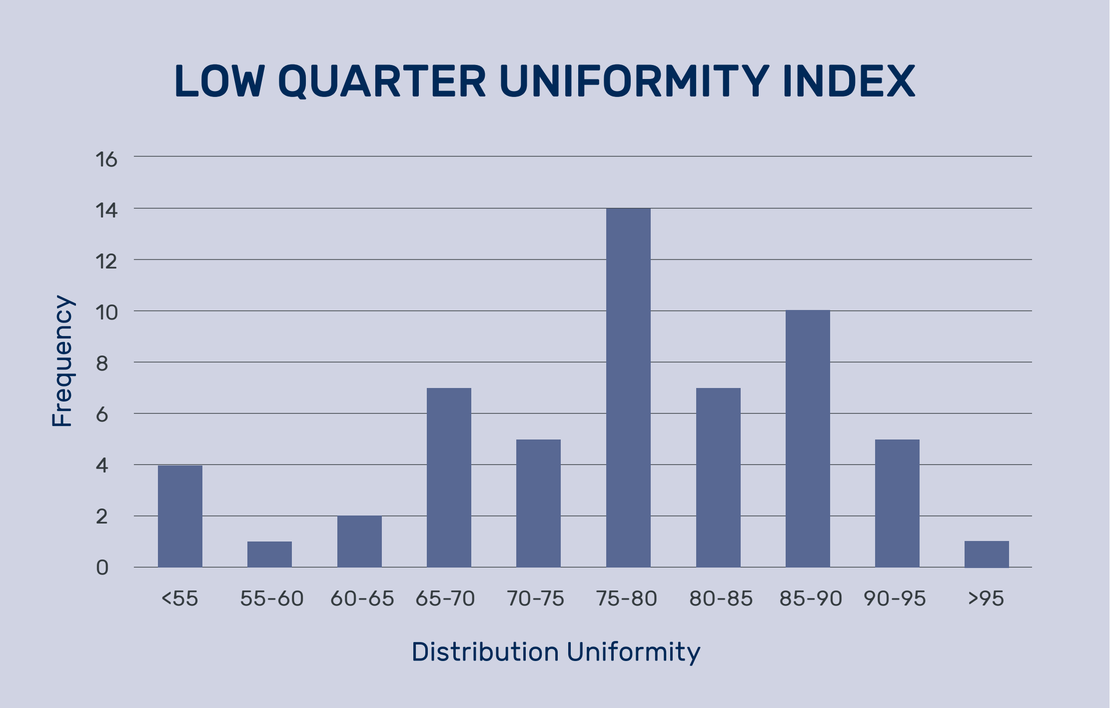


Figure 14. Frequency (y-axis) of sprinkler irrigation distribution uniformity as measured from 56 individual field evaluations.

Table 3A (SI Units). Average evapotranspiration (ET) and water received (irrigation and rainfall) of two Yuma cropping systems. The ET values from Erie et al. (1982), where they exist, are compared with eddy covariance observations measured in this study.

Crop	# of Sites	Irrigation Method	Evapotranspiration (ET)		Water Received	Application Efficiency (AE)
			Erie	Measured		
			mm	mm (SD)[1]	mm (SD)[1]	% (SD)[1]
FALL-WINTER-SPRING VEGETABLES						
Broccoli	4	Sprinkler/Furrow	500	361 (15)	442 (65)	83 (17)
Cauliflower	4	Sprinkler/Furrow	472	409 (35)	472 (4)	87 (12)
Celery	3	Furrow	-	418 (71)	643 (80)	65 (3)
Celery	1	Sprinkler/Drip	-	457	484	94
Lettuce-Boston	2	Sprinkler	-	185 (71)	232 (18)	81 (37)
Lettuce-Iceberg	8	Sprinkler/Furrow	216	271 (23)	371 (99)	76[4] (17)
Lettuce-Leaf	2	Sprinkler/Furrow	-	213 (6)	264 (32)	81 (12)
Lettuce-Romaine	3	Sprinkler/Furrow	-	287 (39)	328 (14)	87 (9)
Lettuce-Romaine	1	Sprinkler	-	269	257	100
Spinach	8	Sprinkler	-	110 (16)	119 (23)	96 (25)
Spring Mix	6	Sprinkler	-	126 (31)	151 (46)	96 (25)
SPRING-SUMMER ROTATIONAL SYSTEMS						
Cantaloupes	1	Drip/Bare Soil	-	472	591	80
Cantaloupes[2]	-	Furrow	521 & 427	-	-	-
Cotton[3]	7	Furrow	1047	1085 (202)	1092 (220)	-
Durum Wheat	6	Basin	648	630 (54)	717 (169)	90 (9)
Summer Fallow	2	-	-	137 (17)	4 (5)	-
Sudan Grass	3	Basin	-	653 (40)	979 (449)	76 (29)
Watermelon	4	Drip/Plastic Mulch	-	398 (25)	400 (22)	100 (15)

[1] Standard deviation of the mean.
[2] Erie reported one value for spring melons and a 2nd for fall melons.
[3] For cotton, the sites in the Lower Colorado River Valley accessed ground water from the water table late season, which we could not measure. Thus, we cannot accurately estimate AE.
[4] Several lettuce sites occurred during period of above average rainfall events. If the above average rainfall events are excuded, AE would average 85%.

Table 3B (English Units). Average evapotranspiration (ET) and water received (acre-inch [ac-in], irrigation and rainfall) of two Yuma cropping systems. The ET values from Erie et al. (1982), where they exist, are compared with eddy covariance observations measured in this study.

Crop	# of Sites	Irrigation Method	Evapotranspiration (ET)		Water Received	Application Efficiency (AE)
			Erie	Measured		
			ac-in	ac-in (SD)[1]	ac-in (SD)[1]	% (SD)[1]
FALL-WINTER-SPRING VEGETABLES						
Broccoli	4	Sprinkler/Furrow	19.7	14.2 (0.6)	17.4 (2.6)	83 (17)
Cauliflower	4	Sprinkler/Furrow	18.6	16.1 (1.4)	18.6 (0.2)	87 (12)
Celery	3	Furrow	-	16.5 (2.8)	25.3 (3.1)	65 (3)
Celery	1	Sprinkler/Drip	-	18.0	19.1	94
Lettuce-Boston	2	Sprinkler	-	7.3 (2.8)	9.1 (0.7)	81 (37)
Lettuce-Iceberg	8	Sprinkler/Furrow	8.5	10.7 (0.9)	14.6 (3.9)	76[4](17)
Lettuce-Leaf	2	Sprinkler/Furrow	-	8.4 (0.3)	10.3 (1.2)	81 (12)
Lettuce-Romaine	3	Sprinkler/Furrow	-	11.3 (1.5)	12.8 (0.6)	87 (9)
Lettuce-Romaine	1	Sprinkler	-	10.6	10.1	100
Spinach	8	Sprinkler	-	4.2 (0.6)	4.7 (0.9)	96 (25)
Spring Mix	6	Sprinkler	-	4.7 (0.6)	5.9 (1.8)	96 (25)
SPRING-SUMMER ROTATIONAL SYSTEMS						
Cantaloupes	1	Drip/Bare Soil	-	18.6	22.8	80
Cantaloupes[2]	-	Furrow	20.5 & 16.8	-	-	-
Cotton[3]	7	Furrow	41.2	43.1 (7.7)	43.0 (8.7)	-
Durum Wheat	6	Basin	25.5	24.8 (2.1)	28.2 (6.7)	90 (9)
Summer Fallow	2	-	-	5.4 (0.7)	0.2 (0.2)	-
Sudan Grass	3	Basin	-	25.7 (1.6)	33.1 (8.6)	76 (29)
Watermelon	4	Drip/Plastic Mulch	-	15.7 (1.0)	15.7 (0.9)	100 (15)

[1] Standard deviation of the mean.
[2] Erie reported one value for spring melons and a 2nd for fall melons.
[3] For cotton, the sites in the Lower Colorado River Valley accessed ground water from the water table late season, which we could not measure. Thus, we cannot accurately estimate AE.
[4] Several lettuce sites occurred during period of above average rainfall events. If the above average rainfall events are excuded, AE would average 85%.

Celery seasonal water AE with furrow irrigation were less than most of the other cool season crops. Celery is a long-season vegetable crop, approximately 130 days, and receives eight or more irrigations after stand establishment. The roots of the transplants are shallow and frequent irrigation is required to keep this initially shallow rooting zone moist to avoid stress. Because of this poorly developed root system in the early season, there are leaching fractions on the early irrigation events. In fact, AE for the furrow irrigated celery sites averaged only 62% the first half of the season and 84% for the second half of the season, resulting in a seasonal average of 65%. In contrast, the sole drip irrigated celery site had a much higher AE at 94%. The drip system allowed for wetting of the shallow root system without an excess leaching fraction. Work in California has demonstrated the potential for improved irrigation of celery by drip systems, but outcomes can vary depending on management (Breschini and Hartz, 2002).

The ETc for some of the spring-summer rotational systems are also shown in Tables 3A and 3B (pages 31-32). Durum wheat (*T. turgidum*) is commonly grown as a rotational crop in desert agriculture. In Yuma, its ETc averaged 630 mm (24.8 ac-in) and is close to the value reported by Erie et al. (1982) of 648 mm (25.5 ac-in) for common wheat (*T. aestivum*). Seasonal AE for wheat are high, averaging 90%. This result was unexpected as wheat is irrigated in basins, and the densely planted crop would result in high friction to water advance, increasing the opportunity time for deep percolation losses toward the inlet end of the field. Several improvements in irrigation infrastructure were noted in the previous report including laser leveling, large flow turnout gates to accommodate large inlet flow rates, and manipulating border width and field length. Furthermore, expert manipulation of flow and cutoff distance, combined with the low infiltration rate of these fine textured soils, has resulted in less leaching and more efficient water applications for wheat. The other basin-irrigated crop with dense stands is Sudan grass. While average ETc for Sudan grass was close to durum wheat, the water applied was generally higher and more variable, reflecting differing management across the region. Two of the three Sudan grass sites were single cut, and AE for these two sites were 86% and 98% respectively. The other site was a double cut site, and AE averaged 45% the first cut and 79% the second cut for a seasonal average of 60%. This one site with lower AE was an irregular shaped field and efficient surface water application may have been difficult.

The cotton data collection included sites in Yuma and Central Arizona because Cotton Incorporated was a funding partner interested in cotton water use across the state. Experimental sites in Yuma averaged 993 mm (39 ac-in) while sites in Central Arizona averaged 1154 mm (46 ac-in). Average ETc for cotton across both regions was 1085 mm (43.1 ac-in), a little higher than the value of 1047 mm (41.2 ac-in) reported by Erie et. al (1982). The lower water use in Yuma area cotton appears to be due to the relatively short cotton season in Yuma where the crop is often terminated mid-summer to clear ground for produce. Another interesting observation for some Yuma cotton sites is that the irrigation water applied was sometimes less than ETc, reflecting cotton roots tapping the water table late season. The shallow groundwater is saline; however, cotton is salt tolerant (Maas and Hoffman, 1977).

Watermelon and cantaloupe are also rotational crops, although acreages are very small and site opportunities were limited. Erie et al. (1982) reported ETc of 427 mm (16.8 ac-in) for furrow irrigated spring melon, and an ETc of 521 mm (20.5 ac-in) for furrow irrigated fall melon. This difference is perhaps explained by the length of the growing period where the fall crop matures in fewer days than the spring crop. In our evaluations, the site of spring drip irrigated cantaloupe produced a measured ETc of 472 mm (18.6 ac-in), close to that of Erie for furrow irrigated spring cantaloupe. This site was in the Yuma Valley and showed AE of 80%. The watermelon sites were in the YID and NGIDD, produced with drip irrigation under plastic mulch, and water applied was very close to ETc.

The Quantitative Assessment of Water and Salt Balance for Cropping Systems in the Lower Colorado River Region project provided an opportunity to look at summer fallow programs in the BWD. Due to capillary rise of water from the shallow groundwater through the fine textured soils, an average water loss to evaporation of 137 mm (5.4 ac-in) was measured during the 90-day fallow period (Figure 15). This is much greater than the 0.7-7.5 mm (0.03-0.3 in) rainfall that occurred over the fallow period.

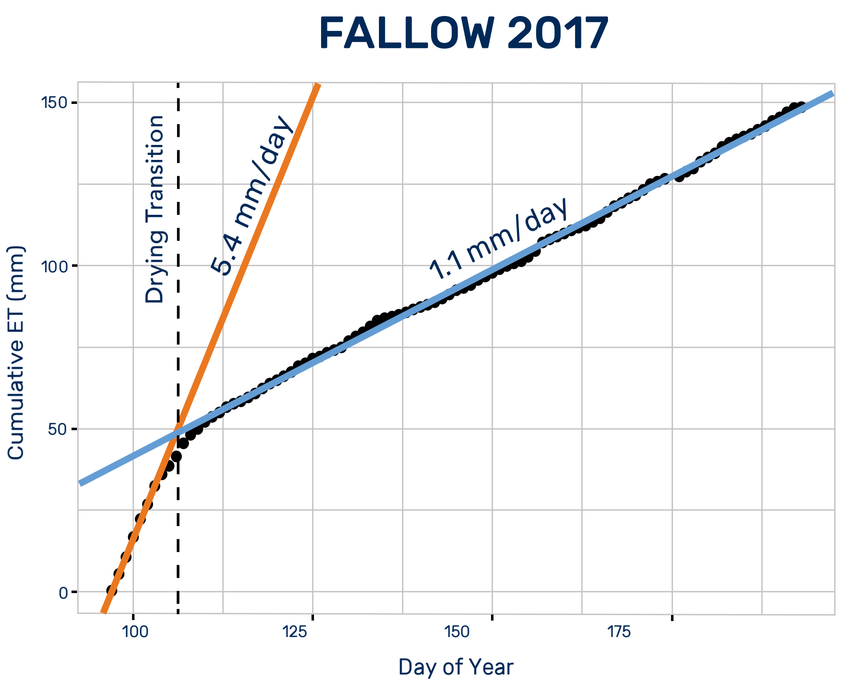


Figure 15. Measured cumulative evaporation from a summer fallow site in the BWD. The initial evaporation rate was 5.4 mm/day (0.2 in/day) for the first 10 days (before vertical dashed line), then decreased to a constant 1.1 mm/day (0.04 in/day) thereafter.

Salt Balance

The data for sprinkler irrigation stand establishment show that this practice is often a salt loading event (Tables 4A and 4B, page 34). As noted above, this practice is meant to modify the climate and allow germination during warm temperatures by evaporative cooling; the evaporation further concentrates salinity in the water received at the soil surface.

Table 4A (SI Units). Salt balance during sprinkler irrigation stand establishment.

Site	Leaching Fraction Required[1]	Leaching Fraction Achieved	Sprinkler Irrigation Salt Load	Soil Water Salt 30 cm Depth		Soil Water Salt 45 cm Depth	
			Metric tons per hecter				
				Before	After	Before	After
YID 16A	0.31	0.31	1.2	2.7	2.3	3.8	4.4
YID 16B	0.31	0.27	1.2	2.7	2.9	4.5	4.8
WMIDD 16A	0.33	0.26	1.1	2.7	2.7	3.3	4.0
WMIDD 16B	0.34	0.39	1.4	2.1	2.5	3.2	4.0
WMIDD 16C	0.30	0.44	1.0	2.2	2.6	3.2	5.6
BWD 16	0.27	0.00	1.1	2.8	3.6	3.6	5.3

[1] The leaching required is based on the weighted measured EC_w that the soil receives, which is higher than the irrigation water applied due to evaporation.

Table 4B (English Units). Salt balance during sprinkler irrigation stand establishment.

Site	Leaching Fraction Required[1]	Leaching Fraction Achieved	Sprinkler Irrigation Salt Load	Soil Water Salt 12-inch Depth		Soil Water Salt 18-inch Depth	
			Tons per acre				
				Before	After	Before	After
YID 16A	0.31	0.31	0.54	1.2	1.0	1.7	2.0
YID 16B	0.31	0.27	0.54	1.2	1.3	2.0	2.1
WMIDD 16A	0.33	0.26	0.49	1.2	1.2	1.5	1.8
WMIDD 16B	0.34	0.39	0.62	0.9	1.1	1.4	1.8
WMIDD 16C	0.30	0.44	0.45	1.0	1.2	1.4	2.5
BWD 16	0.27	0.00	0.49	1.2	1.6	1.6	2.4

[1] The leaching required is based on the weighted measured EC_w that the soil receives, which is higher than the irrigation water applied due to evaporation.

YID - Yuma Irrigation District
WMIDD - Wellton-Mohawk Irrigation and Drainage District
BWD - Bard Water District

The previous section demonstrates that in-season AE values are high for most cropping systems, and one cannot expect a 20% leaching requirement to be achieved within the cropping season for most Yuma vegetable cropping systems. Therefore, we would anticipate salt accumulation during the cropping period. The frequency and average in-season salinity increase for all cropping systems are summarized in Table 5.

Table 5. Summary of salt balance sites. Listed are crop types, the total number of sites where salt balance was tracked, the percent of sites with a net in-season increase in salt content, soil electrical conductivity (EC_e) before and after cropping, and chloride ion in saturated paste extracts (Cle) before and after cropping.

Crop	# of Sites[1]	Sites[2] with EC_e Increase	Average[3] EC_e Before	Average[3] EC_e After	Sites[2] with Cle Increase	Average[3] Cle Before	Average[3] Cle After
		%	dS/m (SD)[4]	dS/m (SD)[4]	%	mg/L (SD)[4]	mg/L (SD)[4]
FALL-WINTER-SPRING VEGETABLES							
Broccoli	3	100	3.4 (1.2)	3.9 (1.4)	100	134 (29)	226 (53)
Cauliflower	1	100	3.3	5.8	100	127	215
Celery	3	100	2.6 (0.2)	5.2 (0.9)	100	112 (29)	370 (126)
Lettuce-Boston	2	100	4.3 (0.1)	5.7 (0.2)	100	116 (41)	217 (54)
Lettuce-Iceberg	9	56	3.8 (1.4)	4.1 (1.5)	67	156 (44)	194 (81)
Lettuce-Leaf	2	100	2.8 (0.6)	5.2 (0.1)	100	98 (7)	414 (89)
Lettuce-Romaine	3	67	3.4 (2.0)	3.2 (0.3)	100	210 (117)	268 (147)
Spinach	8	63	2.7 (1.4)	3.1 (1.0)	63	172 (76)	182 (61)
Spring Mix	3	67	2.1 (1.2)	2.4 (1.8)	67	171 (60)	195 (119)
SUMMER-SPRING ROTATIONAL SYSTEMS							
Cantaloupe	1	100	3.3	4.5	100	164	250
Fallow	2	100	2.7 (0.6)	3.8 (0.5)	100	121 (11)	140 (9)
Sudan Grass	3	33	5.0 (2.2)	4.1 (3.1)	33	193 (67)	222 (125)
Watermelon	3	100	3.1 (0.5)	4.3 (0.1)	100	147 (13)	264 (36)
Wheat	6	33	3.7 (1.7)	3.5 (1.4)	83	248 (72)	303 (107)

[1] Total sites where salinity was tracked across season.
[2] Percent sites where EC_e or Cle increased. EC_e is electrical conductance, Cle is chloride concentration in saturated paste extracts.
[3] Average of all sites.
[4] Standard deviation of the mean.

Where salinity was tracked for lettuce (iceberg and romaine), seven out of twelve sites showed an increase in EC_e and nine out of twelve sites showed an increase in chloride ion. Both EC_e and Cl^- increased during the season for all leaf and Boston lettuce study sites. As noted previously, because chemical precipitation of salts is possible, Cl^- analysis is often a better measure of leaching than EC_e. No lettuce sites showed a net decrease in both EC_e and Cl^-. The field-wide increase in salinity for one lettuce site is shown in Figure 16 as an example.

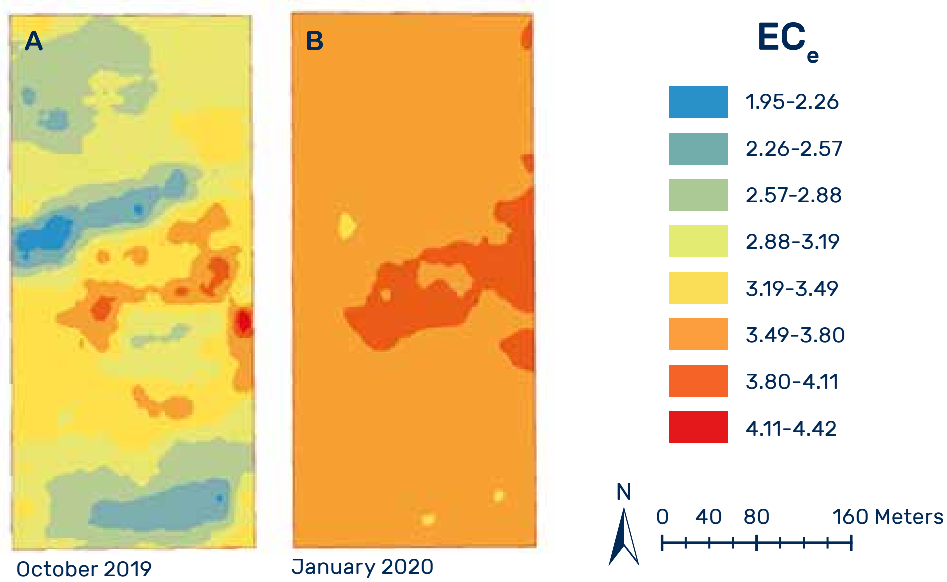
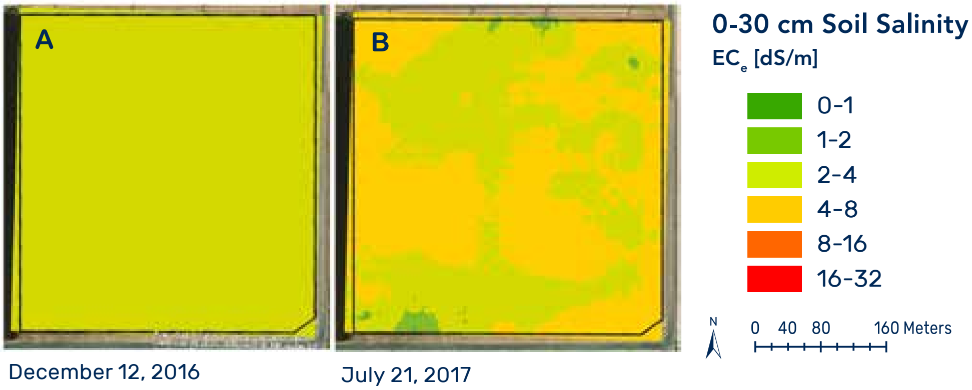


Figure 16. Field-wide salinity (dS/m) before and after romaine lettuce for NGIDD 19-20.

Broccoli and cauliflower showed a seasonal increase in salinity for all sites where root zone salinity was tracked. Baby spinach and spring mix showed an increase in root zone salinity in 8 out of 11 sites where salinity was tracked. Generally, salinity increased when the leaching fraction was near or below 20%. For two sites where in-season salinity did not increase, there was substantial rainfall shortly after sprinkler irrigation events. Baby leaf crops have ETc less than 130 mm (5.1 ac-in), and rainfall events after an irrigation event can result in significant leaching. With furrow irrigated celery, seasonal leaching fractions exceeded 25%, but late season irrigations were efficient and end of season salinity had increased at all sites.

The in-season salt accumulation for some of the rotational crops is also shown in Table 5 (page 36). As noted, AE for wheat is generally high, except for one site on loamy sand. Although seasonal total salts as measured by EC_e only increased on two sites, Cl^- accumulation in the root zone increased for all sites except the loamy sand site. The mineral precipitation may be a reason for the lower measured EC_e in many of these sites at harvest. Levels of cations and anions in the soil water are much higher than the concentration in irrigation water. The increase is especially pronounced for HCO_3^-. Plant roots and soil microbes produce CO_2 during respiration. While much of it diffuses to the atmosphere, some of it goes into the soil solution affecting carbonate chemistry. The chemical equilibrium analysis using MINTEQ indicates the soil solution was supersaturated with respect to Ca^{+2} and Mg^{+2} ions. Thus, precipitation of salts as soil minerals is a likely mechanism of EC_e reduction in many scenarios in the Yuma region. However, Cl^- is more soluble than other anions and would be a better reflection of ion transport and leaching depth under conditions where the propensity for precipitation exists. The field-wide increase of salinity for one durum wheat site is shown in Figure 17 as an example.

Figure 17. Field-wide changes in root zone salinity before (A) and after (B) wheat for YID 16-17.



Sudan grass showed an increase in EC_e or saturated paste Cl^- in two of three study sites. Both sites were single cutting Sudan. The single instance where both EC_e and Cle decreased was a two cutting Sudan crop, and it had a season leaching fraction of 40%. For this site, a pre-irrigation event prior to fall produce did not reduce soil salinity further (Figure 18).

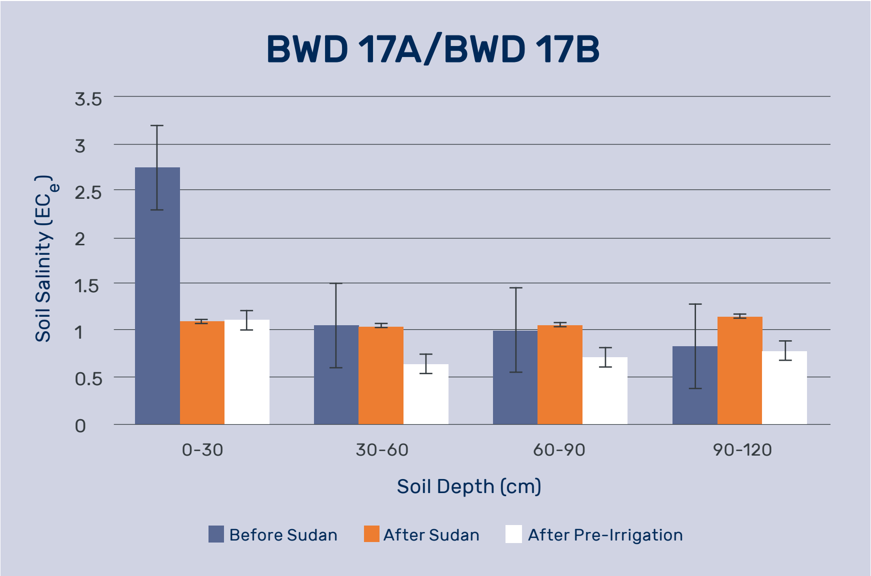


Figure 18. Field salinity as measured by EC_e before planting Sudan grass, after Sudan grass harvest, and after a pre-irrigation before fall vegetables (BWD 17A/BWD 17B).

There is also potential for salt accumulation to increase during more than one crop cycle in a rotation system. Compounded salinity increases are possible where successive crops in a rotation have high AE as shown for a lettuce/wheat (Figure 19) and a lettuce/watermelon (Figure 20, page 39) rotation. Often, where an adequate leaching fraction is obtained in one crop it may not be adequate in another crop within the rotation. For example, one iceberg lettuce site had a seasonal 35% leaching fraction due to seasonal 24 mm (1 in) rainfall, and thus no salinity accumulation. However, salinity subsequently increased during the following cantaloupe crop (Figure 21, page 39).

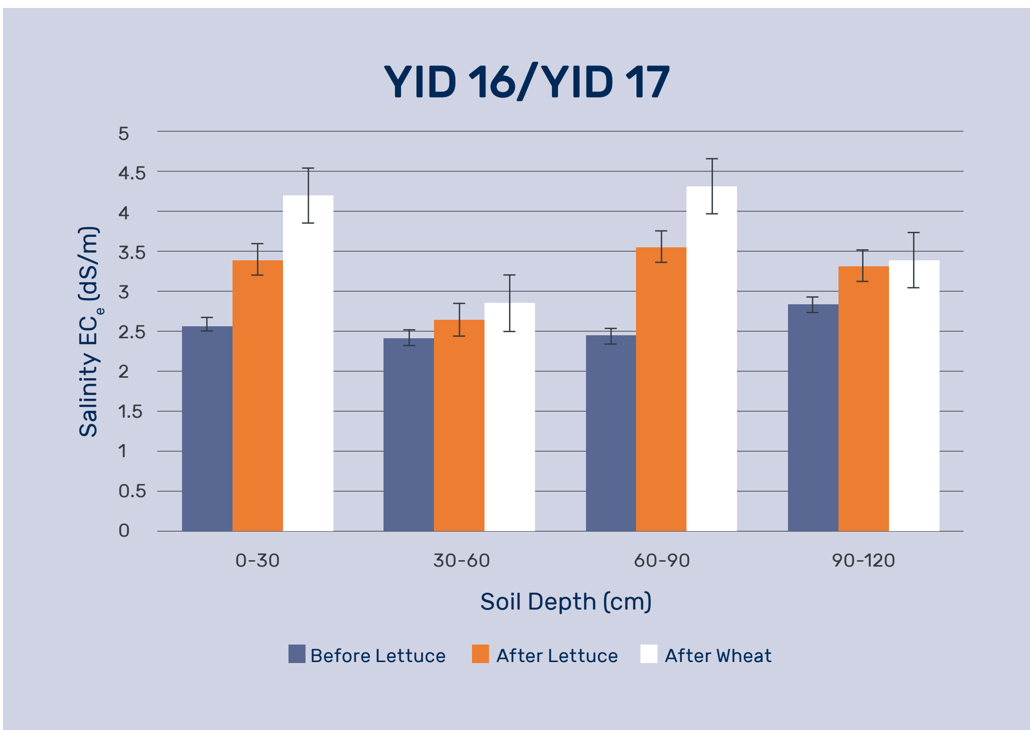


Figure 19. Field salinity as measured by EC_e for a lettuce (YID 16)/wheat (YID 17) rotation.

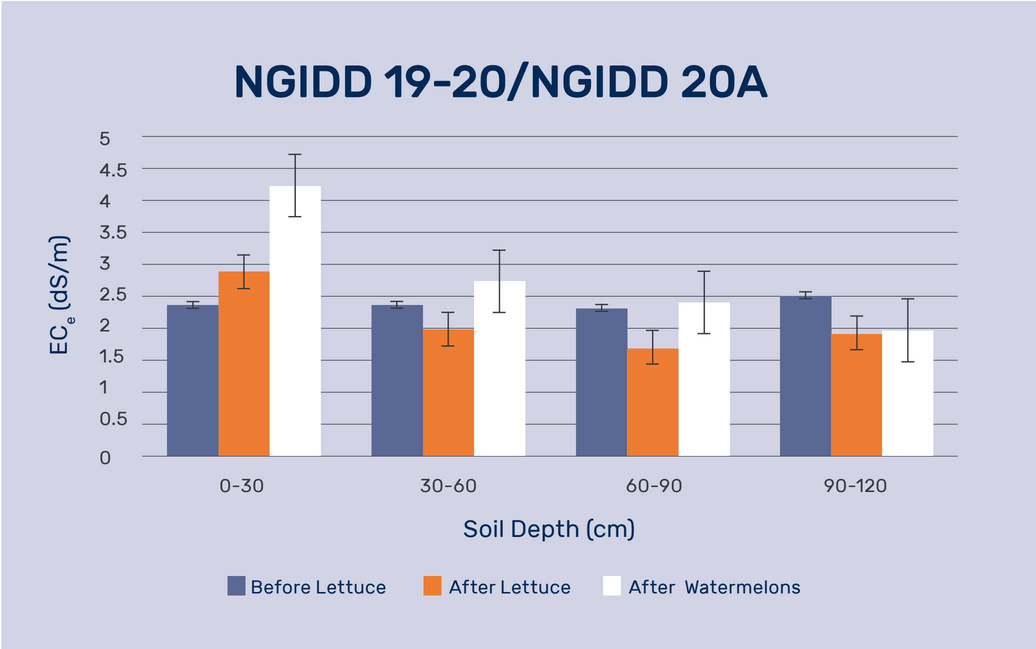


Figure 20. Field salinity as measured by EC_e for a romaine lettuce (NGIDD 19-20)/watermelon (NGIDD 20A) rotation.

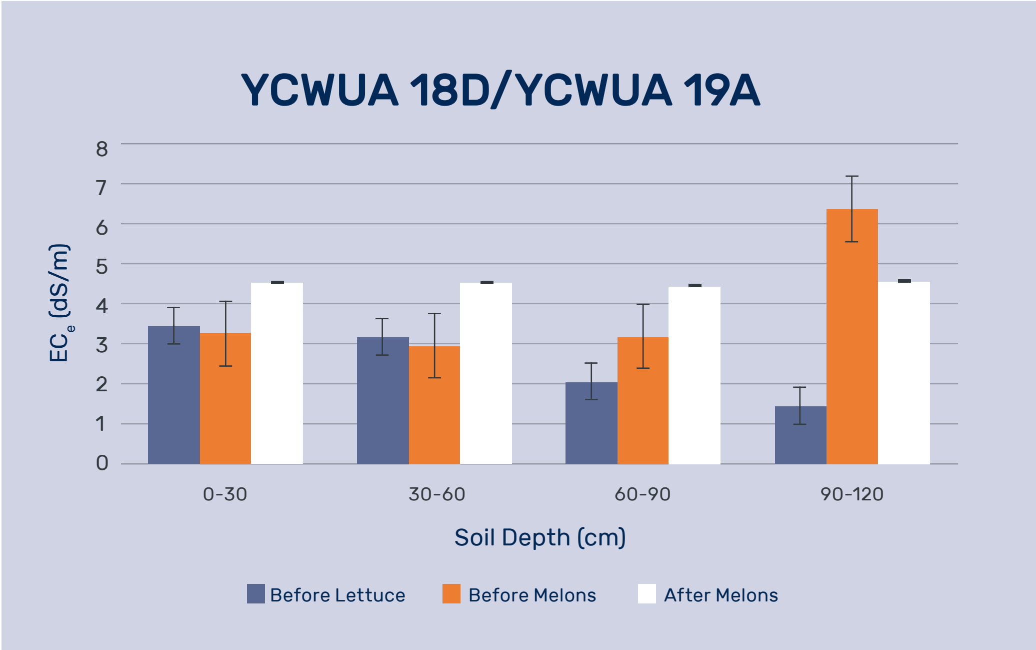
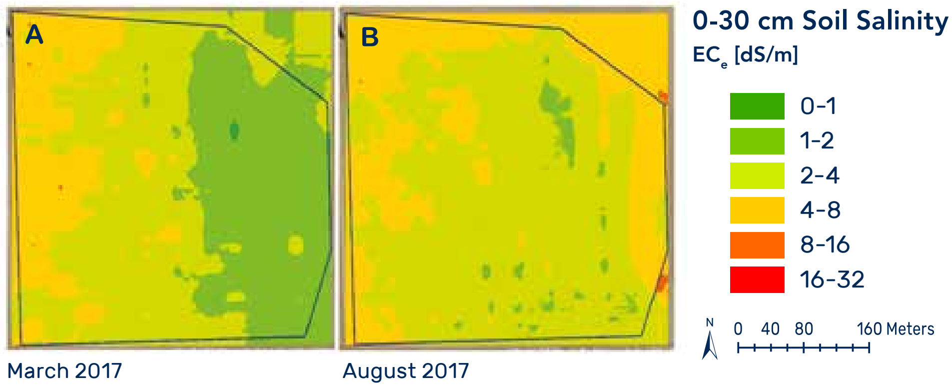


Figure 21. Salinity changes, as measured by EC_e for a lettuce (YCWUA 18D)/cantaloupe (YCWUA 19A) rotation.

Salinity increased for both summer fallow sites evaluated as part of these studies (Figure 22). The fallow period was approximately 90 days, and it appears that the shallow groundwater which continued to move up by capillarity is much more saline than irrigation water from the Colorado River.

Figure 22.
Field-wide distribution of salinity, as represented by soil electrical conductivity (EC_e), increased from ~1 dS/m before imposition of a summer fallowing (A) to >4 dS/m after fallowing (B) in the BWD.



Overall, these data show a leaching requirement deficit for most crop production systems (Table 6, page 41). Furthermore, without this required leaching, significant yield losses are projected based on the established relationship between lettuce yield and soil salinity (Figure 23). A pre-irrigation would be required to restore salt balance to these sites for continued crop production.

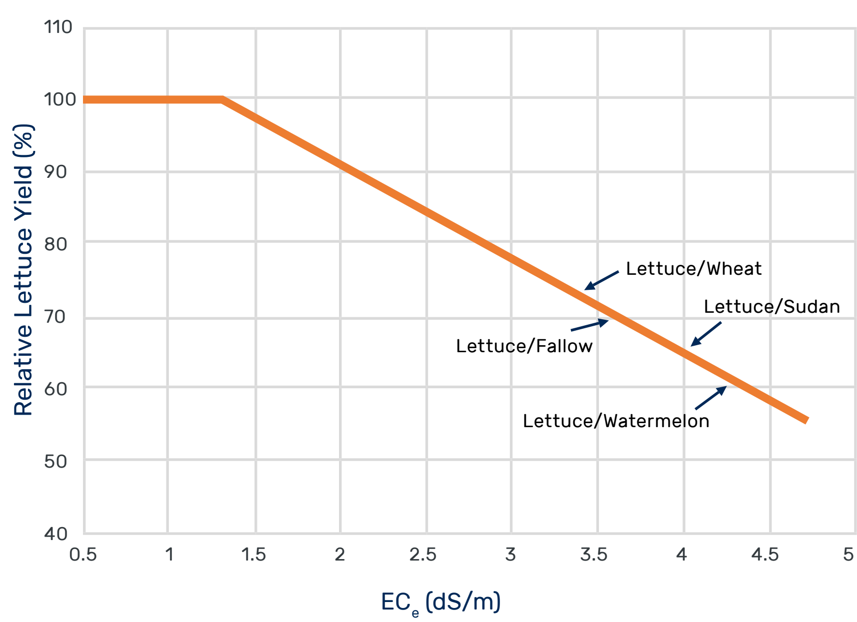


Figure 23. Projected lettuce yields following several lettuce rotations based on measured average EC_e across sites after full rotations. We project significant production losses without summer leaching.

Table 6. Water required (RLD + ETc) for all crops and leaching depth deficits for salt balance.

Crop	Irrigation Method	Water Required for ETc and salt balance[1]	Water Received	Leaching Depth Deficit	Water Required for ETc and salt balance[1]	Water Received	Leaching Depth Deficit
		mm	mm	mm	ac-in	ac-in	ac-in
FALL-WINTER-SPRING VEGETABLES							
Broccoli	Sprinkler/Furrow	454	442	11.5	17.9	17.4	0.45
Cauliflower	Sprinkler/Furrow	514	472	41.8	20.2	18.6	1.6
Celery	Furrow	525	643	0.0	20.7	25.3	0.0
Celery	Sprinkler/Drip	574	484	90.1	22.6	19.1	3.5
Lettuce-Boston	Sprinkler	232	233	0.4	9.1	9.1	0.0
Lettuce-Iceberg	Sprinkler/Furrow	340	371	0.0	13.4	14.6	0.0[2]
Lettuce-Leaf	Sprinkler/Furrow	268	264	3.6	10.5	10.4	0.1
Lettuce-Romaine	Sprinkler/Furrow	361	326	34.6	14.2	12.8	1.4
Lettuce-Romaine	Sprinkler	338	257	81.0	13.2	10.1	3.2
Spinach	Sprinkler	134	119	15.0	5.3	4.7	0.6
Spring Mix	Sprinkler	151	151	0.0	5.9	5.9	0.0
SPRING-SUMMER ROTATIONAL SYSTEMS							
Cantaloupes	Drip/Bare Soil	593	591	2	22.6	23.3	0.1
Cotton	Furrow	1374	1092	282	54.1	43.0	11.1
Durum Wheat	Basin	792	717	74	31.6	28.2	3.4
Summer Fallow	---	172	4	168	6.8	0.2	6.6
Sudan Grass	Basin	820	841	0	32.3	33.1	0.0
Watermelon	Drip/Plastic Mulch	500	400	100	19.6	15.7	3.9

[1]Water required is ETc plus the required leaching depth (RLD) where ETc are the average values from Tables 3A/3B and RLD = ETc (LR/(1-LR)). We used the threshold for lettuce for all crops since lettuce is produced on all vegetable ground at minimum every other year, and the ground must remain suitable for lettuce.

[2]As noted previously, several iceberg lettuce sites occurred during periods of above average rainfall. If we average only sites with average rainfall, the leaching volume deficit becomes 52 mm (2 ac-in).

8 Discussion

A prolonged drought has prompted a reconsideration of water utilization within the Lower Colorado River Basin. Because agriculture accounts for over 70% of the total diversion of the Colorado River (Cohen et al., 2013), agricultural interests are being challenged to use water more efficiently. Although the USBR estimates that vegetable crops are historically less than 10% of the consumptive use of the total agriculture diversion, and forages account for over 70% (USBR, 2023), all water users must do their part. This reality was the basis for this project originally funded by the YCAWC and coordinated through YCEDA, which aimed to quantify the existing water and salt management practices and to identify opportunities for improvement. We wish to discuss these data in the context of some of the discussions currently ongoing within the basin.

These studies show that the irrigation efficiencies of vegetable and rotational cropping systems in the flood plain districts near Yuma are generally high (80-90%). The data also show net in-season salt accumulations over a majority of sites, meaning pre-season irrigation for salt leaching is of paramount importance to sustainability.

One strategy frequently proposed by outside organizations and regulatory entities for improved irrigation efficiency is to provide incentives to growers to adopt drip irrigation. The rationale for these proposals is that the initial cost for installation is the major obstacle to widespread adoption. In fact, there are multiple and equally important obstacles to using drip systems in the Yuma area. These include non-uniform plant emergence due to uneven soil moisture distribution, inability of drip systems to leach shallow salts, and inflexibility of reconfiguring drip-equipped fields for different crops throughout the growing season (YCAWC, 2015). Drip irrigation has been evaluated by the UArizona (Pier and Doerge, 1995; Thompson and Doerge, 1995; 1996), and periodically in the Yuma production fields, for more than three decades. This practice has been implemented where it could be justified based on production and economics. It is widely used in cantaloupe and watermelon systems in the Yuma area. Drip irrigation has also been evaluated by more than one grower in lettuce production systems. However, because it provided no sustained production, economic, or water conservation advantages, it was subsequently abandoned in lettuce. As data in this report show, seasonal irrigation efficiencies for most crops, across a majority of the soils in the flood plain irrigation districts, are already high using an optimized sprinkler and furrow irrigation system (Sanchez et al., 2008). Due to a lingering requirement of salt management, and the need to manage this salt regardless of irrigation method, it is not likely that wide-spread implementation of drip irrigation would result in water savings from the vegetable production systems in the floodplain districts near Yuma since any in-season water saving would increase subsequent off-season leaching requirements.

Having acknowledged the limitations of drip irrigation for Yuma vegetable cropping systems, it is important to note potentially relevant and niche applications. As discussed, AE values for celery are low, due to early season leaching, and drip technology could potentially be a way to effectively increase them for this shallow rooted crop. Another opportunity may be for sites with coarse textured soils. As the vegetable industry has expanded into such areas, it is difficult to irrigate efficiently using the current furrow system design. Therefore, drip irrigation may be an effective alternative. It has been reported that pressurized irrigation, including drip and micro-sprinklers, would provide water conservation benefits on the sandy soils of the Yuma Mesa (YCAWC, 2015). Drip irrigation would also potentially produce positive outcomes in other parts of Arizona where soil texture, field length, and flow limit opportunities for efficient surface irrigation. It should also be noted that the expanded use of sprinklers on coarse textured soils would be another viable option, as currently practiced for some leafy vegetable production systems.

In light of the challenges facing the Colorado River, the federal government has suggested that it may use a combination of voluntary and involuntary water cutbacks to achieve additional conservation. One possible short-term consequence of water cutbacks would be fallowing of land, either during the spring-summer rotation period or for the entire year. The summer fallowing program currently ongoing in the BWD allowed the research team to do some preliminary evaluations of fallowed fields. As noted above, capillary rise of shallow saline water during fallow periods increased salinity in the root zone, so a pre-irrigation would be required to restore conditions suitable for salt-sensitive vegetable crops.

Salt management will remain a major challenge as climate change models predict less runoff into the Colorado River system and therefore higher salt concentrations (NRC, 2007). The USBR mitigation programs for salinity in the basin have been very successful and their efforts in this area will continue (Borda, 2004; CRBSCF, 2011; USBR, 2013). There are uncertainties due to drought and climate change regarding the continued success of this program, and we should anticipate lingering salt management challenges. With in-season irrigation for vegetable systems generally highly efficient, regardless of irrigation method, a pre-irrigation leaching event will continue to be required for salt management and sustainability. As water scarcity continues, the aim should be to apply only what leaching is needed for salt balance. Inadequate leaching compromises sustainable production, but excess leaching is wasteful. Although most cropping systems show in-season increases in soil salinity, some do not, and the degree of this increase varies considerably due to soil type, management, and occasionally rainfall. Therefore, the water quantity required to restore salt balance varies, and tools to predict this requirement are needed. The DesertAgWISE app developed as part of this overall project is one such tool; it tracks water and salt balance over multiple seasons, and will help growers optimize water use while maintaining sustainability. Future research should seek improved tools that better predict and manage this necessary leaching fraction.

9 Literature Cited

Allen, R., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and Drainage Paper No. 56.

Arizona Department of Environmental Quality. 1995. Ambient groundwater quality of the Yuma Basin; An ADEQ 1995 Baseline Study. https://static.azdeq.gov/wqd/gw/fs/01-03_yumabasin_fs.pdf

Ayers, R. S. and D. W. Westcot. 1994. Water quality for agriculture. FAO Irrigation and Drainage Paper No. 29 Rev. 1.

Borda, C. 2004. Economic Impacts from Salinity in the Lower Colorado River Basin. Technical Memorandum Number EC-04-02. Bureau of Reclamation. Denver, CO.

Brown, P. W., T. Machibya and B. Russell. 1995. Wind Flow Patterns at the University of Arizona Agricultural Centers. Technical Bulletin 268. University of Arizona Agricultural Experiment Station. 215 p.

Breschini, S. J., and T. K. Hartz. 2002. Drip irrigation affects celery yield and quality. Hort. Sci. 37: 894-897.

Burt, C. M., A. J. Clemmens, T. S. Strelkoff, K. H. Solomon, R. D. Bliesner, L. A. Hardy, T. A. Howell, and Dean E. Eisenhauer. 1997. Irrigation Performance Measures: Efficiency and Uniformity. J Irrig Drain Eng 123: 423-442.

Cohen, M., J. Christian-Smith, and J. Berggren. 2013. Water to supply land: Irrigated agriculture in the Colorado River basin. Oakland CA, Pacific Institute, pp 93.

Colorado River Basin Salinity Control Forum (CRBSCF). 2011. Water quality standards for salinity Colorado River system.: 2011 Review. https://www.coloradoriversalinity.org/docs/2011%20REVIEW-October.pdf

Colorado River Basin Salinity Control Forum (CRBSCF). 2020. Water quality standards for salinity Colorado River system.: 2020 Review.
https://www.coloradoriversalinity.org/docs/2020%20REVIEW%20-%20Final%20w%20appendices.pdf

Corwin, D. L., J. D. Rhoades, and J. Simunek. 2007. Leaching requirement for soil salinity control: Steady state versus transient models. Agricultural Water Management 90:165-180.

Cowan, I. R. 1982. Regulation of water use in relation to carbon gain in higher plants. Physiological Plant Ecology 11, Water relations and carbon assimilation. Berlin: Springer, pp. 589-614.

Dickinson, J. E., M. Land, C. Faunt, S. Leake, E. Reichard, J. Fleming, and D. Pool. 2006. Hydrogeologic Framework Refinement, Ground-Water Flow and Storage, Water-Chemistry Analyses, and Water-Budget Components of the Yuma Area, Southwestern Arizona and Southeastern California. USGS Scientific Investigations Report 2006-5135.

Erie, L. J., O. F. French, D. A. Bucks, and K. Harris. 1982. Consumptive use of water by major crops in the Southwestern United States. United States Department of Agriculture, Conservation Research Report No. 29.

Hunsaker, D.J., Barnes, E.M., Clarke, T.R., Fitzgerald, G.J., Pinter Jr, P.J., 2005. Cotton irrigation scheduling using remotely sensed and FAO-56 basal crop coefficients. Transactions of the ASAE. 48(4): 1395-1407.

Hunsaker, D.J., Fitzgerald, G.J., French, A.N., Clarke, T.R., Ottman, M.J., Pinter Jr., P.J., 2007. Wheat Irrigation Management Using Multispectral Crop Coefficients: I. Crop Evapotranspiration Prediction. T. ASABE 50, 2017-2033.

Hunsaker, D.J., Pinter, Jr., P.J., Cai, H. Alfalfa basal crop coefficients for FAO-56 procedures in the desert regions of the southwestern U.S. Trans. ASAE 45(6):1799-1815. 2002.

Maas, E. V. 1990. Crop Salt Tolerance. In: Tanji, K., Ed., Agricultural Salinity Assessment and Management, ASCE Manuals & Reports on Engineering Practice No. 71, ASCE, 262-304.

Maas, E. V. and G. J. Hoffman. 1977. Crop Salt Tolerance-Current Assessment. Journal of the Irrigation and Drainage Division, 103, 115-134.

NRC. 2007. Colorado River Basin management: Evaluating and adjusting to hydraulic variability. Washington D.C. The National Academies of Science.

Pier, J. W., and T. A. Doerge. 1995. Concurrent evaluations of agronomic, economic, and environmental aspects of trickle irrigated watermelon production. J. Environ. Qual. 24:79-86.

Rains, D. W. 1987. Salinity stress energy cost of plant cells exposed to salinity. Models in Plant Physiology and Biochemistry Vol. III D. W. Newman and K. G. Wilson (ed) CRC Press Inc. Boca Raton. 91-93.

Rhoades, J.D. 1974. Drainage for Salinity Control. In J. Van Schilfgaarde (Ed.), Drainage for Agriculture pp. 433-468.

Rhoades, J.D. 1996. Salinity: Electrical conductivity and total dissolved salts. In: D.L. Sparks (ed.) Methods of Soil Analysis. Part 3. Chemical Methods. Soil Sci. Soc. Am. Book Series No. 5, 1996, P. 869-920.

Sanchez, C. A., D. Zerihun, and K. L. Farrell-Poe. 2008. Management guidelines for efficient irrigation of vegetables using closed-end level furrows. Agricultural Water Management. 96:43-52.

Sanchez, C. A., and J. C. Silvertooth. 1996. Managing saline and sodic soils for the production of horticultural crops. HortTechnology 6:99-107.

Thompson, T. L., and T. A. Doerge. 1995. Nitrogen and water rates for subsurface trickle irrigated romaine lettuce. HortScience 30:1233-1237.

Thompson, T. L., and T. A. Doerge. 1996. Nitrogen and water interactions in subsurface trickle irrigated leaf lettuce. II. Agronomic, economic, and environmental outcomes. Soil Sci. Soc. Am. J. 60: 168-173.

United States Bureau of Reclamation (USBR). 2013. Quality of Water – Colorado River Basin Progress Report No. 24. Upper Colorado Region, Salt Lake City, UT.

United States Bureau of Reclamation (USBR). 2023. Colorado River Accounting and Water Use Reports. https://www.usbr.gov/lc/region/g4000/wtraccttypes.html. Accessed 2023.

Yuma County Agriculture Water Coalition. 2015. A Case Study in Efficiency – Agriculture and Water Use in the Yuma, Arizona Area.

Zerihun, D., C. A. Sanchez, and K. Nolte. 2014. Field-Scale Sprinkler Irrigation System Hydraulic Model. I: Hydraulic Characterization. J. Irrig. Drain Eng., 10.1061/(ASCE)IR.1943- 4774.0000727, 04014019.

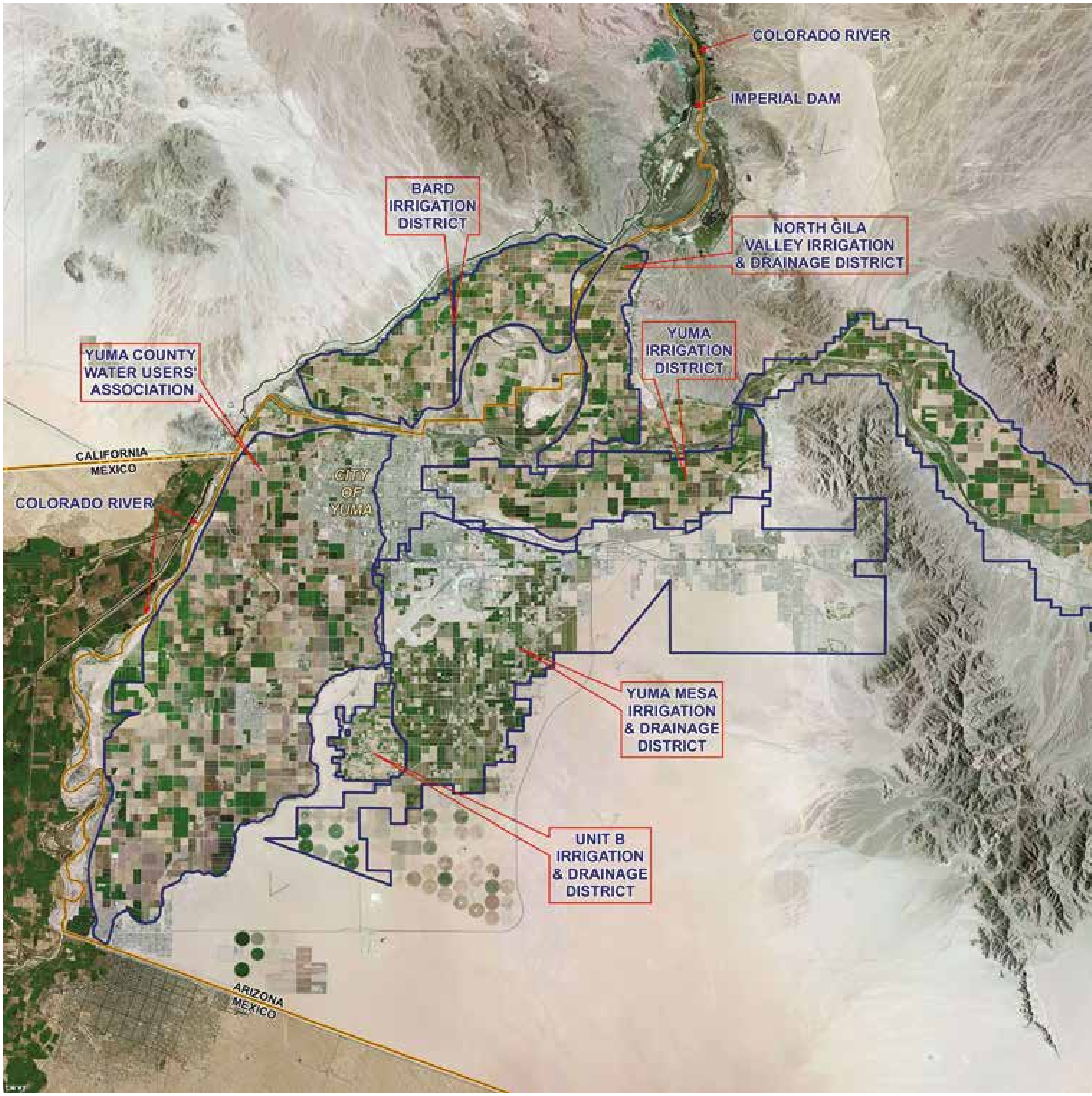
Zerihun, D. and C. A. Sanchez. 2014. Field-Scale Sprinkler Irrigation System Hydraulic Model. II: Hydraulic Simulation. J. Irrig. Drain Eng.,10.1061/(ASCE)IR.1943-4774.0000723, 04014020.

10 Glossary of Acronyms and Abbreviations

ac-in	acre-inch or acre-inches
AE	application efficiency/efficiencies
AZMET	Arizona Meteorological Network
BWD	Bard Water District
Ca^{+2}	calcium ion
Cl^-	chloride
Cle	chloride concentration of soil paste extract
cm	centimeter or centimeters
CO_2	carbon dioxide
DU	low quartile or low quarter
EC	electrical conductivity
EC_e	electrical conductivity of soil paste extract
EC_{dw}	electrical conductivity and drainage water
EC_{iw}	electrical conductivity of irrigation water
EC_w	electrical conductivity of water
ECV	eddy covariance
EM38	electromagnetic conductance surveys
ESAP	EC_e Sampling And Prediction software
ESAP-RSSD	ESAP Response Surface Sampling Design software
ETc	crop evapotranspiration
ETos	reference evapotranspiration for short crops (grass)
ET	evapotranspiration
FAO-56	U.N. Food and Agriculture Organization paper 56
ft	foot or feet
G	ground heat flux
Hz	hertz
GPS	Global Positioning System
H	sensible heat flux
HCO_3^-	bicarbonate
HU	heat units
in	inch or inches
K^+	potassium ion

Kc	crop coefficients
LCRAS	Lower Colorado River Accounting System
LE	latent heat flux
LF	leaching fraction ($LF = EC_{iw}/EC_{dw}$)
LR	leaching requirement ($LR = EC_{iw}/(5EC_e - EC_{iw})$) where EC_e is lettuce tolerance
m	meter or meters
Mg^{+2}	magnesium ion
MINTEQ	freeware for chemical equilibrium modeling for natural waters
mm	millimeter or millimeters
N	nitrogen
Na^+	sodium ion
NASA	National Aeronautics and Space Administration
NASA GSFC	NASA Goddard Space Flight Center
NASA JPL	NASA Jet Propulsion Laboratory
NDVI	Normalized Difference Vegetation Index
NGIDD	North Gila Irrigation and Drainage District
NO^-_3	nitrate
R_n	net radiation
RLD	required leaching depth
SAR	sodium adsorption ratio
SO_4^{-2}	sulfate
TDS	total dissolved solids
UArizona	University of Arizona
Unit B	Unit B Irrigation and Drainage District
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USDA-ARS ALARC	USDA Agricultural Research Service, U.S. Arid Land Agricultural Research Center
USDA-ARS USSL	USDA-ARS United States Salinity Laboratory
WMIDD	Wellton-Mohawk Irrigation and Drainage District
YCAWC	Yuma County Agriculture Water Coalition
YCEDA	Yuma Center of Excellence for Desert Agriculture
YCWUA	Yuma County Water Users' Association
YID	Yuma Irrigation District
YMIDD	Yuma Mesa Irrigation and Drainage District

11 Yuma Area Water Management Jurisdictions Map

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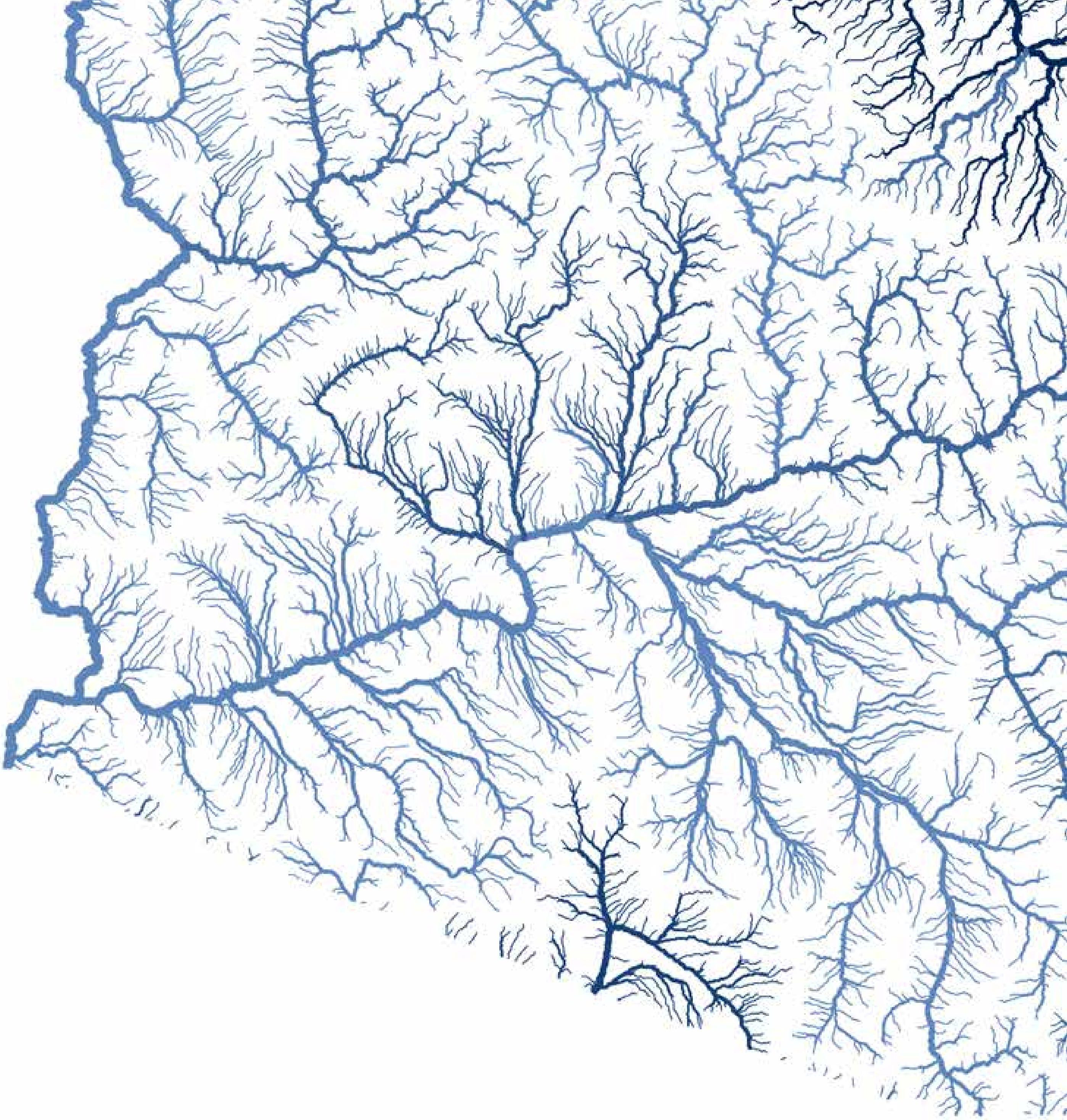

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