Depletion Accounting for Irrigation Water Rights in Utah

A Review of Potential Agricultural Depletion Accounting Methods

Final

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Utah Department of Natural Resources

Legislative Agricultural Water Optimization Task Force

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Depletion Accounting for Irrigation Water Rights in Utah Project Team

This project would not have been possible without the vision, insight, and expertise of the following individuals:

Legislative Agricultural Water Optimization Task Force Members

This project was identified and funded by the Legislative Agricultural Water Optimization Task Force as part of the implementation of its 2019 Research Plan. The Task Force provided critical input on project drivers, objectives and questions to be answered at its December 20, 2019 meeting, and input and review thereafter. The Task Force is composed of the following members:

- Ron Gibson – Chair/Agriculture Industry Interests Representative
- Jay Olsen – Utah Department of Agriculture and Food Representative
- Kyle Stephens – Utah Division of Water Resources Representative
- James Greer – Utah Division of Water Rights Representative
- Erica Gaddis & Jim Bowcutt – Utah Division of Water Quality Representatives
- Paul Burnett – Environmental Interests Representative
- Paul Monroe – Water Conservancy District Representative
- Ken White – (Non-Voting) Higher Education Representative

Expert Panel Members

An Expert Panel was formed to collect input from experts with a diverse range of experience and expertise in irrigation and depletion accounting methods and understanding of Utah water rights and water resources and to make final recommendations. The Expert Panel met on January 24 and February 28, 2020 to discuss and develop their recommendations and on April 10, 2020 to approve the final recommendations. The Expert Panel was composed of the following members:

- Niel Allen, PhD, PE, Utah State University
- Richard Allen, PhD, PE, Evapotranspiration Plus LLC
- James Greer, PE, Utah Division of Water Rights
- Lawrence Hipps, PhD, Utah State University
- Craig Miller, PE, Utah Division of Water Resources
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- David Jones, PE, Utah Division of Water Rights
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Acronyms and Abbreviations

AFA	acre-feet per acre
ALEXI	Atmosphere-Land Exchange Inverse
ASCE	American Society of Civil Engineers
BREB	Bowen Ratio-Energy Balance
CU	consumptive use
DisAlexi	Disaggregated Atmosphere-Land Exchange Inverse
EC	eddy covariance
EPA	U.S. Environmental Protection Agency
ET	evapotranspiration
ET_{aw}	evapotranspiration of applied water
ET_c	crop evapotranspiration
G	soil heat flux
K_c	crop coefficient
km	kilometer(s)
LAI	leaf area index
METRIC	mapping evapotranspiration at high resolution and internalized calibration
MODIS	moderate resolution imaging spectroradiometer
NASA	National Aeronautics and Space Administration
NDVI	normalized difference vegetation index
PT-JPL	Priestley-Taylor Jet Propulsion Laboratory
R_n	net radiation
SEBAL	surface energy balance algorithm for land
SIMS	satellite irrigation management support
SR	surface renewal
TOPS	Terrestrial Observation and Prediction System
UAES	Utah Agricultural Experiment Station

Executive Summary

Producers have asked the Utah Division of Water Rights to consider new means of administering water rights by depletion rather than the historic method of irrigation diversion duty and number of acres irrigated. Administering irrigation rights by depletion requires accurate, effective, and defensible means to measure and account for actual 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 and accounting for actual depletion in Utah. Depletion accounting provides a means to quantify water use and incentivize and enable water optimization at the field scale and basin scale. The objectives of this project were to identify and evaluate available methodologies and recommend methodologies for depletion accounting to be validated for use in Utah via a pilot program.

Methods

An Expert Panel was formed in January 2020 to identify and evaluate numerous available and emerging methodologies to measure and account for actual depletion. Methods were discussed via email and telephone and at an in-person workshop held on January 22, 2020. Discussion at the first workshop clarified applications for depletion accounting, decision criteria, and created a short list of both ground-based and remote sensing methods to carry forward. Eight ground-based methods and three remote sensing methods were investigated in more detail and summarized in a draft report. Discussion at the Expert Panel's second workshop on February 28, 2020, further clarified criteria for methods to be used in each of 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. These discussions also included the benefits and disadvantages of each method and provided recommendations for implementation in Utah and for validation in a Case Study (Figure ES-1).

Recommendations

The Expert Panel developed and recommended a layered approach that identifies the most effective depletion accounting method for a given application while also providing validation of results from the other applications (Figure ES-1). The approach integrates the applications to provide scalability and defensibility and maximize value to water users, water managers, and the State of Utah over time. For example, the State of Utah could start with Ground-based Methods for Field-scale Depletion Reporting only, then begin to implement Remote Sensing Methods for Field-scale to Basin-scale Depletion Assessments, and then implement Ground-based Methods for Field-scale Depletion Validation as funds becomes available. All three applications are complementary, and each provides additional utility and defensibility for the others as they are implemented.

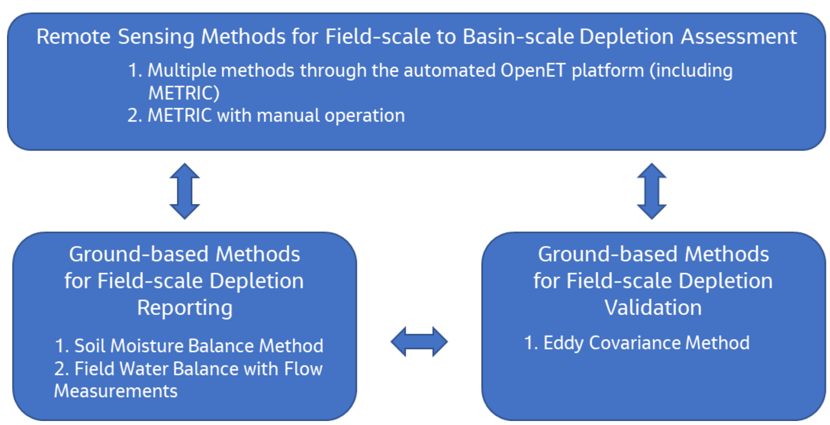

Figure ES-1. Recommended Layered Approach and Depletion Accounting Methods to be Validated in the Case Study for Use in Utah (2021-2022)

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 is designed to validate the recommended methodologies for use in Utah. The Case Study is expected to be initiated in 2020 and completed in early 2022.

1. Introduction

1.1 Purpose and Need

This project was identified as a high priority by the Legislative Agricultural Water Optimization Task Force (Task Force) following review of initial results from implementation of its 2019 Research Plan and in response to inquiries received by the Utah Division of Water Rights from water users around the state. Accurate measurement and accounting of available water supplies, demands, and actual water consumption were identified by the Task Force as a critical step toward protecting and enhancing Utah's agricultural economy and water resources in light of the increasing demands for Utah's limited water resources. Accurate and timely monitoring of water supplies, demands, and consumption and forecasting of conditions provide farmers, ranchers, and water managers with the knowledge to make informed decisions. Informed decisions lead to better results and innovation that improves the sustainability of Utah's water supply and the profitability of Utah's agricultural operations.

1.1.1 2019 Agricultural Water Optimization Research Plan

House Bill 381 (HB 381) formed the Task Force in 2018 to identify and complete research that identifies how the state could: (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.

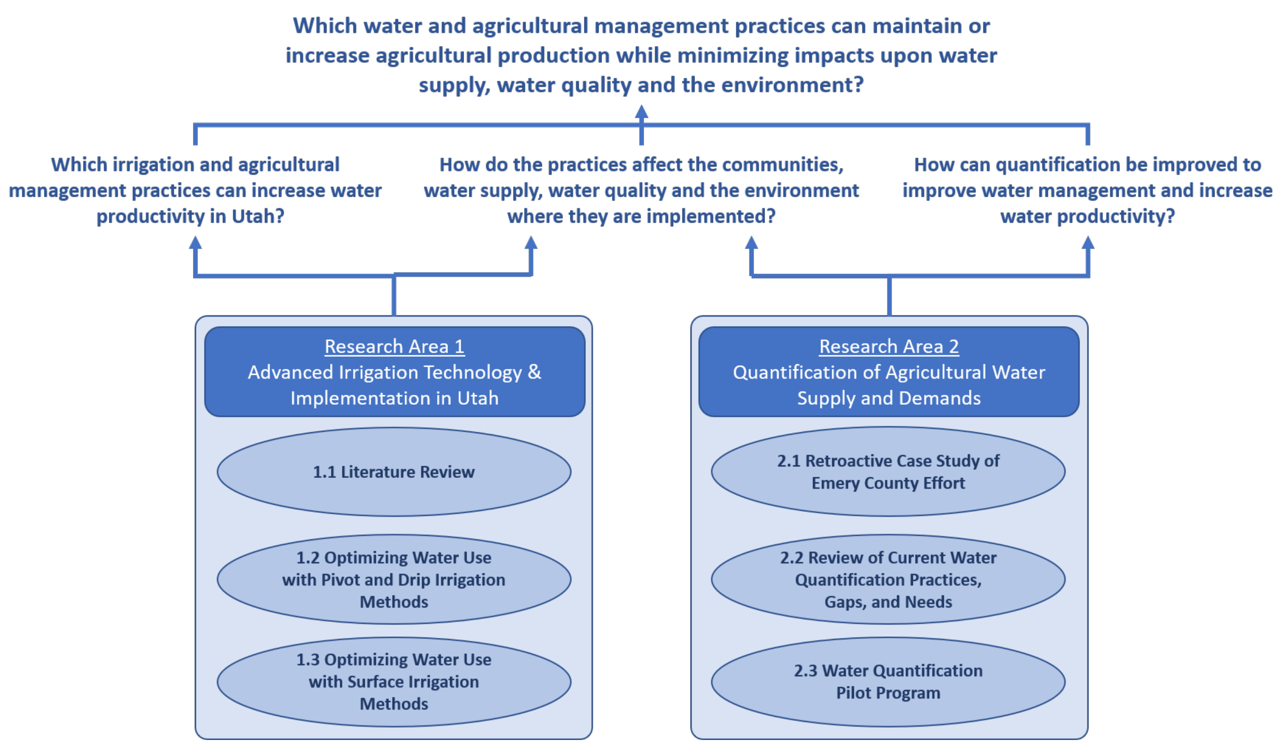

Figure 1-1. 2019 Agricultural Water Optimization Research Framework

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 there are several benefits of optimizing irrigation to increase agricultural production, there are also concerns with the impact on the overall depletions of water resources at the basin scale and on downstream water users. With irrigation improvements that increase crop yields, there is often an associated increase in crop evapotranspiration and depletions (UAES 1982). In addition, there is concern that irrigation water optimization projects that increase irrigation efficiency and crop yields can actually increase depletions (Samani and Skaggs 2008; Ward and Pulido-Velazquez 2008).

These initial findings led to the conclusion that accurate measurement and accounting of actual depletion are important in documenting the value of water optimization. Depletion accounting provides a means to quantify water use, incentivize and enable water optimization at the field scale and basin scale, and protect water rights, water quality, and the environment. The Task Force determined that further study is needed to evaluate alternatives for measurement and accounting of actual depletion and validate them for use in Utah via a pilot program (see Project 2.3 in Figure 1-1).

1.1.2 Administering Irrigation Water Rights by Depletion

The Task Force was formed to identify management practices that can maintain or increase agricultural production while minimizing impacts on water supply, water quality, and the environment. Limited water resources in some basins in Utah are encouraging producers to investigate and implement methods to reduce their diversions or depletions. New laws are being developed and proposed by the Legislature to provide new 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 optimize water productivity and maximize their yields and revenues. Managing diverted water by depletion, rather than by duty and acreage, could allow some producers to expand their acreage and irrigate with the same or less volume of water. Taken together, producers have significant incentives to innovate and have asked the Utah Division of Water Rights to consider new means of administering their water rights by depletion rather than the historic method of irrigation diversion duty and number of acres irrigated.

Administering irrigation rights by depletion requires accurate, effective, and defensible means to measure and account for actual depletion. With numerous available and emerging methodologies to do so, the Utah Division of Water Rights sought to evaluate and identify the most practicable, effective, and defensible means of measuring and accounting for actual depletion in Utah. Combined with the stated objectives and needs identified by the Legislature and Task Force, the Utah Division of Water Rights' pressing need provided the requisite synergy to initiate a project to evaluate alternatives and recommend methods for use in Utah.

1.2 Project Objectives

The objectives of this project were to identify and evaluate available methodologies to measure and account for actual depletion in Utah and recommend methodologies to be validated for use in Utah via a pilot program.

2. Background

This section provides background on the definition of depletion in the context of Utah water rights management and on the various needs for depletion measurement and accounting in Utah.

2.1 What is Depletion?

The term "depletion" in the hydrologic context within Utah means the consumptive use (CU) or evapotranspiration (ET) of applied water. While all ET depletes the amount of water within a hydrologic basin, the ET of applied water (ET_{aw}) results from exercising a water right that is regulated by the State. ET_{aw} is also known as supply-limited CU, irrigation CU, or, in the context of this project, actual depletion (ET) of applied water. ET through access by crops or native vegetation and bare soils to shallow groundwater or stored soil water from precipitation can occur in absence of active management of diverted water. This portion of ET is not considered depletion in the context of water right management and, as a result, must be separated from the ET_{aw} when accounting for depletion.

As defined in Utah Agricultural Experiment Station (UAES) (1989), depletion is defined as follows:

$$Depletion = ET_c - SM_{co} - P_{eff}$$

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

In the context of irrigation water planning, the potential depletion is the same as the net irrigation water requirement (NIWR) of a crop. For well-drained sites without crop access to shallow groundwater, the NIWR or potential depletion is calculated the same as depletion but uses the potential ET_c as opposed to the actual ET_c. For sites with crop access to shallow groundwater, additional work is required to evaluate the portion of ET supported by applied water versus the portion of ET supplied through access to shallow groundwater. In addition, any portion of shallow groundwater that is built up over time by the addition of applied irrigation water and supplies a portion of ET_c should be counted as part of the depletion.

2.2 Needs for Depletion Measurement and Accounting in Utah

There are numerous existing and evolving needs for depletion measurement and accounting in Utah. The State of Utah has historically evaluated water right change applications by evaluating proposed diverted and depleted volumes of water. With a proposed water right change, neither the allowed quantity of water diverted in the water right nor the estimated depleted quantity of water is allowed to increase. This condition is required to prevent the impairment of other water rights.

Allowed seasonal diversion volumes for irrigation water rights are determined by the Utah Division of Water Rights on the basis of the irrigation area described in the water right and the allowed irrigation duty, which varies depending upon climate conditions throughout the state. Irrigation duties are measured on the basis of volume of water per unit area over the course of an irrigation season and are typically expressed in units of acre-feet per acre (AFA). The map used by the Utah Division of Water Rights to determine the allowed irrigation duty for a water right, based upon location, is presented as Figure 2-1. As shown, allowable irrigation duties vary from 3.0 AFA in cooler and wetter regions to 6.0 AFA in warmer and drier regions.

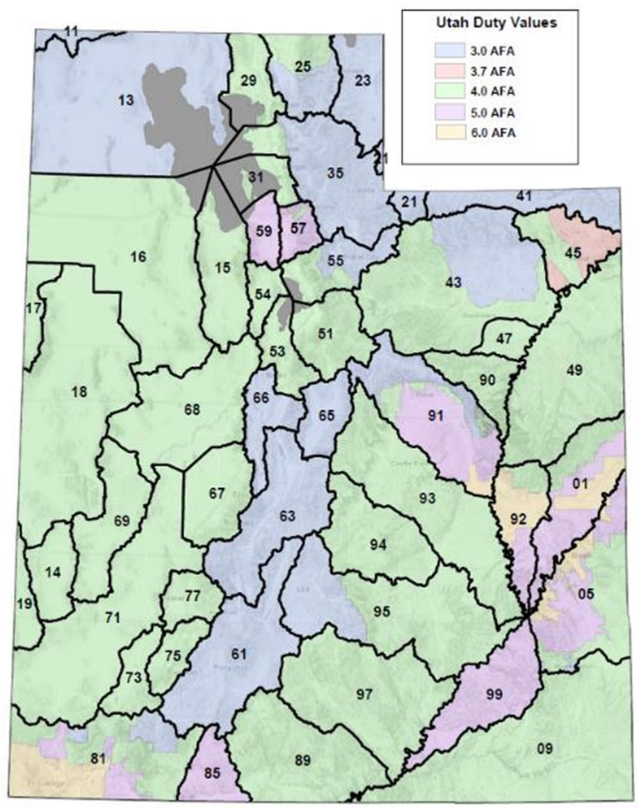

Figure 2-1. Map of Standard Irrigation Water Right Duty Values by Region Across Utah

The assumed irrigation depletion for each irrigation water right is defined by the Utah Division of Water Rights as "the volume of water that is potentially consumed as evapotranspiration during beneficial use for irrigation on the basis of the most consumptive crop which can be grown on the limited acreage, usually alfalfa". Although a more recent estimate of CU for crops in Utah was developed in 2011 (UAES 2011), the assumed irrigation depletion used in practice and by code is currently based on the 1994 study, "Consumptive Use of Irrigated Crops in Utah" (UAES 1994). In this study, the total ET and NIWR were determined monthly and annually for major crops at 111 National Weather Station sites across Utah (Figure 2-2). As an example of the differences in depletion estimates across regions, the estimated consumptive use tables for St. George, in the southwestern corner of the state, and Logan, near the northern border of the state, are presented in Appendix A. In the UAES (1994) study, the annual NIWR for alfalfa is 43.00 inches (3.58 AFA) at St. George and 23.62 inches (1.97 AFA) at Logan.

The difference between the allowable irrigation duty and assumed irrigation depletion represents the potential return flow from irrigation uses. Irrigation return flows can occur through canal seepage, direct surface runoff, and deep percolation of diverted or applied irrigation water and generally return to the hydrologic basin.

Examples of allowable irrigation duties, estimated depletion, and potential irrigation return flow for the two reference locations are summarized in Table 2-1. For the Logan example, the estimated depletion is 1.97 AFA or 49 percent of the 4.00 AFA maximum allowable irrigation duty, and the assumed potential irrigation return flow is 2.03 AFA or 51 percent of the maximum allowable irrigation duty. For the higher CU example at St. George, the estimated depletion is 3.58 AFA or 60 percent of the 6.00 AFA maximum allowable irrigation duty, and the assumed potential irrigation return flow is 2.42 AFA or 40 percent of the maximum allowable irrigation duty.

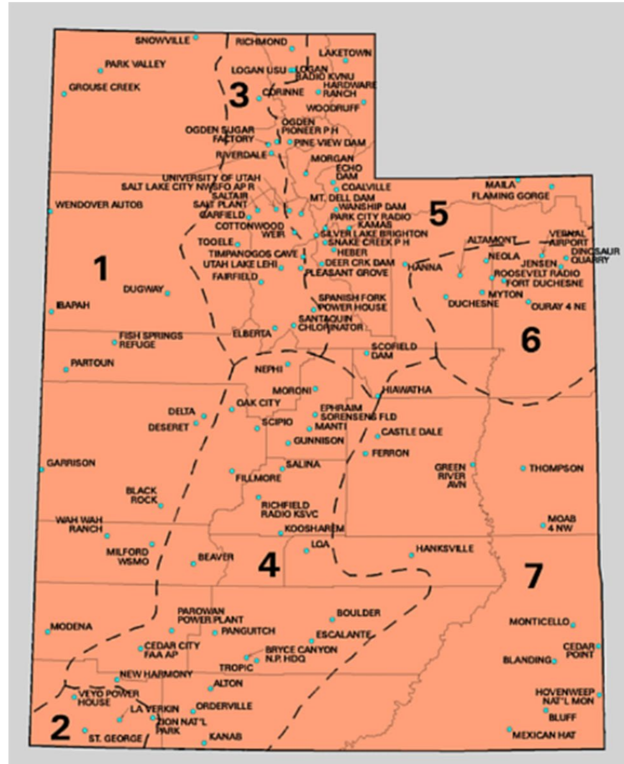

Figure 2-2. Map of Utah National Weather Station Sites Used in Determining Consumptive Use in UAES (1994).

In evaluating irrigation water right change applications, if a water user proposes to limit their diversions and duty to a value not greater than the estimated depletion, the Utah Division of Water Rights will typically approve the change without requiring additional evidence of the depletions expected with the proposed new irrigation use. This approach provides relatively conservative assurance that the newly allowed use will not exceed historic depletions. However, this approach also requires the water user to reduce their allowed diversion rate and annual irrigation duty.

Table 2-1. Example Allowable Irrigation Duties, Estimated Depletions, and Potential Return Flows for Logan and St. George, Utah

	Logan	St. George
Maximum Allowable Irrigation Duty (AFA)	4.00	6.00
Estimated Depletion (AFA)	1.97	3.58
Estimated Depletion Fraction	0.49	0.60
Potential Return Flow (AFA)	2.03	2.42
Potential Return Flow Fraction	0.51	0.40

For irrigation water right change applications in which the water user does not propose to restrict future diversions and water duties to within the estimated historical depletion, the Utah Division of Water Rights requires the water user to provide evidence that the proposed change will not increase the amount of water diverted or the amount of water depleted as a result of exercising the water right. In the past, the methods used by water users in estimating the changes to diversions and depletions have varied from application to application.

As a condition of approval of a water right change application, the Utah Division of Water Rights requires the applicant to monitor and provide evidence of water use, both in terms of total diversion and total depletion. The Utah Division of Water Rights evaluates this information and may perform additional independent evaluations of estimated depletion to regulate the use and protect against injury to other water rights. Again, the methods used by water users in estimating the changes to diversions and depletions and the methods used by the Utah Division of Water Rights have varied.

Another need for determining accurate measurements of actual depletion is to comply with Utah's two interstate compacts, the Bear River Compact and the Colorado River Compact. Both compacts require the State of Utah to report depletions in the respective river basin within state boundaries. Identification and validation of different methods to measure and account for depletion would provide the State of Utah and water users added flexibility and confidence in their reporting and the means to accurately measure actual depletion in a consistent manner across each basin. The State of Utah seeks to identify different methods that can be used to validate and ground truth regional measurements and calculations of actual ET made with remote sensing and other cutting-edge methods.

In recent years, there has also been increasing interest in new and different forms of water right changes. Examples of water right changes that require careful examination of potential impacts on depletions include:

- **Irrigated Acreage Expansion.** Under this change, the water user proposes to expand the existing allowed irrigated acreage in a water right on the basis of using lower CU crops or irrigation systems. An example might include changing cropping from alfalfa to a lower CU seasonal crop, such as field corn.
- **Split-season Leasing.** Under this change, the water user proposes to exercise the water right at the existing place of use for a portion of the irrigation season, then transfer the water right for additional places of use and potentially for different types of uses for the remainder of the irrigation season. An example might include using the water right for an existing grass hay crop through a specified cutoff date (e.g., June 30), then forbearing water on the hay crop for the remainder of the year and transferring the water right from July 1 through the end of the irrigation season to another use (e.g., in-stream flow, municipal use).
- **Conversion of Irrigation Water Use to Commercial Water Use.** Under this use, the water user may propose converting its volume of actual depleted water from an irrigation use to another use such as for domestic, dairy, feedlot, or stock water use.

Each of the needs listed above must be carefully considered as methods to measure and account for actual depletion in Utah are evaluated. Each need illustrates that methods for evaluating depletion must be accurate and defensible to prevent the impairment of other water rights.

3. Criteria

In developing the scope for this project, the Task Force prepared a list of criteria 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 that could meet a variety of uses, supporting farmers and state agencies in managing irrigation for agricultural production and water resources across Utah.

The criteria provided by the Task Force to guide this evaluation are as follows:

1) Method should measure/estimate water depletion at both the farm and basin scales as accurately as possible.
2) Method should provide for the ability to acquire and process the data in a timely manner. A specific timeline has not been defined, but the State would rather have data that are actionable rather than simply documenting historical performance. Real-time or near-real-time data are ideal.
3) Method should be readily accepted in the industry. The method may still be in development, but the equipment and protocol should be available for use and readily implementable by water users.
4) Method should be accurate and defensible. The method should provide for ground-truth-based verification.
5) Method should be flexible enough to account for change in the industry.
6) Method should allow the State to implement it statewide for use by agricultural water users and resource management agencies.
7) Remote sensing and ground-based methods should be considered. Similarly, both energy balance and mass balance approaches are possible. The key is answering the question, "What is the best method(s) to be implemented in the State of Utah?"

In considering these criteria, the Expert Panel determined that multiple methods could be appropriately used by water users and the State for different purposes. For instance, multiple ground-based methods 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 applications. For basin-scale application and application on a statewide basis, remote sensing estimates 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 are also recommended for comparison and validation.

Therefore, the evaluation of depletion accounting methods considers three complementary applications (Figure 3-1):

1) **Ground-based Methods for Field-scale Depletion Reporting**. These methods should be suitable for use by water users in 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 is 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 Depletion Validation**. These methods are required for validating or ground-truthing results provided by basin-scale methods (i.e., remote sensing methods) and may be used for validating or ground-truthing results 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) **<u>Remote Sensing Methods for Field-scale to Basin-scale Depletion Analysis</u>**. These methods focus on the ability to 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.

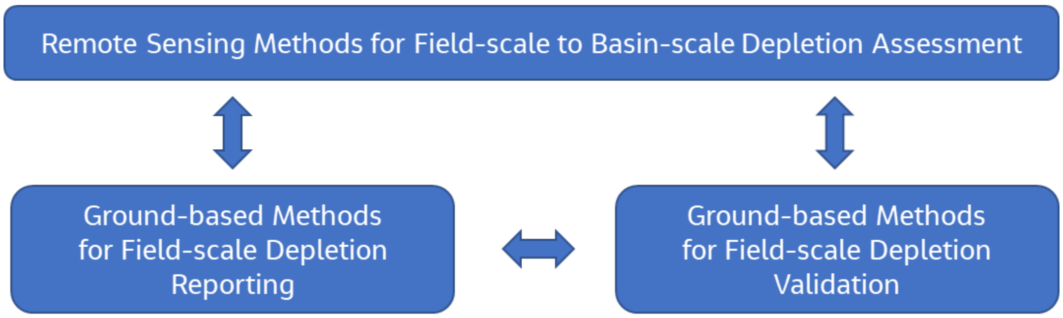

Figure 3-1. Three Applications for Consideration in Evaluating Depletion Accounting Methods

The Expert Panel developed and recommended a layered approach that identifies the most effective depletion accounting method for a given application while also providing validation of results from the other applications (Figure 3-1). The approach integrates the applications to provide scalability and defensibility and maximize value to water users, water managers, and the State of Utah over time. For example, the State of Utah could start with Ground-based Methods for Field-scale Depletion Reporting only, then begin to implement Remote Sensing Methods for Field-scale to Basin-scale Depletion Assessments, and then implement Ground-based Methods for Field-scale Depletion Validation as funds becomes available. All three applications are complementary, and each provides additional utility and defensibility for the others as they are implemented.

4. Potential Methods for Depletion Accounting

The most common and potentially applicable methods for estimating actual ET_c in Utah are presented in this section. This section summarizes each method for determining actual ET_c and then discusses methods for depletion accounting for determining actual depletion of applied water (ET_{aw}) from ET_c.

4.1 Ground-based Methods for Estimating Crop Evapotranspiration

The Expert Panel identified available ground-based methods for estimating ET_c at its first workshop and developed a shortlist to be carried forward for further evaluation. This includes the most common ground-based methods that could be used for depletion reporting or for remote sensing validation applications. Shortlisted ground-based methods are summarized in the following sections.

4.1.1 Meteorological Measurements and Crop Coefficients

The most common method historically used for estimating ET_c involves the use of meteorological measurements, either by pan evaporation or weather station data, to estimate the ET of a reference crop (grass ET_o or alfalfa ET_r) coupled with empirical crop coefficients (K_c) to estimate potential ET_c (Allen et al. 1998; ASCE 2016). This process is based on research that developed standard methods for relating meteorological measurements to direct lysimeter measurements of actual ET for the reference crop under ideal growing conditions. The K_c values applied to estimate crop-specific ET are likewise typically developed with paired reference ET measurements and direct lysimeter or other actual ET measurement methods of a specific crop under similar ideal growing conditions. When properly developed and then applied under similar conditions as used to develop the K_c values, the combination of accurate weather station data, information on crop start and end of growth periods, and cutting or harvest dates can provide a defensible method for estimating the potential ET of specific crops.

While use of reference ET measurements and crop coefficients is a standard method for estimating potential ET_c under ideal conditions and as a target for irrigation scheduling, actual ET_c often departs from and is lower than potential ET_c when considered at the field scale. This is the result of conditions that impair optimum growing conditions such as non-ideal soil conditions, excess salinity, fertility limitations, physiological limitations to transpiration, pests, disease, variations in crop variety, and non-uniform or inadequate irrigation applications. To estimate actual ET_c under non-ideal conditions, additional information on factors that limit ET_c, such as soil moisture, soil salinity, and actual plant cover, can be used to develop adjustments to ideal K_c values. Due to the differences between potential and actual ET_c, application of meteorological measurements and crop coefficients typically overestimate actual ET_c with greater deviation between actual and estimated ET_c as the scale of measurement increases (Allen et al. 2011a).

In the following sections, the two most common reference ET methods are discussed, followed by a brief discussion on crop coefficients.

4.1.1.1 Reference ET from Pan Evaporation

Evaporation from an open water surface was historically used to estimate reference ET by measurement of water loss in a standard measurement pan and by application of empirical pan coefficients. Problems with this method include: the temperature of the water in the pan being distorted due to the small size of the pan and effects of its immediate surroundings; the differences in behavior of water losses from an open water surface and a cropped surface; and the sensitivity of the empirical pan coefficients to pan siting conditions. For instance, pan coefficients for a Class A pan can vary from 0.35 to 0.85 depending upon siting conditions (Allen et al. 1998; ASCE 2016). In addition, this method requires daily physical maintenance and is typically only practical during non-freezing periods. Pan evaporation is no longer used to estimate reference ET and has been replaced by improved methods for reference ET calculation from meteorological measurements as discussed in the next section.

4.1.1.2 Reference ET from Weather Stations

Meteorological measurements of solar radiation, wind speed, air temperature, and relative humidity are collected and used to estimate reference ET (ET_o or ET_r). Although multiple calculation methods have been used historically to estimate reference ET with similar results (e.g., Allen et al., 1998) and the quality of ET measurements used to validate the equations are variable, the American Society of Civil Engineers (ASCE) Penman-Monteith method (ASCE 2005) is recommended as the standardized method for reference ET calculation. By comparison to direct lysimeter measurements of reference ET, application of the ASCE Penman-Monteith method has been shown to reproduce actual seasonal reference ET within -10 to +10 percent of measured values and estimated peak monthly reference ET within -18 to +7 percent across a range of arid to humid climates (ASCE 2016). Use of quality-controlled weather station data collected from well-watered agricultural settings and application of the ASCE Penman-Monteith method are recommended for the meteorological measurements and crop coefficients accounting methods.

4.1.1.3 Crop Coefficients

Crop coefficients have been developed for most major crops globally to guide water users in irrigation water management (Wright 1982; Allen et al. 1998; ASCE 2016). For major crops in Utah, historic estimates of potential ET_c using the 1982 Kimberly Penman method (Wright 1982) and estimated depletion were presented in UAES (1994) and are still used by the Utah Division of Water Rights for potential depletion estimates. Additional crop coefficients were presented by UAES (2011) for crops and open water in Utah and by Allen and Robison (2007) for crops grown in Idaho, including crop coefficients developed by Wright (1982) using lysimeters at the Kimberly, Idaho, research station. These publications provide relevant information for estimating potential ET_c using valid reference ET measurements, crop phenology and irrigation management data, and applicable crop coefficients. For highest accuracy, the crop coefficients are partitioned into transpiration and soil evaporation components using the dual crop coefficient approach with daily calculation timesteps (Allen et al. 1998; Allen and Robison 2007; ASCE 2016).

4.1.2 Weighing Lysimeter

Figure 4-1. Weighing Lysimeter Station planted to alfalfa at Colorado State University Arkansas Valley Research Center, Rocky Ford, CO (*Source: Steve Evett*)

Weighing lysimeters consist of a confined section of soil within a buried container placed on a load cell capable of measuring small changes in soil column weight over time (Figure 4-1). Changes in weight are largely due to changes in water stored in the soil column. When coupled with direct measurements of precipitation, applied irrigation water, and deep percolation drainage from the soil column, changes in soil water storage and actual ET_c can be directly calculated. Weighing lysimeters were historically considered the most accurate method for ET_c measurement. However, drawbacks of this method include the high cost of initial construction, problems under high water table conditions, challenges with maintaining representative vegetation growth and areal extent inside the lysimeter, protection of the equipment, and required regular (daily to weekly) physical maintenance to ensure reliable results. The most significant of these problems in producing reliable depletion measurements using lysimeters are not having the same vegetation structure inside the lysimeter as the surrounding field, lack of active vegetation immediately outside the lysimeter with subsequent spreading of lysimeter vegetation that increases capture of solar radiation and incorrectly increases ET measurement, and the fixed bottom of the lysimeter that alters root distribution and results in soil moisture profiles that differ from the "real" field conditions (Allen et al. 2011a).

A concept for lower-cost, three-dimensional (3D)-printed, plastic lysimeters is currently under development by staff with the Utah Division of Water Resources. The conceptual plastic lysimeters are smaller in footprint and depth. While this would lower the cost of construction, the smaller footprint increases edge effects, and the smaller depth limits the application to shallow-rooted crops. The same challenges with maintaining representative vegetation growth and areal extent inside the lysimeter, protection of the equipment, and required regular (daily to weekly) physical maintenance to ensure reliable results would also apply. An application with shallow-rooted crops to determine ET_c in a field environment could be beneficial considering the significantly lower cost of the proposed conceptual lysimeter.

4.1.3 Soil-Water Balance

Figure 4-2. Soil Water Balance Station in Weber County, Utah

The soil-water-balance approach consists of directly measuring major inflows and outflows within a crop root zone, except for ET_c, which is estimated as the residual of the soil-water-balance equation as follows:

$$ET_c = Precipitation + Irrigation + Other\ Water\ Sources - Deep\ Percolation - Runoff - Change\ in\ Soil\ Water\ Storage$$

Typically, this approach is applied for sites where "other water sources," such as run-on or shallow groundwater inflow to the root zone, are not a factor and where runoff is not a factor or can be easily collected and measured. Soil water storage can be measured by multiple soil water sensors directly installed through the crop root zone depth (Figure 4-2) or by access tubes installed past the extent of crop rooting to provide access for permanently installed or portable soil moisture measurement devices. While daily ET_c can be measured from change in soil water during periods when no irrigation, precipitation, or deep percolation is occurring, this method is most credible for longer-term (weekly) estimates. The accuracy of ET_c estimates generally improves as the time period between measurements increases since the change in soil water storage term becomes smaller relative to the precipitation and irrigation terms in the equation. In addition, it is critical that the soil moisture measurements be made accurately over the entire depth of the rooting zone, which can be difficult, as sensor installation often occurs before such knowledge is available. Multiple measurement sites in a field also improve the accuracy of estimates due to variability in irrigation application depths and soil and crop conditions throughout a field. Since the soil-water balance does not account for consumptive irrigation losses from evaporation of water before entering the soil, other estimating methods may be needed to account for this loss.

4.1.4 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 a field water balance approach. When used alone, this method requires 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. These conditions are rarely satisfied except when irrigating using high-efficiency pressurized systems with accurate flow measurement and with consistent deficit irrigation of crops in arid climates with limited rainfall and no access to shallow groundwater, and with minor change in total soil water content between the start and end of the growing season.

Estimation of ET_{aw} with this method is conservative in that any unmeasured deep percolation or surface runoff that does occur will tend to cause an overstatement of estimated ET_{aw}.

An example application of this method is provided here for illustration. For a recent project evaluated in Weber County, Utah, an accurate flowmeter measured a total season irrigation application on a drip irrigated onion field of 21.4 acre-feet on a 17.6-acre field, for an irrigation application of 1.22 AFA (14.6 inches). There was no irrigation runoff from the field, and soil moisture sensors indicated there was no deep percolation and only a slight decrease in soil water over the growing period. For this application, the seasonal ET_{aw} is estimated at 1.22 AFA (14.6 inches) (Allen 2020).

4.1.5 Bowen Ratio-Energy Balance Method

The Bowen Ratio-Energy Balance (BREB) method provides an indirect means for quantifying actual ET_c by measuring net radiation (R_n) and soil heat flux (G) and the vertical gradients of air temperature and humidity above a cropped surface. A typical station installation is shown in Figure 4-3, and required instruments are described in Cook and Sullivan (2019). The latent energy (actual ET_c) is estimated using the measured R_n-G and the ratio of the gradients. The sensible heat flux from the surface is estimated from direct measurements of R_n and vertical gradients of air temperature and humidity. The soil heat flux is estimated using an array of soil temperature and soil heat flux sensors in the field (Fritschen and Simpson 1989). A BREB system typically uses a station with two arms that must be downwind of the study area and adjusted to remain above crop height. This method was implemented more commonly in the past, before eddy covariance sensors became more reliable and less expensive, because of its simplicity, relatively low cost, and robustness. A BREB system does require expert installation, regular maintenance, and expert data reduction and interpretation (Allen et al. 2011a; Liu and Xu 2019).

Figure 4-3. Bowen Ratio-Energy Balance System (*Source: O'Dell et al., 2014*)

The advantages of the BREB method "include straight-forward, simple measurements; it requires no information about the aerodynamic characteristics of the surface of interest; it can integrate latent heat fluxes over large areas (hundreds to thousands of square meters); it can estimate fluxes on fine time scales (less than an hour); and it can provide continuous, unattended measurements. Disadvantages include sensitivity to the biases of instruments that measure very small gradients and energy balance terms; the possibility of discontinuous data when the Bowen ratio approaches -1; and the requirement, common to micrometeorological methods, of adequate fetch to ensure adherence to the assumptions of the method (Todd et al. 2000)." The method also assumes that the sources and sinks for heat and water vapor are identical, an assumption that is generally not true. The BREB method may work well in conditions where there is an ample water supply but has been shown to be less accurate in dry, arid conditions (Angus and Watts 1984).

Although this project's Expert Panel considered the BREB method to be a viable method, the Expert Panel expressed a concern related to field equipment availability and the scientific community largely abandoning the approach. Increased use of other methods such as the eddy covariance method has reduced implementation of the BREB method. This has resulted in a reduced demand for BREB instrumentation, low production volumes, and a scarcity of suppliers of BREB systems.

4.1.6 Eddy Covariance

The eddy covariance (EC) method provides a direct and continuous estimate of energy, momentum, and mass fluxes and thus is the most widely accepted standard for ground-truthing ET_c estimates provided by other methods (Liu and Xu 2019). An EC system typically includes a 3D sonic anemometer and special sensors to accurately measure temperature, carbon dioxide (CO_2), and water vapor fluctuations at high frequency (Figure 4-4). These are generally coupled with measurements of R_n and G to allow a complete surface energy balance to be estimated. EC systems are expensive and require expert installation, a consistent power supply, maintenance, and often complex data reduction analyses and interpretation for highest accuracy.

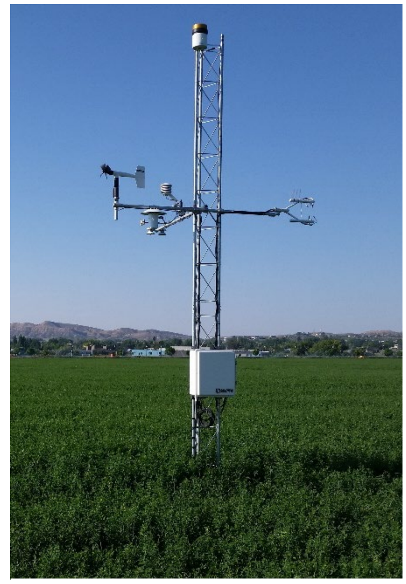

Figure 4-4. Eddy Covariance Tower, U.S. Bureau of Reclamation, Vernal, Utah (*Source: Lawrence Hipps*)

According to Liu and Xu (2019), "The advantages of the EC method include (1) direct measurement of the sensible heat, latent heat, CO_2, and momentum fluxes and other scalars, (2) continuous collection of fine temporal (e.g., 30 minutes, 1 hour) and spatial (hundreds of meters) resolution data, and (3) automatic operation in the field. The disadvantages are (1) the requirement for careful data processing and corrections, (2) the requirement of a substantial homogeneous source area or field size (hundreds of meters), (3) the uncertainty in how to treat the "unclosed" energy balance [sum of energy fluxes not exactly balancing available energy] in the surface layer due to numerous reasons which vary from site to site, and (4) the requirement for regular instrument calibration. When installed and operated by trained experts having strong physics backgrounds, the EC method can provide relatively consistent and accurate measurements for ET_c. A recent comparison of EC to BREB and cross-comparison against measured soil moisture and soil moisture balance models was presented by Fischer et al. (2018). In general, there was better agreement between the EC and the soil moisture balance based ET_c estimates when EC data were adjusted for lack of energy balance closure.

4.1.7 Scintillometers

Figure 4-5. Optical Microwave Scintillometer System (*Source: Kipp & Zonnen brochure*)

Scintillometers indirectly quantify actual ET_c by measuring atmospheric scintillation of a beam of light caused by turbulence over a fixed path length near the ground surface (Figure 4-5). A scintillometer transmits and receives a beam of electromagnetic radiation with a known wavelength across a fixed length of field (100 meters to 4.5 kilometers, depending on the type of sensor) (Moorhead et al. 2017). Fluctuations in beam intensity are measured to determine fluctuations in the refractive index of air and temperature and humidity structure and are used to compute the sensible heat flux (H). Calculations to obtain sensible heat flux from scintillometers are based on a number of aspects of turbulence theory, including Monin–Obukhov Similarity Theory (MOST) (de Bruin and Wang 2017). ET_c is determined via a surface energy balance equation as $ET_c = R_n - G - H$, where R_n and G are net radiation and soil heat flux that are also measured in the same field using high-accuracy, ground-based measurements.

Scintillometers must be paired with a local meteorological station, require expert installation, regular maintenance, and expert data reduction and interpretation. They can be more expensive but can be simpler to operate and maintain than EC stations. When combined with an adequate number of R_n and G estimates, they provide a path-averaged estimate of actual ET over the length of the path rather than at one point. One type of sensor (Scintec SLS) results in paths about the same or smaller than EC. The other (Large Aperture Scintillometer [LAS]) can reach up to a few kilometers under optimal atmospheric conditions. Results for large fields (e.g., up to 2 kilometers in size) are difficult to interpret as multiple evaporative surfaces are included, and one would have to measure R_n and G in all of them. Alternatively, a LAS can be deployed in smaller center pivot fields where uniform crop cover is present over shorter path lengths (e.g., 800 meters). Some reported drawbacks include data interpretation being complex; errors can be large; and poor meteorological conditions, and tower vibrations can affect long-term operation (Liu and Xu 2019).

4.1.8 Surface Renewal

Figure 4-6. Solar powered surface renewal field station established in a vineyard in California (*Source: McElrone et al, 2013*)

Surface Renewal (SR) is a micrometeorological method for estimating actual ET_c (Figure 4-6). It is similar in many ways to some other energy balance methods in that it does not calculate ET_c directly, but estimates ET_c as a residual of the energy balance equation, $ET_c = R_n - G - H$. The SR uses a relatively inexpensive method for determining H by using fine wire thermocouples to measure high-frequency air temperature fluctuations at the surface-atmosphere interface (Hu et al 2018). While some commercial applications of the SR method rely upon remote sensing-based estimates of R_n and G to lower the cost of measurement, reliable and accurate estimates of ET_c using this method require ground-based measurements of R_n and G at the station site just like the EC, BREB, and Scintillometer methods.

A significant drawback from employing the SR 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 (Paw U et al 1995; Hu et al 2018). Some published studies report reasonable results when compared to eddy covariance (Shapland et al. 2012). Castellvı´ (2004) has proposed using Monin-Obukov Similarity expressions and measurements of mean horizontal wind to estimate H without the eddy covariance calibration. There is still some uncertainty about using the SR without calibration. A recent study, not yet published, tested the uncalibrated SR approach against high-quality energy balance measurements and found poor performance. While methods are being developed to avoid calibration using direct measurements of horizontal wind speed, this approach is still under development and has not been fully validated. SR application is also limited to areas without high humidity, and while the thermocouples are low cost and are generally reliable, they are also prone to damage in high-wind conditions.

The low cost and ease of operation of the SR method, when coupled with pre-determined calibration factors and remote sensing-based estimates of R_n and G, make the SR method appear to be an attractive option. However, the Expert Panel recommended that the SR method can currently only be deployed successfully for field-scale depletion validation if deployed in conjunction with the EC or Scintillometer methods and with expert installation, maintenance, and data reduction. This method should be monitored for progress and successful in-field application over a range of conditions, especially as it relates to the elimination of the calibration requirements with EC stations.

4.2 Remote Sensing Methods for Estimating Evapotranspiration

Remote sensing methods for estimating ET_c have been under development and in transition from research to commercial applications since the 1990s (Kalma et al. 2008; Liou and Kar 2014; Karimi and Bastiaanssen 2015; ASCE 2016). Remote sensing methods use aerial imagery, often in combination with ground-based measurements, to estimate actual ET_c. Although satellite imagery is the most applicable sensor vehicle to collect data over large land areas, airplanes and unmanned aerial vehicles (UAVs) may also be used for data collection. Spatial resolutions vary across sensors and sensor vehicles, ranging in application from regional/global scales to the sub-field scale. The models applied for estimating ET_c also vary widely from full energy balance methods to empirical methods that rely upon vegetation indexes, such as estimates of Leaf Area Index (LAI) using Normalized Difference Vegetation Index (NDVI) from multispectral data, to develop K_c corrections and ET_c estimates. While remote sensing methods offer substantial advantage over ground-based methods for evaluating ET_c over large land surface areas, the combination of remote sensing models and more traditional ground-based measurements usually results in increased accuracy (ASCE 2016).

This section provides an overview of remote sensing methods for estimating ET_c categorized into three primary applications:

- Energy Balance Methods
- Vegetation Index Methods
- Aerial Crop Surveys with Crop Coefficients

The following overviews are not intended to be comprehensive but instead are intended to be a starting point for the reader to understand the key inputs, outputs, limitations, and the current state of application and development for each method. Also, the list of energy balance and vegetation index methods presented in this section is limited to methods currently being built into the OpenET platform (discussed later in this section).

This section concludes with a discussion of potential delivery platforms for remote sensing data processing and access.

4.2.1 Energy Balance Methods

Energy balance methods consist of methods that estimate ET_c using a land surface energy balance where ET_c is estimated as the differences between the three primary energy sources and sinks as $ET_c = R_n - G - H$, where R_n, G, and H are net radiation, soil heat flux and sensible heat flux that are all derived from a satellite (such as Landsat), airplane, or UAV having a thermal imager. Emissions of long-wave infrared thermal spectra radiation at the land surface are sensed by the thermal imager and are used to estimate the land surface temperature. When coupled with other models that can be driven with additional remotely sensed data and ground-based meteorological measurements, ET_c can be estimated as the residual of the energy balance equation.

Four energy balance methods are summarized in the following to demonstrate a range in potential methods.

4.2.1.1 METRIC

Mapping Evapotranspiration at High Resolution and Internalized Calibration (METRIC) was developed by the University of Idaho in partnership with the Idaho Department of Water Resources, the U.S. Geological Survey (USGS) and National Aeronautics and Space Administration (NASA) and is maintained by the University of Idaho Kimberly Research and Extension Center and Evapotranspiration Plus, LLC. The METRIC model uses a surface energy balance approach to solve for ET_c based on a combination of input data from Landsat satellites, general information on land cover and elevation data, and weather station information. The METRIC algorithm internally calibrates based on ground-based reference ET and is suitable for assessing ET_c at the field level at 30-meter spatial resolution when applied with Landsat.

METRIC is available to the public; however, due to complex processing requirements, the model's application is typically carried out by trained professionals for a fee. Expertise is required for the critical selection of optimal "cool" and "hot" pixels from a given satellite image; these pixels provide distinction between areas with and without crop cover and end points of lowest and highest remotely sensed surface temperature, which are critical to the ET that results in all other locations. Processing of images to remove areas with cloud cover and to interpolate ET_c estimates on a pixel-by-pixel basis between image dates are other key processing steps.

METRIC is currently used by many states to help manage their water resources. It has also been used to assist settlement of interstate conflicts, such as between Montana and Wyoming over the Tongue and Powder Rivers. Other recent applications include water conservation efforts within the Klamath Basin and assessing the cost-benefit impact of a salt-cedar tree eradication program in Texas. The Idaho Department of Water Resources, in partnership with University of Idaho, currently employs METRIC to provide near-real-time estimates of ET_c over the Snake River Plain of southeast Idaho where ET_c results from the prior month are produced within five working days following the end of each month. This program is part of monitoring depletion reductions associated with mitigation of groundwater pumping impacts.

Additional information can be found in Allen et al. (2007; 2011b).

4.2.1.2 SEBAL

Surface Energy Balance Algorithm for Land (SEBAL) predates METRIC and is similar in its approach in that it uses spatial variations in surface temperature to determine the H for each pixel, then estimates ET_c as a residual of the energy balance. In both cases, the R_n and G are determined separately from remote sensing inputs. However, unlike METRIC, SEBAL does not rely on a ground-based reference ET (typically determined by application of the Penman-Monteith equation). The energy balance approach does require limited knowledge of land cover and elevation; however, it does not require knowledge of soil type or hydrologic conditions. The SEBAL model first determines instantaneous ET_c at the time a satellite image is available. From there, estimates for daily ET_c (or longer periods) are calculated. Similar to METRIC, SEBAL requires the identification of "hot" and "cool" pixels within a given thermal image. SEBAL has been used and validated across the globe in more than 30 countries.

Additional information can be found in Bastiaanssen et al. (2005) and Karimi and Bastiaanssen (2015).

4.2.1.3 ALEXI/DisALEXI

Atmosphere–Land Exchange Inverse (ALEXI) is a regional scale model (10^3 meters) that relies on thermal imagery input from the Geostationary Operational Environmental Satellite (GOES). It is often used in combination with the Disaggregated Atmosphere–Land Exchange Inverse (DisALEXI) model. DisALEXI produces a higher resolution output (approximately 30 meters) using an additional Landsat-based processing step. This algorithm is based on a two-source model that includes both soil surfaces and vegetation that was developed by Norman et al. (2003) and follows a two-step process to implement the ALEXI model. First, the lower-resolution ALEXI is executed to obtain ET_c for approximately 4-kilometer pixels and determines other inputs for the higher resolution models. Then daily Moderate Resolution Imaging Spectroradiometer (MODIS) data (100 meters to 1 kilometer) is downscaled to the 30-meter Landsat resolution by an algorithm that is validated and calibrated with each Landsat overpass. Next, the two-source model that treats soil and vegetation separately is executed with higher resolution surface temperature and vegetative cover. The result is 30-meter estimates of all terms in the energy balance except ET_c, which is simply determined by residual. As with METRIC and SEBAL, DisALEXI can account for plant stress resulting from soil water depletion, disease, and salinity.

The model has been tested and validated at a range of locations and conditions. Additional information can be found in Anderson et al. (1997), and Semmens et al. (2016).

4.2.1.4 SSEBop

SSEBop (Simplified Surface Energy Balance) was developed and is maintained by the USGS and relies on a simplification of the surface energy balance approach. As opposed to METRIC and SEBAL, SSEBop does not solve for each component of the surface energy balance directly, but instead assumes a linear relationship between surface temperature and ET_c. The primary inputs for SSEBop are land surface temperature, maximum air temperature, and reference ET. The primary output for SSEBop is a fraction of reference ET. Actual ET_c is obtained by multiplying the reference ET by this fraction.

Additional information can be found in Senay et al. (2014).

4.2.2 Vegetation Index Methods

With the vegetation index methods, LAI or aerial vegetation cover is typically estimated using the NDVI. NDVI is calculated using red and near infrared (NIR) spectral reflectance data as follows:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Where NIR and Red are reflectances in the near infrared and red 'bands' of a satellite or aerial image.

NDVI values respond to the areal cover of green vegetation or photosynthetically active leaf area at the ground surface, up to some maximum level. NDVI can be correlated to leaf area index (LAI) and aerial percent vegetation cover, which can subsequently be used to adjust K_c values or to incorporate other adjustments to traditional ET_c estimating methods. A limitation of the vegetation index methods is their inability to sense plant water stress, except for the indirect and delayed effect water stress may have on development and extent of green leaf areas.

Two potential energy balance vegetation index methods are summarized in the following.

4.2.2.1 SIMS

Satellite Irrigation Management Support (SIMS) is supported by NASA. In combination with the Terrestrial Observation and Prediction System (TOPS), also maintained by NASA, the SIMS objective is to provide field-scale data for crop cover, K_c, and ET_c for use in irrigation scheduling and water management. SIMS, unlike the other models described previously, does not compute actual ET_c, nor is it based on an energy balance approach. Instead, the method uses empirical approaches to compute the maximum expected daily ET_c based on a given set of plant cover conditions, referred to earlier as potential ET_c. Because of this, the method is prone to overestimation of actual ET_c in the case of irrigation practices such as deficit irrigation. One key advantage of SIMS over others such as METRIC and SSEBop is that SIMS can be more easily fully automated. This method is simple and straightforward compared to the energy balance approaches, requiring a less skilled data processor.

However, the simplicity of SIMS comes at the "price" of increased generality. It was developed particularly for irrigated agriculture in California. While still under development, to date, the primary application of SIMS has been in providing data to support irrigation management decisions in California's Central Valley, San Joaquin Valley, and North Coast. Data from the California Irrigation Management Information System serve as a primary dataset informing SIMS on reference evapotranspiration.

Additional information can be found in Melton et al. (2012).

4.2.2.2 PT-JPL

The Priestley-Taylor Jet Propulsion Laboratory (PT-JPL) algorithm is part of the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) mission carried out by NASA and is based on a reduced version of the Penman-Monteith equation. The approach is based on earlier methods that were designed for extensive and full-cover surfaces that are generally not water limited. This simplified representation does not require inputs related to stomatal and aerodynamic resistances. Similar to Penman-Monteith, the initial output from PT-JPL is related to potential ET, or evapotranspiration under zero water stress/limitations. To obtain actual ET_c, a unique factor (0 to 1) is applied to convert potential ET to actual ET_c based on atmospheric moisture, surface temperature, and vegetation indexes. PT-JPL relies on input variables, including R_n, near surface air temperature, water vapor pressure, and surface reflectance. While the method is simple, there is a large dependence on the empirical factor operated by PT-JPL.

Additional information can be found in Fisher et al. (2008).

4.2.3 Aerial Crop Surveys with Crop Coefficients

ET_c at the basin scale has historically been assessed in Utah using a combination of aerial irrigated lands delineations coupled with ground-based crop survey information to estimate irrigated area by crop within a specified area. This information is then coupled with ground-based meteorological data from weather stations and crop coefficients to estimate the total ET_c and depletion. Methods used by Utah and other Upper Colorado River basin states to manage water use from the Colorado River are summarized in URS et al. (2013).

Common limitations of this method include inaccuracies associated with ground-based crop surveys, such as periodic survey availability, and limited site-specific management data, such as crop rotations, intercropping, and deficit irrigation; inaccuracies associated with sparse weather station data in some locations; and inaccuracies associated with use of crop coefficients that do not account for site-specific management and water stress.

4.2.4 Remote Sensing Data Delivery Platforms

A key consideration in the evaluation and selection of remote sensing methods is the method by which producers, water managers, and government agencies can access and implement the methods. These methods vary in complexity and require varying degrees of expert interaction. It is recommended that each method be implemented either by qualified experts or via an automated delivery platform that is well documented to specify step-by-step calculation methods.

In many cases, ET_c products produced by satellite-based remote sensing are housed on public sites for access by users. An example is the housing of all ET_c data produced by the University of Idaho for southern Idaho using the METRIC model by the Idaho Department of Water Resources (https://data-idwr.opendata.arcgis.com/pages/gis-data).

This section provides a brief overview of two potential delivery platforms.

4.2.4.1 Expert Processing

Although many of the remote sensing methods have been validated under a range of applications and the intent is to develop them for widespread use, all methods require multiple steps of data acquisition and data processing/calculation and, in many cases, expert judgement and awareness. As a result, remote sensing estimates of ET_c are typically only developed by researchers and trained professionals. Each method is benefited by the oversight and review of the developer, a researcher, or trained professionals who have an in-depth understanding of the underlying science, input data, methodology, and potential shortcomings of the methods to process and interpret the data and implement the method. These individuals or groups can be contracted to perform these services, but the availability of qualified individuals or groups can still be a limiting factor for widespread use.

4.2.4.2 OpenET

OpenET is a collaborative effort by multiple research institutes, government agencies, and private foundations with a long-term goal of testing ET models, lowering their cost, and increasing the accessibility of ET data for producers and water managers across 17 western states, including Utah. Unlike the remote sensing methods described above, OpenET is not in and of itself a unique method or model but instead provides a user access to actual ET_c estimates using multiple models for a given area (approximately 0.22 acre at its current resolution). The collection of methods currently includes ALEXI/DisALEXI, METRIC, PT-JPL, SEBAL, SIMS, and SSEBop. The anticipated launch date is 2021 and will use a web-based platform and user interface to disseminate ET data to users. OpenET researchers hope to improve upon each method after conducting an intercomparison study that will determine the best model or combination of models for locations, crop types, and seasons. Both their short-term and long-term goals also require many more validation checks with "best available" ET measurements. Additional information can be found at www.etdata.org.

4.3 Methods for Depletion Accounting

The full accounting for depletion often requires the application of multiple measurements or cross checks to estimate actual ET_c and the portion of ET_c representing actual depletion from applied water (represented as ET_{aw}) (see Section 2.1). As shown in the depletion equation (Section 2.1), precipitation and soil moisture must be accounted for to better distinguish depletions (ET_{aw}) from total ET_c. The following section describes two commonly found field conditions and their associated assumptions related to determining the depletion of applied water (ET_{aw}).

4.3.1 Well-drained Sites Without Crop Access to Shallow Groundwater

For well-drained sites without crop access to shallow groundwater, reducing the measured actual ET_c by the calculated effective precipitation (P_{eff}) is the most common approach to calculating actual depletions. The most common estimates of P_{eff} include the Soil Conservation Service (SCS) method and the constant fraction method. However, a daily accounting of runoff and deep percolation is a more accurate, albeit more involved, procedure (Allen and Robison 2007; ASCE 2016).

For the SCS method (USDA-ARS 1970), a combination of monthly total precipitation and monthly total ET_c are used in the following equation:

$$P_{eff} = SF(0.70917\ P_{total}^{0.82416} - 0.11556)(10^{0.02426\ ET_c})$$

where:
P_{eff} = average monthly effective precipitation (inches)
P_{total} = monthly mean total precipitation (inches)
ET_c = average monthly crop evapotranspiration (inches)
SF = soil water storage factor

The soil water storage factor is defined by:

$$SF = (0.531747 + 0.295164\ D - 0.057697\ D^2 + 0.003804\ D^3)$$

where:
D = the usable soil water storage (inches)

P_{eff}/P_{total} fractions generally vary between 45 and 95 percent, with higher ratios associated with larger ET_c /P_{total} fractions. During typical irrigation season months, when ET_c /P_{total} fractions are greater than 3, P_{eff} is typically in the 70 to 90 percent range of P_{total}.

A simplified method based on the typical range of P_{eff} during the majority of the irrigation season is to use a constant P_{eff}/P_{total} fraction. For instance, in the UAES (1994) report used by the Utah Division of Water Rights for depletion estimates, P_{eff} was estimated as a constant 80 percent of P_{total}.

Application of all P_{eff} methods requires accurate precipitation measurements. Since local precipitation amounts can vary substantially in response to thunderstorms and other isolated events, local meteorological stations and careful analyses are necessary.

4.3.2 Sites with Crop Access to Shallow Groundwater

For sites with crop access to shallow groundwater, methods for depletion accounting are more difficult. If groundwater is providing a source of water for ET_c, then it must be quantified and separated from the portion of ET_c supplied by water from precipitation and irrigation. The most robust approach for depletion accounting on these sites is to evaluate ET_c of reference sites under the same groundwater, soil, and crop conditions with and without irrigation. An example of this type of application was presented by Cuenca et al. (2013) for irrigated pasture sites in the Klamath Basin of Oregon. Using Bowen Ratio measurements collected over an entire irrigation season (May 1 through Sep 30) at nearby paired sites, this study measured a total of 498 millimeters (mm) or 1.63 AFA of ET_c at the unirrigated site and 746 mm (2.45 AFA) of ET_c at the irrigated site. For this irrigated site, the depletion or ET_{aw} would be estimated as 248 mm (0.81 AFA) or less than 50 percent of the total ET_c. Studies like this one demonstrate how significant the difference between total ET_c and ET_{aw} can be for sites with crop access to shallow groundwater and the challenges in making accurate measurements.

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5. Evaluation of Methodologies

This section provides an overview of the process used and the results of the evaluation of the advantages and disadvantages of the different ground-based and remote sensing-based methods for application in Utah.

5.1 Evaluation Process

An Expert Panel was initially formed in November 2019 as part of a joint proposal to complete this project. The Expert Panel included subject matter experts from the research, academic, industry, and Utah water rights and water resources management sectors and was relied upon for their experience and expertise to identify the "best fit" methods for application in Utah. The Expert Panel included the following members:

- Niel Allen, PhD, PE, Utah State University
- Richard Allen, PhD, PE, Evapotranspiration Plus, LLC
- James Greer, PE, Utah Division of Water Rights
- Lawrence Hipps, PhD, Utah State University
- Craig Miller, PE, Utah Division of Water Resources
- Jason Smesrud, PE, CWRE, Jacobs Engineering Group Inc.
- Alfonso Torres-Rua, PhD, Utah State University

The facilitator and Project Manager for the Expert Panel was Jeff DenBleyker, PE, Jacobs Engineering Group Inc. and Aaron Austin, Utah Division of Water Resources, was the Task Force Project Manager for this project. Work by the Expert Panel on the project formally began in January 2020.

Figure 5-1 illustrates the evaluation process used to identify and evaluate methodologies and develop consensus around the Expert Panels final recommendations. Each element completed is summarized below.

1) **Workshop #1 – December 20, 2019.** Jeff DenBleyker met with the Task Force to review the proposed approach for this project (Figure 5-1), confirm the project objectives (Section 1), identify key criteria that the depletion accounting methods should address (Section 3), and desired outcomes (Sections 1, 2, and 3).
2) The Expert Panel was then tasked to identify suitable, available and emerging methodologies to measure and account for actual depletion and make recommendations for methods for application in Utah. Information was identified and discussed by the Expert Panel via email and telephone in preparation for Workshop #2.
3) **Workshop #2 – January 22, 2020.** This workshop served as an in-person kick-off meeting for the Expert Panel. Discussion initially focused on Task Force objectives and criteria for use in this project and led into an in-depth discussion about Utah water rights administration, the definition of depletion, and potential applications for depletion accounting in Utah. The Expert Panel discussed suitable, available and emerging methods and developed a shortlist of eight ground-based methods and three remote sensing methods to carry forward.
4) Input from Workshops #1 and #2 were integrated with information provided by the Expert Panel into an initial working draft report. The Expert Panel was asked to review the working draft document, provide corrections or additional information, and provide input on the various methodologies. The goal of this exercise was to verify that all information was correct and included in the evaluation and to stimulate a comparative analysis by each member, ultimately providing a framework for discussion at Workshop #3.

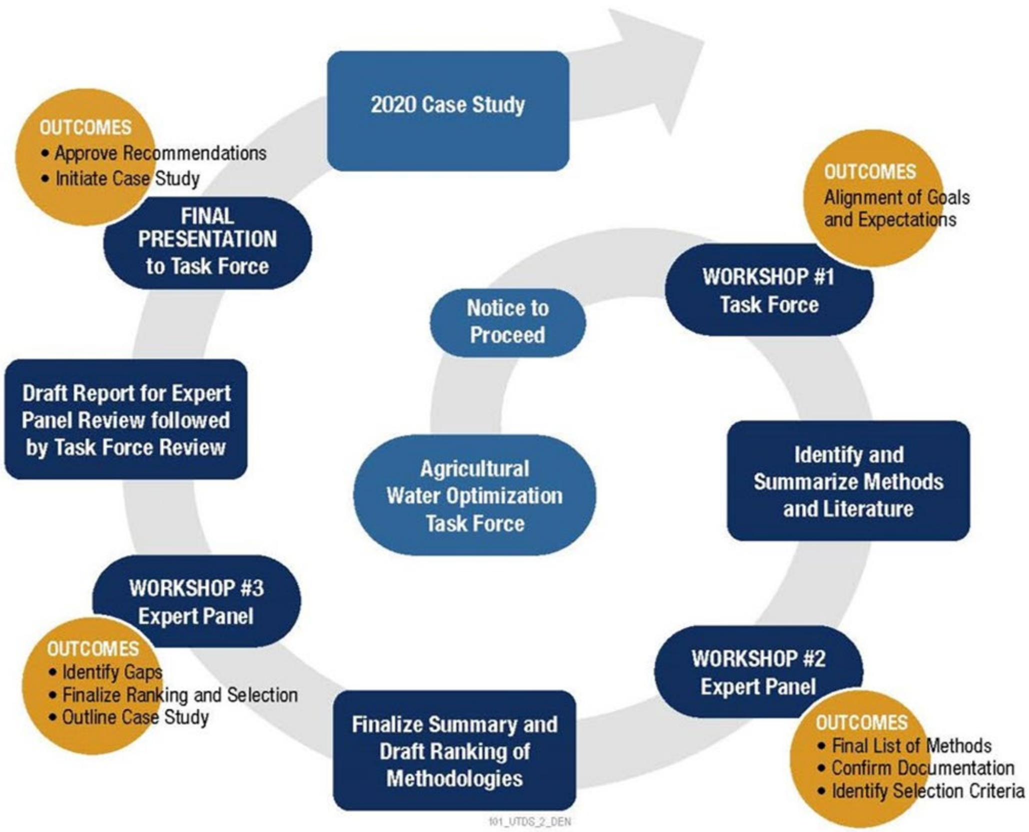

Figure 5-1. Approach for Identifying, Evaluating, and Providing Recommendations for Agricultural Depletion Accounting Methods in Utah

5) **<u>Workshop #3 – February 28, 2020.</u>** The final workshop reassembled the Expert Panel with the primary objective of making recommendations for methods to measure and account for actual depletion of agricultural water use in Utah and recommending a Case Study to validate the recommended methodologies for use in Utah. Discussion initially focused upon comments regarding the working draft document and then upon clarifying criteria for each of the three applications (Ground-based Methods for Field-scale Depletion Reporting, Ground-based Methods for Field-scale Depletion Validation, and Remote Sensing Methods for Field-scale to Basin-scale Depletion Assessment). The Expert Panel discussed gaps in the working draft document, a comparative analysis of the alternatives, the costs, and uncertainty associated with each of the alternatives before coming to a preliminary recommendation of methodologies for use in each of the three applications and to be validated in the Case Study. These included:

   a) Ground-based Methods for Field-scale Depletion Reporting

      i. Soil-Water Balance Method

      ii. Field Water Balance Method with Flow Measurement

   b) Ground-based Methods for Field-scale Depletion Validation

      i. Eddy Covariance Method

   c) Remote Sensing Methods for Field-scale to Basin-scale Depletion Assessments

      i. Multiple methods through the automated OpenET platform (including METRIC)

      ii. METRIC with manual operation

6) A complete draft report was prepared for Expert Panel and Task Force review and comment. The Expert Panel met via a web meeting on April 10, 2020 to finalize its recommendations for methodologies for use in Utah (Section 6) and for the Case Study for validation of those recommendations (Section 7). A final report was then submitted to the Task Force for final review and approval.

5.2 Evaluation Results

Table 5-1 provides a comparison of estimated equipment costs and level of effort for annual monitoring and maintenance for the ground-based methods. A similar cost comparison table for remote sensing methods is not provided since the OpenET platform will be very low in cost and an independent METRIC analysis was unanimously selected by the Expert Panel for inclusion in the case study. Tables 5-2 and 5-3 present the advantages and disadvantages of the ground-based and remote sensing methods, respectively, that were discussed at the workshops. Table 5-4 is also provided to summarize the typical errors in estimation for several of the actual ET_c measurement methods as reported by Allen et al. (2011a). After the workshops, the Expert Panel and project team continued to evaluate and vet potential Case Study methods through additional email and phone correspondence. A final recommendation is discussed in detail in Section 6.

Table 5-1. Estimated Equipment Costs and Level of Effort for Ground-Based Methods

Ground-Based Method	Estimated Equipment Cost (±50%)	Estimated Annual Monitoring & Maintenance (hours)	Notes
Agro-Meteorological Station	$9,000	100	Includes a standard agro-met station with measurement of solar radiation, air temp, wind speed, humidity, rainfall, and soil temp/moisture. Includes ~1 hr/week to review data and 4hrs/month maintenance.
Lysimeter (temporary vs research grade)	$5,000-$100,000	120-250	Temporary vs research grade. Includes 1 day to reinstall 2X per year, 4hrs/month for maintenance, & 1 hr/week to review data OR, 3hr/week to review data and 8hr visit every month for maintenance.
Soil Moisture Station	$8,000	120	Includes 6 probes/nest and 3 nests plus tipping bucket raingauge. Includes 1 day/install 2X per year, 6 one day visits for maintenance, 1 hr/week to review data.
Field Water Balance with Flow Meters	$5,000	60	Includes one 12-inch magmeter for metering of a single 125-acre center pivot. Includes ~1 hr/week to review data and maintenance.
Bowen Ratio Station	$25,000	150	Includes BREB system with Rn and G measurement. Includes 2 hr/week to review data and 4hrs/month maintenance.
Eddy Covariance Station	$40,000	250	Includes EC system with Rn and G measurement and NDVI enabled field camera. Includes 3hr/week to review data and 8hr visit every month for maintenance.
Surface Renewal Station	$14,000	150	Includes Rn and G measurement - Does not include cost of EC use for calibration. Includes 2 hr/week to review data and 4hrs/month maintenance.
Scintillometer Station	$63,000	250	Includes large aperture dual-disk scintillometer with path reduction aperture (500-6000 m path length) and Rn and G measurement. Includes 3hr/week to review data and 8hr visit every month for maintenance.

Notes:

Costs are provided for a typical application with independent stand-alone installations for comparative purposes. Costs can be reduced when combining measurement methods at the same site by sharing certain equipment and measurements.

All station costs include equipment for remote monitoring via cell phone connection.

Actual costs can vary +/- 50% or more from estimates shown so are not budgetary estimates.

Assumes 12 months of operation.

Travel costs are not included.

Table 5-2. Advantages and Disadvantage of Ground-based Methods for Site-Scale to Field-Scale Applications

Method Description	Advantages	Disadvantages
Meteorological Measurements and Crop Coefficients	▪ Well known. ▪ Historically used by the Utah Division of Water Rights and Utah Division of Water Resources. ▪ Simple, easy to implement. ▪ Relatively low cost. ▪ Uses existing meteorological stations. ▪ Defensible at the basin spatial scale and annual time scales where field-to-field variability is averaged out and where customized K_c values exist.	▪ Does not measure actual ET_c; a critical objective for depletion accounting. ▪ May overestimate ET_c as potential ET_c is often greater than actual ET_c. ▪ Requires detailed crop management information (crop types, planting, and harvest/cutting dates) for accurate application. ▪ Method does not capture reduced ET_c from plant stress resulting from soil water deficits, pests/disease, fertility, soil compaction, and salinity. ▪ Difficult to estimate depletion under high water table conditions. ▪ Weather stations have a limited radius for validity. ▪ Does not calculate actual depletion (ET_{aw}) directly. ET_{aw} is determined from ET_c.
Weighing Lysimeter	▪ Well-known. ▪ High accuracy when properly constructed and maintained. ▪ The only direct measurement of ET_c from all ground-based methods.	▪ Available equipment is very expensive. ▪ Not always representative of field-scale conditions. ▪ Lysimeter designs are often limited to certain crops. ▪ Interferes with farming operations. ▪ High groundwater tables can pose problems. ▪ High physical maintenance requirements. ▪ Difficult to move or relocate equipment. ▪ Does not calculate actual depletion (ET_{aw}) directly. ET_{aw} is determined from ET_c.
Soil-Water Balance	▪ Well known. ▪ Can be used to independently measure actual ET_c and estimate depletion (ET_{aw}). ▪ Method can capture reduced ET_c from plant stress resulting from soil water deficits, pests/disease, fertility, soil compaction, and salinity. ▪ Relatively low cost compared to other ground-based direct measurements. ▪ Can work in high water table conditions with appropriate instrumentation. ▪ Can be installed to minimally interfere with farming operations.	▪ Multiple sites and sensor depths often needed to represent a field. ▪ Difficult to install correctly without soil disturbance. ▪ Is best suited for fields with high irrigation uniformities. ▪ May require custom calibration. ▪ Mostly limited to weekly or greater time scales.
Field Water Balance Using Flow Measurements	▪ Requires little instrumentation except for accurate flow and irrigated area measurement ▪ Provides estimates of ET_{aw} as equal to water deliveries for an entire field area under limited conditions where there are no appreciable deep percolation, runoff, or other water losses aside from crop consumptive use. ▪ Can be used in combination with soil moisture measurements to independently validate irrigation amounts and provide estimates of deep percolation.	▪ Does not measure actual ET_c; develops an estimate of ET_{aw}. ▪ Will tend to overstate ET_{aw} where unmeasured deep percolation or runoff occurs. ▪ Will tend to understate ET_c where ET from precipitation or shallow ground water occurs. ▪ Mostly limited to monthly or greater time scales.

Method Description	Advantages	Disadvantages
Bowen Ratio-Energy Balance Method	▪ Method can capture reduced ET_c from plant stress resulting from soil water deficits, pests/disease, fertility, soil compaction, and salinity. ▪ Can integrate latent heat fluxes over large areas (hundreds to thousands of square meters). ▪ Can estimate fluxes on fine time scales (less than an hour). ▪ Works in any surface with adequate size and uniformity. ▪ Can provide continuous, unattended measurements.	▪ Equipment for Bowen ratio stations may have limited availability due to limited suppliers currently manufacturing the equipment. ▪ Expensive, high maintenance. ▪ Sensitivity to the biases of instruments that measure temperature and humidity gradients. ▪ Possibility of discontinuous data when the Bowen ratio approaches -1. ▪ Degraded accuracy when latent heat flux is low (e.g., low ET_c conditions). ▪ Requirement, common to all micrometeorological methods, of adequate upwind fetch to ensure adherence to the assumptions of the method. ▪ Does not calculate actual depletion ($ET_{aw)}$ directly. ET_{aw} is determined from $ET_{c.}$
Eddy Covariance	▪ Current standard approach for site-scale measurement of actual ET_{c}. ▪ Method can capture reduced ET_c from plant stress resulting from soil water deficits, pests/disease, fertility, soil compaction, and salinity. ▪ Science efforts continue improving this method. ▪ Can integrate latent heat fluxes over large areas (hundreds to thousands of m^2). ▪ Can estimate fluxes on fine time scales (less than an hour). ▪ Works in any surface with adequate size and uniformity. ▪ Can provide continuous, unattended measurements.	▪ Expensive, high maintenance. ▪ Requires a careful selection of site and correct deployment of sensors. ▪ Requirement, common to all micrometeorological methods, of adequate fetch to ensure adherence to the assumptions of the method. ▪ A great deal of expert post processing required. ▪ Does not calculate actual depletion ($ET_{aw)}$ directly. ET_{aw} is determined from $ET_{c.}$
Scintillometers	▪ Similar to EC, but for extremely large fields. ▪ Similar performance as eddy covariance but simpler to operate and maintain. ▪ Provides a path-averaged estimated of actual ET_c over the length of the path to integrate measurements over relatively large areas. ▪ Method can capture reduced ET_c from plant stress resulting from soil water deficits, pests/disease, fertility, soil compaction, and salinity.	▪ Expensive. ▪ Complex to operate and maintain. ▪ Requires a careful selection of site. ▪ Not used alone; it is combined with local measurements of net radiation and soil heat flux and sometimes remote sensing datasets in addition to determine ET_c of a field/region. ▪ Does not calculate actual depletion ($ET_{aw)}$ directly. ET_{aw} is determined from $ET_{c.}$
Surface Renewal	▪ Inexpensive compared to other ground-based methods when short-cuts are taken to rely upon remote sensing-based estimates of R_n and G (not recommended for highest accuracy and reliability applications) ▪ Thermocouple field equipment is accessible, easy to operate, and low-cost. ▪ Data collection and processing is relatively straightforward. ▪ Missing data can be avoided by redundant installations of thermocouples (possible due to low cost). ▪ Can be applied to rough, nonhomogeneous surfaces and hilly fields.	▪ Method is still under development and not ready for widespread application for water rights management. ▪ Requires crop/surface specific calibration of sensible heat flux (H). ▪ Still most frequently requires an eddy covariance station for calibration at the site. ▪ Not suitable for high-humidity conditions. ▪ Thermocouples can be easily damaged by high-wind conditions or other physical disturbance. ▪ Does not calculate actual depletion ($ET_{aw)}$ directly. ET_{aw} is determined from $ET_{c.}$

Table 5-3. Advantages and Disadvantage of Remote Sensing Methods for Field-Scale to Basin-Scale Applications

Method Description	Advantages	Disadvantages
Energy Balance Methods	▪ These procedures can provide ET_c information at both the field- and basin-scales. ▪ Methods can capture reduced ET_c from plant stress resulting from soil water deficits, pests/disease, fertility, soil compaction, and salinity. ▪ Science behind the methods has matured to be used operationally. ▪ Its accuracy has been demonstrated in a number of case studies, and it has been defensible in court. ▪ Costs per acre become relatively inexpensive when ET from large areas is of interest.	▪ Relies on other ground-based data to adjust parameters (weather, soils, and land cover). ▪ Needs ground-based validation within a region to build confidence in the specific application of a model. ▪ Due to complex calculations and data processing, methods typically require trained professionals to implement. ▪ Does not calculate actual depletion ($ET_{aw)}$ directly.. ET_{aw} is determined from ET_c .
Vegetation Index Methods	▪ This procedure can provide ET_c information at both the field- and basin-scales. ▪ Method can capture reduced ET_c from plant stress resulting from soil water deficits, pests/disease, fertility, soil compaction, and salinity to the extent that these factors occur over extended periods so that they affect plant leaf area over time. ▪ Easier than most energy balance methods to fully automate; does not require as skilled of data processor.	▪ Requires knowledge of crops being grown. ▪ Method does not capture real-time effects of reduced ET_c from soil water stress. ▪ Relies on other ground-based data to adjust parameters (weather, soils, and land cover). ▪ Needs ground-based validation within a region to build confidence in the specific application of a model. ▪ Does not calculate actual depletion ($ET_{aw)}$ directly.. ET_{aw} is determined from $ET_{c.}$
Aerial Crop Surveys with Crop Coefficients	▪ Well known. ▪ Historically used by the Utah Division of Water Rights and Utah Division of Water Resources. ▪ Simple, easy to implement. ▪ Relatively low cost. ▪ Uses existing meteorological stations.	▪ Method does not capture reduced ET_c from plant stress resulting from soil water deficits, pests/disease, fertility, soil compaction, and salinity. ▪ Relies on independent knowledge of crops being grown and irrigated areas. ▪ Inaccuracies associated with ground-based crop surveys, such as periodic survey availability, and limited site-specific management data, such as crop rotations, intercropping, and deficit irrigation. ▪ Difficult to estimated depletion under high water table conditions. ▪ Weather stations have a limited radius for validity. ▪ Does not calculate actual depletion ($ET_{aw)}$ directly.. ET_{aw} is determined from $ET_{c.}$

Table 5-4. Typical Errors Expected for Various Types of Actual ET_c Measurement System

Method	Typical Combined Processing and Equipment Error (%)	Analysis Error for Experienced Expert, Trained and Steeped in Physics of Process (%)	Analysis Error for Novice or Person Working Outside Specialty Area (%)	Additional Error Caused by Physical or Equipment Malfunction (%)
Weighing Lysimeter	5-15	5	20-40	5-40
Soil-Water Balance	10-30	10	20-70	10-40
Bowen Ratio-Energy Balance	10-20	10	20-50	5-40
Eddy Covariance	15-30	10-15	30-50	10-40
Scintillometers	10-35	10-15	20-50	5-30
Remote Sensing Using Energy Balance Methods	10-20	5-15	30-40	5-10
Remote Sensing Using Vegetation Index Methods	15-40	10-30	20-40	5-10

Source: Allen et al., 2011a

Note: Errors are expressed as one standard deviation from the true mean value.

6. Recommendations

Numerous ground-based and remote sensing methods for estimating 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. 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 the criteria listed in previous sections of this report 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.

This section provides an overview of the Expert Panel's final recommendations for depletion accounting methods and how they might be implemented in Utah to measure and account for actual depletion by agriculture.

6.1 Recommended Methods for Measuring Actual Crop Evapotranspiration by Depletion Accounting Application

The three primary depletion accounting applications assessed in this project were Ground-based Methods for Field-scale Depletion Reporting, Ground-based Methods for Field-scale Depletion Validation, and Remote Sensing Methods for Field-scale to Basin-scale Depletion Assessments. Figure 6-1 illustrates the recommended depletion accounting methods for each of these three applications. A summary of the final recommendations for selection of the most appropriate ground-based methods (i.e. Applications 1 and 2) is presented in Table 6-1. Further discussion of the recommendations and potential applications is provided in the following sub-sections.

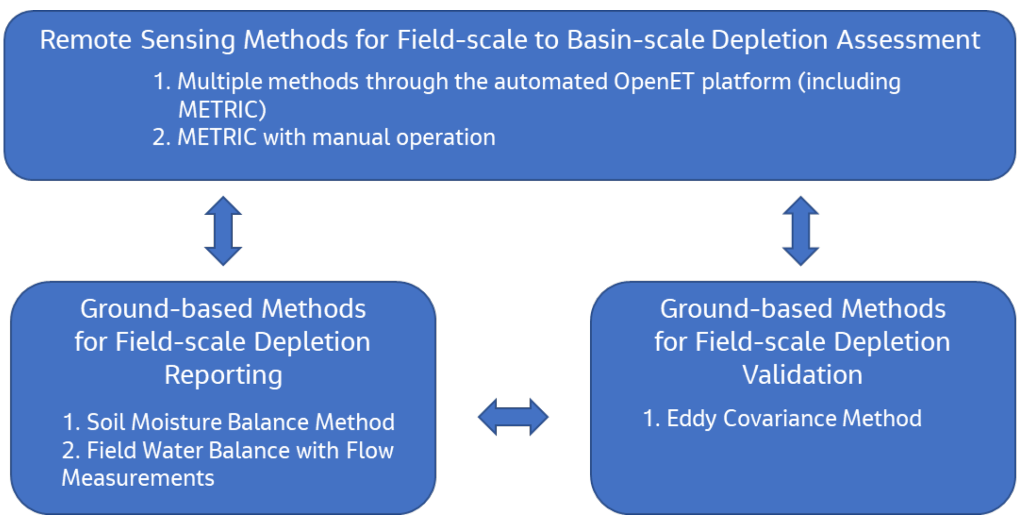

Figure 6-1. Recommended Layered Approach and Depletion Accounting Methods for Use in Utah

Table 6-1. Recommendations for Ground-Based Methods by Depletion Accounting Application

Method Description	Ground-Based Methods for Field-Scale Depletion Reporting	Ground-Based Methods for Field-Scale Depletion Validation
Meteorological Measurements and Crop Coefficients	Not Recommended. Does not measure actual ET_c.	Not Recommended. Does not measure actual ET_c.
Weighing Lysimeter	Not Recommended. High cost of installation and maintenance.	Not Recommended. High cost of installation and maintenance.
Soil Water Balance	Recommended. Widely used in irrigation industry and capable of measuring actual ET_c accurately on weekly intervals and estimating ET_{aw}.	Not Recommended. Not suitable for precise instantaneous to daily interval ET_c measurement desired for remote sensing validation.
Field Water Balance Using Flow Measurements	Recommended (where conditions allow). Suitable for ET_{aw} estimates under limited field conditions with no appreciable deep percolation, runoff, or other water losses.	Not Recommended. Does not measure actual ET_c.
Bowen Ratio-Energy Balance Method	Not Recommended. High cost of instrumentation and complexity.	Not Recommended. Challenges with equipment procurement and low ET_c measurement.
Eddy Covariance	Not Recommended. High cost of instrumentation and complexity.	Recommended. Most widely accepted method for accurate ground-based measurement of actual ET_c.
Scintillometers	Not Recommended. High cost of instrumentation and complexity.	Not Recommended. High cost of instrumentation.
Surface Renewal	Not Recommended. Still under development and requires eddy covariance measurements for calibration.	Not Recommended (as stand-alone). Still under development and requires eddy covariance measurements for calibration.

6.1.1 Ground-Based Methods for Field-Scale Depletion Reporting

Purpose: These methods should be suitable for use by water users in 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 is accessible on the market and may be implemented directly by the water user or with the assistance of a consultant.

With the approval of a water right change application, the Utah Division of Water Rights requires that a user measure and report their diversions and their depletions to verify compliance with the revised water right conditions. The Expert Panel recommends that monitoring of diverted and applied water continue as a foundation for quantifying agricultural water use. While flow measurements to report diversions and applied water volumes are relatively straight-forward, measuring actual depletion (ET_{aw}) requires more sophisticated measurements and analysis. It is the goal of the Task Force and the Utah Division of Water Rights to identify equipment and develop standard procedures for depletion reporting that are reliable and accurate but are also cost-effective and can be readily implemented by agricultural producers.

In evaluating the purpose and goals of this application, the Expert Panel narrowed the recommended solutions down to two primary ground-based methods for depletion reporting: 1) Soil water balance; and 2) Field water balance using flow measurements. Both of these methods use equipment and approaches already widely used in the irrigation industry. The first method is capable of accurately measuring actual ET_c on weekly intervals and estimating ET_{aw}. The second method is capable of estimating ET_{aw} under restricted conditions when there is no appreciable runoff, deep percolation, or other water losses.

Other more accurate but more expensive and complicated methods were not recommended for this application but could be used if a producer is willing to invest and partner with qualified experts to implement the methods.

6.1.2 Ground-Based Methods for Field-Scale Depletion Validation

Purpose: These methods are required for validating or ground-truthing results provided by basin-scale methods (i.e., remote sensing methods) and may be used for validating or ground-truthing results reported by water users. These methods therefore 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.

Remote sensing methods can be used to both measure actual ET_c at the field scale and basin scale and to validate actual ET_c values reported at field scale by agricultural producers. Results from various remote sensing methods and data processing approaches, however, must also be validated to maximize confidence in these methods. An independent, accurate, and precise method is needed to validate the actual ET_c values reported from remote sensing methods. The validation measurements can also be made independently, as needed, to validate the accuracy of ground-based methods used by producers for depletion reporting.

The Expert Panel discussed several ground-based methods that could provide the requisite high level of confidence for field-scale depletion validation. Methods such as lysimeters, scintillometers, BREB method, and EC method are all proven to provide accurate and precise results. The EC method, however, rapidly rose to the top of the list and was recommended by the Expert Panel for use in field-scale depletion validation in Utah. The EC method is expensive and complex, but it provides best-in-class accuracy and is the most widely used method for calibrating other methods or validating their results.

The Task Force recommends that EC stations be strategically placed in Utah to validate basin-scale results from remote sensing methods, and thereby, also indirectly validate field-scale results from ground-based methods implemented by producers. A network of EC stations, if representative of field-crop-water stresses found in co-located basins, would be invaluable in providing accurate ground-based data for calibrating and validating remote sensing methods.

6.1.3 Remote Sensing Methods for Field-Scale to Basin-Scale Depletion Assessment

Purpose: These methods focus on the ability to 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 recognizes that there is significant interest in managing water rights by depletion, and implementation of the approach could expand rapidly. A remote sensing solution is required that can measure actual ET_c at the field-scale and across entire basins to independently confirm and provide accountability for actual depletion reported by producers. Remote sensing methods will provide the added benefit to individual producers of the option to choose, as an alternative to implementing their own ground-based method, to use results from remote sensing to manage their water rights. Basin-scale data provided by remote sensing methods will also provide the significant benefit to planners and managers of providing accurate quantification of actual depletion for planning, reporting, and protecting basin water resources.

Several remote sensing methods were evaluated by the Expert Panel, each having its own advantages and disadvantages. The OpenET 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 sensed, actual ET_c measurements directly to producers and water managers at very low cost. As an automated and still evolving platform, interpretation of results by experts is still needed for maximum confidence. Thus, the Expert Panel also recommends that the State of Utah implement METRIC directly by expert users and compare those results with results from the automated METRIC and other automated methods available within OpenET. METRIC is widely used when a defensible field-scale and basin-scale solution is required, especially in the western United States. The combination of evaluating multiple automated remote sensing methods available within OpenET and a comparison of automated and expert-processed METRIC methods provides the Utah Division of Water Rights with an option to directly implement an accurate remote sensing solution while positioning itself for the evolving automated OpenET.

6.2 Recommendations for Depletion Accounting

The full accounting for depletion often requires the application of multiple measurements or cross checks to estimate actual crop ET and the portion of ET representing actual depletion from applied water. The Task Force recommends the following to facilitate the translation of actual ET_c into actual depletion (ET_{aw}) and provide validation of the assumptions and calculations required to do so:

1) Maintain a robust network of meteorological stations throughout Utah, particularly in basins where there is significant irrigation water use. Determination of reference ET and local precipitation measurements is still an invaluable tool for managing water resources and can provide an additional cross-check to measurements of actual ET_c and $ET_{aw.}$
2) Maintain a network of groundwater monitoring wells to confirm groundwater levels and conditions at or near sites where water rights are managed by depletion.
3) Require the measurement and reporting of flow measurements at diversions and points of application to the parcel (shared canal lateral recordings, if available, will not work unless a regimented rotation scheme per parcel is implemented). This information will provide an estimate of ET that can be compared to a more robust water balance and measures of actual ET_c and ET_{aw}.
4) Maintain a robust database to house the information from these methods and make the data freely available to water users.

6.3 Proposed Case Study

The Expert Panel recommends that the Task Force develop, fund, and implement a Case Study to examine and validate the recommended ground-based and remote sensing methods for measuring and estimating actual depletion (ET_{aw}) and framework for application of depletion accounting methods. The proposed Case Study is outlined in the next section.

Upon validation of the recommended methods by the Case Study, the State of Utah should identify equipment and potential funding sources and develop standard operating procedures, documentation, and training for use by producers and water managers to implement the methods for measuring actual crop evapotranspiration and depletion accounting.

7. Proposed Case Study

One of the central objectives of this project was to outline a proposed Case Study with the objective of validating the recommendations presented in this report and providing data that the Utah Division of Water Rights can use in establishing procedures for managing water rights by depletion. This Section provides a proposed framework for the Case Study. The framework follows the U.S. Environmental Protection Agency's (EPA) Data Quality Objectives (DQO) process (Figure 7-1). The DQO process is used for systematic planning and is helpful in studies where experimental data is used to select between various alternatives (EPA 2006).

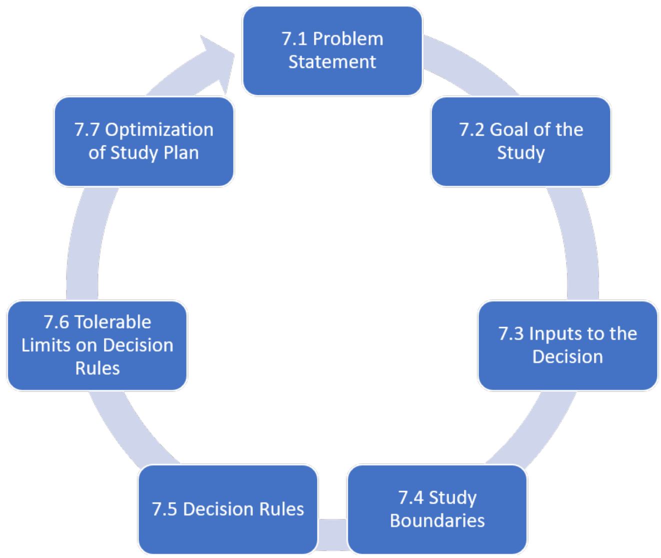

Figure 7-1. Data Quality Objectives Framework for the Agricultural Depletion Accounting Case Study

7.1 Problem Statement

7.1.1 Background and Purpose

This project was identified as a high priority by the Legislative Agricultural Water Optimization Task Force (Task Force) following review of initial results from its 2019 Research Program and in response to inquiries received by the Utah Division of Water Rights from water users around the state. Accurate measurement and accounting of available water supplies, demands, and actual water consumption was identified by the Task Force as a critical step toward protecting and enhancing Utah's agricultural economy and water resources in light of the increasing demands for Utah's limited water resources. Accurate and timely monitoring of water supplies, demands, and consumption and forecasting of conditions provide producers and water managers with the knowledge to make informed decisions. Informed decisions lead to better results and innovation that improves the sustainability of Utah's water supply and the profitability of Utah's agricultural operations. The Case Study works to validate recommended methodologies to measure and account for actual depletion of agricultural water use in Utah and provide data that the Utah Division of Water Rights can use to establish procedures for managing water rights by depletion.

7.1.2 Description of the Problem

Limited water resources in some basins in Utah are encouraging producers to investigate and implement methods to reduce their diversions or depletions. New laws are being developed and proposed by the Legislature to provide new 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 also created new opportunities for producers to optimize water productivity and maximize their yields and revenues. Managing diverted water by depletion rather than by duty and acreage could allow some producers to expand their acreage and irrigate with the same or less volume of water. Taken together, producers have significant incentive to innovate and have asked the Utah Division of Water Rights to consider new means of administering their water rights by depletion rather than the historic method of irrigation diversion duty and number of acres irrigated.

Administering irrigation rights by depletion requires accurate, effective, and defensible means to measure and account for actual depletion of applied water (ET_{aw}). With numerous available and emerging methodologies to do so, the Utah Division of Water Rights sought to evaluate and identify the most practical, effective, and defensible means for measuring and accounting for actual depletion of applied water in Utah. Combined with the stated objectives and needs identified by the Legislature and Task Force, the Utah Division of Water Rights' pressing need provided the requisite synergy to initiate this project. The purpose of the project was to evaluate potential depletion accounting methods, recommend methods for use in Utah, and outline a proposed Case Study that could be used to validate the recommendations of the project and to further define recommended depletion accounting approaches for use by the Utah Division of Water Rights.

7.1.3 Planning Team and Decision Makers

The Task Force will oversee the Case Study with the assistance of the Utah Division of Water Rights and Utah Division of Water Resources. The Task Force is 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 will contract with a selected contractor for execution of the Case Study and provide administrative support.

7.1.4 Study Partner

The Task Force, working with the Utah Division of Water Rights and the Utah Division of Water Resources, has identified a water user willing to participate in the Case Study. Holt Farms, located in the Escalante Valley (Figure 7-2) of southwest Utah (New Castle, Enterprise, and Beryl), has requested that the Case Study be performed on two adjacent, center-pivot irrigated fields that are part of their operation.

Agreements for site access and completion of the work for the Case Study will be acquired and maintained by the State of Utah. The contractor(s) will be required to actively coordinate with Holt Farms throughout execution of the Case Study per the State's agreements and to maximize the success of the study.

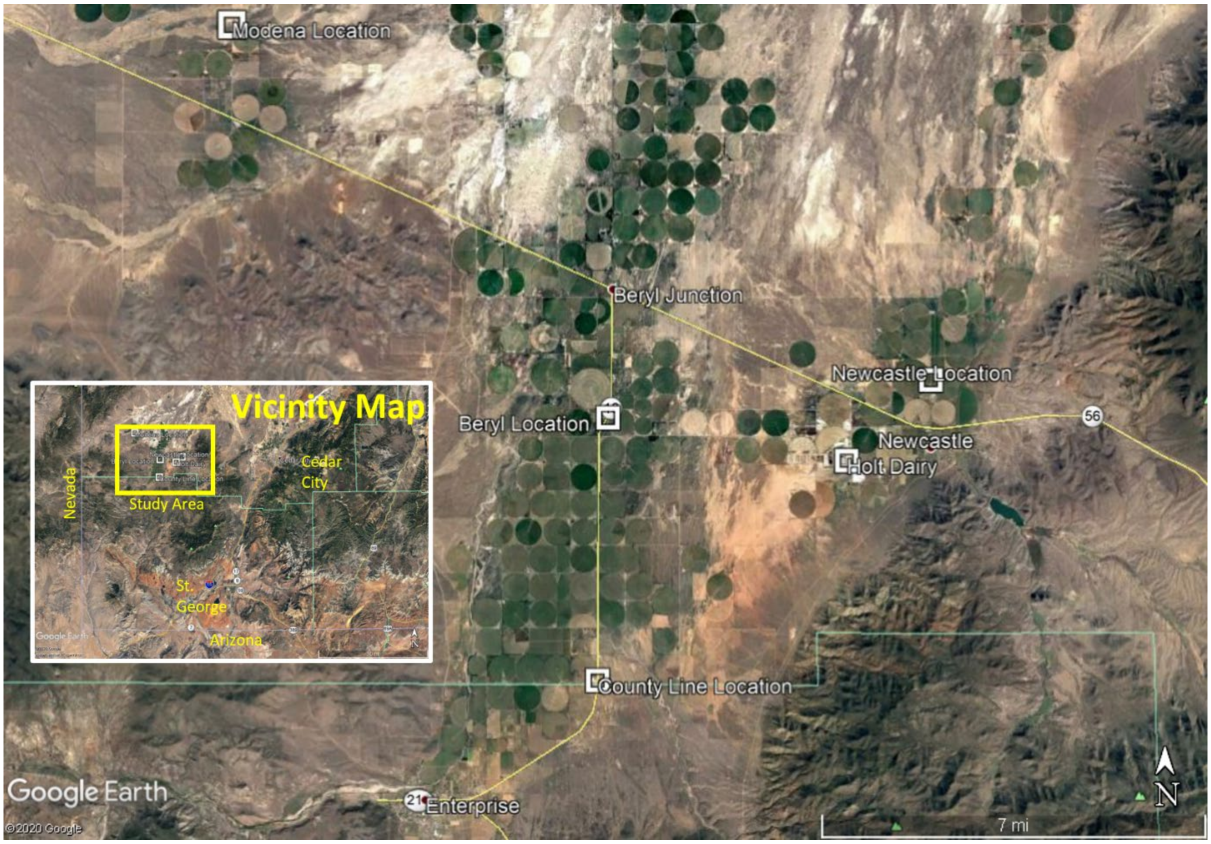

Figure 7-2. Location of Holt Farms near New Castle, Enterprise and Beryl Junction, Utah

7.1.5 Case Study Phasing

The Task Force's goal for the Case Study is to implement a pilot study during one growing season, April 1 through October 30. An added goal of Holt Farms is to compare the annual actual depletion of one field planted with alfalfa to an adjacent field double cropped with corn from May through September and triticale from October through May. An added benefit of conducting the study over this extended period will be multiple years of data and an evaluation of double cropping as a means for agricultural water optimization. Holt Farms will work with the Task Force to complete the Case Study in two phases spanning from May 2020 through December 2021.

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

Niel Allen, PhD, and Utah State University (USU) will be contracted by the Task Force to complete the following studies from May 2020 through October 2021:

1) Evaluate Meteorological Measurements and Crop Coefficients method. Install, operate, and maintain a meteorological station from May 2020 through October 2021. The station will be installed, operated, and maintained by USU to measure solar radiation, wind speed, air temperature, relative humidity, and precipitation at the study site on Holt Farms for the Phase I study period. The ASCE Penman-Monteith method (ASCE 2005) will be used to estimate reference ET rates using crop coefficients.
2) Evaluate Soil Water Balance method. Install, operate, and maintain three soil water balance stations on each of the two center-pivot irrigated fields from May 2020 through October 2021. Each station will include six

soil moisture sensors at 3-, 6-, 12-, 24-, 36-, 48-, and 72-inch depths. All six stations will be installed in May 2020. The three stations in the alfalfa field will be left in the field through October 2021. The three stations in the corn/triticale field will be demobilized in September 2020, when corn is harvested; re-installed in October 2020, after triticale is planted; demobilized in May 2021, when triticale is harvested; re-installed in May 2021, when corn is planted; and then removed in October 2021, when corn is harvested.

3) Evaluate Field Water Balance method. The Holt Farms has already installed magnetic flux flowmeters with data loggers on each of the two center-pivots and has flowmeters on its groundwater wells. USU will independently verify the accuracy of the Holt Farms' flowmeters to validate reported flow data.

4) Other measurements and data collection. USU will evaluate site soils to verify Natural Resources Conservation Service (NRCS) soil survey maps for the study site. USU will remotely monitor the soil water balance stations and make three site visits per year to maintain the systems. USU will have AggieAir fly the fields once in 2020 to gather remotely sensed data from the fields. Holt Farms will provide USU with local groundwater well monitoring data (groundwater levels are expected to be greater than100 feet deep) and a schedule of agronomic and irrigation methods used on both fields.

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

Phase II of the Case Study will involve the additional ground-based methods for depletion validation and retroactive analysis of remote sensing data. This phase of the study will include installation, operation, and maintenance of eddy covariance and surface renewal data collection systems for at least the period of April through October 2021, but preferably January through October 2021. Phase II will include analysis of ground-based data collected in both Phase I and II and remote sensing data for the period of May 2020 through October 2021. The contractor for Phase II will validate and analyze all data and compare all depletion accounting methods used in Phases I and II and will submit a final report summarizing the overall Case Study's methods, assumptions, results, observations, and recommendations.

7.1.6 Available Resources

The Task Force will fund the Case Study with monies appropriated under HB 381. The Case Study is envisioned to be completed by one contractor with one or more principal investigators. The contractor will coordinate, acquire and provide for the required installation, operation, maintenance, and removal of systems to collect the required data; manage, process, and evaluate the datasets; complete the required evaluations; provide the Task Force with recommendations for next steps; and document methods, assumptions, results, and recommendations in a report. Equipment and data will likely be acquired by the contractor for the Case Study but be owned by and transferred to the State of Utah after the Case Study is complete.

7.1.7 Relevant Deadlines

Niel Allen, PhD, and USU have already coordinated with Holt Farms, submitted a workplan to the Task Force, and will be under contract to begin installation of instrumentation in May 2020. An interim report for Phase I will be submitted to the Task Force by November 2021.

A contractor for Phase II will be selected by August 1, 2020. Project Kickoff will be in November 2020. Work planning and agreements will be completed by January 30, 2021. Equipment will be acquired and installed to allow field data collection to begin by April 1, 2021. Field data collection will be completed during April through October 2021, with a preliminary methods report submitted to the Task Force by January 30, 2022, and a complete draft report submitted to the Task Force by March 1, 2022. The final report will be due by June 1, 2022. All Phase II reports will incorporate results from the Phase I report submitted in November 2021.

7.1.8 Deliverables

It is assumed that the Task Force will require 3 weeks to review deliverables and provide meaningful comments. The primary deliverable for Phase I will be an interim report documenting methods, data, and findings submitted by November 2021. The following deliverables for Phase II are recommended:

1) Draft experimental Work Plan and Quality Assurance Project Plan (QAPP) – December 1, 2020
2) Monthly coordination meetings beginning in January 2021
3) Monthly progress reports beginning in January 2021
4) Final experimental Work Plan and QAPP – January 30, 2021
5) Three interim reports summarizing quality of field data and corrective actions taken
6) Draft Report summarizing field methods – January 30, 2022
7) Draft Report with results and recommendations – March 1, 2022
8) Final Report – June 1, 2022

7.2 Goal of the Study/Decision Statements

7.2.1 Goals

The primary goal of the Case Study is to implement a pilot study to validate recommended agricultural water depletion accounting methods for use in Utah. Results from the Case Study will ensure that the recommended methods provide the requisite tools for water users and the Utah Division of Water Rights to manage water rights by depletion rather than the historic method of irrigation diversion duty and number of acres irrigated.

An added goal of Holt Farms is to compare the annual actual depletion of one field planted with alfalfa to an adjacent field double cropped with corn from May through September and triticale from October through May. This will benefit the Task Force by providing an evaluation of double cropping as a means for agricultural water optimization.

7.2.2 Decisions

The principal question that the Case Study will answer is:

> *What are the most practical, effective, and defensible means for measuring and accounting for actual depletion of agricultural water in Utah?*

All work completed by this Case Study must be focused to answer the principal question above.

The Expert Panel developed a layered approach for the Case Study that identifies the most effective depletion accounting method for a given application while also providing validation of results from the other applications (Figure 7-3). The approach integrates the complementary applications to provide scalability and defensibility and to maximize value to water users, water managers, and the State of Utah over time. The Meteorological Measurements and Crop Coefficients method and Surface Renewal 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, are recommended components of the Case Study as they will provide inexpensive additional points of comparison to the other methods.

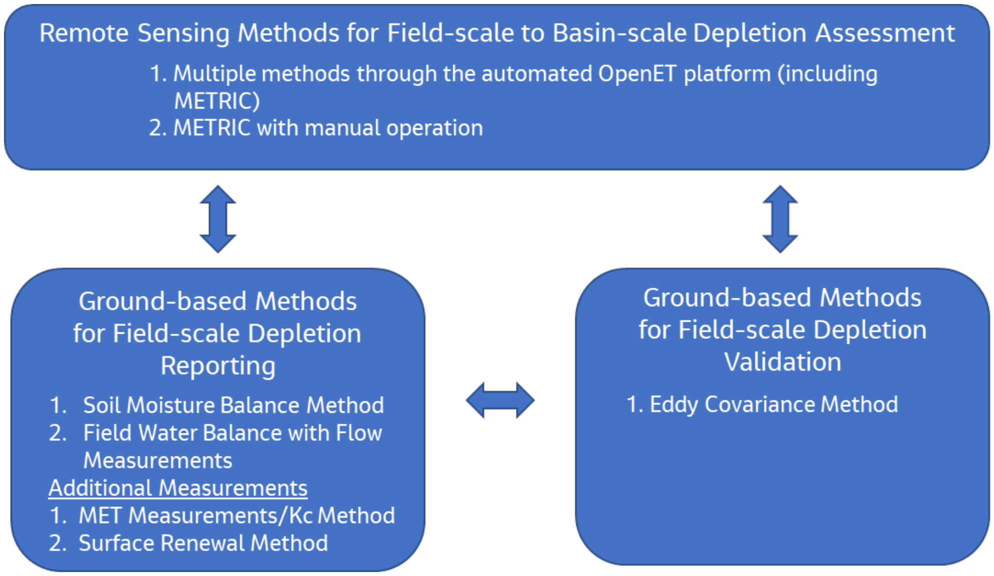

Figure 7-3. Recommended Layered Approach and Depletion Accounting Methods to be Validated in the Case Study for Use in Utah

This Case Study will seek to answer questions regarding:

1) The proposed methods to measure actual ET_c
2) The proposed methods for depletion accounting
3) Effects of site conditions on Case Study results
4) Recommendations to the State and water users

These questions are as follows:

7.2.2.1 Measuring Actual ET_c

Specific questions pertaining to the various methods for measuring actual ET_c include:

Ground-based Methods for Field-Scale Depletion Reporting

1) How practical, effective, and defensible is the Meteorological Measurements and Crop Coefficients method for estimating reference ET? How does it perform versus other ground-based methods? What are the limitations of this method? How does accuracy vary from field to field?
2) How practical, effective, and defensible is the Soil Moisture Balance method for measuring actual ET_c and estimating actual ET_{aw}? What is the best equipment and protocol for implementation of this method? How does the method perform versus ground-based validation measurements? What are the limitations of this method? How does accuracy vary from field to field?
3) How practical, effective, and defensible is the Field Water Balance Method with Flow Measurement for measuring ET_{aw}? What is the best equipment and protocol for implementation of this method? How does the method perform versus ground-based validation measurements? What are the limitations of this method? How does accuracy vary from field to field? Can ranges in expected error be established?

4) How practical, effective, and defensible is the Surface Renewal method for measuring actual ET_c and estimating actual ET_{aw}? What is the best equipment and protocol for implementation of this method? How does the method perform versus ground-based validation measurements when using 1) pre-calibration factors vs. calibration to the Case Study's EC results and 2) ground-based vs. remote-sensed measurements of R_n and G? What are the limitations of this method?

<u>Remote Sensing Methods for Field-Scale to Basin-Scale Depletion Assessment</u>

1) How practical, effective, and defensible are the automated remote sensing methods available within OpenET for measuring actual ET_c? How do each of the individual remote sensing methods with OpenET perform versus ground-based validation measurements? What are the limitations of this method? What are the best and most cost-effective means to validate the remote sensing methods locally and regionally?
2) How practical, effective, and defensible is the METRIC remote sensing method for measuring actual ET_c? How does it perform when fully automated (i.e., OpenET) versus completed by experts using site-specific meteorological station data? How does the method perform versus ground-based validation measurements? What are the limitations of this method?

<u>Ground-based Methods for Field-Scale Depletion Validation</u>

1) How practical, effective, and defensible is the Eddy Covariance Method for measuring actual ET_c? What is the best equipment and protocol for implementation of this method? What are the limitations of this method? What recommendations can be made regarding numbers of stations and replication to reduce uncertainties? How did results from duplicate net radiometers and 3D sonic anemometers compare?

7.2.2.2 Methods for Depletion Accounting

The full accounting for depletion often requires the application of multiple measurements or cross checks to estimate actual ET_c and the portion of ET_c representing actual depletion from applied water (see Section 4.3). The Case Study will address the following questions to document the full water budget and calculate the actual depletion during the study period. Despite the different time scales that each of the documented ground and remote sensing methods can provide, ET_c and water depletion will be reported at monthly scale due to P_{eff}.

1) What were the local meteorological conditions and how did they change throughout the study period? How did site-specific meteorological data vary from nearby meteorological stations.? What was the P_{eff}? What are the accuracies of the P_{eff} methods and estimates? How can estimates of P_{eff} be improved?
2) What was the diverted and applied flow volume and schedule for the study field(s)?
3) How did the local groundwater level change at the study site throughout the study period? Did shallow groundwater contribute to the ET_c?
4) What was the potential ET_c for the study field(s) using data from the local, study meteorological station?
5) What return flows occurred, either via groundwater or surface waters, during the Case Study?
6) What is the actual depletion (ET_{aw}) calculated for each of the recommended methods?
7) What is the range in uncertainty or error in the ET_{aw} estimates?

7.2.2.3 Site Conditions

Conditions at the study site throughout the study period are an essential element in interpreting the results.

1) What are the soil types and conditions at the study site(s)?

2) What are the site topography and drainage characteristics?
3) What tillage, crop type, planting, cutting, and/or harvest schedule were used in the study period? How typical were these practices and characteristics?
4) How did the vegetation condition change throughout the Case Study?
5) What were the yields from the study site during the Case Study? How do they compare to nearby fields with similar conditions or compared to previous years?

7.2.2.4 Method Evaluation

1) What were the costs and labor required to install, operate, and maintain the equipment and process the data for each method?
2) Can each method be effectively implemented (i.e., correctly installed, effectively maintained, and data correctly interpreted) by a water user or water manager? If not, with what assistance?
3) What are the challenges, costs, and labor required to install, operate, and maintain each station, process the data, and report final results for each method?
4) How does the actual ET_c and depletion (ET_{aw}) calculated using each method compare with each other? How do they compare with the actual ET_c measured using the Eddy Covariance Method? How do they compare with depletion estimated from potential ET_c?
5) What is and how can the uncertainty of each method's results be explained?
6) Is there a legal threshold for uncertainty in depletion accounting results? How do the results from each method compare with that threshold?
7) How do the results from this Case Study compare to those from similar studies?
8) Which methods are recommended for use for agricultural depletion accounting in Utah for each of the three different applications presented (e.g. ground-based methods for reporting at field scales, ground-based for validation at field scales, and remote-sensing based for field-to-basin scale applications)?

Specific management decisions will not be made with the data from this study; however, these data will be used to inform the Task Force and its recommendations.

7.2.3 Possible Outcomes

The study contractor should identify factors that could influence potential outcomes and develop a contingency plan to address each potential outcome. The following study outcomes are possible and should be considered by the contractor:

1) Data from all systems are collected at the specified time and with the appropriate quality.
2) Due to physical conditions at the site (e.g., equipment failure, site disturbance, extreme weather), complete data cannot be collected from the data collection systems during study period.
3) Significant changes in field conditions (e.g., water availability, farm operations, construction) may affect site operations and ground-based data collection systems and will require an evaluation and modification to this plan.
4) Resources (e.g., vehicles, equipment) malfunction, are not available, or do not allow for the investigator to complete the planned data collection and analysis.

5) Site conditions and resources are adequate to evaluate the performance of each depletion accounting method, and the necessary information provides the State with tools to manage water rights by depletion.
6) Information is not adequate to evaluate the performance of each of the depletion accounting methods; the investigator will work with the Task Force to evaluate options and make a final determination.

7.3 Inputs to the Decision

7.3.1 Informational Inputs

The Case Study will collect the following information during the study period for the study site(s):

1) One meteorological station to monitor meteorological conditions (solar radiation, air temperature, relative humidity, wind speed and direction, and precipitation) over a maintained reference crop surface.
2) Three soil moisture balance stations per field with adequate sensors (six per station) to monitor soil moisture to a depth below the estimated root zone or groundwater table.
3) Certified and professionally installed flowmeters to document diverted and applied water rates and volumes for each field. Flowmeter measurements made by the study partner will be independently verified by the study contractor.
4) One eddy covariance station located at the same site as the soil moisture balance and flow measurement stations (only one eddy covariance station for the entire study). The eddy covariance station should have two net radiometers and two 3D sonic anemometers, each from a different manufacturer, to provide redundancy and comparison of results from instruments made by different manufacturers.
5) Thermocouples will be added to and maintained with the eddy covariance station as a means to evaluate the Surface Renewal method.
6) Required remote sensing data to evaluate all automatically processed methods available within OpenET and the METRIC methods by both OpenET automated and expert-processed methods for the duration of the study period
7) Agronomic methods used within pilot study fields
8) Irrigation methods and schedule (e.g., timing, applied water flow rates, etc.)
9) Field runoff flow rates and volumes (water quality samples if possible)
10) Ground water level fluctuations
11) High-resolution aerial photo of the study site with topography
12) Soil properties including layering, organic matter, and amounts of surface mulch
13) Vegetation condition during the growing season
14) Estimated yields and value of crop at harvest
15) Planting and harvest dates and specific crop variety, including brand name and variety number
16) Costs for installation of all equipment and data collection systems
17) Tracking of labor to install, operate, maintain, and demobilize equipment and process and report results
18) Narrative describing operation and maintenance of irrigation and flow measurement equipment

19) Narrative of challenges encountered, and benefits obtained by the participant from installation and operation of equipment and use of results

7.4 Study Boundaries

7.4.1 Temporal

Phase I of the Case Study will be completed from May 2020 through October 2021, with its final report in November 2021. Phase II will be completed beginning in August 2020 through June 2022 (field studies to be completed April through October 2021). Work planning and agreements for Phase II will be completed by January 30, 2021. Equipment will be acquired and installed to allow field data collection to begin by April 1, 2021. Field data collection will be completed during April through October 2021, with a preliminary methods report submitted to the Task Force by January 30, 2022, and a complete draft report submitted to the Task Force by March 1, 2022. The final report will be due by June 1, 2022.

7.4.2 Spatial

The Case Study will be completed on two adjacent, center-pivot irrigated fields at Holt Farms (Figure 7-2). Holt Farms is willing to provide access to its fields and equipment and participate in data collection, analysis, and reporting in 2020 and 2021. All depletion accounting methods will be evaluated for the same two fields at Holt Farms. Holt Farms is located within current Landsat flight paths in an arid area of Utah that typically practices deficit irrigation. Figure 7-4 presents a hypothetical layout for the study site. The actual fields will be selected by Niel Allen, PhD/USU in conjunction with Holt Farms.

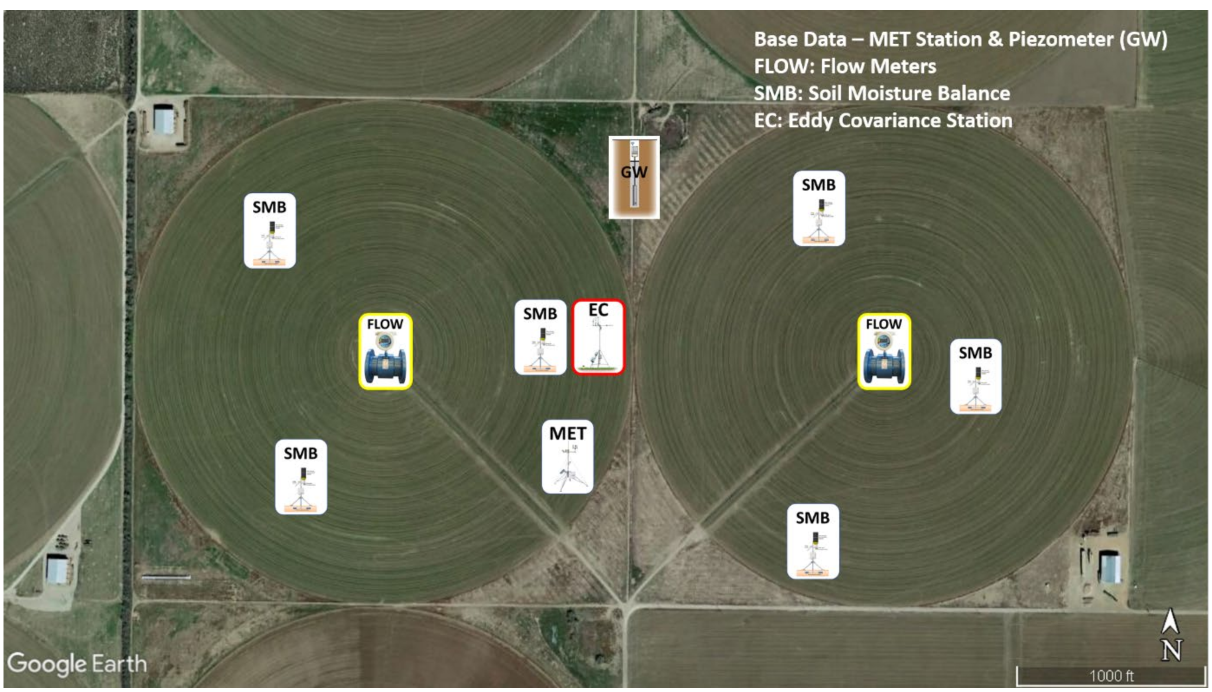

Figure 7-4. Hypothetical Layout for Ground-based Methods at the Study Site

7.4.3 Practical Constraints on Data Collection

The study contractor should identify potential challenges or constraints that could influence the success of the Case Study and develop contingency plans. The following are examples of potential constraints on data collection:

1) Availability of vehicles and field equipment, as well as equipment functionality, may limit some activities.
2) An inability to obtain access onto private property may limit ability to install, operate, and maintain equipment.
3) Weather is a major constraint for all field activities; storms can limit the ability to safely conduct installation, operations, maintenance, and data collection activities in the study area. Extensive cloudiness can limit the frequency and total number of clear Landsat images.
4) Equipment or site conditions may be damaged or altered by farm operations, lack of water, construction, weather, or other uncontrollable factors.
5) Data could be lost due to equipment malfunction or failure.
6) Required data for the analyses may not be available.
7) Availability of staff to complete required tasks.
8) State and Federal restrictions to travel and quarantine conditions.

7.5 Decision Rules

The study contractor should evaluate the criteria identified by the Expert Panel in this study, update the criteria with input from the Task Force, and use the criteria to evaluate the methods and provide the Task Force with recommended methods. Additional criteria could include:

1) Actual implementation cost of each method
2) Ease of and level of effort for implementation of each method
3) Applicability in different regions of Utah
4) Applicability for different groundwater conditions
5) Use for different applications in water rights management (e.g., ground-based methods for reporting at field scales, ground-based for validation at field scales, and remote-sensing based for field-to-basin scale applications)
6) Defensibility of results
7) Accuracy of actual depletion results as compared among methods and against the Eddy Covariance Method results
8) Uncertainty of results and source of that uncertainty

7.6 Tolerable Limits on Decision Rules

The study contractor should identify, evaluate, and recommend quality assurance and quality control requirements to the Task Force for approval prior to collecting data. A method to determine the uncertainty of method results should be developed. The study contractor should evaluate and recommend tolerable uncertainty limits for Task Force approval as part of the experimental work plan.

7.7 Optimization of Study Plan

After detailed consideration of reasonable alternatives, the following design is the most resource effective:

1) Two adjacent, center-pivot irrigated fields at Holt Farms for use in the Case Study will be identified by Niel Allen, PhD/USU and Holt Farms.
2) A location for installation of equipment will be selected after consultation with and approval of the Task Force prior to selecting a contractor.
3) Regular project meetings will be held with the Task Force to communicate progress, anticipate and address challenges, plan activities, and review results.
4) Regular communication with Holt Farms will be needed to facilitate coordination and proactively address concerns.
5) Active change management. Notify and discuss unexpected outcomes with Project Manager and Task Force as they happen; recommend adjustments or changes and/or request input from the Task Force; follow up with results from new approach and continue to adjust accordingly.
6) Collaborate with the Task Force to obtain input and to communicate/implement site safety and security measures.
7) Collaborate with the Task Force, Utah Division of Water Rights, and Utah Division of Water Resources for technical assistance and equipment and personnel to assist with installation and maintenance of the study site and collection of data.
8) Use trained personnel with oversight from study principal investigators to conduct installation, maintenance, and operation of site infrastructure and complete required measurements and evaluations.
9) Use established standard operating procedures in the field and office, accessible equipment and vehicles, and data management procedures.
10) Visit study site on a frequent basis to confirm the successful operation of equipment, document conditions, and maintain the site as necessary.
11) Evaluate data and results at regular intervals during data collection to identify and proactively correct potential problems.

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Appendix A
Example Consumptive Use Tables from Utah Agricultural Experiment Station's Research Report 145

Estimated Consumptive Use for the NWS Station at ST GEORGE
From a Calibrated SCS Blaney-Criddle Equation using data from ST GEORGE 10-14-1994
Years of Data Available; NWS: 1961-1990 ST GEORGE: 1987-1991 Elev. 2760 ft., Lat. 37.12

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
% Day Light	6.90	6.77	8.30	8.87	9.89	9.93	10.11	9.49	8.38	7.80	6.85	6.72	100.00
Avg Temp F	40.44	46.49	52.81	60.53	69.96	79.34	85.56	83.38	75.05	63.31	50.08	40.85	62.32
Std Dev Temp	3.11	3.05	3.10	3.41	2.83	2.58	1.62	2.09	2.83	2.89	2.15	2.91	1.16
Avg Prec in.	1.07	0.84	1.11	0.51	0.39	0.17	0.60	0.76	0.54	0.52	0.84	0.71	8.06
Std Dev Prec	0.98	0.75	1.07	0.63	0.49	0.22	0.45	0.66	0.58	0.66	0.71	0.70	2.69
SCS-BC f in.	1.09	1.55	2.64	3.95	6.21	8.35	10.09	8.93	6.20	3.87	1.90	1.09	55.88
Std Dev f	0.24	0.27	0.40	0.54	0.59	0.62	0.43	0.51	0.54	0.42	0.21	0.21	2.36
ALFALFA													
Cal SCS-BC k			0.93	1.18	1.16	0.97	0.82	0.81	0.88	0.83	0.20		
Cal SCS-BC Et			2.47	4.65	7.24	8.14	8.27	7.26	5.45	3.21	0.38		47.06
Std Dev Et			0.37	0.64	0.69	0.60	0.35	0.42	0.47	0.35	0.04		2.15
Net Irr in.			1.58	4.24	6.92	8.00	7.79	6.66	5.02	2.80			43.00
PASTURE													
Cal SCS-BC k		0.08	0.85	0.91	0.90	0.80	0.72	0.65	0.68	0.65	0.42		
Cal SCS-BC Et		0.12	2.26	3.59	5.61	6.68	7.28	5.82	4.25	2.50	0.80		38.89
Std Dev Et		0.02	0.34	0.49	0.53	0.50	0.31	0.33	0.37	0.27	0.09		1.75
Net Irr in.			1.37	3.18	5.29	6.54	6.80	5.21	3.81	2.08	0.13		34.42
SP GRAIN													
Cal SCS-BC k		0.32	0.95	1.36	1.35	0.34							
Cal SCS-BC Et		0.49	2.50	5.39	8.40	2.87							19.65
Std Dev Et		0.08	0.37	0.74	0.80	0.21							1.50
Net Irr in.			1.61	4.98	8.09	2.73							17.41
CORN													
Cal SCS-BC k				0.16	0.42	0.95	1.05	0.83	0.10				
Cal SCS-BC Et				0.62	2.58	7.95	10.58	7.45	0.65				29.83
Std Dev Et				0.08	0.24	0.59	0.45	0.43	0.06				1.27
Net Irr in.				0.21	2.27	7.81	10.10	6.84	0.22				27.45
ORCHARD													
Cal SCS-BC k			0.31	0.89	1.31	1.33	1.21	1.05	0.90				
Cal SCS-BC Et			0.81	3.50	8.13	11.09	12.19	9.38	5.56				50.65
Std Dev Et			0.12	0.48	0.77	0.82	0.52	0.54	0.48				2.31
Net Irr in.				3.09	7.82	10.95	11.71	8.77	5.13				47.46
TURF													
Cal SCS-BC k		0.08	0.84	0.78	0.78	0.69	0.62	0.56	0.59	0.56	0.36		
Cal SCS-BC Et		0.12	2.21	3.09	4.83	5.75	6.27	5.01	3.66	2.15	0.69		33.79
Std Dev Et		0.02	0.33	0.42	0.46	0.43	0.27	0.29	0.32	0.23	0.08		1.52
Net Irr in.			1.32	2.68	4.52	5.62	5.79	4.40	3.22	1.74	0.02		29.31
GARDEN													
Cal SCS-BC k			0.17	0.40	0.67	0.94	0.69	0.23	0.21	0.14			
Cal SCS-BC Et			0.45	1.57	4.15	7.85	6.95	2.03	1.31	0.54			24.84
Std Dev Et			0.07	0.22	0.39	0.58	0.30	0.12	0.11	0.06			1.19
Net Irr in.				1.16	3.84	7.71	6.47	1.42	0.87	0.13			21.60
E-LAKE													
Cal SCS-BC k	1.27	1.24	1.37	1.19	1.04	0.82	0.74	0.72	0.82	0.85	1.07	1.32	
Cal SCS-BC Evap	1.38	1.93	3.63	4.70	6.43	6.84	7.43	6.46	5.09	3.28	2.03	1.43	50.65
Std Dev Evap	0.30	0.33	0.54	0.65	0.61	0.51	0.32	0.37	0.44	0.36	0.22	0.27	2.25
Net Loss in.	0.31	1.09	2.52	4.19	6.04	6.67	6.83	5.70	4.55	2.76	1.20	0.72	42.58
ET Ref													
Cal SCS-BC k	1.41	1.38	1.53	1.40	1.39	1.23	1.11	1.00	1.05	0.99	1.19	1.46	
Estimated Etr	1.53	2.15	4.03	5.52	8.63	10.28	11.20	8.95	6.53	3.84	2.26	1.59	66.50
Std Dev Et	0.33	0.37	0.60	0.76	0.82	0.76	0.48	0.51	0.57	0.42	0.25	0.30	2.92

All Values are 30 Year Averages. Effective Precipitation is 80 Percent of Total During Growing Season
Blank values (if any) of ET Ref in early and late months denotes only seasonal calibration data
Adapted from Hill, 1994, Consumptive Use of Irrigated Crops in Utah, Ut Ag Exp Stn Res Rpt #145 Utah State Univ., Logan UT

Estimated Consumptive Use for the NWS Station at LOGAN UTAH ST U
From a Calibrated SCS Blaney-Criddle Equation using data from LOGAN 5SW / USU NF 10-13-1994
Years of Data Available; NWS: 1961-1990 LOGAN 5SW / USU NF: 1980-1989 Elev. 4790 ft., Lat. 41.75

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
% Day Light	6.61	6.61	8.27	8.98	10.15	10.25	10.41	9.67	8.41	7.67	6.60	6.39	100.00
Avg Temp F	23.43	28.48	36.99	46.23	55.47	64.40	72.94	71.37	61.23	50.04	36.93	25.67	47.77
Std Dev Temp	4.84	5.40	4.46	3.82	2.67	3.11	2.02	2.32	3.48	3.61	2.77	4.36	1.42
Avg Prec in.	1.38	1.65	2.02	2.15	2.04	1.57	0.78	0.97	1.62	1.87	1.73	1.72	19.47
Std Dev Prec	0.78	0.95	0.97	1.32	1.24	1.15	0.68	1.28	1.55	1.23	1.15	1.12	5.25
SCS-BC f in.	0.46	0.57	1.07	2.04	3.65	5.30	7.20	6.36	3.85	2.14	0.82	0.49	33.96
Std Dev f	0.10	0.12	0.29	0.44	0.44	0.62	0.47	0.48	0.53	0.39	0.14	0.08	1.85
ALFALFA													
Cal SCS-BC k				1.10	1.62	1.07	0.92	1.04	1.01	0.20			
Cal SCS-BC Et				2.25	5.92	5.65	6.61	6.60	3.90	0.43			31.35
Std Dev Et				0.49	0.71	0.66	0.43	0.50	0.54	0.08			1.87
Net Irr in.				0.53	4.29	4.39	5.99	5.82	2.60				23.62
PASTURE													
Cal SCS-BC k				0.85	1.03	0.94	0.77	0.77	0.80	0.49			
Cal SCS-BC Et				1.74	3.75	5.00	5.55	4.89	3.08	1.05			25.06
Std Dev Et				0.38	0.45	0.59	0.36	0.37	0.42	0.19			1.48
Net Irr in.				0.02	2.12	3.75	4.93	4.11	1.79				16.71
OTHR HAY													
Cal SCS-BC k				1.18	1.70	1.40	0.47	0.35	0.26	0.14			
Cal SCS-BC Et				2.41	6.19	7.41	3.36	2.22	0.98	0.30			22.88
Std Dev Et				0.52	0.74	0.87	0.22	0.17	0.14	0.06			1.68
Net Irr in.				0.69	4.57	6.15	2.74	1.45					15.59
SP GRAIN													
Cal SCS-BC k				0.27	0.96	1.43	1.11	0.20					
Cal SCS-BC Et				0.56	3.51	7.60	7.99	1.29					20.94
Std Dev Et				0.12	0.42	0.89	0.52	0.10					1.33
Net Irr in.					1.88	6.35	7.36	0.51					16.10
CORN													
Cal SCS-BC k					0.29	0.47	0.86	1.12	0.70				
Cal SCS-BC Et					1.07	2.48	6.22	7.12	2.69				19.57
Std Dev Et					0.13	0.29	0.40	0.54	0.37				0.97
Net Irr in.						1.22	5.60	6.34	1.39				14.56
SWE CORN													
Cal SCS-BC k					0.29	0.52	0.95	0.72					
Cal SCS-BC Et					1.07	2.75	6.81	4.59					15.22
Std Dev Et					0.13	0.32	0.44	0.35					0.75
Net Irr in.						1.50	6.19	3.81					11.50
TURF													
Cal SCS-BC k			0.27	0.93	0.93	0.81	0.66	0.66	0.69	0.53			
Cal SCS-BC Et			0.29	1.90	3.41	4.31	4.78	4.20	2.66	1.14			22.68
Std Dev Et			0.08	0.41	0.41	0.51	0.31	0.32	0.37	0.21			1.38
Net Irr in.				0.18	1.78	3.06	4.16	3.43	1.36				13.96
GARDEN													
Cal SCS-BC k					0.44	0.65	0.89	0.72	0.16				
Cal SCS-BC Et					1.61	3.43	6.44	4.56	0.62				16.66
Std Dev Et					0.19	0.40	0.42	0.34	0.09				0.84
Net Irr in.						2.18	5.82	3.79					11.78
E-LAKE													
Cal SCS-BC k	2.00	2.00	2.00	1.71	1.37	1.10	0.88	0.94	1.07	1.22	1.94	1.82	
Cal SCS-BC Evap	0.93	1.14	2.14	3.48	5.00	5.84	6.36	6.00	4.13	2.60	1.59	0.90	40.11
Std Dev Evap	0.19	0.25	0.57	0.76	0.60	0.68	0.41	0.45	0.57	0.48	0.27	0.15	2.35
Net Loss in.			0.13	1.33	2.97	4.27	5.58	5.03	2.51	0.73			22.55
ET Ref													
Cal SCS-BC k	2.25	3.04	2.60	1.90	1.67	1.45	1.19	1.18	1.23	1.37	2.16	2.02	
Estimated Etr	1.04	1.74	2.78	3.87	6.09	7.70	8.54	7.52	4.74	2.93	1.77	0.99	49.71
Std Dev Et	0.22	0.37	0.74	0.84	0.73	0.90	0.55	0.57	0.65	0.54	0.30	0.17	2.88

All Values are 30 Year Averages. Effective Precipitation is 80 Percent of Total During Growing Season
Blank values (if any) of ET Ref in early and late months denotes only seasonal calibration data
Adapted from Hill, 1994, Consumptive Use of Irrigated Crops in Utah, Ut Ag Exp Stn Res Rpt #145 Utah State Univ., Logan UT