ASSESSING AGRICULTURAL CONSUMPTIVE USE in the Upper Colorado River Basin

Phase III Report
November 2022

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This Phase III Report provides a summary of the analysis and results of the Consumptive Use Study for the 2020 irrigation season, an intercomparison with results from the 2017-2019 irrigation seasons, and related recommendations.

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This group of academic researchers and water resource managers is working to advance our scientific understanding and improve the accuracy of consumptive water use estimation for better management of western water, and to enhance the infrastructure, underlying data, processes, and related tools that increase our understanding of this important component of water use in the Upper Colorado River Basin.

Disclaimer

This report, the *Upper Colorado River Basin (UCRB) Assessing Agricultural Consumptive Use – Phase III Report* (Report), is the culmination of a decade-long initiative and study to evaluate the available science and methods related to the estimation of agricultural consumptive water use for interstate purposes in the UCRB. Concluded in 2021, the study and this Report contain experimental and investigative summary data and results, including supporting data in related appendices. This information led the authors of the Report (a coalition of federal, state, and academic advisors, scientists, and experts in the field) (Authors) to make recommendations concerning the selection of a remote-sensing method and related processes for estimating basin-wide agricultural consumptive water use in the UCRB.

The Upper Division States, through the Upper Colorado River Commission (UCRC), unanimously adopted by resolution the Report's recommended method and processes for estimating agricultural consumptive water use for interstate purposes within the UCRB. The resolution directs the UCRC staff to continue to work with the Upper Division States and Reclamation to monitor and institute improvements to agricultural consumptive use estimation in the UCRB as the science evolves and the methods are further developed. In adopting the resolution, the UCRC Commissioners considered method and process accuracy, consistency with available science, relative cost, and the ability of the method to produce timely information.

The Report was prepared solely by the Authors and is presented for general informational purposes only with the goal of educating the reader as to the basic approach of Phase III of the study, which led to the Authors' recommendations. The data and results contained in the Report are unique to the parameters and purposes of the study and, therefore, cannot be applied, utilized, or repurposed for any other application, function, or concern outside the context of the study; nor does any information presented establish any precedents or formal declarations related to agricultural consumptive water use within the UCRB. Any past performance, projection, forecast, or simulation of results contained and summarized in the Report is not necessarily indicative of the future or likely accuracy of any estimation of agricultural consumptive use in the UCRB.

The Authors, Upper Division States, UCRC, and the Bureau of Reclamation, accept no responsibility or liability for the accuracy of the data and results contained in the Report or any use made of the data and results outside of the context of the study and shall not be liable for any loss or damage resulting from any such inaccuracy or use of the information. The Authors, Upper Division States, UCRC, and the Bureau of Reclamation make no warranty, express or implied, including warranties of fitness for any particular purpose, nor assume any legal liability or responsibility for any errors or omissions, the accuracy, completeness, or usefulness of any information provided in the Report and related appendices.

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Definitions

The following are key terms used throughout the Report.

Actual Consumptive Use from Irrigation Water (CU_{irr}): the volume of diverted irrigation water that is removed from available supplies through conversion of liquid to vapor due to evapotranspiration or harvested with the crop

Actual Evapotranspiration (ET_a): the rate of water that is removed from available supplies, both irrigation and precipitation, through a combination of evaporation and transpiration from vegetation

Crop Irrigation Water Requirement (CIR): the quantity of water required from an irrigation source, in addition to precipitation, to grow a well-watered crop under optimal conditions

Effective Precipitation (P_e): the portion of total precipitation that is available for crop consumption

Fetch: the spatial distribution of the surface fluxes and their corresponding magnitude measured by the eddy covariance tower, also known as tower footprint

Fraction of Alfalfa Reference ET (ET_rF): the calculated ET divided by the reference ET at the time of satellite overpass

gridMET: a dataset of daily high-spatial resolution (~4-km, 1/24th degree) surface meteorological data covering the contiguous United States from 1979 to present developed by the University of Idaho (Abatzoglou, 2012)

Normalized Difference Vegetation Index (NDVI): a commonly used vegetation index derived from the red and near infrared (NIR) spectral bands of remotely sensed imagery that is correlated with green vegetation amount and ET, calculated as (NIR reflectance – red reflectance) / (NIR reflectance + red reflectance)

Potential Evapotranspiration (ET_p): the amount of water that is required to grow a well-watered crop under optimal conditions having a full water supply from irrigation and precipitation

Reference Evapotranspiration (ET_r): potential ET from an alfalfa crop that is actively growing and is at full cover and standard height

Acronyms

CU_{irr} – Crop Consumptive Use from Irrigation

CCM – Crop Coefficient Method

CU&L – UCRB Consumptive Uses and Losses Report

CUWG – Consumptive Use Working Group

EC Tower – Eddy Covariance Tower

ET – Evapotranspiration

ET_a – Actual Evapotranspiration

ET_p – Potential Evapotranspiration

ET_r – Alfalfa Reference Evapotranspiration

ET_rF – Fraction of Reference ET

LST – Land Surface Temperature

METRIC – Mapping EvapoTranspiration at High Resolution with Internal Calibration

NDVI – Normalized Difference Vegetation Index

NIR – Near Infrared

QA/QC – Quality Assurance and Quality Control

RSM – Remote Sensing Models

SSEBop – Simplified Surface Energy Balance – Operational

UCRB – Upper Colorado River Basin

USGS – United States Geological Survey

1.0 Introduction

The Upper Colorado River Commission (Commission); the four states of the Upper Division (Colorado, New Mexico, Utah, and Wyoming); and the Upper Colorado Region and Denver Office of the Bureau of Reclamation (Reclamation), collectively referred to as the Consumptive Use Working Group (CUWG), are involved in an ongoing assessment (Consumptive Use Study, study) designed to evaluate and improve timelines, accuracy, support, and cost effectiveness of agricultural consumptive use estimates across the entire Upper Colorado River Basin (UCRB). Phase 1 of the study identified current methodologies used by the states and Reclamation and included suggestions for improvements. Phase 2 of the study identified improvements that could be made in collection of agricultural evapotranspiration (ET) data by expanding the meteorological network and conducted preliminary studies to evaluate remote sensing methodologies and their feasibility for use in the UCRB.

Phase 3 included an independent evaluation of estimated potential and actual ET compared to site-specific measured consumptive use from irrigation (CU_{irr}) and a comparison of estimated CU_{irr} for the UCRB. As shown in Figure 1, two different approaches for estimating ET were investigated: (1) thermal-based remote sensing ET models (RSM) and (2) Crop Coefficient Methods (CCM). Two RSMs were compared: METRIC (Mapping EvapoTranspiration at High Resolution with Internal Calibration) and SSEBop (Simplified Surface Energy Balance – Operational), and two CCMs were compared: Modified Blaney-Criddle with an elevation adjustment and Penman-Monteith. Eddy Covariance Towers (EC Towers) were installed in each of the four UCRB states to measure ET directly for comparison to the results from the four methods investigated. This report compares the results of the different methods and evaluates the modeling processes, costs, and resource requirements to estimate CU_{irr} for each method for the 2020 irrigation season. This report also summarizes the results of the different methods from 2020 and the three previous years investigated (2017, 2018, and 2019). The Phase 3 work, as summarized in this report, is the final contemplated phase of the Consumptive Use Study.

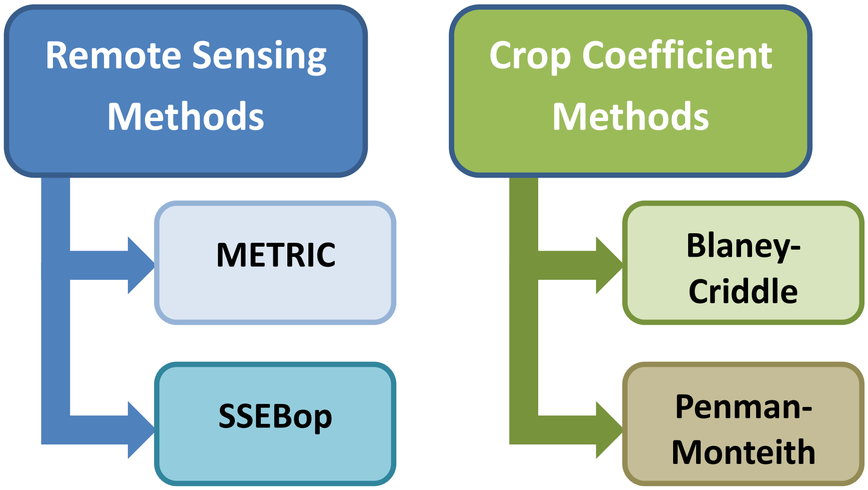


Figure 1. Approaches and methods for ET estimation evaluated for Phase 3

Reclamation calculates crop consumptive use from irrigation for the UCRB on an annual basis and provides the results as part of the UCRB Consumptive Uses and Losses Report (CU&L Report). Reclamation currently uses Modified Blaney-Criddle without an elevation adjustment to estimate CU_{irr} and incorporates shortage criteria as the basis for estimating crop consumptive use. The accuracy, processing time, and resource requirements associated with each method investigated were compared to those associated with Reclamation's current method.

2.0 Background

The following provides background on the datasets developed and used in the Phase 3 analyses.

2.1 Eddy Covariance Towers

The eddy covariance approach used in this project is a high-quality standard for measuring the key fluxes from a land surface including momentum, heat, water vapor, and carbon dioxide (CO_2). It is the only method allowed for the global network of water and carbon flux estimates (https://fluxnet.fluxdata.org/about/). The EC Tower systems employed in four locations in the UCRB include three-dimensional sonic anemometers and fast-response open-path infrared gas analyzers. When sited properly, these measurements, along with several additional analyses, yield the flux of water vapor (ET). Several additional measurements were used to verify the reliability of the ET values including net radiation (incorporating incoming and outgoing components of radiation), soil heat flux, and various weather data including air temperature, vapor pressure, precipitation and mean horizontal wind speed. Figure 2 shows a photograph of the EC Tower station at Vernal, Utah.

Figure 2. Eddy Covariance Tower located over an alfalfa field near Vernal, Utah

The water vapor flux measured by the EC Tower originates from the upwind areas surrounding the EC Tower. The size and shape of the area being measured by the tower can vary throughout the day due to surface roughness of the land, wind speed, wind direction and atmospheric stability. To ensure the most reliable crop ET measurements with eddy covariance, the agricultural field surrounding the EC Tower should contain a single crop and be large enough such that the measurements of fluxes made from the near surface air stream characterize an appropriate "footprint" or region that includes only the surface desired. Various factors can affect the uncertainty of the ET measurements from the eddy covariance data, including highly variable wind directions and footprints, sensor and/or recording equipment malfunctions, and the skill of the analysts who perform the quality assurance and quality control procedures (QA/QC).

Although an exact determination of the uncertainty of eddy covariance estimates of ET is not possible, various studies have determined the approximate magnitude of some key sources of errors. The replication ability of identical towers was investigated by Alfieri et al. (2011) that concluded that in non-advective conditions, the identical towers produced very similar results. Kosugi and Katsuyama (2006) and Scott (2010) compared seasonal values of ET from eddy covariance to values obtained from a soil water balance. Independent measurements of available energy (net radiation minus soil heat flux) have also been used to check how well the sensible and latent heat flux measured by eddy covariance account for the available energy at the surface.

The combined published research on uncertainty of eddy covariance suggests that under optimal situations (best practices followed by experienced investigators, at ideal sites) daily, monthly, and seasonal levels can achieve accuracy within 10 percent (Foken et al. 2012). This corresponds to the EC Tower measurement uncertainty compared to actual values of 10 to 15 percent reported by Allen et al. (2011).

One EC Tower was installed in each of the four Upper Division states in 2017 (Figure 3); however, only the Vernal EC Tower was operational early enough to be used in the 2017 comparison. All four towers were operational during the 2018, 2019, and 2020 growing seasons, and the associated data are included in this report. Note that in 2020, the Bloomfield tower was moved to a neighboring alfalfa field that was irrigated using a center pivot. The location, elevation, crop type, and irrigation method of the ground cover below the four EC Towers in 2020 are presented in Table 1. The towers were sited to represent the irrigated acreage variability in the UCRB.

Table 1. Descriptions of the Four EC Towers in 2020

Station Name	State	Elevation (ft)	Crop Type	Irrigation Method
Palisade	Colorado	4,742	Peach Orchard	Ground Sprinkler
Bloomfield	New Mexico	5,563	Alfalfa	Center Pivot
Vernal	Utah	5,464	Alfalfa	Side Roll Sprinkler
Big Piney	Wyoming	6,990	Foxtail Grass	Flood

Standard maintenance and calibration procedures at all four sites, as well as expert QA/QC procedures and additional data analyses, allowed most of the observed data to be confidently used for year 2020. Dates of events that could impact the observed data, including precipitation, irrigation, and crop cutting, are addressed in the resulting comparisons. Crop cutting dates were determined using timed photographs taken every 20 minutes during daylight hours at each location. Irrigation application was determined using timed photographs, as well as through analysis of soil moisture, wetness sensor and precipitation data. Irrigation and cutting dates are for the location of the tower. At the Vernal, UT and Bloomfield, NM sites, side roll sprinklers and center pivots are moved continuously throughout the field and nearby fields.

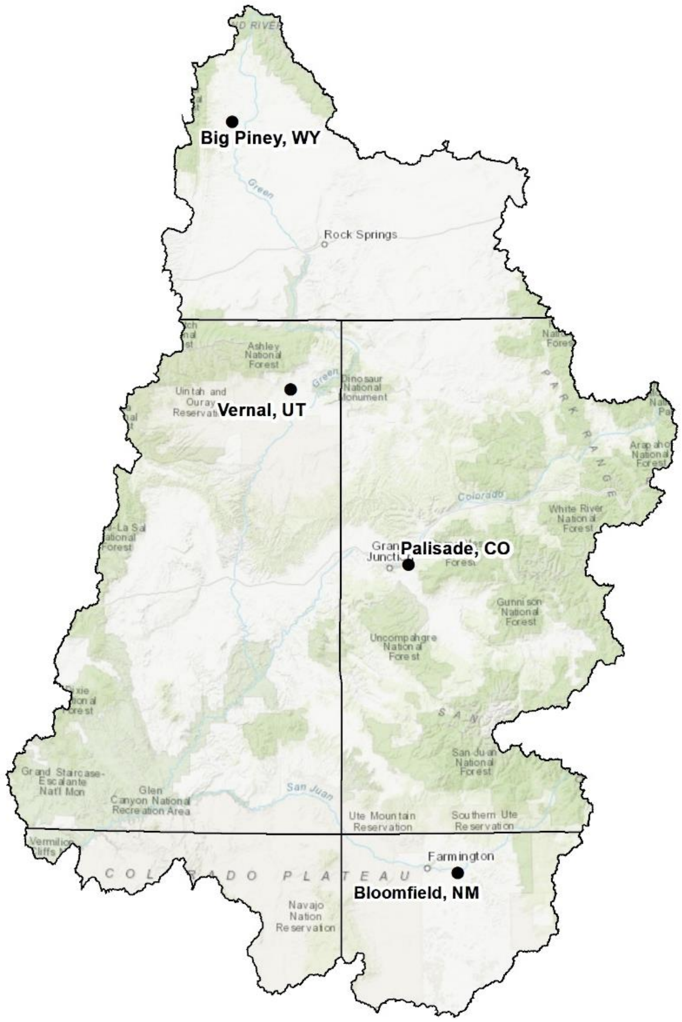


Figure 3. EC Tower Locations

2.2 Remote Sensing Models

Two thermal-based ET models were used in Phase 3: SSEBop and METRIC. Both models used 2020 remotely sensed imagery from the Landsat 7 and Landsat 8 satellites to produce spatial data maps of monthly total actual ET (ET_a) on a 30m x 30m pixel basis across the entire UCRB. The spatial maps were superimposed onto UCRB irrigated polygons. Each Upper Division state typically develops irrigated acreage polygons on either an annual basis or every five years. While the states of Wyoming, Utah, and New Mexico provided annual irrigated crop maps for 2017, 2018, and 2019, the states had yet to develop a 2020 map at the time of this analysis. Therefore the 2019 irrigated crop maps for Utah and New Mexico were used, and the 2018 irrigated crop map for Wyoming was used. Colorado's latest crop map provided by the state of Colorado represents 2015 conditions. Because the availability of irrigation water varied between the irrigated crop map year used for each state and 2020, the irrigation status of individual field polygons across the UCRB were changed to 'not irrigated' if the mean value of 2020 seasonal maximum Normalized Difference Vegetation Index (NDVI, calculated from multidate Landsat imagery) within each polygon was less than 0.3. NDVI values less than 0.3 reflect the lack of green vegetation due to little or no irrigation in the 2020 season. Appendix H provides more detail on the process used to develop the irrigated acreage layer used for 2020. Irrigated acreage by state for each year of the project (2017, 2018, 2019, and 2020) is summarized in Table 2. Irrigated acreage varied by only 3 percent across the UCRB during the four-year study period. Note that the statewide totals for irrigated acreage are slightly different than the totals shown in Appendix H. In order to compare the remote sensing models to the crop coefficient models, the irrigated acreage layer is intersected with a 4 km by 4 km gridMET layer. This only affects the statewide totals, total basinwide acreage was not affected.

Table 2. Irrigated Acreage by state for 2017, 2018, 2019, and 2020

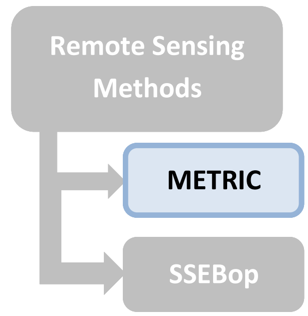
State	2017 Acres	2018 Acres	2019 Acres	2020 Acres
Colorado	798,894	786,626	798,359	798,196
New Mexico	82,771	83,121	83,013	83,013
Utah	312,628	353,585	354,727	354,291
Wyoming	321,986	322,392	333,384	305,757

Both RSMs (METRIC and SSEBop) are thermally based. METRIC computes all components of the surface energy balance (net radiation (Rn), soil heat flux (G), sensible heat flux (H), and latent heat flux (LE)) using weather data, spectral reflectance imagery, and thermal imagery. SSEBop is a simplified partial energy balance model that only solves for LE and assumes fixed surface albedo and aerodynamic resistance terms over a dry-bare ground, computing ET from weather data and thermal imagery alone. Both thermal-based ET models estimate actual ET, reflecting crop consumptive use from available water sources (precipitation and irrigation). Water supply availability is captured in the estimates, unlike potential ET (ET_p) calculated by most crop coefficient methods.

Accuracy of the RSMs is dependent on several variables, and can be affected by environmental conditions, weather data used by the models, model calibration, and operator expertise. METRIC ET results have been compared to weighing lysimeter measurements and shown to produce similar results (Tasumi et al, 2005; Allen et al, 2007). Likewise, SSEBop results have been shown to compare favorably to lysimeter and eddy covariance data sets (Gowda et al, 2009; Senay et al., 2013, 2016; Velpuri et al, 2013). According to Allen et al. (2011), the typical uncertainty of thermal-based remote sensing models is 10 to 20 percent both monthly, and seasonally.

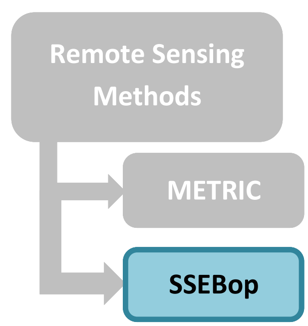
The thermal image pixels, which are 100m x 100m for Landsat 8 and 60m x 60m for Landsat 7, are resampled and provided at a 30m x 30m pixel size. This can create additional uncertainty in field-scale ET estimates for pixels falling along the boundary of areas evaporating and/or transpiring at different rates. When looking at large areas containing thousands of acres of tightly packed irrigated agricultural fields, these errors tend to cancel-out one another; but border pixels of agricultural fields adjacent to unirrigated lands can experience significant reductions in estimated ET_a.

2.2.1 METRIC Remote Sensing Method



The METRIC ET model was developed at the University of Idaho (Allen et al. 2007 a, b; 2011) and is one of the most widely used ET models. The model utilizes satellite image data acquired in the visible through shortwave infrared and thermal infrared portions of the electromagnetic spectrum to compute all four components of the energy balance for every pixel in the image. The classical form of METRIC is calibrated using weather data from a nearby weather station such that hourly ET for a selected vigorous, full canopy agricultural field equals some multiple of hourly alfalfa reference ET (ET_r; usually 1.05) calculated from weather station data. In the EEFlux and eeMETRIC versions of METRIC that operate on the Google Earth Engine, gridded NLDAS weather data are used during calibration and an ET_rF (fraction of hourly alfalfa reference ET) of 1.0 is assigned during an image-wide blocked search for calibration end points. The ET_rF image is generated by dividing the calculated hourly ET by the hourly reference ET at the time of satellite overpass, and then these ET_rF values are multiplied by daily ET_r to generate daily ET_a estimates. The METRIC technical report for Phase 3 efforts is included in Appendix A and provides more detailed information on the process, calibration efforts, and ET results.

2.2.2 SSEBop Remote Sensing Method



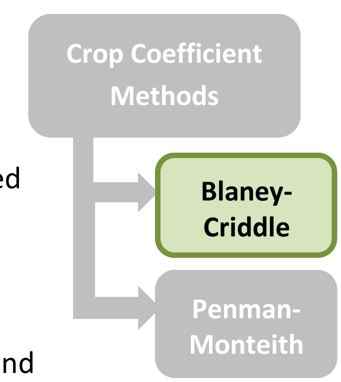
The SSEBop ET model was developed by the United States Geological Survey (USGS) (Senay et al. 2013, 2016, 2017). It is an operational parameterization of the Simplified Surface Energy Balance (SSEB) model (Senay et al., 2007). Unlike METRIC, it is a partial energy balance model that only solves for the latent heat flux component at a daily time scale using a Satellite Psychrometric Approach (Senay, 2018). The SSEBop model estimates ET fraction (ETf – synonymous with ET_rF) as a linear function of a pixel's temperature (dry bulb) between two extremes; the land surface temperature (LST) of a well-watered, vigorous agricultural field (wet bulb); and a bare field (dry limit) producing zero ET. The wet bulb temperature is estimated as a fraction (known as the c-factor) of a gridded daily maximum air temperature (Tmax) dataset. The difference in temperature between the wet bulb and dry limit conditions is pre-calculated daily for every 1 km^2 in the contiguous United States assuming a gray-sky condition for net radiation and weather variables (Senay et al., 2021). Daily actual ET is then calculated as the product of ETf and daily reference ET. In 2020 the SSEBop model was run using the Google Earth Engine cloud computing platform, which was a change from the previous years' analyses. The SSEBop technical report for 2020 is included in Appendix B and provides detailed information on the process used in 2020.

In 2017, the SSEBop and METRIC teams were directed to use the same Landsat satellite images for their analyses. In 2018, 2019, and 2020, the teams were allowed the flexibility to choose the images used based on their expertise and judgment. Cloud masks used by both teams came from the QA band of the Landsat images; however, the METRIC team expanded the cloud masks using spatial filtering methods. Total monthly ET_a from both RSMs was calculated for each UCRB irrigated acreage polygon using ArcGIS. To allow direct comparison to the CCMs, the UCRB irrigated acreage polygons were split at Gridded Surface Meteorological dataset (gridMET) grid cell boundaries. GridMET provides daily gridded weather data (temperature, wind, humidity, and radiation) at an approximate 4 km resolution.

2.3 Crop Coefficient Methods

Two crop coefficient methods were employed for Phase 3 to estimate potential consumptive use of crops: Penman-Monteith and Modified Blaney-Criddle with an elevation adjustment. ET from crop coefficient methods represent potential crop ET, i.e., the maximum amount of water the crops could use if they had a full supply from a combination of precipitation and irrigation.

2.3.1 Modified Blaney-Criddle Potential ET

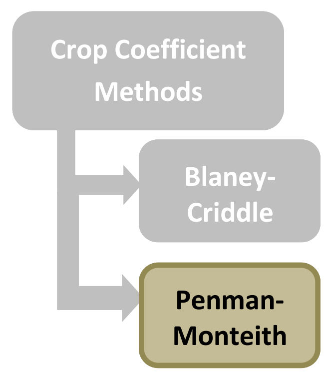


Modified Blaney-Criddle is calculated on a monthly time step and requires only monthly average air temperature and daylight hours to determine ET_p. Because of the minimal data requirements, data availability often dictates the use of Modified Blaney-Criddle. Modified Blaney-Criddle, as outlined in SCS Technical Release 21 (USDA, 1967) (TR-21), has been widely used around the world; despite studies showing it is less accurate than some other methods and tends to underestimate reference ET in arid climates (ASCE Manual 70, 1990 and 2016).

A standard elevation adjustment was applied to the Modified Blaney-Criddle results to better represent climate conditions at higher elevations (Pochop et al., 1983). When implementing an elevation adjustment, ET_p is increased by 10 percent for every 1,000 meters in elevation above sea level or above the location where the crop coefficients for the specific crop were developed. Without additional information, the crop coefficients used in this study were assumed to be developed near sea level. Currently, Reclamation calculates consumptive use for the CU&L Reports using Modified Blaney-Criddle without an elevation adjustment.

The methodology for calculating Modified Blaney-Criddle for Phase 3 is outlined in SCS Technical Release 21. As noted above, a standard elevation adjustment was applied to the resulting ET_p. GridMET weather data were used in the calculations, and results were provided on a 1/24-degree (approximately 4 km) grid cell basis. Crop-specific ET depths were calculated for each grid cell and multiplied by the associated crop acreage within each cell to generate ET volumes. Growing season start and stop dates were determined by Reclamation's XCONS model using cumulative growing degree days and temperature-dependent planting or days to full cover estimates. This process is described in more detail in Appendix C. UCRB irrigated acreage polygons were split at gridMET grid cell boundaries to allow for accurate calculation of crop acreages within each grid cell. This facilitated comparison of results to those produced by Penman-Monteith and the RSMs.

2.3.2 Penman-Monteith Potential ET



The ASCE Standardized Penman-Monteith equation (ASCE Manual 70, 2016) combines energy balance and aerodynamic equations to calculate reference ET on an hourly or daily basis. Solar radiation, wind speed, and saturation vapor pressure deficit, in addition to air temperature data, are required by the Penman-Monteith equation. A simplified Penman-Monteith approach without a variable stomatal resistance is widely used and is the preferred standard method for calculating reference ET, as documented in ASCE Manual 70, as it is a physically based method that has been compared to lysimeters and EC Towers and shown to outperform other estimates of reference ET. Crop coefficient curves are applied to Penman-Monteith reference ET to calculate potential ET. As with Modified Blaney-Criddle crop coefficient curves, the crop coefficient curves used with the Penman-Monteith method were developed outside of the UCRB.

The ET Demands software was used to calculate Penman-Monteith reference ET values, as described in Appendix D. GridMET weather data were used in the calculations and results were provided on a 4 km grid cell basis. The FAO-56 (Allen et al., 2005) dual crop coefficient method was used to calculate crop specific potential ET from reference ET. Growing season start and stop dates were determined using cumulative growing degree days and temperature dependent planting or days to full cover estimates. As with the Modified Blaney-Criddle method, crop-specific ET depths were calculated for each grid cell and multiplied by the associated crop acreage within each cell to generate ET volumes. This aggregation of results by grid cell allowed for comparison of ET results between both crop coefficient methods and both RSMs on a 4 km spatial scale.

2.3.3 Effective Precipitation Estimates for Crop Coefficient Methods

Effective precipitation in this report was calculated using the SCS method outlined in TR-21, consistent with the approach used by Reclamation to determine CU_{irr} for the Consumptive Uses and Losses Report. As outlined in TR-21, and shown in equation 1, monthly effective precipitation (Peff) is estimated based on derived relationships between rainfall (R_t) and potential ET (ET). Total monthly rainfall was obtained from gridMET, and results were provided on the same 4 km grid cell basis as monthly ET_p. For the Modified Blaney-Criddle estimates, effective precipitation was calculated using ET_p values from the corresponding Modified Blaney-Criddle calculation (either with or without elevation adjustment). Likewise, for the Penman-Monteith model, effective precipitation was calculated using the Penman-Monteith estimated ET_p. Note that the OpenET comparison in Appendix G utilizes a different effective precipitation method, as documented in Appendix G.

$$\begin{aligned} Peff &= (0.7091 * R_t^{\,0.82416} - 0.11556) * (10^{(0.02426*ET)}) * F \\ F &= 0.531747 + 0.295164D - 0.057697D^2 + 0.003804D^3 \end{aligned} \qquad \text{Eq. 1}$$

The RSMs determine ET_a occurring from a mixture of both irrigation and precipitation. Therefore, to determine ET only from irrigation sources (CU_{irr}), as required for the CU&L Report and for basin-wide comparisons to CCM results, effective precipitation was removed from the RSM results. Effective precipitation for the RSMs was determined using the SCS method to be consistent and facilitate comparisons to the CCMs. Because ET_p is not determined by METRIC and SSEBop, but required for the SCS method, the decision was made to calculate effective precipitation for the RSMs using Penman-Monteith $ET_{p,}$ rather than using Modified Blaney-Criddle ET_p. As discussed above, Penman-Monteith is a physically based method that has compared well to lysimeter and EC Tower estimates; therefore, is more appropriate to use as the basis for effective precipitation estimates for RSM.

The CUWG continues to look at alternative options for estimating effective precipitation and may use a different method in future analyses. Appendix I provides a comparison memo on the different methods that could be used to determine effective precipitation in the UCRB.

2.3.4 Indicator Gage Method Applied to Crop Coefficient Methods

To allow a direct comparison with remote sensing estimates, the ET_p from the crop coefficient methods was reduced to account for estimated shortages in irrigation supply (supply limitations). The Reclamation Indicator Gage Method, documented in the Phase 1 report and in more detail in Appendix E, was used to determine supply limitations that occurred in Wyoming, Colorado, and Utah during 2020 consistent with the CU&L Report. New Mexico provides an estimate of shortages to Reclamation for the CU&L Report and typically assumes lands irrigated from the San Juan and Animas Rivers receive a full supply. New Mexico uses an Indicator Gage Method similar to Reclamation's method to estimate shortages for about 2,500 irrigated acres along the La Plata River. New Mexico provided an estimate of 65 percent shortage in 2020 that was applied to the La Plata basin acreage.

The Indicator Gage Method was developed by Reclamation in the 1960s. Acreage was identified as "shorted" if it did not receive enough irrigation water to supply the crop's irrigation water demand in any year during the study period. Shorted lands were associated with indicator stream gages and a flow threshold was determined for each gage. When the flow at the assigned stream gage drops below the threshold, the corresponding lands are assumed to no longer receive an irrigation supply. The assignment of lands to gages was made at a watershed level (approximately the scale of the USGS Hydrologic Unit Code 8 level). Note that the watersheds were split at state lines as can be seen in the maps provided in Appendix E.

There are two tiers of flow-based shortages in each watershed: one for alfalfa and one for grass pasture. When the streamflow threshold occurs, the percentage of shorted lands associated with the gage are assumed to no longer receive an irrigation supply for the remainder of the growing season, and consumptive water use is assumed to cease on that date. Alfalfa and pasture grass have different streamflow triggers in each watershed and the percent of the total acreage assigned as shorted varies in each watershed. In some areas, alfalfa and/or grass pasture acreage is assumed to always receive a full supply and crop irrigation requirements are always met. Crops other than alfalfa and pasture grass are assumed to receive a full supply for the entire irrigation season. The 2020 irrigated crop map indicated that alfalfa accounted for 24 percent of the total crops in the UCRB, grass pasture accounted for 67 percent, and other crops accounted for 9 percent.

Reclamation staff performed a detailed review of the shortage criteria used from 1971 to present in the Indicator Gage Method, as provided in Appendix E. The review showed that the shortage criteria for Colorado, Utah, and Wyoming has changed since 1971. Reclamation staff were unable to definitively determine whether the shortage criteria were purposefully adjusted or erroneously adjusted over time in the series of spreadsheets used by Reclamation to apply the Indicator Gage Method. Reclamation's review identified unusually low shortage percentages currently used for Colorado (typically 0 percent shortage for alfalfa and 5 percent shortage for grass pasture), compared to both shortage percentages applied to Utah and Wyoming and to shortage estimated by the state of Colorado. Figures in Appendix E show the series of shortage percentages used by Reclamation. Regardless of these identified issues, the current lack of detailed and standardized water supply information for all irrigated lands in the UCRB necessitates the use of a standardized method, such as the Indicator Gage Method, to allow a consistent method to be applied throughout the UCRB in the CU&L Reports. Therefore, the current Indicator Gage Method is implemented for the Section 4 comparisons.

As part of the 2019 analysis, the Indicator Gage Method was re-applied to Penman-Monteith and Modified Blaney-Criddle estimates in Colorado for 2017, 2018, and 2019 using the original 1971 shortage percentages identified in Appendix E. The original shortage percentages first used in 1971 were considerably larger than the shortage percentages currently being used in the Indicator Gage Method for CU&L estimations. To understand how the change in shortage affects Colorado's consumptive use values, the total amount of consumptive use shortage was compared for the growing season in 2018, a hydrologically dry year, and 2019, a hydrologically wet year. Table 3 shows total growing season consumptive use shortages, by state, determined by applying the Indicator Gage Method current shortage percentages and the original 1971 shortage percentages for Colorado to CU_{irr} estimated using Penman-Monteith.

Table 3. Growing season shortages by state for Penman Monteith using the current Indicator Gage Method percent of shorted lands in Colorado, Utah and Wyoming and the 1971 Indicator Gage Method percent of shorted lands in Colorado.

State	2019		2018	
	Current Percent Shortages	1971 Percent Shortages*	Current Percent Shortages	1971 Percent Shortages*
Colorado	1%	10%	2%	15%
New Mexico	2%	NA	4%	NA
Utah	16%	NA	22%	NA
Wyoming	14%	NA	20%	NA
Basin-wide	7%	12%	10%	17%

*Note that 1971 shortage percentages were only applied to Colorado

As shown in Table 3, Colorado's total growing season shortages are significantly greater when the 1971 estimated percentage of shorted lands is used. Colorado's total CU_{irr} for 2019 (calculated using Penman-Monteith) was reduced by roughly 160,000 acre-feet when the 1971 shortages were applied. However, even with the larger 1971 estimates, consumptive use shortages in Colorado are still less than shortages in Utah and Wyoming. In addition, the shortages shown in Table 3 for Colorado are significantly less than the state of Colorado's estimated shortages for 2018 and 2019. This likely indicates that even the higher percentage of the lands assigned as shorted in 1971 do not accurately reflect shortage conditions in Colorado. Nevertheless, the 1971 estimates of shorted acreage are believed to be a step in the right direction for Colorado. The 1971 estimates of shorted acreage for Colorado are applied to the CCM estimates in this report and were applied in the 2019 report.

The comparisons in this report provide the opportunity to understand the limitations of the current shortage method, investigate other options for estimating crop consumptive use shortages in the UCRB, and provide information to support conducting additional investigations to verify the Indicator Gage Method in each of the states.

3.0 Consumptive Use Comparison Approach

Three different comparisons of the methods were considered:

1. **Actual ET Comparisons at the Eddy Covariance Tower**. As discussed, the EC Tower directly measures combined ET_a from irrigation, precipitation, and stored soil water sources. The two RSMs also estimate combined ET_a from irrigation, precipitation, and stored soil water sources; therefore, these were compared to the EC Towers directly at daily, monthly, and growing season time intervals. The CCMs were compared to the EC Towers at monthly and growing season time intervals, after accounting for site specific estimated supply limitations if needed.

2. **Basin-wide Crop Consumptive Use from Irrigation Comparisons**. Basin-wide and state-wide CU_{irr} estimates were made on a monthly and growing season time interval, similar to the format used in the CU&L Report. The RSMs directly estimate combined ET_a from both irrigation and precipitation; therefore, ET_a from the RSMs was reduced by effective precipitation to estimate CU_{irr}. ET_p estimates from the CCMs were calculated for the estimated growing season, defined by temperature-driven, crop specific start and end dates, then reduced by effective precipitation and limitations in irrigation supply based on the Indicator Gage Method. For comparison purposes, CU_{irr} from each of the methods was only considered from April 1 to October 31, even though there were several instances when growing season start and end dates calculated by the CCMs fell outside that period. RSMs show ET almost year round, therefore it was decided to only compare the models between April 1 and October 31st. Very little CU_{irr} in the UCRB occurs outside of the April 1 to October 31 period.

3. **Comparisons of CCM Estimates of Crop Consumptive Use from Irrigation.** The CU_{irr} results for the CCMs were compared to better understand differences between the current method used for the CU&L Report (Modified Blaney-Criddle without an elevation adjustment), and the two methods investigated during Phase 3 (Modified Blaney-Criddle with an elevation adjustment, and Penman-Monteith). The comparison considered the differences in estimated CU_{irr} basin-wide and grouped by elevation.

Figure 4 shows the approach that was taken to post-process each dataset for the final comparisons.

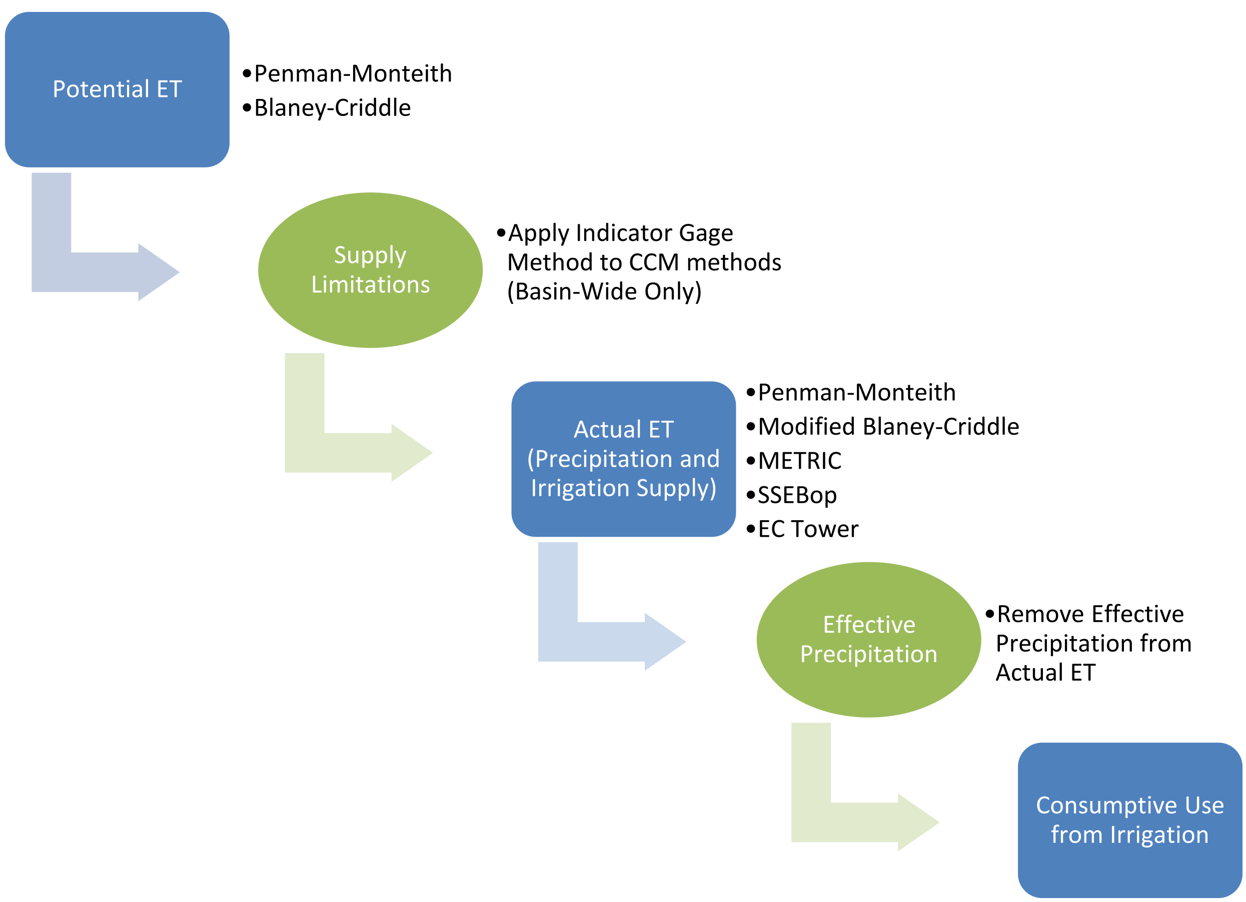


Figure 4. Approach used to determine Potential ET, Actual ET, and Irrigation Consumptive Use for each method

This approach varies from the typical approach used with CCM methods where ET_p is usually reduced by effective precipitation before supply limitations are considered, either based on a measured supply or the Indicator Gage Method. However, to compare ET_a from the CCMs to that from the RSMs, CCM ET_p results first had to be reduced to reflect irrigation supply limitations, as RSMs ET_a includes the effective precipitation supply. Because the Indicator Gage

Method simply "cuts off" the irrigation supplies independent of the irrigation demand, the results are not impacted by changing the typical order. As noted below, the Indicator Gage Method was only used in the basin-wide comparison of CU_{irr}, as site specific information including soil moisture sensors was used to estimate any supply limitations at the EC Towers.

3.1 Actual ET Comparison at Eddy Covariance Tower Approach

Accuracy of ET_a estimates from the RSMs was assessed by comparing the estimates to measured ET_a at the EC Towers. Note that the accuracy of the RSMs at the towers may not be an indication of accuracy in other areas of the UCRB; however, the four active tower sites in 2020 provide a range of validation assessments for different crop types, elevations, and weather conditions. ET_a from the EC Tower and RSMs was compared over daily, monthly, and growing season time intervals to understand and assess agreement for each time interval. ET_a from RSMs was determined for the area estimated to be within the EC Tower's daily fetch, then summed for the monthly and growing season comparison. As described in Appendix F, hourly fetch was determined from hourly fetch rasters. Daily fetch rasters were then developed from the hourly fetch rasters by first rescaling the hourly fetch rasters so that all cells sum to 1.0 and then weighting the rescaled fetch rasters by the proportion of its hourly ET_r to the total ET_r measured. The weighted and rescaled hourly fetch rasters were summed to generate a daily fetch raster.

In 2020, fetch rasters were not used for the Bloomfield EC Tower site due to the influence of non-irrigated lands just east of the tower. Instead, a 150-meter circular buffer around the tower was created and then clipped to the field boundary. That polygon was then moved 60 meters west of the tower to help mitigate the affects of the non-irrigated lands east of the tower. The average daily ET_a was extracted from each RSM using the developed shapefile at the Bloomfield tower.

ET_p estimates from the two CCMs were also compared to ET_a measured at the EC Tower on a monthly and growing season time interval. Although supply limitations were assigned to the CCMs based on the Indicator Gage Method for the state-wide and basin-wide comparisons, the Indicator Gage Method was not used to estimate shortage at the EC sites. Irrigator-supplied information indicated that the acreage around all four EC Towers received a full supply in 2020.

Daily EC Tower estimates were determined by computing hourly fluxes for Rn, G, H, and LE. All non-negative hourly fluxes were summed from 0100 hours through 2400 hours each day. Daily LE values were converted to daily ET in mm using latent heat of vaporization corrected for temperature. Ideally, the sum of the energy used in ET plus the sensible heat flux should balance the energy available to drive these processes (Rn - G). When the sum of the ET and sensible heat fluxes are lower than available energy, a question arises as to whether to adjust the sensible and latent heat flux values to force a balance.

There is no consensus at present in the micrometeorological community about the most appropriate action related to energy balance closure. Numerous scientists, notably Foken et al. (2012) and Leuning et al. (2012), argue that the original ET values are actually accurate as they are, and the perceived imbalance is an artifact of the other measurements not matching the same scales of time and space as ET. Others support the idea of adding the latent and the sensible heat fluxes, so that taken together they force the turbulence fluxes to match the available energy, often referred as "forced closure".

This of course, raises the ET values by an amount proportional to the lack of initial closure. The project scientists at Utah State University (USU) who collected and analyzed the eddy covariance data are cooperating with other micrometeorologists in the community to investigate this important issue further. Recently, Mauder et al. (2020), provided an up to date overview of the surface energy balance closure issue. They noted that some conclusions are now evident, such as there is no problem with the measurements of the sensors nor the approaches used to analyze the data. The main culprit appears to be small scale mesoscale flows that can exist at the sites. Some evidence suggests that sensible heat flux (H) is more affected than ET (LE), and that more should be added to H than LE. This implies the typical methods for forcing closure are over estimating ET. However, they conclude by noting the issue is not yet properly resolved.

For 2020, two sets of ET values were provided to the project; original values and larger values after closure was forced. The forced closure data set was used for the comparison at all EC Tower sites except the Big Piney, Wyoming site. Only the original values (unclosed) were used at Big Piney due to the nearly continuous flood irrigation and standing water at the site, which caused the soil heat flux measurements to be unreliable. More details on forced closure and hourly gap filling are provided in Appendix F.

The calculated growing seasons for crops using the CCMs at the four EC Tower sites were temperature driven, and do not correspond with the April 1 to October 31 date range used with the RSMs. Table 4 shows the temperature driven start and stop dates for each tower location in 2020 and the crop coefficient curves (Kc) used at each location. Descriptions of how start and stop dates are calculated can be found in Appendix C for Modified Blaney-Criddle and Appendix D for Penman-Monteith. Crop coefficient curves published in TR-21 were used for the Modified

Blaney-Criddle calculation. Alfalfa reference basal crop coefficient curves, outlined in Allen and Robinson, 2009 and Huntington et al., 2015, were used in the Penman-Monteith calculation. The grass hay curve used by Penman-Monteith was developed by Allen and Robinson, 2007 and is based on the Alfalfa reference ET and the AgriMet grass hay curve.

Table 4. Growing season start and stop dates and the crop type used for the crop coefficient curves for each EC Tower location and CCM for 2020

EC Tower	Crop Type Coefficient Curve	Penman-Monteith		Modified Blaney-Criddle with an Elevation Adjustment	
		Start Date	End Date	Start Date	End Date
Palisade, CO	Orchard with Cover	3/30	10/24	3/30	11/8
Bloomfield, NM	Alfalfa	3/21	11/9	4/7	12/6
Vernal, UT	Alfalfa	4/10	10/24	4/23	11/19
Big Piney, WY	Grass Hay	4/28	10/21	5/9	9/29

As shown, Big Piney and Vernal EC Tower sites had shorter growing seasons than the April 1 through October 31 period used at the EC Towers. The start and stop dates in Table 4 influence estimated ET over the growing season and can impact the direct comparison to EC Tower measurements as discussed in the results section below.

3.2 Basin-wide Crop Consumptive Use from Irrigation Comparison Approach

As discussed above, effective precipitation was subtracted from the CCM ET_p estimates for April 1 to October 31, and supply limitations were considered using the Indicator Gage Method to estimate CU_{irr}. As explained in section 2.3.4, a modified Indicator Gage Method was used for 2020, in which the original 1971 percentage of shorted lands was used for Colorado instead of the percentage of shorted lands currently used by Reclamation in the CU&L Report. The other states' percentages of shorted lands were not affected. Effective precipitation was subtracted from the RSMs ET_a estimates to provide CU_{irr}, allowing a consistent basis of comparison across methods. CU_{irr} was also compared basin-wide at monthly and growing season time steps.

3.3 Comparison of Crop Consumptive Use from Irrigation for CCMs by Elevation Approach

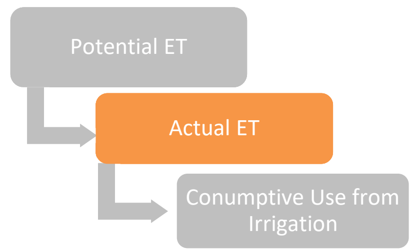
As noted above, the CU_{irr} estimated for the annual CU&L Report is currently calculated using the Modified Blaney-Criddle method without an elevation adjustment to estimate ET_p, removing effective precipitation based on the SCS method, and accounting for supply limitations using the Indicator Gage Method. This approach was compared to the two CCMs used in Phase 3 to understand how CU_{irr} could change with the application of an elevation adjustment to Modified Blaney-Criddle and with the Penman-Monteith method. Monthly total CU_{irr} was summed for all three methods into defined elevation "bands" (for example between

4,000 and 5,000 feet above mean sea level), based on the location of irrigated acreage polygons. This provides an opportunity to understand CU_{irr} at different elevations across the upper basin.

4.0 Consumptive Use Comparison Results

The following summarizes the results of the consumptive use comparisons.

4.1 Actual ET Comparison at the Eddy Covariance Towers



ET_a was measured at the four EC Towers and compared to daily METRIC and SSEBop estimates. Both the CCMs and RSMs were compared to the four EC Towers estimates on a monthly and growing season basis.

4.1.1. Daily ET_a Comparison – EC Tower to Remote Sensing Methods

The METRIC and SSEBop models produce ET_rF images for each successful image acquisition, which when multiplied by daily ET_r, produce daily ET_a images. Although images with extensive cloud cover over agricultural lands could not be processed, images with partial cloud cover were processed. Areas of a given ET_rF image that were obscured by clouds or cloud shadow were filled in using linear temporal interpolation from the most recent previously and subsequently acquired images with valid ET_rF data. The regularly spaced, wedge-shaped data gaps occurring in Landsat 7 imagery were filled differently by the two RSMs. SSEBop used the same temporal linear interpolation algorithm used to fill cloud-covered areas, while METRIC interpolated spatially using the ‘natural neighbor’ interpolation algorithm within ArcGIS which uses ET_rF values and patterns adjacent to the data gaps – without data from other ET_rF images.

Daily ET_a images from the RSMs were developed for every day of each month by temporally interpolating ET_rF values between successful image acquisitions and multiplying the results by the daily ET_r grids. Values from the resultant images generated the image-based (i.e., METRIC and SSEBop) ET_a data that were compared to the daily eddy covariance ET data.

The ET_a data derived from actual satellite imagery were expected to correlate more strongly with ET_a data from the EC Tower compared to ET_a data derived from interpolated ET_rF data between successful image acquisitions; therefore, these datasets are presented separately below. Figures 5 through 8 show the Palisade, Bloomfield, Vernal, and Big Piney EC Tower ET_a data plotted against METRIC and SSEBop ET_a data for image acquisition dates only. Images that had cloud cover issues or had a significant portion of the fetch raster contained within the

Landsat 7 data gap were excluded from this analysis. The linear regression equations (with regression lines forced through the origin) and the coefficients of determination are shown on each graph. A perfect comparison would result in the regression equation y=1.0x and the coefficient of determination (R^2) equal to 1. The number of data points (n) are also shown.

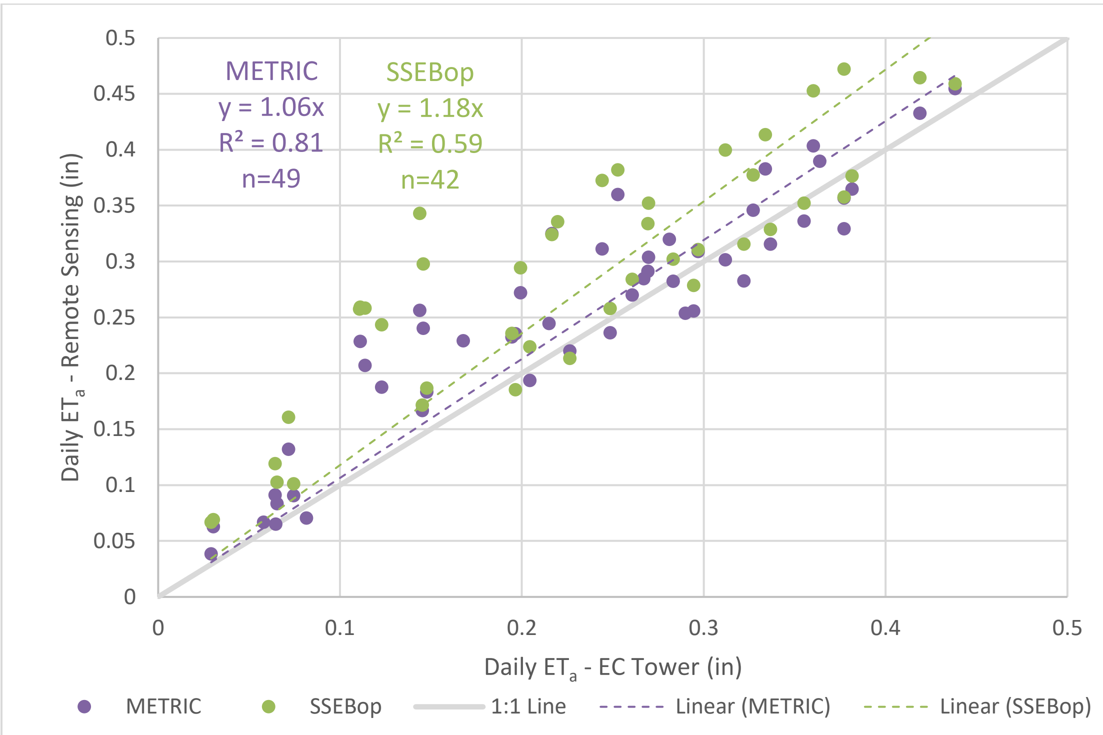


Figure 5. RSMs and Palisade, CO EC Tower Forced Daily ET_a for Days of Image Acquisition

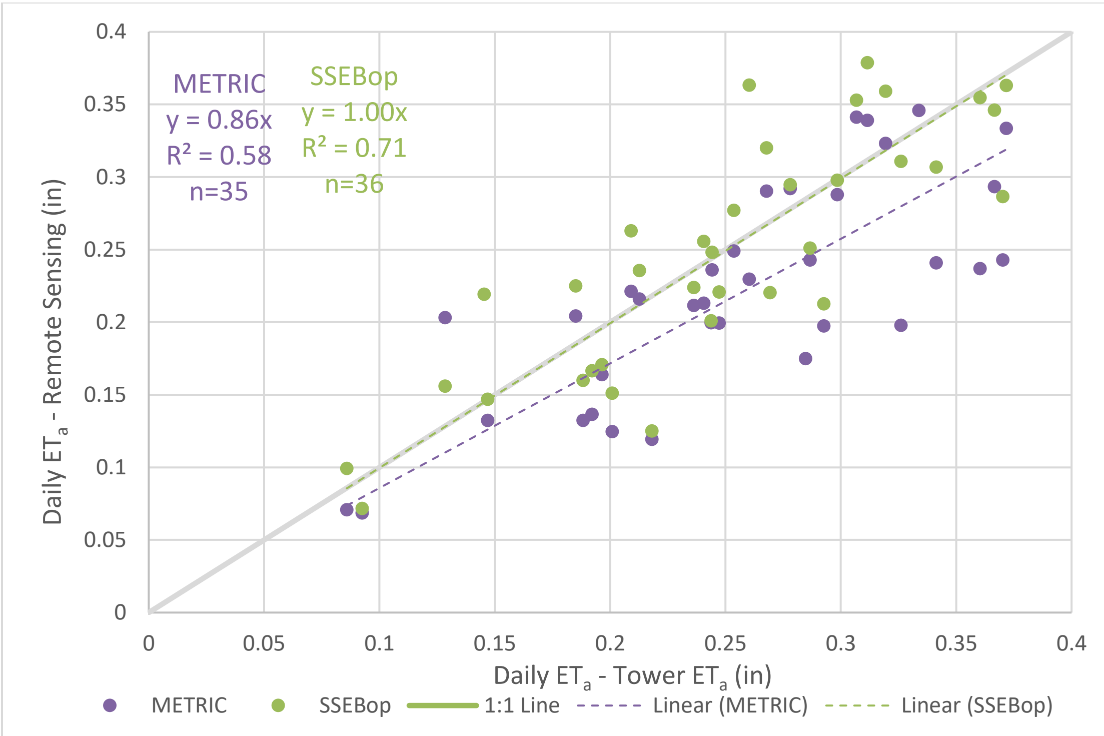


Figure 6. RSMs and Bloomfield, NM EC Tower Forced Daily ET_a for Days of Image Acquisition

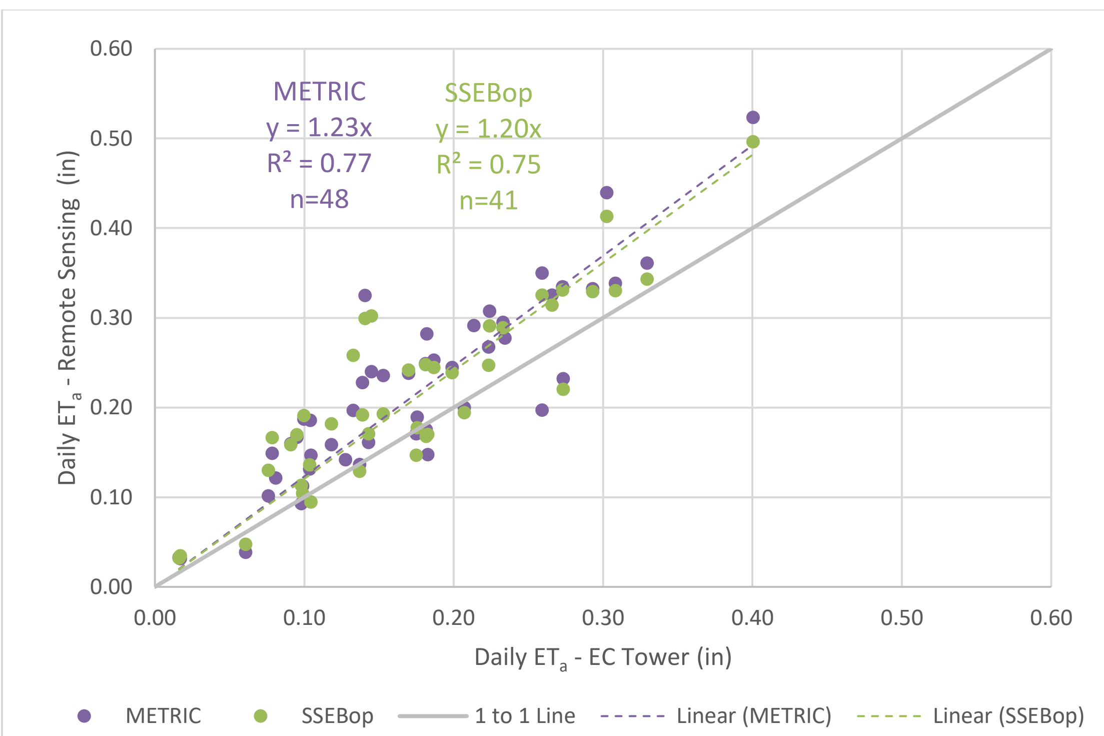


Figure 7. RSMs and Vernal, UT EC Tower Forced Daily ET_a for Days of Image Acquisition

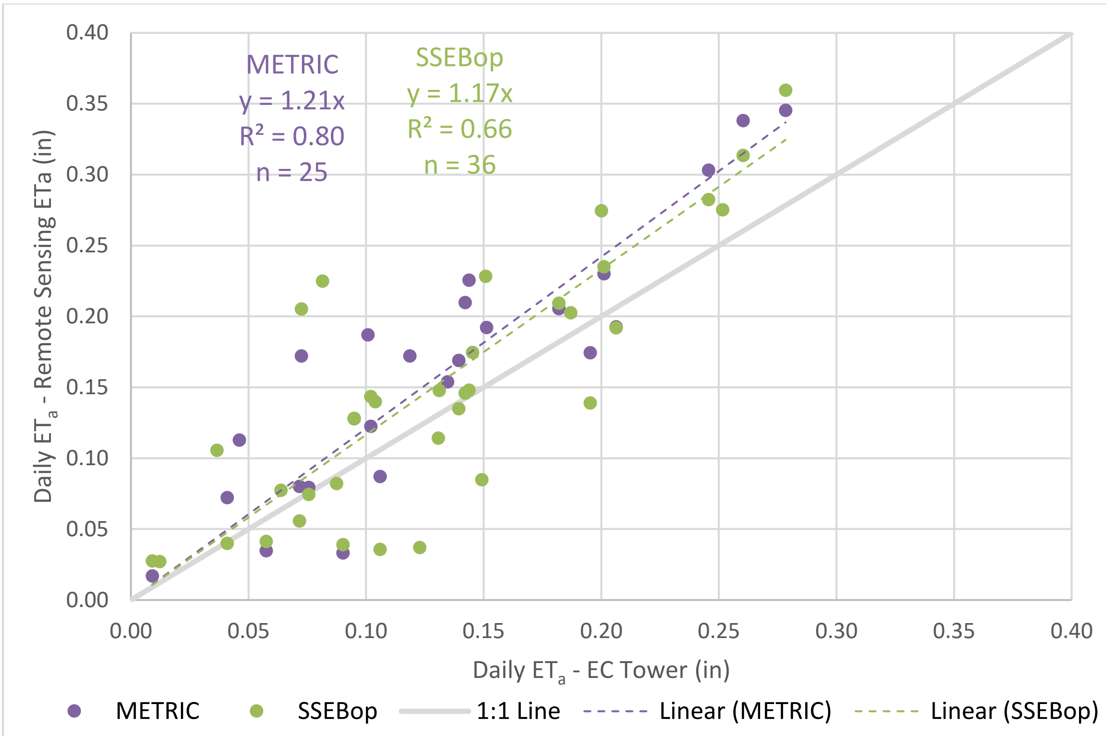


Figure 8. RSMs and Big Piney, WY EC Tower Unforced Daily ET_a for Days of Image Acquisition

Each of the four EC Towers are in overlap zones between adjacent Landsat paths. The Vernal and Palisade sites are located towards the center of the UCRB, while the Big Piney and Bloomfield sites are located closer to the periphery of the UCRB. SSEBop processed and used the overlapping Landsat paths at all four tower locations. METRIC processed and used the overlapping Landsat paths at the Bloomfield, Vernal and Palisade tower sites, but only processed and used one Landsat path for the Big Piney tower site; therefore, at that site there are eleven more data points for SSEBop as for METRIC in Figures 8. Note that allowing the models to select which Landsat images to process is potentially causing differences between the models.

The following observations can be made based on Figures 5 through 8.

- METRIC and SSEBop tended to overestimate ET_a at the Palisade, Vernal, and Big Piney, with the note that the Big Piney site used unclosed data so that the EC estimates for ET at Big Piney might be understated by some unknown amount.
- METRIC had the lowest correlation at the Bloomfield tower, while SSEBop had the lowest correlation at the Palisade tower.
- Ratios of METRIC ET_a to measured ET_a ranged from 0.87 to 1.23 and R^2 ranged from 0.57 to 0.81 across the four sites.

- Ratios of SSEBop ET_a to measured ET_a ranged from 1.01 to 1.20 and R^2 ranged from 0.59 to 0.75 across the four sites.

Datasets including overpass days and data interpolated between image acquisition dates are presented in Figures 9 through 12. METRIC and SSEBop use different processes to perform the temporal daily interpolation of ET_rF values between image acquisition dates. The SSEBop temporal interpolation was performed using all available ET_rF data at each pixel, regardless of Landsat path. Consequently, only one interpolated ET_rF (and subsequent ET_a) image was created for each day. These data are plotted in Figures 9 through 12. METRIC ET_rF temporal interpolation was done exclusively using images from the same Landsat path. Therefore, for the Palisade, Bloomfield, and Vernal EC sites which were covered by two Landsat paths of METRIC ET_a data (Figures 9, 10, and 11, respectively), the two METRIC values for each day of the growing season were averaged to generate the plotted value, except for image acquisition dates when the value from the image acquired that day was plotted.

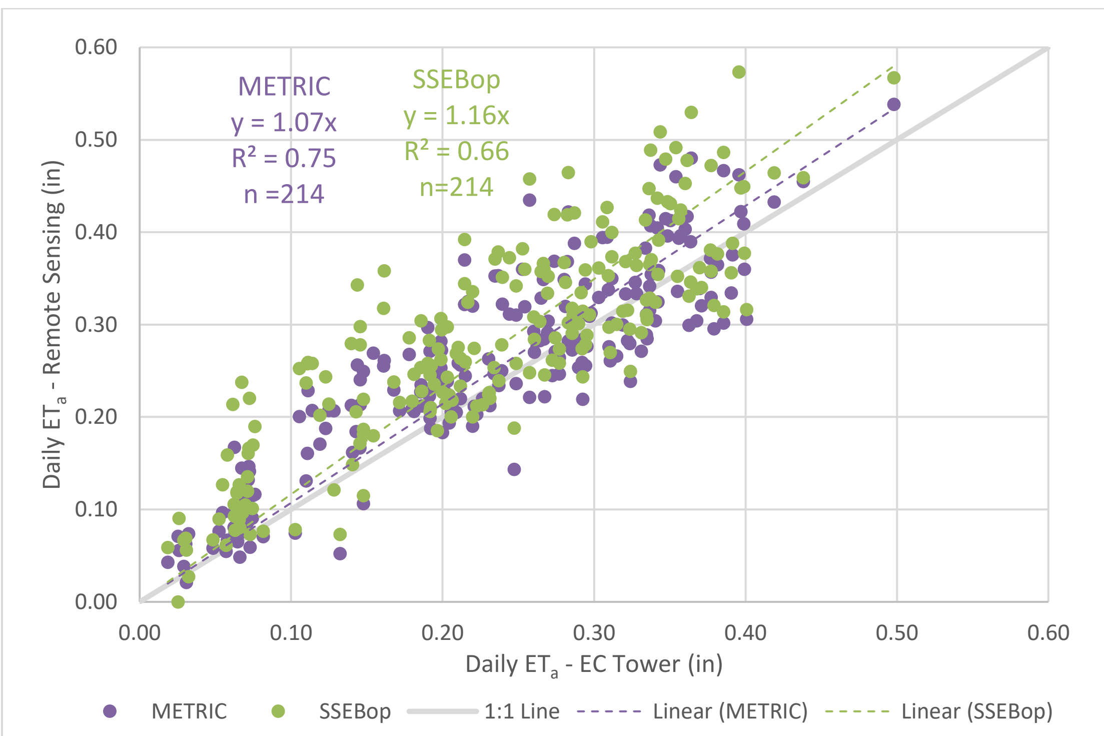


Figure 9. RSMs and Palisade, CO EC Tower forced Daily ET_a Comparison using all data

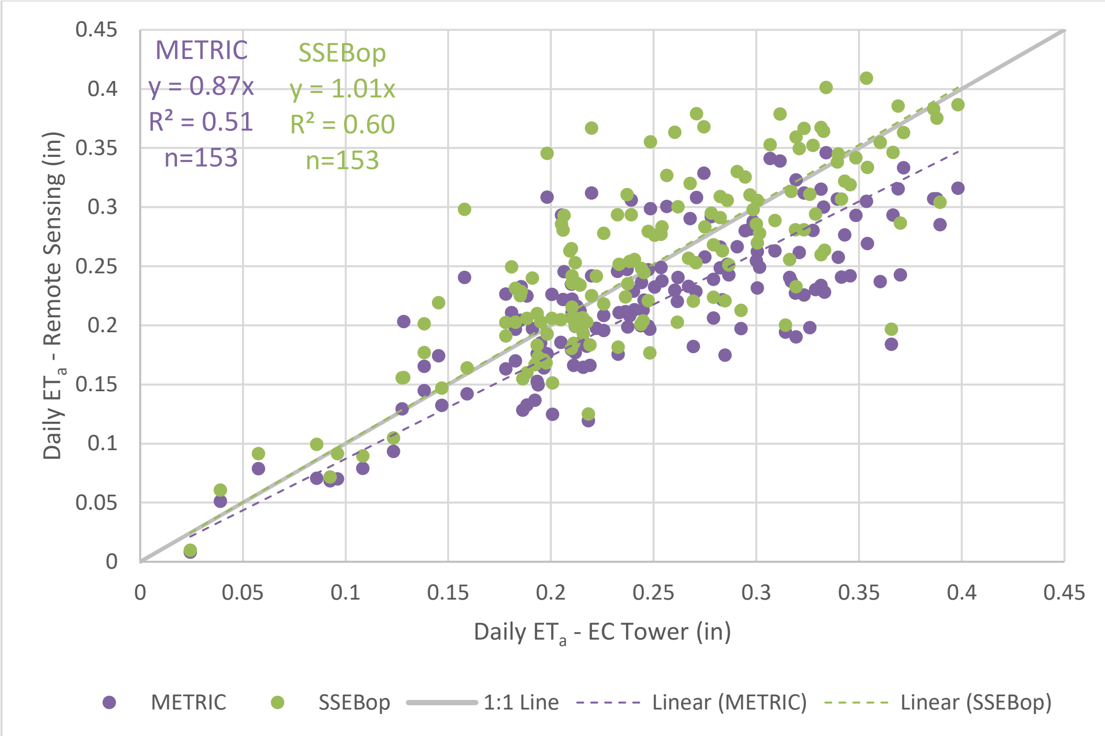


Figure 10. RSMs and Bloomfield, NM EC Tower forced Daily ET_a Comparison using all data

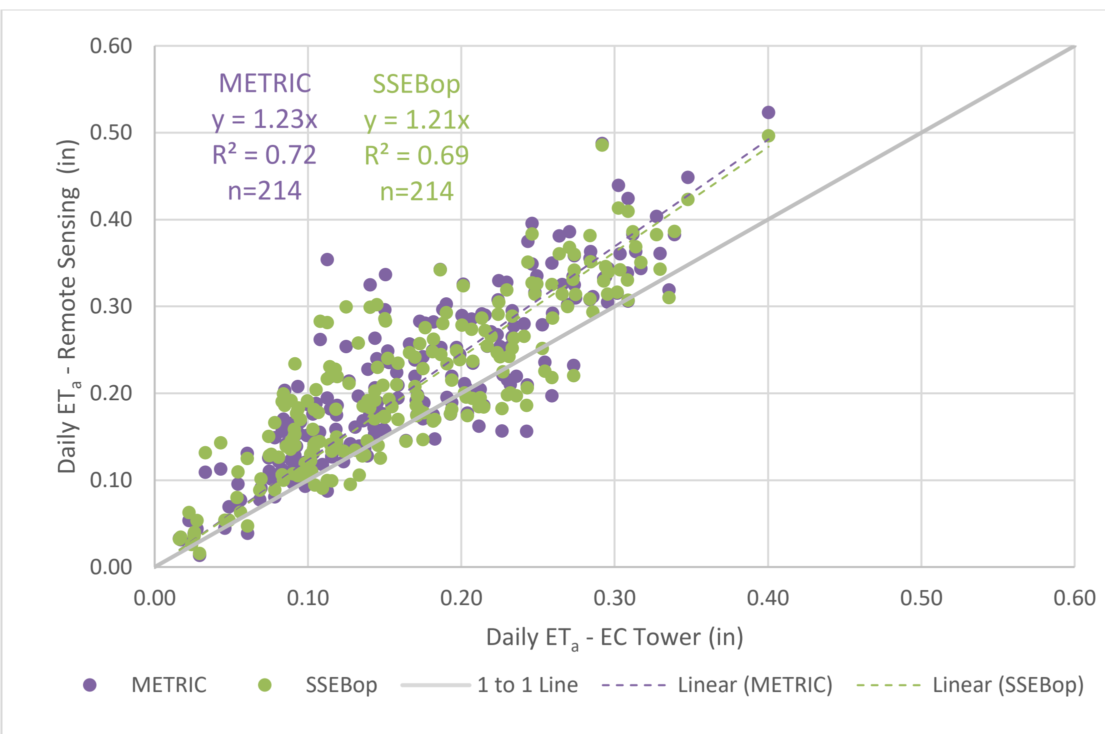


Figure 11. RSMs and Vernal, UT EC Tower Daily forced ET_a Comparison using all data

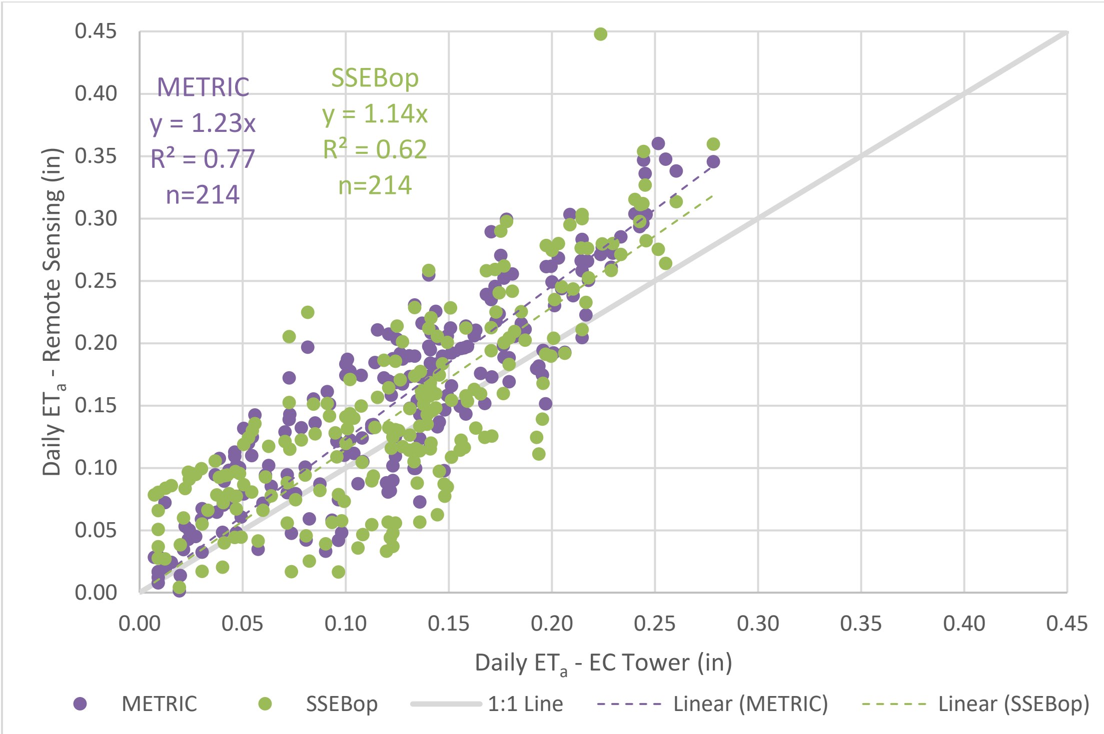


Figure 12. RSMs and Big Piney, WY EC Tower Unforced Daily ET$_a$ Comparison using all data

The following observations can be made based on Figures 9 through 12.

- The correlations between METRIC and SSEBop and the EC Tower decreased when all data was included, except for SSEBop at the Palisade EC Tower, where the R^2 increased.
- Both METRIC and SSEBop followed similar trends at all four EC Towers.
- SSEBop had close to an unbiased relationship with the Bloomfield EC Tower measurements (slope =1.01), however there was substantial scatter around the 1:1 line.

Figures 13 through 16 show daily ET$_a$ from the EC Tower, METRIC and SSEBop plotted as time series from April 1 to October 31, 2020 for each EC Tower site.

Precipitation and irrigation events can impact the EC Tower data and could be a source of discrepancy between the RSMs and the EC Tower data. Heavy precipitation events can produce inaccurate readings by the sonic anemometer that measures turbulent fluctuations on the EC Tower. Heavy irrigation events can affect the soil heat flux plate readings, which can affect the forced energy balance closure. Crop cutting events could have occurred between image acquisition days that would have been missed by the interpolation methods employed by the RSMs, causing a discrepancy in the RSM until the next image acquisition date. If a cutting occurred directly after an image acquisition day, this would cause the largest amount of error, due to the number of days before another image can be acquired. This will continue to be an issue in the future, especially on a basin-wide scale; however, reporting on a monthly and growing season basis may reduce the impact of this issue. Note that the timing of crop cuttings between image acquisition days was also a factor in the differences between the RSM and EC Towers in Figures 5 to 12.

Precipitation, irrigation events, and cuttings are included in Figures 13 through 16. The Big Piney EC Tower experienced near wetland conditions due to constant flood irrigation, therefore irrigation is not shown on Figure 16. Note that irrigation resulting in near wetland conditions when water is available is not uncommon on higher tributaries in the UCRB where supply is primarily available only during the period of runoff.

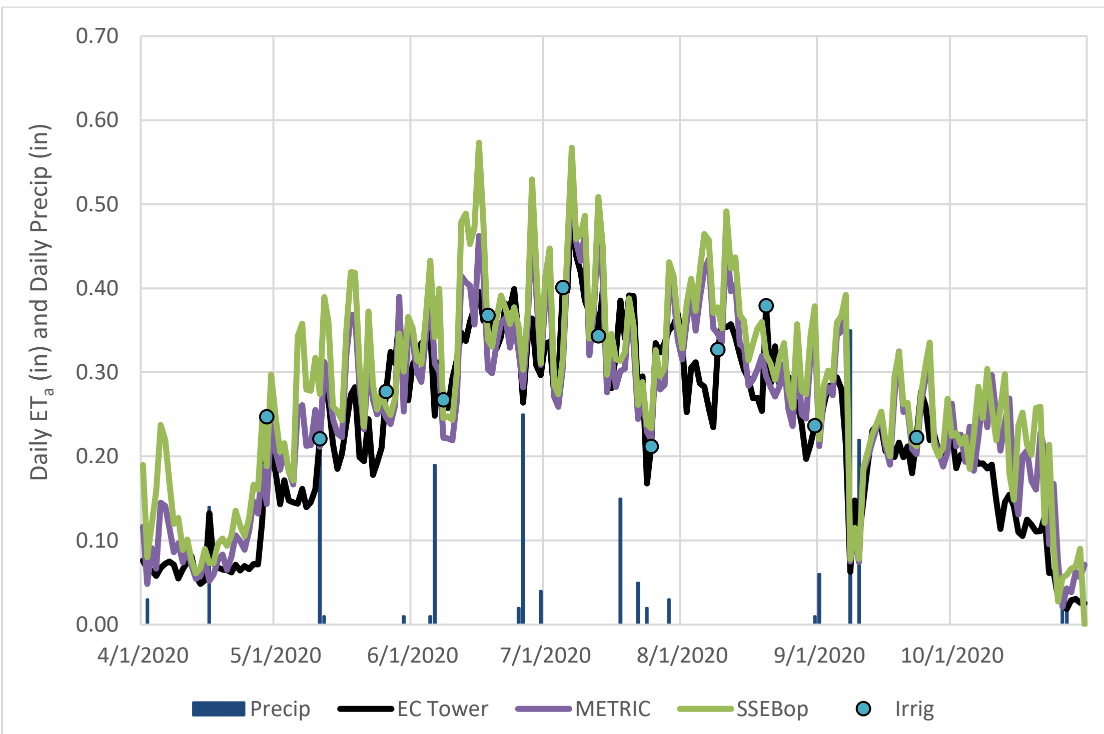


Figure 13. RSMs and Palisade, CO EC Tower Forced Daily ET$_a$ Comparison

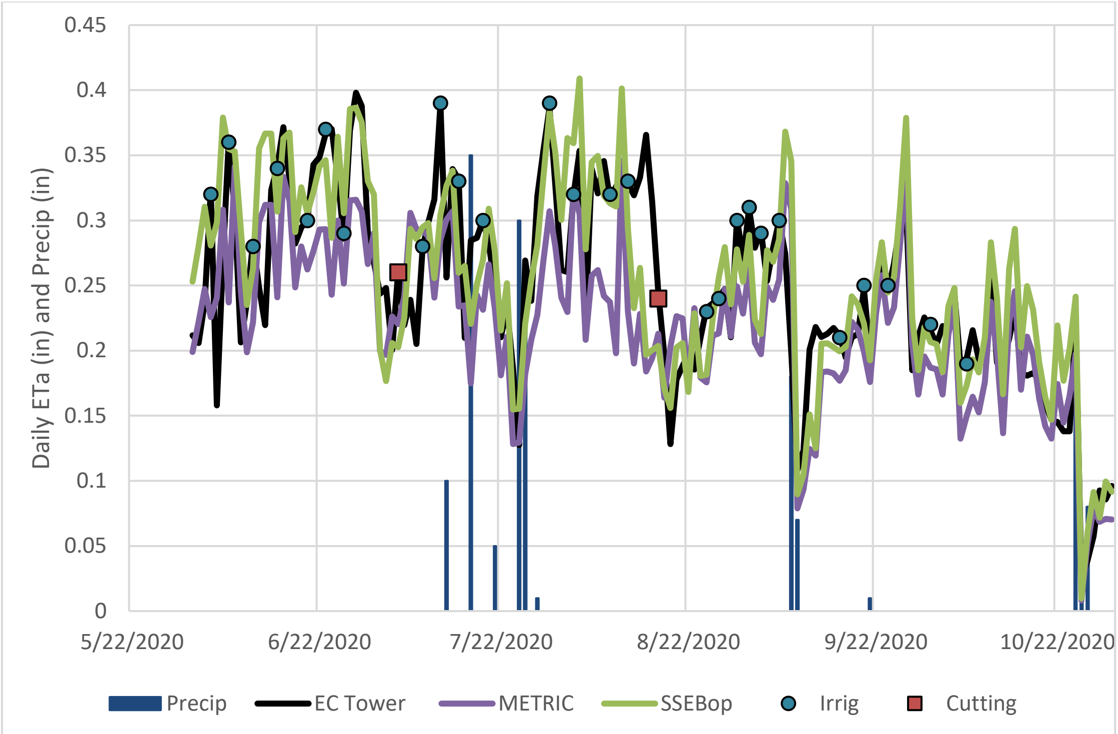


Figure 14. RSMs and Bloomfield, NM EC Tower Forced Daily ET_a Comparison

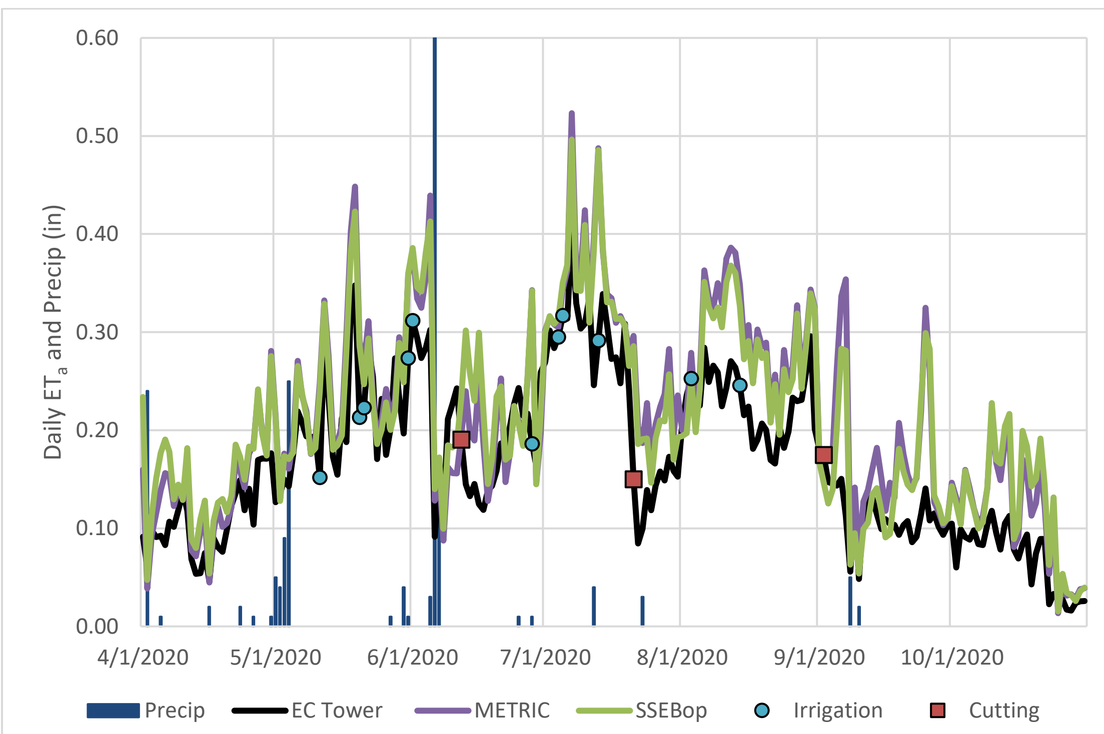


Figure 15. RSMs and Vernal, UT EC Tower Daily Forced ET_a Comparison

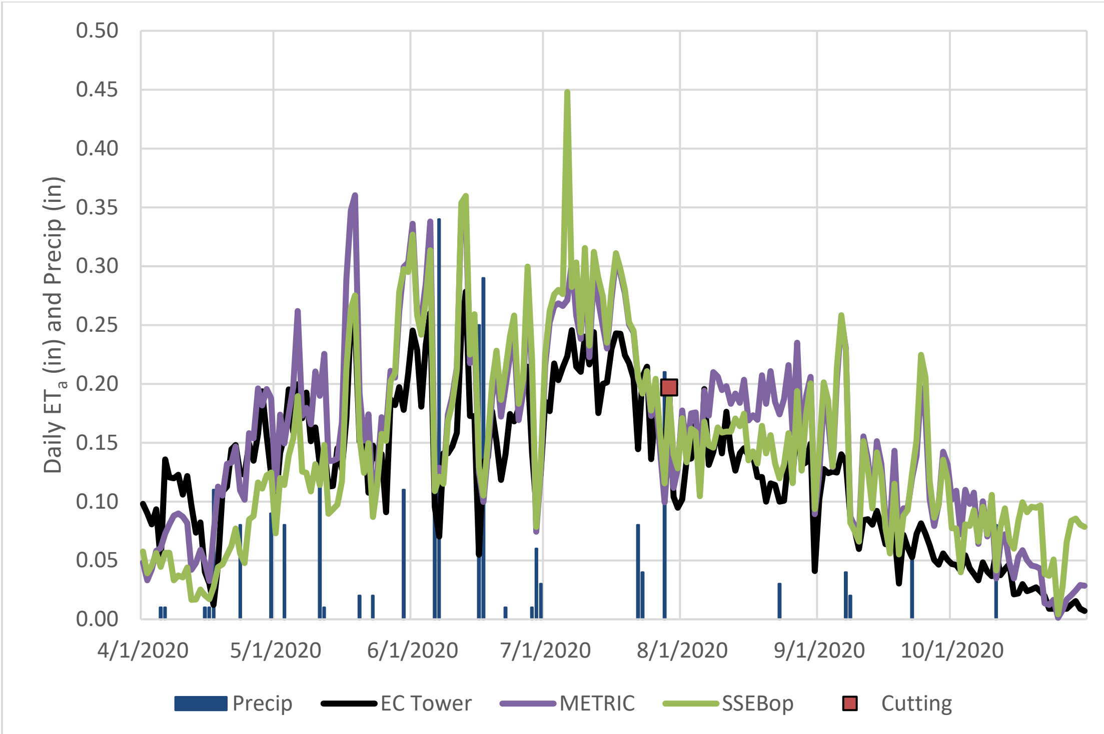


Figure 16. RSMs and Big Piney, WY EC Tower Unforced Daily ET_a Comparison

The following observations can be made based on Figures 13 through 16.

- SSEBop underestimated ET_a in the beginning of the growing season at the Big Piney EC Tower; both METRIC and SSEBop tended to overestimate ET_a at the end of the growing season at the Big Piney EC Tower.
- Both METRIC and SSEBop were not able to represent the initial drop in ET at the beginning of the growing season at the Bloomfield EC Tower.
- METRIC and SSEBop generally followed the trend of the daily ET_a at all four EC Towers.
- METRIC and SSEBop reflected the cuttings that occurred at the Palisade, Bloomfield, Vernal and EC Towers, and picked up the storm that came through the basin in early September (9/8 to 9/10) that dramatically decreased surface temperatures and ET.

4.1.2 Monthly ET_a Comparison – EC Tower to Remote Sensing Models and Crop Coefficient Models

EC Tower daily ET_a was summed to monthly to compare to both the CCMs and the RSMs. As discussed above, shallow soil water measurements and user-supplied information at the Palisade, Bloomfield, Vernal, and Big Piney towers indicated that those locations received a full irrigation supply in 2020.

Figures 17 through 20 show monthly ET_a estimates at each tower for all methods. Note that the Estimated Range of Accuracy shown in the graphs is plus or minus 15 percent of the EC Tower monthly ET_a. The percent differences (calculated using Eq. 2) for each of the methods compared to the EC Towers are shown in Tables 5 through 8. Positive values indicate that the method resulted in higher ET_a compared to the EC Tower; negative values indicate that the method resulted in lower ET_a compared to the EC Tower.

$$Percent\ Difference = \left(\frac{ET_{Remote\ Sensing\ or\ CCM} - ET_{EC\ Tower}}{ET_{EC\ Tower}}\right) * 100 \qquad \text{(Eq. 2)}$$

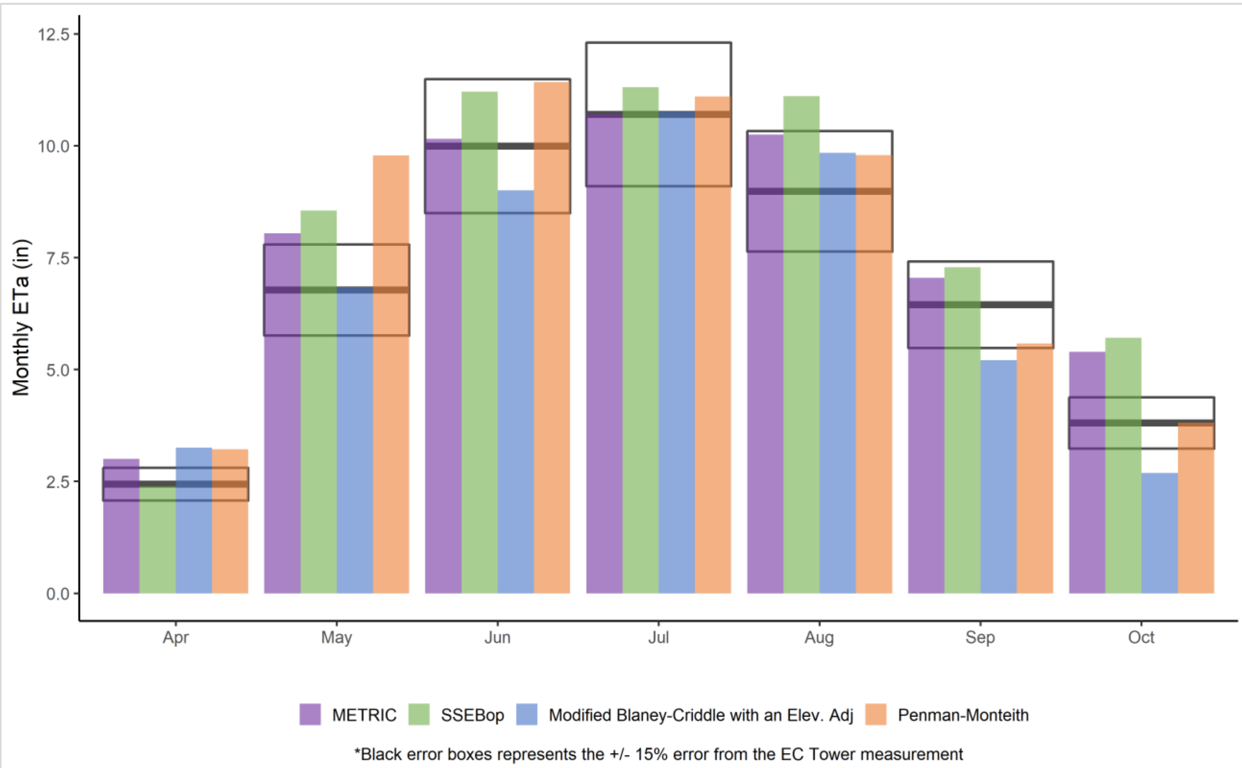


Figure 17. Monthly ET_a Estimates at the Palisade, CO EC Tower Site

Table 5. Percent Difference of Monthly ET Estimates compared to the Palisade, CO EC Tower measured ET_a

Method	April	May	June	July	August	September	October
METRIC	23%	19%	2%	0%	14%	9%	42%
SSEBop	64%	34%	13%	6%	24%	15%	50%
Modified Blaney-Criddle with Elev. Adj.	34%	1%	-10%	1%	10%	-19%	-29%
Penman-Monteith	32%	44%	14%	4%	9%	-13%	0%

The following are observations for the Palisade EC Tower based on Figure 17 and Table 5.

- Penman-Monteith was within 15 percent of the tower measurements five months during the growing season, while SSEBop, METRIC and Modified Blaney-Criddle were within 15 percent in four months. METRIC and Penman-Monteith were within 15 percent of the tower during the peak growing season months (June to September).
- SSEBop, METRIC, and Penman-Monteith tended to overestimate ET at the tower, while Modified Blaney-Criddle did not consistently over or underestimate ET at the tower.

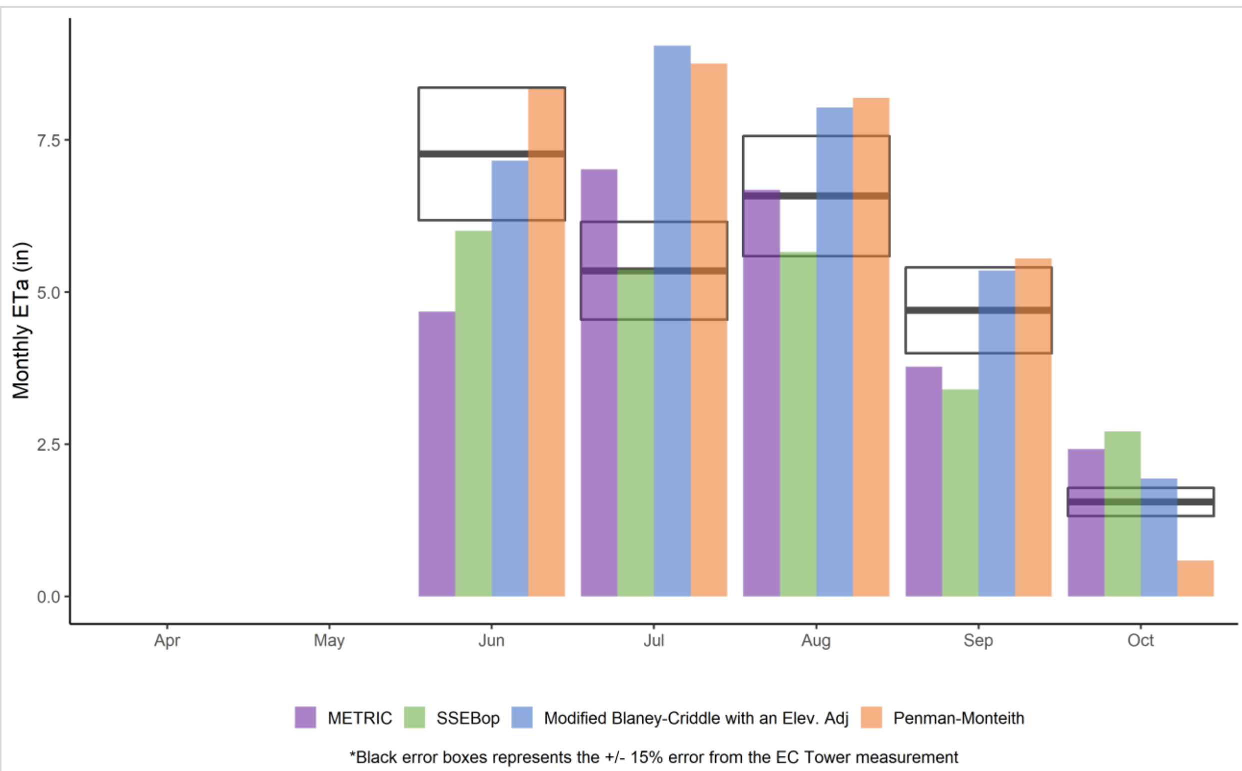


Figure 18. Monthly ET_a Estimates at the Bloomfield, NM EC Tower Site

Table 6. Percent Difference of Monthly ET compared to the Bloomfield, NM EC Tower measured ET_a

Method	April*	May*	June	July	August	September	October
METRIC			-9%	-11%	-16%	-10%	-7%
SSEBop			9%	-2%	-2%	0%	9%
Modified Blaney-Criddle with Elev. Adj.			-4%	19%	12%	-26%	-48%
Penman-Monteith			13%	-6%	-7%	4%	-47%

*Note that the EC Tower was not operational until May 22nd. No model comparisons were made for April and May.

The following are observations for the Bloomfield EC Tower based on Figure 18 and Table 6.

- METRIC tended to report values less than the EC Tower, while SSEBop estimates tended to be close to the EC Tower results.
- The Bloomfield alfalfa field was cut twice during the 2020 growing season (7/15 and 8/17). Although Penman-Monteith modeled four alfalfa cuttings (5/27, 7/8, 8/17, and 10/3), the two cuttings in the middle of the growing season lined up well with when the actual cuttings occurred and kept Penman-Monteith within 15 percent of the EC Tower from June to September.
- While no models are shown for April and May, it's important to note that the RSMs were able to pick up on the alfalfa field being planted late in 2020. The CCMs used temperature driven start and stop dates to determine when the field should have begun growing or begun greening up from a prior year's planting. The temperature driven start and stop dates would result in the CCMs over estimating ET_a for the new crop of alfalfa in the early growing season.

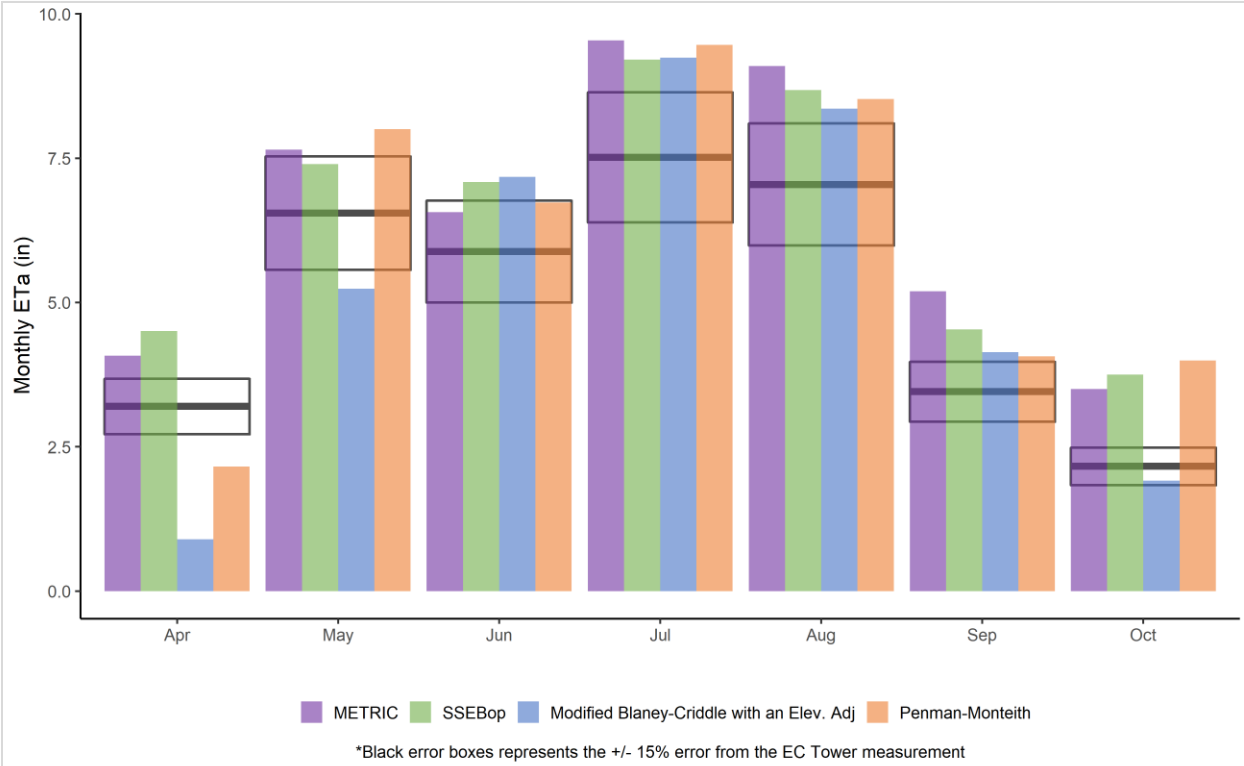


Figure 19. Monthly ET_a Estimates at the Vernal, UT EC Tower Site

Table 7. Percent Difference of Monthly ET compared to the Vernal, UT EC Tower measured ET_a

Method	April	May	June	July	August	September	October
METRIC	28%	17%	12%	27%	29%	50%	62%
SSEBop	41%	13%	20%	23%	23%	31%	73%
Modified Blaney-Criddle with an Elev. Adj.	-72%	-20%	22%	23%	19%	20%	-11%
Penman-Monteith	-33%	22%	14%	26%	21%	18%	85%

The following are observations for the Vernal EC Tower based on Figure 19 and Table 7.

- All four methods tended to estimate higher ET than that recorded by the Vernal EC Tower.
- The EC Tower operators noted that irrigation on the alfalfa field appeared to be less uniform than in past years. Upwind sections of the field were irrigated extensively in spatially variable patterns. This could have reduced the energy balance closure as the soil water and ET conditions upwind of the tower may not have reflected the available

energy measured near the tower. It could be related to both RSMs and CCMs showing an overestimate of ET_a throughout the growing season.

- The CCMs temperature-driven start of growing season dates likely caused the low values compared to the tower measurements in April for both Penman-Monteith (start date was April 10) and Modified Blaney-Criddle (start date was April 23).

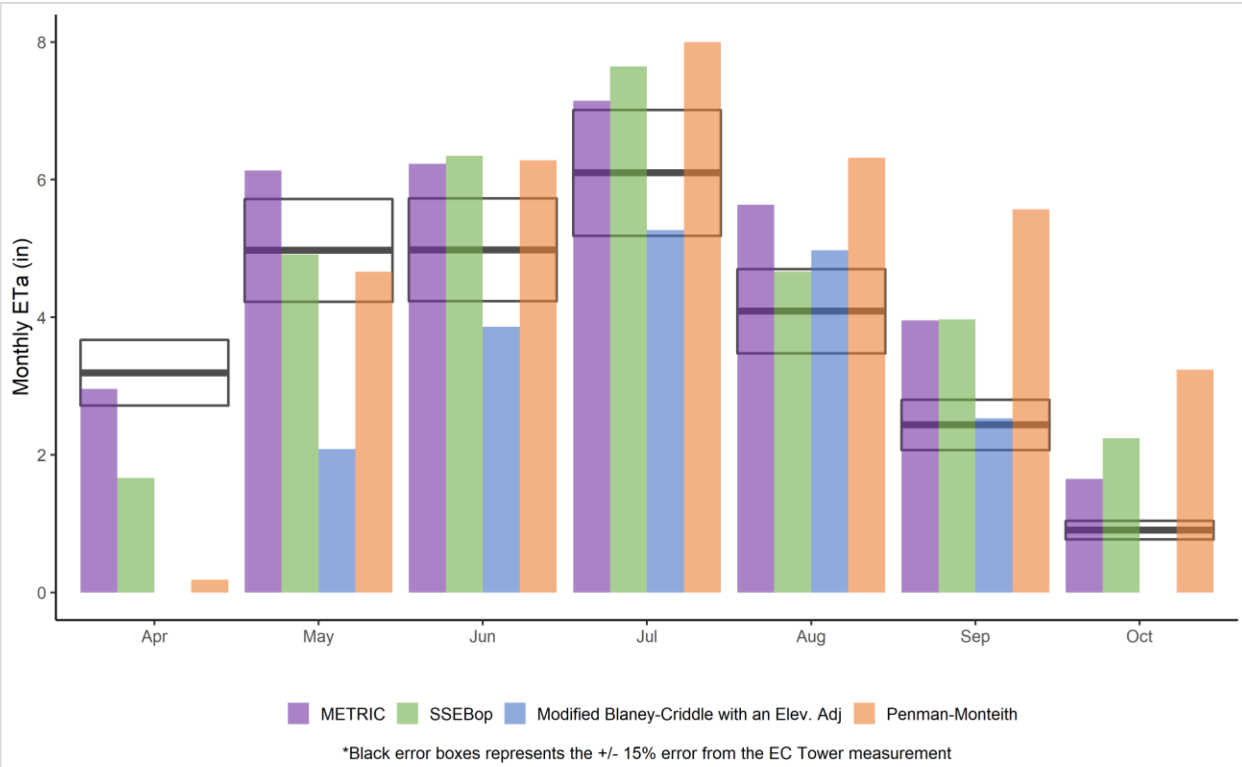


Figure 20. Monthly ET_a Estimates at the Big Piney, WY EC Tower Site

Table 8. Percent Difference of Monthly ET compared to the Big Piney, WY EC Tower measured ET_a

Method	April	May	June	July	August	September	October
METRIC	-7%	23%	25%	17%	38%	62%	82%
SSEBop	-48%	-1%	27%	25%	14%	63%	147%
Modified Blaney-Criddle with an Elev. Adj.	-100%	-58%	-23%	-14%	22%	4%	-100%
Penman-Monteith	-94%	-6%	26%	31%	55%	129%	258%

The following are observations for the Big Piney EC Tower based on Figure 20 and Table 8.

- METRIC, SSEBop and Penman-Monteith tended to estimate higher ET vales than the EC tower, especially during the peak growing season months (June to September).
- Having to use unforced (i.e. no forced closure of the energy balance) EC Tower ET_a estimates likely reduced reported ET_a values from the EC Tower to an unknown extent. This may be related to the results showing that METRIC, SSEBop and Penman-Monteith appear to overestimate ET.
- None of the methods were consistently within 15 percent of the tower.
- Both CCMs showed either no or very little ET_p during April due to the temperature-driven growing season start dates. Penman-Monteith growing season was April 28 through October 21, and Modified Blaney-Criddle growing season extended from May 9 to September 29.
- The large percent differences at the end of growing season can be attributed to the inherent error in the percent difference calculation when calculating percent difference between small values.

While none of the methods were consistently within any of the EC Towers' 15 percent estimated inherent uncertainty for every month, SSEBop and Penman-Monteith were within 15 percent more frequently (11 out of 26 months) and METRIC was within 15 percent 10 out of 26 months across all four tower locations. The largest percent differences for every method at all locations tended to occur during the months of April and October, likely reflecting the low ET_a in those months which can bias the error percentage. If April and October are excluded, the season for SSEBop and Penman-Monteith were within 15 percent most often (10 out of 19 months) during the growing season. Both METRIC and Modified Blaney-Criddle were within 15 percent 8 out of 19 months.

4.1.3 Growing Season ET_a Comparison – EC Tower to Remote Sensing and CCM Methods

Tables 9 through 12 show April-October growing season estimated ET_a for the CCMs and the RSMs at the four tower locations and percent differences compared to the EC Tower growing season ET_a. Positive values indicate that the method resulted in higher ET_a compared to the EC Tower; negative values indicate that the method resulted in lower ET_a compared to the EC Tower.

Table 9. ET_a at Palisade, CO EC Tower and Percent Difference Compared to EC Tower ET_a

Method	April 1 - Oct 31 Total (inches)	Percent Difference
EC Tower	49.1	-
METRIC	54.6	11%
SSEBop	60.0	22%
Modified Blaney-Criddle with an Elev. Adj.	47.6	-3%
Penman-Monteith	54.7	11%

Table 10. ET_a and ET_p at Bloomfield, NM EC Tower and Percent Difference Compared to EC Tower ET_a

Method	June 1 – Oct 31 Total (inches)	Percent Difference
EC Tower	37.9	-
METRIC	33.8	-11%
SSEBop	38.8	2%
Modified Blaney-Criddle with an Elev. Adj.	35.9	-5%
Penman-Monteith	35.9	-5%

Table 11. ET_a at the Vernal, UT EC Tower and Percent Difference Compared to EC Tower ET_a

Method	April 1 - Oct 31 Total (inches)	Percent Difference
EC Tower	35.8	-
METRIC	45.6	27%
SSEBop	45.2	26%
Modified Blaney-Criddle with an Elev. Adj.	37.0	3%
Penman-Monteith	42.9	20%

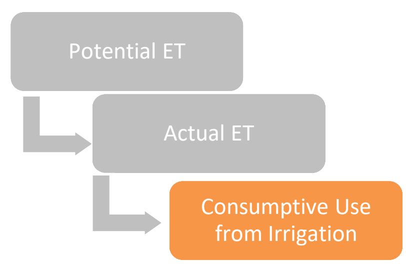
Table 12. ET_a at Big Piney, WY EC Tower and Percent Difference Compared to EC Tower ET_a

Method	April 1 - Oct 31 Total (inches)	Percent Difference
EC Tower	26.7	-
METRIC	33.7	26%
SSEBop	31.4	18%
Modified Blaney-Criddle with an Elev. Adj.	18.7	-30%
Penman-Monteith	34.3	28%

The following are observations based on growing season comparisons shown in Tables 9 through 12.

- METRIC estimates are within 15 percent at the Palisade and Bloomfield EC Towers, while SSEBop estimates are within 15 percent only at the Bloomfield EC Tower.
- Modified Blaney-Criddle estimates were within 15 percent at the Palisade, Bloomfield, and Vernal EC Towers.
- Penman-Monteith was only within 15 percent at the Palisade and Bloomfield EC Tower.
- All four models tended to overestimate ET_a at the Palisade, Vernal and Big Piney EC Tower locations.

4.2 Basin-wide Crop Consumptive Use from Irrigation



Growing season CU_{irr} by state and for the UCRB is summarized in Table 13 for the CCM and RSMs. The full April 1 through October 31 growing season was used for this comparison. Figures 21 through 24 shows monthly potential CU, CU from precipitation, CU_{irr}, and shortages for the CCMs for each state, and CU from precipitation and CU_{irr} for the RSMs for each state.

Table 13. April through October CU_{irr} by State (acre-feet)

	METRIC	SSEBop	Modified Blaney-Criddle with an Elev. Adj	Penman-Monteith
Colorado	1,560,815	1,612,740	1,633,768	2,188,551
New Mexico	243,761	249,340	226,201	274,836
Utah	843,023	893,795	773,920	1,003,101
Wyoming	616,301	560,135	300,187	583,640
Basin Total	3,263,900	3,316,011	2,934,076	4,050,127

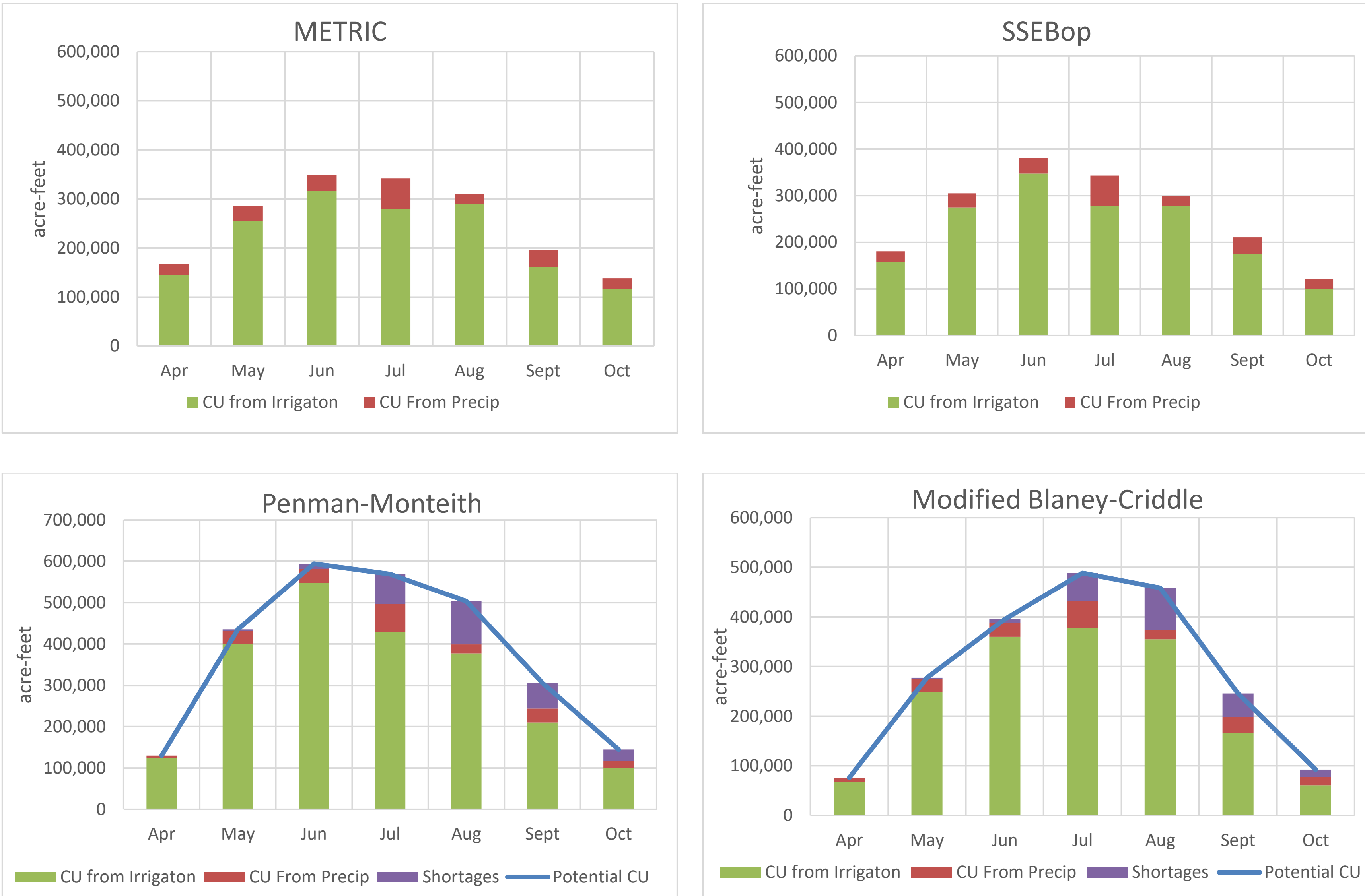


Figure 21. Estimated Monthly CU and shortages for each method for Colorado

Figure 22. Estimated Monthly CU and shortages for each method for New Mexico

Figure 23. Estimated Monthly CU and shortages for each method for Utah

Figure 24. Estimated Monthly CU and shortages for each method for Wyoming

The following are observations based on Table 13 and Figures 21 through 24.

- Penman-Monteith reported the highest annual UCRB total CU_{irr} and the highest annual estimates in all states except Wyoming. Modified Blaney-Criddle estimates were only higher than RSMs in Colorado, most likely due to the underestimation of shortages in Colorado by the Indicator Gage Method.
- While the CCMs produced values similar to the RSM values at the EC Towers on a monthly and growing season time step, the EC Towers fields were provided a full water supply, unlike the majority of the UCRB as shown in the basin-wide analysis. The generally higher seasonal ET_a estimates from the CCMs likely include inaccuracies associated with irrigation shortage estimates from the Indicator Gage Method as well as inaccuracies associated with crop coefficient curves and growing season begin and end dates. Also, as noted above, ET_p estimated using both CCM methods assume full-supply conditions with uniform irrigation. The general irrigation practices and non-leveled fields in the UCRB make it unlikely that ET_p could be reached during much of the growing season, even with an adequate supply. The Indicator Gage Method assumes that ET_p can be met every month if provided with a full irrigation supply.
- METRIC and SSEBop followed similar monthly trends in all four Upper Division States. SSEBop reported slightly higher CU from irrigation values than METRIC in April through June, while METRIC reported higher CU from irrigation values for July through September in Colorado, New Mexico, and Utah. METRIC tended to be higher than SSEBop in all months in Wyoming.
- Modified Blaney-Criddle with an elevation adjustment tended to provide lower values than the RSMs in every month in Wyoming.

Figure 25 shows the difference between METRIC and SSEBop average growing season ET_a for HUC 8 drainages. Hydrologic Unit Code (HUC) 8 subbasins are considered medium-sized river basins. Figure 26 shows the difference between Penman-Monteith and Modified Blaney-Criddle with an elevation adjustment average growing season ET_a. The legend on each figure also indicates how many irrigated acres fall into each category shown on the maps.

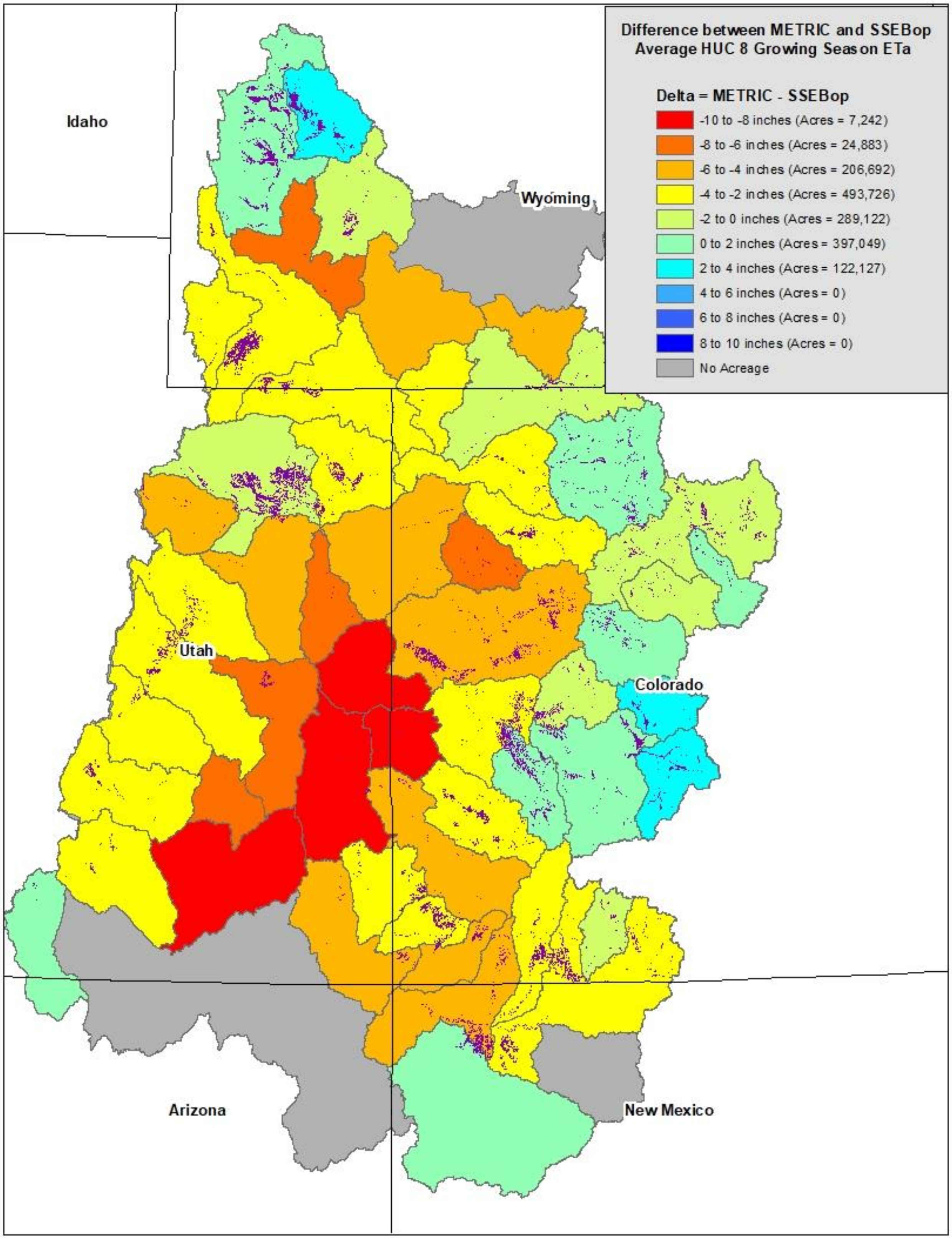


Figure 25. The difference between METRIC and SSEBop average growing season ET_a in inches for HUC 8 drainages.

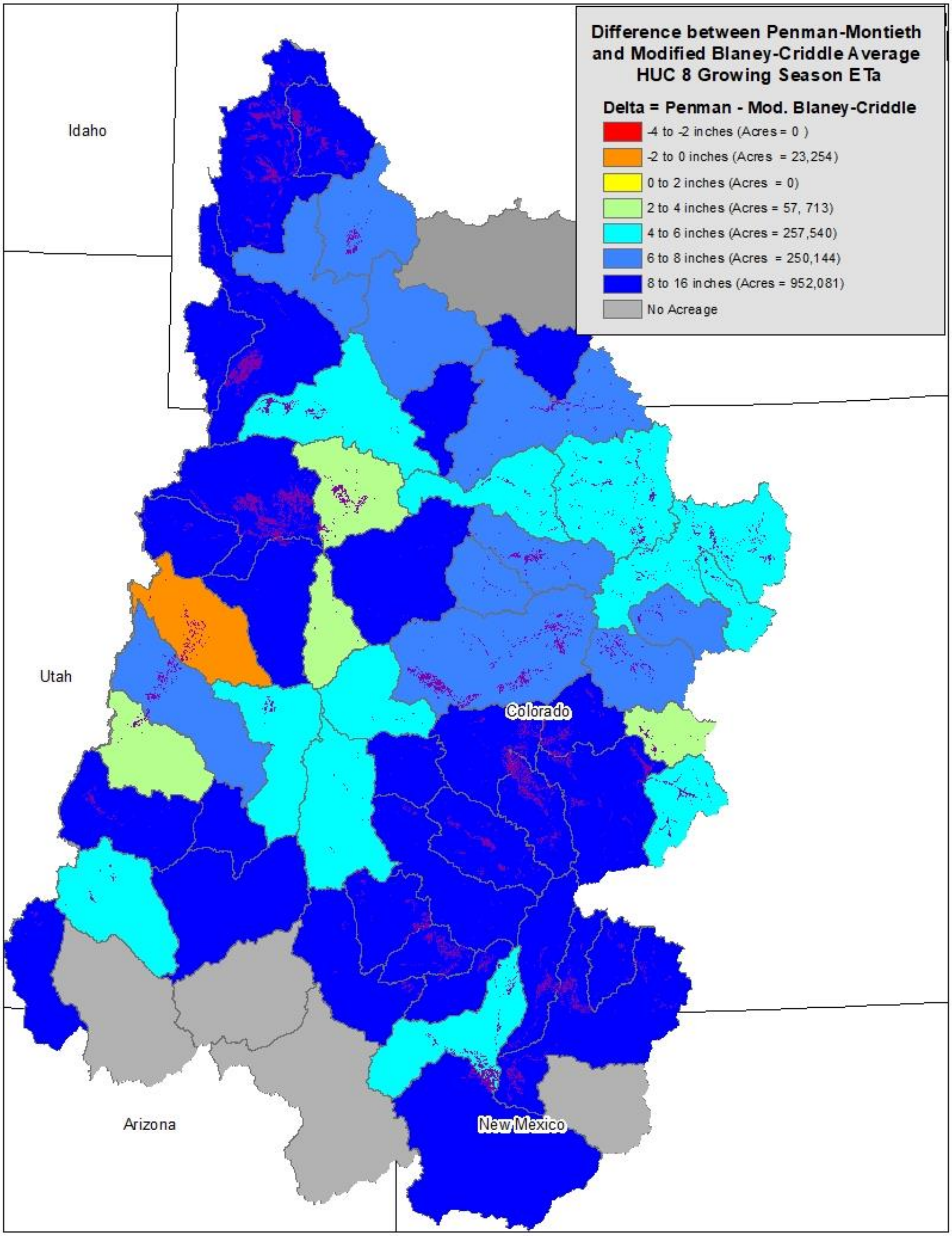
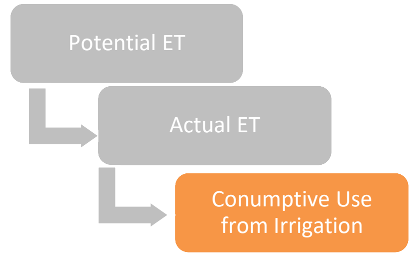


Figure 26. The difference between Penman-Monteith and Modified Blaney-Criddle with an Elevation Adjustment average growing season ET_a in inches for HUC 8 drainages.

The following are observations based on Figure 25 and 26.

- SSEBop estimates tended to be larger than METRIC's estimates across the basin, while both models reported closer results at lower elevation HUCs. The HUCs with the largest difference between the models (6 to 11 inches) have only small amounts of acreage.
- Roughly 85 percent of the irrigated acreage fell in HUCs where the RSM models results varied by less than four inches over the growing season, while 45 percent of the acreage fell within HUCs where both model results varied by less than two inches.
- Across the basin Penman-Monteith tended to report significantly higher ET values than Modified Blaney-Criddle with an elevation adjustment. The majority of the acreage falls in HUCs where the CCMs had differences greater than 8 inches.

4.3 CCM Comparison to Modified Blaney-Criddle without an Elevation Adjustment



To date, Reclamation's Consumptive Uses and Losses reporting for the UCRB uses Modified Blaney-Criddle without an elevation adjustment to estimate ET_p and CU_{irr}. To understand the potential impacts of moving to another CCM for reporting, this section compares Modified Blaney-Criddle CU_{irr} with and without an elevation adjustment and Penman-Monteith CU_{irr} estimates on a state level and by elevation bands (e.g., 4,000 to 5,000 feet). Table 14 also shows the percent difference between Modified Blaney-Criddle without an elevation adjustment and the CCM methods investigated in this report. Figure 27 shows total (April to October) CU_{irr} for all three methods at different elevation bands across the UCRB.

As discussed above, the Indicator Gage Method was used to apply shortages to ET_p less effective precipitation for each of the CCMs. Therefore, even though the Indicator Gage Method is believed to underestimate shortages, especially in Colorado, the application of the method to reduce ET_p estimated by each CCM provides a meaningful comparison. Note that all three CCMs shown in Table 14 use the 1971 Colorado Indicator gage shortage percentages.

Table 14. Total Crop Consumptive Use from Irrigation by State for CCMs for 2020

State	Modified Blaney-Criddle Without an Elevation Adjustment	Modified Blaney-Criddle with an Elevation Adjustment	Penman-Monteith	Percent Difference	
				Modified Blaney-Criddle with an Elevation Adjustment / Blaney-Criddle without an Elevation Adjustment	Penman-Monteith / Blaney-Criddle without an Elevation Adjustment
Colorado	1,347,169	1,633,768	2,188,551	21%	62%
New Mexico	191,026	226,201	274,836	18%	44%
Utah	654,847	773,920	1,003,101	18%	53%
Wyoming	226,383	300,187	583,640	33%	158%
Total	2,419,424	2,934,076	4,050,127	21%	67%

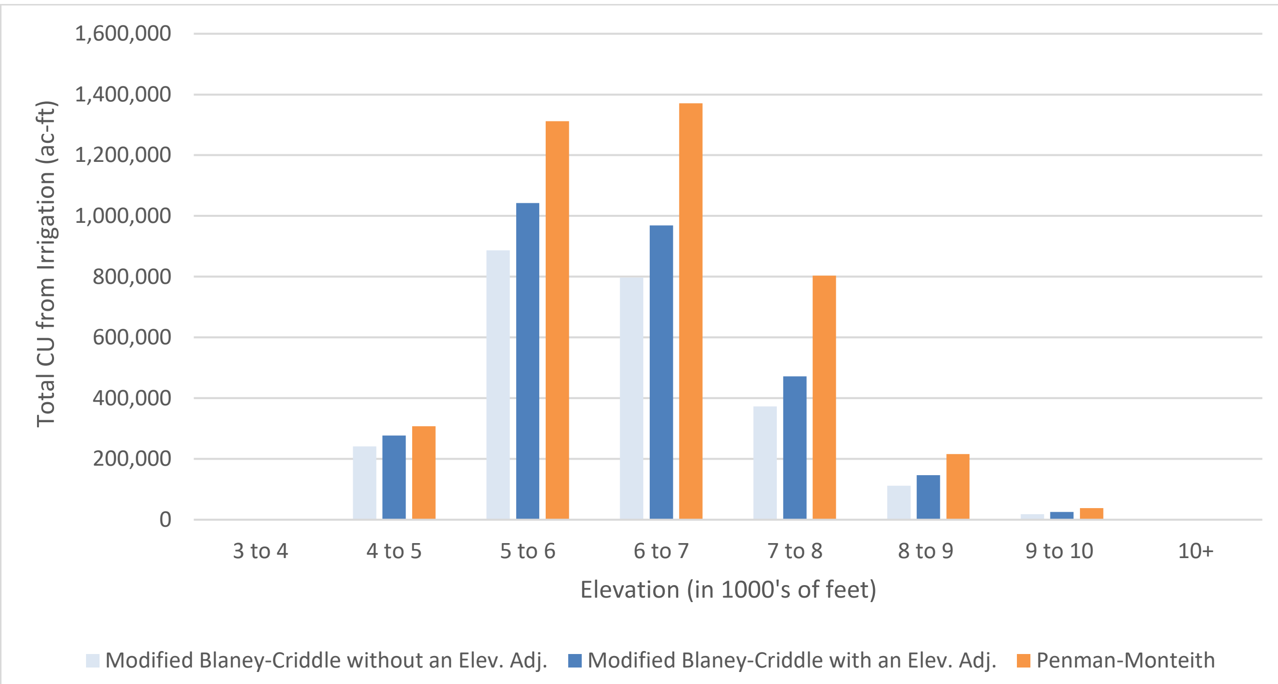


Figure 27. Total Basin-wide Crop Consumptive Use from Irrigation by Elevation Band for 2020

The following observations are based on Table 14 and Figure 27:

- Modified Blaney-Criddle with an elevation adjustment and Penman-Monteith result in increased estimates for basin-wide total CU_{irr} compared to historical estimates using Modified Blaney-Criddle without an elevation adjustment, as both methods estimate higher ET_p.

- Modified Blaney-Criddle with an elevation adjustment and Penman-Monteith estimated CU_{irr} show the largest increase in CU_{irr} compared to Modified Blaney-Criddle without an elevation adjustment at higher elevations. The largest increase is in Wyoming, followed by Colorado, as more of the irrigated acreage in those states is at higher elevations.
- The largest portion of the UCRB's CU_{irr} occurs within the 6,000 to 7,000 feet elevation band. Penman-Monteith estimated CU_{irr} is 72 percent higher than Modified Blaney-Criddle without an elevation adjustment for acreage in that elevation band.

4.4 EC Tower Comparisons for Period 2017 through 2020

As discussed above, only the Vernal EC Tower was operational long enough for a useful ET time series to be calculated in 2017 (June 10 to October 31). In addition, sensor malfunctions and climatic conditions during 2017 caused the EC Tower data to be "Gap Filled" over multiple days. Most of this multi-day gap filling occurred from late June to early July. In 2018, 2019, and 2020 all four EC Towers were operational for the full growing season, running continuously from April 1 to October 31. Single day gap filling, using the hourly gap filling procedures outlined in Appendix F, was required intermittently at each location. Multiple day gap filling was generally not required in 2018, 2019, and 2020, with the only notable period occurring at the Bloomfield tower from June 7 through June 15, 2019.

Figure 28 compares the 2017, 2018, 2019 and 2020 RSMs and CCMs monthly results at the Vernal EC Tower. Figures 29 to 31 compare the 2018, 2019 and 2020 RSMs monthly results at the Palisade, Bloomfield, and Big Piney EC Towers, respectively. Table 15 shows the growing season percent difference between the EC Towers and the RSMs and CCMs for 2017 (Vernal only), 2018, 2019 and 2020.

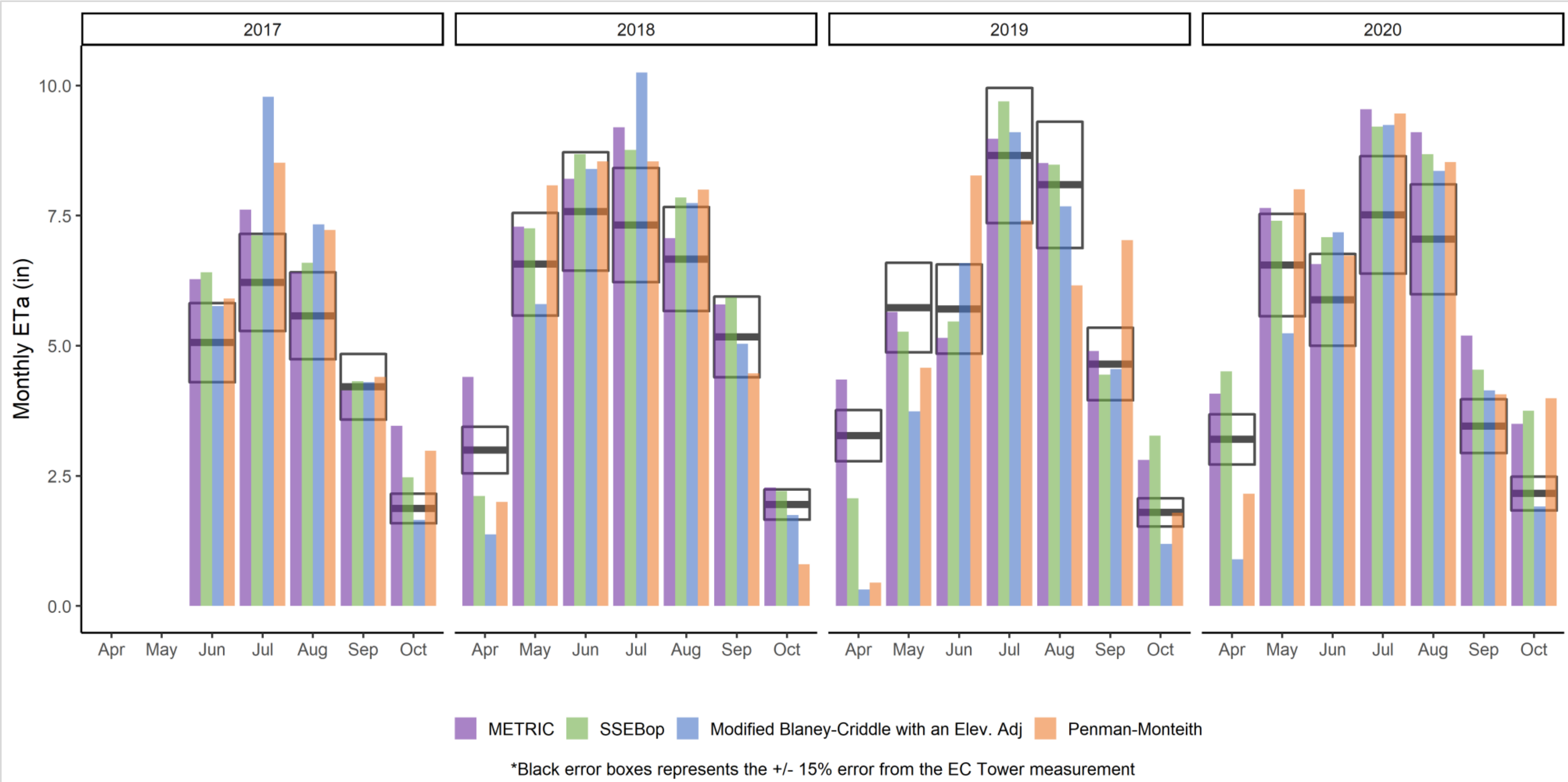


Figure 28. Monthly RSMs results at the Vernal EC Tower for 2017, 2018, 2019, and 2020

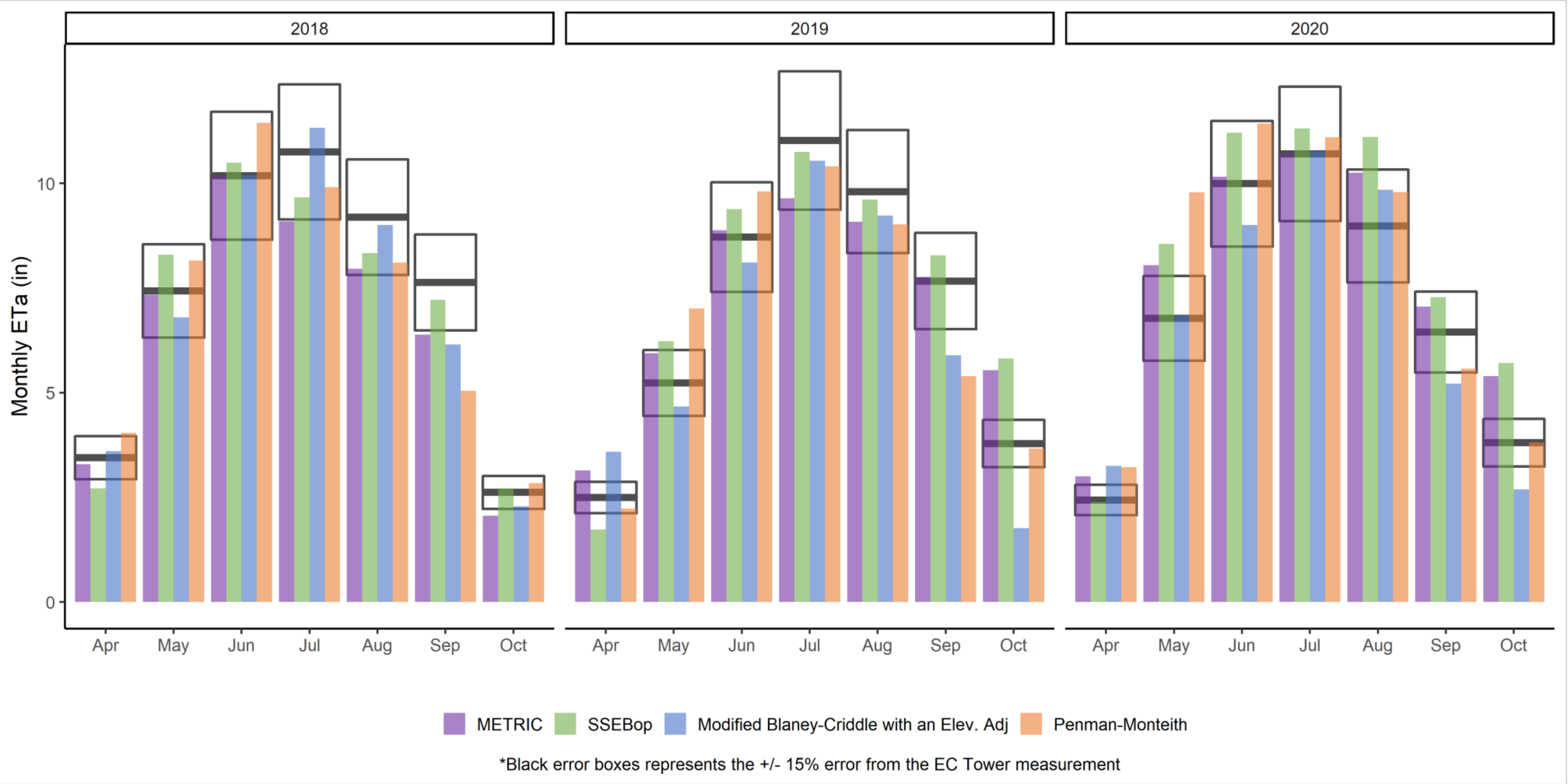


Figure 29. Monthly RSMs results at the Palisade EC Tower for 2018, 2019, 2020

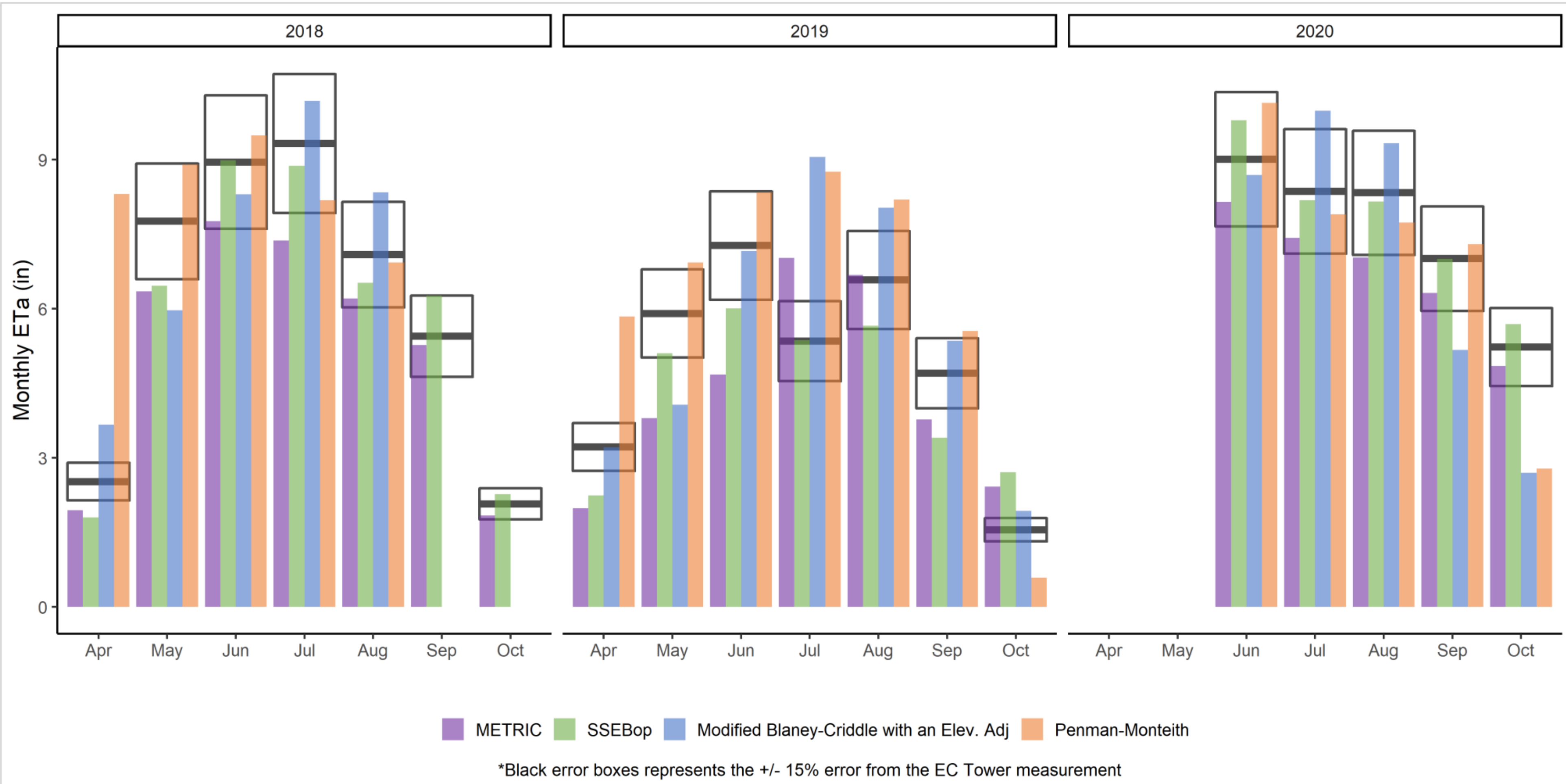


Figure 30.Monthly RSMs results at the Bloomfield EC Tower for 2018, 2019, and 2020

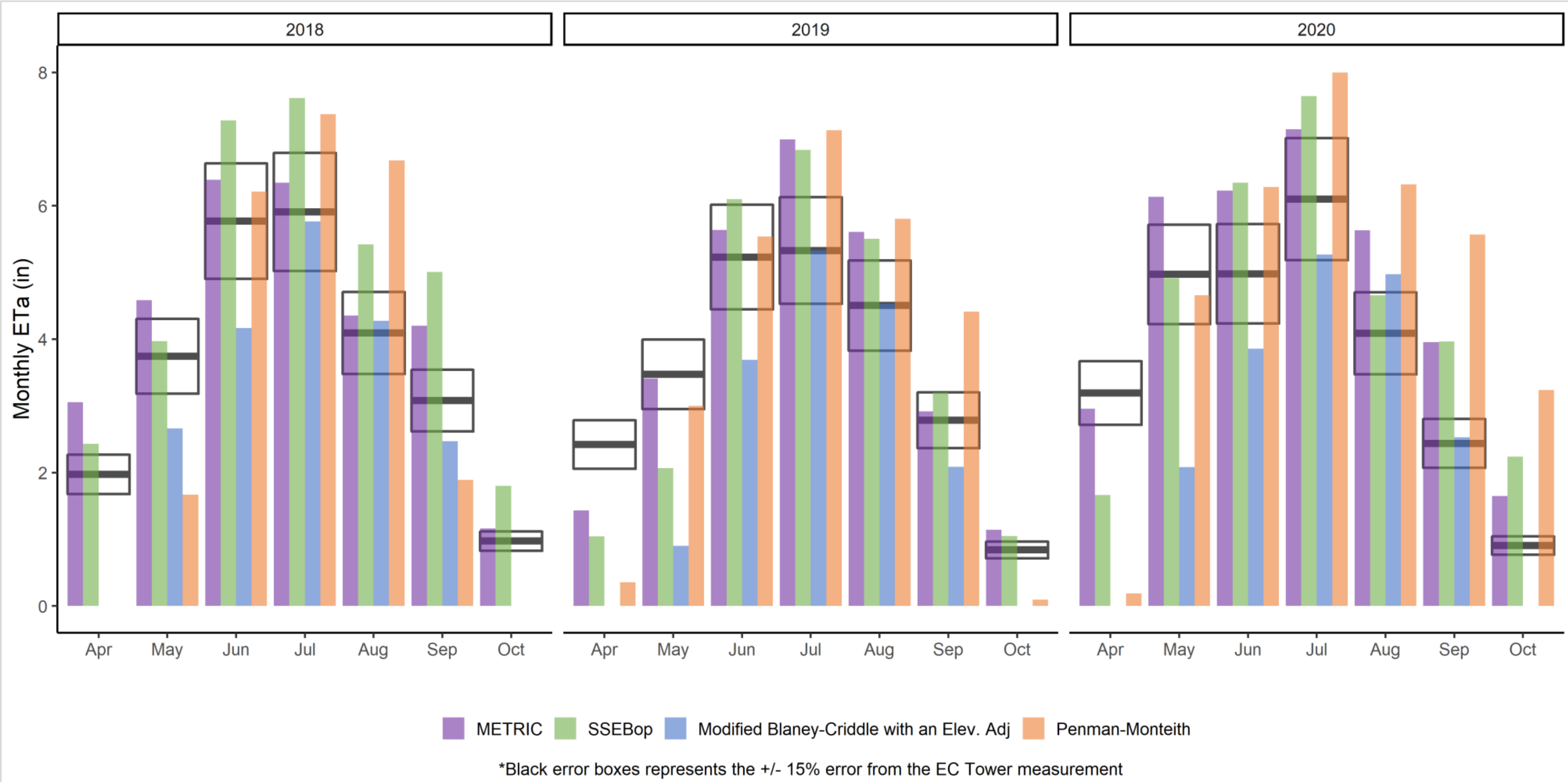


Figure 31. Monthly RSMs results at the Big Piney EC Tower for 2018, 2019, and 2020

Table 15. Growing Season percent differences for each EC Tower for 2017 to 2020. Positive percentages indicate the method results are higher than the EC Tower measurements, negative percentages indicate the method results are lower than the EC Tower measurements.

Method	Vernal				Palisade			Bloomfield			Big Piney		
	2017	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
METRIC	22%	16%	6%	27%	-10%	3%	11%	-15%	-12%	-9%	18%	10%	26%
SSEBop	17%	12%	2%	26%	-4%	6%	17%	-5%	-12%	3%	31%	5%	18%
Modified Blaney-Criddle with an Elev. Adj.	26%	6%	-12%	3%	-4%	-10%	-3%	-16%	12%	13%	-24%	-33%	-30%
Penman-Monteith	27%	6%	-6%	20%	-3%	-2%	-2%	-3%	28%	32%	-7%	7%	28%

The following observations are based on Table 15 and Figures 28 to 31:

- METRIC, SSEBop, and Penman-Monteith tended to overestimate ET_a at the Vernal EC Tower, especially from July to September in all four years.
- The RSMs were most often within 15 percent at the Palisade EC Tower site for 2018 through 2020 on both a monthly and growing season time step.
- Both RSMs tended to overestimate ET_a at the Big Piney EC Tower for 2018 through 2020, while they tended to underestimate ET_a at the Bloomfield EC Tower on both a monthly and growing season time step.
- The CCMs were most often within 15 percent at the Palisade EC Tower across all years. This may be due to the models not having to model a cutting at the Palisade EC Tower. Differences in actual cuttings versus when the models estimate a cutting can cause large monthly errors between the CCMs and the EC towers.
- The RSMs tended to estimate ET_a closest to the EC Tower results in 2019 at the Vernal, Palisade, and Big Piney EC Towers on the growing season time step. The RSMs performed the best in 2020 at the Bloomfield EC Tower.

4.5 Basin-Wide Comparisons for Period 2017 through 2020

Variations in hydrology and irrigation season weather make it difficult to compare estimates of annual basin-wide CU from year to year. In general, 2017 runoff was above average in each state, whereas runoff was well below average in 2018 in Colorado and New Mexico. The runoff pattern in 2019 was average to slightly above average in each state and the runoff was well below average in each state in 2020. Growing season temperatures were average or above average throughout the basin for the four years analyzed and none of the four years experienced significant “monsoonal” irrigation season precipitation.

Figures 32 to 35 show monthly CU from irrigation estimates for each state and each model. Figure 36 summarizes growing season CU from irrigation estimates for each state and model and Figure 37 and 38 shows the HUC 8 average growing season difference in ET_a between the different models.

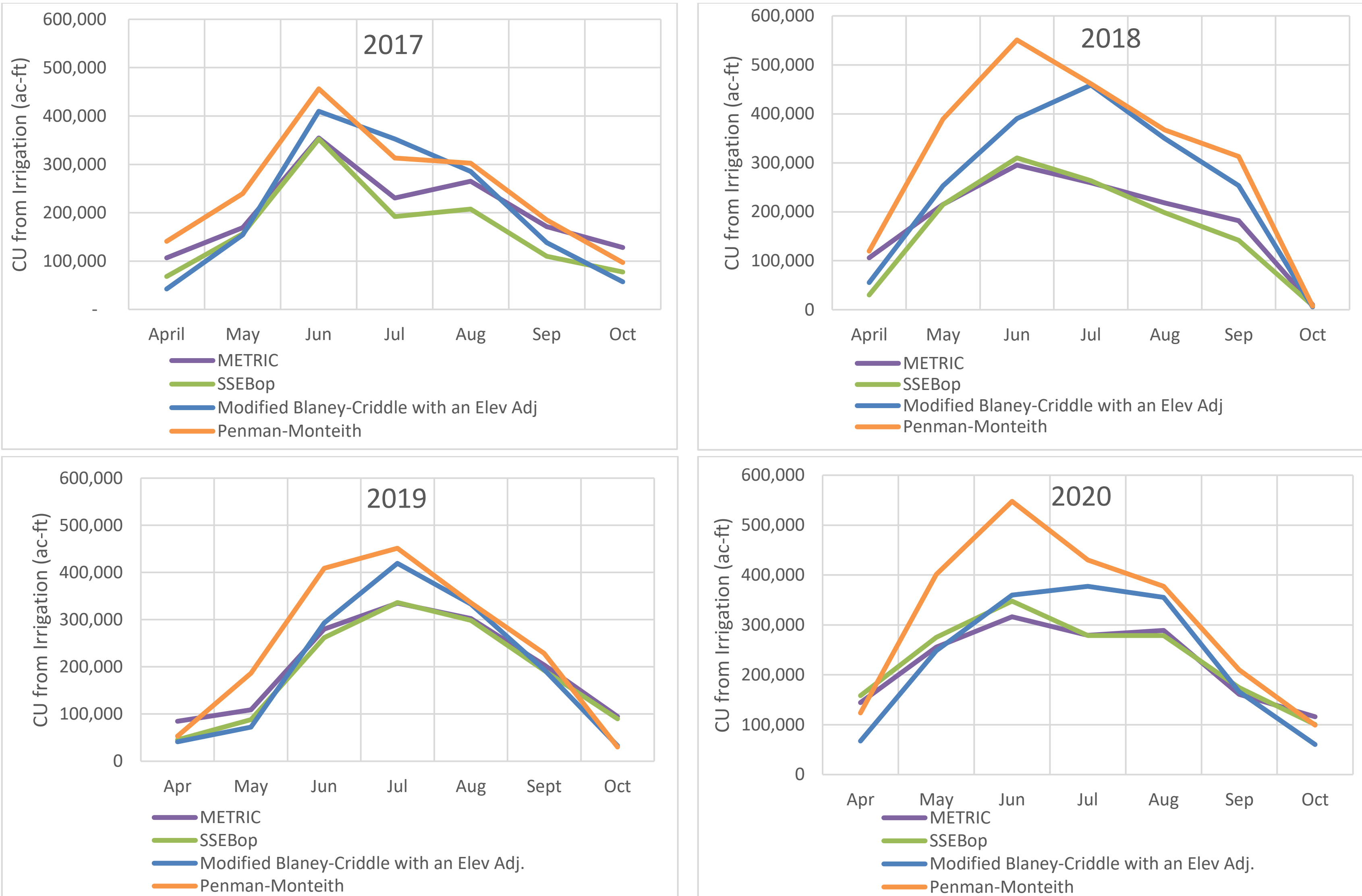


Figure 32. 2017 to 2020 Estimated Monthly CU from Irrigation for Colorado

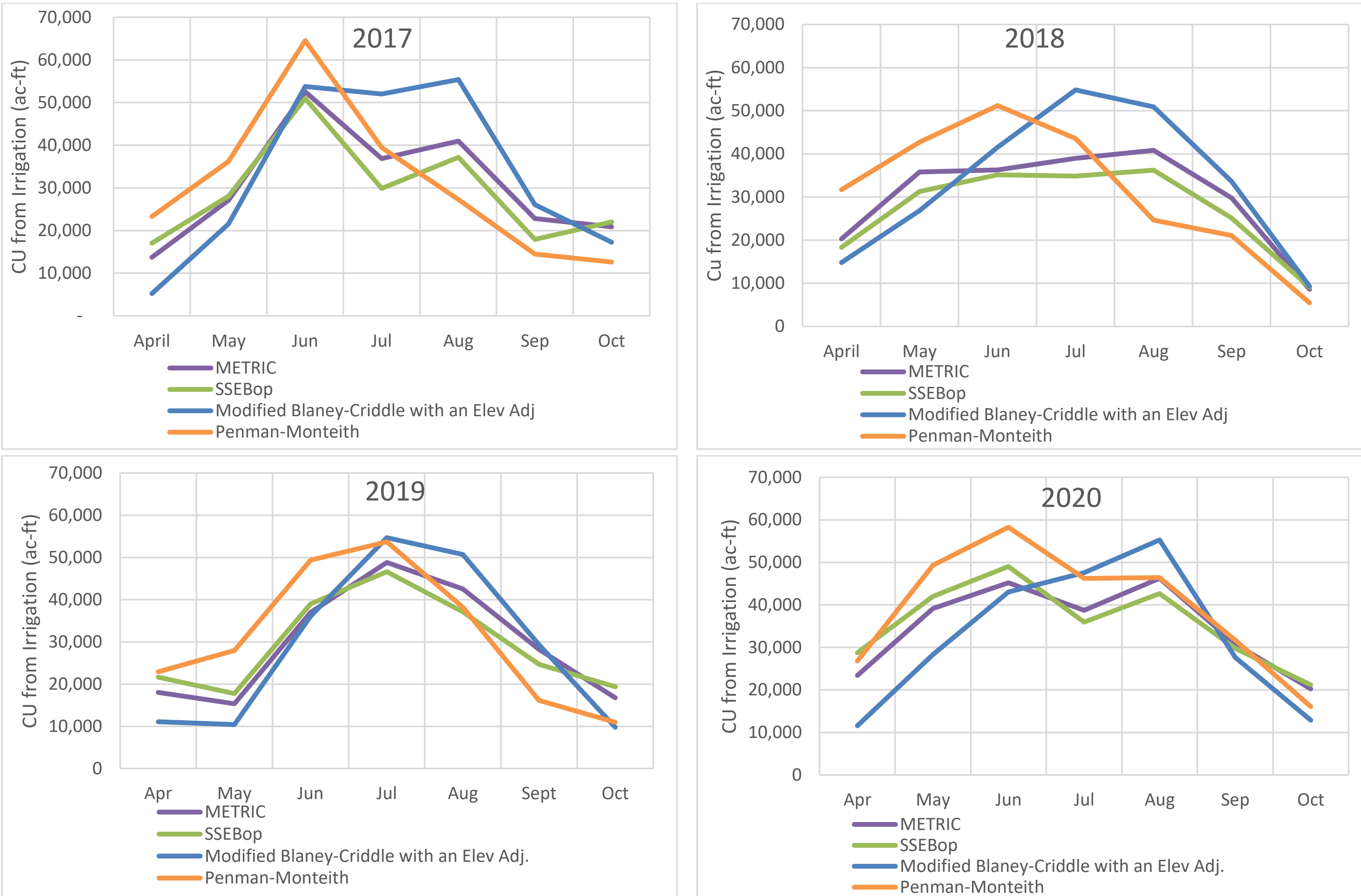


Figure 33. 2017 to 2020 Estimated Monthly CU from Irrigation for New Mexico

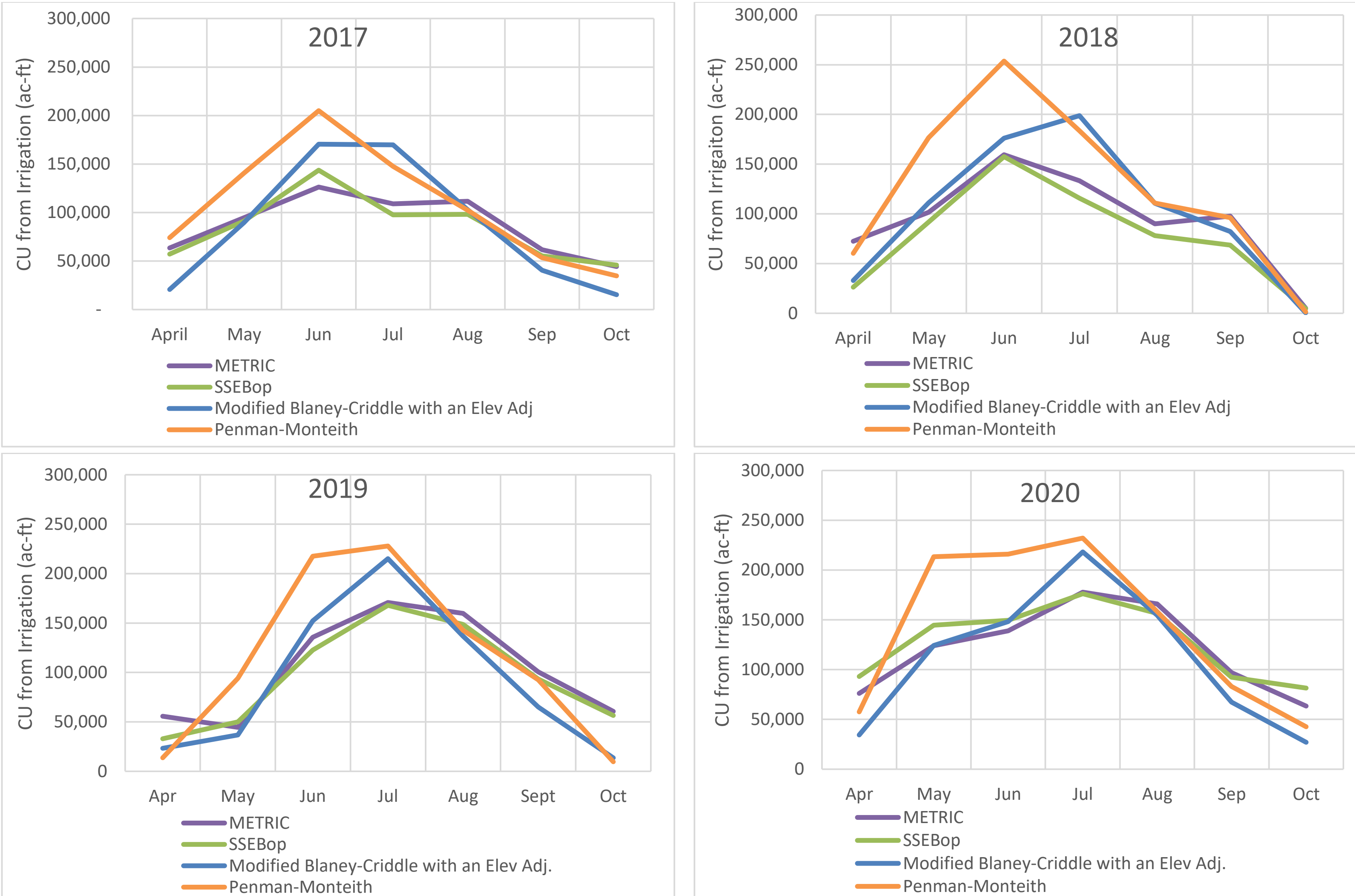


Figure 34. 2017 to 2020 Estimated Monthly CU from Irrigation for Utah

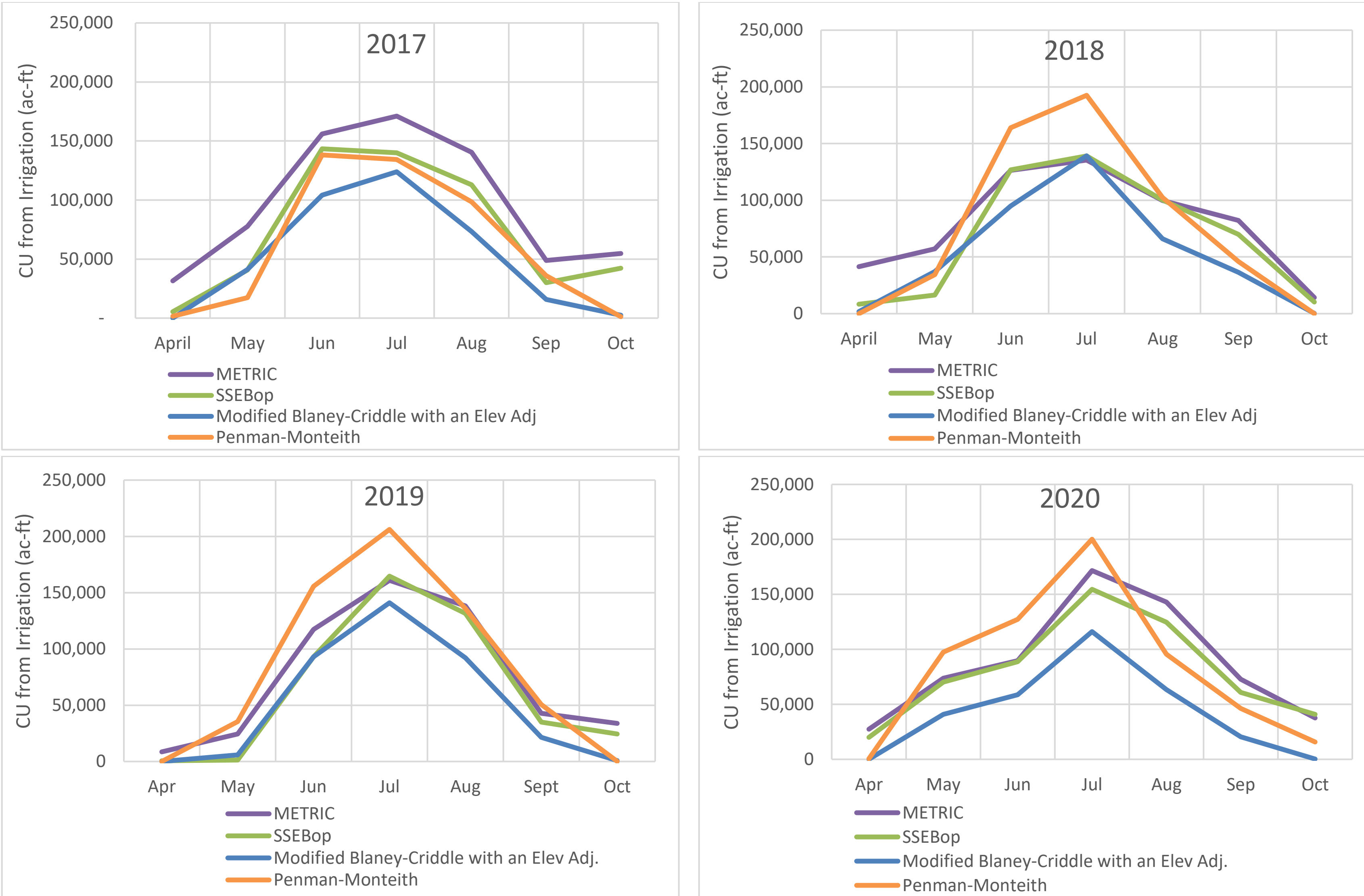


Figure 35. 2017 to 2020 Estimated Monthly CU from Irrigation for Wyoming

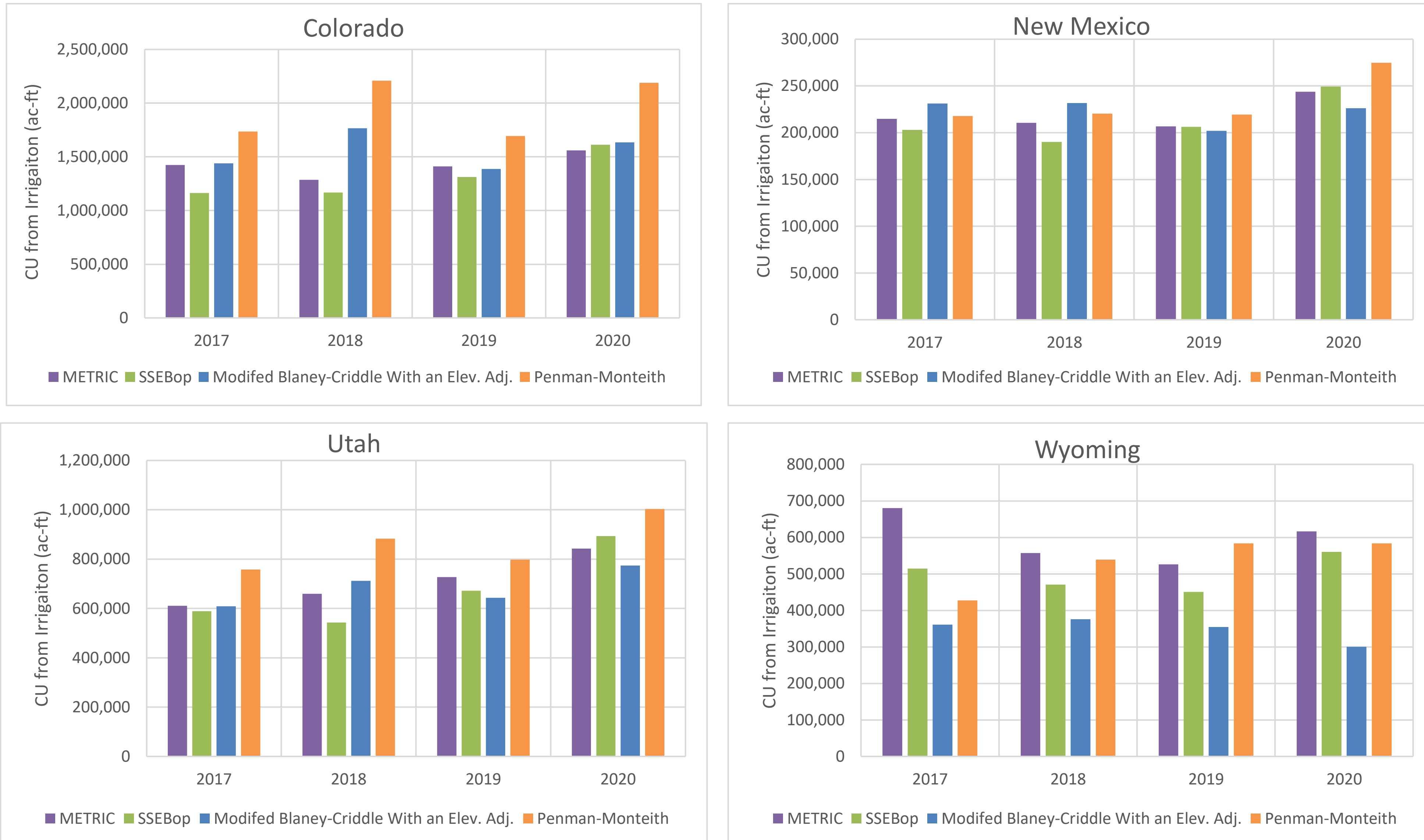


Figure 36. Summary of Growing Season CU from Irrigation by State and Model for each Year

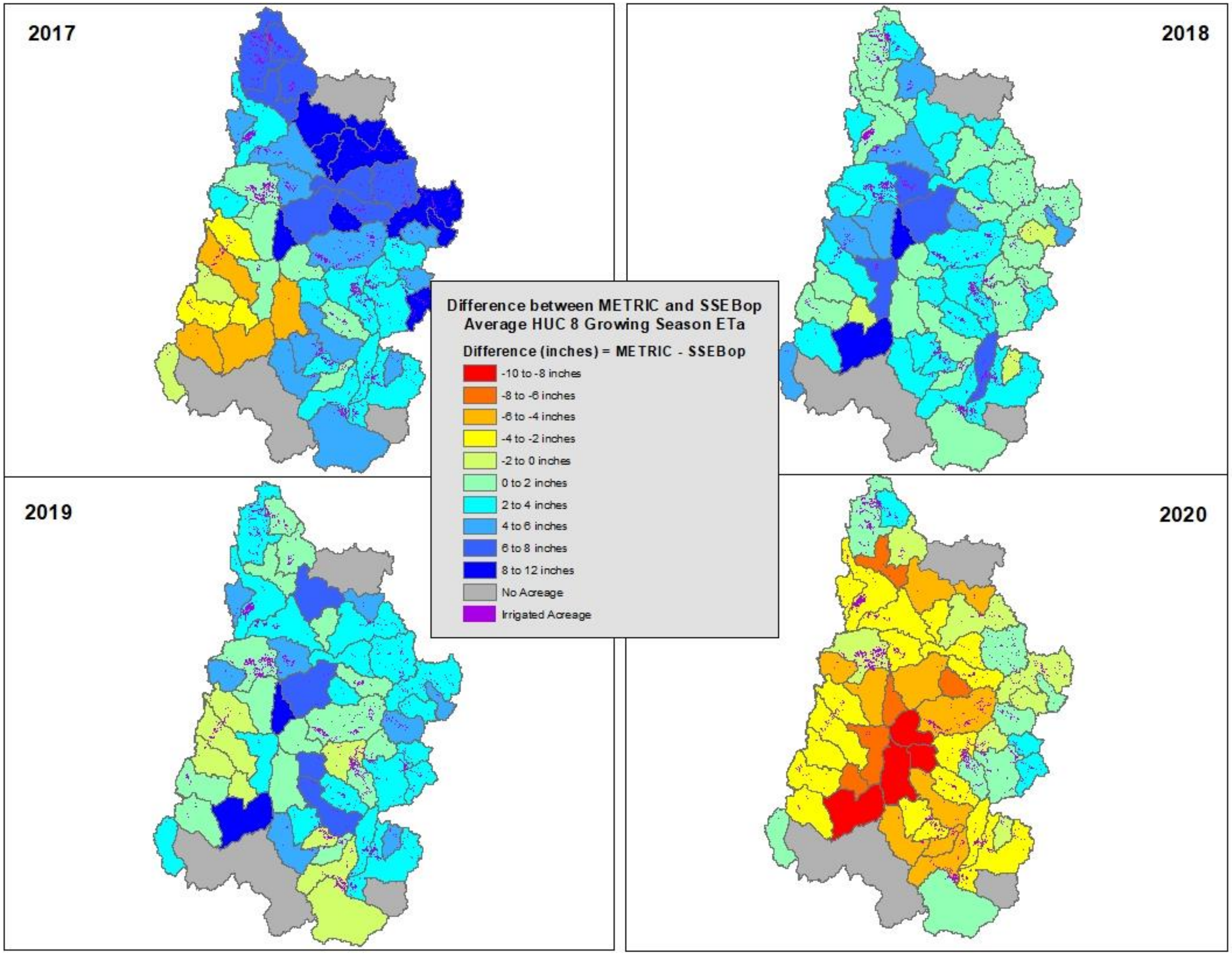


Figure 37. Difference between METRIC and SSEBop Average HUC 8 growing Season ET_a in inches for 2017 to 2020

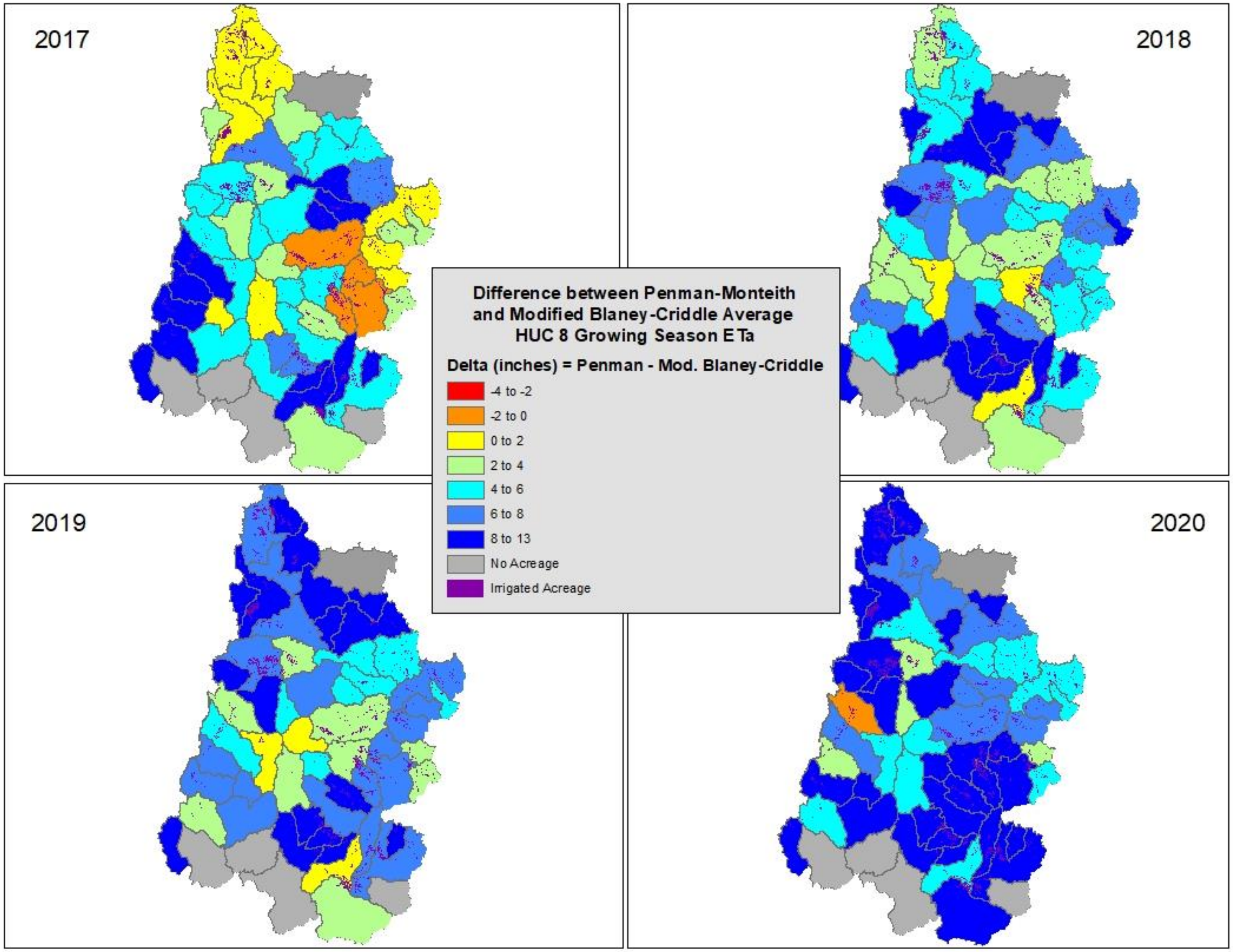


Figure 38. Difference between Penman-Monteith and Modified Blaney-Criddle with an Elev. Adj. Average HUC 8 growing Season ET_a in inches for 2017 to 2020

The following observations are based on Figures 32 to 38:

- The four methods estimated relatively close growing season CU from irrigation in New Mexico in all four years.
- METRIC and SSEBop provided closest results across the basin in 2018, 2019 and 2020 but had larger differences in 2017. Model improvements were made to both SSEBop and METRIC over the past four years that overall has shown SSEBop and METRIC to provide similar results.
- METRIC and SSEBop RSM methods had monthly trends and values that were much closer to one another than to the two CCM methods and fell between the two CCM methods for nearly all years for all four states.
- Penman-Monteith and Modified Blaney-Criddle with an elevation adjustment had the largest basin-wide differences in 2020. Because 2020 was the hydrologically driest year out of the four-year analysis, this likely indicates that the identified Indicator Gage Method issues with representing shortages is exacerbated in extremely dry hydrologic years.
- All four models had large differences in growing season CU from irrigation estimates in Wyoming. This is likely in part due to most of Wyoming's acreage being at higher elevations.

5.0 Cost and Time Comparison

Annual processing time and costs for the different methods used to estimate Crop Consumptive Use from irrigation are shown in Table 16. Annual processing times assume that the person doing the processing is knowledgeable and highly experienced, and no training is required. Time estimates were provided based on hours of labor. To keep the costs comparable, it was assumed that the producer of each method bills at $150 an hour and works a typical 8-hour day. Note that Penman-Monteith estimates were not yet available at the release of this report, the Penman-Monteith estimates for 2019 are being shown instead. These numbers will be updated when they become available.

Table 16. Annual Time and Costs for Methods based on 2020

Method	Annual Processing Time (days)[1]	Post Processing Time (days)[2]	Annual Labor Costs
METRIC	61	3	$ 76,800
SSEBop	10	3	$ 15,600
Modified Blaney-Criddle	12	1	$ 15,600
Penman-Monteith	17.5	2	$ 23,400

1. *Estimates do not account for time required to develop documentation*

2. *Post Processing Time is the amount of time Wilson Water Group spent on post processing of datasets received from other contractors*

The primary purpose of determining the cost of the various methods is to compare the potential costs to develop information for the CU&L Report. As such, the EC Tower purchasing and operating costs are not included, as the EC Towers do not provide basin-wide estimates and may not be operated into the future.

In addition to labor costs, there are costs associated with maintaining agricultural climate station networks to provide weather data to calculate a bias corrected ET_r required for the Penman-Monteith, SSEBop, and METRIC models. Each of the UCRB states have agricultural climate station networks that require state and, in some cases, federal funds to operate. Phase 2 of this study identified locations in each state where additional climate stations were required to improve accurate estimates of weather for irrigated acreage, and funding was secured by Reclamation for purchase and installation of the additional stations. Note that the Modified Blaney-Criddle method as Reclamation currently applies the method requires only mean monthly temperature and summed monthly precipitation, which can be obtained from the NOAA Cooperative Observer Network or, as is the case for this project, from climate station networks that more appropriately provide coverage for the irrigated acreage in each state. There are on-going operation and maintenance costs for the agricultural climate networks that are not included, as the costs are consistent regardless of the methodology selected and the networks are used by the states and other federal agencies for a variety of purposes.

Additional labor costs are required for the development of bias corrected ET_r grids for the UCRB, which are used by Penman-Monteith, SSEBop, and METRIC. It is estimated that these grids take roughly 16 days each year (approximately $20,000 based on $150 per hour) to develop. All methods also require irrigated acreage data. Reclamation estimates that a standardized UCRB irrigated acreage shapefile takes approximately seven staff days (approximately $8,400 based on $150 per hour) to develop every year.

The cost and time estimates shown in Table 16 might change as ET data become more widely available. Both SSEBop and METRIC are operational on the OpenET platform that operates on Google Earth Engine. As of fall 2021, the OpenET platform is now operational. OpenET hosts six different remote sensing models. OpenET also provides an “ensemble result”, which is the median of the six different remote sensing models and has shown to line up well with EC Towers, according to the OpenET team. Since Open ET could be potentially used in the future by Reclamation and/or by the upper division states a comparison of the results in this report were made to OpenET results. This comparison can be found in Appendix G. Note that the models included in OpenET/Appendix G could also be run independently of OpenET and are also potential options for Reclamation and/or the upper division states.

Typically, development of consumptive use estimates for Reclamation's CU&L Report takes approximately twelve days to compile the necessary climate data and calculate the Modified Blaney-Criddle results. Switching to Penman-Monteith to estimate ET_p, would increase processing time by about 6.5 days, due the complexity of the Penman-Monteith model compared to the Modified Blaney-Criddle model. Switching to Penman-Monteith would also require the development of the reference ET grids, adding roughly another 16 days to the process, and would also require more time in the initial deployment years, as there is a learning curve to running and operating the ET Demands model used to determine ET. In addition, there may be initial costs to potentially refine crop coefficient curves and growing season start and ending dates (see Appendix D).

If Reclamation switched to RSM to estimate CU_{irr} for the CU&L Report, the amount of processing time and related cost would increase; however, it would likely increase the accuracy of the basin-wide consumptive use estimates over the current Indicator Gage method. As noted above, switching to RSM still requires using a CCM method to determine ET_p so that shortages can be quantified. Reclamation has already made the investment in states' agricultural climate networks and would need to continue to help state networks pay for operation and maintenance of station data if the UCRB switched to a RSM and Penman-Monteith method. As noted above, although the NOAA Cooperative Observer Network stations have been used in the past to support the Modified Blaney-Criddle calculations, it is likely that the agricultural climate networks will be used moving forward regardless of whether Reclamation continues with Modified Blaney-Criddle or moves to Penman-Monteith to calculated ET_p.

6.0 2020 Summary

The following summarizes observations from the EC Tower comparisons for 2020 results.

- Both RSMs estimates followed the daily trend of the EC Towers well in 2020, however they were not consistently within 15 percent of any of the towers on a monthly time step. METRIC was within 15 percent of the Palisade and Bloomfield towers, and SSEBop was within 15 percent of the Bloomfield tower on a growing season time step.
- Both RSMs tended to estimate ET_a higher than that the EC Towers, except at the Bloomfield tower, where METRIC tended to underestimate and SSEBop was not consistently over or underestimating.
- ET_a estimates from all four methods were within 17 percent of Palisade EC Tower measurements on a growing season time step. However, on a monthly time step none

of the methods were consistently within 15 percent of the EC Tower monthly measurements.

- Both CCMs estimated CU_{irr} varied significantly from the EC Towers measurements during some months. Monthly variation may be partially due to the difficulty for CCMs to predict when cuttings occur and the temperature driven start and stop dates.

The following summarizes the basin-wide consumptive use comparison for 2020 results.

- METRIC and SSEBop CU_{irr} results were similar to each other for all states (0 to 10 percent difference) and basin-wide (2 percent difference).
- Both Penman-Monteith and Modified Blaney-Criddle with an elevation adjustment resulted in higher CU_{irr} estimates in Colorado; most likely due to a combination of identified underestimation of shortages from the Indicator Gage Methods, the temperature driven growing season start and stop dates, and the crop coefficient curves used in the analyses.
- Compared with Penman-Monteith, the Modified Blaney-Criddle CU_{irr} results were closer to the METRIC and SSEBop results for all states except Wyoming. If the indicator gage method is re-evaluated and larger shortages are implemented, Penman-Monteith results are expected to be closer to METRIC and SSEBop in Colorado and Utah.
- Penman-Monteith reported the highest CU_{irr} estimate in Colorado, New Mexico, Utah, and basin-wide, while Modified Blaney-Criddle reported the lowest CU_{irr} estimates in New Mexico, Utah, and Wyoming.

In Colorado, the CCMs generally reported higher CU_{irr} estimates from 2017 to 2020 than the RSMs. It has been shown that the Indicator Gage Method does not accurately reflect shortages in Colorado. Although using the 1971 original percentages of shorted lands did decrease Colorado CCM results, the shortages were still lower than Utah and Wyoming's Indicator Gage shortages, estimates from the RSMs, and estimates from Colorado's farm balance methods. If the Indicator Gage Method continues to be used for the CU&L Report, the acreages subject to shortage and the rules determining when shortages occur need to be reassessed.

Use of the Penman-Monteith method for estimating ET_p would increase the estimated consumptive use from irrigation reported in the CU&L Report. It would also increase the amount of time and cost required to develop CU_{irr} estimates. Penman-Monteith is the widely accepted standard for calculating reference ET (ASCE 1990, 2016). It significantly overestimated and underestimated some monthly results compared to the EC Tower estimates and was only within 11 percent of one of the four EC Towers measurements on a growing season time step. Refinement of the crop coefficients and growing season start and stop dates could help to improve Penman-Monteith's performance on a monthly time step. If the UCRB states adopt the method, it is important to assess the impact it would have on future UCRB depletion estimates.

As discussed, Reclamation staff spent significant time while performing the 2017 and 2018 analyses tracking down backup information and historical revisions made to the Indicator Gage Method used to estimate shortages for the CU&L Report. Although documentation describing the reasons for shortage criteria revisions over time was not found, identification and confirmation of clear issues that result in potentially significantly underestimated shortages in UCRB states, especially in Colorado, is an important outcome of this project. The identification of the issues, summarized in Appendix E, was critical to understanding and comparing basin-wide results of the CCMs and RSMs.

METRIC requires greater time and both RSMs require greater time and money to apply than the current method being used for the CU&L Report for estimating ET_a; however, they provide field-specific spatial ET_a information without the need for ditch-level water supply information or the use of the Indicator Gage Method. SSEBop is the more automated of the two methodologies, requires the least amount of calibration, and takes significantly less time to complete than METRIC. METRIC requires more time, expertise, and calibration. However, both methods are available on the OpenET site. The 2020 results showed that current versions of SSEBop and METRIC both perform well at all four EC Towers and provide similar growing season basin-wide results.

7.0 Consumptive Use Method Recommendation

At the request of CUWG, Wilson Water Group developed a recommendation for the approach to estimate CU in the UCRB. This recommendation is based on results documented in this report and the 2017, 2018, and 2019 reports. The recommendation includes methodologies for the following components: (1) Irrigated Acreage, (2) Reference ET, (2) Potential ET, (3) Actual ET, (4) Effective Precipitation, (5) Consumptive Use from Irrigation and Shortages.

7.1 Irrigated Acreage Recommendation

Each of the Upper Division states develops spatial polygon coverage of irrigated acreage within the UCRB for their respective states. However, each state develops the spatial coverage using a different timeline and a different methodology. For this project, the Upper Division states shared their most recent polygon coverages and Reclamation combined and post-processed the data to develop annual coverages for 2017 through 2020.

State spatial coverage of irrigated acreage is currently not developed on the time frame Reclamation requires for CU&L reporting and is not developed using the same procedures across all Upper Division states. Reclamation therefore developed three different approaches to mapping irrigated acreage in the UCRB, that could be potentially used for CU&L reporting.

1. Develop ET thresholds using remote sensing data to define irrigated and non-irrigated land status
2. Define thresholds of seasonal maximum NDVI values to define irrigation status
3. Use output from the IrrMapper application to map irrigation status

All three methods were compared to irrigated crop maps generated by the Upper Division states over multiple years. Although none of the methods precisely replicated the states' irrigated acreage estimates, the states' estimates also likely have some error, as every parcel does not go through a vigorous ground-truthing process each year. Both the first and second approach above attempted to use a common threshold value for the entire UCRB.

As part of the update for the Indicator Gage Method, DRI has begun development of a process to use NDVI time series to identify shorted versus fully irrigated fields, and to define irrigation status similar to the Reclamation approach. The DRI approach shows promise to categorize fallow, shorted, and fully irrigated lands throughout the entire basin, but requires further refinement of timing and NDVI thresholds as well as validation throughout the basin.

WWG recommends combining the work from both Reclamation and DRI to develop annual irrigated acreage maps for the entire basin. Based on preliminary results from both projects, NDVI can be used to define irrigation status, but more work needs to be done to refine thresholds and perform validation. As DRI continues its investigation, WWG recommends that Reclamation incorporate the findings to enhance their use of NDVI time series on an annual basis to develop irrigated acreage maps and continue to use the cropland data layer to help determine annual crop types in areas with frequent crop rotation. In the higher elevations of the basin, perennial crop types rarely change.

7.2 Reference ET Recommendation

Method

As discussed earlier in this report and in Appendix G, reference ET is the amount of ET from a standard reference crop, usually well-watered grass or alfalfa. Reference ET is used as an input to the remote sensing models to calculate actual ET and is also used by some crop coefficient methods, including FAO-56 dual crop coefficient method (Penman-Monteith), to estimate potential crop ET. The remote sensing models investigated in this report estimate the fraction of reference ET occurring at specific satellite overpass times. This fraction is then interpolated to a daily time step and multiplied by reference ET to obtain actual ET. The ASCE Standardized Penman-Monteith reference crop equation was used to calculate reference ET for use in both the remote sensing and Penman-Monteith methods. More specifically, alfalfa reference was used because the height, and therefore the aerodynamic roughness, of the majority of crops in the UCRB (grass hay and alfalfa) is more similar to reference alfalfa than reference grass.

WWG recommends continued use of the ASCE Standardized Penman-Monteith equation to calculate alfalfa reference ET. Penman-Monteith is the preferred standard method for calculating reference ET, as documented in ASCE Manual 70. In addition, alfalfa reference is the standard reference crop used in the METRIC and SSEBop models.

OpenET also uses the Standardized Penman-Monteith equation to calculate reference ET; however, OpenET uses a hybrid approach that utilizes both the grass reference and the alfalfa reference. As noted in Appendix G, in OpenET, both eeMETRIC and SSEBop convert the grass reference ET to an alfalfa reference ET to perform their internal calculations; but apply the grass reference for the time integration between satellite overpasses. One reason OpenET decided to use grass reference was that alfalfa reference can give unrealistically large ET values during the winter months and OpenET quantifies vegetation use throughout the year, not just during the growing season as was done in this project. Appendix G provides more detail on reference ET and OpenET.

Climate Data

The standardized Penman-Monteith equation requires daily climatic data to calculate reference ET including solar radiation, wind speed, temperature, and humidity. For this project, as discussed above and in Appendix D, daily climate data and reference ET was obtained from the gridMET climate dataset. gridMET provides daily meteorological estimates, as well as ASCE Penman-Monteith reference ET (alfalfa and grass) estimates, at 4km resolution from 1979 to present for the contiguous United States. gridMET reference ET data was bias-corrected to local agricultural climate station measurements using stations included in and located within 50 miles of the basin boundary. All stations and datasets included in the bias correction workflow were reviewed for data quality and station location criteria to ensure well-watered conditions. Direct comparisons of gridMET and station reference ET indicated a consistent high bias in gridMET estimates of reference ET in irrigated areas located in arid and semi-arid regions such as the UCRB. Adjustments using station observations account for local and near-surface climate conditioning processes that occur due to irrigation and subsequent ET not represented in the gridMET climate dataset. WWG recommends that the UCRB continue to utilize bias-corrected gridMET data.

OpenET currently uses daily gridMET climate data bias-corrected to climate stations throughout the western United States, including the same climate stations within the UCRB used for bias correction in this study. The bias correction interpolation process used in this project and OpenET differ slightly but produce similar results. OpenET may consider use of other gridded climate data in the future and, as long as the data is bias-corrected to stations within the basin, another gridded data set may be appropriate.

Reference ET Model

WWG recommends that the UCRB use the bias corrected ASCE reference ET estimates from gridMET. If reference ET estimates are not available from gridMET, WWG recommends that the UCRB utilize the Ref-ET model developed and maintained by Richard Allen and the University of Idaho to estimate reference ET (https://www.uidaho.edu/cals/kimberly-research-and-extension-center/research/water-resources/ref-et-software).

7.3 Potential ET Recommendation

Method

Potential ET, as defined in this report, is the theoretical maximum amount of water that a well-watered crop could use under optimal growth and management conditions. Potential ET is typically estimated using crop coefficient models, where reference ET is scaled using crop specific crop coefficients. In this report, Modified Blaney Criddle with an elevation adjustment and Penman-Monteith dual crop coefficient method were investigated. Remote sensing methods calculate actual ET (the actual water used by a crop from both irrigation and precipitation, as well as access to shallow groundwater in some locations). Because of supply limitations throughout the UCRB, a potential ET method was not chosen as the primary method to estimate actual ET. However, a potential ET method is still needed in the UCRB for several reasons:

1. Even though unlikely, the UCRB should be prepared for periods of time when satellite imagery may not be available, whether from cloud cover, smoke, or satellite failure.
2. According to the 1948 UCRB compact, the Upper Division states are required to submit annual estimates of shortages and the CU&L report provides estimates of annual shortages.
3. A method to calculate potential ET could be useful in other modeling projects pursued by the Upper Division States and/or Reclamation.

Reclamation currently uses Modified Blaney-Criddle without an elevation adjustment. This method has significant shortcomings and is no longer consistent with the state of the science. As the report showed, even when adding the recommended standard elevation adjustment, Modified Blaney-Criddle still tended to underestimate potential ET in high elevation areas, for example at the Big Piney EC Tower. Modified Blaney-Criddle performed best at lower elevation

EC Tower locations. The dual crop coefficient method used within ET Demands and applied to alfalfa Reference ET performed well at the well-irrigated EC Towers, specifically at the Palisade tower where it was not necessary to estimate cutting dates. Penman-Monteith with the FAO-56 dual crop coefficient method also reported values that were more similar to those from METRIC and SSEBop in well irrigated fields. Again, as noted above, ASCE Manual 70 recognizes Penman-Monteith as the most accurate reference ET crop coefficient method. Therefore, WWG recommends that Penman-Monteith alfalfa-based reference ET with the ET Demands dual crop coefficient model be used to calculate potential ET in the UCRB. Detailed information on the ET Demands dual crop coefficient model can be found in Appendix D.

Crop Coefficients

Crop specific coefficients vary throughout the growing season as the crop goes through different growth stages. In some areas of the UCRB, studies have been performed to develop locally calibrated crop coefficients. WWG recommends using these coefficients to calculate potential ET only in areas where they were developed. In areas without locally calibrated values, standardized crop coefficients from ASCE Manual 70 and FAO-56 should be used. WWG also recommends that Upper Division states and Reclamation consider developing locally calibrated crop coefficients as time/funds allow. Locally calibrated coefficients will enable ET Demands and other Penman-Monteith based approaches to more accurately calculate potential ET for specific crops and areas of interest.

Potential ET Model

For this project, potential ET was calculated using the ET Demands model. The ET Demands model uses Reclamation, FAO-56, and Manual 70 based crop coefficient curves along with temperature information to simulate growing season, crop stage, and crop development. Remotely sensed NDVI information is used to inform calibration of growing season timing, crop development, and cutting dates each year. WWG recommends that the ET Demands model continue to be the tool used to estimate potential ET throughout the UCRB. Note that model source code and documentation were developed in collaboration with DRI, University of Idaho, and Reclamation and are freely available and tracked using Git version control software. Ideally, Reclamation and the Upper Division states should develop the expertise to operate, calibrate, and process the results from the model annually.

Penman-Monteith estimates the theoretical maximum potential ET, which can be difficult to achieve in practice. It may be appropriate to apply a reduction factor to theoretical maximum potential ET to the majority of fields in the UCRB, as most fields are not laser leveled and it may be difficult to irrigate at a maximum efficiency. WWG does not believe one reduction factor (sometimes termed “efficiency” factor in the CUWG) is appropriate for the entire UCRB;

instead, WWG recommends that the CUWG continue to investigate and justify factors for specific areas. The CUWG should also consider that fields could be leveled or irrigated differently in the future, and factors developed now would need to be updated. Comparing actual ET estimates from the remote sensing approaches with the potential rates derived from ET Demands can help identify areas and regions where optimal growth is rarely achieved, and where corrections may need to be applied to account for water stress or heterogeneity in the crop canopy.

7.4 Actual ET Recommendation

Method

The METRIC and SSEBop remote sensing ET models were used to produce actual ET estimates from 2017 through 2020 for this project. The versions of METRIC and SSEBop models used in this study were operated by the science teams who developed these models. Both methods have been improved over time and generally produce actual ET estimates that are closer to the EC Tower results and provide basin wide actual ET values that are reasonable when compared to other methods used in the UCRB, primarily Colorado's farm balance method. The remote sensing methods estimate actual ET and do not require the use of a method to estimate crop water shortages, growing season start and stop dates, or cuttings. WWG recommends that a remote sensing method be used as the primary method to calculate actual ET in the UCRB.

Actual ET Model

This project considered results from METRIC and SSEBop remote sensing methods. When OpenET estimates became available in 2021, results from the fully automated version of these models, along with data from other satellite-driven ET models utilized in OpenET, were also added to the comparison (Appendix G). Improvements have been made to both the SSEBop and METRIC models as a result of this project. Throughout the project, METRIC consistently performed better in the UCRB than SSEBop, although the SSEBop issues identified and corrected during the project resulted in closer agreement between the two models. Still, METRIC is the more established model, while SSEBop is still being refined as was seen during this project. Cost and time to obtain results from the models were also considered, showing that the supervised data production with SSEBop was both more cost-effective and required less time than supervised data production with METRIC. However, both models have now been fully automated within the OpenET framework.

In OpenET, eeMETRIC, the version of METRIC used on the OpenET platform, is included in the suite of remote sensing options. This version of METRIC runs on the Google Earth Engine platform and was shown to provide results similar to the supervised, semi-automated version of the METRIC model application used in this project. When run on the OpenET platform, eeMETRIC requires considerably less time and is in-line with SSEBop costs for data production. Although long-term funding for OpenET is not guaranteed, the eeMETRIC model could potentially be run independent of the full OpenET platform. WWG recommends the use of the eeMETRIC model to estimate actual ET in the UCRB.

OpenET publicly launched in the fall of 2021. Appendix G provides detailed information on the remote sensing models used in OpenET and the ensemble estimate calculated as the mean of all methods after filtering for outliers using a median absolute deviation approach. As described in Appendix G, WWG agrees that regional biases in some of the models cause the ensemble mean results to be low in areas of complex terrain and land cover. OpenET is currently reviewing these biases and will continue to refine and improve models during future applications. As the models are refined and improved, WWG recommends that the CUWG continue to monitor and understand results generated in OpenET, as it may be appropriate to use the ensemble in the future. The use and application of multiple remote sensing models allows for identification of anomalies in the individual satellite-driven ET models through intercomparison and review. This type of analysis is an important addition to the comparison of ET data against the four flux tower sites that are currently available within the UCRB.

7.5 Effective Precipitation Recommendation

Method

The primary purpose of this project was to analyze and compare methods to estimate consumptive use from irrigation in the UCRB. The focus was mainly on the different methodologies that could compute actual ET without the need for water supply information, which is not readily available. However, actual ET data from the satellite-driven models include consumptive use from both irrigation supply and precipitation. Removing the amount of effective precipitation consumed by the crop and bare soil evaporation is needed to determine the amount of irrigation water consumed by the crop (refer to the Effective Precipitation and Consumptive Use section of Appendix G for a detailed discussion on effective precipitation). The study discussed and documented effective precipitation methods but did not specifically analyze the methods. Instead, a simple effective precipitation method was adopted and used consistently for all consumptive use from irrigation comparisons.

This report, and previous reports for 2017, 2018, and 2019, adopted the TR21 SCS effective precipitation method for calculating effective precipitation, primarily because it is the method currently used by Reclamation for the CU&L reports. WWG and the CUWG, as part of this project, discussed different effective precipitation methods and WWG compiled a memo, included as Appendix I of this report, documenting the pros and cons of the different methods and example results from the different methods.

Although each method has pros and cons; an on-farm soil water balance is the most accurate method when irrigation supply is known or can be estimated. This method can be computed on a daily time step and accounts for winter effective precipitation carried over into the growing season. Although irrigation supply is not known throughout the basin on a daily time step and must be estimated, WWG recommends using a soil water balance for the effective precipitation method.

Effective Precipitation Model

The ET Demands model estimates effective precipitation using a daily soil water balance, including accounting of winter precipitation storage and losses. It is currently not possible to accurately estimate irrigation events across the UCRB, therefore the ET Demands model assumes well-watered conditions and models an irrigation event when water stored in the root zone is depleted below a set threshold (e.g., 50 percent). The soil water balance is simulated in conjunction with potential ET, allowing for estimation of effective precipitation and Net ET at daily time steps without requiring a separate model. The gridMET climate data set used to calculate reference ET includes precipitation, so an additional data set and data processing is not required. Therefore, WWG recommends using the ET Demands model to estimate effective precipitation using a soil water balance with potential future improvements.

WWG recommends that the CUWG investigate improvements that could be made to the soil water balance within the ET Demands model including:

- Winter effective precipitation. Studies completed in areas adjacent to the UCRB indicate that a significant portion of winter precipitation is not available to store in the soil zone, due to sublimation during periods of high wind and/or low relative humidity. WWG recommends that the CUWG investigate options to use the gridded climate data (which includes estimates of both humidity and wind) to develop a method to estimate sublimation with ET Demands, thereby improving the estimates of winter effective precipitation.

- Runoff period effective precipitation. Many areas in the UCRB receive the majority of their irrigation supply during the peak runoff season, and experience significant supply shortages as streamflow drops. In some cases, the amount of water applied during the limited irrigation season results in saturated soils for a period of time. As noted above, the current algorithm used in ET Demands does not represent flood irrigated conditions. Instead, the model applies irrigation water whenever the soil maximum allowable depletion threshold is reached. This simplification likely causes ET Demands to overestimate effective precipitation during the runoff period for this acreage, since the root zone is not continuously saturated and is able to store spring precipitation. WWG recommends that members of the CUWG identify acreage that generally receives an irrigation supply only during the runoff and over-irrigates to take advantage of the limited supply. WWG recommends that ET Demands be enhanced to increase irrigation events for the corresponding grid cells during the typical peak runoff period.

- Late irrigation season effective precipitation. The assumed irrigation in ET Demands likely has the opposite impact during the late irrigation season on acreage that relies on their full irrigation supply during the peak runoff. In the late season, the assumption of irrigation events likely underestimates effective precipitation. WWG recommends that ET Demands be enhanced to decrease or cease irrigation events for the acreage identified for each state in the late irrigation season. In addition, in many of the higher elevation areas within the UCRB, ranchers only have one grass hay cutting around the beginning of August, and do not irrigate the rest of the growing season, even if irrigation supply is available. WWG recommends that the CUWG identify acreage in this category so ET Demands can be flagged to cease irrigation in the corresponding grid cells.

7.6 Consumptive Use from Irrigation and Shortages

Method

Reclamation reports consumptive use in the UCRB from an irrigation supply and reports corresponding shortages. Consumptive use of precipitation is not "charged" as a UCRB consumptive use as precipitation consumptive use occurred on the native vegetation prior to development. Consumptive use from irrigation (CU_{irr}) is simply calculated as Actual ET less effective precipitation. As noted above, WWG recommends that Actual ET be estimated using eeMETRIC and effective precipitation be estimated using the soil water balance algorithm in ET Demands, with potential enhancements discussed above. Shortages are simply calculated as Potential ET estimated from ET Demands less Actual ET estimated using eeMETRIC.

The method recommended to quantify CU_{irr} and associated shortages relies on eeMETRIC. Even though unlikely, the UCRB should be prepared for periods of time when satellite imagery may not be available, whether from cloud cover, smoke, or satellite failure. Currently, Reclamation uses the indicator gage method to calculate CU_{irr} and associated shortages. Reclamation relies on their XCONS model that employs the modified Blaney-Criddle method to estimate Potential ET and the SCS effective precipitation method. Shortages are estimated using the indicator gage method, developed in the 1970s. As discussed in this report, there is an on-going effort to update and document the indicator gage method so it can be available as a back-up to satellite-reliant remote sensing methods. The effort is being driven by the CUWG and DRI. WWG recommends continuing and finalizing this effort so it can be used as a surrogate method, if necessary.

7.7 Recommendation Summary

Figure 39 summarizes the methods and models recommended to calculate CU_{irr} and associated shortages in the UCRB. These methods were chosen based on accuracy, cost, and accessibility. Note that the methods and tools recommended were not available to Reclamation when they developed their current procedure. As such, WWG recommends that the CUWG continue to monitor the science and update to new methodologies and/or tools.

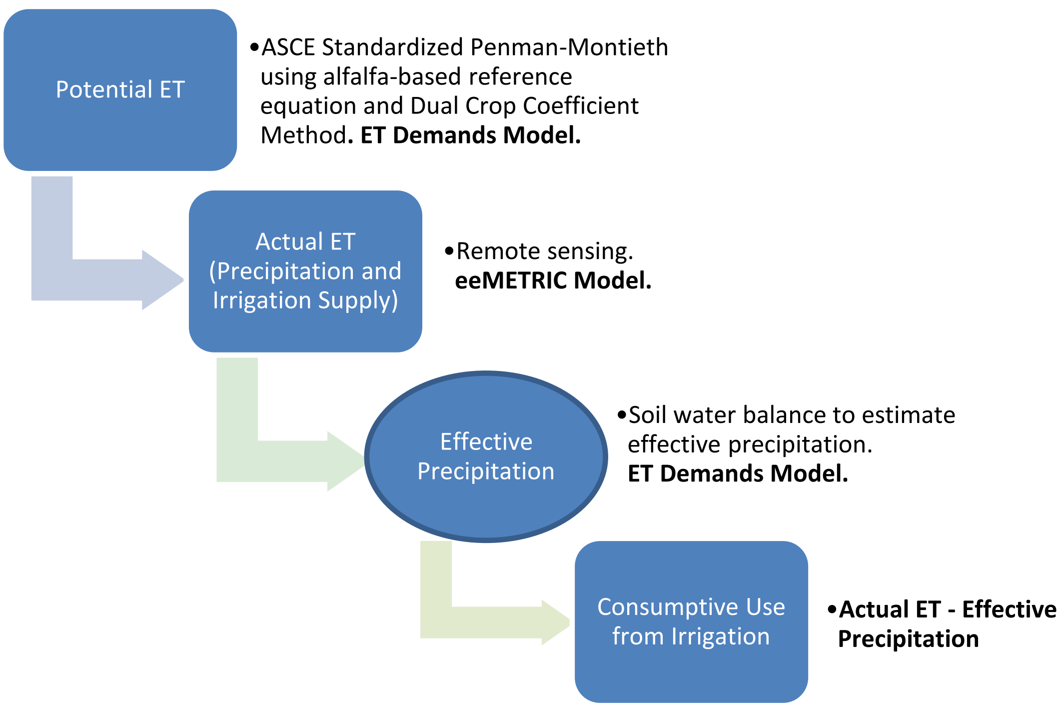


Figure 39. Recommended approach used to determine Potential ET, Actual ET, and Irrigation Consumptive Use for each method

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