

# Energy Balance Approach to Estimating Evapotranspiration on Montane Grass Hay Pastures in a Colorado Water Conservation Program

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## Abstract

Consumptive use (CU) and conserved CU (CCU) was studied under a compensated, temporary and voluntary water conservation program on irrigated montane grass pastures, which dominate agricultural water use in Western Colorado. The thermal-based eeMETRIC model was used to perform this study on 8 treatment sites totaling 1,115.5 ac under two approaches to water conservation through irrigation withdrawal in 2020 and 5 fully irrigated reference sites totaling 397.6 ac where conventional irrigation was maintained. The amount of CU conserved on the fields under irrigation withdrawal was estimated by comparing an adjusted CU rate accounting for effective precipitation of the treatment sites to: 1) a control range of prior years, and; 2) contemporaneous neighboring reference sites. The CCU was also evaluated annually for three years following the year of irrigation withdrawal. Using 5 prior years as a control (2015-2019), the adjusted CU rate (inches) averaged 48.3% lower for sites where irrigation was completely withdrawn in 2020 versus this baseline for the same sites. Subsequently, rates in 2021, 2022, and 2023 were 1.4%, 16.1%, and 6.7% lower, respectively, than the prior years control of 5 years. For the sites that adhered to a partial-season irrigation withdrawal approach in 2020, adjusted CU was 9.5% lower, versus the 5 prior years baseline, then a negligible difference, followed by 28.3%, and 10.7% lower in 2021, 2022, and 2023. Using the contemporaneous neighboring reference, the adjusted CU was 55.6% lower for sites where irrigation was completely withdrawn in 2020 versus their fully irrigated reference pairs. Subsequently, annual adjusted CU in 2021, 2022, and 2023 was 10.3%, 11.8%, and 8.6% lower, respectively, which conformed to producer observations of field impacts. The sites that adhered to a partial-season irrigation withdrawal approach exhibited water use patterns that were 21.0% lower than their companion reference fields, then 10.1%, 15.2%, and 11.5% lower in 2021, 2022, and 2023. The selection of reference condition greatly impacts the amount CU estimated to be conserved. In this study, the amount of CCU calculated was 994.59 acre feet using the prior years control approach and 1,045.10 acre feet using the same year reference condition, representing a difference of approximately 5% between the two methods. Although exhibiting gradual recovery, both approaches show the effect of the irrigation withdrawal lingered for the fully cutoff fields for several years.

# 1. Introduction and Background

Effective water resources planning depends on accurate quantification of the water balance to ensure that policy translates into meaningful impacts without unintended consequences and unrealistic expectations (Kuhn and Fleck, 2019). In light of this reality, the Colorado Basin Roundtable (CBRT) and the Colorado Water Conservation Board (CWCB), initiated this study in 2020 of consumptive use (CU) in a ranching area approximately 6,000 ft above Mean Sea Level (MSL) near Kremmling, CO. The goal was to simulate a water conservation program and estimate CU under irrigation withdrawal (defined periods of time without irrigation) on large (median 104.35 ac; range 31.4 - 345.2 ac) montane fields of grass, forbs, and sedges with varying soils and groundwater levels. Irrigation withdrawal programs are a strategy for augmenting flows in the Colorado River during times of natural drought and/or water sharing arrangements that compensate producers for voluntarily and temporarily withdrawing use of their irrigation water. As such, these programs are aimed at conserving CU by reducing a portion of beneficial CU inherent to the water rights appurtenant to irrigated land. This is accomplished by diverting less water than permitted, leaving an increase in supply in the river and delivery system.

Despite comprising the majority (>80%) of agricultural land in western Colorado, CU rates of irrigated montane grass hay pastures have not been extensively studied. Heterogenous micrometeorology at higher elevations can uniquely affect CU (Allen et al., 1998; Henning and Henning, 1981; Li et al., 2008; Goulden and Bales, 2014; Liou and Kar, 2014). For example, both temperature and vapor pressure decrease with increasing altitude, patterns that are described by the atmospheric lapse rate. These cooler and drier conditions contribute to reduced CU (Goldblatt, 2016; Constantinos, 2019). Conversely, lower atmospheric pressure and higher solar radiation levels at higher altitudes can contribute to increased CU (Adhikari, 2016; Constantinos, 2019).

A key contribution of this study is its provision of rare, field-scale data on actual evapotranspiration ( $ET_a$ ) under conditions of irrigation withdrawal. These administratively imposed reductions in water application have not been widely studied, even though the effectiveness of agricultural water conservation programs fundamentally depends on how much *actual water* goes unused by vegetation that would have consumed it had the program not been implemented. Since the term “consumptive use” became the legal nomenclature for  $ET_a$  in contexts such as changes of water rights, substitute water supply planning, and augmentation for depletion replacement, numerous methods have been used to estimate historical crop water use (Smith et al., 1996). While many of these approaches are statutorily acceptable and adequate for regulatory purposes, they often lack the precision required for effective planning in increasingly critical and occasionally contentious water management scenarios.

The U.S. Bureau of Reclamation (USBR), for example, developed the Indicator Gage Method to perform seasonal CU calculations, enabling the assessment of water supply limitations in critical regions like the Colorado River Basin (Bruce et al., 2018). Widely recognized for its practicality, the method plays a key role in guiding decisions related to water allocation. Diversion records on many ditch systems lack the fine granularity necessary, however, to use this method at the parcel scale where irrigation withdrawal programs are implemented (URS, 2013).

Similarly, physically-based models (Modified Blaney-Criddle, Hargreaves, Penman-Monteith) estimate crop water use by first calculating a reference ET value from local weather data and then applying crop-specific coefficients to represent the water demands of different vegetation types. These models must be calibrated using intensive work, often involving lysimeters, but at best provide estimates of potential ET ( $ET_p$ ) at high elevations without accounting for infield characteristics or management activities (Kruse and Haise, 1974; Walter et al., 1990; Leonard Rice Consulting Engineers, 1994; Smith, 2004). For example, Pochop et al. (1984) applied altitude-based correction factors to improve  $ET_p$  estimates along

elevation gradients when using the Blaney-Criddle method. In some cases, these models have exhibited significant estimation errors in semi-arid, high-elevation environments (Temple et al., 2000; Smith, 2008). Moreover, given that  $ET_p$  represents well-watered conditions, using this parameter as a historical reference can artificially inflate the amount of water that is presumed conserved. Additionally, the need for idealized crop coefficients renders these models inapplicable for estimating water use under water-supply limited conditions. Before the adoption of remote sensing approaches, however, water administrative agencies relied on these models to estimate crop water use (UCRC and Wilson Water Group, 2018).

Alternatively, the direct measurement of  $ET_a$  using lysimetry offers high accuracy but is limited to single-point locations, which may not represent the diverse ecological and meteorological conditions of larger areas enrolled in water conservation programs. Moreover, the method is prohibitively expensive to implement and maintain across multiple fields with varying irrigation practices (Walter et al., 1990; Carlson et al., 1991; Tang et al., 2009).

More accurate, scalable, and transferrable approaches for estimating  $ET_a$  are therefore needed for agricultural water conservation and drought resilience programs to be cost-effectively implemented, monitored, and verified across large, diverse, and administratively decentralized areas (Jones and Colby, 2012). Given the methodological and practical limitations of the methods described earlier, remote sensing-based models have been adopted as a tool for large-scale CU evaluations (UCRC, 2022; Mefford et al., 2022). These models have the capability to estimate actual water consumption over substantially large geographic areas, which helps mitigate many of the limitations associated with previously used methods (Burkhalter et al., 2013; Cuenca et al., 2013). In the Colorado River Basin specifically, the Simplified Surface Energy Balance (SSEBop) model has been used to model spatial  $ET_a$  validated with eddy covariance and HUC8-derived water balance-based data (Senay et al., 2016; Senay et al., 2018).

Certain limitations of remote sensing-based modeling should be acknowledged. To begin with, the accuracy of remote sensing models can be affected by environmental conditions and availability of local weather data. Continual ground-based monitoring therefore becomes critical because satellite passes are still infrequent enough for remotely sensed data to be limited by cloud cover, which can affect image quality, especially at higher elevation areas where cloud cover can be more frequent. This limitation can be resolved through additional effort using a “time integration approach” by which the temporally irresolute ET estimates are correlated with weekly or even daily estimates from ground-based monitoring and local reference ET using the Gridded Surface Meteorological (gridMET) dataset (Allen et al., 2007). Also, given that the most accurate approach to estimate  $ET_a$  with remotely sensed spatial data is now recognized to utilize energy-balance principles, another limitation exists as the Landsat suite of satellites are the only space-borne units with the highest spatial resolution (100 m) in the thermal band needed for energy-balance modeling (Kjaersgaard et al., 2011). The size of this thermal band means that it can be contaminated from adjacent areas outside of the site boundaries, which imposes a minimum area requirement at which models can be used. This limitation can be resolved by resampling or disaggregating thermal data estimates down to the resolution of multispectral measurements (30 m), requiring professional expertise in image post-processing techniques. In fact, a threshold minimum of expertise is highly recommended to properly execute and interpret these models and assure levels of accuracy needed for effective water supply planning (Allen et al., 2011).

Remote sensing techniques nevertheless continue to improve to address these limitations. For instance, easy access to these models, which are now automated the Google Earth Engine (GEE) on the OpenET webpage ([www.etdata.org](http://www.etdata.org)) based on the work of Melton et al. (2021), somewhat compensates for the expertise needed to execute them, although professional experience is still recommended to interpret this

output. Gaps also still exist between research and practical applications, so evaluation projects are useful for improving awareness among water administrators about the benefits and limitations of remote sensing-based modeling (Bastiaanssen and Bos, 1999; Bastiaanssen et al., 2000; Ambast et al. 2002).

In this study, remote sensing-based energy balance modeling was used to assess  $ET_a$  on montane grass hay pastures before, during, and after a simulated large scale water conservation program. The amount of conserved CU (CCU) removed from the fields under irrigation withdrawal was estimated by comparing the  $ET_a$  rates of the withdrawn irrigation sites against two reference conditions: 1) a control range of prior years, and; 2) contemporaneous neighboring reference sites. This study makes two key contributions: first, it provides a rare evaluation of  $ET_a$  on montane grass hay pastures at high elevations; and second, it examines how these pastures respond under varying stages of irrigation withdrawal. By applying remote-sensing-based  $ET_a$  models, the study offers insights into water conservation outcomes under real-world irrigation reduction practices, contributing to broader discussions on drought resilience and water supply management in the Colorado River Basin.

## 2 Study Location and Methods

The study utilized a hybrid paired site approach (Clausen and Spooner, 1993). This approach compares conservation practices, designated as treatment (TRT) conditions, against reference (REF) conditions that are irrigated according to conventional timing and amounts (Figure 2.1). Paired sites were selected based on their proximity, which supported the presumption of similar soil, slope, vegetation, hydrology, and weather (e.g., temperatures, precipitation), with historically equivalent irrigation and grazing practices. Fields in this region are irregularly shaped and not easily delineated into traditional research plots, so the study field boundaries were delineated based on how and where irrigation could be realistically withdrawn without imposing significant management challenges for the participating irrigators.



**Figure 2.1** Generic paired field study experimental design contrasting well-irrigated pasture vs fields under irrigation withdrawal. This figure was generated using an AI image creator, based on user-provided input and guidance.

### 2.1 Study Location and Field Characteristics

The study took place near Kremmling in Grand County, Colorado, at an elevation exceeding 7,000 feet above mean sea level (MSL), within the headwaters of the Colorado River. Agriculture in this region reflects typical patterns on the Western Slope of the Rockies, where irrigated fields are primarily used for hay production and livestock grazing. The area receives an average of 12 inches (305 mm) of rainfall, 55 inches (1,397 mm) of snowfall, and has about 70 frost-free days annually. Under these conditions, cool-season grasses generally begin to green up in late April to early May, following snowmelt and soil warming. The irrigated grass pastures studied include commonly used cool-season species such as smooth

brome (*Bromus inermis*), timothy (*Phleum pratense*), tall fescue (*Festuca arundinacea*), intermediate wheatgrass (*Thinopyrum intermedium*), and Kentucky bluegrass (*Poa pratensis*). Ranches participating in the study rely on irrigation water from the Colorado River, conveyed through 18 separate ditches sourced from Bull Run, Pass Creek, Red Dirt Creek, and Williams Fork, with water rights ranging from 0.5 to 221 ft<sup>3</sup>/s for direct flow and 240 to 1,870 acre-feet for storage. Soils are predominantly loams and clay loams, with Leavitt (Loam), Binco (Clay Loam), Harsha (Loam), and Cumulic Cryaquolls commonly found, particularly in meadow settings.

The 5 primary REF fields were always irrigated according to conventional timing and amounts. The water conservation study sites included 6 TRT fields under full-season irrigation withdrawal and 2 TRT fields under partial-season withdrawal (Table 2.1). In total, the study evaluated 397.6 ac of reference irrigation conditions, 954.7 ac of land under full irrigation withdrawal, and 160.8 ac of land under partial irrigation withdrawal. An agreement between ranchers sharing the same conveyance ditch, required JLM T1 and SBT T1 to participate in the water conservation program, but were not used in the analysis.

**TABLE 2.1.** Summary of Field Characteristics and Irrigation Practices for Treatment and Reference Fields\*

Field Name	Irrigation Practice	Field Size (ac)	Field Size (ha)
<i>Fields Subjected to Irrigation Withdrawals in 2020</i>			
BMR T1 2020	Full season, no irrigation	31.4	12.7
GPR T1 2020	Full season, no irrigation	202.8	82.1
GPR T2 2020	Full season, no irrigation	345.2	139.7
HSR T1 2020	Full season, no irrigation	85.5	34.6
RCR T1 2020	Split Season, no irrigation after June 15	37.6	15.2
RSR T1 2020	Split Season, no irrigation after June 15	123.2	49.9
SBR T1 2020	Full season, no irrigation	70.2	28.4
SPR T1 2020	Full season, no irrigation	220.6	89.3
<b>Total</b>		<b>1,115.5</b>	<b>452.0</b>
<i>Not Included in Remote Sensing Evaluations</i>			
JLM T1 2020	Full season, no irrigation	15.8	6.4
SBT T1 2020	Full season, no irrigation	9.1	3.7
<b>Total</b>		<b>24.8</b>	<b>10.1</b>
<i>Reference Fields Experiencing No Irrigation Withdrawal</i>			
GPR R1 2020	Reference, historical irrigation	93.4	37.8
RCR R1 2020	Reference, historical irrigation	225.9	91.4
RSR R1 2020	Reference, historical irrigation	21.0	8.5
SBR R1 2020	Reference, historical irrigation	28.7	11.6
SPR R1 2020	Reference, historical irrigation	28.6	11.6
<b>Total</b>		<b>397.6</b>	<b>160.9</b>

\*REF and TRT sites are designated as R and T. This data is publicly available, but names have been removed to protect the anonymity.

## 2.2 Paired Site Correlation Analysis

Data from 1991-2019 was used to perform a Pearson correlation analysis to determine whether the paired REF and TRT were suitably similar enough for the contemporaneous neighboring reference approach. The Pearson correlation coefficient ( $r$ ) for each pair was calculated for monthly water use during the typical growing season (April-September). Pearson correlation analysis was particularly appropriate for this data because it measures the linear relationship between two continuous variables. The analysis provides a quantitative value, indicating both the strength and direction of the relationship, where values

close to 1 or -1 denote strong positive or negative correlations, respectively, and values near 0 indicate weak or no correlation.

### *2.3 Conceptual Model for Irrigation Withdrawal Fields*

In irrigated systems, the water balance equation (Equation 1) accounts for inputs and outputs to determine crop water deficits and surpluses. The general form of this equation is:

$$IR + P_{\text{eff}} + SM_{\text{init}} + CR = ET_a + D + R + SM_{\text{final}} \quad \text{Equation (1)}$$

where  $ET_a$  has been previously defined, and  $IR$  = irrigation requirement,  $P_{\text{eff}}$  = effective precipitation;  $SM_{\text{init}}$  = initial soil moisture;  $CR$  = capillary rise;  $D$  = deep percolation;  $R$  = runoff; and  $SM_{\text{final}}$  = final soil moisture, and all units are in inches or mm.

In irrigation-deprived systems, it is important to interpret and understand the interplay between the terms of the water balance appropriately, specifically with regards to  $IR$ . Typically,  $IR$  represents the amount of water needed to fully meet crop water demand, assuming supplemental watering will occur to drive optimal production levels, and compensate for any deficit caused by limited precipitation. In the case of non-irrigated conditions, however, the water balance equation simplifies to include only  $P_{\text{eff}}$ ,  $SM_{\text{init}}$ ,  $ET_a$ ,  $SM_{\text{final}}$ , and potentially  $CR$  if the groundwater table is close enough to the lower root zone. Even though  $ET_a$  may exceed  $P_{\text{eff}}$ , the absence of the  $IR$  term in this non-irrigated context can be confusing, as there is no “requirement” being fulfilled to meet  $ET$  demand through irrigation. Fundamentally, this means that in an irrigation withdrawal scenario, the fraction of  $ET_a$  that is not attributable to  $P_{\text{eff}}$  must come from stored soil moisture and can be calculated as  $SM_{\text{init}} - SM_{\text{final}}$  (Gómez et al., 2022). For this study, the term “Soil Moisture Supplied Consumptive Use” abbreviated  $SM-CU$  is used to describe this portion of  $ET_a$ , clarifying that in non-irrigated hay pastures, vegetative water use will be partially sustained by soil moisture reserves which can ultimately be depleted throughout the growing season.

Naturally supplied water that enters the soil and remains within the root zone is generally defined as  $P_{\text{eff}}$ . Historically,  $P_{\text{eff}}$  in the Upper Colorado River Basin has been estimated using the United States Department of Agriculture Soil Conservation Service TR21 method (USDA-SCS, 1970). The StateCU model maintained and utilized by the Colorado Division of Water Resources, for example, utilizes the TR21 method (CDWR, 2021). However, this study ultimately resolved to calculate  $P_{\text{eff}}$  using the U.S. Bureau of Reclamation (USBR) ET Demands model. This approach models the soil water balance and  $ET_p$  to estimate  $P_{\text{eff}}$  at a daily timestep. The ET Demands model makes use of the FAO-56 dual crop coefficient model (Allen et al., 1998) and relies on meteorological data from the gridMET climate dataset and soil composition data from the NRCS State Soil Geographic (STATSGO) database (USDA-NRCS, 1991). As such,  $P_{\text{eff}}$  can be calculated on a field-by-field basis. The calculations used in this study were produced using methodology published by Pearson et al. (2024), reporting large interannual variability of  $P_{\text{eff}}$  for Colorado ( $1.04 \pm 0.16$  ft/year).

### *2.4 Modeling Approach for Estimating and Mapping ET*

The automated version of the Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) model (Allen et al., 2005; Allen et al., 2007) was applied to estimate  $ET_a$  at the study sites. The METRIC model uses a thermal-based energy balance approach, relying on satellite measurements of surface temperature and reflectance combined with other key land surface and weather variables. Allen et al. (2011) determined that modeling by a user competent in atmospheric biophysics can produce estimates which may err 5-10%, but novice users may be accurate within no better than 30-40%. The automated version and associated calibration algorithms were developed, therefore, to improve user performance (Allen et al., 2013; Morton et al., 2013), and allow the model to be accessed through the Google Earth Engine (GEE) under an automated version of METRIC (eeMETRIC). Results from the

eeMETRIC model have demonstrated conformity with other methods, including lysimeter, Bowen ratio, and eddy flux techniques (Tasumi et al., 2005; Allen et al., 2007; Allen et al., 2011; Irmak et al., 2011).

For this study, the eeMETRIC model was used to estimate monthly  $ET_a$  for the REF and TRT sites. Model results were mapped and evaluated in QGIS (Free Software Foundation, Inc.) as raster data for the study years 2016-2021. The OpenET platform archives baseline data dating back to 1991, allowing access to 29 years of data before this study was initiated. Spatial averages of field parameters were derived from the entirety of pixels analyzed within the field boundaries. As such 2.47 ac (1 ha) contains approximately 11 pixels (30 x 30 m). For example, at 203.7 ac and 344.9 ac, the GPR T1 and GPR T2 site  $ET_a$  averages are based on 915 and 1,551 separate estimations for each Landsat pass. Annual  $ET_a$  rates for the study sites were then calculated as the sum of the spatially averaged monthly means. Appendix A provides clear definitions for the key remote sensing and water balance variables used in this study, as developed by the Desert Research Institute. These definitions are essential for understanding how water consumption, shortages, and legally transferrable water volumes were calculated throughout the study.

### *2.5 Advancing Accuracy in ET Estimation*

The estimates of ET previously reported in Evaluation of Conserved Consumptive Use in the Upper Colorado: 2022 Annual Report (Cabot et al., 2022) used eeMETRIC model version 0.20.26. While this version of the model performed well compared with ET data derived from the eddy-covariance station at the Kremmling, CO study site, ET models based on remote sensing can undergo periodic development as modeling methodologies are refined and new or improved input data are made available. The eeMETRIC model underwent refinement in 2024 as part of a comprehensive evaluation of model performance within the Upper Colorado River Basin (UCRB). The changes to the eeMETRIC model were published within OpenET as eeMETRIC model version 0.20.33 and described in Pearson, et al. (2024).

A review of eeMETRIC model version 0.20.26 in the UCRB identified that areas of irrigated agriculture were often misclassified as non-agricultural by the Cropland Data Layer (CDL) (USDA-NASS) which describes agricultural landcover at 30-meter resolution CONUS-wide. To improve classification of agricultural lands within the UCRB, the National Land Cover Database (NLCD) (Dewitz, 2024) was used in conjunction with CDL, to distinguish areas of cultivated agriculture versus natural vegetation (e.g. grasslands and wetlands). These inputs are important as they influence calculations of soil heat flux and estimates of aerodynamic roughness (Allen et al., 2010). eeMETRIC version 0.20.33 additionally integrated improvements to estimates of land surface temperature across elevation gradients and refined automated calibration which reduced the influence of extreme values in key inputs such as NDVI, land surface temperature, and albedo in model calibrations. These changes implemented in eeMETRIC version 0.20.33 reduced uncertainty in estimates of agricultural  $ET_a$  throughout the UCRB, however detailed, field-scale evaluation of model performance has not conducted as of the data of this publication.

### *2.6 Estimating Conserved Consumptive Use*

The distinction between  $P_{eff}$  and SM-CU is essential for accurately estimating CCU, particularly within the framework of Colorado water law and the definition of "beneficial consumptive use." In conventional water leasing,  $P_{eff}$  is excluded from CCU calculations because it represents naturally supplied water and supplies CU demands over and above water diverted for irrigation (UCRC and Wilson Water Group, 2018). In contrast, water supplied from soil moisture should be included when estimating CCU because it meets crop water demand that exceeds what is provided by effective precipitation. This excess demand must be fulfilled by a stored supply, and in irrigated systems, that stored soil moisture typically originates from earlier irrigation events, effectively functioning as a reserve or "bank" created by diverted water.

By applying this distinction, the estimated CCU rates correspond to water use that is legally transferrable, namely that which is derived from diverted water rights (WECO, 2021). After subtracting  $P_{eff}$  from the  $ET_a$  for the research sites, the analysis used in this study isolated the impact of irrigation withdrawal on water consumption solely based on sources that are reasoned to have originated with irrigation.

For the prior years control approach, the reference condition is based on the same fields that experienced irrigation withdrawal in 2020, using their own historical IR under full irrigation as the baseline for comparison. The CCU rates calculated using this approach are based on the following equation:

$$CCU = IR' - SM-CU_{TRT} \quad \text{Equation (2)}$$

where units are in inches,  $IR'$  is the IR for the TRT sites prior to the irrigation withdrawal year, and  $SM-CU_{TRT}$  quantifies the water use during irrigation withdrawal. By averaging IR across multiple years prior to the irrigation withdrawal, this approach provides a baseline for what would be expected under typical full irrigation. However, the outcome is highly sensitive to the length of the historical window selected in calculating  $IR'$ . While this method does not account for year-specific weather variability, it provides valuable context for understanding the magnitude of ET reductions observed in 2020. Because the effects of irrigation withdrawal develop gradually and are not associated with a single identifiable onset date, and because early-season water demands tend to be similar across years regardless of irrigation status, total annual IR was used as the basis for comparison. This approach captures the full cumulative impact of reduced water application throughout the program year 2020, while also accounting for antecedent soil moisture conditions that may influence early-season plant water use. Relying on the complete annual IR avoids the need to define an arbitrary seasonal window and ensures that both the legacy effects of pre-withdrawal conditions and the progression of water limitation over time are represented in the analysis.

For the contemporaneous reference approach, CU on the treatment fields was compared to nearby fields that remained fully irrigated during the same growing season. Using spatially averaged water use from remote sensing estimates, this approach allows for direct year-to-year comparison while controlling for interannual climatic variation. By holding the year constant, differences in water use can be more confidently attributed to irrigation status rather than to variability in weather or atmospheric demand. Reference fields were selected based on producer input and their similarity in species composition, management practices, and environmental conditions, ensuring a meaningful basis for comparison. The CCU rates calculated using this approach are based on the following equation:

$$CCU = IR_{REF} - SM-CU_{TRT} \quad \text{Equation (3)}$$

Where units are in inches and  $IR_{REF}$  is the calculated IR for the REF site paired with its respective TRT site, and  $SM-CU_{TRT}$  is the plant water use from stored soil moisture during the effective timeframe of the irrigation withdrawal. Because it is not possible to precisely determine when reduced irrigation began to impact plant water use, annual water use values were applied to ensure consistency across sites. This decision was reasoned by the fact that early-season water use in Grand County is typically very low, and the REF and TRT fields were selected based on their proximity and similarity in management and biophysical conditions. Consequently, early-season differences were expected to be minimal. Using annual rates, therefore, provided a standardized basis for comparison both within and across fields. Given that irrigation was resumed during the recovery period following withdrawal, IR validly represents CU from non-natural sources during those years. Accordingly, this approach was used to calculate CCU for years subsequent to irrigation withdrawal.

The actual CCU volume (acre-feet) for each treatment field was calculated by multiplying the CCU rates derived from Equations 2 and 3 by the corresponding field area.

### 3 Results

The conservation activities were implemented effectively, and the impact of irrigation withdrawal was clearly evident (Figure 3.1). In most circumstances, the participants successfully maintained the separation between REF and TRT fields that was precise and impressive, considering the nature of the “wild flood” systems they operate.

#### 3.1 Estimating Consumptive Use with Remote Sensing

To highlight the difference between modeling approaches estimates, Table 3.3.1 summarizes basic ET data for January through December, averaged across all the project study sites for 2016-2019. \*At the start of the project, Thompson (2021) estimated  $ET_p$  during this period from DWR Mountain Meadow crop coefficients at Kremmling NOAA Weather Station USC00054664 to be 30.25 in. Data from the CSU CoAgMet station northeast of Kremmling, CO was used to calculate  $ET_p$  using the ASCE Standardized Reference Evapotranspiration Equation (ASCE-EWRI, 2005) and evaluated to be 29.68 in. Estimates from the results of a lysimeter study conducted in Grand County by Carlson et al. (1991) was only able to produce estimates for the May–September timeframe but still estimated ET for this region at 39.06 in.

Estimates were also made for  $ET_a$  on the total acreage for sites listed in Table 2.1 using eeMETRIC version 0.20.06 and eeMETRIC version 0.20.33. Despite the update to eeMETRIC, the annual average  $ET_a$  across all sites for the period 2016-2019 was relatively minor.



**Figure 3.1.** Healthy vegetation under irrigated conditions abutting dry conditions where irrigation water was withdrawn, showing evident difference between irrigated (REF) and non-irrigated (TRT) at the SPR R1 and T1 sites. Photo taken 08/27/20.

**TABLE 3.3.1.** Comparison of  $ET_p$  to  $ET_a$  on Study Sites (Average for 2016-2019)

Method	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Estimated $ET_p$ <sup>1</sup>	0.14	0.21	0.41	1.28	4.72	7.41	6.54	5.33	3.35	0.52	0.24	0.1	30.25
ASCE-EWRI $ET_p$ <sup>2</sup>	0.00	0.00	0.00	0.60	5.09	6.43	6.98	5.09	4.28	1.21	0.00	0.00	29.68
Lysimeter $ET$ <sup>3</sup>	0.00	0.00	0.00	3.80	5.17	6.42	6.73	6.13	5.63	3.03	1.42	0.73	39.06
eeMETRIC $ET_a$ v. 0.20.06	0.11	0.37	1.08	1.16	2.68	6.52	7.24	4.94	2.44	1.32	0.56	0.17	28.59
eeMETRIC $ET_a$ v. 0.20.33	0.12	0.39	1.02	1.07	2.56	6.48	7.26	4.98	2.39	1.30	0.57	0.19	28.33

<sup>1</sup> PET calculated using DWR Mountain Meadow crop coefficients at Kremmling NOAA station USC00054664 (Thompson, 2021)

<sup>2</sup> PET calculated with data from CSU CoAgMet site (40°06'55.44" N, 106°16'58.80" W, 7,534 ft MSL NE of Kremmling, CO using the ASCE Standardized Reference Evapotranspiration Equation (ASCE-EWRI, 2005) with grass hay Kc and April 1 greenup date. 2016-2017 data was not available for ASCE-EWRI  $ET_p$  calculations.

<sup>3</sup> Grand County lysimeter results (Carlson et al., 1991), calculated using average of Blaney-Criddle crop coefficients (Smith et al., 2008) at Kremmling NOAA in StateCU

Similarity between  $ET_p$  and lysimeter rates is expected, given that both approaches are designed to estimate ET for well-watered systems. The estimations produced from the remote sensing-based models, however, clearly depict the difference between  $ET_p$  and  $ET_a$ , observing that the  $ET_p$  approaches likely

\* 2016-2019 was an initial study period used before the OpenET project provided further analysis prior to 2016.

overestimate the amount of water actually consumed on these landscapes, which often do not receive their full demand of water uniformly across the entire field. Additionally, it is recognized that reference ET equations do not represent measurable quantities during non-growing periods, while remote sensing-based modeling is generally capable of better estimating  $ET_a$  at lower temperature ranges. Coefficient-based ET equations also cannot capture actual diminished ET during re-growth conditions after cutting or grazing.

### *3.2 Determining Conserved Consumptive Use*

Under Colorado water law, the amount of water that is considered transferable is based on the historical consumptive use (HCU) of the water right. This is considered water historically consumed by the crop, not the total water diverted or applied, but rather the portion of water actually used and not returned to the system. The goal of the transfer process is to ensure that the change in water use does not injure other users by increasing the overall consumption beyond what has historically occurred.

When an irrigator voluntarily does not use a water right, the difference constitutes a foregone diversion removing a proportion of beneficial historical CU originating from the appropriation (Colorado Water Institute, 2016). If all other factors (e.g., grass conditions, field area) remain generally constant, sites where irrigation water is not used will have lower CU compared to the HCU in prior years for these fields, and theoretically a well-irrigated paired reference site. The proportion that is not consumed on the field is the previously discussed CCU that can be utilized elsewhere through a temporary transfer of water use (CAWA, 2008; GVVUA and J-U-B Engineers, Inc., 2017). This CCU is presumed to remain in the river as a quantifiable volume despite its “theoretically estimated” nature, thereby balancing the concept of a physical reality with the legal and administrative frameworks that rely on estimations. To ensure the water reaches its intended downstream target, CCU must be legally protected from appropriation by others through a legal approach referred to as “shepherding” (MacDonnell and Castle, 2017).

For this study, the basis of the CCU calculations is the timeseries of monthly  $ET_a$  rates between 2020-2023 derived from eeMETRIC for the TRT fields subjected to irrigation withdrawals in 2020 described in Table 2.1. Since the calculation of CCU requires a knowable reference condition, two approaches were employed similar to other studies that have evaluated the impacts of irrigation withdrawal (Allen and Torres-Rua, 2018). Approach 1 applies a prior years control that leverages the historical data of the study field as a baseline. This approach assumes that past performance represents normal conditions without the irrigation withdrawal (Kharrou et al., 2021; Yang et al., 2014). Approach 2 uses a contemporaneous neighboring reference control that assigns a nearby reference field as a baseline. This approach ensures a comparison between the treatment and control under the same environmental and meteorological conditions (Papadavid et al., 2012; Yang and Shang, 2013; Lei et al., 2014).

### *3.3 Site Correlation Analysis for Prior Years Control*

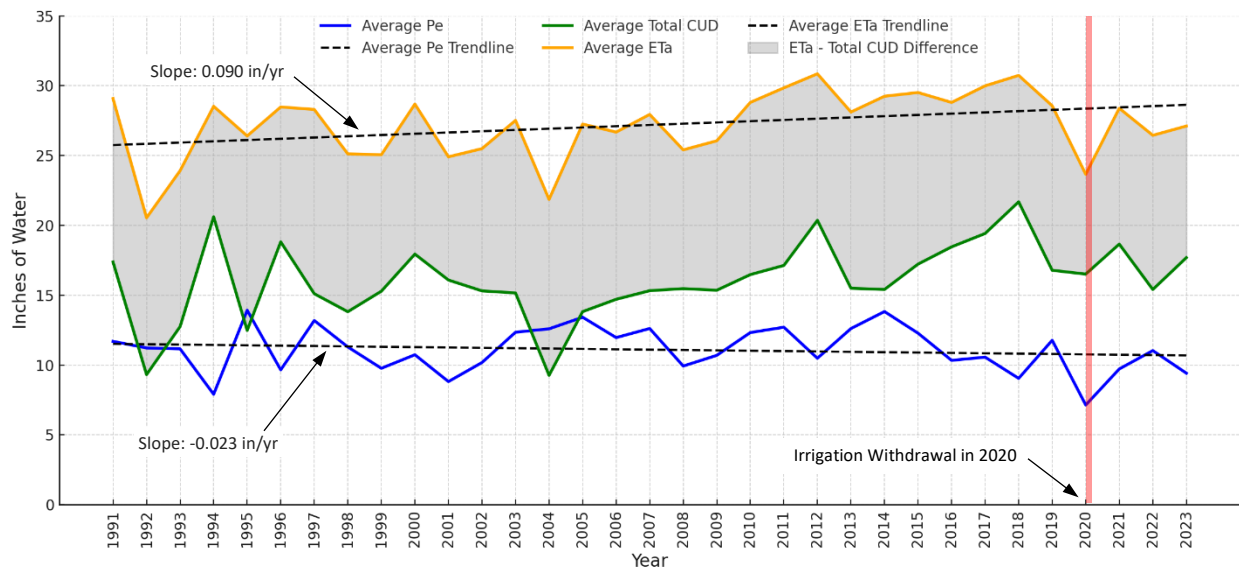
To assess the premise of the Prior Years Control that HCU on the TRT fields is adequate as a baseline reference, the Coefficient of Variation (CV) and Percent Change in Standard Deviation (PCSD) were calculated for annual  $ET_a$  and IR for each site across the years 1991-2019 (Table 3.3.1). Since the Prior Years Control focuses exclusively on the TRT sites (GPRT1, GPRT2, SPRT1, SBRT1, BMR, and HSR), the CV and PCSD were calculated just for these fields. Lower CV indicates more consistent ET rates, while a higher CV reflects greater variability across years. Values of CV between 0.05-0.15 are generally acceptable for most natural and environmental datasets, where some variability is expected. The PCSD measures how much  $ET_a$  and IR change from one year to the next. Smaller values indicate that water use patterns exhibit smoother, more gradual changes over time, while larger values suggest greater volatility.

Most sites exhibit CV values within a range of 0.05–0.15 for  $ET_a$ , indicating a slightly increasing trend over time (Figure 3.3.1). All sites, however, have CV values for IR that are outside the acceptable range

that would define reasonable similarity. The PCSD (%) values for  $ET_a$  are smoother in terms of interannual variability, averaging 15.75%, though PCSD for IR shows more variability, reflecting the dynamic nature of crop water demand, driven by changing precipitation rates (Figure 3.3.2). While the variability of prior year  $ET_a$  on the TRT sites is low, these results underscore the increasing trend in IR, which may confound the selection of a suitable baseline for the Prior Years Control approach.

**TABLE 3.3.1.** Interannual correlations in water use for TRT study sites across range of years prior to the irrigation withdrawal program (1991-2019) using Coefficient of Variation (CV) and Percent Change in Standard Deviation (PCSD; %)

	Site							
	BMR	GPRT1	GPRT2	HSR	RCRT1	RSRT1	SBRT1	SPRT1
CV $ET_a$	0.097	0.117	0.102	0.141	0.119	0.103	0.107	0.158
PCSD $ET_a$	14.0%	15.1%	12.4%	17.9%	17.3%	12.7%	16.3%	20.3%
CV IR	0.189	0.240	0.190	0.242	0.293	0.185	0.174	0.336
PCSD IR	28.1%	35.8%	25.9%	35.3%	46.2%	28.5%	29.4%	92.3%



**Figure 3.3.2** Trends in  $P_{eff}$ ,  $ET_a$ , and the total consumptive use deficit (CUD) are shown, with CUD serving as a generalized term to represent irrigation requirements (IR) prior to the irrigation withdrawal program, soil moisture-derived CU (SM-CU) during the program, and a return to IR in the years following the program.

### 3.4. Conserved Consumptive Use based on Prior Years Control

The rate (in/ac) and amount (ac-ft) of CCU calculated using the prior years control was calculated from Equation 2. Three prior year baselines were considered: 1) 1991–2019, the 29-year period representing all data available from eMETRIC modeling; 2) 2010-2019, a 10-year period corresponding to the statutory period for demonstrating historical consumptive use (HCU) in Colorado water rights cases, and; 3) 2015-2019, a 5-year period often used under the System Conservation Pilot Program (SCPP) to assess baseline CU patterns of participating fields prior to program enrollment. A major limitation of this approach is that it does not consider if a site may have been water-supply limited due to irrigation supply or farming practices or if  $P_{eff}$ , early season soil moisture and groundwater contributions have been markedly different in prior years. This means that a prior year IR baseline may result in a lower estimated CCU if conditions for sites under withdrawal have been significantly different in the past.

The time periods analyzed for both full and partial withdrawal sites in 2020 were assessed on an annual basis (January–December). This approach ensured consistency with prior-year reference calculations,

which were also conducted on a full-year basis. By analyzing the entire treatment year (2020) for all sites, a more accurate comparison was provided with the same annual time frame from previous years.

Table 3.4.1 summarizes CU rates and volumes analyzed over the 3 baseline periods.

**TABLE 3.4.1.** Prior Years Control IR Baselines and Analysis for 2020 Conserved Consumptive Use

Site	Size (ac)	Prior Years Control IR Baseline				CCU based on SM-CU in 2020					
		All (in/ac)	10 yr (in/ac)	5 yr (in/ac)	2020 (in/ac)	All (in/ac)	10 yr (in/ac)	5 yr (in/ac)	All (ac-ft)	10 yr (ac-ft)	5 yr (ac-ft)
BMR	31.4	16.26	17.48	18.15	7.84	8.42	9.64	9.47	22.00	25.20	24.75
GPRT1	202.8	16.22	18.56	19.35	4.43	8.38	10.73	10.67	141.71	181.32	180.37
GPRT2	345.2	18.36	20.14	21.31	11.69	10.52	12.30	12.63	302.73	353.85	363.33
HSR	85.5	15.15	18.00	19.46	12.00	7.32	10.16	10.78	52.16	72.44	76.84
RCRT1	37.6	12.82	13.70	15.36	17.98	4.99	5.87	6.68	15.62	18.38	20.93
RSRT1	123.2	18.19	20.17	20.48	20.89	10.36	12.34	11.80	106.32	126.63	121.16
SBRT1	70.2	18.13	18.88	18.74	14.16	10.29	11.05	10.07	60.23	64.65	58.90
SPRT1	220.5	12.06	15.14	16.75	8.73	4.22	7.30	8.07	77.62	134.20	148.31
<b>TOTAL</b>									<b>778.39</b>	<b>976.67</b>	<b>994.59</b>

Full withdrawal sites generally show positive conserved CU values, with higher totals under shorter baseline periods (e.g., 5-year baselines result in greater conserved CU). Partial withdrawal sites (RCRT1 and RSRT1) exhibited lower CCU in all cases, owing to the nature of the partial season irrigation program. Previous studies have also shown that partial-season withdrawal programs generate limited CCU (Allen and Torres-Rua, 2018; Cabot et al., 2018), although there could be other environmental benefits such as streamflow enhancement that are separate aspects outside these types of water conservation approaches.

Overall, total CCU for all sites during the year of irrigation withdrawal ranged was 778.39, 976.67, and 994.59 ac-ft for the all years, 10-year, and 5-year baseline, clearly reflecting the impact of baseline choice on estimated water conservation. These differences derive largely from the increase in  $ET_a$  during prior years, coupled with the decrease in  $P_{eff}$ . The baseline IR in more recent years is simply larger, thereby establishing a higher baseline against which to compare the CU of the fields during the year of withdrawal. Using 5 prior years as a control (2015-2019), for instance, the adjusted CU rate averaged 48.3% lower for sites where irrigation was completely withdrawn in 2020 versus this baseline. Conversely, the lower average IR for the longer timeframes results in a lower calculated CCU during the year of the irrigation withdrawal. For instance, during the 1991–2019 timeframe,  $P_{eff}$  averaged 11.35 inches, reflecting the contribution of precipitation toward meeting  $ET_a$  demand and reducing the reliance on irrigation water to satisfy grass pasture water requirements. In contrast, precipitation in more recent years is lower, increasing reliance on irrigation. While the temporal relationship for  $P_{eff}$  is not statistically significant ( $p$ -value = 0.40), correlation analysis reveals a slight negative correlation (-0.15) for  $P_{eff}$  over time, suggesting a marginal downward trend (blue line) over the analyzed period (1991–2023). Comparing the periods before and after the irrigation withdrawal program, the average  $P_{eff}$  decreased modestly from 11.35 inches (1991–2019) to 9.30 inches (2020–2022). Although this difference is not statistically significant ( $p$ -value = 0.21), it is sufficient to influence the calculated CCU values. The relationships between  $P_{eff}$ ,  $ET_a$ , and total CU deficit (CUD) highlight how variable precipitation affects irrigation requirements and water use over time.

Tables 3.4.2 through 3.4.4 summarize CCU for 2021, 2022, and 2023, analyzed over 3 baseline periods. Values are reported again as rate and volume, for the January–December period across all sites. In 2021, most sites exhibit negative CCU values under the all-years baseline, likely due to the dry conditions that

existed in this area in 2021. Shorter baseline periods then yield increasingly positive values, reflecting greater levels of estimated conservation.

**TABLE 3.4.2.** Prior Years Control IR Baselines and Analysis for 2021 Conserved Consumptive Use

Site	Size (ac)	Prior Years Control IR Baselines				CCU based on Irrigation Requirement in 2021					
		All (in/ac)	10 yr (in/ac)	5 yr (in/ac)	2021 (in/ac)	All (in/ac)	10 yr (in/ac)	5 yr (in/ac)	All (ac-ft)	10 yr (ac-ft)	5 yr (ac-ft)
BMR	31.4	16.26	17.48	18.15	20.04	-3.78	-2.56	-1.88	-9.88	-6.68	-4.92
GPRT1	202.8	16.22	18.56	19.35	18.10	-1.88	0.46	1.25	-31.76	7.85	21.13
GPRT2	345.2	18.36	20.14	21.31	20.94	-2.58	-0.80	0.37	-74.13	-23.00	10.69
HSR	85.5	15.15	18.00	19.46	21.74	-6.58	-3.74	-2.28	-46.93	-26.65	-16.25
RCRT1	37.6	12.82	13.70	15.36	16.31	-3.48	-2.60	-0.95	-10.92	-8.16	-2.98
RSRT1	123.2	18.19	20.17	20.48	19.14	-0.94	1.04	1.34	-9.68	10.63	13.79
SBRT1	70.2	18.13	18.88	18.74	20.02	-1.89	-1.14	-1.28	-11.08	-6.67	-7.48
SPRT1	220.5	12.06	15.14	16.75	11.90	0.16	3.24	4.85	3.01	59.59	89.16
<b>TOTAL</b>									<b>-191.36</b>	<b>6.91</b>	<b>103.14</b>

**TABLE 3.4.3.** Prior Years Control IR Baselines and Analysis for 2022 Conserved Consumptive Use

Site	Size (ac)	Prior Years Control IR Baselines				CCU based on Irrigation Requirement in 2022					
		All (in/ac)	10 yr (in/ac)	5 yr (in/ac)	2022 (in/ac)	All (in/ac)	10 yr (in/ac)	5 yr (in/ac)	All (ac-ft)	10 yr (ac-ft)	5 yr (ac-ft)
BMR	31.4	16.26	17.48	18.15	16.63	-0.38	0.85	1.52	-0.99	2.21	3.97
GPRT1	202.8	16.22	18.56	19.35	16.90	-0.68	1.66	2.45	-11.55	28.06	41.34
GPRT2	345.2	18.36	20.14	21.31	18.09	0.27	2.05	3.22	7.72	58.84	92.54
HSR	85.5	15.15	18.00	19.46	17.14	-1.99	0.86	2.32	-14.17	6.11	16.51
RCRT1	37.6	12.82	13.70	15.36	10.70	2.12	3.00	4.66	6.65	9.41	14.59
RSRT1	123.2	18.19	20.17	20.48	15.09	3.11	5.09	5.39	31.89	52.20	55.36
SBRT1	70.2	18.13	18.88	18.74	17.19	0.94	1.69	1.55	5.49	9.91	9.09
SPRT1	220.5	12.06	15.14	16.75	9.99	2.07	5.15	6.75	37.96	94.54	124.11
<b>TOTAL</b>									<b>63.00</b>	<b>261.28</b>	<b>357.51</b>

**TABLE 3.4.4.** Prior Years Control IR Baselines and Analysis for 2023 Conserved Consumptive Use

Site	Size (ac)	Prior Years Control IR Baselines				CCU based on Irrigation Requirement in 2023					
		All (in/ac)	10 yr (in/ac)	5 yr (in/ac)	2023 <sup>†</sup> (in/ac)	All (in/ac)	10 yr (in/ac)	5 yr (in/ac)	All (ac-ft)	10 yr (ac-ft)	5 yr (ac-ft)
BMR	31.4	16.26	17.48	18.15	15.54	0.72	1.94	2.61	1.87	5.07	6.82
GPRT1	202.8	16.22	18.56	19.35	20.38	-4.16	-1.82	-1.04	-70.40	-30.80	-17.51
GPRT2	345.2	18.36	20.14	21.31	19.34	-0.98	0.80	1.97	-28.19	22.93	56.63
HSR	85.5	15.15	18.00	19.46	19.29	-4.14	-1.30	0.16	-29.51	-9.23	1.16
RCRT1	37.6	12.82	13.70	15.36	13.54	-0.71	0.17	1.82	-2.23	0.52	5.71
RSRT1	123.2	18.19	20.17	20.48	18.51	-0.31	1.66	1.97	-3.22	17.09	20.25
SBRT1	70.2	18.13	18.88	18.74	20.22	-2.10	-1.34	-1.48	-12.27	-7.86	-8.67
SPRT1	220.5	12.06	15.14	16.75	11.90	0.16	3.24	4.85	2.88	59.46	89.04
<b>TOTAL</b>									<b>-141.08</b>	<b>57.19</b>	<b>153.43</b>

In 2022, more sites show positive CCU across all baselines, with the total CCU increasing to 63.00, 261.28, and 357.51 ac-ft for all-years, 10-year, and 5-year baselines, respectively. Similarly, in 2023, most sites exhibit positive CCU under the 5-year baseline, though variability persists, particularly for partial withdrawal sites RCRT1 and RSRT1.

Overall, the total CCU for all sites ranges from negative values under the all-years baseline to increasingly positive values under shorter baselines, underscoring the sensitivity of CCU estimates to baseline selection but also the gradual recovery of irrigation practices over the years following the withdrawal program. Notably, a forage recovery analysis conducted as part of this project did not indicate negative conservation rates. This analysis documented sustained impacts on yields through 2023, providing strong evidence that conservation rates likely remained positive, as yield biomass offers a reliable indicator of actual field conditions.

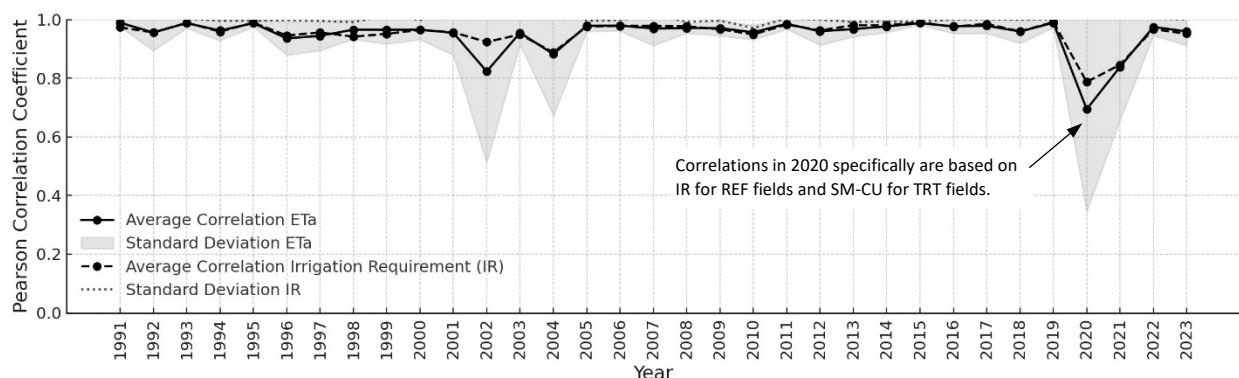
Despite the suggestion of negative CCU in some cases, the prior years control approach demonstrates that the impacts of irrigation withdrawal programs on field conditions can persist for several years. This raises important questions about whether the lag effects of diminished CU should be incorporated into CCU estimates over the full duration of such programs.

### 3.5 Site Correlation Analysis for Contemporaneous Neighboring Reference Control

To assess the premise of the Contemporaneous Reference Control approach that paired sites are comparable, the Pearson correlation analysis evaluated the temporal consistency between the site pairs (GPRR1 and BMR, GPRR1 and GPRT1, GPRR1 and GPRT2, GPRR1 and HR, RCRR1 and RCRT1, RSRR1 and RSRT2, SBRR1 and SBRT1, SPRR1 and SPRT1), for water use variables from 1991 to 2023. The objective was to determine whether environmental and irrigation conditions at one site were similarly affecting other sites, indicating shared patterns across different locations.

The Pearson correlation coefficient ( $r$ ) was calculated for each site pair annually using data for April-September enabling the assessment of trends during the primary growing season. The average  $r$  across all site pairs for each year was calculated, providing a summary of the general trend of correlations over time (Figure 3.3.3). Note that the IR term is valid prior to and after 2020, given that irrigation occurred on all fields. For 2020, SM-CU is the proper variable to describe water consumed beyond that supplied by rainfall on the TRT fields where no irrigation practices were altered. From 1991-2019,  $ET_a$  and IR for the site pairs were strongly correlated, where  $r = 0.9617$  and  $0.9651$ , respectively, supporting the premise that the environmental and irrigation conditions affecting the paired sites are comparable. A few years do exhibit greater variability (e.g., 2002, 2004), driven by drought periods or site-specific interventions.

Figure 3.5.1 shows a significant drop in the average  $r$  due to irrigation withdrawals implemented in 2020 on the TRT sites. Irrigation cutoff predictably disrupted the strong correlations between the site pairs. In



**Figure 3.5.1.** Pearson correlation analysis of  $ET_a$  and IR between REF and TRT site pairs across multiple years. Standard deviations are represented using either shaded areas or dotted lines.

subsequent years, as irrigation requirements were met on all fields, correlations rebounded to levels consistent with pre-withdrawal conditions, reestablishing the similarity in water use among sites.

### 3.5 Conserved Consumptive Use based on Contemporaneous Neighboring Reference Control

The amount of CCU derived using the contemporaneous neighboring reference control was calculated from Equation 3, repeating this calculation for pairs in subsequent years. This approach can obviate the effect of the varying annual weather conditions evident in the prior years control analysis since comparing fields in the same year considers local weather conditions as causing equal impact to the REF and TRT fields. The major limitation of this method is that it assumes the selection of a comparable REF condition, and thus requires careful consideration of specific site differences that may be caused by pasture health, soil fertility, or underlying soil conditions. The purpose of selecting sites with considerable size and spatial variability for this project was to ameliorate some of these concerns. In this study, the Pearson correlation analysis confirmed that the paired sites could be considered equivalent for the purpose of this analysis (Figure 3.5.1). Except for a drought period during 2002-2004, the correlation between both  $ET_a$  and IR for the REF and TRT site pairs was close to 1.0.

Table 3.5.1 presents the CCU analysis from 2020 to 2023 for the contemporaneous neighboring reference control, providing detailed insights into water conservation under both full-season and partial-season irrigation withdrawal practices. In 2020, full-season irrigation withdrawals resulted in substantial reductions in CU, with an average reduction of 55.6% across the fields. For instance, GPRT1 and GPRT1 conserved 294.11 and 291.50 ac-ft, respectively. In contrast, partial-season irrigation withdrawals yielded an average reduction of 21%, with sites RCRT1 and RSRT1 conserving 6.59 and 99.14 ac-ft. Overall, the total CCU for 2020 across all fields was calculated at 1,045.10 ac-ft, highlighting the significant impact of irrigation withdrawal practices during the first year of the program.

**TABLE 3.5.1.** Contemporaneous Reference Control IR Analysis for 2020-2023 Conserved Consumptive Use (Jan-Dec)

Site Pairs			2020†			2021			2022			2023		
REF	TRT	Size* (ac)	REF (in)	TRT (in)	CCU (ac-ft)	REF (in)	TRT (in)	CCU (ac-ft)	REF (in)	TRT (in)	CCU (ac-ft)	REF (in)	TRT (in)	CCU (ac-ft)
<i>Full Season Irrigation Withdrawal</i>														
GPRR1	BMR	31.35	21.83	7.84	36.55	22.50	20.04	6.44	19.76	16.63	8.18	20.29	15.54	12.42
GPRR1	GPRT1	202.83	21.83	4.43	294.11	22.50	18.10	74.43	19.76	16.90	48.34	20.29	19.61	11.54
GPRR1	GPRT2	345.20	21.83	11.69	291.50	22.50	20.94	45.04	19.76	18.09	48.11	20.29	18.50	51.67
GPRR1	HSR	85.55	21.83	12.00	70.03	22.50	21.74	5.46	19.76	17.14	18.70	20.29	18.36	13.78
SBRR1	SBRT1	70.22	26.16	14.16	70.18	22.42	20.02	14.01	18.46	17.19	7.43	19.59	20.05	-2.66
SPRR1	SPRT1	220.49	18.36	8.73	177.01	10.05†	11.90	---	9.72†	9.99	---	12.21†	10.97	---
Sub-Total CCU					939.37	145.38			130.76			86.75		
Average Reduction					55.6%	10.3%			11.8%			8.6%		
<i>Partial-Season Irrigation Withdrawal (no irrigation after June 15)</i>														
RCRR1	RCRT1	37.58	20.08	17.98	6.59	17.86	16.31	4.86	12.16	10.70	4.56	13.92	12.63	4.07
RSRR1	RSRT1	123.16	30.55	20.89	99.14	21.60	19.14	25.29	18.49	15.09	34.97	21.01	18.16	29.30
Sub-Total CCU					105.73	30.16			39.53			33.36		
Average Reduction					21.0%	10.1%			15.2%			11.5%		
<b>TOTAL Water Conserved</b>					<b>1,045.10</b>	<b>175.54</b>			<b>170.29</b>			<b>120.11</b>		

\* Acreage of the TRT Field

† REF IR on this site is lower than TRT due to untimely grazing earlier in the season than expected by 92 bulls accessing the field, causing CCU to be negative.

In 2021, lingering effects of the 2020 irrigation withdrawal program were evident, with CU remaining lower on the TRT fields. Full-season irrigation withdrawal sites showed an average CU reduction of 10.5%, while partially irrigated fields exhibited a smaller average reduction of 12.3%. Full irrigation withdrawal in the program year generally resulted in a continuing effect of more water consumed than on the partially irrigated TRT. Some challenges arose at the SPRR1 vs. SPRT1 site pair, where untimely grazing of the REF field by 92 bulls resulted in negative CCU values calculated. This irregularity led to the exclusion of this site pair from the 2021, 2022, and 2023 analyses. Despite this, most site pairs reflected sustained reductions in CU, indicating residual impacts of the withdrawal program.

By 2022, some fields showed signs of recovery, with overall CU reductions averaging 10.3% for TRT fields subjected to full irrigation withdrawal in the program year and 10.1% for the partially irrigated fields. Total CCU across all fields in 2022 was 175.54 ac-ft, suggesting a gradual return to pre-withdrawal conditions. Notably, one of the partially-irrigated fields (RSRT1) continued to exhibit CCU (18.41 ac-ft) despite the return to full irrigation for 2 years.

In 2023, the trends were more variable. Several TRT fields exhibited larger differences, with sites like GPRT2 still conserving 51.67 ac-ft, an increase over the previous two years. On the other hand, TRT fields impacted by partial irrigation in the program year showed a return to near-normal conditions suggesting comparable vigor between TRT and REF fields. The total CCU for 2023 was 120.11 ac-ft, reflecting an overall reduction in conservation compared to 2020 but consistent with the recovery trajectory observed over time.

Overall, the contemporaneous neighboring reference analysis reveals that while CU reductions were most significant in 2020, the residual effects of irrigation withdrawal persisted for several years, particularly at full-season withdrawal sites. These findings suggest that incorporating lag effects into CCU estimates may improve the accuracy of long-term evaluations for irrigation withdrawal programs.

A complementary forage recovery analysis, presented in a separate report, aligns with these trends and supports the observations of this study. Sustained impacts on forage yields through 2023 have been documented, particularly in fully withdrawn fields, consistent with the prolonged reductions in CU observed. Additionally, producer observations from participating fields corroborate these findings, indicating that partially irrigated fields recovered faster, while fully withdrawn fields experienced ongoing impacts to forage productivity.

### *3.6 Spatial Mapping and Summary of ET rates*

Although this report used spatial averages for  $ET_a$  across study fields, addressing spatial heterogeneity is an important technical aspect needed to understand methods for estimating  $ET_a$  across large fields using remote sensing. Assuming uniform  $ET_a$  rates across a field can lead to inaccurate estimates of water conservation. Even fields with similar grass species exhibit significant variability in CU rates due to factors such as differences in soil composition, proximity to water sources, and the influence of adjacent fields. This variability directly impacts remote sensing-based ET estimates, which in turn affect estimates of conserved water. While logical methods and values for water conservation can be devised, it is essential to acknowledge that on-the-ground conditions are inherently complex and spatially variable.

Landowners participating in water conservation programs must actively manage fields without irrigation, which requires continuous oversight to adapt to changing conditions. This includes addressing water flow through ditches and managing system requirements, often necessitating significant effort. Compensation for landowners reflects not only potential yield loss but also the additional management burdens they bear. To account for these complexities, conservation programs must adopt transparent rules that

incorporate spatial differences in  $ET_a$ , such as using geo-buffers, calculating median or average  $ET$  values, and delineating field boundaries carefully in GIS. These considerations transform water conservation into a programmatic question that integrates biophysical data with practical management strategies. Clear, well-defined methods for interpreting  $ET_a$  data are essential for designing effective programs and supporting informed decision-making by both program administrators and participants.

Appendix B illustrates the spatial distribution of annual  $ET_a$  for years prior to irrigation withdrawal (2016 to 2019), the irrigation shutoff year (2020), and the recovery years of the project. The mapping reveals that field scale  $ET_a$  patterns are often influenced by hydrologic processes that extend beyond mapped boundaries, clearly demonstrating that fields do not function as hydrologically independent units. This highlights the need to account for cross boundary water movement when interpreting field scale  $CU$  estimates. Field and property boundaries do not represent fixed limits for water movement. Rather, seepage, runoff, and subsurface flow allow water to move across field boundaries, leading to unintended redistribution of moisture. For example, at the reference site GPRR1,  $ET_a$  dropped sharply along its southern edge adjacent to the treatment field GPRT1 in 2020, reflecting reduced water availability in the neighboring field. In contrast, the northern boundary of GPRT2 exhibited elevated  $ET_a$  due to seepage from an adjacent irrigation delivery ditch, which likely contributed to sub irrigation and increased vegetation growth.

Spatial mapping also highlights the additional complexity arising from site specific features, as seen at the SBR site during the irrigation shutoff year (2020) and the return year (2021). At SBRT1,  $ET_a$  was noticeably higher near an onsite pond, while the eastern field edge showed influence from the nearby Colorado River. Interestingly, the western edge, which also borders the river, did not exhibit similar effects, emphasizing the highly localized nature of these interactions. Such patterns suggest that both mapped and unmapped hydrologic influences, including movement of water from adjacent sources, must be considered when interpreting remote sensing data at the field scale.

Additional variation in  $ET_a$  appeared to reflect activities within individual fields, such as grazing, hay cutting, and shading from large trees. Management decisions also influenced outcomes; for instance, although nitrogen fertilizer was commonly applied in other years, most landowners chose not to apply it in 2020 due to cost constraints and the planned reduction in irrigation, which led to reduced vegetation growth and demand for water. These findings show that even within a single field, operational choices and environmental conditions can have a meaningful impact on water use. By accounting for these spatial differences and management factors, this analysis emphasizes the importance of incorporating field specific processes, neighboring influences, and broader external drivers into remote sensing-based estimates of water conservation.

## 4 Discussion

Given recent developments in the formal adoption of remote sensing tools by water administrative agencies, this research underscores their applicability for both individual projects and broader programmatic and policy objectives. Notably, the Upper Colorado River Commission (UCRC) issued a resolution on methods for estimating agricultural  $CU$ , stating that the “*Commission and Upper Division States unanimously support the Commission's use of eeMETRIC to measure Upper Basin agricultural consumptive use,*” and directing staff to work with the Upper Division States - Colorado, New Mexico, Utah, and Wyoming - to “*implement the use of eeMETRIC to measure agricultural consumptive use*” (UCRC, 2022). The resolution also acknowledges the evolving nature of the science, affirming that “*as the science evolves and improved consumptive use measurement methods develop, the Commission will*

*continue to work with the Upper Division States and coordinate with Reclamation to monitor progress and institute improvements.”*

The findings from this study offer insights into methods for estimating CCU under irrigation withdrawal programs. By applying approaches that used either  $ET_a$  from prior years of the same field or from neighboring fields during the same season as comparative references, the analysis demonstrates how remote sensing can effectively estimate CCU. The prior years control approach relies on historical  $ET_a$  and irrigation data from the same field, while the contemporaneous reference approach draws comparisons to nearby, fully irrigated fields with similar environmental conditions. Although these methods differ in their reference conditions - temporal versus spatial - they produce comparable CCU values, lending confidence to the consistency and reliability of the estimates.

The impacts of irrigation withdrawal were clear. For fields where irrigation was fully withdrawn in 2020, both the prior years control approach and the contemporaneous reference approach demonstrated substantial reductions in  $ET_a$ , with estimates of 48.3% and 55.6%, respectively. These results indicate significant reductions in CU during the first year of the withdrawal program, emphasizing the immediate impact of full season irrigation cessation. In contrast, fields with partial season withdrawals showed more moderate reductions in  $ET_a$ , averaging 9.5% using the prior years approach and 21.0% using the contemporaneous reference. While both methods yielded comparable trends, the differences reflect how each approach captures site conditions and variability, reinforcing the value of applying multiple comparative methods when evaluating the outcomes of conservation programs.

A key observation from this study is the significant influence that baseline selection has on CCU estimates, as demonstrated by the prior years control approach. Comparing three different baseline periods from the years prior to irrigation withdrawal, including the full historical record (29 years, 1991 to 2019), the most recent 10 years, and the most recent 5 years, revealed notable variation in calculated CCU values. The shorter 5-year baseline consistently produced higher CCU estimates, likely because it more accurately reflects recent irrigation practices and climatic conditions. For example, in 2020, total CCU ranged from 778.39 ac-ft using the full historical record to 994.59 ac-ft using the 5-year baseline. These differences highlight the importance of using baselines that are reflective of recent climate conditions and current water use patterns, particularly in regions where environmental and management conditions have changed over time.

In the years following irrigation withdrawal, lingering effects on CU remained evident, though the magnitude of reductions diminished over time. In the first year after withdrawal, fields generally continued to show reduced CU, as vegetation was still recovering, and the effects of reduced irrigation remained visible despite the return of water. These patterns were further influenced by drier than average conditions that year, which likely limited recovery on TRT fields and impacted REF fields. By the second year of resumed irrigation, CU at full season withdrawal sites remained somewhat below reference levels, while partially irrigated fields began to approach pre withdrawal conditions. By the third year, variability across site pairs became more pronounced. Some full season withdrawal fields continued to exhibit lower CU compared to their reference counterparts, raising the question of whether this reduction still constitutes conserved CU. Meanwhile, most partial season fields had returned to near normal conditions, with minimal differences observed between treatment and reference fields.

Spatial variability in  $ET_a$  emerged as another critical factor influencing CCU estimates. As shown in the spatial analyses,  $ET_a$  rates were highly heterogeneous across fields, even within the same treatment categories. This variability is driven by factors such as soil composition, proximity to water sources, and neighboring field conditions. It is also noted that because the intent of remote sensing-based modeling is

to estimate an actual rate of ET happening in the specific biophysical system where measurements are being taken, this means that all manner of field operations will also be considered. All ranching operations, for example, will make management modifications for fertilizer rates, hay cutting schedules, and grazing plans, thereby compelling endogenous variables to affect  $ET_a$ . These observations highlight the necessity of incorporating spatial data into CCU estimates to account for real biophysical processes that may otherwise be overlooked in uniform field-level analyses. They also emphasize the need for transparent program designs that account for such complexities, possibly including geo-buffers and detailed field delineations in GIS.

Further analysis is recommended to expand upon the findings of this study. Two key questions emerged during the ongoing evaluation of the spatial  $ET_a$  data. The first asks: does the calculated  $ET_a$  or CCU for a field change meaningfully if the averaging is based on a different subset of pixels rather than a simple mean across the entire field? Future analysis will explore alternative pixel selection methods to account for edge effects and influences from neighboring fields. These alternatives may include applying a buffer of one or two pixels to exclude boundary zones, removing outliers influenced by nearby water sources such as ponds or ditches, selecting values within a single standard deviation of the mean, or using the median instead of the mean for aggregation. The second question asks: can additional spatial statistical tools help reveal meaningful patterns in  $ET_a$  that are not captured by field averages alone? Potential approaches include the use of spatial autocorrelation or semivariance analyses to better understand clustering and variability within and across fields.

## 5 Conclusions

This study highlights the complexity of estimating conserved consumptive use under irrigation withdrawal programs, emphasizing the importance of baseline selection, spatial variability, and field management in shaping CCU estimates. Remote sensing and modeling, particularly with tools like the eeMETRIC model, proved effective for estimating  $ET_a$  on high-elevation pastures and hay fields in Western Colorado. Substantial reductions in  $ET_a$ , particularly in fields with full season irrigation withdrawal were observed. These findings align with efforts by water administrators, including the Upper Colorado River Commission, to formally adopt remote sensing methods like eeMETRIC for CU estimation.

A companion forage recovery analysis, along with producer observations, supported these findings by showing that reductions in  $ET_a$  often aligned with declines in forage production. Forage recovery patterns revealed lasting impacts on yield through 2023, consistent with the continued effects of earlier irrigation withdrawal on fields enrolled in water conservation programs. Producers also pointed to several challenges in managing these fields, including the long duration of forage recovery, difficulty adjusting to changing water availability, and the influence of irrigation practices on nearby fields.

The study also raises important questions about the long-term implications of irrigation withdrawal programs. While CCU reductions were most significant in 2020, residual effects persisted for several years, particularly at full-season withdrawal sites. By 2023, partially irrigated fields had largely recovered and returned to parity with their reference conditions, while fully withdrawn fields continued to exhibit modest divergence. This suggests that incorporating lag effects into CCU estimates can enhance the accuracy of long-term evaluations and better capture the true impacts of conservation programs on water use and field conditions.

Several important questions remain for consideration by water administrators and policy makers. For instance, how should the concept of “recovery” be defined in the context of irrigation withdrawal? Should forage recovery data be incorporated alongside CCU estimates to provide a more complete picture of field

level outcomes? Administrators must also contemplate which comparative approach, either the prior years control or contemporaneous neighboring reference approach, offers the most reasoned representation of water conservation on enrolled fields. While remote sensing offers a robust and scalable method for estimating consumptive use, spatial variability across landscapes will continue to present interpretation challenges. These questions warrant careful reflection, as their resolution will shape how conservation outcomes are measured, verified, and communicated. By thoughtfully addressing these issues and building on the insights from this study, water conservation programs can evolve to better reflect field conditions and support sustainable management practices.

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## Appendix A

These are the simplified explanations for each of the variables provided by the Desert Research Institute, and used in the study:

*ACRES\_IRRIGATED* quantifies the irrigated acreage in each polygon.

*ETDa [MONTH] [YEAR] in.* This variable represents the crop-specific potential evapotranspiration (ET) under ideal conditions, tailored to grassland or pasture settings, which most of the sites fall under. Since the sites are not cultivated agriculture but primarily classified as "Grassland/Pasture," these values apply to managed pasture areas, reflecting the estimated water needs for those conditions.

*Peft and Prz Variables.* *Peft* represents the portion of precipitation that is available exclusively for transpiration by plants, without accounting for soil evaporation. *Prz* represents the moisture available for both transpiration by plants and evaporation from the soil, giving a more comprehensive view of water availability.

*NIWR [MONTH] [YEAR] in.* The Net Irrigation Water Requirement (NIWR) represents the amount of water needed to satisfy crop ET that is not provided by stored soil moisture or precipitation. It excludes effective precipitation, groundwater, and changes in soil water content. A negative NIWR might indicate that the effective precipitation or groundwater was sufficient to meet or exceed the water requirements for that period, complicating its use for some sites that have groundwater access.

*ETa [MONTH] [YEAR] in.* *ETa* represents the actual evapotranspiration rate, which should match the potential ET rate (*ETDa*) in well-watered conditions. When there is no water limitation, *ETa* aligns with *ETDa*.

*ET\_VOLUME [MONTH] [YEAR] acft.* This variable represents the total actual ET volume in acre-feet, including contributions from both irrigation and effective precipitation, indicating the complete water consumption by the vegetation.

*ET\_SHORTAGE\_VOLUME [MONTH] [YEAR] acft.* This variable measures the difference between potential ET (*ETDa*) and actual ET, representing the "shortage" of water needed to meet the full ET potential. A larger value indicates a higher irrigation deficit.

*IRR\_CU\_VOLUME [MONTH] [YEAR] acft.* *IRR\_CU\_VOLUME* is the volume of ET after subtracting the effective precipitation (*Prz*), making it the correct variable to use when assessing irrigation needs excluding effective precipitation, which cannot be legally transferred in water leasing contexts.