Case Study: Validating Methods for Measuring Evapotranspiration and Accounting for Actual Depletion in Utah

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Legislative Agricultural Water Optimization Task Force

Depletion Accounting for Irrigation Water Rights in Utah
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Document history and status

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Case Study Supporters and Participants

This case study would not have been possible without the vision, insight, and expertise of the individuals listed here.

Legislative Agricultural Water Optimization Task Force

This case study was identified and funded by the Legislative Agricultural Water Optimization Task Force (Task Force) as part of the implementation of its 2019 Research Plan. The Task Force provided critical input throughout completion of this study. The Task Force comprises the following members:

- Mike Adams – Agricultural Producer/Irrigator
- Dustin Christensen – Agricultural Producer/Irrigator
- Ron Gibson (cochair) – Agricultural Producer/Irrigator
- Jay Olsen (cochair) – Utah Department of Agriculture and Food Representative
- Kyle Stephens – Utah Division of Water Resources Representative
- Jim Reese – Utah Division of Water Rights Representative
- John Mackey – Utah Division of Water Quality Representatives
- Jordan Nielson – Environmental Interests Representative
- Paul Monroe – Water Conservancy District Representative
- Ken White (nonvoting) – Higher Education Representative
- Brandon Yardley – Agricultural Producer/Irrigator

Case Study Team

Principal case study investigators were as follows:

- Niel Allen, PhD, PE – Utah State University
- Richard Allen, PhD, PE – Evapotranspiration Plus LLC
- Jeff DenBleyker, PE – Jacobs Engineering Group Inc.
- Lawrence Hipps, PhD – Utah State University
- Alfonso Torres-Rua, PhD – Utah State University
- Scott Morrison –Jacobs Engineering Group Inc.

Additional case study team members were as follows:

- Aaron Austin – Utah Division of Water Resources
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- Laura Christiansen – Utah State University
- Oliver Hargreaves – Utah State University
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Peer Reviewers

The authors appreciate the valuable peer reviews provided by the case study team members and the Division of Water Rights.

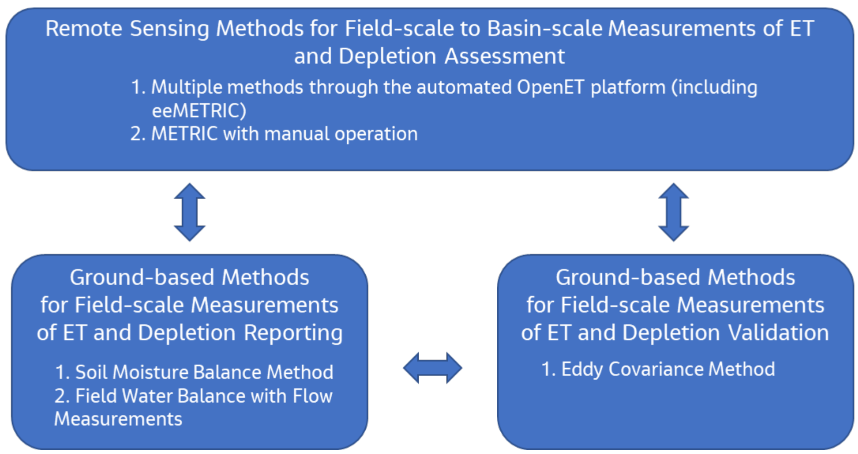
Executive Summary

Producers have asked the Utah Division of Water Rights to consider new means of administering water rights by depletion rather than the historical method of irrigation diversion duty and number of acres irrigated. An accurate, effective, and defensible means to measure and account for actual depletion, a process herein referred to as *depletion accounting*, is required for administering irrigation rights by depletion. With numerous available and emerging methodologies to do so, the Legislative Agricultural Water Optimization Task Force sought to evaluate and identify the most practical, effective, and defensible means of measuring evapotranspiration (ET) and accounting for actual depletion in Utah. Depletion accounting provides a means to quantify water use, enabling water optimization efforts to be supported by incentive programs. The objectives of this case study were to validate methodologies for measuring ET and to evaluate depletion accounting results across methods commonly used in Utah.

Methods

An Expert Panel was formed in January 2020 to identify and evaluate numerous available and emerging methodologies to measure ET and account for actual depletion. Eight ground-based methods and three remote-sensing methods were investigated in more detail in alignment with three applications: (1) ground-based methods for field-scale depletion reporting, (2) ground-based methods for field-scale depletion validation, and (3) remote-sensing methods for field-scale to basin-scale depletion assessment. The Expert Panel narrowed the list of alternative methods, made final recommendations for methods to measure and account for actual depletion of agricultural water use in Utah (see Figure ES-1), and recommended a case study that was designed to validate the recommended methodologies for use in Utah. This document provides a summary of the methods and results from this case study.

Figure ES-1. Recommended Layered Approach and and Methods for Measuring Evapotranspiration for Use in Utah



Case Study Results and Conclusions

Seasonal crop ET (ET_c) estimates using the soil moisture-based ET (SMET) and remote-sensing methods OpenET Google Earth Engine implementation of the Mapping Evapotranspiration at High Resolution with Internalized Calibration Model (eeMETRIC) and Manual implementation of the Mapping Evapotranspiration at High Resolution with Internalized Calibration Model (Manual METRIC) show closer agreement with eddy covariance (EC) method results compared with the other methods investigated. Current depletion estimation methods were investigated and compared using EC ET_c. The depletion volume for one alfalfa field was calculated across methods recommended by the expert panel. Overall the field water balance method provided the best agreement with EC based depletion results. Depletion results using methods that provided ET_c estimates followed the ET_c trends with SMET and METRIC models showing the best agreement, trending lower in depletion volumes, similar to ET_c results.

Based strictly on the results of this case study, the field water balance method provided the most practical and effective means for accounting for actual depletion of applied agricultural water but the limitations of the field water balance method need to be well understood before applying this conclusion elsewhere. SMET and eeMETRIC based depletion values were within 10% of EC based depletion results (within the EC method's margin of error) and may be more practical for other producers based on site conditions and available equipment. Notably, eeMETRIC based depletion provided similar results to SMET requiring lower expenditure for the user and a lower level of effort to obtain the data.

The case study team recommends repeating this case study in other areas and for other crops before making any policy recommendations as results could vary. Methods for estimating SM_{co} and P_{eff} should be investigated further as part of future case studies for use in translating ET rates into actual depletion.

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Acronyms and Abbreviations

ΔSWC	change in soil-water content
ALEXI	Atmosphere-Land Exchange Inverse
API	Application Programming Interface
ASCE	American Society of Civil Engineers
CU	consumptive use
DisAlexi	Disaggregated Atmosphere-Land Exchange Inverse
EC	eddy covariance
eeMETRIC	OpenET Google Earth Engine implementation of the Mapping Evapotranspiration at High Resolution with Internalized Calibration Model
ET	evapotranspiration
ET_{aw}	evapotranspiration of applied water
ET_c	crop evapotranspiration
ET_{na}	evapotranspiration with no advection
ET_r	reference evapotranspiration
G	soil heat flux
geeSEBAL	Google Earth Engine Implementation of the Surface Energy Balance Algorithm for Land
H	sensible heat flux
HB	House Bill
I	irrigation
LE	surface latent heat flux
LEPA	low-energy precision application
LESA	low-elevation spray application
MESA	mid-elevation spray application
METRIC	Mapping Evapotranspiration at High Resolution and Internalized Calibration
NA	not applicable

P_{eff}	effective precipitation
PT-JPL	Priestley-Taylor Jet Propulsion Laboratory
R_n	net radiation
SEBAL	surface energy balance algorithm for land
SIMS	satellite irrigation management support
SM_{co}	carry-over soil moisture
SMET	soil moisture-based evapotranspiration
SR	surface renewal
SSEBop	Operational Simplified Surface Energy Balance
SWB	soil-water balance
UAES	Utah Agricultural Experiment Station
UDWRe	Utah Division of Water Resources
USDA	United States Department of Agriculture
USU	Utah State University

1. Introduction

1.1 Purpose and Need

The Utah Legislature is proposing and developing new laws to provide flexibility and incentives for water users to reconsider how they manage and use their water supply. Improvements in field and irrigation practices and new funding from the Legislature have created new opportunities for producers to attempt to optimize water productivity and maximize their yields and revenues, while reducing depletion. Managing diverted water by depletion, rather than by duty and acreage, could allow some producers to be compensated for reductions in depletion or potentially expand their acreage and irrigate with the same or less volume of water. As a result, producers have asked the Utah Division of Water Rights to consider new means of administering water rights by depletion rather than the historical method of irrigation diversion duty and number of acres irrigated.

Administering irrigation rights by depletion would require accurate, effective, and defensible means to measure and account for actual depletion of applied water. The process of measuring and accounting for actual depletion of applied water is herein referred to as *depletion accounting*. With numerous available and emerging methodologies to do so, the Legislative Agricultural Water Optimization Task Force identified and evaluated several practical, effective, and defensible means for measuring evapotranspiration (ET) and accounting for actual depletion in Utah (Jacobs 2020). The most practical, effective, and defensible means were selected for evaluation in this case study to validate their use within the state of Utah.

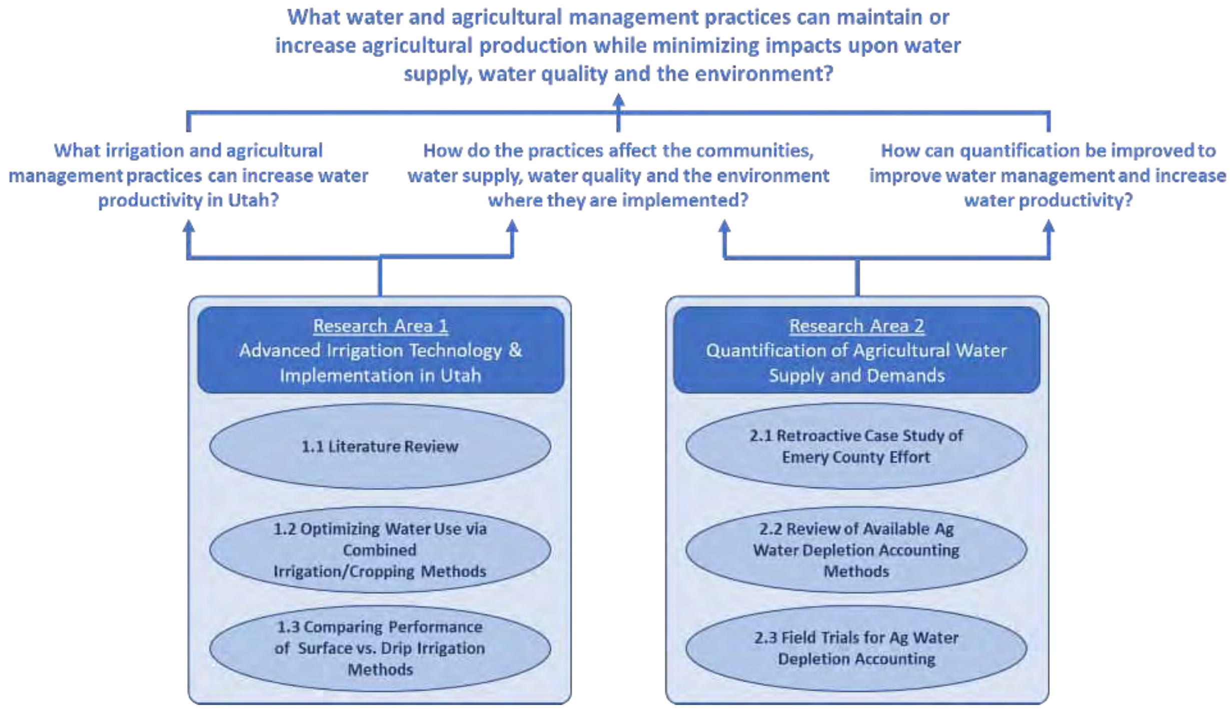
1.2 Case Study Objectives

The objectives of this case study were to field-verify and validate selected methodologies to measure and account for ET_c and actual depletion in Utah.

1.3 Background

House Bill 381 (HB 381) formed the Task Force in 2018 to identify and complete research that identifies how the state could accomplish the following: (1) optimize agricultural water supply and use and (2) improve quantification of agricultural water use on a basin level. The Task Force developed a research framework in 2019 to identify and prioritize research to achieve these objectives. Figure 1-1 illustrates the Task Force's 2019 Research Plan framework.

Figure 1-1. 2019 Agricultural Water Optimization Research Framework



Initial results from field studies of improved irrigation methods (Project 1.2) and the Emery County Case Study (Project 2.1) illustrated the benefits of quantifying available water supplies and diversions as well as the value in quantifying actual agricultural water depletions. Improved irrigation methods (Project 1.2) reduced required diversions and indicated improved yields over traditional surface irrigation methods (Allen 2020). Interviews with water users and managers and an evaluation of methods used in Emery County (Project 2.1) indicated that quantification of available water supplies and diversions increased transparency, improved crop production, reduced conflicts, and reduced fertilizer, herbicide, pesticide, and salt loading to the water systems (Rural Water Technology Alliance 2020).

Although optimizing irrigation to increase agricultural production has several benefits, its impact on the overall depletions of water resources at the basin scale and on downstream water users is a concern. As reported by the Utah Agricultural Experiment Station (UAES), with irrigation improvements that increase crop yields, crop ET (ET_c) and depletions often increase (UAES 1982). In addition, whether irrigation water optimization projects that increase irrigation efficiency and crop yields can actually increase depletions is a concern (Samani and Skaggs 2008; Ward and Pulido-Velazquez 2008).

These initial findings led to the conclusion that accurate measurement of ET and accounting of actual depletion are important in documenting the value of water optimization. Depletion accounting provides a means to quantify water use, enabling water optimization efforts to be supported by incentive programs, ultimately protecting water rights, water quality, and the environment. The Task Force determined that further study was needed to evaluate alternatives for measurement of ET and accounting of actual depletion (Jacobs 2020) and to validate the methods for use in Utah via this case study (see Project 2.3 on Figure 1-1).

2. Methodologies for Measuring Evapotranspiration

2.1 Approach

The Task Force prepared a list of criteria in 2020 (Jacobs 2020) to guide the evaluation and selection of depletion accounting methodologies for use in water rights management in Utah. These criteria helped focus the evaluation and final recommendations on methods for measuring ET and implementing depletion accounting that could meet a variety of uses, supporting farmers and state agencies in managing irrigation for agricultural production and water resources across Utah. Further discussion regarding evaluation criteria is provided in *Depletion Accounting for Irrigation Water Rights in Utah* (Jacobs 2020).

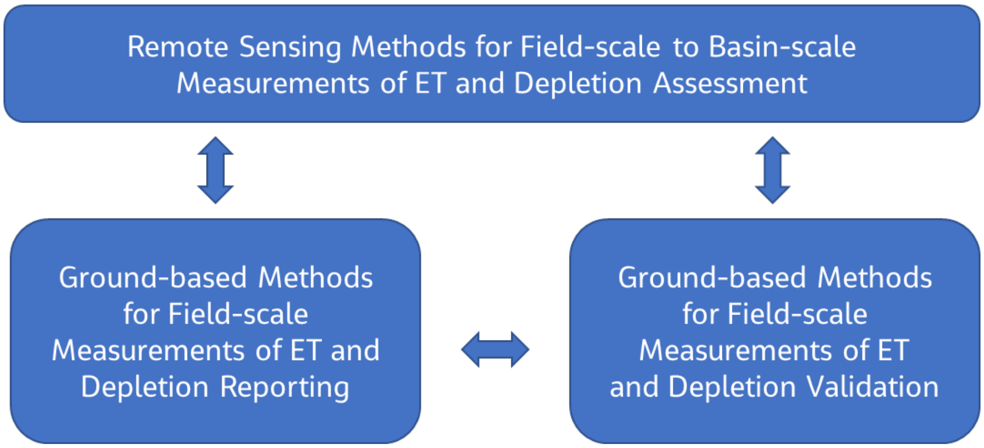
In considering these criteria, the Expert Panel determined that multiple methods for measuring ET could be appropriately used by water users and the state to implement depletion accounting for different purposes. For instance, multiple ground-based methods for measuring ET may be appropriate for application to estimate future depletions with a water right change and to measure and validate actual use after a water right change is implemented. However, a significant limitation to ground-based methods is that the scale of measurement and application is usually limited to field-scale or subfield-scale applications. For basin-scale application and application on a statewide basis, remote-sensing estimates of ET that cover large areas without the requirement of independent data sources for irrigated area, cropping, or water diversion/delivery data are most suitable. To evaluate different remote-sensing-based estimating methods in Utah, accurate ground-based methods for measuring ET were also recommended for comparison and validation.

Therefore, the evaluation of methods for measuring ET considered three complementary applications:

1) **Ground-Based Methods for Field-Scale Measurements of ET**. These methods should be suitable for use by water users in measuring ET and reporting depletions associated with an individual water right at the field-scale to the state, as required with an irrigation water right change approval. The equipment should be accessible on the market and may be implemented directly by the water user or with the assistance of a consultant.
2) **Ground-Based Methods for Field-Scale Measurements of ET Validation**. These methods are required for validating or ground-truthing results for ET provided by basin-scale methods (that is, remote-sensing methods) and may be used for validating or ground-truthing results of ET reported by water users. Therefore, these methods require a high level of confidence in measurement accuracy and precision at the field scale. The ground-based methods for validation typically require expensive equipment, are complex, and require expert supervision and data processing but provide best-in-class accuracy.
3) **Remote-Sensing Methods for Field-Scale to Basin-Scale Measurements of ET**. These methods focus on the ability to measure ET and evaluate depletion over large land areas but are also applicable for assessing depletions at the field scale. The methods provide data that can be used for assessment of depletions across entire basins and potentially the entire state of Utah.

The Expert Panel developed and recommended a layered approach to identify the most effective method for measuring ET and implementing depletion accounting for a given application while also providing validation of results from the other applications (Figure 2-1). This approach was intended to integrate the applications to provide scalability and defensibility and maximize value to water users, water managers, and the state of Utah over time.

Figure 2-1. Three Applications for Consideration in Evaluating Methods for Measuring Evapotranspiration and Implementing Depletion Accounting



2.2 Evaluation Results and Recommendations

Numerous ground-based and remote-sensing methods for measuring actual ET_c and accounting for actual depletion were identified by the Expert Panel. The advantages and disadvantages of each method and applicability for the three primary applications were assessed (further details are provided in *Depletion Accounting for Irrigation Water Rights in Utah* ([Jacobs 2020]). Methods were evaluated for use independently and in combination where the strengths of different methods could be integrated into a more robust solution. Selected methods had to meet prescribed criteria and the objectives of the three primary applications, but most importantly, they had to be deemed by the Expert Panel to be the best solution and provide the highest value in meeting the state of Utah's objectives and the needs of the agricultural community.

Figure 2-2 illustrates the recommended methods for measuring ET_c for each of these three applications discussed in Section 2-1. A summary of the final recommendations is presented in Table 2-1.

Figure 2-2. Recommended Layered Approach and Methods for Measuring Evapotranspiration for Use in Utah

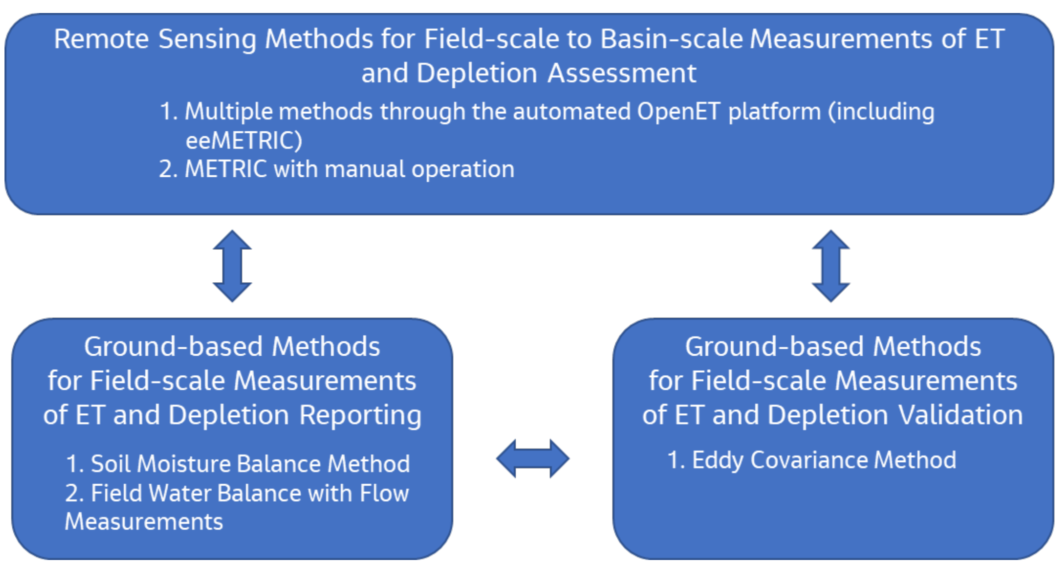


Table 2-1. Recommended Methods for Measuring Evapotranspiration

Method	Method Description
Ground-based methods for field-scale ET measurements	
Soil Water Balance	Widely used in irrigation industry and capable of measuring actual ET_c accurately on weekly intervals and estimating depletion.
Field water balance using flow measurements	Suitable for depletion estimates under limited field conditions with no appreciable deep percolation, runoff, or other water losses.
Ground-based methods for field-scale of ET measurement validation	
Eddy Covariance	Most widely accepted method for accurate ground-based measurement of actual ET_c.
Remote sensing methods for field-scale to basin-scale ET measurements	
OpenET	The OpenET[a] platform provides the state of Utah with a unique opportunity to participate in the development of an automated remote-sensing platform intended to bring remote-sensing actual ET_c measurements directly to producers and water managers at very low cost. The OpenET platform computes and allows a comparison of ET_c values generated using seven different methodologies including eeMETRIC and an ensemble result that includes results from all six supporting methods.
METRIC (manual implementation)	METRIC is widely used when a defensible field-scale and basin-scale solution is required, especially in the western United States. Implementation of METRIC directly by expert users also allows comparison of results with the automated METRIC and other automated methods available within OpenET.

[a] Details about OpenET's data products can be found at https://openetdata.org/about/.

Notes:

EC = eddy covariance
ET = evapotranspiration
ET_c = crop evapotranspiration
METRIC = Mapping Evapotranspiration at High Resolution and Internalized Calibration

3. Case Study Details and Results

The objective of this case study was to validate the recommended methodologies discussed in Section 2.2.1 and provide data that the Utah Division of Water Rights can use in developing procedures for managing water rights by depletion. The case study details and results are provided in the sections to follow.

3.1 Planning Team and Decision Makers

The Task Force oversaw the case study with the assistance of the Utah Division of Water Rights and Utah Division of Water Resources. The Task Force was responsible for developing the case study design and requirements, reviewing and approving any changes in objectives, design, and execution that emerge during implementation of the case study, and reviewing and approving case study deliverables. The Utah Division of Water Resources contracted with Utah State University (USU) for execution of the case study and provided administrative support.

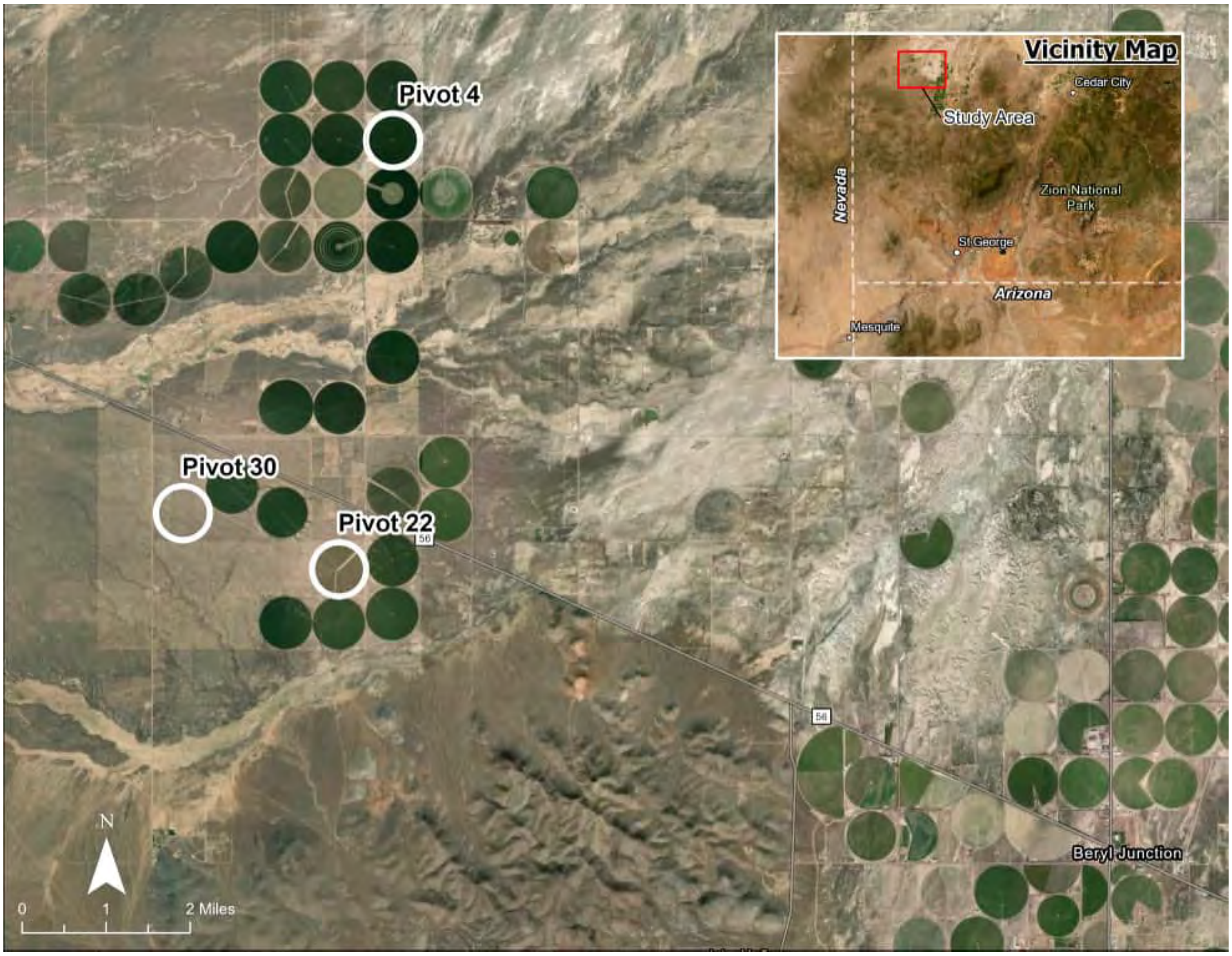
3.2 Available Resources

The Task Force funded the case study with monies appropriated under HB 381. USU coordinated, acquired and provided for the required installation, operation, maintenance, and removal of systems to collect the required data; manage, process, and evaluate the data sets; complete the required evaluations; provide the Task Force with recommendations for next steps; and document methods, assumptions, results, and recommendations in provided reports.

3.3 Study Partner

The Task Force, working with the Utah Division of Water Rights and the Utah Division of Water Resources, identified Holt Farms, a water user located in the Escalante Valley in southwestern Utah (New Castle, Enterprise, and Beryl) who was willing to participate in the case study (study area illustrated on Figure 3-1). Holt Farms originally requested that the case study be performed on two adjacent, center-pivot irrigated fields that are part of their operation and located within current Landsat flight paths. One field was planted with alfalfa (Pivot 22) and the second double cropped with corn from May through September and triticale from October through May (Pivot 30). A third double cropped field with corn and triticale was added in 2021 (Pivot 4).

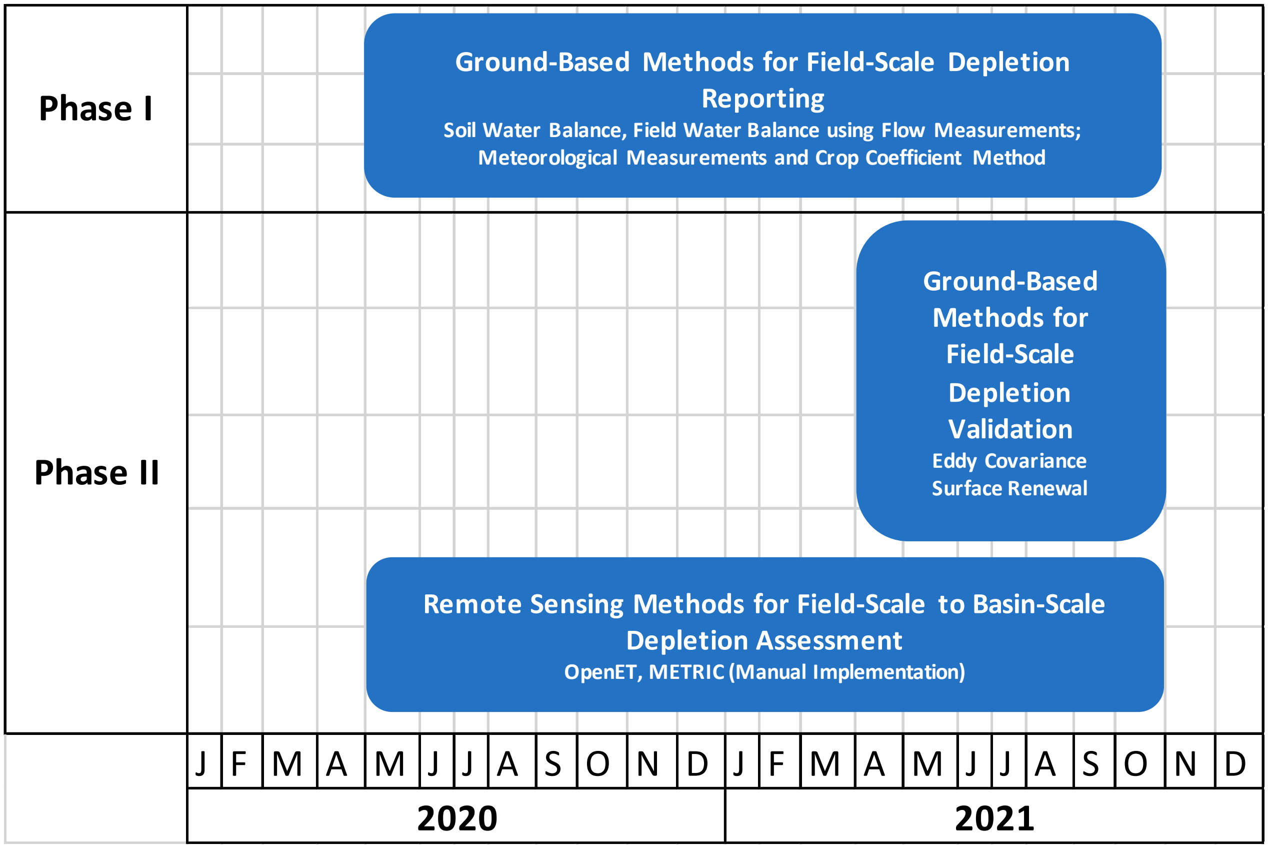
Figure 3-1. Location of Holt Farms Study Area near New Castle, Enterprise, and Beryl Junction, Utah



3.4 Case Study Details

Holt Farms worked with the Task Force to complete the case study in two phases spanning from May 2020 through December 2021. The case study components and timeline are illustrated on Figure 3-2; additional details are provided in the subsections to follow.

Figure 3-2. Summary of Timeline and Activities for Case Study Phases I and II



3.4.1 Phase I – Ground-Based Methods for Reporting – May 2020 through October 2021 Field Study

Niel Allen, PhD, and USU was contracted by the Task Force to complete the following studies from May 2020 through December 2020:

1) **Evaluate meteorological measurements and crop coefficients method**[1] by installing, operating, and maintaining a meteorological station adjacent to Pivot 22 (see Figure 3-1 and 3-3) from May 2020 through October 2021. The station was installed, operated, and maintained by USU to measure solar radiation, wind speed, air temperature, relative humidity, and precipitation. Reference ET (ET_r) rates were calculated to support soil moisture-based ET (SMET) quantification methods. Potential ET_c data, based on the mean crop coefficient method, for Pivot 22 were obtained from *Crop and Wetland Consumptive Water Use and Open Water Surface Evaporation in Utah* (UAES 2011).

2) **Evaluate soil-water balance (SWB) method** by installing, operating, and maintaining three soil moisture stations on each of the two center-pivot irrigated fields (Pivots 22 and 30, see Figure 3-3) from May 2020 through December 2020. Each station included soil moisture sensors that were installed in May 2020. The three soil moisture water balance stations in the alfalfa field (Pivot 22) were left in the field through October 2021. The three stations in the first corn/triticale field (Pivot

[1] The Meteorological Measurements and Crop Coefficients method were not recommended for use for agricultural depletion accounting by the Expert Panel in Utah, but when coupled with the other elements of the Case Study, were included in the Case Study as they provide inexpensive additional points of comparison to the other methods.

30) were demobilized in September 2020, when corn was harvested; re-installed in October 2020, after triticale was planted and left in place through December 2021.

3) **Evaluate field water balance method** by using magnetic flux flowmeters with data loggers already installed by the Holt Farm on each of the two center-pivots (Pivot 22 and Pivot 30) and flowmeters on its groundwater wells. USU independently verified the accuracy of the Holt Farms' flowmeters to validate reported flow data.

3.4.2 Phase II – Ground-Based Methods for Validation and Remote Sensing – January 2021 through October 2021 Field Study and May 2020 through October 2021 Remote Sensing Analysis

The USU team of Niel Allen, Alfonso Torres, Lawrence Hipps, Rick Allen (Allen Engineering) and Jeff DenBleyker (Jacobs) was contracted by the Task Force to complete the following Phase II studies beginning in January 2021.

1) **Continue Phase I field measurements (meteorological, soil moisture, and applied water)** in the two irrigated fields (Pivot 22 and Pivot 30) with the addition of conducting the same measurements (soil moisture and applied water) via the same methods in another corn/triticale field, Pivot 4 (Figure 3-3).
2) **Install, operate, and maintain eddy covariance (EC) and surface renewal (SR)[2] data collection systems** at Pivot 22 for the period of April through October 2021.
3) **Analyze the ground-based data** collected in both Phase I and II for validation of ET measurements.
4) **Conduct retroactive analysis of remote-sensing data**[3] (OpenET and METRIC) for the period of May 2020 through October 2021.

3.4.3 Equipment Installations

Soil moisture sensor installations are detailed in Table 3-1; pivot locations, associated soil moisture profiles, and EC footprint are shown on Figure 3-3 (Christiansen 2022). The EC station was installed northeast of the footprint based on a prevailing winds study performed by Dr. Lawrence Hipps [additional details provided in *Eddy Covariance Results for Actual ET and Validation of Surface Renewal Model* (Hipps 2023)].

Table 3-1. Summary of Soil Moisture Sensor Installations

Pivot	Crop Type	Irrigation System	Number of Soil Profiles	Sensors per Soil Profile	Sensor Depths Below the Surface (inches)
4	Corn/triticale	MESA sprinkler – 2020 LESA sprinkler – 2021	3	8	3, 3, 6, 6, 12, 24, 36, 48
30	Corn/triticale	LEPA sprinkler	3	8	3, 3, 6, 6, 12, 24, 36, 48
22	Alfalfa (dairy)	MESA sprinkler – 2020 LESA sprinkler – 2021	3	6-7	East and West: 3, 6, 12, 24, 36, 48, 60 North[a]: 3, 6, 12, 24, 36, 48

[a]Soil characteristic prevented the installation of a sensor at 60 in. in the north profile of Pivot 22.

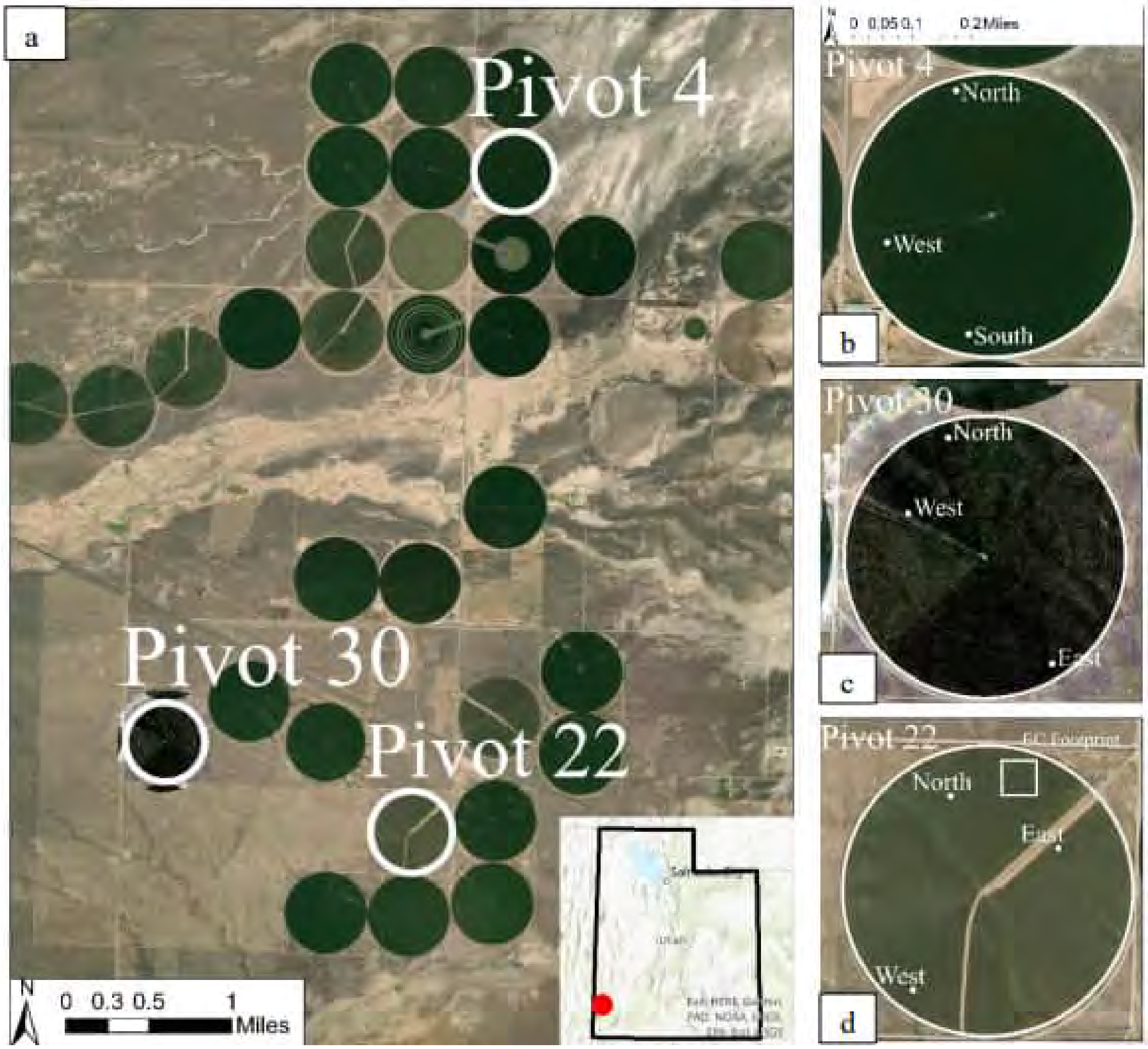
Notes:

LEPA = low-energy precision application
LESA = low-elevation spray application
MESA = mid-elevation spray application

[2] The SR method was not one of the recommended methods for use for agricultural depletion accounting by the Expert Panel in Utah because it is still experimental; however, when coupled with the other elements of the case study, it was included in the case study because it provides inexpensive additional points of comparison with the other methods.

[3] Analysis of remote-sensing data was only performed on the 2021 growing season due to availability of EC ET_c estimates.

Figure 3-3. Locations of Case Study Pivots and Associated Soil Moisture Stations and Eddy Covariance Footprint (Pivot 22)



Source: Christiansen (2022)

3.5 Case Study Results

Key Findings: Seasonal ET_c estimates using the SMET and remote-sensing methods OpenET eeMETRIC and Manual METRIC show closer agreement with EC method results compared with other methods investigated. Seasonal EC ET was 7 percent greater than SMET, 8 percent greater than OpenET eeMETRIC, and 11 percent greater than Manual METRIC estimates. Current depletion estimation methods were investigated and compared using EC ET_c. Depletion volume for Pivot 22 was calculated across all ET_c measurement methods, with the exception of SR, using field soil moisture data to determine SM_{co} and an 80 percent approximation of measured precipitation to determine P_{eff}. Agreement with EC-based depletion results followed the ET_c trends with SMET and METRIC models showing the best agreement, trending lower in depletion volumes. The field water balance method had the closest agreement with EC ET_c based depletion volume across all methods, a difference of 0.4%.

3.5.1 Estimating Crop Evapotranspiration

3.5.1.1 Methods

The first step in accomplishing the case study objectives was to measure actual ET_c. ET_c as referenced in this study represents the total ET from the field in question and includes ET of water obtained from soil moisture, precipitation and applied water. ET_c measurements and estimates were performed using the following methods:

- **Ground-based methods for estimating actual and potential ETc for field-scale depletion reporting**
  - **SMET method (actual ET_c) —** The SWB method originally proposed by Jacobs (2020) was found to be unable to reliably estimate ET for days where soil-water content was increasing due to irrigation or precipitation. The frequency of irrigation events at this study site necessitated a significant amount of gap filling to estimate ET. For this reason, the SWB method could not and was not used in this study to estimate ET (Christiansen 2022). The SMET method was employed in place of the SWB method and is described in detail by Hargreaves (2022) and Christiansen (2022).
  - **Crop coefficient method (potential ET_c) —** Potential ET_c data, based on the mean crop coefficient method, for Pivot 22 were obtained from *Crop and Wetland Consumptive Water Use and Open Water Surface Evaporation in Utah* (UAES 2011). The Meteorological Measurements and Crop Coefficients method were not recommended for use for agricultural depletion accounting by the Expert Panel in Utah, but when coupled with the other elements of the case study, were included in the case study as they provide inexpensive additional points of comparison to the other methods
- **Ground-based methods for measuring actual ETc for field-scale depletion validation**
  - **EC method —** The EC method is described in detail by Hipps (2023).
  - **SR method —** The SR method was not one of the recommended methods for use for agricultural depletion accounting by the Expert Panel in Utah because it is still experimental; however, when coupled with the other elements of the case study (EC station), it was included in the case study because it provides inexpensive additional points of comparison to the other methods. The SR method is described in detail by Hipps (2023).
- **Remote sensing methods for estimating actual ETc for field-scale to basin-scale depletion assessment**
  - **Automated OpenET methods —** This method includes both the ensemble, a single "ensemble value" from the six satellite-driven models, and eeMETRIC, Google Earth engine implementation of the METRIC model, models. The evaluation using data from OpenET is described in detail by Christiansen (2022).
  - **Manually operated METRIC model —** This method is described in detail by Allen et al. (2022).

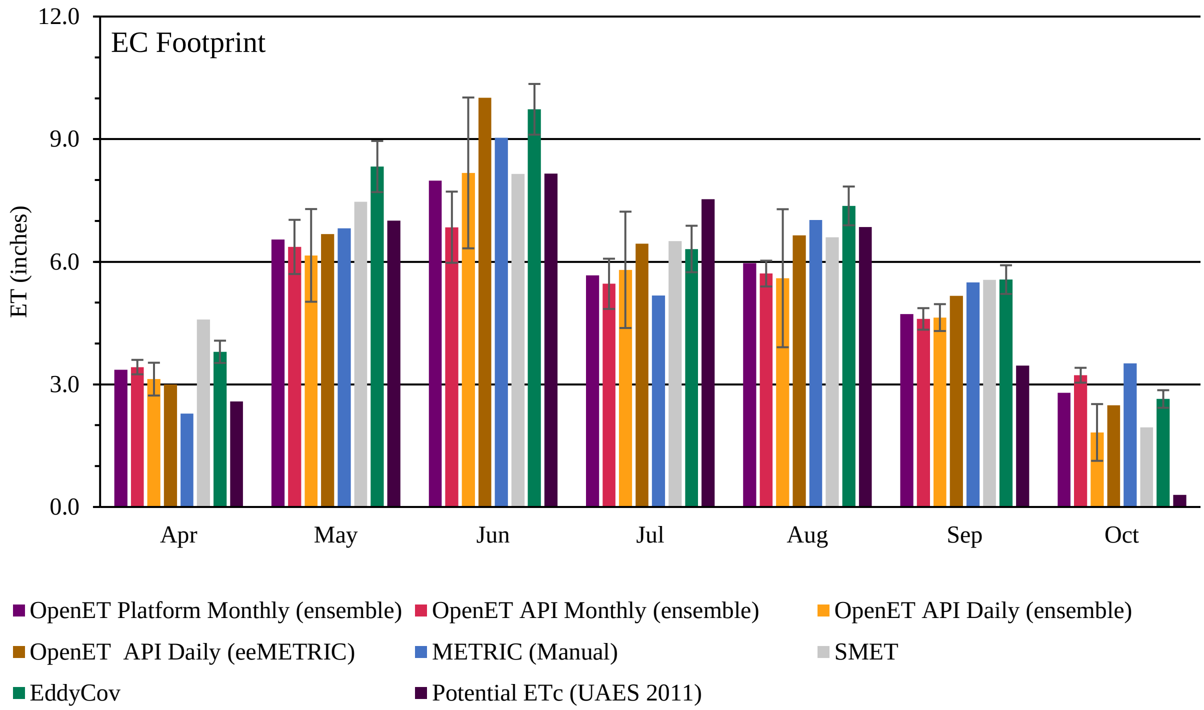
3.5.1.2 Results

Monthly ET_c results within the EC footprint for the various methods are summarized on Figure 3-4 for the 2021 measurement period, April 1 – October 22, 2021, hereafter referred to as the growing season. Results presented herein are limited to 2021 data from Pivot 22 due to the availability of EC station results for comparison and ground-based method validation. Although the EC method is the most widely accepted method for accurate ground-based measurement of actual ET_c and thus the method recommended by the Expert Panel for field-scale depletion validation, EC installations require significant expertise and even in best cases, the resulting data include some uncertainty. Specific to the case study, the Modena EC station installation suffered from occurrences of prevailing winds that did not support data collection, leading to a larger than expected number of data points that needed to be gap filled (Hipps 2023).

Case study results include Monthly ET_c values aggregated from daily scale during the growing season. Potential ET_c values from UAES (2011), obtained via the mean crop coefficient method, were not recommended for use for agricultural depletion accounting in Utah by the Expert Panel (Jacobs 2020) but are provided as a reference as they provide inexpensive additional points of comparison to the other methods. The following summarize the data sets presented:

- **OpenET Platform Monthly (ensemble) —** Estimated actual ET_c data (ensemble model) based on field selection or point of interest obtained directly through the OpenET website (https://explore.etdata.org/auth). Data provided were obtained for each of the three fields and EC footprint at a monthly timescale.
- **OpenET API Monthly (ensemble) —**Raster (pixelized) estimated actual ET_c data (ensemble model) based on field identifier or a coordinate-defined area provided through OpenET's Application Programming Interface (API). Data provided were obtained for each of the three fields at a monthly timescale. Monthly area average ET_c estimates for the EC footprint were extracted from the raster images.
- **OpenET API Daily (ensemble) —** Raster (pixelized) estimated actual ET_c data (ensemble model) based on field identifier or a coordinate-defined area provided through OpenET's API. Data provided were originally obtained as individual OpenET model data (ALEXI/DisALEXI, eeMETRIC, geeSEBAL, PT-JPL, SIMS, SSEBop) on a daily timescale. This individual model data were used to compute the daily ensemble mean and then aggregated to a monthly timescale for each of the three fields. ET_c estimates for the EC footprint were extracted from the raster images.
- **OpenET API Daily (eeMETRIC) —** Raster (pixelized) estimated actual ET_c data (eeMETRIC model) based on a field identifier or a coordinate-defined area provided through OpenET's API. Data provided were obtained at a daily timescale and aggregated to a monthly timescale for each of the three fields. Monthly area average ET_c estimates for the EC footprint were extracted from the raster images.
- **SMET —** Estimated actual ET_c data based on an empirical SMET model that estimates ET based on soil moisture and ET_r (Hargreaves 2022). Additional information can be found in Hargreaves (2022) and Christiansen (2022). ET_c was estimated daily and aggregated to a monthly timescale for each of the three fields.
- **EddyCov —** Measured actual ET_c from an EC station installed on Pivot 22 at the Modena site. Additional information can be found in *Eddy Covariance Results for Actual ET and Validation of Surface Renewal Model* (Hipps 2023). ET_c was calculated daily for the EC footprint and aggregated to a monthly timescale.
- **METRIC (Manual) —** Estimated actual ET_c data produced using a manual implementation of the METRIC model developed by the University of Idaho (Allen et al. 2007a, 2007b, 2011a, and 2011b). Additional information can be found in *Report on the Production of Landsat Overpass and Monthly Evapotranspiration Maps for the Beryl Junction area of Utah for Years 2020 and 2021 using the METRIC^{tm} Model* (Allen et al. 2022). ET_c was estimated daily and aggregated to a monthly timescale for each of the three fields.
- **Potential ET_c —** Potential ET_c, based on the mean crop coefficient method, for Pivot 22 was obtained from *Crop and Wetland Consumptive Water Use and Open Water Surface Evaporation in Utah* (UAES 2011) using Alfalfa (Dairy) as the crop and USU Beryl Junction West as the site.

Figure 3-4. Summary of Monthly Crop Evapotranspiration Results within the Eddy Covariance Footprint for the 2021 Growing Season (April 1 through October 22) for All Methods



Note: Error bars represent the standard deviation or found variability of the respective method where available.

In the EC footprint, the monthly EC ET_c values differ from comparison methods to varying degrees each month. Table 3-2 summarizes the average monthly deviation in ET_c estimates compared to the EC station results.

Table 3-2. Summary of Average Monthly Deviation in Crop Evapotranspiration Estimates Compared with Eddy Covariance Results

ET Estimation Method	Average Monthly Deviation from EC Results (inches)[a]
OpenET API Daily (eeMETRIC)	0.6
SMET	0.7
METRIC (Manual)	0.9
OpenET Platform Monthly (ensemble)	1.0
OpenET API Daily (ensemble)	1.2
OpenET API Monthly (ensemble)	1.3
Potential ET_c (UAES 2011)	1.5

[a]Absolute value of deviations were used to compute average.

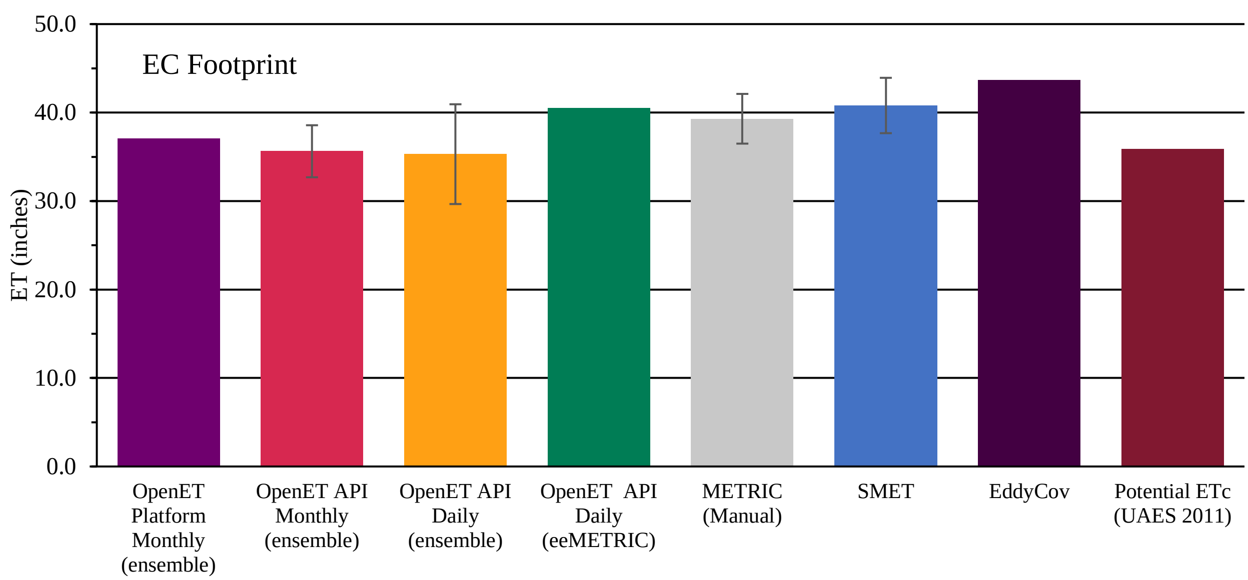
Note: Results ordered least to greatest.

OpenET eeMETRIC model results had the most consistent agreement with EC ET_c monthly values followed by SMET, METRIC (Manual), the remaining OpenET methods, and finally potential ETc, which had the weakest agreement with EC ET_c monthly values. Given the high irrigation frequency of Pivot 22 and use of ET_r values calculated based on data from the Modena meteorological station (in place of published values from UAES [2011]) would have likely led to better agreement between EC ET and potential ETc results. This is not always the case; where water stress may occur, potential ET_c is expected to exceed actual ET_c, an important limitation of using potential ET_c for depletion quantification.

Observed deviation in remote-sensing method results warrant further discussion. The observed deviation in OpenET ensemble model results (Platform Monthly, API Monthly, API Daily) is primarily due to differences in data acquisition methods and differences in data averaging, whether field- or pixel-based. Platform results are reflective of a single point (pixel) selection for the EC footprint. API data for the EC footprint were extracted from field raster (pixelized) images. Differences in daily and monthly results were related to differences in data averaging methods within OpenET. Differences in the eeMETRIC and METRIC (Manual) results are likely due to a more a simplified interpolation technique used in the manual implementation of METRIC to fill between satellite dates.

Seasonal ET_c results within the EC footprint are summarized on Figure 3-5 for the 2021 growing season. Results presented are limited to 2021 data due to the availability of EC station results for comparison and ground-based method validation. Seasonal totals are based on the aggregation of data at each available timescale; daily to seasonal total, monthly to seasonal total.

Figure 3-5. Summary of Seasonal Crop Evapotranspiration Results within the Eddy Covariance Footprint for the Growing Season (April 1 through October 22) 2021 for All Methods



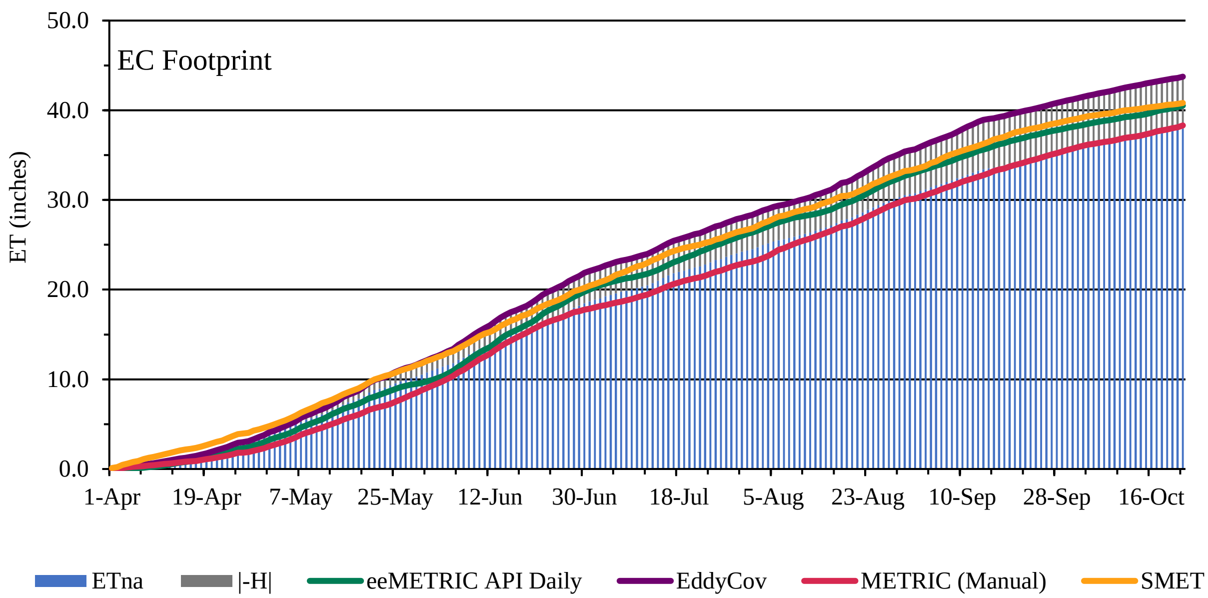
In the EC footprint, seasonal EC ET_c values were 7 percent greater than SMET, 8 percent greater than OpenET eeMETRIC API Daily, 11 percent greater than METRIC (Manual), 18 percent greater than OpenET Platform Monthly (ensemble), 23 percent greater than OpenET API Monthly (ensemble), 24 percent greater than OpenET API Daily (ensemble) and 22% greater than potential ET_c.

The OpenET ensemble model-based methods were found to consistently underestimate ET_c compared to results of the EC method. Analysis of the EC components performed by Dr. Lawrence Hipps (2023) indicates that advection is an important contribution to ET_c at this location providing up to 30 percent of the observed ET_c. Analysis of the advective contribution was completed at seasonal scale. Figure 3-6 provides the 2021 timeseries of EC ET_c with the advection component of the energy balance shown to illustrate how agreement with SMET and METRIC method results are impacted by inclusion or exclusion of advection.

Horizontal advection at the field boundary impacts some OpenET model results more than others. eeMETRIC results exhibited improved agreement with the EC station's calculated ET_c compared to the ensemble model in this case study but horizontal advection can impact all models (including eeMETRIC) causing border pixels of agricultural fields adjacent to unirrigated lands to show significant reductions in estimated ET (Mefford and Prairie, eds. 2022).

After the advective contribution was removed from the EC ET_c values, eeMETRIC and METRIC (Manual) results were in much closer agreement with EC ET_c values. Although the results of this study suggest that an advection correction applied to OpenET data sets would lead to improved agreement with actual ET_c as measured by an EC station, many other potential causes of the deviation in ET_c values across all methods exist.

Figure 3-6. 2021 Time Series of Eddy Covariance Evapotranspiration with Advection Component of Energy Balance Shown



where:

ET_{na} = ET without advection included
|-H| = flux of sensible heat at the surface (advection)

The SR method for measuring actual ET_c was also investigated as part of the case study. SR calculates the sensible heat flux (H) in surface energy balance equation (see Equation 1); net available radiation at the surface (G) and available net radiation (R_n) at the surface is provided by instruments associated with the EC station. Once these variables are known, the resulting surface latent heat flux (LE) , is equivalent to ET_c.

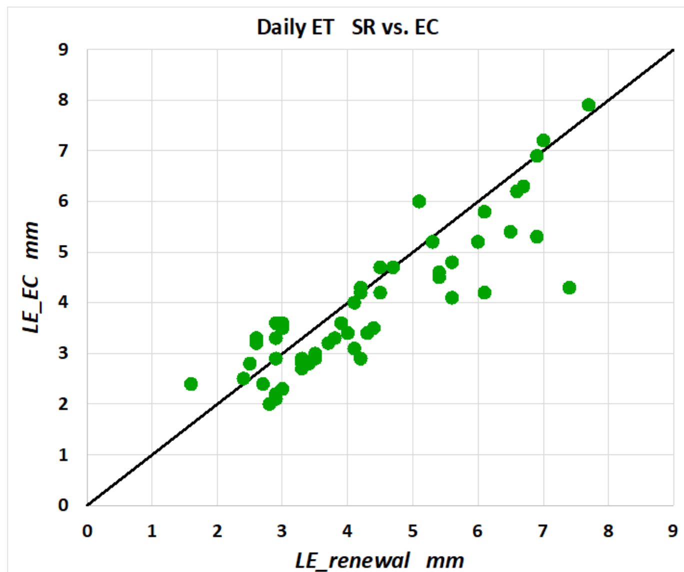
$$R_n = H + LE + G \quad \textit{Equation 1}$$

SR method results were compared against EC station results for days where favorable wind directions supported reliable quantification, see Figure 3-7. As illustrated on Figure 3-7, SR ET_c tended to exceed the measured ET_c from the EC station. The root mean square difference is about 0.8 mm/day; the mean of all daily values was 3.9 mm for EC and 4.3 mm for SR.

Table 3-3 presents a summary of the ET_c comparison results as well as other methods investigated as part of this case study effort. The EC method is the most widely accepted method for accurate ground-based measurement of actual ET_c and thus the basis for which the other methods were evaluated against for ET_c accuracy. Cost and labor details that support the results presented in Table 3-3 are provided in Appendix A.

Review of Table 3-3 suggests that actual ET obtained via the eeMETRIC method supports a practical and effective means for measuring and accounting for actual depletion of agricultural water in Utah. Although the SMET method provided the best agreement with the seasonal observed ET_c from the EC station (-7 percent), eeMETRIC model data available from OpenET provided similar results (-8 percent) requiring lower expenditure and a lower level of effort for the user to obtain the data. Limitations of eeMETRIC model data exist with seasonal ET_c accuracy reported at +/- 15 percent (Mefford and Prairie, eds. 2022) but continuous improvement of OpenET supported models, including eeMETRIC, are ongoing and accuracies are expected to improve with time

Figure 3-7. Comparison of Crop Evapotranspiration (Surface Latent Heat Flux) Results from Surface Renewal and Eddy Covariance Methods



3.5.2 Estimating Depletion

The term "depletion" in the hydrologic context within Utah means the consumptive use (CU) or ET of applied water (ET_{aw}). While all ET depletes the amount of water within a hydrologic basin, ET_{aw} results from exercising a water right that is regulated by the state. ET_{aw} is the value we seek to use when describing depletion in the context of water rights. ET_{aw} is also known as supply-limited CU, irrigation CU, or, in the context of this case study, actual depletion of applied water (Jacobs 2020). ET_c as measured and estimated by the methods in this case study represents actual ET from soil moisture, effective precipitation (P_{eff}), and applied water. As defined in UAES (1989), depletion is defined in Equation 2:

$$Depletion = ET_c - SM_{co} - P_{eff} \qquad \textit{Equation 2}$$

where:

ET_c = crop evapotranspiration
SM_{co} = soil moisture carried over from the previous nongrowing season that is available for crop water use in the subsequent growing season
P_{eff} = effective precipitation during the growing season

Table 3-3. Summary of Crop Evapotranspiration Method Comparison Results

<table>
<tr><th rowspan="2">Method</th><th colspan="2">How Practical?</th><th colspan="2">How Effective/Defensible?</th><th rowspan="2">What are Limitations?</th></tr>
<tr><th>Estimated Cost[a]</th><th>Level of Effort Required (Labor Days, Season)</th><th>Comparison with Seasonal EC Method Results</th><th>Documented Accuracy in the Literature</th></tr>
<tr><td colspan="6">Ground-based methods for field-scale ET measurements</td></tr>
<tr><td>SMET (employed in place of SWB method)</td><td>$41,800</td><td>26.75</td><td>-7%</td><td>Correlation of SMET to actual ET from EC station in Vernal = ~0.8[b]</td><td>• Further validation is required with other crop types and locations before being recommended for widespread use.[c]
• Data collection timeframe (growing season) is limited.[c]
• Sensor accuracy for soil moisture content is limited.[c]
• Soil moisture sensors require proper installation and maintenance, which are not economically or time appropriate for some water users.[c]
• SMET method is recommended for users willing to invest time and money into the process for increased accuracy.[c]
• Soil moisture data must be collected from entire root zone.[b]
• Site-specific calculation of α constant might be required.[b]
• SMET model may not work as well at drip-irrigated sites due to increased irrigation frequency and resulting lack of days where soil moisture is declining, which is needed for SMET.[b] This also holds true for sites with high frequency of irrigation or precipitation events, regardless of irrigation method.</td></tr>
<tr><td>Field water balance with flow measurements</td><td>$10,350</td><td>5.3</td><td>NA; does not measure ET</td><td>NA</td><td>• Minimal conveyance loss from diversion to the application point, minimal surface runoff or deep percolation of applied water, and insignificant change in soil-water storage over an extended time period are required.[d]
• ET_{aw} estimate with this method is conservative in that any unmeasured deep percolation or surface runoff that does occur will tend to overstate estimated ET_{aw}.[d]</td></tr>
</table>

Method	How Practical?		How Effective/Defensible?		What are Limitations?
	Estimated Cost[a]	Level of Effort Required (Labor Days, Season)	Comparison with Seasonal EC Method Results	Documented Accuracy in the Literature	
Crop coefficient method (potential ETc)[e]	$18,624	8.5	-22%	NA	• Potential ET_c is relative to ET_r, which is the ET rate of an idealized reference crop that is not waterstressed[f]; thus, potential ET_c values are typically higher than actual ET_c. In this case, using published potential ET_c values in place of calculated values based on 2021 meteorological data and high irrigation frequency likely led to potential ET_c being less than actual ET_c for Pivot 22.
Ground-based methods for field-scale ET measurement validation					
EC	$117,575	51	NA	+/-10%[g]	• Equipment is specialized, sensitive, and expensive. • Equipment requires proper installation, care, and maintenance, which are not economically or time appropriate for some water users. • Significant expertise is required to operate systems and process and interpret data. • Equipment requires an understanding of prevailing wind directions to avoid unnecessary data gap filling.

<table>
<tr><th rowspan="2">Method</th><th colspan="2">How Practical?</th><th colspan="2">How Effective/Defensible?</th><th rowspan="2">What are Limitations?</th></tr>
<tr><th>Estimated Cost[a]</th><th>Level of Effort Required (Labor Days, Season)</th><th>Comparison with Seasonal EC Method Results</th><th>Documented Accuracy in the Literature</th></tr>
<tr><td>SR method</td><td>$92,575</td><td>51</td><td>Not available since days with unfavorable wind directions were not included in analysis</td><td>Expect similar to EC</td><td>• Reliable and accurate ET_c estimates require ground-based measurements of R_n and G at the station site; currently this will need to be paired with an EC station.[d]
• A significant drawback from employing this method is that, for increased accuracy, its application requires calibration of H measured using the SR method to H measured with an EC station for each unique crop surface condition.[h]
• While methods are being developed to avoid calibration using direct measurements of horizontal wind speed, this approach is still being developed and not fully validated.[d]
• SR application is limited to areas without high humidity.[d]
• Thermocouples are prone to damage in high-wind conditions (one of two sensors failed during this study).[d]</td></tr>
<tr><td colspan="6">Remote-sensing methods for field-scale to basin-scale ET measurements</td></tr>
<tr><td>OpenET models</td><td rowspan="5">$11,500 (API daily methods assumed with field verification for emergence and harvest)</td><td rowspan="5">8.5
(API daily methods assumed with field verification for emergence and harvest)</td><td></td><td></td><td rowspan="5">• Cloud cover increases data interpolation.
• Horizontal advection at field boundary in arid areas may impact result accuracy.
• This method does not include wind drift losses.
• Depletion related to sources other than applied irrigation and precipitation are included (for example, subirrigation).
• Crop cuttings that occur directly after a satellite pass are missed in model interpolation[i] impacts to season ET_c are expected to be minimal.</td></tr>
<tr><td>Platform monthly (ensemble)</td><td>-18%</td><td></td></tr>
<tr><td>API monthly (ensemble)</td><td>-23%</td><td></td></tr>
<tr><td>API daily (ensemble)</td><td>-24%</td><td></td></tr>
<tr><td>API daily (eeMETRIC)</td><td>-8%</td><td>+/- 15% for growing season and annual ET_c (eeMETRIC)[i]</td></tr>
</table>

Method	How Practical?		How Effective/Defensible?		What are Limitations?
	Estimated Cost[a]	Level of Effort Required (Labor Days, Season)	Comparison with Seasonal EC Method Results	Documented Accuracy in the Literature	
METRIC (manual)	$78,300[j]	65.3	-11%,	Expected to be consistent with eeMETRIC; +/- 15% reported for growing season and annual ET_c (eeMETRIC)[i]	• Expertise is required to manually operate the model. • Cloud cover increases interpolation of data. • Horizontal advection at field boundary in arid areas may impact result accuracy. • Wind drift losses are not included. • Depletion related to sources other than applied irrigation and precipitation are included (for example, subirrigation). • Crop cuttings that occur directly after a satellite pass are missed in model interpolation[i] impacts to season ET_c are expected to be minimal.

[a] Cost includes all first-year costs including labor and equipment with an assumed labor rate of $150 per hour.
[b] Source: Hargreaves 2022.
[c] Source: Christiansen 2022.
[d] Source: Jacobs 2020.
[e] This assumes a meteorological station is installed for local ET calculation to support potential ETc measurements. Published ET_c values are readily available based on weather observation data from 1971 to 2008(UAES 2011).
[f] Source: Doorenbos 1977.
[g] Source: Hipps 2023.
[h] Source: Paw U et al. 1995; Hu et al. 2018.
[i] Source: Mefford and Prairie, eds. 2022.
[j] Cost to perform analysis on a large geographical area, not just Pivot 22.

Notes:

% = percent
+/- = plus/minus
API = Application Programming Interface
EC = crop evapotranspiration
eeMETRIC = OpenET Google Earth Engine implementation of the Mapping Evapotranspiration at High Resolution with Internalized Calibration Model
ET = evapotranspiration
ET_{aw} = applied water evapotranspiration
ET_c = crop evapotranspiration
ET_r = reference evapotranspiration
G = soil heat flux
H = sensible heat flux
METRIC = Mapping Evapotranspiration at High Resolution and Internalized Calibration
NA = not applicable
R_n = net radiation
SMET = soil moisture-based evapotranspiration
SR = surface renewal
SWB = soil-water balance

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In Section 3.4.1, both ground-based and remote-sensing methods were discussed to evaluate ET_c. None of the methods presented in Section 3.4.1 provide for direct calculation of depletion without additional information or analysis to determine the carry-over soil moisture (SM_{co}) and P_{eff} components. Section 3.5.2.1 discusses current and emerging approaches for estimating SM_{co} and P_{eff} and calculating resulting depletion.

3.5.2.1 Summary of Current and Emerging Approaches for Estimating Depletion

Efforts related to the quantification of depletion in the state of Utah have been ongoing for many years. Utah's Division of Water Rights maximum potential depletion values for administration of change applications are based on *Consumptive Use of Irrigated Crops in Utah* (UAES 1998), which provides ET_c and the net irrigation requirement for various crops based on locations in Utah. *Field Verification of Empirical Methods for Estimating Depletion* (UAES 1989) describes a process to estimate SM_{co} when soil moisture data are not available using nongrowing season precipitation and crop water use. More recent efforts by OpenET are detailed in Appendix G of *Assessing Agricultural Consumptive Use in the Upper Colorado River Basin - Phase III Report* (Mefford and Prairie, eds. 2022) where P_{eff} raster data sets, which encompass the nongrowing season to support quantification of SM_{co}, were generated and combined with OpenET model data to calculate irrigation CU, synonymous with ET_{aw}.

These approaches to quantify depletion and approaches when soil moisture is known are described in the next subsections and summarized as follows:

- Per Consumptive Use of Irrigated Crops in Utah (UAES 1998)
- Per Field Verification of Empirical Methods for Estimating Depletion (UAES 1989)
- Approaches when soil moisture is known
- Provided directly through a third party such as OpenET

3.5.2.1.1 Depletion Per *Consumptive Use of Irrigated Crops in Utah*

Consumptive Use of Irrigated Crops in Utah (UAES 1998) provides the basis for maximum potential depletion values associated with water rights in the state of Utah. Maximum potential depletion values associated with water rights and change applications are calculated using the net irrigation requirement of alfalfa, taken from the CU station(s) that are closest to the water right of interest, multiplied by the number of irrigated acres.

The net irrigation requirement is defined as ET minus P_{eff}. For estimating depletion based on case study results, this equates to Equation 3:

$$\boldsymbol{Depletion\ (inches) = ET_c - P_{eff}} \qquad \textit{Equation 3}$$

where:

ET_c = crop evapotranspiration
P_{eff} = 80 percent of USU meteorological station precipitation (inches)

In this approach, SM_{co} was not included, which leads to a higher depletion value than if winter precipitation was considered.

3.5.2.1.2 Depletion Per *Field Verification of Empirical Methods for Estimating Depletion*

Field Verification of Empirical Methods for Estimating Depletion (UAES 1989) provides a more detailed approach that similarly assumes P_{eff} is 80 percent of measured precipitation but also includes a SM_{co} calculation. SM_{co} is calculated using nongrowing season (November 2020 through March 2021) crop water use and precipitation data, the available water capacity and water content at 15 bar from the Soil Survey Geographic database (NRCS 2023), and crop rooting depth for alfalfa (UDWRe 2022). Equation 4 provides the depletion calculation considering SM_{co}:

$$\boldsymbol{Depletion\ (inches) = ET_c - SM_{co} - P_{eff}} \qquad \textit{Equation 4}$$

where:

ET_c = crop evapotranspiration
SM_{co} = non-growing season precipitation stored in the soil that may be used in meeting the crop's evapotranspiration requirement in the subsequent growing season per UAES (1989)
P_{eff} = 80 percent of USU meteorological station precipitation (inches)

3.5.2.1.3 Depletion When Soil Moisture is Known

Soil moisture measurements on a field where depletion values are sought expands the available calculation approaches. Determining SM_{co} becomes a straightforward exercise of simply subtracting the ending soil moisture from the previous growing season from the starting soil moisture for the season where depletion values are sought, using the measured soil moisture in inches across the root zone.[4] Determining P_{eff} can be done using a simple approximation of 80 percent of measured precipitation at the nearest meteorological station consistent with 1 and 2 or by performing a more involved SWB such as the monthly balance included in Chapter 2 of the USDA's *Part 623 National Engineering Handbook* (USDA 1993), or a daily balance included in the *FAO Irrigation and drainage paper 56* (Allen, et al. 1998).

3.5.2.1.4 Provided Directly through a Third Party such as OpenET

Recent efforts by OpenET are detailed in Appendix G of *Assessing Agricultural Consumptive Use in the Upper Colorado River Basin - Phase III Report* (Mefford and Prairie, eds. 2022) where P_{eff} raster data sets, which encompass the nongrowing season to support quantification of SM_{co}, were generated and combined with OpenET model data to calculate irrigation CU, synonymous with depletion or ET_{aw}. The P_{eff} raster data sets were derived from the daily SWB model within the ET Demands model, described more thoroughly in Huntington et al. (2015) and Allen et al. (2020). Crop weighted P_{eff} rasters were developed and then subtracted from remote-sensing estimates of ET_c to calculate irrigation CU (ET_{aw}). Although this approach is in development and not yet publicly available, it presents a future opportunity for state agencies and producers to obtain depletion estimates without having to post process ET_c data, representing a significant step forward.

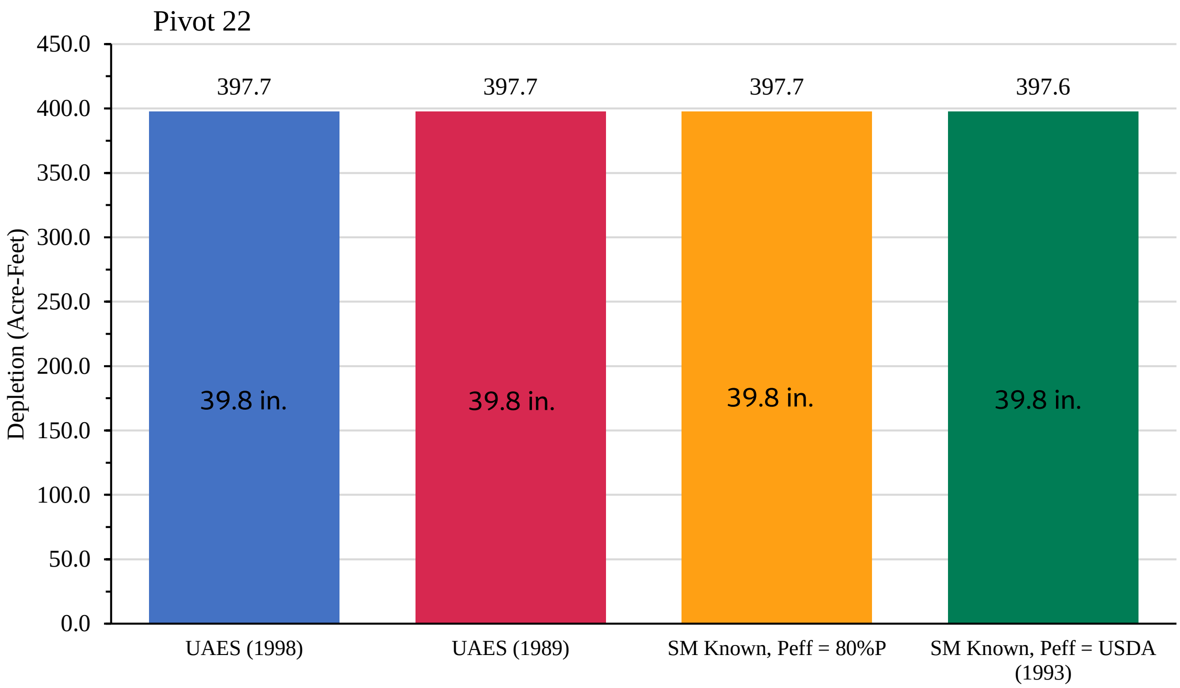
3.5.2.2 Comparison of Eddy Covariance Based Depletion Results Using Current Depletion Calculation Approaches

Using the EC ET_c results, a comparison of depletion values calculated via the currently available depletion approaches (1 through 3 previously) was conducted for the 2021 growing season on Pivot 22. ET_c results

[4] An alternative approach to calculating SM_{co} was investigated but not detailed in this report where SM_{co} is equal to the water available at the start of the growing season which is above the allowable depletion (Orloff et al. n.d.). This approach resulted in 0.27 inch of SM_{co} and a corresponding depletion reduction of 2.7 acre-feet for all methods with the exception of the field water balance (which does not directly include SM_{co} in the calculation).

from the EC footprint were applied to the entire area of Pivot 22 to complete the depletion comparison. The results are presented on Figure 3-8.

Figure 3-8. Summary of Depletion Results for Pivot 22 Using the Reviewed Currently Available Methods



The two UAES methods resulted in the same depletion volume, 397.7 acre-feet, due to the lack of any SM_{co} being assumed or calculated and the use of the same 80% approximation for P_{eff}. In the case of UAES 1998, SM_{co} is not included in the analysis. In the case of UAES 1989, nongrowing season ET_c exceeded the measured precipitation, thus, no SM_{co} resulted.

In the methods where soil moisture was known and included, depletion volumes were approximately the same as the UAES methods due to the lack of available SM_{co} (the starting soil moisture in 2021 was less than the ending soil moisture in 2020). Where an 80% estimate was used for P_{eff}, the resulting depletion, 397.7 acre-feet, was equal to UAES methods. Calculating P_{eff} per USDA (1993), resulted in a P_{eff} of 80%, equal to the UAES (1989, 1998) approximations, thus resulting in an equivalent depletion volume of 397.6 acre-feet. A daily water balance per the method included in *FAO Irrigation and drainage paper 56* (Allen, et al. 1998) was not conducted because it was beyond the scope of this case study.

Accuracy of depletion estimates can be improved where SM_{co} can be measured directly through soil moisture sensors as this avoids the use of estimates that may not be directly applicable to the site, although in this case, the approximation method and use of soil moisture sensors led to the same depletion result. Determining P_{eff} can be challenging as the controlling processes are involved and the parameter data typically uncertain or unavailable, thus simplified methods have been developed and used to predict the fraction of precipitation that is effective (USDA 1993). The simplified methods for estimating P_{eff} reviewed as part of the case study led to similar depletion results.

3.5.2.3 Depletion Estimates for Case Study Methods Remote Sensing, Eddy Covariance, and Soil Moisture-Based Evapotranspiration

In this case study, daily soil moisture data provided the means to determine SM_{co} directly, although no SM_{co} resulted; P_{eff} was calculated using the USU meteorological precipitation data and the assumption that 80 percent of precipitation was considered effective [consistent with UAES (1989) and UAES (1998)] due to its wide use for depletion estimates in Utah and insignificant change in depletion results calculated using the USDA (1993) method, see Section 3.5.2.2. Using this approach, depletion was calculated for all methods with the exception of the SR method due to an incomplete ET_c data set, as previously discussed (Hipps 2023). The depletion accounting approach details and results using ET_c from remote-sensing, EC, and SMET methods applied to Pivot 22 are provided in the following subsections. ET_c results from the EC footprint were applied to the entire area of Pivot 22 to complete the depletion analysis.

SM_{co} was assumed to be the difference in soil moisture between the start of the 2021 growing season and the end of the 2020 growing season, to a depth of 54 inches, the rooting depth for alfalfa (UDWRe 2022).

P_{eff} was determined by applying an 80 percent effectiveness factor to the total precipitation depth received during the growing season. This resulted in a P_{eff} of 4.0 inches. Following these determinations for SM_{co} and P_{eff}, depletion across the 2021 growing season was calculated for remote-sensing, EC, and SMET methods per Equation 5:

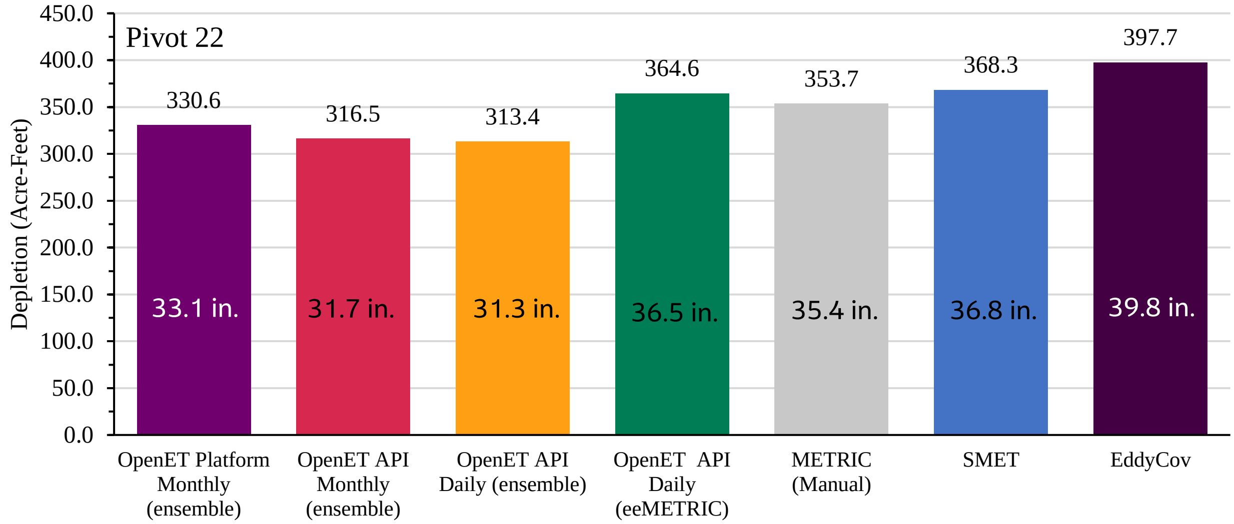
$$\boldsymbol{Depletion\ (acre - feet) = \frac{ET_c - 4.0\ in.}{12\ (\frac{in.}{ft.})} * 120\ acres} \qquad \textit{Equation 5}$$

where:

Depletion = growing season depletion
ET_c = growing season crop evapotranspiration

The results of the depletion calculations for remote-sensing, EC, and SMET methods are provided on Figure 3-9.

Figure 3-9. Summary of Depletion Results for Pivot 22



The relative depletion results align consistently with the ET_c results. Seasonal depletion values based on EC ET_c were 8 percent greater than SMET, 9 percent greater than OpenET eeMETRIC API Daily, 12 percent greater than METRIC (Manual), 18 percent greater than OpenET Platform Monthly (ensemble), 23 percent greater than OpenET API Monthly (ensemble), 24 percent greater than OpenET API Daily (ensemble).

3.5.2.4 Depletion Estimate for Case Study Method Field Water Balance Using Flow Measurements

In limited cases, simple flow measurement of water diverted for irrigation purposes can be used to estimate depletion (ET_{aw}) using field water balance approach. When used alone, this method requires an assumption of minimal conveyance loss from the diversion to the point of application, minimal surface runoff or deep percolation of applied water, and insignificant change in soil-water storage over an extended time period (Jacobs 2020).

Christiansen (2022) employed a simplified SWB equation (Equation 6) to quantify the unaccounted for water in the system (Residual) including surface runoff and deep percolation:

$$Inflow - \Delta SWC - ET = Residual \qquad \textit{Equation 6}$$

where:

Inflow = the sum of irrigation (I) and effective precipitation (P)
Residual = water unaccounted for in the system
ΔSWC = change in soil-water content

The calculated residual is the sum of the measurement errors of I, P, ΔSWC, and the estimated ET, and potentially includes water lost to deep percolation and runoff. Assuming minimal measurement error, a positive residual suggests that water is leaving the system likely through deep percolation and runoff. Assuming minimal measurement error, a negative residual suggests that water has entered the system from an unidentified source (Christiansen 2022). Assuming minimal measurement error, as the residual approaches zero, irrigation volume (I) becomes increasingly equivalent to depletion volume (ET_{aw}).

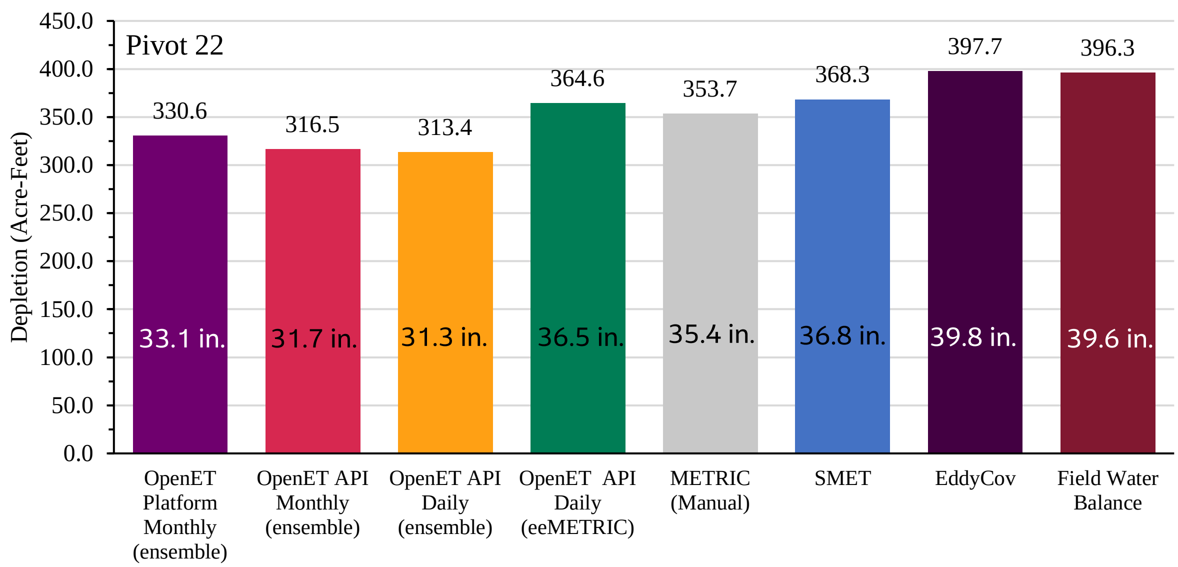
IM3000 flow meters installed within the case study irrigation system recorded daily measurements of water application (I) throughout the 2021 season. Precipitation data were acquired from the USU Climate Center (www.climate.usu.edu) managed weather station located in the study area of this case study. ΔSWC was obtained from the soil moisture data set.

The water balance residual results varied but most notably, the residual for the EC footprint was -0.5″ suggesting the irrigation volume is a reasonable estimation for depletion on the Pivot 22 field.[5] The applied irrigation volume measured during the 2021 growing season was approximately 396 acre-feet (39.6 inches).

3.5.2.5 Comparison of Depletion Estimates

A summary of depletion estimates for all methods suggested by the Expert Panel (see Table 2-1) applied to Pivot 22 is provide on Figure 3-10.

Figure 3-10. Summary of Depletion Estimates for All Expert Panel-Suggested Methods Applied to Pivot 22



Remote-sensed and SMET method-based depletion volumes fell short of calculated depletion based on EC ET_c, relative differences aligned with the depletion depths presented on Figure 3-9. The field water balance had the best agreement with EC ET_c based depletion volume results, a difference of 0.4% percent, suggesting that losses such as runoff and deep percolation and the availability of sub-irrigation water were not significant.[5]

[5] Although the soil moisture measurements far exceeded the sum of the available water supply ([AWS], equal to the available water capacity [AWC] times the root zone depth) and the water contained in the soil at the wilting point (water content, 15 bar), both obtained from the Natural Resource Conservation Service Web Soil Survey (NRCS 2023), agreement with the EC results provided on Figure 3-10 suggest that there was not a significant amount of deep percolation that was occurring.

3.6 Case Study Conclusions and Recommendations

3.6.1 Case Study Conclusions

Key Findings: Based strictly on the results of this case study, the field water balance method provided the most practical and effective means for accounting for actual depletion of applied agricultural water but the limitations of the field water balance method need to be well understood before applying this conclusion elsewhere. SMET and eeMETRIC based depletion values were within 10% of EC based depletion results (within the EC method's margin of error) and may be more practical for other producers based on site conditions and available equipment. Notably, eeMETRIC based depletion provided similar results to SMET requiring lower expenditure for the user and a lower level of effort to obtain the data.

The case study team recommends repeating this case study in other areas and for other crops before making any policy recommendations as results could vary. Methods for estimating SM_{co} and P_{eff} should be investigated further as part of future case studies for use in translating ET rates into actual depletion.

The principal question that the case study sought to answer was as follows: *What are the most practical, effective, and defensible means for measuring and accounting for actual depletion of agricultural water in Utah?*

Although the case study was focused primarily on methods to quantify ET_c, the resulting ET_c values are needed to calculate depletion (refer to Equation 1) when a field water balance is not performed. Calculating depletion required additional analysis to inform the SM_{co} and P_{eff} components. The inclusion of soil moisture and precipitation measurements as part of this case study made this possible with the measured soil moisture difference between the start of the growing season 2021, and the end of the growing season 2020, serving to define SM_{co}, and an 80 percent approximation of measured rainfall serving to define P_{eff}. Answering the principal question of the case study first requires a review of the practicality and limitations of methods to quantify ET_c. Table 3-3 summarizes the ET_c comparison results, as well as other methods investigated as part of this case study effort.

The comparisons reviewed in this case study are specific to conditions observed at Pivot 22 in 2021 where the EC station was installed and that challenges in EC station data collection were reported. These challenges may have impacted the accuracy of results, thus the same results may not be witnessed in other areas or with other crops. Conclusions regarding methods for measuring ET_c are summarized as follows:

- Although the EC method is the most widely accepted method for accurate ground-based measurement of actual ET_c, cost of installation and post-processing level of effort make it unrealistic for the typical producer to install and operate.
- The SR method was performed in conjunction with the EC method. SR ET_c results typically exceeded the EC method results with a root mean square difference of about 0.8mm per day. The SR method has lower equipment costs than the EC method, but the cost of installation and post-processing level of effort remain at a level that make this method unrealistic for the typical producer to install and operate. Further, the SR method is still considered experimental.
- The SMET method provided the best agreement with the seasonal observed ET_c from the EC station (-7 percent) but installation level of effort is far greater than the level of effort required for obtaining

remote-sensing ET_c data, which provided comparably accurate results. The SMET method's accuracy is also expected to decline with increased frequency of irrigation and precipitation events and the SMET method is empirical in nature, calibrated towards alfalfa, and thus, additional research efforts should be conducted before applying SMET to other crops.

- eeMETRIC model data available from OpenET provided ET_c values that were 8 percent lower than the EC station and required lower expenditure and a lower level of effort than the other actual ET_c methods to obtain the data. Further, eeMETRIC results from OpenET are generally available within 14 days with future improvements (reductions) in data lag expected as satellite overpass frequency improves. By comparison, the SMET method requires post-processing following the irrigation season to reach the accuracy reported in the case study and is most effective at the seasonal time step. Limitations of eeMETRIC model data exist such as the potential for advective impacts to cause lower than actual ET_c to be reported but continuous improvement of OpenET supported models, including eeMETRIC, are ongoing and accuracies are expected to improve with time.
- The manual implementation of the METRIC model had similar results to eeMETRIC obtained from OpenET but requires significant expertise and effort to run manually.
- OpenET ensemble model results had weaker agreement with the EC ET_c results compared to the other methods likely due to horizontal advection at the field boundaries, see Section 3.5.1.2.
- OpenET ensemble model results indicated improved accuracy with increasing timestep duration (monthly ET results were more accurate than aggregated daily ET results). A review of eeMETRIC results by Dr. Alfonso Torres-Rua at USU indicates a similar trend where seasonal ET_c values show the best agreement with EC ET_c, followed by monthly and finally daily values.
- Comparisons with other OpenET models have been performed by Dr. Alfonso Torres-Rua at USU. Growing season eeMETRIC ET_c showed the best agreement with EC ET_c.

Conclusions regarding methods for calculating depletion are summarized as follows:

- Once accurate ET_c values are obtained, calculating SM_{co} and P_{eff} can be accomplished through a number of different reported methods, see Section 3.5.2.1, to enable calculation of depletion (refer to Equation 1).
  - Comparison of depletion estimation methods using EC ET_c data resulted in equivalent depletion volumes for all methods.
  - Estimating SM_{co} via UAES (1989) did not result in any SM_{co} due to nongrowing season ET_c exceeding measured precipitation.
  - Estimating P_{eff} via USDA (1993) resulted in a P_{eff} of 80%, consistent with UAES (1989, 1998).
- Calculated depletion volumes followed a similar pattern of relative agreement of ET_c methods with EC station results. Seasonal depletion volumes based on EC ET_c were 8 percent greater than SMET, 9 percent greater than OpenET eeMETRIC API Daily, 12 percent greater than METRIC (Manual), 18 percent greater than OpenET Platform Monthly (ensemble), 23 percent greater than OpenET API Monthly (ensemble), 24 percent greater than OpenET API Daily (ensemble). The field water balance method provided the best agreement with EC ET_c depletion volume, a difference of 0.4% percent.

Based strictly on the results of this case study, the field water balance method provided the most practical and effective means for accounting for actual depletion of applied agricultural water but the limitations of the field water balance method need to be well understood before applying this conclusion elsewhere. SMET and eeMETRIC based depletion values were within 10% of EC based depletion results (within the EC method's margin of error) and may be more practical for other producers based on site conditions and available equipment. Notably, eeMETRIC based depletion provided similar results to SMET requiring lower expenditure for the user and a lower level of effort to obtain the data.

The case study team recommends repeating this case study in other areas and for other crops before making any policy recommendations as results could vary. Methods for estimating SM_{co} and P_{eff} should be investigated further as part of future case studies for use in translating ET rates into actual depletion.

3.6.2 Recommendations and Next Steps

Following are recommendations for next steps:

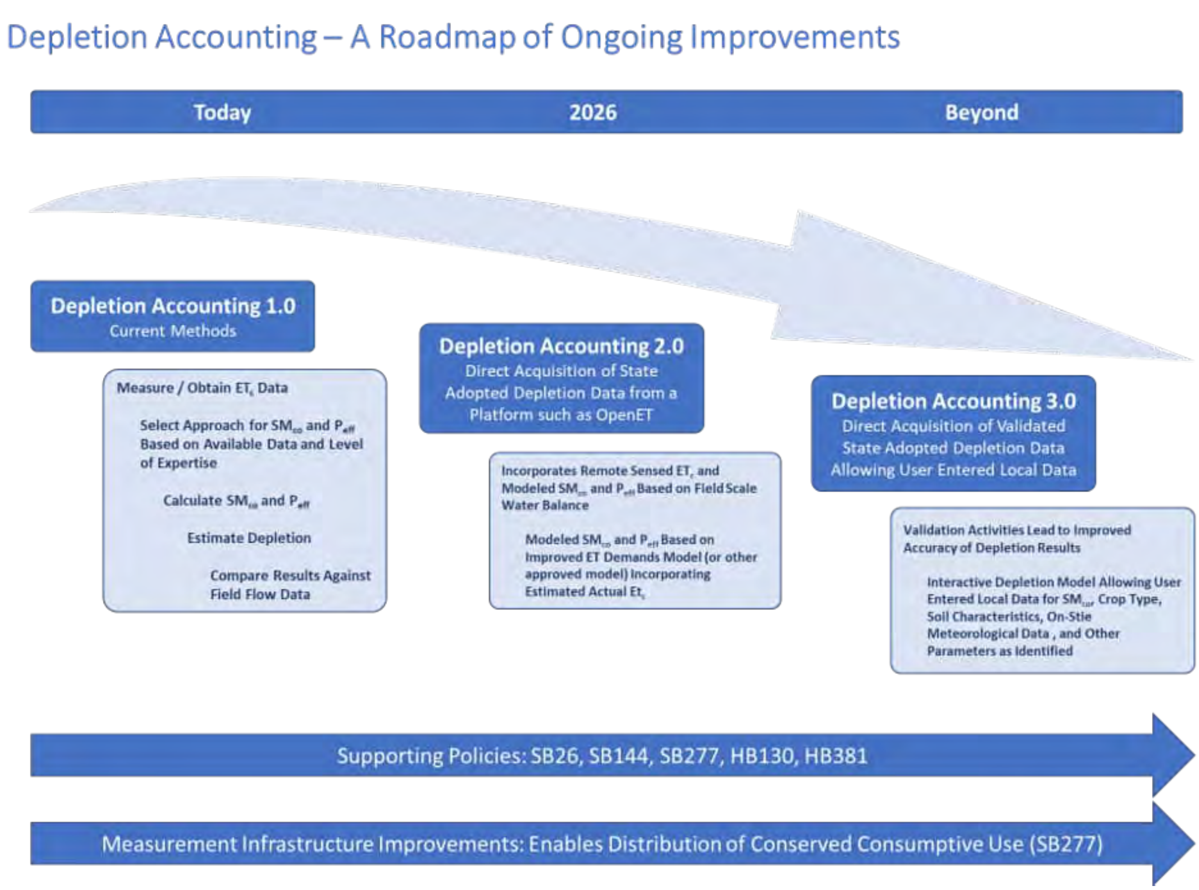
- Variations in wind direction and frequency of irrigation were problematic for case study data acquisition and post-processing, likely leading to lower accuracy ET_c results for the EC and SMET methods respectively. Repeating this case study at other sites in Utah and with other crops is recommended to build a broader understanding of the practicality and accuracy of the methods investigated.
- Consistent with the Resolution of the Upper Colorado River Commission signed June 14, 2022, using eeMETRIC is recommended to measure agricultural CU (UCRC 2022). For producers, obtaining daily eeMETRIC ET can be accomplished through either OpenET's platform via raster view or the API; monthly eeMETRIC data can be obtained either directly through the OpenET platform via either field selection or raster view or alternatively through their API. The platform approach offers a more user friendly path to ET data retrieval. The lag period for data availability is currently expected to be approximately 2 months for platform data and 2 weeks for data through the API.
- More work is needed in the area of depletion estimation, and stakeholders are recommended to work together to identify an approved depletion estimation method and validate through future case studies. This collaborative work should include evaluating estimation methods for SM_{co} and P_{eff} to improve future depletion estimates.
- The ET_c comparison provided herein should be expanded to include Blaney-Criddle and Penman Monteith based ET_c estimates using local meteorological station data.
- Given the methods available today, when estimating depletion at large scales, using estimation methods to obtain SM_{co} and P_{eff} is recommended. When estimating depletion at the field scale, measuring SM_{co} directly and performing a SWB to determine P_{eff} are expected to lead to improved accuracy over approximation methods.
- Comparing OpenET model results at additional EC station sites is recommended. Ensemble model results documented as part of this case study may improve in other locations.
- Using applied water measurements to calculate depletion is limited to sites with minimal conveyance loss from the diversion to the point of application, minimal surface runoff or deep percolation of applied water, and insignificant change in soil-water storage over an extended time period (Jacobs 2020). However, site specific measurements of applied water provide a useful comparison against calculated depletion volumes and may provide accurate results. Measuring applied water is recommended.
- Optimizing water productivity provides flexibility to producers, including their ability to take advantage of current incentive programs that allow temporary and voluntary repurposing of reduced depletion to a downstream beneficial use. Future case studies are recommended that mature these concepts to maximize the value of a producers water right and maximize the resiliency of both the producer's and the state's water supply.
- Accounting for actual depletion of applied water is a significant achievement, however, completing additional work is recommended to incentivize changes that reduce the depletion of applied water,

account for reductions in the depletion of applied water, and enable the distribution of these reductions to the intended downstream beneficial use.

Interest in the topic of depletion accounting is increasing as the effects of recent drought have illustrated the sensitivity of the supply and demand water balance. As we assess current methods for depletion accounting and consider future improvements that will progress this important capability to support producers and state agencies alike, the roadmap provided on Figure 3-11 provides a summarized view of current activities that are underway and future efforts needed.

Current methods to estimate depletion, identified as Depletion Accounting 1.0 on Figure 3-11, were discussed herein. Additional case studies are recommended that better inform these estimates. These case studies include validation of ET_c estimation methods and further investigation into best practices for estimating SM_{co} (when soil moisture measurement devices are not available) and P_{eff}. As we look forward to Depletion Accounting 2.0, a state-adopted approach is needed for estimating depletion to support distribution of water rights per Senate Bill 277 and the related improved resiliency and flexibility for producers. Depletion Accounting 3.0 improves upon the state-adopted depletion model through validation activities and model users' ability to input location-specific data when available. Supporting policies and measurement infrastructure improvements are parallel improvement tracks that support progression of depletion accounting initiatives.

Figure 3-11. Depletion Accounting Road Map of Ongoing Improvements



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Appendix A
Case Study Cost and Labor Details

Appendix A. Case Study Cost and Labor Details

Method	Task	Labor (days)	Labor Cost	Equipment and Travel Costs
Eddy Covariance	Identification of station location	6	$7,200	$5,025
	Equipment orders		$0	$45,000
	Annual operations and maintenance	18	$21,600	$4,050
	Annual data quality control	6	$7,200	
	Post-processing time	18	$21,600	$1,300
	Reporting	3	$3,600	
	Sensor calibration	0	$0	$1,000
	First Year Total	**51**	**$61,200**	**$56,375**
Surface Renewal	Identification of station location	6	$7,200	$5,025
	Equipment orders		$0	$20,000
	Annual operations and maintenance	18	$21,600	$4,050
	Annual data quality control	6	$7,200	
	Post-processing time	18	$21,600	$1,300
	Reporting	3	$3,600	
	Sensor calibration	0	$0	$1,000
	First Year Total	**51**	**$61,200**	**$31,375**
Soil Moisture E	Identification of station location	3	$3,600	
	Equipment orders	0.25	$300	$5,150
	Installation	1	$1,200	
	Monthly operations and maintenance	1	$8,400	$650
	Monthly data quality control	2	$16,800	
	Post-processing time	1	$1,200	
	Reporting	0.5	$600	
	First Year Total	**26.75**	**$32,100**	**$9,700**

Method	Task	Labor (days)	Labor Cost	Equipment and Travel Costs
***Field Water Balance with Flow Measurements* (Time per field would be lower for large farms)**	Ordering equipment (one time for many years)	0.5	$600	$3,950
	Installation (one time for many years)	0.833	$1,000	
	Monthly O&M	0.25	$300	
	Monthly Data QC	0.25	$300	
	Post-processing time	0.25	$300	
	Reporting	0.25	$300	
	First Year Total	**5.333**	**$6,400**	**$3,950**
Crop Coefficient Method	Identification of station location	0.25	$300	
	Equipment orders	0.25	$300	$7,124
	Installation	0.75	$900	
	Monthly operations and maintenance	0.25	$300	$186
	Monthly data quality control	0.5	$600	
	Post-processing time	1.5	$1,800	
	Reporting	0.5	$600	
	First Year Total	**8.5**	**$10,200**	**$8,424**
METRIC (Manual)	Data	3	$3,600	
	Annual operations and maintenance	6	$7,200	
	Monthly data quality control	1	$1,200	
	Post-processing time	1	$1,200	
	Reporting	0.9	$1,080	
	First Year Total	**65.3**	**$78,360**	**$0**
OpenET	Data	1	$1,200	$1,300
	Annual operations and maintenance	2	$2,400	
	Monthly data quality control	0.5	$600	
	Post-processing time	1.5	$1,800	
	Reporting	0.5	$600	
	First Year Total	**8.5**	**$10,200**	**$1,300**