

Evaluating Conserved Consumptive Use in the Upper Colorado 2020 Report

Study funded by the
Colorado Water Conservation Board

With support from
Colorado River Basin Roundtable
The Nature Conservancy
Trout Unlimited
American Rivers

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November 18, 2021

Table of Contents

Tables & Figures	4
Executive Summary	5
Consumptive Use Evaluations	6
Forage Impacts, Recovery Patterns, and Crop Production Functions	7
Farm Enterprise Budgeting	7
Hydrological Impacts	8
Avian Monitoring	8
Social Perspectives	8
Next Steps	9
SECTION ONE Project Overview	10
1.1 Introduction	10
1.2 Project Partners	11
1.3 Project Goals	11
1.4 Research Overview	12
1.4.1 Evaluate remote sensing models as a tool to estimate water conservation at scale.....	13
1.4.2 Evaluate impacts and recovery for forages subjected to different levels of reduced irrigation.	14
1.4.3 Evaluate economic costs, benefits, and social aspects of water conservation for agricultural producers.	15
1.4.4 Evaluate the impacts of water conservation on wildlife habitat.	15
SECTION TWO Consumptive Use Evaluations	17
2.1 Existing Literature and Methods.....	17
2.2 Methodology.....	21
2.2.1 Estimation of ET from Landsat and Weather Data	21
2.2.2 Estimation of ET using Eddy Covariance	23
2.2.3 Estimation of ET using a Soil Water Balance.....	24
2.2.4 Estimation of ET using Atmometers.....	27
2.3. Results and Findings.....	27
2.3.1 Approach 1: Field Averaged Conserved Consumptive Use based on Prior Years ET.....	27
2.3.2 Approach 2: Field Averaged Conserved Consumptive Use from Comparison Field ET	31
2.3.3 Comparison of ET Rates from Remote Sensing and Eddy Covariance Data	32
2.3.4 Comparison of ET Rates between Remote Sensing and Atmometer Data.....	34

2.3.5 Comparison of ET Rates between Remote Sensing and Soil Moisture Data	35
2.4 General Observations	37
SECTION THREE Forage Impacts & Recovery.....	38
3.1 Existing Literature and Methods.....	38
3.2 Methodology.....	39
3.3 Results and Findings.....	40
3.3.1 Comparison of Yield Data between Sites.....	40
3.3.2 Comparison of Forage Protein Data between Sites.....	41
3.4 General Observations	43
SECTION FOUR Economics & Enterprise Budgeting	44
4.1 Methodology.....	44
SECTION FIVE Hydrological Impacts.....	47
5.1 Methodology.....	47
5.2 2020 Field Campaign.....	47
SECTION SIX Avian Monitoring	48
SECTION SEVEN Social Perspectives	49
REFERENCES.....	50
APPENDIX.....	54

Tables & Figures

Table 1.1: Designations and Description for Fields Under Evaluation for the Project.....	12
Table 2.1. Comparison of PET to AET on Project Fields (Average for 2016-2019).....	28
Table 2.2. Other Recorded Project Field Data (Average for 2016-2019).....	28
Table 2.3. Comparison of Ensemble AET on Project Fields (GPR, RSR, SBR, SPR) in 2016-2020.....	29
Table 2.4. Comparison of AET on Project (Reference only) Fields Between 2016-2020.....	29
Table 2.5. Comparison of AET on Project Treatment fields between 2016-2020.....	30
Table 2.6. Comparison of AET between Grand County Reference and Treatment fields in 2020.....	31
Table 2.7. Comparison of AET for Eddy Covariance (EC) and Ensemble Approach (Ens) at GPR T1 in 2020.....	32
Table 2.8. Atmometer and Rain Gage Data for 2020.....	34
Table 2.9. Field Capacity by Practical Determination Method (PDM-FC), Initial and Final Soil Water Deficit ($D_{initial}$ and D_{final}), and Water Balance AET (WB-AET) Estimation from Soil Moisture Sensors at Project Fields.....	35
Table 3.1. Colorado Water Division total: Irrigated Areas by Elevation Bands (MWH et al., 2012).....	37
Table 3.2. Grass Forage Yield from 2020 Season for Project Sites.....	40
Table 3.3. Grass Forage Quality from 2020 Season for Fully Curtailed Sites.....	41
Table 4.1. Example 2020 Enterprise Budget (Revenue Section) Spreadsheet developed from CSU Agricultural Business Management Spreadsheet Tool.....	44
Table 4.2. Example 2020 Enterprise Budget (Expenses and Returns Section) Spreadsheet developed from CSU Agricultural Business Management Spreadsheet Tool.....	45
Figure 2.1. Simplified data processing flowchart that illustrates some of the steps required to model ET using Landsat and weather data. (Allen and Torres-Rua, 2018).....	21
Figure 2.2 Panoramic view of eddy covariance tower on the GPR T1 field taken on April 21, 2021.....	22
Figure 2.3 Eddy covariance tower on the GPR T1 field take on September 21,2021.....	23
Figure 2.4 Soil moisture sensor installation representing depths of 0-12, 12-24, 24-36, and 36-48 cm below the soil surface.....	24
Figure 2.5 Research assistant Cordelia Anderson performing routine quality control assessment at a research enclosure.....	25
Figure 2.6 Timeseries of Ensemble ET for Project Sites (2016-2019).....	27
Figure 2.7. Estimated ET (mm/day) for closed and unclosed energy balance using eddy covariance.....	32
Figure 2.8 Comparison of ET estimates by eddy covariance methodology and modeled results using remote sensing.....	33
Figure 3.1. Forage sampling enclosure to protect from animal grazing and maintain grass growth throughout the season.....	38

Executive Summary

The Colorado River Basin supplies water to seven U.S. states, the Republic of Mexico, and 29 federally recognized Tribes. The Basin provides domestic water supplies to an estimated 40 million people and irrigates more than five million acres of agricultural lands. It also fuels a multi-billion-dollar recreational economy and supports diverse wildlife and fish found nowhere else in the world. Since 2000, the Colorado River Basin has experienced significant drought conditions and warming temperatures. It is estimated that climate change will likely reduce flows in the Colorado River by a range of 5% to 20% by 2050 (Udall and Overpeck, 2017). Lakes Powell and Mead have also witnessed stark declines in the past two decades and are facing historically low levels. This trend is alarming for a resource as critical as the Colorado River. Without determination and collaborative action to address the impacts of aridification, persistent drought and the effects of a changing climate on the basin, the health of the river and water security for people are all at risk (Kuhn and Fleck, 2019).

The “Evaluating Conserved Consumptive Use in the Upper Colorado” Project (hereafter referred to as “the Project”) Project, as described in this report, is a multi-year field research project engaging agricultural producers in the Kremmling area, researchers from multiple universities, and conservation groups in directly tackling the information gaps related to voluntary water conservation measures on high altitude, irrigated grass pastures that support livestock. The Project is guided by a desire to develop, test, and evaluate water conservation tools that can support productive agriculture, the associated communities, and the environment. Project results will address these key questions:

1. *How can we accurately and cost-effectively estimate water use and water conservation at scale?*
2. *What are the impacts of reduced irrigation on perennial grass fields and how do they recover under normal irrigation?*
3. *What does participation in a water conservation project mean for producers’ bottom line and for the ag-based community and economy of the region?*
4. *How do water conservation projects impact river flows and wildlife habitat?*

This information will help agricultural water users, water managers, State entities, and other stakeholders better determine how, and under what conditions, agricultural water conservation can provide drought resilience and help address local, state, and regional water supply challenges.

The Project has two phases. Phase 1, completed in 2020, involved applying reduced irrigation treatments to 1142.6 acres of irrigated pastures near Kremmling, Colorado and establishing another 405.6 acres as reference fields for comparison purposes. Instruments to measure soil water content and groundwater were installed in both treatment and reference fields, and soil and forage samples were taken to begin assessing consumptive water conservation and potential impacts from the application of reduced irrigation treatments. Under Phase 2, beginning in 2021, the treatment fields will be returned to normal irrigation and we will evaluate recovery through the 2023 irrigation season. Phase 2 of the evaluation directly builds on Phase 1 by measuring water use and agronomic impacts over the period of 3 years, the time period experts estimate the fields are likely to normalize.

This report summarizes the overall project, methodology and initial results from the first year of research. **Section 1** of this report provides an overview of the Project, the partners involved, the research approach, and the main research objectives. **Section 2** of the report summarizes the methods, models, and available information used to estimate consumptive use (CU) and the work done to evaluate the performance of remote sensing methods for irrigated and unirrigated pastures in the Project area. **Section 3** of the report deals with the assessment yield impacts and recovery on fields that have undergone a period of reduced irrigation. **Section 4** covers the enterprise budgeting approach to evaluating field scale and regional

economic considerations related to agricultural water conservation. **Section 5** describes the methodology for evaluating streamflow impacts resulting from the Project. **Section 6** covers the work on assessing potential impacts to avian habitat, and **Section 7** provides an overview of our approach to better understanding the decisions that agricultural water users consider in evaluating whether to implement water conservation activities in their operations. Additional information will be included in future reports as more data becomes available and the project team is able to complete analysis across multiple years. Below we provide a short summary for each of the focal research areas, which are covered in further detail in the full report.

Consumptive Use Evaluations

Accurate and cost-effective tools to estimate water use that are both transparent and trusted are essential if agricultural water conservation is going to be a viable and effective strategy to help address a drier future. The Project will use an ensemble of remote sensing models to estimate consumptive use (CU) and conserved consumptive use (CCU) on large irrigated high-elevation pastures and will also compare estimates between the remote sensing models and field data from eddy covariance instrumentation, soil water balance instrumentation, and local weather stations. The Colorado Division of Water Resources is also providing estimates of CU for the Project fields using their Lease Fallow Tool as another point of reference.

To further understand the actual amount of water conserved under the project and its impact on stream conditions, estimates of CU and CCU from remote sensing and the CWCB/DWR will be combined with a companion study evaluating hydrological changes resulting from the project's water conservation practices. Lotic Hydrological will complete this work by assessing hydrological changes along reaches of the Colorado River, Pass Creek, Red Dirt Creek, Williams Fork and Bull Run during the summer and early fall of 2020 and 2021 and compare them with historical data.

Taken together, results from the Project can help inform a policy discussion around an approach to estimate water conservation at scale that would balance the precision offered by available science against what is administratively feasible, cost effective, and practical for participants and stakeholders. Based on the work to date, we offer the following observations on the applicability of using remote sensing to estimate water use and conserved consumptive use at scale:

First, the Project fields evaluated under the condition of full-season curtailment exhibited 43.6% and 41.1% reductions in actual evapotranspiration (AET) for May-September, respectively, based on a *prior year approach* and a *comparison field approach*. Additionally, split-season curtailment resulted in 14.6% and 22.3% AET reductions during the same period, based again on the prior year and comparison field approaches. The difference in reduction between the full-season and split-season programs is not surprising. Previous studies have also shown that partial-season curtailment conditions offer limited amounts of conserved consumptive use (Allen and Torres-Rua, 2018; Cabot et al., 2018), although there are clear environmental benefits, such as later season streamflow enhancement.

Second, when estimating reductions in AET using remote-sensing, we did not observe a significant difference in the results when using the prior years approach or the comparison field approach.

Finally, the comparison of AET estimated from remote sensing methods and ground-based eddy covariance instrumentation at a field subjected to full-season curtailment has further increased the body of knowledge pertaining to these limited-water arrangements. The comparison between ET estimates derived from these two methods was quite high ($R^2 = 0.95$), offering greater confidence in the use of remote sensing as a scalable and transferrable tool to be used in other areas where water-sharing arrangements may take place.

Forage Impacts, Recovery Patterns, and Crop Production Functions

Understanding the immediate effects and potential long-term recovery issues associated with reduced irrigation on high elevation perennial grass fields is essential for evaluating the overall viability of agricultural water conservation. Results from the Project will provide the critical information agricultural producers need to evaluate compensated water conservation activities and the terms for such activities. For a larger scale water conservation program, results on crop impacts can help inform overall program costs and potential water conservation volumes given what is agriculturally viable.

Project research is focused on the agronomic and biophysical impacts of irrigation curtailment versus irrigation to maximize yield or irrigation to fully utilize water throughout the season (i.e., “typical” irrigation). This work includes regular forage sampling throughout the year, analyzing the samples for yield, forage quality, plant carbohydrates, root depth, and nutrient carryover. These results can then be combined with other Project data to better understand how yield and forage quality relate to water use and how reduced yields and compensation for water conservation impact an agricultural operation’s budget.

In 2020, this task involved collecting data from both reference and treatment fields on yield, plant count and density, forage protein, plant carbohydrates, nutrient carryover, and weed pressure. This data will help establish a baseline that will allow the project team to assess the recovery period and pattern of vegetation on fields that have undergone a period of reduced irrigation in future years.

As anticipated, the impact of irrigation curtailment on yields for the project treatments fields was significant. On fields where no water was applied for the entire season (full curtailment), the lack of water caused an approximately 79% reduction in dry matter biomass weight at the lower producing areas for the Jun-Aug sampling period, as compared with their fully irrigated reference counterparts. The irrigation curtailment also caused an approximately 84% biomass loss for the same time period at the higher producing areas, again compared with their reference fields. Dry matter biomass weights on the partial curtailment sites (no water after June 15) were unaffected, of course, before water was cut off. After June 15th, however, biomass was reduced by 93% and 95% for only the August sampling. Looking at the entire season however, the losses were less severe, amounting to only 33% and 25%, respectively, for the low and high production areas.

It is worth noting that *functionally available yield*, that is what is agronomically feasible to bale, graze, or otherwise harvest, is different than research assessments of reduced biomass. In this study, participating producers did not harvest any grass from the treatment fields in 2020. However, since the overall goal of the project is to evaluate forage recovery once fields return to normal irrigation, it will be important to compare the yield impacts in 2020 with the yield data from subsequent years. This recovery data will be addressed in more detail in future reports.

Farm Enterprise Budgeting

As stakeholders in the Colorado River Basin continue to explore opportunities to compensate agricultural producers to temporarily reduce their water use, a better understanding of economic factors is needed for determining the amount of compensation, the factors on which that is based, and how compensation for reduced water use may fit into the operational planning for agricultural producers.

In this project, enterprise budgets will be used to compare economics at the field, farm, and regional scale between the treatment fields with water conservation activities and the reference fields with “business as usual” scenarios. An enterprise budget is a tallying of estimates for the full economic costs and returns projected to accrue to an agricultural activity, such as raising livestock, producing hay, or in the case of the Project, receiving payment for implementing water conservation activities. The economic data from this

work will inform two main aspects of voluntary water conservation activities. First, agricultural producers need a thorough understanding of both scenarios to evaluate whether and how to participate in any water conservation activity. This research will help water users compare compensation with reduced yields and other potential impacts and benefits to an operation engaged in water conservation. Second, stakeholders and decision makers evaluating water conservation programs more broadly need an accurate understanding of the potential costs for compensation as well as any associated management costs required for temporary activities.

Hydrological Impacts

As a component of the overall project effort to evaluate the viability of voluntary water conservation measures on high altitude, irrigated grass pastures, the Project team will assess hydrological changes resulting from the water conservation activities.

For this work, Lotic Hydrological is collecting data along reaches of the Colorado River, Pass Creek, Red Dirt Creek, Williams Fork, and Bull Run during the summer and early fall of 2020 and 2021 and will compare this with historical data to characterize changes in surface water hydrology caused by the project. Additionally, this effort will provide an accounting of water conserved by the project between the participating parcels and the confluence of the Colorado River and Blue River. Data and information produced by this effort may be used to characterize potential effectiveness of water conservation projects at delivering water to the outlet of a drainage basin, evaluate environmental benefits or impacts, and for other purposes. This work can also inform efforts to develop streamlined tools for similar projects across the Colorado River basin.

Avian Monitoring

Irrigated agricultural lands throughout Colorado provide important wildlife habitat for a number of avian species and given the potential need for agricultural water conservation there is a critical need to understand how, where, and to what degree, reduced irrigation may influence this bird habitat. To address this, the Project team is working with Audubon Rockies to evaluate the avian response on five participating fields from 2020 – 2022.

Avian monitoring will occur annually in late June using the *Integrated Monitoring in Bird Conservation Regions* (IMBCR) sampling protocol. This protocol uses randomized point counts and is designed to be statistically rigorous, biologically accurate, and to produce data for analyses of population trends for most breeding, diurnal land bird species.

Social Perspectives

To compliment the technical and economic aspects of the Project research, the Project team is working with MacIlroy Research & Consulting to complete a longitudinal study using a series of interview and surveys to explore what people considered when making their decision about participation in the Project and to examine how social networks informed their decision about participation. Drawing on the extensive experience from the project participants and their perception of the issues at hand, results from this effort can help stakeholders and decision makers better understand the challenges, considerations, and potential paths forward in relation to water conservation in Colorado and the Upper Colorado River Basin.

Initial interviews with project participants and neighboring non-participants, as well as social network surveys, will begin in 2021 and continue annually through the remainder of the project.

Next Steps

Research and reporting on the project will continue through 2023. No additional, large scale water conservation activities are anticipated, although some small scale activities are being considered to evaluate the yield and agronomic impacts of more frequent irrigation curtailments. ET and forage recovery data will continue to be collected through 2023. Hydrological impacts will be assessed based on data collected in 2020 and 2021, with reporting complete in 2022. Enterprise budgets will continue to be refined annually with the forage recovery data and the broader economic impact evaluation will occur in 2022. Because the social perspectives work is a longitudinal study that requires ongoing engagement with the project participants, these results will not be delivered until the end of the data-gathering period in early 2024.

SECTION ONE Project Overview

1.1 Introduction

The Colorado River Basin supplies water to seven U.S. states, the Republic of Mexico, and 29 federally recognized Tribes. The Basin provides domestic water supplies to an estimated 40 million people and irrigates more than five million acres of agricultural lands. It also fuels a multi-billion-dollar recreational economy and supports diverse wildlife and fish found nowhere else in the world. Since 2000, the Colorado River Basin has experienced significant drought conditions and warming temperatures. It is estimated that climate change will likely reduce flows in the Colorado River by a range of 5% to 20% by 2050 (Udall and Overpeck, 2017). Lakes Powell and Mead have also witnessed stark declines in the past two decades and are facing historically low levels. This trend is alarming for a resource as critical as the Colorado River. Without determination and collaborative action to address the impacts of aridification, persistent drought and the effects of a changing climate on the basin, the health of the river and water security for people are all at risk (Kuhn and Fleck, 2019).

While the Colorado River Basin is no stranger to drought, and water managers have successfully used a number of tools to avoid major disruptions to water supply to date, the most current science indicates that the Basin is undergoing the process of permanent aridification due to climate change. To address this, stakeholders throughout the basin are discussing what additional tools may be needed to adequately prepare for a persistently drier future. Over the past several years, multiple efforts have focused on investigating how voluntary, temporary, and compensated reductions in agricultural water use can play a role in tackling these challenges. However, significant knowledge gaps exist about how this can work in practice for the high-altitude perennial grasses that make up the majority of the irrigated acreage on Colorado's Western Slope.

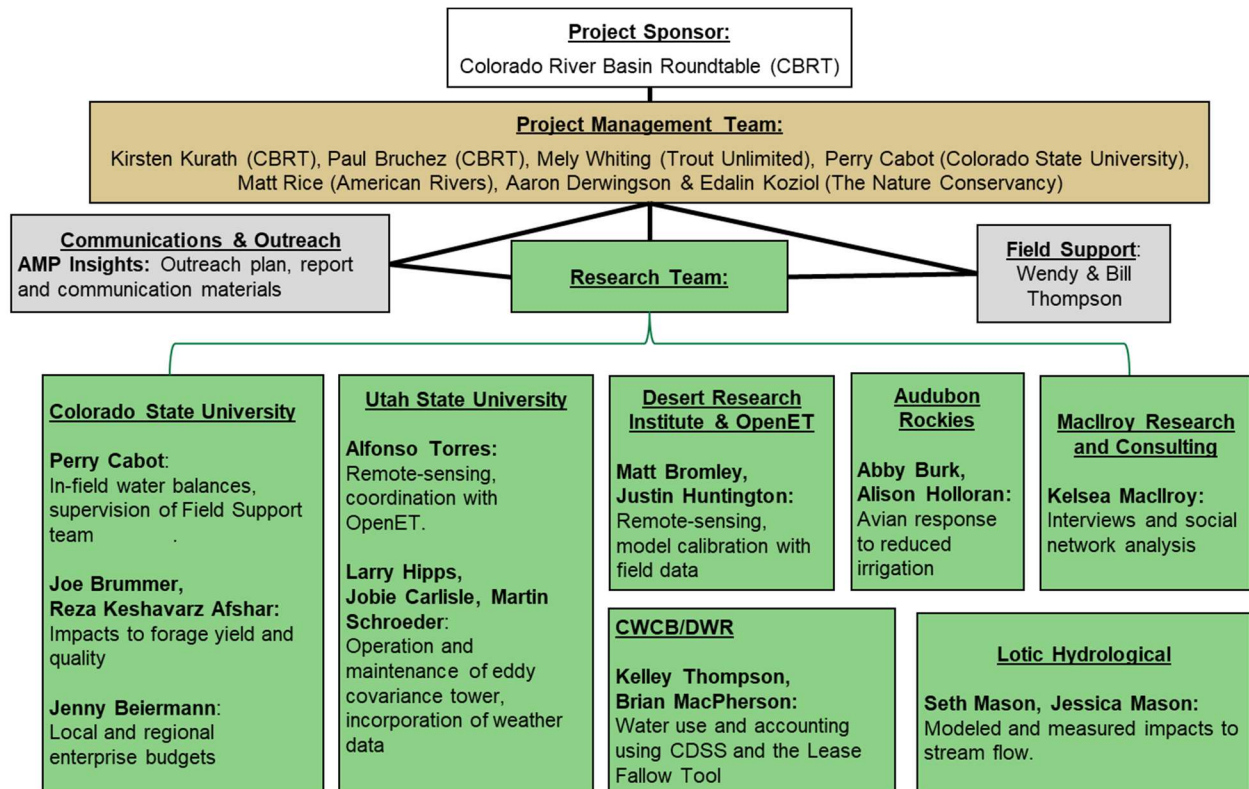
The Project, as described in this report, is a multi-year field research project engaging agricultural producers in the Kremmling area, researchers from multiple universities, and conservation groups in directly tackling the information gaps related to voluntary water conservation measures on high altitude, irrigated grass pastures that support livestock. The Project is guided by a desire to develop, test, and evaluate water conservation tools that can support productive agriculture, the associated communities, and the environment. Project results will address these key questions:

- 1. How can we accurately and cost-effectively estimate water use and water conservation at scale?***
- 2. What are the impacts of reduced irrigation on perennial grass fields and how do they recover under normal irrigation?***
- 3. What does participation in a water conservation project mean for producers' bottom line and for the ag-based community and economy of the region?***
- 4. How do water conservation projects impact river flows and wildlife habitat?***

This information will help agricultural water users, water managers, State entities, and other stakeholders better determine how, and under what conditions, agricultural water conservation can provide drought resilience and help address local, state, and regional water supply challenges.

1.2 Project Partners

The Project is sponsored by the Colorado River Basin Roundtable (CBRT). The CBRT is a group of water managers and stakeholders charged with water planning for the main-stem Colorado River Basin within Colorado. It is one of nine basin roundtables in Colorado created by the state legislature in 2005 in the Water for the 21st Century Act. The CBRT is committed to being proactive in exploring the challenging issues related to Colorado River water use and potential solutions to ongoing drought and declining water supplies and is providing critical leadership for the project. Direct research and project implementation are being provided by a robust partnership between State agencies, research universities, conservation NGOs, and consultant support along with critical engagement and leadership from the agricultural producers participating in the project.



1.3 Project Goals

The overarching goal of the Project is to work with local water users to use on the ground research to address key feasibility questions related to temporary reductions in agricultural water use. The Project is guided by a desire to develop, test, and evaluate water conservation tools that can support productive agriculture, the associated communities, and the environment.

Research for the Project integrates multiple facets of agricultural water management in evaluating water conservation, including science-based estimations of consumptive use for perennial grasses, strategies for reduced consumption, economic considerations, forage yield and quality impacts, and producer involvement and feedback. The Project also provides a unique opportunity to evaluate the applicability and accuracy of various modeling tools to evaluate new frameworks oriented towards conserving consumptive use on irrigated grass pastures. Results will help inform the CBRT, the Colorado Water Conservation Board

(CWC), and other stakeholders about the viability of reducing water use on high elevation (> 6,000 ft) irrigated pasture to supply water for a number of potential purposes including, but not limited to, drought response, enhancing environmental flows, and providing temporary municipal supplies in times of shortages.

1.4 Research Overview

Field research is taking place with local agricultural producers on nine different ranches near Kremmling, Colorado. This includes 1142.6 acres on ten distinct treatment fields and 405.6 acres on five reference fields. The reference fields are being irrigated and operated as normal for the duration of the Project (2020-2023), while the treatment fields received either no irrigation for the full season or no irrigation after June 15th in 2020 and will receive normal irrigation in 2021 and through the remainder of the Project. Fields were selected based on a combination of producer interest in participating in the Project, reliable water rights, and fields with a range of soil, plant, and hydrologic conditions. By comparing data on water use, forage yield and quality, agricultural economics, and wildlife habitat between treatment and reference fields, this work aims to produce results that are applicable beyond the Project fields and scalable to perennial grass fields across Colorado and the Upper Colorado River Basin.

Following the selection of treatment and reference fields, the Project team and the participating producers installed fixed research enclosures (REs) that will serve as permanent locations for water balance monitoring and forage sampling for the duration of the Project. In selecting locations within the fields for the REs, the team developed and applied the concept of a “productivity gradient” to address the variability in production that occurs across these large fields. Since productivity is largely influenced by grass species and underlying soil conditions, selecting areas of high and low productivity for the REs serves as a means of packaging several research variables into a single location. Every RE has been enclosed with fencing to protect against animal intrusion and grazing.

As outlined in Table 1.1, the evaluation locations include research equipment enclosures at six locations and an eddy covariance station at one location. An alpha-numeric coding system was created for each research enclosure (RE), based on sub-designations for the ranch name, research condition, and productivity level. For example, GPR R1 designates the 3-letter abbreviation for the ranch name, 1-letter designation for R or T (REF or TRT), 1 number for field name. Research enclosure locations were further designated by an additional 1 letter H or L, indicating high or low forage productivity. Research enclosures were georeferenced and are intended to be permanent locations for monitoring and sampling in sequential years. Each high productivity RE contains the instrumentation for calculating a soil water balance, which provides an accurate, but very local, estimate of water use. This instrumentation includes soil moisture sensors at depths of 6, 18, 30 and 42 cm, a groundwater observation well, and neutron probe access. Given the importance of understanding the relationship between water use and the associated effects of reduced irrigation for the Project, the team installed an eddy covariance measurement system at the GPR T1H location. Eddy covariance is considered the most reliable method for determining the accuracy of remotely-sensed evapotranspiration (ET) estimates. While eddy covariance data for grass pastures under irrigated conditions is available, high elevation pasture fields under curtailment have not been evaluated and the Project offered a unique opportunity to obtain this data.

Table 1.1: Designations and Description for Fields Under Evaluation for the Project

Field Name⁺	Water Conservation Practice	Acres	Research Instrumentation*
BJM T1 2020	Full season, no irrigation	31.359	None
GPR T1 2020	Full season, no irrigation	203.055	H/L Enclosure, SMS, GW, NP, EC
GPR T2 2020	Full season, no irrigation	345.729	H/L Enclosure, SMS, GW, NP
HSR T1 2020	Full season, no irrigation	85.617	None
JLM T1 2020	Full season, no irrigation	15.800	None
RCR T1 2020	Split Season, no irrigation after June 15	37.625	H/L Enclosure, SMS
RSR T1 2020	Split Season, no irrigation after June 15	123.317	H/L Enclosure, SMS, GW, NP
SBR T1 2020	Full season, no irrigation	70.278	H/L Enclosure, SMS, GW, NP
SBT T1 2020	Full season, no irrigation	9.120	None
SPR T1 2020	Full season, no irrigation	220.708	H/L Enclosure, SMS, GW, NP
Sub-Total		1142.608	
GPR R1 2020	Reference, historical irrigation	93.503	H/L Enclosure, SMS, GW, NP
RCR R1 2020	Reference, historical irrigation	233.710	H/L Enclosure
RSR R1 2020	Reference, historical irrigation	21.054	H/L Enclosure, SMS, GW, NP
SBR R1 2020	Reference, historical irrigation	28.683	H/L Enclosure, SMS, GW, NP
SPR R1 2020	Reference, historical irrigation	28.672	H/L Enclosure, SMS, GW, NP
Sub-Total		405.622	

Based on landowner interest and research goals, irrigation was intentionally curtailed on 981.7 acres for the full irrigation (no water applied in 2020) and partially curtailed on 160.9 (no irrigation after June 15, 2020). The water rights for these parcels were also granted SB13-019 protection status, which provides that any decrease in CU resulting from reduced irrigation rates will not be considered in any future judicial quantification of the historical CU (HCU) of the water rights for a maximum of five years out of the ten-year period.

The following are the *primary research objectives* for the Project that will be addressed in further detail in this report:

1.4.1 Evaluate remote sensing models as a tool to estimate water conservation at scale.

Accurate and cost-effective tools to estimate water use that are both transparent and trusted are essential if agricultural water conservation is going to be a viable and effective strategy to help address a drier future. More specifically, our project team has identified three basic needs related to estimating water use and water conservation to facilitate a successful water conservation program:

1. Parties to any water conservation agreement need preliminary estimates of CU and CCU for project development and due diligence as well as for negotiating the agreement and associated compensation.
2. Those same parties, and other key stakeholders, need verification that the water conservation activity occurred as described in the agreement, and need an estimate of the final volume of CCU created given water availability, weather, and other field conditions.
3. Finally, a successful water conservation program at scale needs a process to address what happens when the preliminary estimates differ from the post-project verification.

Given the ability to conduct spatially broad estimates with reasonable accuracy, the use of satellite remote-sensing to study ET has grown significantly over the past three decades. In brief, remote-sensing is a technique that employs proxy measurements, such as surface energy fluxes or spectral signatures, that are then correlated to ET using spatial algorithm and models. Because these models are based in GIS and require technical proficiency, they have largely been the purview of research institutions. More recently however, a collaborative effort to make these models available to the broader public was initiated by OpenET (openetdata.org).

The Project will use an ensemble of remote sensing models available in OpenET to estimate consumptive use (CU) and conserved consumptive use (CCU) on large irrigated high-elevation pastures characterized by various grasses, forbs, and sedges under varying soil and groundwater conditions, representing typical conditions for fields across western Colorado. The Project team will also complete a comparative evaluation between the remote sensing models and field data from eddy covariance instrumentation, soil water balance instrumentation, and local weather stations. The Colorado Division of Water Resources is also providing estimates of CU for the Project fields using their Lease Fallow Tool as another point of reference.

To further understand the actual amount of water conserved under the project and its impact on stream conditions, estimates of CU and CCU from OpenET and the CWCB/DWR will be combined with a companion study evaluating hydrological changes resulting from the project's water conservation practices. Lotic Hydrological will complete this work by assessing hydrological changes along reaches of the Colorado River, Pass Creek, Red Dirt Creek, Williams Fork and Bull Run during the summer and early fall of 2020 and 2021 and compare them with historical data. This effort will provide an accounting of water conserved by the project between the participating parcels and the confluence of the Colorado River and Blue River. Data and information produced by this effort may be used to characterize potential effectiveness of water conservation projects at delivering water to the outlet of a drainage basin, evaluate environmental benefits or impacts, and for other purposes. This effort will also inform efforts to develop streamlined tools supportive of similar projects across the Colorado River basin. Taken together, results from the Project can help inform a policy discussion around an approach to estimate water conservation at scale that would balance the precision offered by available science against what is administratively feasible, cost effective, and practical for participants and stakeholders.

1.4.2 Evaluate impacts and recovery for forages subjected to different levels of reduced irrigation.

Understanding the immediate effects and potential long-term recovery issues associated with reduced irrigation on high elevation perennial grass fields is essential for evaluating the overall viability of agricultural water conservation. Results from the Project will provide the critical information agricultural producers need to evaluate compensated water conservation activities and the terms for such activities. For a larger scale water conservation program, results on crop impacts can help inform overall program costs and potential water conservation volumes given what is agriculturally viable.

Project research is focused on the agronomic and biophysical impacts of irrigation curtailment versus irrigation to maximize yield or irrigation to fully utilize water throughout the season (i.e., “typical” irrigation). Understanding how variations in crop species, soil moisture, and depth to groundwater impacts yield and forage quality under reduced irrigation and recovery with full irrigation is a priority research question for the Colorado Basin Roundtable, local water users, and other stakeholders evaluating potential water conservation programs. The Project team will complete regular forage sampling throughout the year, analyzing the samples for yield, forage quality, plant carbohydrates, root depth, and nutrient carryover. These results can then be combined with other Project data to better understand how yield and forage quality relate to water use and how reduced yields and compensation for water conservation impact an agricultural operation’s budget.

In 2020, this task involved collecting data from both reference and treatment fields on yield, plant count and density, forage protein, plant carbohydrates, nutrient carryover, and weed pressure. This data will help establish a baseline that will allow the project team to assess the recovery period and pattern of vegetation on fields that have undergone a period of reduced irrigation in future years.

1.4.3 Evaluate economic costs, benefits, and social aspects of water conservation for agricultural producers.

Opportunities to compensate agricultural producers to temporarily reduce their water use is one potential solution to address the increasing pressure that persistent drought and climate change are putting on our limited water supplies. However, a better understanding of economic factors is needed for determining the amount of compensation, the factors on which that is based, and how compensation for reduced water use may fit into the operational planning for agricultural producers.

In this project, enterprise budgets will be used to compare economics at the field, farm, and regional scale between the treatment fields with water conservation activities and the reference fields with “business as usual” scenarios. An enterprise budget is a tallying of estimates for the full economic costs and returns projected to accrue to an agricultural activity, such as raising livestock, producing hay, or in the case of the Project, receiving payment for implementing water conservation activities. The economic data from this work will inform two main aspects of voluntary water conservation activities. First, agricultural producers need a thorough understanding of both scenarios to evaluate whether and how to participate in any water conservation activity. This research will help water users compare compensation with reduced yields and other potential impacts and benefits to an operation engaged in water conservation. Second, stakeholders and decision makers evaluating water conservation programs more broadly need an accurate understanding of the potential costs for compensation as well as any associated management costs required for temporary activities.

In addition to economic considerations, we know from past work that there are multiple reasons why agricultural producers may or may not choose to participate in water conservation activities. To better understand these social factors, the Project team will complete a longitudinal study using a series of interview and surveys to explore what people considered when making their decision about participation in the Project and to examine how social networks informed their decision about participation. Results from his effort can help inform future conversations and help stakeholders and decision makers better understand the challenges, considerations, and potential paths forward in relation to water conservation in Colorado and the Upper Colorado River Basin.

1.4.4 Evaluate the impacts of water conservation on wildlife habitat.

Irrigated agricultural lands throughout Colorado provide important wildlife habitat for a number of avian species and given the potential need for agricultural water conservation there is a critical need to understand how, where, and to what degree, reduced irrigation may influence this bird habitat.

To address this, the Project team is working with Audubon Rockies to evaluate the avian response on five participating fields from 2020 – 2022. Avian monitoring will occur annually in June using the *Integrated Monitoring in Bird Conservation Regions* (IMBCR) sampling protocol.

SECTION TWO Consumptive Use Evaluations

Interest in the Project is driven by the need to examine the viability of full and partial season irrigation curtailment as a practice to measurably conserve water without causing long-term adverse impacts to the pastureland where these practices occur. The practice of “irrigation curtailment” refers to the action taken whereby a field does not receive irrigation for a specific period of time (Burt et al., 1997). This practice is distinct from the prevalent use of the term “deficit irrigation,” which is an optimization strategy in which irrigation is applied during drought-sensitive growth stages of a crop for the purpose of altering some particular crop attribute of interest. This evaluation contributes information needed to coordinate methods for estimating CU on irrigated lands in the entire Upper Colorado River Basin (URS, 2013). The Nature Conservancy (TNC), Trout Unlimited (TU) and American Rivers (AR) worked with Colorado State University (CSU), Utah State University (USU), and the Desert Research Institute (DRI) in Nevada to lead these evaluations of consumptive use (CU) and conserved consumptive use (CCU) estimations on pastureland enrolled in a voluntary, compensated, and temporary irrigation curtailment program in 2020. The CCU term has previously been proposed to describe the proportion of historical, beneficial CU, originating from a water right because of diverting less than the historical rate to an irrigated cropping system (CAWA, 2008).

This section reports on the 2020 results of one of the Project’s major objectives, which is to use remotely sensed satellite data to estimate CU on grass pastures in the Upper Colorado River Basin, specifically in an area of Grand County dominated by grass pastures on 10 fields located at elevations that range from 7,598 to 8,281 feet and average 7,770 feet. The Project applies remote sensing methods in a manner consistent with other evaluation efforts conducted for the same purpose of evaluating CU (Cuenca et al., 2013; Allen and Torres-Rua, 2018). Three Project-specific characteristics distinguish the Project from previous work completed, however. The first is the application of remote-sensing to a large area of higher-elevation (< 6,000 ft) irrigated pasturelands that dominate much of the Colorado western slope. The second is the sheer size of the fields being evaluated under the condition of full-season curtailment, which are larger than any previously evaluated at this size by remote sensing. Finally, the third is the comparison between CU estimates derived by remote sensing methods and ground-based eddy covariance instrumentation, specifically installed at a location subjected to full-season curtailment. The evaluation of CU on a project that combines these characteristics together are key to understanding the value of remote sensing methods as scalable, transferrable, and effective tools for estimating CU across a broad landscape.

2.1 Existing Literature and Methods

Evapotranspiration (ET) is the process by which water moves into the atmosphere by evaporation from the soil surface and transpiration from growing plants. Evaporation and transpiration have been historically difficult to study separately, so the two processes are quantified together to estimate agricultural water use in common practice (Taylor and Ashcroft, 1972). Crop consumptive use (CU) is a close analog to ET, emerging from the vernacular of agricultural water rights. The term CU describes the amount of water that is put to beneficial use through evapotranspiration and incorporation into plant tissue. As the term implies, CU is water that is consumed and ultimately rendered unrecoverable for immediate reuse. The scientific literature is replete with explanations distinguishing ET and CU, in regard to both terminology and process (Burt et al., 1997; Allen and Jensen, 2016). Because the main focus of the Project is to quantify water consumed by agriculture, irrespective of underlying processes, estimation of ET and CU was undertaken as an identical pursuit without consideration of legal and technical distinctions. Therefore, the terms ET and CU are used interchangeably, with some exceptions for describing specific processes.

Mapping accurate and precise ET estimates is especially becoming important for managing water at the field-scale level, specifically for crop stress detection, sub-field water use assessment, irrigation scheduling, and agricultural water transfers (Bastiaanssen et al., 2000). ET depends upon land cover/land use, vegetation or crop type, soil water, weather conditions and management practices. Unlike other water budget components like precipitation, irrigation and flow, ET is a water vapor flux thus rendering a physical/mechanical measurement difficult (Senay et al., 2016).

One of the most commonly used method of determining crop ET for field water management is the estimation of an upper limit of potential ET (PET) for a reference crop. The PET represents a theoretical rate of ET under ideal weather and vegetative conditions that are not limited by soil moisture. Currently, the most readily accepted method of estimating PET is the standardized Penman-Monteith equation combined with the use of generalized crop coefficients (Kamble et al., 2013). Application of this method relies on 3 basic assumptions: one, crop PET can reliably be based off standard reference crops; two, empirically-derived tabulated crop coefficients under certain idealized agroclimatic conditions are applicable; three, tabulated crop growth stage lengths for applying crop coefficients are applicable. According to Johnson & Trout (2012), the general tabulations (for both crop coefficient values and crop growth stage lengths) are general guides that may not be applicable everywhere, and local observations of plant development are recommended.

Contrasted with PET, other methods exist for estimating actual ET (AET), involving measurements based on soil moisture sensors, sap-flow sensors, scintillometers, and eddy covariance towers, all of which are either point or footprint based, thus limiting large spatial coverage, and necessitating enormous human and capital investments. The goal of these methods is to estimate ET through a process that measures the quantity of water actually removed from a surface due to evaporation and transpiration. When conditions are ideal, AET should approach PET, but seasonal variations in water variability and different irrigation practices may affect this difference.

Remote sensing approaches have the capability to cover large areas with a consistent dataset and can standardize benchmarks for ET assessment and comparison across large spatial scales. These methods are being considered as an alternative to traditional methods largely due to their potential for reliably estimating basin consumptive use, their large-scale geographic applicability, their non-reliance on water supply information, and their potential for relatively rapid processing. This is especially important for Upper Colorado River Basin areas like Colorado's Western Slope, where there is a growing interest in establishing reliable temporary water sharing arrangements over large spatial scales (Cabot et al., 2017). These approaches can largely eliminate the need to rely on various assumptions and generalizations for estimating ET. One of the most common approach to assess ET using remote sensing data is physically-based land surface energy balance in which ET is calculated as the flux residual of energy budget at the terrestrial surface. Models like Surface Energy Balance Index (SEBI) (Menenti & Choudhury, 1993), Two Source Model (TSM) (Norman et al., 1995), Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998), ET Mapping Algorithm (ETMA) (Loheide & Gorelick, 2005), Atmosphere-Land Exchange Inverse (ALEXI) (Anderson et al., 1997), Disaggregated ALEXI (DisALEXI) (Norman et al., 2003), Mapping ET with Internalized Calibration (METRIC) (Allen et al., 2007), Remote Sensing of ET (ReSET) (Elhaddad & Garcia, 2008 and 2011), etc. are largely based on this concept.

Limitations of remote sensing do exist, however, specifically in terms of spatial and temporal resolution. Landsat suite of satellites are the only systems with the highest spatial resolution in the thermal band (Kjaersgaard et al., 2011), at 100 m for Landsat 8 and 60 m for Landsat 7, and this thermal band may be contaminated from adjacent areas outside of the field boundaries. Therefore, modeling that uses the thermal band at this resolution may not suffice for ET assessments at smaller field sizes that may only be a few

hundred meters across in north-south and/or east-west directions. This limitation can be resolved but disaggregating thermal data estimates down to the scale of multispectral measurements, taken at 30 m resolution. Temporal resolutions of Landsat satellites (16 days at best for one Landsat; 8 days at best for both Landsat 8 and 7) may not be adequate because of clouds affecting the quality of the images, especially at higher elevation areas where cloud cover can be more frequent. This limitation can be resolved using a “time integration approach” by which the temporally irresolute ET estimates from remote sensing are used to model weekly or even daily estimates through correlation with local reference ET using the Gridded Surface Meteorological (gridMET) dataset (Allen et al., 2007).

Recently, Sentinel 2 satellites have been of interest in the scientific community because they offer high spatial (10-30 m) and temporal resolution (approximately 10 days with Sentinel-2a currently; approximately 5 days with combined Sentinel 2a and Sentinel 2b (Bisquert et al., 2016). These satellites do not have a thermal sensor aboard their platform but are useful for modeling that uses multi-spectral data.

According to Ambast et al. (2002), there is still a gap between research studies and practical application of remote sensing techniques for water management. Reliable estimates of the amount of water transferred to the atmosphere by ET and CU are critical to support two major premises on which water sharing arrangements rest. The first basic premise is that the transferable fraction of a water right is its historical, beneficial CU. This quantity is determined by the proportion of annual crop ET (less effective precipitation) that can be shown to have been met by the water right, for a representative period of years, using a representative period of hydrologic years. (Waskom et al., 2016). Secondly, another premise is that foregone diversions and reduced irrigations will “conserve” water and it will remain elsewhere in the delivery system, since lower ET is expected for the cropping system receiving less water, all other factors (e.g., crop type, field area) remaining the same. The term Conserved Consumptive Use (CCU) has therefore been proposed to describe the proportion of historical, beneficial CU, originating from a water right because of diverting less than the historical rate to an irrigated cropping system (CAWA, 2008). This estimation is at the core of this evaluation, given that water sharing arrangements require reasonably accurate estimation of CCU to “shepherd” shared water and assure equitable negotiations (Cuenca et al., 2013).

For both pricing and planning purposes, a reasonable degree of confidence is needed in the baseline CU used for water sharing arrangements. In Colorado, the modified Blaney-Criddle method (1962) is used to quantify transferrable CU in water court (Walter, 2004; Montgomery, 2005). The primary crop CU determination method used in the Colorado Division of Water Resources (DWR) Decision Support System StateCU model is the modified Blaney-Criddle method (Colorado DWR, 2011), but the original Blaney-Criddle is also used in StateCU for high mountain meadows (CDWR, 2010). Another common approach for estimating CU and CCU uses is the Denver Water High Altitude Coefficients for high mountain meadows (Walter et al., 1990). These coefficients were produced from a 5-year lysimeter study conducted to estimate the amount of transferrable CU made available by the purchase of water rights from approximately 40,000 acres near South Park, Colorado. These results have been extrapolated to other locations and scales to estimate CU and CCU for grasses with the original Blaney-Criddle methodology in the Western Slope river basins. Although the Denver Water High Altitude coefficients were developed at elevations greater than 6,500 ft, they have also been adapted at lower elevations under substitute water supply plans. Using these coefficients, CCU is quantified by assigning a “Percent Reduction in CU Credit” for native grass and alfalfa, as a function of depth to groundwater at the field to which the water rights are appurtenant (CWCB and CDWR, 2013). There are noted inconsistencies and dissimilarities, however, when characterizing CU in other regions, as observed in other evaluations such as the Upper Gunnison (Smith, 2008; Juday et al., 2011).

The Colorado Decision Support System (CDSS) Lease Fallow Tool (LFT) software and data available from CDSS systems are also used to evaluate CU. The LFT was designed to simplify, streamline, and standardize historical CU analyses particularly for temporary projects where reducing engineering costs is important. The LFT has access to data used in and produced by the CDSS basin wide West Slope StateCU/StateMOD models. Although StateCU is primarily used with the Blaney-Criddle ET, the LFT can use the more accurate “statewide ET dataset” that utilizes the ASCE Standardized ET Equation (ASCE Std.). The limitation of the LFT is that it relies on equations for PET rather than AET values that can produce more accurate inventories of available CU.

The Project was undertaken to address a recognized need for methods that acquire data at geographically large scales characterized by spatial variability. The need for greater accuracy in quantifying CU and CCU over large expanses is important for water resources planning, water sharing, and water regulation (Allen et al., 2011). This data is also needed to build equitable agreements under which agricultural water users temporarily forgo diversions, reduce irrigation, and transfer water. One critique of using crop-coefficient approaches for estimating CU and CCU is that these methods are always to some degree tied to local hydrometeorological conditions, making their applicability limited across larger regions. This is particularly problematic on the Western Slope, where most irrigated grass hay fields and pastures are scattered over hundreds of thousands of acres and weather stations are not abundant. Even in localized conditions, significant variation in CU has been observed. For instance, in the Upper Gunnison River Basin, which is a relatively small region of irrigated agriculture relative to the overall irrigated acreage of the Western Slope, a 5-year lysimeter study reported May, June, and July ET rates ranging from 3.79-8.22, 5.33-9.63 and 4.43-9.33 inches, respectively, from nine lysimeters (Juday et al., 2011). Imprecise monitoring and measuring of CCU has also led to difficulty in assessing the impacts and successes of water sharing programs. The Klamath Water Bank in Oregon, for example, could not quantify its true impact because the observed increases in river levels during the program were still within streamflow measurement error and could not be determined to have resulted from reduced irrigations (USGS, 2005; GAO, 2005). Water transfer proposals have also been prohibited or regulated for fields near canals that exhibit water seepage, fields with deep-rooted crops like alfalfa, or fields with shallow groundwater (Colby et al., 2012; CDWR, 2005). These prohibitions and regulations are imposed because even if reliable diversion records are available, these records are unable to directly differentiate between the beneficial and non-beneficial CU that occurs after the diversions.

Due partly to the lack of other verified methods, the shortcomings of current CU estimation methods have been accepted. Nevertheless, a growing chorus of proponents argue that the successful operation of broad water-sharing programs involving agriculture will require a better approach to cost-effectively manage and monitor CU and CCU across large and administratively decentralized areas (Jones and Colby, 2012; URS, 2014). Reliable assessment of CCU is also crucial because of the nature of temporary arrangements where the net economic benefits are small compared to the outright purchase of agricultural water rights. In other words, because CCU serves as the fundamental basis of compensation to agricultural water users who participate in water sharing programs, a fair baseline is needed to estimate the amount of water being conserved by fallowing, reduced, or partial-season irrigation. As the pressure to share water on the Colorado River increases, interest in accurately quantifying CU rates by crop, parcel, and region will increase.

Remote sensing is of interest as a water resource planning tool, having emerged as an alternative approach that addresses some of the limitations of current and previous methods for estimating actual CU (ACU) under irrigation curtailment programs. Diversion records, for instance, are regarded by some as too coarse to make estimates of CU and CCU at the parcel scale where irrigation curtailment programs are administered (URS, 2014). Empirical methods (Blaney-Criddle, Hargreaves, Penman-Monteith) have been

used in the past to estimate CU from local weather data to calculate water balances for individual parcels but may also not be sufficiently site-specific for parcel-based water sharing arrangements and program monitoring (Cuenca et al., 2013) or they may be installed at locations that are not reflective of the meteorological conditions for the parcels enrolled. These methods also estimate potential CU (PCU) rather than actual CU (ACU), and therefore may over-estimate the quantity of CU conserved and ultimately transferrable. In some cases, these traditional methods have also exhibited estimation errors in semi-arid, high-altitude environments (Smith, 2008), which constitute the largest portion of irrigated agriculture on the Colorado Western Slope. Advanced instrumentation using lysimeters, eddy covariance, and soil moisture monitoring are effective and accurate, but too costly to implement and maintain for multiple parcels across broad areas under various irrigation conditions (Walter et al., 1990; Carlson et al., 1991; Tang et al., 2009).

In contrast, remote sensing methods are designed to estimate AET over large spatial areas at relatively frequent intervals (8 days). Because these methods measure AET from both precipitation and irrigation, they may have advantages over traditional methods that estimate PET based on empirical data and then rely on measurements or estimates of water availability to determine AET. It should be noted that these techniques currently present a number of implementation challenges including the need to fill data between satellite overpasses, the very large spatial area for processing, and the requirement for ground-based verification/calibration.

2.2 Methodology

The concept proposed to estimate water conservation from irrigation curtailment is to calculate the difference between actual ET for normally irrigated reference pastures ($ET_{a,r}$) and actual ET for treatment pastures ($ET_{a,t}$) which experience CU reductions because of *diminished grass cover*. Because precipitation rates are quite low in the Grand County region, a simplifying assumption can be made that the effective precipitation (P_{eff}) rate is $P_{eff} = 1.0 * P$, where P = measured precipitation depth. This consideration is immaterial, however, to the calculated difference between $ET_{a,r}$ and $ET_{a,t}$ as the reference and treatment pastures for each site are assumed to receive the same precipitation amount, due to their close proximity to each other. In other words, because the effective precipitation is the same for both fields, the difference in ET is expected to be attributed to the irrigation curtailment.

2.2.1 Estimation of ET from Landsat and Weather Data

Remote sensing of ET entails the use of radiation and energy balance approaches to calculate the evaporative flux of a vegetative surface under observation at the time of a satellite overpass. These instantaneous fluxes are then converted to daily, monthly, and seasonal fluxes using trends obtained from local weather data to determine the evapotranspiration of the vegetated surface for the complete growing season.

The importance of improving remote sensing methods to evaluate ET is a major impetus behind the work of OpenET (<https://openetdata.org/>), an online platform that performs satellite-based modeling of ET rates at daily, monthly, and annual timesteps at field scales (30m x 30m pixels). The remote sensing analyses of ET were produced for the evaluation area by DRI using an “ensemble approach” in order to model ET occurring on pastureland that were enrolled in the temporary curtailment program, as well as their accompanying reference fields. This workflow provided modeled ET rates at the monthly timescale for years 2016-2020. The ensemble approach provides the average results of 4 separate and diverse ET models: EEMETRIC (Allen et al., 2005; Allen et al., 2007), PT-JPL (Fisher et al., 2008), SIMS (Melton et al., 2012; Pereira et al., 2020), and SSEBop (Senay et al., 2014; Senay et al., 2018). The EEMETRIC, PT-JPL and SSEBop models are based on the surface energy balance approach, which relies on satellite

measurements of surface temperature and surface reflectance combined with other key land surface and weather variables to model ET. In contrast, the SIMS model relies on surface reflectance data and crop type information to compute ET using a crop coefficient approach for agricultural lands.

Figure 2.1 is a simplified data processing flowchart that illustrates some of the steps required to model ET using remotely sensed Landsat data. Landsat is currently the primary satellite dataset used within the OpenET platform. The Landsat program, a joint program of NASA and the U.S. Geological Survey, is the only operational satellite that combines thermal and optical data at the spatial and temporal resolution needed to assess individual agricultural fields. This data is used as a primary input to characterize land cover and vegetation conditions. The analysis computes the ET (vapor) flux at the of time of the Landsat images. The computed ET for the specific time is then used in conjunction with local weather data to model the instantaneous ET on a pixel-by-pixel basis for the entire day of the Landsat snapshot. The instantaneous ET values are used to determine crop coefficients for the day of the imagery. Daily crop coefficients between Landsat images are interpolated from the crop coefficients calculated for Landsat image dates. These crop coefficients are used to model ET through the growing season. The ET of a field is the average ET of the Landsat pixels (30m x 30m) within the field. Landsat 7 and 8 data are generally available every 8 days. While most images during the summer are adequate for calculating ET, some images on cloudy days are unsuitable for use.

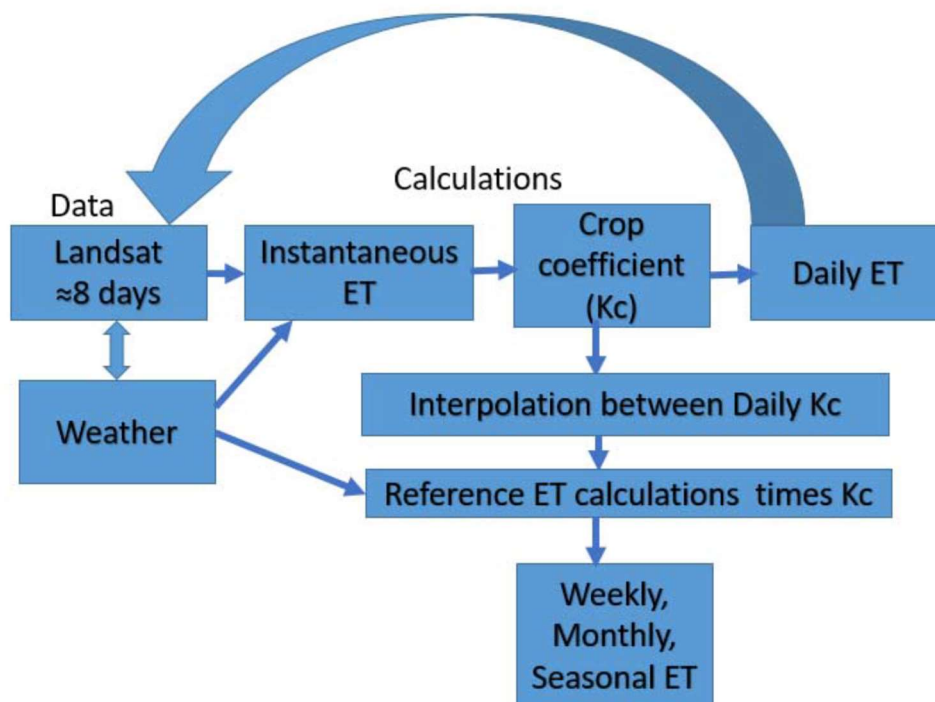


Figure 2.1. Simplified data processing flowchart that illustrates some of the steps required to model ET using Landsat and weather data. (Allen and Torres-Rua, 2018)

Reference ET (ET_o) was calculated using the GridMET gridded meteorological product (Abatzoglou, 2013) and calculated ET_o using the American Society of Civil Engineers Penman-Montieth equation (Walter, 2000). This makes possible a more detailed estimation of daily actual ET in between every eight-day Landsat satellite overpass, by using the fraction of reference ET (ET_{oF}) values to linearly interpolate to a daily timestep. In other words, ET_o data was used to support the calculation of actual ET in between Landsat satellite overpasses, which occur every 8 days (Allen et al., 2007). For each model used in the

ensemble, reference ET was used to calculate the fraction of reference ET for each satellite overpass date by dividing the satellite calculated ET by ET_o . Fraction of reference ET (ET_{oF}) values were then linearly interpolated to a daily timestep and are then multiplied by the daily ET_o values to calculate a daily time series of actual ET for every pixel. These per-pixel daily time series of actual ET were then aggregated to monthly timesteps.

Using remotely sensed data for the Project area, ET rates were modeled at the monthly timescale for years 2016-2019 and 2020, the year during which irrigation curtailments occurred.

2.2.2 Estimation of ET using Eddy Covariance

Given the importance of understanding the relationship between water use and the associated effects of irrigation curtailment for the Project, an eddy covariance measurement system was installed at the GPRT1H location, which was subjected to full-season irrigation curtailment in 2020. While eddy covariance data for grass pastures under irrigated conditions is available, high elevation pasture fields under curtailment have not been evaluated using this technology. The Project therefore offered a once-in-a-decade opportunity to obtain data for grassland pastures under extremely dry conditions caused by voluntary curtailment.



Figure 2.2 Panoramic view of eddy covariance tower on the GPR T1 field taken on April 21, 2021.

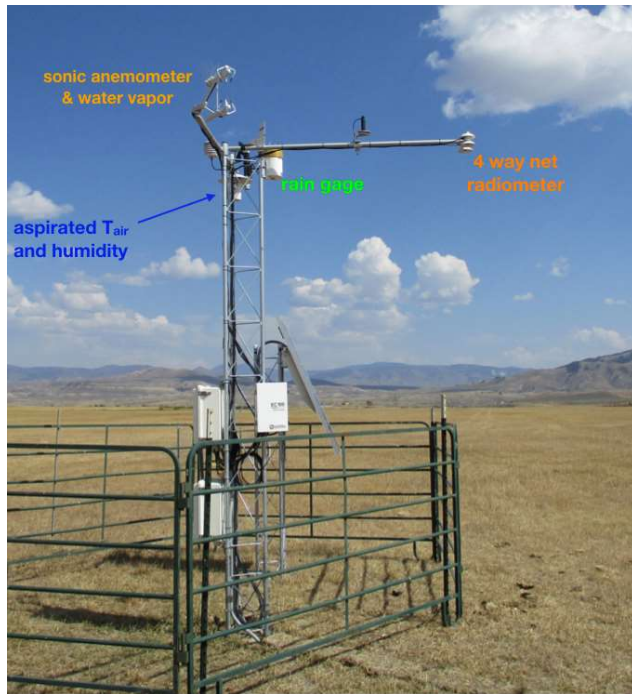


Figure 2.3 Eddy covariance tower on the GPR T1 field take on September 21, 2021

Eddy covariance uses micro-meteorological tools to directly observe the exchanges of gas, energy, and vapor between earth surfaces and the atmosphere. It is considered the most reliable method for comparison to modeled ET rates derived from remotely-sensed data. The eddy covariance and energy balance station instrumentation consists of: 1) fast-response sonic anemometer measuring three wind components and temperature, 2) fast-response and open path infrared gas analyzer measuring water vapor density, 3) four way net radiometer, 4) aspirated unit for average air temperature and humidity of air, 5) Soil heat flux plates and soil temperature and water content probes, 6) CR6 (Campbell Scientific) data logger, 7) Tipping bucket rain gage, 8) solar panel-battery power system, and 8) cell signal telemetry.

2.2.3 Estimation of ET using a Soil Water Balance

The evaluation also utilized in-situ Acclima TDR-315 sensors and Solar DataSnap SDI-12 data loggers (Acclima, Inc., Meridian, ID) at GPRR1H, GPRT1H, GPRT2H, RCRT1H, RSRR1H, RSRT1H, SBRR1H, SBRT1H, SPRR1H and SPRT1H as another ground-check to compare with the ensemble approach using the remote sensing data. These Acclima TDR-315 sensors were chosen based on comparisons between various soil moisture measuring tools (Varble and Chavez, 2011). The TDR-315 sensors measure volumetric water content (VWC) (0% to 100%), soil permittivity (1 to 80), soil bulk electrical conductivity (EC) (0 to 5000 $\mu\text{S}/\text{cm}$), soil temperature (-40 to $+60$ $^{\circ}\text{C}$) and pore water EC (Hilhorst Model) (0 to 55000 $\mu\text{S}/\text{cm}$). Sensors were installed at depths of 6, 18, 30 and 42 cm. These depths were selected based on available data and visual evaluations of the effective root zone at these locations. Each depth was considered the center of a soil depth interval within the effective root zone. In other words, the sensors at 6, 18, 30 and 42 cm represented identical 12 cm sub-zones of 0-12, 12-24, 24-36, and 36-48 cm below the soil surface. Data loggers were programmed to record measurements every 15 minutes, allowing detailed measurement of the changes in soil moisture. Total soil moisture level in the effective root zone (cm) was then derived by multiplying the sensor-measured VWC (%) by the soil interval depth (12 cm) and summarized for all 4 sub-zones every 15 minutes.



Figure 2.4 Soil moisture sensor installation representing depths of 0-12, 12-24, 24-36, and 36-48 cm below the soil surface.

A one-dimensional soil water balance (SWB) method was used to estimate AET (mm/d) by algebraic closure using the equation $AET = P_{\text{eff}} + Irr + U - SRO - DP - (D_p - D_c)$ where D_c and D_p are soil moisture deficits for current and previous day and P_{eff} is effective precipitation, Irr is irrigation, U is up flux groundwater contribution (capillary rise), SRO is surface runoff and DP is deep percolation. The soil moisture deficit (D) is calculated by subtracting the current moisture level in the root zone from the field capacity (FC) of the root zone. Rather than using laboratory-derived analysis, a practical determination method (Simmons et al., 2007) was used to estimate FC for each soil depth interval. This method assumes that noticeable points of inflection in the VWC data can be used to estimate FC based on general patterns that emerge throughout the season. After each irrigation event, for example, a rapid spike in soil water content indicates that the soil is saturated above the field capacity and quickly drains as water percolates through the profile. After this short draining period (typically 1-3 days) the rate of change in VWC becomes more gradual, reflecting a slower rate of water extraction caused by ET. The point where the VWC exhibits a clear transition from drainage to extraction is evident by a clear inflection point, which is assumed by the practical determination method as an estimate of FC . The VWC data can be further examined for another general pattern that shows moisture is extracted from the soil by ET until some critical moisture content is reached when evapotranspiration is no longer controlled by meteorological conditions. After this point, the VWC flattens and practically determines the permanent wilting point (PWP) of the soil.

As grasses grow and extract water from the soil to satisfy ET demand, the stored soil water is gradually depleted (Evetts et al., 2012). In the case of full curtailment, therefore, the estimate of AET by closure could be calculated using only the D_p and D_c terms, which are derived from the measurements of soil moisture levels and the P_{eff} term measured by the rain gages. This evaluation therefore assumes that all precipitation infiltrates. Data from groundwater level loggers and EC measurements from the TDR-315 sensors was used to verify there was no contribution from U. By calculating the SWB only during those time periods when fields were not being irrigated or subjected to saturation, the Irr and D_p terms could also be eliminated. Limitations to the SWB approach include difficulty in capturing intra-field variability and the reliance on sensors that frequently require gravimetric calibration (Varble and Chávez, 2011). Nevertheless, because the SWB is an in-situ monitoring technique, it is a valuable field method for evaluating soil water movement.

Rain gages data were installed at GPR (6/17-9/18), RCR (6/17-9/17), RSR (6/17-9/17), SBR (6/17-9/18), and SPR (6/17-9/17) parcels. Because a one-dimensional SWB was applied at the sites, lateral flow of water was not measured. However, instrumentation was installed to assess the potential contribution of groundwater, which was measured using 1.0' PVC observation wells and Solinst® Level Logger Junior™ pressure transducers. The transducers installed in the observation wells were corrected for barometric pressure using Solinst® Barologgers™.



Figure 2.5 Research assistant Cordelia Anderson performing routine quality control assessment at a research enclosure.

2.2.4 Estimation of ET using Atmometers

Atmometer data was also obtained at the GPR (6/25-9/07), RCR (7/14-9/07) and RSR (6/17-9/07) parcels using the alfalfa (#54) canvas cover for estimating alfalfa-reference potential ET (PET). Atmometers are inexpensive, simple, low maintenance tools for estimating PET (Broner and Law, 1991; Alam and Trooien, 2001) and available commercially (ETgage Company, Loveland, CO). The cannister has no contact with the soil, so it is not influenced by irrigation or field practices. A canvas cover is used to simulate alfalfa-based reference ET and farmers can then correct the atmometer observations using crop coefficients to obtain estimated ET rates for their crops. Gleason et al. (2013) compared the accuracy of atmometers against the ASCE Standardized Equation for PET and observed daily underestimation 88% of the time, with an average underestimation of 0.05 inches per day. These authors noted that underestimation reported by the atmometer was most frequently correlated with higher wind speeds.

2.3. Results and Findings

The AET rates provided by the remote sensing ensemble approach are modeled values for field water use per pixel. These individual values are then aggregated by averaging the AET rates for all the pixels within a project field for a chosen period of evaluation (e.g., monthly, seasonally, annually). Because each pixel is the same size for the Landsat satellites, a weighted-average across the field is not necessary. As the curtailment in irrigation is expected to reduce the AET, any reduction in AET during an enrollment year would indicate water being conserved against the entitled water right for the parcel, assuming the water right is in priority and water is physically available for irrigation.

This evaluation applied two approaches for considering a reference condition against which to estimate CCU during a program year of irrigation curtailment. The amount of CCU can generally be calculated as the deviation in AET (or Δ AET) between the selected chosen reference condition and the irrigation curtailment condition. One approach is to subtract the amount of CU on a field under curtailment in the program year from the average of modeled AET results across selected local fields or the exact irrigation-curtailed field for prior years with typical irrigation. Another approach is to use a nearby field under typical irrigation with similar soil and vegetative conditions as a reference, and then estimate CCU based on subtracting the field averaged AET results from the irrigation-curtailed field from AET on the nearby reference field, during the same year of the program.

2.3.1 Approach 1: Field Averaged Conserved Consumptive Use based on Prior Years ET

The *Prior Years Approach* assumes that the comparison years have similar ET patterns and irrigation water availability. For each individual project field, a timeseries was produced consisting of monthly rates of ET for the period of 2016-2020. One consideration of this method is that it may not take account whether a field may have been historically water-supply limited due to irrigation supply or farming practices or, on the other hand, if effective precipitation rates, early season soil moisture, and groundwater contributions have been markedly different in prior years. In other words, the approach may render the amount of CCU lower if the field under curtailment may have received significantly less irrigation in the past in comparison to the year of enrollment in a curtailment program. Effective precipitation rates can be calculated for prior years as an additional step in this analysis, but soil moisture and groundwater data would only be available if instrumentation existed prior to the evaluation. This consideration may be addressed by simply disregarding years that may neutralize the effect of physically and legally available water supply, or excessively abnormal (wet or dry) precipitation in prior years. On the other hand, the objective of this evaluation is to understand AET for fields that may be enrolled in water sharing arrangements, so more accurate HCU rates may be both desirable and equitable. It is worth pointing out that the fields under evaluation by this project do not indicate and record of abnormal water-supply limitations in prior years.

A relatively predictable and stable pattern was exhibited in annual AET for all sites during 2016-2019 (Figure 2.6).

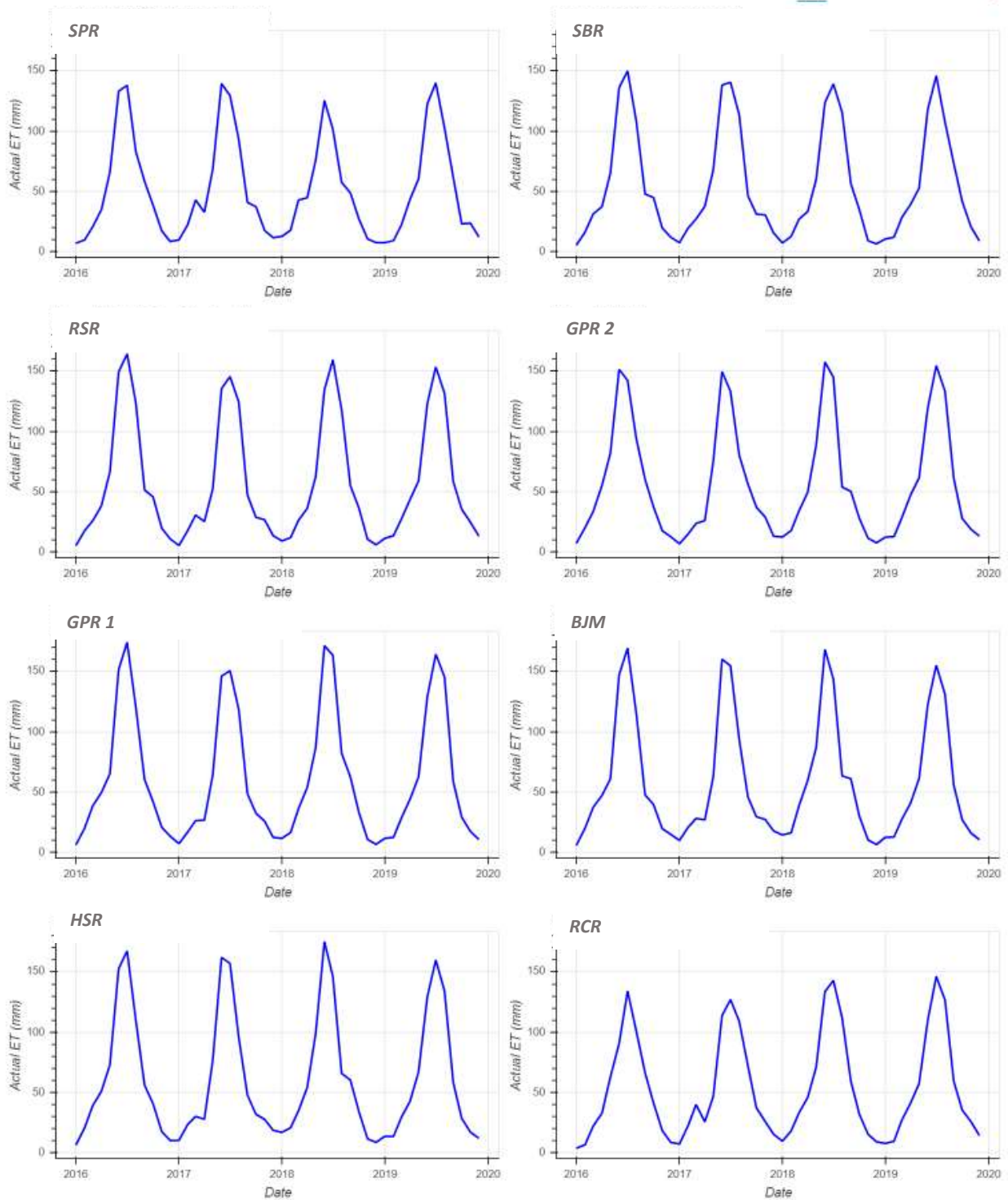


Figure 2.6 Timeseries of Ensemble ET for Project Sites (2016-2019)

In Table 2.1, calculated PET rates are shown, calculated from DWR Mountain Meadow crop coefficients at Kremmling NOAA Station USC00054664 (Thompson, 2021). ET results from the Grand County lysimeter study (Carlson et al., 1991) are also included. Estimation of wintertime demands are less certain, but the May through September months are the most relevant timeframe that would likely bracket the lease period for water-sharing arrangements. Table 2.1 summarizes the May-September monthly totals of AET for the ensemble approach averaged for the 9 primary project fields (1134 acres), along with 3 others included in the CWCB water-sharing arrangement (414 acres), totaling 1548 acres, in order to define a range of values for baseline, pre-treatment conditions based on the prior years 2016-2019. Table 2.2 summarizes other data pertaining to these fields. The purpose of these tables is to describe the entire range of PET, AET and other data for the field presented as total reference conditions performed by Kelley Thompson, P.E. (Senior Lead Modeler at the Colorado Division of Water Resources, Modeling and DSS Team, State Engineers Office, Denver CO) for general consideration throughout this report.

Table 2.1. Comparison of PET to AET on Project Fields (Average for 2016-2019)

ET in inches	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	May-Sep
Estimated PET ¹	0.14	0.21	0.41	1.28	4.72	7.41	6.54	5.33	3.35	0.52	0.24	0.10	27.35
Lysimeter ET ²	0.00	0.00	0.00	0.60	5.09	6.43	6.98	5.09	4.28	1.21	0.00	0.00	27.87
Ensemble AET	0.28	0.51	1.11	1.49	2.38	5.18	5.56	3.98	1.88	1.31	0.74	0.40	18.98
Precipitation	0.71	0.64	0.64	0.94	1.25	0.89	1.43	1.3	1.19	0.93	0.69	0.74	6.06
Effective Precip	0.67	0.6	0.6	0.88	1.16	0.83	1.32	1.21	1.1	0.87	0.65	0.69	5.62

¹ PET using DWR Mountain Meadow crop coefficients at Kremmling NOAA station USC00054664

² From Grand County Lysimeter Results from Carlson et al. 1991, as calculated using average of Blaney-Criddle crop coefficients (from Smith et al. 2008) at Kremmling NOAA in StateCU

Table 2.2. Other Recorded Project Field Data (Average for 2016-2019)

Observation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Precip (in)	0.71	0.64	0.64	0.94	1.25	0.89	1.43	1.3	1.19	0.93	0.69	0.74	11.35
Eff Precip (in)	0.67	0.6	0.6	0.88	1.16	0.83	1.32	1.21	1.1	0.87	0.65	0.69	10.58
Divs (ac-ft)	0	0	3	78	1169	2384	1210	147	424	133	0	0	5549
Max Div (ac-ft)	0	0	41	540	2701	3777	2443	934	1210	617	2	0	9344

Table 2.3 compares modeled ensemble AET estimates for 2016-2020 on the 9 Project Fields (1134 acres) that comprise the primary REF and TRT fields under evaluation as shown in Table 1.1 in the previous chapter (GPR, RSR, SBR, SPR) for 2016-2020. It should be noted that because remote sensing models estimate AET rates resulting from both precipitation and irrigation. The estimate supplied by OpenET, in other words, include effective precipitation, so the modeled AET is the cumulative sum of water lost from the soil-surface/vegetation regardless of the source of the water. The effective precipitation fraction (shown in Table 2.1), for instance, could be removed from remote sensing AET quantifications to more accurately estimate CU that occurs only from irrigation supplies. This separation may consequently affect the amount

of conserved consumptive use (CCU) available for water sharing, but it is further worth noting that effective precipitation rates as low as experienced in this area would likely affect both REF and TRT fields similarly, thus not significantly altering the relative relationship between AET on fields under typical irrigation versus curtailed conditions.

Table 2.3. Comparison of Ensemble AET on Project Fields (GPR, RSR, SBR, SPR) in 2016-2020.

ET in inches	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	May-Sep
2016	0.14	0.50	1.17	1.61	2.28	5.14	5.68	4.09	1.73	1.58	0.70	0.33	18.92
2017	0.25	0.70	1.09	0.99	2.33	5.40	5.44	3.94	1.74	1.22	1.05	0.58	18.86
2018	0.37	0.52	1.29	1.76	2.72	5.53	5.45	3.30	1.93	1.29	0.41	0.28	18.93
2019	0.37	0.31	0.91	1.60	2.19	4.65	5.67	4.60	2.10	1.14	0.79	0.41	19.22
2020 (REF only)	0.36	0.29	0.66	1.72	3.38	5.11	5.33	3.29	2.25	1.10	0.56	0.32	19.35

Table 2.4 differs from Table 2.3 in that it compares modeled ensemble AET estimates for 2016-2020 on the 4 Project Fields that comprise only the primary reference fields (172 acres) under evaluation as shown in Table 1.1 in the previous chapter.

Comparing the AET rates between various prior year baselines indicates that despite the lesser acreage uses as reference, these fully irrigated REF fields in 2020 maintained an average May-Sep AET rate (19.35 inches; Table 2.3) that was very similar to those observed in the 2016-2019 timeframe for all fields (1548 acres) enrolled in the CWCB water-sharing arrangement (18.98 in; Table 2.1) and the 9 primary fields (1134 acres) under evaluation (18.90 inches; Table 2.2). These similarities indicate that the basis of using various prior year comparisons as reference is a reasonable assumption. The percent change from the 2020 reference field AET rates, for instance, ranged between -3.7% to +0.6% when compared with the 2016-2019 AET rates (Table 2.4).

Table 2.4. Comparison of AET on Project Fields (Reference only) Between 2016-2020.

ET in inches	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	May-Sep	% Diff
2016	0.14	0.47	0.98	1.56	2.27	5.23	5.59	3.76	1.80	1.65	0.70	0.31	18.64	-3.7
2017	0.24	0.67	1.16	1.04	2.33	5.45	5.40	4.05	1.66	1.28	0.99	0.54	18.89	-2.4
2018	0.35	0.48	1.32	1.88	2.72	5.39	5.36	3.31	1.84	1.25	0.42	0.27	18.62	-3.8
2019	0.35	0.27	0.79	1.72	2.37	4.79	5.64	4.50	2.17	1.10	0.83	0.43	19.46	+0.6
2020 (REF only)	0.36	0.29	0.66	1.72	3.38	5.11	5.33	3.29	2.25	1.10	0.56	0.32	19.35	--

Table 2.5 summarizes the AET rates provided by the ensemble approach for 2016-2019 in order to determine the relative change in field averaged AET for the *different types of curtailment conditions* in 2020 enrolled in the CWCB water-sharing arrangement under full season curtailment (981 acres) and split-season curtailment (161 acres).

Table 2.5. Comparison of AET on Project Treatment fields between 2016-2020.

ET in inches	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	May-Sep
2016 – NC	0.16	0.60	1.39	1.82	2.30	5.38	5.82	4.29	1.67	1.53	0.71	0.37	19.45
2017 – NC	0.28	0.71	0.97	1.01	2.53	5.62	5.55	3.74	1.64	1.15	1.10	0.60	19.09
2018 – NC	0.39	0.55	1.32	1.77	2.83	5.78	5.43	2.97	1.96	1.29	0.36	0.28	18.96
2019 – NC	0.40	0.34	0.96	1.54	2.12	4.64	5.73	4.66	2.15	1.10	0.71	0.37	19.30
2020 - FULL	0.29	0.22	0.76	1.71	2.59	2.53	2.43	1.88	1.42	0.57	0.48	0.29	10.83
2016 – NC	0.09	0.27	0.88	1.09	2.24	4.24	5.45	4.14	1.81	1.62	0.69	0.28	17.88
2017 – NC	0.21	0.71	1.29	0.83	1.73	4.64	5.20	4.33	2.20	1.28	1.04	0.61	18.10
2018 – NC	0.35	0.53	1.16	1.50	2.41	5.09	5.68	4.25	2.02	1.35	0.53	0.27	19.45
2019 – NC	0.30	0.29	0.96	1.51	2.03	4.38	5.60	4.64	1.82	1.31	0.96	0.49	18.47
2020 - SPLIT	0.30	0.19	0.43	1.22	3.09	4.64	4.46	2.27	1.29	0.71	0.48	0.36	15.76

NC designates “not curtailed”; FULL designates “full curtailment”; SPLIT designates “split-season curtailment with irrigation cutoff 6/15

Fields that were fully curtailed in 2020 exhibited reductions in May-Sep AET that averaged 43.6% (ranging from 42.9% to 44.3%) in comparison to the 2016-2019 prior year baseline for these same fields. The fields that had irrigation curtailed after June 15 in 2020 exhibited reductions in May-Sep AET that averaged 14.6% (ranging from near 11.9% to 19.0%) in comparison to the 2016-2019 prior year baseline for these same fields.

2.3.2 Approach 2: Field Averaged Conserved Consumptive Use from Comparison Field ET

The *Comparison Field Approach* is simple because it does not require estimates of effective precipitation, irrigation, change in available soil moisture, and groundwater contribution (where applicable). The amount of CCU is equal to the ensemble approach AET for a TRT field subtracted from the ensemble approach AET for a comparison field. A condition of this method is that it assumes the selection of a comparison field with physical and legal water availability, and thus does not consider specific field-by-field AET differences that may be caused by pasture health, soil fertility, or underlying soil conditions. The fields under evaluation for the Project, however, are considered sufficiently large and spatially variable enough, so as to ameliorate this concern by field-average across a broad range of underlying field conditions.

Table 2.6 summarizes the AET for conditions for the 9 primary REF Project Fields. More specifically, the table summarizes the AET rates for the 4 primary TRT fields that were under full-season curtailment in 2020 (840 acres) and the 1 primary TRT field that was under split-season curtailment (123 acres). The total acreage for the REF fields against with these TRT fields were compared was 150 acres and 21 acres, respectively, for the full-season and split-season curtailed fields.

Table 2.6. Comparison of AET between Grand County Reference and Treatment fields in 2020.

ET in inches	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	May-Sep
<i>Full Season Irrigation Curtailment</i>													
2020 (REF)	0.35	0.24	0.57	1.70	3.26	5.00	5.04	3.16	2.21	0.99	01.51	0.32	18.67
2020 (TRT)	0.27	0.21	0.67	1.61	2.52	2.56	2.55	1.93	1.43	0.61	0.51	0.31	11.00
<i>Split-Season Irrigation Curtailment (no irrigation after June 15)</i>													
2020 (REF)	0.38	0.44	0.93	1.78	3.75	5.43	6.18	3.66	2.36	1.44	0.68	0.34	21.38
2020 (TRT)	0.44	0.36	0.61	1.48	3.26	5.23	4.65	2.26	1.20	0.64	0.52	0.35	16.60

Based on the Reference Field Approach, the percent change in field averaged AET between the 2020 REF and TRT fields was 41.1% for the fully curtailed condition and 22.3% for the split-season curtailment condition.

2.3.3 Comparison of ET Rates from Remote Sensing and Eddy Covariance Data

It is estimated that for grassland/pastureland cover, the difference between EC estimates of ET using a closed energy balance and the OpenET ensemble model estimates is generally less than 20% based on previous studies. For this analysis, site-specific EC measurement, processing and analysis of EC data was conducted on one of the TRT fields (GPRT1H), producing an estimate of daily ET rates for comparison against the ensemble approach results.

A multitude of studies indicate that the turbulent heat fluxes are generally underestimated using eddy-covariance measurements, and hence, the energy balance is not closed, leaving some energy unaccounted, which may thus affect estimated ET values. The energy balance closure on a daily basis was quite high, however, for this evaluation differing by less than 8% or more specifically, exhibiting a ratio of 0.92 between the unclosed and force-closed energy balance. These similarities are depicted graphically in Figure 2.2. Initial interpreted data from the eddy covariance station at GPRT1H shows that the ET rate declined from 0.16 in/day to 0.02 in/day over the course of the evaluation period (06/18 through 10/22). Some increase in ET occurred as a result of a rainfall event that happened near the end of July. Initial ET was very likely due to stored soil moisture, but no groundwater contribution was evident based on the observation wells.

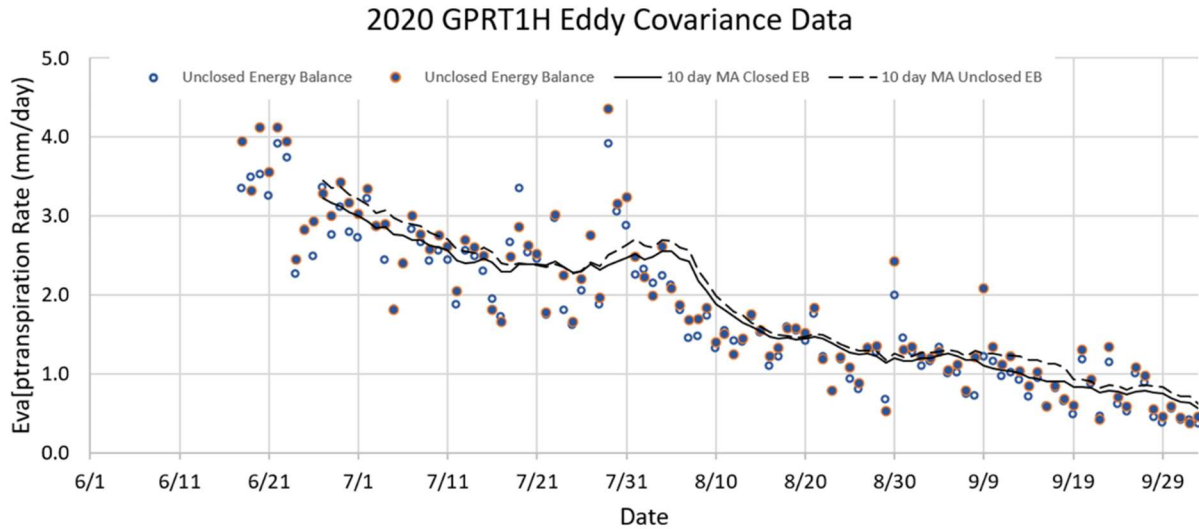


Figure 2.7. Estimated ET (mm/day) for closed and unclosed energy balance using eddy covariance.

Table 2.7 summarizes the ET estimates from the eddy covariance method and the results from the ensemble model on the particular days of satellite passes by Landsat 7 and 8. Both estimates are in fairly good agreement with minor anomalies, likely when climatic conditions and local weather conditions may have differed.

Four metrics for each model were calculated as measures of agreement between the and modeled ET values and the ET calculated from the EC tower data. These four metrics are: 1) coefficient of determination (R^2); 2) mean absolute error (MAE); 3) slope of the best fit line through the origin, and 4) root mean squared error (RMSE). These collectively provide an assessment of model bias and model error relative to the flux tower measurements.

Table 2.7. Comparison of AET for Eddy Covariance (EC) and Ensemble Approach (Ens) at GPR T1 in 2020.

<u>ET (in/day)</u>			<u>ET (in/day)</u>			<u>ET (in/day)</u>		
<u>Date</u>	<u>EC</u>	<u>Ens</u>	<u>Date</u>	<u>EC</u>	<u>Ens</u>	<u>Date</u>	<u>EC</u>	<u>Ens</u>
6/23/2020	0.146	0.103	7/26/2020	0.080	0.084	9/28/2020	0.018	0.025
7/1/2020	0.107	0.103	8/3/2020	0.084	0.066	10/5/2020	0.021	0.034
7/2/2020	0.126	0.123	8/10/2020	0.052	0.075	10/6/2020	0.013	0.036
7/9/2020	0.095	0.104	8/18/2020	0.062	0.068	10/13/2020	0.013	0.032
7/10/2020	0.100	0.092	9/4/2020	0.052	0.048	10/14/2020	0.021	0.033
7/17/2020	0.067	0.072	9/12/2020	0.040	0.041	10/21/2020	0.019	0.025
7/18/2020	0.104	0.085	9/27/2020	0.035	0.047	10/22/2020	0.014	0.034

Further data processing was conducted to determine the spatial extent (fetch) represented by the eddy-covariance station. This analysis primarily relied on measurements of wind direction and speed at the station. A static fetch as well as a dynamic fetch area for ET modeling was developed to represent the site conditions under EC evaluations at a monthly timestep. Model-specific, single-day estimates of fetch ET were compared to daily ET calculated by the EC station. Individual ET model data was aggregated into a mean value over the fetch area. This mean of all models compared well to estimates of ET from the EC station, resulting in an R^2 value of 0.95 and a RMSE of 0.40 (mm of ET/day) as depicted in Figure 2.3.

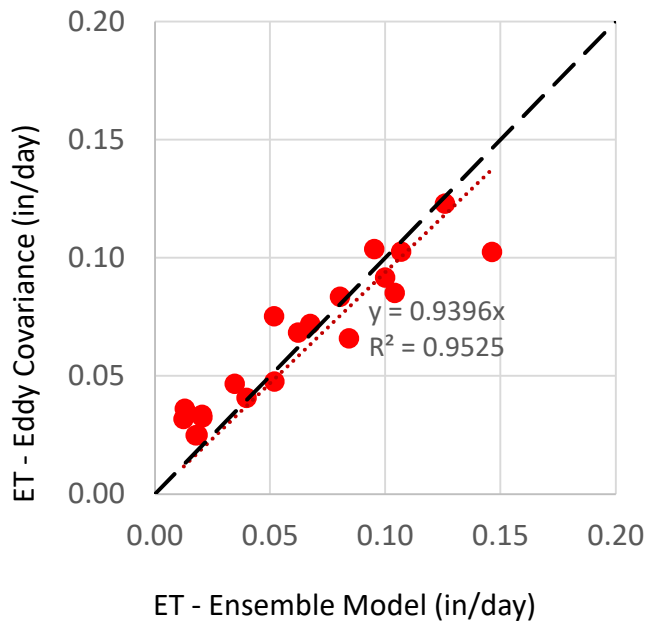


Figure 2.8 Comparison of ET estimates by eddy covariance methodology and modeled results using remote sensing

2.3.4 Comparison of ET Rates between Remote Sensing and Atmometer Data

Atmometer data was obtained at the GPR (6/25-9/07), RCR (7/14-9/07) and RSR (6/17-9/07) parcels using the alfalfa (#54) canvas cover for estimating alfalfa-reference ET. The PET total obtained for the equivalent periods at these sites were 17.96, 13.10, and 19.99 inches. Average PET rates showed consistency for the GPR, RCR and RSR were 0.28, 0.21, and 0.23 in/day for an average of 0.24. Since these rates apply mostly to the July through August time period, it is interesting to compare them with the 2020 AET rates derived from the ensemble approach for the most similar time period, which were 0.17 and 0.11 in/day, for an average of 0.14. This indicates that the atmometer method overestimates AET by a large amount, which is not surprising given that the atmometer results are intended to estimate PET rather than AET for an alfalfa reference condition. This result implies that atmometer results are probably somewhere between PET calculated from the ASCE standardized method and AET from remote sensing methods. Nevertheless, there may be some value in utilizing atmometers as an affordable means of estimating ET rates when the number of fields under evaluation is numerous and a local EC tower or other advanced instrumentation is available. In order for these tools to be utilized, however, a crop coefficient approach would be needed in order to develop the relationship between atmometer-estimated PET and remotely-sensed AET.

Given that atmometers are designed to estimate PET, there is some value in comparing 2016-2019 PET values derived from the DWR Mountain Meadow crop coefficients at Kremmling NOAA station USC00054664 and the 2016-2019 ET values derived from Grand County Lysimeter Results from Carlson et al. 1991. The PET rates estimated by these two methods for July were 0.22 and 0.23 in/day and for August were 0.17 and 0.16, indicating a higher level of consistency.

Rain gage data was also measured at the GPR (6/17-9/18), RCR (6/17-9/17), RSR (6/17-9/17), SBR (6/17-9/18), and SPR (6/17-9/17) parcels.

Table 2.8. Atmometer and Rain Gage Data for 2020.

Site	Dates of Observation	Days of Observation	Atmometer ET (in)	Atmometer ET (in/day)	Precipitation (in)
GPR	6/26 - 9/07	73	20.79	0.28	1.28
RCR	7/14 - 9/07	55	11.69	0.21	0.71
RSR	6/17 - 9/07	82	19.21	0.23	1.01
SBR			---	---	0.66
SPR			---	---	1.50

2.3.5 Comparison of ET Rates between Remote Sensing and Soil Moisture Data

The observations from the water balance data show a much smaller AET rate than would be expected based on the comparison with both the eddy covariance and remote sensing data. Although a consistent decline in soil moisture was observed at each location, the resultant AET rates are significantly lower than both the eddy covariance and remote sensing data for the range of dates measured. While the readings at GPR T1 are consistent between the installation by USU and CSU, the sensors may not be capturing the total input of the root zone. A relationship between periodically measured neutron probe data and the soil moisture sensor readings will have to be developed in subsequent years, but a preliminary evaluation on August 27, 2020 indicated good correspondence between neutron probe evaluations and soil moisture sensing results. This will be possible given that the neutron probe access tubes installed in 2020 are set to approximately 36” below ground level.

No influence of groundwater was observed on treatment fields, based on the data obtained from the groundwater observation wells. This conclusion is drawn from the absence of water in the wells throughout the course of the irrigation season during which the curtailment program was implemented.

Table 2.9. Field Capacity by Practical Determination Method (PDM-FC), Initial and Final Soil Water Deficit (D_{initial} and D_{final}), and Water Balance AET (WB-AET) Estimation from Soil Moisture Sensors at Project Fields.

Site ¹	Depth (in)	Dates	PDM FC (in)	D _{initial} (in)	D _{final} (in)	Δ D (in)	Precip (in)	WB-AET (in)
GPR T1 H	0 - 4.72	6/17-9/29	2.12	1.17	1.85	0.68		
	4.72 - 9.45	6/17-9/29	2.17	1.46	1.31	0.15		
	9.45 - 14.17	6/17-9/29	2.26	0.65	0.90	0.25		
	14.17 - 18.90	6/17-9/29	2.26	0.28	0.87	0.59		
	PROFILE	6/17-9/29	8.82	1.23	2.21	1.67	1.28	2.95
GPR T2 H	0 - 4.72	6/25-9/29	2.12	1.89	2.05	0.16		
	4.72 - 9.45	6/25-9/29	2.17	1.47	1.33	0.14		
	9.45 - 14.17	6/25-9/29	2.26	1.27	1.41	0.14		
	14.17 - 18.90	6/25-9/29	2.26	1.35	1.57	0.36		
	PROFILE		8.82	2.78	4.95	0.80	1.28	2.08
RSR R1 H	0 - 4.72	7/15-9/29	2.12	0.00	0.90	0.90		
	4.72 - 9.45	7/15-9/29	2.17	0.00	0.28	0.28		
	9.45 - 14.17	7/15-9/29	2.26	0.00	0.42	0.42		
	14.17 - 18.90	7/15-9/29	2.26	0.00	0.42	0.42		
	PROFILE		8.82	0.00	2.02	2.02	1.01	3.03
RSR T1 H	0 - 4.72	6/17-9/29	2.12	0.00	1.04	1.04		
	4.72 - 9.45	6/17-9/29	2.17	0.00	1.05	1.05		
	9.45 - 14.17	6/17-9/29	2.26	0.17	1.16	0.99		
	14.17 - 18.90	6/17-9/29	2.26	0.17	0.68	0.51		
	PROFILE		8.82	0.34	3.93	3.59	1.01	4.60
SBR R1 H	0 - 4.72	7/15-8/18	2.12					
	4.72 - 9.45	7/15-8/18	2.17					
	9.45 - 14.17	7/15-8/18	2.26					
	14.17 - 18.90	7/15-8/18	2.26					
	PROFILE		8.82					
SBR T1 H	0 - 4.72	6/26-8/27	2.12	1.53	1.61	0.08		
	4.72 - 9.45	6/26-8/27	2.17	1.37	1.47	0.10		
	9.45 - 14.17	6/26-8/27	2.26	1.49	1.64	0.15		
	14.17 - 18.90	6/26-8/27	2.26	1.43	1.60	0.17		
	PROFILE		8.82	5.82	6.32	0.50	0.66	1.16

Site ¹	Depth (in)	Dates	PDM FC (in)	D _{initial} (in)	D _{final} (in)	Δ D (in)	Precip (in)	WB-AET (in)
SPR R1 H	0 - 4.72	6/28-9/30	2.12	0.00	2.01	2.01		
	4.72 - 9.45	6/28-9/30	2.17	0.86	1.98	1.12		
	9.45 - 14.17	6/28-9/30	2.26	0.41	1.52	1.11		
	14.17 - 18.90	6/28-9/30	2.26	0.37	1.28	0.91		
	PROFILE		8.82	1.64	6.79	5.15	1.50	6.65
SPR T1 H	0 - 4.72	6/28-9/16	2.12	1.46	1.85	0.39		
	4.72 - 9.45	6/28-9/16	2.17	1.87	1.87	0.00		
	9.45 - 14.17	6/28-9/16	2.26	1.54	1.55	0.01		
	14.17 - 18.90	6/28-9/16	2.26	1.56	1.52	0.04		
	PROFILE		8.82	6.43	6.79	0.36	1.50	1.86

¹ Unable to install at GPR R1 H

2.4 General Observations

Based on the work to date, some general observations can be made pertaining to the three project-specific characteristics that distinguish this Project from its counterparts.

First, the Project fields evaluated under the condition of full-season curtailment exhibited 43.6% and 41.1% reductions in actual evapotranspiration (AET) for May-September, respectively, based on a *prior year approach* and a *comparison field approach*. Additionally, split-season curtailment resulted in 14.6% and 22.3% AET reductions during the same period, based again on the prior year and comparison field approaches. The difference in reduction between the full-season and split-season programs is not surprising. Previous studies have also shown that partial-season curtailment conditions offer limited amounts of conserved consumptive use (Allen and Torres-Rua, 2018; Cabot et al., 2018), although there are clear environmental benefits, such as later season streamflow enhancement.

Second, when estimating reductions in AET using remote-sensing, we did not observe a significant difference in the results when using the prior years approach or the comparison field approach.

Finally, the comparison of AET estimated from remote sensing methods and ground-based eddy covariance instrumentation at a field subjected to full-season curtailment has further increased the body of knowledge pertaining to these limited-water arrangements. The comparison between ET estimates derived from these two methods was quite high ($R^2 = 0.95$), offering greater confidence in the use of remote sensing as a scalable and transferrable tool to be used in other areas where water-sharing arrangements may take place.

SECTION THREE Forage Impacts & Recovery

Irrigated grass pastures and hayfields on the Western Slope are commonly managed with “wild” flood irrigation systems and are dominated by cool-season grasses with some cool-season legumes. The short growing season generally allows for 1 harvest annually (Pearson et al. 2011). Given these conditions, understanding how forage grasses respond to irrigation curtailment for water conservation programs is essential for multiple reasons. Foremost, these crops are primary users of irrigation water on the Western Slope. In 2012, a reported 252,240 hectares (623,294 ac) were in grass hay production in the region that includes Water Divisions 4, 5, 6, and 7, comprising the Colorado Western slope basins (Table 3.1).

Table 3.1. Colorado Water Division total: Irrigated Acres by Elevation Bands (MWH et al., 2012)

Crop	< 5000	5001-5500	5501-6000	6001-6500	6501-7000	7001-7500	7501-8000	8001-8500	8501-9000	9001-9500	9501-10000	>10000	Total
Alfalfa	20,327	11,967	10,782	13,237	29,159	3,724	2,669	646	0	0	0	0	92,511
Corn Grain	8,532	9,702	5,384	401	49	8	0	0	0	0	0	0	24,076
Dry Beans	139	3,650	963	1,089	4,680	86	0	0	0	0	0	0	10,607
Grass pasture	23,591	38,843	67,832	112,991	122,044	78,170	78,166	63,925	27,486	9,764	190	292	623,294
Orchard w/ Cover	238	84	246	382	201	53	0	0	0	0	0	0	1,204
Orchard w/o Cover	2,262	508	1,912	415	161	6	0	0	0	0	0	0	5,264
Spring Grains	4,733	6,655	5,401	2,843	5,210	1,901	78	764	418	0	0	0	28,003
Vegetables	801	172	74	0	0	0	0	104	0	0	0	0	1,151
Others	1,094	33	635	545	416	293	812	400	428	352	26	0	5,034
Totals	61,717	71,614	93,229	131,903	161,920	84,241	81,725	65,839	28,332	10,116	216	292	791,144

Forages are also known to be more tolerant than row crops to reduced irrigation and water stress and commonly experience significantly less long-term effects on future production (Orloff et al., (2016); MWH, 2012).

3.1 Existing Literature and Methods

While several studies have been conducted on tolerance to water stress for various forage species and varieties, limited information is available related to response and recovery of grass hayfields in regions similar to the Western Slope. In a study conducted in northern Utah, Hill et al. (2000) found that increasing water availability resulted in increased forage production of perennial grasses. Similar findings were reported by Smeal et al. (2005) in the dry environment of northern New Mexico where results indicated that there was no significant forage production when less than 350 mm (13.77 in) of irrigation water was applied evenly throughout the season. Sheaffer et al. (1992) reported that with reduced water supply for a full growing season, yield reductions ranged from 24 to 37% of fully irrigated controls. In comparison, a treatment simulating periods of drought followed by well-watered conditions had yield reductions varying from 54 to 81% of control plots. Jones (2015) reported yield reductions averaging 70% (range 24% to 93%) during a year of complete irrigation involving five sites at higher elevation grass pasture locations in Colorado. After one year of recovery, yields were still 48% (range 13% to 83%) below their fully irrigated reference counterparts. After two years of recovery, yields were only 7% (range 0% to 13%) lower than reference fields that had been continually irrigated. Also, a prevalent theme in grass recovery studies is the suggestion that some species may demonstrate compensatory growth when irrigation is reinitiated, thus

changing the species composition of the pasture, which may have attendant effects on both yield and forage quality.

There have been inconsistent results on the effects of water stress on forage quality. Sheaffer et al. (1992) reported an increase in crude protein (CP) content and reduction in neutral detergent fiber (NDF) and acid detergent fiber (ADF) in perennial grass species experiencing water stress. Researchers concluded that higher forage quality in water stressed plants was due to delayed maturation, increased leafiness, and stem and leaf quality (Sheaffer et al. 1992). In a study comparing various mixtures of perennial grasses and legumes, CP concentrations decreased or were unaffected when plants were under water stress while NDF concentrations were inconsistent between mixtures (Skinner et al. 2004).

3.2 Methodology

Soils in this area are dominated by Leavitt loam soil (fine-loamy, mixed Argic Cryoboroll) with 0 to 6% slopes. Cool-season grasses such as smooth brome (*Bromus inermis* L.), Kentucky bluegrass (*Poa pratensis* L.), quackgrass (*Elymus repens* L.), Timothy (*Phleum pratense*) and meadow foxtail (*Alopecurus pratensis* L.) are common.

Within large fields, different sub-field locations exhibit relatively higher and lower levels of productivity. The concept of selecting high and low areas of productivity for this project was intended as a means of packaging several research variables into a single location, since productivity is largely influenced by grass species and underlying soil conditions. Participating ranchers were able to provide detailed knowledge about which locations were more likely to experience higher and lower levels of productivity. This information was then applied for selecting the locations to install the research enclosures for studying forage impact and recovery sampling.



Figure 3.1. Forage sampling enclosure to protect from animal grazing and maintain grass growth throughout the season.

Forage samples were taken from within the stationary enclosures on approximately a monthly basis from June through September. The intention of this sampling schedule was to gather information during the initial period of the season after early irrigation, the period before hay cutting, and periods after the post-cutting irrigations. The samples taken from inside the enclosure were grasses that remained uncut and ungrazed throughout the season in order to maintain similarity between management conditions within the enclosure footprint.

Forage samples were also obtained at approximately 50 feet away outside of the enclosure. The goal was to obtain five of these comparison samples randomly at each monthly sampling event. The purpose of these additional samples was to compare the yield values calculated from within the enclosure and the surrounding area, since the enclosure samples may have been affected by the sensor installation procedure, and also to address the concern of relying solely on one single sample as being representative of such large field.

Forage samples were collected using a 0.25 m² (2.69 ft²) frame, hand clipped at approximately 7.5 cm (3 inches) to simulate approximate cutter-bar height. Plant material was dried in a forced-air oven at 55°C for 72 hours. Dry weights were then converted to kilograms per hectare and tons/acre.

For forage quality analysis, individual samples were ground through a Thomas Model 4 Wiley® Mill (Philadelphia, PA) with a 2 mm screen followed by a Foss™ Tecator Cyclotec Sample Mill Model 1093 (Eden Prairie, MN) with a 2 mm screen to homogenize the sample for quality analysis. Ground materials were used to determine dry matter (DM) and quality factors, including neutral detergent fiber (aNDF), *in-vitro* true digestibility (IVTD), and crude protein (CP) concentration, for each treatment. To determine DM, 1 gram of sample was weighed into an aluminum dish, dried for a minimum of 24 hours at 102°C, and reweighed. Crude protein content was measured using a LECO TruSpec® CN268 Elemental Combustion Analyzer (LECO Corp., St. Joseph, MI) to determine nitrogen content. Samples from every month and every treatment were analyzed. Crude protein was estimated by multiplying percent nitrogen by a factor of 6.25. Forage quality sampling was conducted at the Colorado State University forage laboratory, with some additional comparison analysis provided by Weld Laboratories (Greeley, CO)

3.3 Results and Findings

3.3.1 Comparison of Yield Data between Sites

Comparing dry matter biomass yields (T/ac) between treatment fields under full season curtailment and their reference counterparts showed an average 62%, 85% and 91% reduction respectively for the June, July, and Aug-Sep samples on the low production fields (Table 3.2). The same comparison for the high production fields exhibited an average 76%, 85% and 93% reduction for June, July, and Aug-Sep samples. Some assistance from stored soil moisture likely lessened the severity of the reduction for the first set of samples, but yield reductions worsened as the effect of irrigation curtailment became more prevalent. By August, the grass stand height was so significantly diminished that sampling was not possible.

An additional comparison against a reference condition was possible for one of the treatment fields (RSR) that was subjected to partial season curtailment (irrigation cessation on June 15). The high and low production fields at this site exhibited relatively consistent dry matter yields during the period before irrigation curtailment. After curtailment, however, yields were lowered by 93% and 95%, as observed for data collected in August.

Table 3.2. Grass Forage Yield from 2020 Season for Project Sites.

Site	Date	IRRIG	Low Production (T/ac)			High Production (T/ac)		
			REF	TRT	YIELD LOSS	REF	TRT	YIELD LOSS
GPR1	Jun 23	FULL ¹	0.50	0.09	82%	0.46	0.13	71%
	Jul 24	FULL	2.77	0.16	94%	3.62	0.26	93%
	Aug 12	FULL	3.29	0.00	100%	2.96	0.00	100%
GPR2	Jun 23	FULL	0.50	0.11	79%	0.46	0.17	62%
	Jul 24	FULL	2.77	0.21	92%	3.62	0.29	92%
	Aug 12	FULL	3.29	0.00	100%	2.96	0.00	100%
SBR	Jun 24	FULL	1.37	0.24	83%	1.81	0.15	92%
	Jul 31	FULL	2.69	0.42	85%	3.14	0.30	91%
	Aug 18	FULL	1.89	0.00	100%	2.68	0.00	100%
SPR	Jun 26	FULL	0.69	0.52	24%	1.88	0.58	69%
	Jul 27	FULL	0.71	0.17	77%	2.34	0.62	73%
	Sep 02	FULL	0.69	0.18	74%	2.20	0.49	78%
RSR	Jun 22		0.48	0.45	8%	0.80	1.03	-28%
	Jul 15		1.32	1.35	-2%	2.53	2.32	8%
	Aug 31	PART ²	1.41	0.09	93%	2.47	0.12	95%

¹ FULL = Irrigation curtailed for all of 2020 season

² PART = Irrigation curtailed for a part of the season: no irrigation after 6/15

3.3.2 Comparison of Forage Protein Data between Sites

Although issues have been raised concerning application of crude protein (CP) as a feed measure, it continues to be a commonly used measure of feed quality. Crude protein content is very different across feeds, but within a feed, higher protein is usually associated with higher quality. Protein levels can range from 8% to 14% in grass hay, and 15% to 22% in legume forages (alfalfa).

Within a given feed, NDF is a good measure of feed quality and plant maturity. For legume forages, NDF content below 40% would be considered good quality, while above 50% would be considered poor. For grass forages, NDF < 50% would be considered high quality and > 60% as low quality. None of the forages, even during the stress periods exhibited low forage quality by these standards.

Forage quality was generally higher at the beginning of the season and declined in each subsequent cutting (Table 3.3). The average seasonal CP levels for the high and low production fully-curtailed sites were 13.0% and 13.4%, respectively. The average seasonal CP levels for the companion reference sites to

the fully curtailed fields were 10.6% and 14.21%, respectively, for high and low production. However, the second cutting samples exhibited interesting percentage differences in CP and dNDF48 (shown in **bold** in Table 3.3). With only one exception, for example, CP for grasses subjected to curtailment was higher than for grasses that did not experience irrigation limitations, showing an average increase of 26% across sites.

Table 3.3. Grass Forage Quality from 2020 Season for Fully Curtailed Sites.

Site	Cut	CP (%)	dNDF48 ¹ (%)	Site	Cut	CP (%)	dNDF48 (%)	Site	Cut	CP (%)	dNDF48 (%)
GPRR1H	1	17.33	31.43	GPRT1H	1	17.68	27.88	GPRT2H	1	16.26	29.12
	2	10.69	34.39		2	12.83	27.06		2	15.07	25.51
	4	9.98	27.93		4	9.31	23.47		4	11.02	24.39
	5	9.38	30.89		5	9.90	23.76				
GPRR1L	1	23.34	34.22	GPRT1L	1	14.64	27.77	GPRT2L	1	14.11	28.16
	2	16.02	37.65		2	14.10	32.95		2	13.51	28.11
	4	14.41	33.67		4	8.52	25.13		4	10.74	22.33
SBRR1H	1	14.37	33.83	SBRT1H	1	16.66	28.86				
	2	9.35	32.39		2	13.48	25.31				
	4	11.28	29.59		4	9.63	22.95				
SBRR1L	1	15.39	32.75	SBRT1L	1	21.11	25.73				
	2	10.29	30.17		2	14.72	25.88				
	4	18.21	30.64		4	9.50	24.01				
SPRR1H	1	10.11	29.20	SPRT1H	1	16.12	31.29				
	2	9.72	29.43		2	13.60	27.22				
	3	6.81	30.37		3	11.62	25.04				
	4	6.36	28.78		4	11.93	24.74				
SPRR1L	1	14.44	30.58	SPRT1L	1	18.24	32.49				
	2	10.54	28.01		2	12.05	28.12				
	3	7.84	27.45		3	11.73	28.02				
	4	7.44	26.77		4	8.71	26.25				

¹ dNDF48 is estimated as the amount of NDF that disappears in 48 hours

3.4 General Observations

As anticipated, the impact of irrigation curtailment on yields for the project treatments fields was significant. On fields where no water was applied for the entire season (full curtailment), the lack of water caused an approximately 79% reduction in dry matter biomass weight at the lower producing areas for the Jun-Aug sampling period, as compared with their fully irrigated reference counterparts. The irrigation curtailment also caused an approximately 84% biomass loss for the same time period at the higher producing areas, again compared with their reference fields. Dry matter biomass weights on the partial curtailment sites (no water after June 15) were unaffected, of course, before water was cut off. After June 15th, however, biomass was reduced by 93% and 95% for only the August sampling. Looking at the entire season however, the losses were less severe, amounting to only 33% and 25%, respectively, for the low and high production areas.

It is worth noting that *functionally available yield*, that is what is agronomically feasible to bale, graze, or otherwise harvest, is different than research assessments of reduced biomass. In this study, participating producers did not harvest any grass from the treatment fields in 2020. However, since the overall goal of the project is to evaluate forage recovery once fields return to normal irrigation, it will be important to compare the yield impacts in 2020 with the yield data from subsequent years. This recovery data will be addressed in more detail in future reports.

SECTION FOUR Economics & Enterprise Budgeting

A better understanding of economic factors is needed for farmers and ranchers to evaluate how compensation for reduced water use fits into their operational planning. The economic impact of participating in water sharing arrangements can be considerable and must be offset by proper compensation in order for a market-based approach to be implemented. This project presents an opportunity to conduct both farm-specific and regional analyses to gather the full range of costs and benefits for water sharing program participants and their communities.

Enterprise budgets are currently being developed for individual participating ranches and the broader region to examine the potential effects of water sharing programs on hay prices and supplies. This information will help determine the impact of reduced yields and the value of the water to the overall ranching enterprise. Results from the budgeting work will form the basis of an economic assessment of impacts of water conservation programs on productive and economically profitable agricultural operations. Because of the need to incorporate the data on yield recovery, this economic info will be covered in further detail in future reports.

4.1 Methodology

One of the most basic and important decisions farmers and ranchers make is choosing the combination of products or enterprises to produce. An enterprise is defined as a single crop or livestock commodity that actually produces a marketable product. Enterprises are the basic building blocks for a farm plan, in order to account for the value of what is being produced, direct input and labor costs associated with production, cost of how the operations and how, determines the profitability of the business. By analyzing revenues and expenses associated with individual enterprises you can determine which enterprises might be expanded and those that should be cut back or eliminated. A manager may also want to compare profitability of one production technique with another technique (e.g., minimum till vs. conventional tillage practices), in order to choose enterprises that meet the goals and objectives of the farm/ranch operation.

An enterprise budget is a listing of all estimated income and expenses associated with a specific enterprise to provide an estimate of its profitability. A budget can be developed for each existing or potential enterprise in a farm or ranch plan. Several budgets could be developed to represent alternative combinations of inputs and outputs. Each budget should be developed on the basis of a small common unit, such as one acre of corn, wheat, or hay, or one head of livestock. This permits comparison of the profit for alternative and competing enterprises.

Reference field budgets serve as the baseline economic comparison for a typical growing season scenario. These budgets will be further detailed to understand operations that only grow hay for selling off-farm as well as operations that grow hay and raise livestock as a combined operation. The latter scenario is more common for larger farms in Colorado, thus presenting a major obstacle to short-term water sharing. Ranchers have reported being disinclined to share water for shorter time periods, since the resultant lack of hay forces them to have to acquire feed from elsewhere, perhaps even at a greater cost. The reason for this outcome is that ranchers will not cull herds temporarily to accommodate a loss of feed for a single year. Anecdotally, ranchers have reported in preliminary interviews that the economic offset for these temporary water-sharing arrangements would have to be quite large in order to gain their interest.

Enterprise treatment budgets will simulate the scenarios under which hay and hay + livestock is grown and raised on operations enrolled in both full-season and split-season curtailments. In preliminary interviews to begin developing these budgets, ranchers have also reported that while the cost of irrigation labor may also be reduced during the period of curtailment, they are also disinclined to let go of employees

in the short-term, especially now that labor is in such short supply. This constraint also results in a higher premium that ranchers say they would need in order to entertain water-sharing arrangements.

For this Project, enterprise budget tools are being developed for scenarios based on the reference and treatment conditions fields (Tables 4.1 and 4.2). For comparison with previous years, the CSU Agricultural Business Management Team summarizes general enterprise budget information by interviewing farmers across various regions, including the Western Slope region. Hay prices in 2016, 2017, 2018 and 2019 were reported at \$150, \$169, \$205, and \$232 per ton, a steady increase that will affect the interest of ranchers in water-sharing. Similarly, the return to management and risk during these same years has been reported at \$91, \$154, \$152, and \$240 per acre, driving an increasing value of water on ranches across the Western Slope.

Table 4.1. Example 2020 Enterprise Budget (Revenue Section) Spreadsheet developed from CSU Agricultural Business Management Spreadsheet Tool

REVENUES					
Budget	QUANTITY		PRICE	REVENUES	REVENUES
	PER ACRE	UNITS	PER UNIT	PER UNIT	PER ACRE
Grass Hay	3	tons	\$217.00		542.50
Other	0	Units	0.00		0.00
Government Payments	0	Field	0.00		0.00
TOTAL REVENUES				217.00	542.50

Table 4.2. Example 2020 Enterprise Budget (Expenses and Returns Section) Spreadsheet developed from CSU Agricultural Business Management Spreadsheet Tool

EXPENSES	PER TON	PER ACRE	YOUR FARM
OPERATING EXPENSES (PRE-HARVEST)			
Establishment Charges for Non-Annual Crops	0.00	0.00	0.00
Land Preparation	0.00	0.00	0.00
Seed/ Transplants & Planting	0.00	0.00	0.00
Fertilizer & Application	8.48	21.20	0.00
Herbicide & Application	0.00	0.00	0.00
Insecticide & Application	0.00	0.00	0.00
Mechanized Weed Control	0.40	1.00	0.00
Irrigation	6.80	17.00	0.00
Irrigation Labor	2.25	5.63	0.00
Labor	2.25	5.63	0.00
Crop Insurance	0.00	0.00	0.00
Interest on Operating Expenses (@ 5.25%)	0.23	0.58	0.00
Total Pre-Harvest Expenses	20.41	51.03	0.00
HARVEST EXPENSES			
Custom Harvest	16.60	41.50	0.00
Hauling	0.00	0.00	0.00
Total Harvest Expenses	16.60	41.50	0.00
TOTAL OPERATING EXPENSES	37.01	92.53	0.00
NET RECEIPTS BEFORE FACTOR PAYMENTS	179.99	449.97	0.00
FACTOR PAYMENTS			
Land Costs	92.50	37.00	0.00
Overhead/Depreciation/RE Taxes/Other Fixed Costs	40.00	16.00	0.00
Total Returns to Land	132.50	53.00	0.00
RETURN TO MANAGEMENT & RISK	47.49	396.97	0.00

SECTION FIVE Hydrological Impacts

As a component of the overall project effort to evaluate the effectiveness, benefits, and impacts of water conservation in high altitude pastures, the Project Team has contracted with Lotic Hydrological (Lotic) to assess hydrological changes resulting from the Project's water conservation activities. For this work, Lotic is collecting data along reaches of the Colorado River, Pass Creek, Red Dirt Creek, Williams Fork, and Bull Run during the summer and early fall of 2020 and 2021 and will compare this with historical data to characterize changes in surface water hydrology caused by the project. Additionally, this effort will provide an accounting of water conserved by the project between the participating parcels and the confluence of the Colorado River and Blue River. Data and information produced by this effort may be used to characterize potential effectiveness of water conservation projects at delivering water to the outlet of a drainage basin, evaluate environmental benefits or impacts, and for other purposes. This work can also inform efforts to develop streamlined tools for similar projects across the Colorado River basin.

5.1 Methodology

Lotic will conduct four field data collection campaigns in the summer and fall of 2020 and 2021. Streamflow will be measured with an Acoustic Doppler Current Profiler on the Colorado River immediately upstream of the point of surface water diversion and downstream of the presumed point of surface and groundwater return flows for three representative participating fields: SBR T1 2020, RSR T1 2020, and GPR T1 2020. Data will be collected in a quasi-synoptic fashion and each discharge measurement will consist of a replicate sample ($n \geq 3$).

Lotic will compare the field data from 2020 and 2021 with historical data and water diversion records, call records and reservoir storage/release records produced in 2020 to characterize the basin-scale hydrological effects of the project in qualitative terms. Specifically, Lotic will evaluate the timing and magnitude of expected impacts to streamflow at the reach scale and at the confluence of the Colorado River and Blue River.

Since the State of Colorado relies on modeling tools to inform estimates of conserved consumptive use resulting from water conservation efforts, it is important to understand the sensitivities of these models like the Lease Fallow Tool (LFT) and their validity when applied to this project. In coordination with the Colorado Division of Water Resources, Lotic will use a water balance approach to complete a modeling sensitivity analysis and an analytical approximation of return flow deficits incurred by the Project.

5.2 2020 Field Campaign

Lotic completed the 2020 field campaign and collected data on: August 9, September 13, October 2, and November 3. Streamflow was measured during each campaign using an Acoustic Doppler Current Profiler on the Colorado River immediately upstream of the point of surface water diversion and downstream of the presumed point of surface and groundwater return flows for the SBR T1 2020 and RSR T1 2020 project sites. Data was collected in a quasi-synoptic fashion. A large number of repeat discharge measurements ($n \geq 8$) were required to reduce measurement error at locations on the Colorado River in the late fall due to interference from periphyton. Measurements were completed with a Marsh McBirney on Pass Creek, bracketing the westernmost participating parcel on GPR T1 2020. Discharge measurement locations were mapped in a GIS and longitudinal plots of discharge were graphed for each stream system. Lotic will utilize the data collected in 2020 and 2021 to compare with historical data and the final results will be shared in 2021.

SECTION SIX Avian Monitoring

Irrigated agricultural lands throughout Colorado provide important wildlife habitat for a number of avian species and given the potential need for agricultural water conservation there is a critical need to understand how, where, and to what degree, reduced irrigation may influence this bird habitat.

To address this, the Project team is working with Audubon Rockies to evaluate the avian response on five participating fields from 2020-2022. It is worth noting that a baseline of avian habitat use for these fields was unavailable due to the time schedule of the creation of this project. Audubon will seek to quantify avian response trends to habitat variability during the 2020 treatment year and subsequent recovery years of 2021 and 2022.

Avian monitoring at the elevation of Kremmling, Colorado is prescribed for late June. Monitoring occurs once per year for a two-day cycle. Averaged results for the two-day avian monitoring effort are reported below in Table 7.1. For 2020 monitoring days occurred on June 24th and 25th. Audubon employed Precision Wildlife Resources, LLC to conduct monitoring using the *Integrated Monitoring in Bird Conservation Regions* (IMBCR) sampling protocol. This protocol uses randomized point counts as the primary sampling technique. The IMBCR protocol is designed to be statistically rigorous, biologically accurate, and to produce data for analyses of population trends for most breeding, diurnal land bird species.

Initial results from the 2020 and 2021 avian monitoring will be covered in the 2021 summary report.

SECTION SEVEN Social Perspectives

Because of the diverse contexts of agricultural production in Colorado and the Colorado River Basin, there is no “one size fits all” when it comes to understanding the feasibility of voluntary water conservation efforts. Furthermore, we know from past work that there are multiple barriers and reasons why agricultural producers do not currently participate in water conservation activities. To better understand these factors, the Project team has contracted with MacIlroy Research & Consulting to complete a longitudinal study to explore what people considered when making their decision about participation in the Project and to examine how social networks informed their decision about participation. Drawing on the extensive experience from the project participants and their perception of the issues at hand, the results of this effort can inform future conversations and help stakeholders and decision makers better understand the challenges, considerations, and potential paths forward in relation to water conservation in Colorado and the Upper Colorado River Basin. This study will also gather data to evaluate the conditions that make partnerships between agricultural water users and other entities possible and valuable.

The approach for this study involves completing a regular series of interviews and social network analysis throughout the course of the project through 2023 to understand the perspective and experience of project participants. The two main research questions are:

1. What is involved for ranchers in deciding about participation in this ATM project?
 - a. How does participant’s thinking about participation change over time?
2. How do the social networks of ranchers related to this ATM project inform their decision about participation?

Initial interviews with project participants and neighboring non-participants will be conducted in 2021. Because this is a longitudinal study that requires ongoing engagement with the project participants, a final report will not be delivered until the end of the data-gathering period in early 2024.

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APPENDIX

Monthly ensemble model ET estimate from OpenET.

BMR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016	0.13	0.64	1.49	1.86	1.89	5.33	6.23	4.51	1.41	1.42	0.74	0.49	26.13
2017	0.31	0.75	0.96	0.72	2.07	5.83	5.76	3.26	1.43	0.96	0.96	0.66	23.67
2018	0.42	0.51	1.60	2.41	2.96	6.17	5.27	2.02	2.03	1.14	0.32	0.24	25.10
2019	0.44	0.31	0.90	1.47	2.18	4.59	5.74	4.88	1.81	0.76	0.58	0.34	23.99
2020	0.29	0.24	1.19	2.02	2.68	2.26	1.58	1.32	1.31	0.39	0.38	0.17	13.82

BSR (RCR T1)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016	0.07	0.00	0.74	0.80	2.27	2.98	4.86	3.56	2.12	1.50	0.63	0.14	19.68
2017	0.20	0.71	1.37	0.67	1.39	3.94	4.68	3.77	2.55	1.42	1.01	0.67	22.39
2018	0.32	0.58	1.26	1.55	2.36	4.89	5.08	3.87	1.87	1.25	0.64	0.29	23.96
2019	0.22	0.19	0.88	1.46	2.04	4.13	5.62	4.53	1.82	1.36	0.89	0.50	23.63
2020	0.16	0.01	0.25	0.95	2.91	4.06	4.28	2.29	1.38	0.78	0.44	0.36	17.86

GPR R1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016	0.16	0.63	1.15	1.98	2.30	5.53	5.92	4.28	2.40	1.30	0.64	0.28	26.54
2017	0.26	0.65	1.02	0.94	2.70	5.71	5.66	4.16	1.91	1.29	1.24	0.48	26.03
2018	0.45	0.62	1.40	1.93	3.31	6.31	6.01	3.06	2.15	1.07	0.39	0.29	27.00
2019	0.39	0.38	0.99	1.78	2.53	4.62	6.03	5.18	2.12	1.00	0.69	0.46	26.17
2020	0.43	0.36	0.95	1.93	2.44	4.85	5.42	3.91	2.85	1.13	0.38	0.23	24.89

GPR T1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016	0.19	0.66	1.29	2.25	2.93	5.56	5.16	3.63	1.98	1.32	0.61	0.35	25.93
2017	0.27	0.60	0.93	1.02	2.97	5.87	5.23	3.13	2.18	1.46	1.16	0.53	25.34
2018	0.50	0.71	1.36	1.96	3.46	6.16	5.63	2.07	1.94	1.12	0.47	0.32	25.69
2019	0.38	0.31	0.96	1.78	2.26	4.45	5.73	4.83	2.07	0.86	0.75	0.49	24.88
2020	0.41	0.31	0.68	1.69	2.40	2.32	1.73	1.19	1.14	0.46	0.35	0.23	12.91

GPRT2	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016	0.15	0.64	1.54	1.98	2.08	5.57	6.48	4.71	1.93	1.52	0.76	0.39	27.76
2017	0.27	0.65	0.99	0.94	2.45	5.64	5.84	4.54	1.78	1.22	0.98	0.47	25.78
2018	0.42	0.62	1.47	2.15	3.28	6.62	6.32	3.08	2.35	1.33	0.41	0.27	28.32
2019	0.37	0.30	0.92	1.64	2.30	4.86	6.10	5.42	1.91	0.90	0.64	0.35	25.71
2020	0.27	0.22	1.32	1.99	2.59	2.73	2.57	2.12	1.63	0.62	0.33	0.20	16.61
0.08													
HR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016	0.15	0.67	1.57	2.08	2.38	5.55	6.19	4.35	1.79	1.47	0.62	0.23	27.04
2017	0.33	0.85	1.08	0.74	2.76	5.94	5.89	3.41	1.53	1.11	1.02	0.65	25.31
2018	0.54	0.67	1.44	2.03	3.46	6.43	5.33	2.11	1.97	1.34	0.40	0.33	26.05
2019	0.47	0.36	0.98	1.57	2.45	4.82	5.93	4.99	1.94	0.85	0.65	0.44	25.44
2020	0.33	0.24	0.69	1.79	2.73	2.67	2.76	2.24	1.46	0.63	0.45	0.33	16.30
RSR R1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016	0.09	0.51	1.06	1.47	2.17	5.60	6.24	4.68	1.55	1.91	0.78	0.46	26.51
2017	0.23	0.70	1.16	1.17	2.28	5.74	5.94	4.97	1.97	1.25	0.97	0.57	26.95
2018	0.37	0.37	1.17	2.09	2.78	5.72	6.29	4.28	2.38	1.46	0.46	0.25	27.61
2019	0.34	0.31	0.93	2.09	2.44	5.05	5.80	4.71	2.34	1.46	0.81	0.46	26.76
2020	0.38	0.44	0.93	1.78	3.75	5.43	6.18	3.66	2.36	1.44	0.68	0.34	27.37
RSR T1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016	0.12	0.55	1.02	1.38	2.22	5.50	6.03	4.72	1.50	1.73	0.75	0.41	25.92
2017	0.23	0.71	1.21	0.99	2.06	5.33	5.72	4.89	1.86	1.14	1.06	0.55	25.75
2018	0.38	0.48	1.05	1.45	2.46	5.30	6.27	4.64	2.16	1.45	0.43	0.25	26.32
2019	0.39	0.39	1.04	1.56	2.02	4.62	5.59	4.75	1.81	1.26	1.03	0.49	24.96
2020	0.44	0.36	0.61	1.48	3.26	5.23	4.65	2.26	1.20	0.64	0.52	0.35	21.01

SBR R1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016	0.20	0.54	1.25	1.69	2.27	5.42	5.65	3.60	1.67	1.93	0.83	0.36	25.41
2017	0.24	0.67	0.93	1.03	2.35	5.62	5.63	4.33	1.51	1.07	1.23	0.70	25.31
2018	0.24	0.42	1.32	2.09	2.38	5.77	5.70	4.00	1.42	1.41	0.36	0.31	25.43
2019	0.40	0.33	0.97	1.52	2.03	4.96	5.74	4.08	2.28	1.39	0.99	0.39	25.09
2020	0.12	0.01	0.30	1.13	4.03	6.01	5.83	3.44	2.08	1.10	0.71	0.44	25.19

0.44

SBR T1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016	0.16	0.50	1.21	1.37	2.25	5.12	5.44	4.27	1.45	1.72	0.77	0.39	24.65
2017	0.23	0.71	0.94	1.33	2.47	5.24	5.30	4.05	1.46	1.08	1.25	0.64	24.69
2018	0.23	0.39	1.03	1.03	1.91	4.65	5.01	4.26	1.73	1.39	0.29	0.26	22.19
2019	0.37	0.36	1.01	1.39	1.78	4.57	5.43	3.91	2.59	1.61	0.83	0.30	24.15
2020	0.21	0.16	0.34	1.38	2.56	2.59	2.95	2.21	1.48	0.67	0.67	0.41	15.63

SPR R1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016	0.11	0.20	0.46	1.11	2.32	4.35	4.55	2.48	1.57	1.47	0.54	0.12	19.30
2017	0.22	0.64	1.52	1.03	1.99	4.73	4.36	2.74	1.25	1.51	0.53	0.40	20.93
2018	0.36	0.50	1.37	1.40	2.42	3.75	3.44	1.91	1.41	1.05	0.46	0.23	18.31
2019	0.26	0.07	0.28	1.50	2.45	4.55	4.97	4.02	1.95	0.57	0.83	0.39	21.84
2020	0.51	0.34	0.45	2.05	3.30	4.15	3.89	2.14	1.70	0.73	0.46	0.28	19.99

SPR T1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016	0.16	0.50	1.21	1.37	2.25	5.12	5.44	4.27	1.45	1.72	0.77	0.39	24.65
2017	0.23	0.71	0.94	1.33	2.47	5.24	5.30	4.05	1.46	1.08	1.25	0.64	24.69
2018	0.23	0.39	1.03	1.03	1.91	4.65	5.01	4.26	1.73	1.39	0.29	0.26	22.19
2019	0.37	0.36	1.01	1.39	1.78	4.57	5.43	3.91	2.59	1.61	0.83	0.30	24.15
2020	0.21	0.16	0.34	1.38	2.56	2.59	2.95	2.21	1.48	0.67	0.67	0.41	15.63

TRT (FULL)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016	0.16	0.60	1.39	1.82	2.30	5.38	5.82	4.29	1.67	1.53	0.71	0.37	26.02
2017	0.28	0.71	0.97	1.01	2.53	5.62	5.55	3.74	1.64	1.15	1.10	0.60	24.91
2018	0.39	0.55	1.32	1.77	2.83	5.78	5.43	2.97	1.96	1.29	0.36	0.28	24.92
2019	0.40	0.34	0.96	1.54	2.12	4.64	5.73	4.66	2.15	1.10	0.71	0.37	24.72
2020	0.29	0.22	0.76	1.71	2.59	2.53	2.43	1.88	1.42	0.57	0.48	0.29	15.15

TRT (SPLIT)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016	0.08	0.26	0.90	1.14	2.22	4.29	5.55	4.12	1.84	1.71	0.71	0.30	23.09
2017	0.22	0.71	1.27	0.92	1.83	4.84	5.31	4.37	2.26	1.34	0.99	0.62	24.67
2018	0.34	0.47	1.22	1.82	2.57	5.30	5.69	4.07	2.13	1.36	0.55	0.27	25.78
2019	0.28	0.25	0.90	1.78	2.24	4.59	5.71	4.62	2.08	1.41	0.85	0.48	25.19
2020	0.27	0.23	0.59	1.36	3.33	4.75	5.23	2.97	1.87	1.11	0.56	0.35	22.62

REF	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2016-ALL	0.14	0.50	1.17	1.61	2.28	5.14	5.68	4.09	1.73	1.58	0.70	0.33	24.96
2017-ALL	0.25	0.70	1.09	0.99	2.33	5.40	5.44	3.94	1.74	1.22	1.05	0.58	24.74
2018-ALL	0.37	0.52	1.29	1.76	2.72	5.53	5.45	3.30	1.93	1.29	0.41	0.28	24.85
2019-ALL	0.37	0.31	0.91	1.60	2.19	4.65	5.67	4.60	2.10	1.14	0.79	0.41	24.73
2020-REF	0.36	0.29	0.66	1.72	3.38	5.11	5.33	3.29	2.25	1.10	0.56	0.32	24.36