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Quantifying Depletion Differences from Irrigation Practice Changes in Utah

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Submitted to

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Abstract

This report was developed to detail the recommendations for quantifying differences in depleted water (depletion) from changing agricultural irrigation practices. Practical definitions of depletion for irrigated fields and conveyance systems were developed as was a practical definition of change in depletion. Methods for quantifying changes in evapotranspiration, consumptive irrigation losses, and open water evaporation were discussed and compared. For evapotranspiration, OpenET evapotranspiration products are recommended. Of the OpenET products, no single model is presently recommended for the entire state. The ensemble product and Google Earth Engine version of the Modeling EvapoTranspiration with Internal Calibration (eeMETRIC™) product are justified in many instances because of precedent or accuracy. OpenET products are less well-suited for hypothetical or predictive purposes and small areas, for which they should be combined with the evaporation fraction method or substituted using appropriate crop coefficient methods. Consumptive irrigation losses are best quantified using empirical relationships, though simple loss fractions may be appropriate in some cases. Canal evaporation can be estimated as a fraction of reference ET or assumed to be zero. In cases where sufficient data for consumptive losses are not available or where quick estimates are needed, efficiency-based methods may be used. One example is the Utah State University Extension Irrigation Conversion Water Savings Destination Calculator, which is periodically updated. All depletion comparisons require an appropriate basis in time, space, or both.

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1 Background and Summary

1.1 Background and Objective

The Utah Department of Natural Resources Division of Water Rights (DWRi) contracted with Utah State University (USU) to collaborate in identifying and ranking methods for quantifying water supply depletion (depletion) changes resulting from voluntary changes in agricultural irrigation practices. The objective of this effort was to recommend appropriate, consistent, and practical methods for quantifying depletion differences from agricultural irrigation practice changes.

This report was developed to detail the resulting recommendations and to serve as a technical reference for DWRi decisions on change applications for reduced depletion from agricultural irrigation projects. This chapter (Chapter 1) contains a summary of the recommendations and the primary conclusions. The following chapters (Chapters 2 – 6) contain the narrative for the development of the recommendations and are, therefore, appendices in nature.

1.2 Irrigation Practice Changes Definition

Changes to agricultural irrigation practices, as considered in this report, are changes intended to reduce on-farm water use and in conveyance systems. This definition is not a legal definition, but a definition used for the purposes of the present discussion. These changes may fit under the definitions of agricultural water optimization, agricultural water conservation, and voluntary agricultural water use changes, to name a few contemporary phrases. The most common, presently considered irrigation practice changes were included in the development of this recommendation effort (Table 1.1).

Table 1.1. Agricultural Irrigation Practice Changes Considered in Depletion Change Methods.

Field-Level Practices	Conveyance System Practices
Changing irrigation systems (e.g., surface irrigation to sprinkler, sprinkler to drip)	Lining canals
Changing irrigation system efficiency (e.g., traditional surface irrigation to surge irrigation, mid-elevation sprinklers to low-elevation sprinklers on center pivots, piping of head ditches)	Piping canals
Changing crops/alternative crops (e.g., convert to short-season or low-water-use crops)	System automation
Irrigation system automation	
Deficit irrigation	
Fallowing or otherwise ceasing irrigation (long-term or short term, full-season or partial-season)	
Improved irrigation management (e.g., use of flow measurement, soil moisture sensors, models, etc.)	

1.3 Depletion

It is prudent for the purposes of this report to select a working definition of depletion. The definition included in *Duty of Water the Bear River Compact: Field Verification of Empirical Methods for Estimating Depletion* by Hill et al. (1989) is a reasonable starting point. They defined depletion as:

> The amount of water lost from a river basin or other hydrologic system resulting from irrigation withdrawals from surface or subsurface sources… It is intended to represent the net loss to the basin after return flow and/or excess irrigation water has returned to the stream or the groundwater system.

In summary, depletion is the net removal of water from either the water source or the hydrologic system. In theory, depletion from irrigation is the difference in consumptive water use (CU; in this report, meaning water removed from the hydrologic basin, typically through evaporation and transpiration) between the irrigated condition and what would have occurred in the non-irrigated condition, e.g., the natural system (Figure 1.1; Figure 1.2). In some contexts, depletion may include water that is removed from a basin via a transbasin diversion. This situation is not considered further herein.

For a field, the difference between irrigated and non-irrigated conditions includes changes in evapotranspiration (ET; with ET representing plant-soil systems and not direct evaporation from water surfaces herein), any direct evaporation of irrigation water, and any change in precipitation that is evaporated or transpired.

For a conveyance system, the difference between the irrigated and non-irrigated conditions includes changes in ET in the conveyance corridor, any direct evaporation of conveyed water, and any change in precipitation that is evaporated or transpired in the corridor. Similar differences exist for drainage infrastructure.

Additionally, irrigation may cause a difference in ET in adjacent areas by changing water flow and timing in surface water, raising water tables, etc. However, these changes are nuanced and may be more appropriate to consider on an irrigation-project basis rather than for a field or portion of an irrigation system.

1.3.1 Depletion Quantification Challenges

Estimating depletion involves some fundamental challenges.

1) It is impossible to observe both the irrigated and non-irrigated conditions for a specific location at the same instant. This is a fundamental challenge that has led to the development of various methods for estimating depletion.
2) Depletion itself is an unmeasurable quantity. In addition to being caused by the first challenge, this is also because depletion is a composite value that must be estimated based on other measurements and/or models.

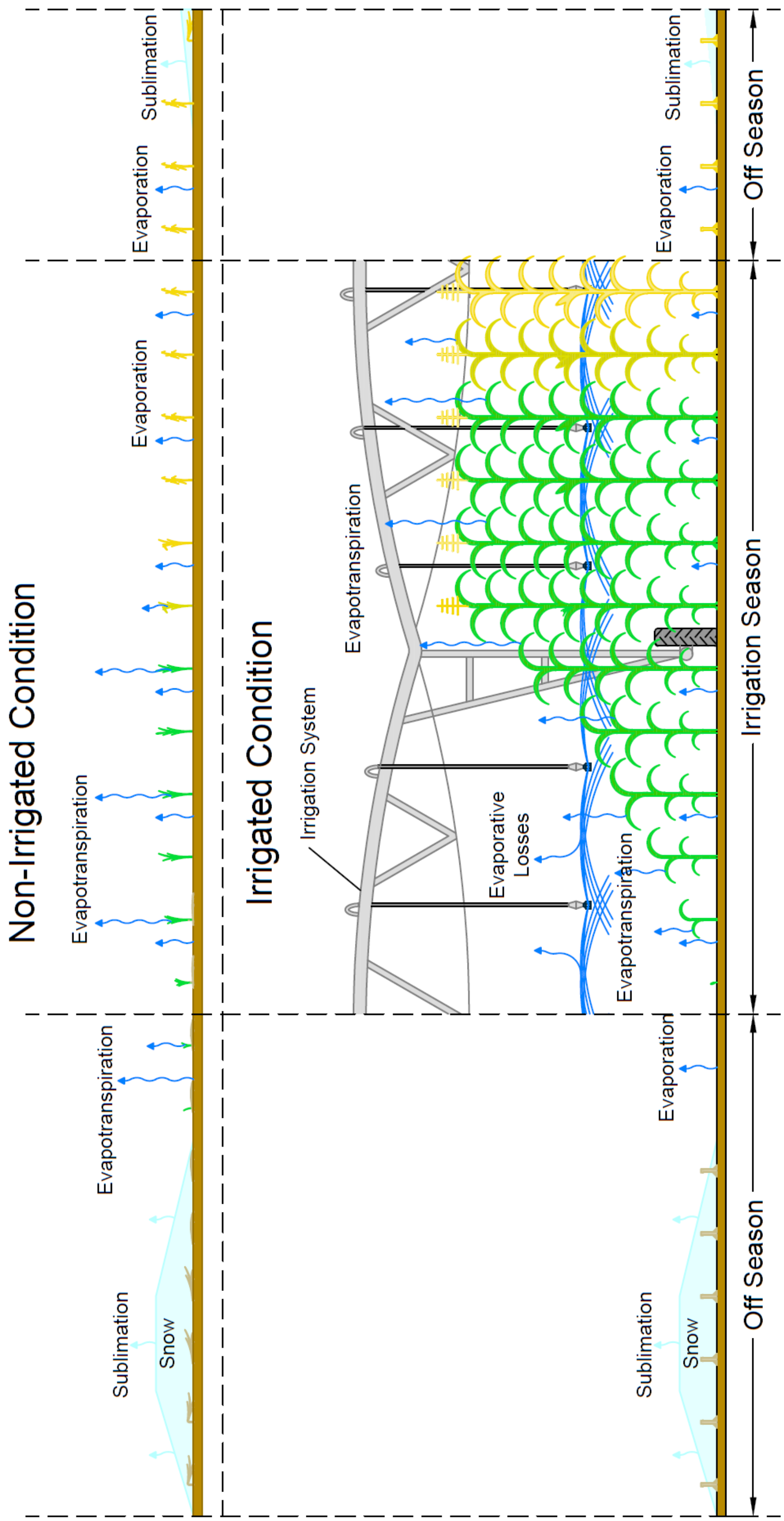

Figure 1.1. Representation of non-irrigated and irrigated consumptive use in a field over the course of a year.

The process of estimating depletion changes resulting from a change in irrigation practice includes two primary components:

1) Estimation of depletion,
2) Comparison of depletion between the "before" and "after" conditions involved in the irrigation practice change.

For many irrigation practice changes, some of the depletion components are the same for the *before* and *after* conditions, thus simplifying the analysis as is demonstrated later in this report.

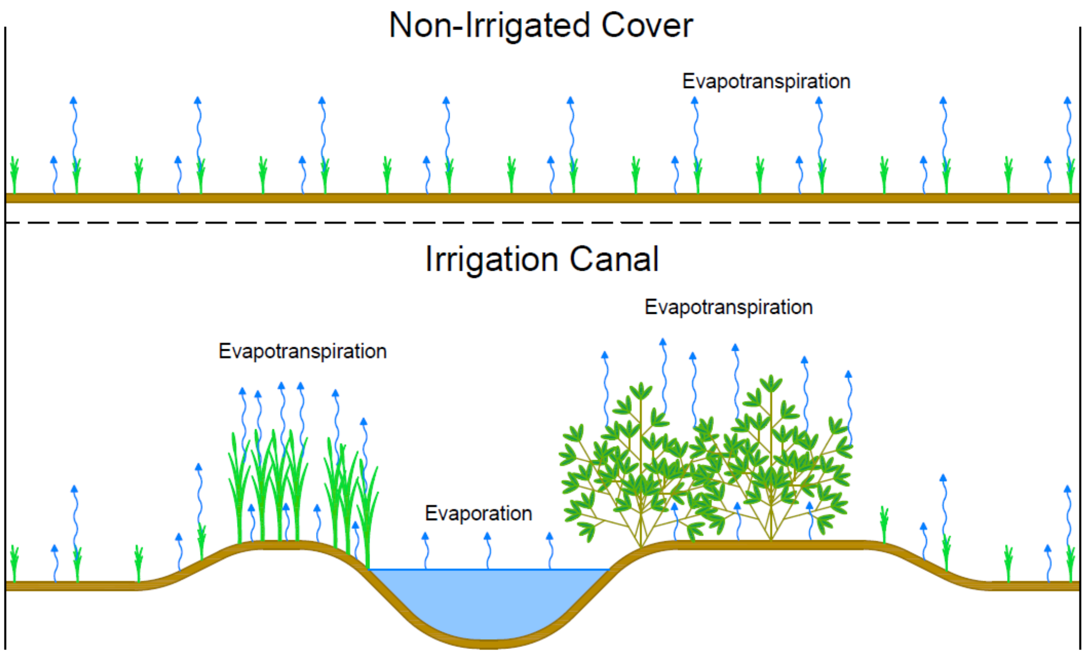

Figure 1.2. Representation of non-irrigated and irrigated consumptive use in a conveyance corridor during a period of actively growing vegetation (e.g., late spring/early summer).

1.3.2 Recommended Practical Definitions of Depletion

Based on the definition in Section *1.3*, depletion is the difference in CU between the irrigated condition and what would have occurred in the non-irrigated condition.

$$D = CU_{Irr} - CU_{Non} \tag{1.1}$$

where:

D	=	Depletion (acre-feet per year, AFY)
CU_{Irr}	=	Consumptive use under the irrigated condition (AFY), and
CU_{Non}	=	Consumptive use under the non-irrigated condition (AFY).

Units for Equation 1.1 and many other equations in this report are specified in acre-feet per year (AFY), because this is a common unit in Utah water rights administration. However, the importance in most equations herein is consistency, they could also be computed in terms of inches per year (in yr^{-1}) or another desired depth or volume unit.

The Equation 1.1 definition holds for both field-level irrigation practices and water conveyance. However, there are some practical differences in computing depletion for fields and conveyance systems.

1.3.2.1 Field Irrigation Practice Changes

For field-level changes to irrigation practices (Table 1.1), CU for the irrigated condition includes crop ET and direct evaporation from applied irrigation water (e.g., evaporation from sprinkler water droplets), which is termed consumptive losses. CU for the non-irrigated condition is the non-irrigated ET, such that:

$$D_{Field} = ET_{Irr} + L_{CU} - ET_{Non} \tag{1.2}$$

where:

D_{Field}	=	Depletion from an irrigated field (AFY),
ET_{Irr}	=	Evapotranspiration from the irrigated field (AFY),
L_{CU}	=	Consumptive losses from applied irrigation water (AFY), and
ET_{Non}	=	Evapotranspiration from the non-irrigated landcover (AFY).

Example

A 100-acre, irrigated, alfalfa field has 37.6 in yr^{-1} of ET, including offseason ET. The Consumptive losses are 5.2 in yr^{-1}. The non-irrigated condition would have an ET of 9.2 in yr^{-1}. The depletion would be:

$$ET_{Irr} = \frac{37.6 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 313 \text{ AFY}$$

$$L_{CU} = \frac{5.2 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 44 \text{ AFY}$$

$$ET_{Non} = \frac{9.2 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 77 \text{ AFY}$$

$$D_{Field} = 313 \text{ AFY} + 44 \text{ AFY} - 77 \text{ AFY} = 280 \text{ AFY}$$

It is common practice to assume that significant differences between the irrigated and non-irrigated conditions only occur during the irrigation/crop growing season because winter CU is small and similar between the two conditions. Therefore, ET_{Irr} becomes crop ET during the growing season (ET_{Crop}), and ET_{Non} is only for the same irrigation/crop growing season:

$$D_{Field} = ET_{Crop} + L_{CU} - (ET_{Non})_{Season} \tag{1.3}$$

where:

D_{Field}	=	Depletion from an irrigated field (AFY),
ET_{Crop}	=	Irrigated crop evapotranspiration (AFY),
L_{CU}	=	Consumptive losses of irrigation water (AFY), and
$(ET_{Non})_{Season}$	=	Evapotranspiration of the non-irrigated landcover during the irrigation season (AFY).

Example

The same 100-acre irrigated alfalfa field as in the previous example has 35.4 in yr^{-1} of ET during the irrigation season and the same consumptive losses as before. The non-irrigated condition would have 7.1 in yr^{-1} of ET during the irrigation season. The depletion would be:

$$ET_{Crop} = \frac{35.4 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 295 \text{ AFY}$$

$$L_{CU} = 44 \text{ AFY}$$

$$(ET_{Non})_{Season} = \frac{7.1 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 59 \text{ AFY}$$

$$D_{Field} = 295 \text{ AFY} + 44 \text{ AFY} - 59 \text{ AFY} = 280 \text{ AFY}$$

An example of how to estimate $(ET_{Non})_{Season}$ is provided by the Upper Colorado River Commission and Wilson Water (2024), who, for the System Conservation Pilot Program in the Upper Colorado River Basin, used ET from nearby non-irrigated areas (e.g., range) to estimate this value.

It is demonstrated in Section *2.1* that $(ET_{Non})_{Season}$ is equal to non-irrigated effective precipitation [precipitation contributing to $(ET_{Non})_{Season}$] plus direct contributions of groundwater to $(ET_{Non})_{Season}$ plus carryover soil moisture [soil moisture from the offseason contributing to $(ET_{Non})_{Season}$]. This yields a second recommended equation for practical estimation of field-level depletion:

$$D_{Field} = ET_{Crop} + L_{CU} - \left(P_{Eff}\right)_{Non} - GW_{Non} - (SM_{CO})_{Non} \tag{1.4}$$

where:

D_{Field}	=	Depletion from an irrigated field (AFY),
ET_{Crop}	=	Irrigated crop evapotranspiration (AFY),
L_{CU}	=	Consumptive losses of irrigation water (AFY),
$(P_{Eff})_{Non}$	=	Effective precipitation for the non-irrigated condition during the irrigation season (AFY),
GW_{Non}	=	Groundwater contributions to the non-irrigated ET during the irrigation season (AFY), and

$(SM_{CO})_{Non}$	=	Carryover soil moisture for the non-irrigation season during the non-irrigated condition (AFY).

The same 100-acre irrigated alfalfa field as in the previous examples has the same crop ET and consumptive losses. The non-irrigated condition would have 3.6 in yr^{-1} of effective precipitation and 3.5 in yr^{-1} in carryover soil moisture. The non-irrigated condition would have negligible groundwater contribution. The depletion would be:

$$ET_{Crop} = 295 \text{ AFY}$$

$$L_{CU} = 44 \text{ AFY}$$

$$(P_{Eff})_{Non} = \frac{3.6 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 30 \text{ AFY}$$

$$GW_{Non} = 0 \text{ AFY}$$

$$(SM_{CO})_{Non} = \frac{3.5 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 29 \text{ AFY}$$

$$D_{Field} = 295 \text{ AFY} + 44 \text{ AFY} - 30 \text{ AFY} - 0 \text{ AFY} - 29 \text{ AFY} = 280 \text{ AFY}$$

A more detailed development of Equation 1.4 is provided in Section *2.1* including detailed descriptions of the terms in the equation.

1.3.2.2 Conveyance Practice Changes

For conveyance practice changes (Table 1.1), CU for the irrigated condition includes ET from the conveyance corridor (e.g., canal bank vegetation) for the irrigated condition plus direct evaporation from the conveyance system (e.g., canal). CU for the non-irrigated condition is the non-irrigated ET from the conveyance corridor, such that:

$$D_{Conv} = ET_{Corr} + E_{Open} + E_{Bed} - ET_{Non} \tag{1.5}$$

where:

D_{Conv}	=	Depletion from conveyed water (AFY),
ET_{Corr}	=	Evapotranspiration from vegetation in the conveyance corridor (AFY),
E_{Open}	=	Direct evaporation from open water surface evaporation (AFY),
E_{Bed}	=	Direct evaporation of wet canal bed evaporation (AFY), and
ET_{Non}	=	Evapotranspiration of the non-irrigated conveyance corridor landcover (AFY).

Example

A 10,000-ft canal segment has a water surface width of 8.7 feet (ft) and bank vegetation extracting water for 4.35 ft on either side of the canal. Open channel and wet canal bed evaporation is 24.9 in yr^{-1} including offseason evaporation from the canal bed. The canal bank vegetation is grass with 31.7 in yr^{-1} of ET including the offseason. The non-irrigated condition ET is 9.2 in yr^{-1}. The depletion would be:

$$Bank\ Area = \frac{2(10{,}000\ \text{ft})(4.35\ \text{ft})}{43{,}560\ \text{ft acre}^{-1}} = 2\ \text{acres}$$

$$Water\ Area = \frac{(10{,}000\ \text{ft})(8.7\ \text{ft})}{43{,}560\ \text{ft acre}^{-1}} = 2\ \text{acres}$$

$$Corridor\ Area = 2\ \text{acres} + 2\ \text{acres} = 4\ \text{acres}$$

$$ET_{Corr} = \frac{31.7\ \text{in y}^{-1}}{12\ \text{in ft}^{-1}} 2\ \text{acres} = 5.3\ \text{AFY}$$

$$E_{Open} + E_{Bed} = \frac{24.9\ \text{in y}^{-1}}{12\ \text{in ft}^{-1}} 2\ \text{acres} = 4.1\ \text{AFY}$$

$$ET_{Non} = \frac{9.2\ \text{in y}^{-1}}{12\ \text{in ft}^{-1}} 4\ \text{acres} = 3.1\ \text{AFY}$$

$$D_{Conv} = 5.3\ \text{AFY} + 4.1\ \text{AFY} - 3.1\ \text{AFY} = 6.3\ \text{AFY}$$

Again, it is common practice to quantify depletion only for the irrigation/growing season, yielding:

$$D_{Conv} = (ET_{Corr})_{Season} + \left(E_{Open}\right)_{Season} + (E_{Bed})_{Season} - (ET_{Non})_{Season} \qquad (1.6)$$

where:

D_{Conv}	=	Depletion from conveyed water (AFY),
$(ET_{Corr})_{Season}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season (AFY),
$(E_{Open})_{Season}$	=	Direct open water during the irrigation season (AFY),
$(E_{Bed})_{Season}$	=	Wet canal bed evaporation during the irrigation season (AFY), and
$(ET_{Non})_{Season}$	=	Evapotranspiration of the non-irrigated conveyance corridor landcover during the irrigation season (AFY).

Example

The same 10,000-ft canal segment as in the previous example has 22.7 in yr^{-1} of open channel plus canal bed evaporation during the irrigation season. Irrigation season canal bank vegetation ET is 29.5 in yr^{-1}. The non-irrigated condition ET during the irrigation season is 7.1 in yr^{-1}. The depletion would be:

$$Bank\ Area = 2\ \text{acres}$$

$$Water\ Area = 2\ \text{acres}$$

$$Corridor\ Area = 4\ \text{acres}$$

$$(ET_{Corr})_{Season} = \frac{29.5 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 2 \text{ acres} = 4.9 \text{ AFY}$$

$$(E_{Open})_{Season} + (E_{Bed})_{Season} = \frac{22.7 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 2 \text{ acres} = 3.8 \text{ AFY}$$

$$(ET_{Non})_{Season} = \frac{7.1 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 4 \text{ acres} = 2.3 \text{ AFY}$$

$$D_{Conv} = 4.9 \text{ AFY} + 3.8 \text{ AFY} - 2.3 \text{ AFY} = 6.3 \text{ AFY}$$

Making an analogous assumption as was done to obtain Equation 1-4 from Equation 1.3, Equation 1.6, yields the following equation for practical estimation of depletion from conveyance systems:

$$D_{Conv} = (ET_{Corr})_{Season} + (E_{Open})_{Season} + (E_{Bed})_{Season} - (P_{Eff})_{Non} - GW_{Non} - (SM_{CO})_{Non} \qquad (1.7)$$

respectively, where:

D_{Conv}	=	Depletion from conveyed water (AFY),
$(ET_{Corr})_{Season}$	=	Evapotranspiration from vegetation in the conveyance Corridor during the irrigation season (AFY),
$(E_{Open})_{Season}$	=	Direct evaporation of conveyed water (open water surface evaporation) during the irrigation season (AFY),
$(E_{Bed})_{Season}$	=	Wet canal bed evaporation during the irrigation season (AFY), and
$(P_{Eff})_{Non}$	=	Effective precipitation for the non-irrigated condition during the irrigation season (AFY),
GW_{Non}	=	Groundwater contributions to the non-irrigated ET during the irrigation season (AFY), and
$(SM_{CO})_{Non}$	=	Carryover soil moisture from the non-irrigation season for the non-irrigated condition (AFY).

Example

The same 10,000-ft canal segment as in the previous example has the same corridor ET and open channel evaporation. The non-irrigated condition has 3.6 in yr^{-1} of effective precipitation, 3.5 in yr^{-1} of carryover soil moisture, and 0 in yr^{-1} of groundwater contributions. The depletion would be:

$$Bank\ Area = 2 \text{ acres}$$

$$Water\ Area = 2 \text{ acres}$$

$$Corridor\ Area = 4 \text{ acres}$$

$$(ET_{Corr})_{Season} = 4.9 \text{ AFY}$$

$$\left(E_{Open}\right)_{Season} + \left(E_{Bed}\right)_{Season} = 3.8 \text{ AFY}$$

$$\left(P_{Eff}\right)_{Non} = \frac{3.6 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 4 \text{ acres} = 1.2 \text{ AFY}$$

$$GW_{Non} = 0 \text{ AFY}$$

$$\left(SM_{CO}\right)_{Non} = \frac{3.5 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 4 \text{ acres} = 1.1 \text{ AFY}^{*}$$

$$D_{Conv} = 4.9 \text{ AFY} + 3.8 \text{ AFY} - 1.2 \text{ AFY} - 0 \text{ AFY} - 1.1 \text{ AFY} = 6.3 \text{ AFY}$$

*$(SM_{CO})_{Non}$ was rounded down so the rounding error would not make D_{Conv} different than the other examples.

1.3.2.3 Concerning Effective Precipitation, Carryover Soil Moisture, and Groundwater Contributions

It is important to emphasize that $(P_{Eff})_{Non}$, GW_{Non}, and $(SM_{CO})_{Non}$ in Equations 1.4 and 1.7 are for the non-irrigated condition, not the irrigated condition. This is important because these or similar terms are often used in computing net irrigation water requirements for irrigation design and management purposes. For those purposes, it is necessary to know how much water is needed to irrigate a crop. The water use of the non-irrigated condition is, therefore, irrelevant. But, for the purpose of estimating depletion, it is the depletion of water caused by the irrigation practice that is of interest. This has been demonstrated in Sections *1.3.2.1* and *1.3.2.2* and in further detail in Sections *2* and *3*.

The reason for this emphasis is because in some depletion estimates, effective precipitation for the irrigated condition has been used. This is also sometimes the case for carryover soil moisture. It is less common to directly account for groundwater contributions, but the previous comments may also apply to groundwater.

1.4 Depletion Changes

The difference in depletion for irrigation practice changes is simply the difference in depletion between the 'new' or '*after'* practice and the 'old', 'base', or '*before'* practice. In this report, they will be referred to as '*after*' and '*before*':

$$\Delta D = D_{After} - D_{Before} \tag{1.8}$$

where:

ΔD	=	Change in depletion *after* the irrigation practice change relative to the condition *before* the change (AFY),
D_{After}	=	Depletion *after* the practice was changed (AFY), and
D_{Before}	=	Depletion *before* the practice was changed (AFY).

This definition is straightforward. The complication relates directly to the first challenge listed in Section *1.3.1*. That is, that the *before* and *after* conditions cannot be observed at the same time. Therefore, strategies must be employed to estimate what D_{Before} would have been, if estimating depletion after the change is made; or to predict what D_{After} will be before a change is made. These challenges are addressed below and in further detail in Section *4.4*.

1.4.1 Field-Level Irrigation Practice Changes

For field-level irrigation practice changes, Equations 1.8 and 1.3 can be combined, yielding:

$$\begin{aligned}\Delta D_{Field} = {} & \left[\left(ET_{Crop}\right)_{After} - \left(ET_{Crop}\right)_{Before}\right] + \left[(L_{CU})_{After} - (L_{CU})_{Before}\right] \\ & - \left\{\left[(ET_{Non})_{Season}\right]_{After} - \left[(ET_{Non})_{Season}\right]_{Before}\right\}\end{aligned} \tag{1.9}$$

where:

ΔD_{Field}	=	Change in field-level depletion from *before* the practice is changed to *after* (AFY),
$(ET_{Crop})_{After}$	=	Irrigated crop evapotranspiration *after* the change (AFY),
$(ET_{Crop})_{Before}$	=	Irrigated crop evapotranspiration *before* the change (AFY),
$(L_{CU})_{After}$	=	Consumptive losses from irrigation water *after* the change (AFY),
$(L_{CU})_{Before}$	=	Consumptive losses from irrigation water *before* the change (AFY),
$[(ET_{Non})_{Season}]_{After}$	=	Evapotranspiration of the non-irrigated landcover during the *after*-condition irrigation season (AFY), and
$[(ET_{Non})_{Season}]_{Before}$	=	Evapotranspiration of the non-irrigated landcover during the *before*-condition irrigation season (AFY).

Where it is not practical to estimate $(ET_{Non})_{Season}$, Equation 1.8 can be combined with Equation 1.4 to give:

$$\begin{aligned}\Delta D_{Field} = {} & \left[\left(ET_{Crop}\right)_{After} - \left(ET_{Crop}\right)_{Before}\right] + \left[(L_{CU})_{After} - (L_{CU})_{Before}\right] \\ & - \left\{\left[\left(P_{Eff}\right)_{Non}\right]_{After} - \left[\left(P_{Eff}\right)_{Non}\right]_{Before}\right\} \\ & - \left[(GW_{Non})_{After} - (GW_{Non})_{Before}\right] \\ & - \left\{\left[(SM_{CO})_{Non}\right]_{After} - \left[(SM_{CO})_{Non}\right]_{Before}\right\}\end{aligned} \tag{1.10}$$

where:

ΔD_{Field}	=	Change in field-level depletion from *before* the practice is changed to *after* (AFY),
$(ET_{Crop})_{After}$	=	Irrigated crop evapotranspiration *after* the change (AFY),
$(ET_{Crop})_{Before}$	=	Irrigated crop evapotranspiration *before* the change (AFY),

$(L_{CU})_{After}$	=	Consumptive losses from irrigation water *after* the change (AFY),
$(L_{CU})_{Before}$	=	Consumptive losses from irrigation water *before* the change (AFY),
$[(P_{Eff})_{Non}]_{After}$	=	Effective precipitation for the non-irrigated condition during the irrigation season *after* the change (AFY),
$[(P_{Eff})_{Non}]_{Before}$	=	Effective precipitation for the non-irrigated condition during the irrigation season *before* the change (AFY),
$(GW_{Non})_{After}$	=	Groundwater contributions to the non-irrigated ET during the irrigation season *after* the change (AFY),
$(GW_{Non})_{Before}$	=	Groundwater contributions to the non-irrigated ET during the irrigation season *before* the change (AFY),
$[(SM_{CO})_{Non}]_{After}$	=	Carryover soil moisture from the non-irrigation season for the non-irrigated condition *after* the change (AFY), and
$[(SM_{CO})_{Non}]_{Before}$	=	Carryover soil moisture from the non-irrigation season for the non-irrigated condition *before* the change (AFY).

For field-level irrigation practice changes that do not materially affect the irrigation season length, the non-irrigated condition terms in Equations 1.9 and 1.10 can be assumed to be equal for both the *before* and *after* conditions. This is because the irrigation practice does not change the non-irrigated condition of the field. Irrigation practice changes where this assumption is generally valid include:

- Changing irrigation systems,
- Changing irrigation system efficiency,
- Crop changes that do not significantly change the growing season,
- Irrigation system automation,
- Deficit irrigation that does not involve ceasing irrigation prematurely in the season or starting irrigation late in the season, and
- Improved irrigation management.

For these conditions, Equations 1.9 and 1.10 can be simplified to:

$$\Delta D_{Field} = \left[\left(ET_{Crop}\right)_{After} - \left(ET_{Crop}\right)_{Before}\right] + \left[(L_{CU})_{After} - (L_{CU})_{Before}\right] \tag{1.11}$$

where:

ΔD_{Field}	=	Change in field-level depletion from *before* the

		practice is changed to *after* (AFY),
$(ET_{Crop})_{After}$	=	Irrigated crop evapotranspiration *after* the change (AFY),
$(ET_{Crop})_{Before}$	=	Irrigated crop evapotranspiration *before* the change (AFY),
$(L_{CU})_{After}$	=	Consumptive losses from irrigation water *after* the change (AFY), and
$(L_{CU})_{Before}$	=	Consumptive losses from irrigation water *before* the change (AFY).

Example

A 100-acre field is used for pasture production. The irrigation system has been a center pivot with mid-elevation sprinklers and is being converted to low-elevation sprinklers. The crop ET is 30 in yr^{-1} in both cases. The consumptive loss before the change is 4 in yr^{-1}. After the change, the consumptive loss is 2 in yr^{-1}. The change in depletion would be:

$$\left(ET_{Crop}\right)_{After} = \left(ET_{Crop}\right)_{Before}, \text{ so no change}$$

$$(L_{CU})_{After} = \frac{2 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 17 \text{ AFY}$$

$$(L_{CU})_{Before} = \frac{4 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 33 \text{ AFY}$$

$$\Delta D_{Field} \approx 17 \text{ AFY} - 33 \text{ AFY} = -16 \text{ AFY}$$

There would be a 16 AFY reduction in depletion. Notice that the crop ET did not change. In a case where the irrigation frequency was changed, crop yield changes, and/or soil wetting was increased or decreased, the crop ET may change.

Equation 1.11 greatly simplifies the computation of ΔD_{Field}. However, for conditions where this assumption may not apply, Equations 1.9 and 1.10 should be used while cancelling out terms that can be justified for the specific condition. Irrigation practice changes requiring the full Equations 1.9 and 1.10 include:

- Crop changes that result in a change in growing season length,
- Deficit irrigation that results in a change in irrigated growing season,
- Full-season fallowing, and
- Partial-season fallowing.

Example

The 100-acre pasture field is to be converted into spring small grain forage production. The irrigation system will remain having mid-elevation sprinklers. Pasture crop ET is 30 in yr^{-1} and spring grain crop ET is 20 in yr^{-1}. The consumptive loss for the pasture is 4 in yr^{-1}. The consumptive loss for spring grain is 3 in yr^{-1}. The carryover soil moisture for the non-irrigated condition is 2.5 in yr^{-1} in both conditions. The non-irrigated effective precipitation is 4 in yr^{-1} for the pasture (long season) and 2 in yr^{-1} for the small grain (short season). Groundwater contributions are negligible in both conditions. The change in depletion would be:

$$\left(ET_{Crop}\right)_{After} = \frac{20 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 167 \text{ AFY}$$

$$\left(ET_{Crop}\right)_{Before} = \frac{30 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 250 \text{ AFY}$$

$$(L_{CU})_{After} = \frac{3 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 25 \text{ AFY}$$

$$(L_{CU})_{Before} = \frac{4 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 33 \text{ AFY}$$

$$\left[\left(P_{Eff}\right)_{Non}\right]_{After} = \frac{3 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 17 \text{ AFY}$$

$$\left[\left(P_{Eff}\right)_{Non}\right]_{Before} = \frac{4 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 33 \text{ AFY}$$

$$(GW_{Non})_{After} = (GW_{Non})_{Before} = 0 \text{ AFY}$$

$$[(SM_{CO})_{Non}]_{After} = [(SM_{CO})_{Non}]_{Before}, \text{so no change}$$

$$\begin{aligned}\Delta D_{Field} &\approx 167 \text{ AFY} - 250 \text{ AFY} + 25 \text{ AFY} - 33 \text{ AFY} - 17 \text{ AFY} + 33 \text{ AFY} \\ &= -75 \text{ AFY}\end{aligned}$$

There would be a 75 AFY reduction in depletion. Notice that the change in crop season affected crop ET, L_{CU}, and the non-irrigated condition terms.

It should be noted that the above examples and equations do not account for changes in depletion associated with consumptive use from return flows (e.g., drainage ditches, or wet areas supplied by runoff or drainage). Changes in these depletions can be estimated using the principles herein, if warranted. Further discussion and detail regarding ΔD_{Field} is provided in Section *4.1*.

1.4.2 Conveyance System Changes

For conveyance system practice changes, Equation 1.6 can be combined with Equation 1.8:

$$\begin{aligned}\Delta D_{Corr} = &\left\{[(ET_{Corr})_{Season}]_{After} - [(ET_{Corr})_{Season}]_{Before}\right\} \\ &+ \left[\left(E_{Open}\right)_{After} - \left(E_{Open}\right)_{Before}\right] + \left[(E_{Bed})_{After} - (E_{Bed})_{Before}\right] \\ &- \left\{[(ET_{Non})_{Season}]_{After} - [(ET_{Non})_{Season}]_{Before}\right\}\end{aligned} \tag{1.12}$$

where:

ΔD_{Conv}	=	Change in depletion from conveyed water from *before* the practice is changed to *after* (AFY),
$[(ET_{Corr})_{Season}]_{After}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season *after* the change (AFY),
$[(ET_{Corr})_{Season}]_{Before}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season *before* the change (AFY),
$(E_{Open})_{After}$	=	Direct evaporation of conveyed water (open water surface evaporation) *after* the change (AFY),
$(E_{Open})_{Before}$	=	Direct evaporation of conveyed water (open water surface evaporation) *before* the change (AFY),
$(E_{Bed})_{After}$	=	Wet canal bed evaporation *after* the change (AFY),
$(E_{Bed})_{Before}$	=	Wet canal bed evaporation *before* the change (AFY),
$[(ET_{Non})_{Season}]_{After}$	=	Evapotranspiration of the non-irrigated landcover during the *after*-condition irrigation season (AFY), and
$[(ET_{Non})_{Season}]_{Before}$	=	Evapotranspiration of the non-irrigated landcover during the *before*-condition irrigation season (AFY).

Where it is not practical to estimate $(ET_{Non})_{Season}$, Equations 1.7 and 1.8 can be combined to produce:

$$\begin{aligned}\Delta D_{Conv} = &\left\{[(ET_{Corr})_{Season}]_{After} - [(ET_{Corr})_{Season}]_{Before}\right\} \\ &+ \left[\left(E_{Open}\right)_{After} - \left(E_{Open}\right)_{Before}\right] + [(E_{Bed})_{After} - (E_{Bed})_{Before}] \\ &- \left\{\left[\left(P_{Eff}\right)_{Non}\right]_{After} - \left[\left(P_{Eff}\right)_{Non}\right]_{Before}\right\} \\ &- \left[(GW_{Non})_{After} - (GW_{Non})_{Before}\right] \\ &- \left\{[(SM_{CO})_{Non}]_{After} - [(SM_{CO})_{Non}]_{Before}\right\}\end{aligned} \tag{1.13}$$

where:

ΔD_{Conv}	=	Change in depletion from conveyed water from *before* the practice is changed to *after* (AFY),
$[(ET_{Corr})_{Season}]_{After}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season *after* the change (AFY),
$[(ET_{Corr})_{Season}]_{Before}$	=	Evapotranspiration from vegetation in the

conveyance corridor during the irrigation season *before* the change (AFY),

$(E_{Open})_{After}$	=	Direct evaporation of conveyed water (open water surface evaporation) *after* the change (AFY),
$(E_{Open})_{Before}$	=	Direct evaporation of conveyed water (open water surface evaporation) *before* the change (AFY),
$(E_{Bed})_{After}$	=	Wet canal bed evaporation *after* the change (AFY),
$(E_{Bed})_{Before}$	=	Wet canal bed evaporation *before* the change (AFY),
$[(P_{Eff})_{Non}]_{After}$	=	Effective precipitation for the non-irrigated condition during the irrigation season *after* the change (AFY),
$[(P_{Eff})_{Non}]_{Before}$	=	Effective precipitation for the non-irrigated condition during the irrigation season *before* the change (AFY),
$(GW_{Non})_{After}$	=	Groundwater contributions to the non-irrigated ET during the irrigation season *after* the change (AFY),
$(GW_{Non})_{Before}$	=	Groundwater contributions to the non-irrigated ET during the irrigation season *before* the change (AFY),
$[(SM_{CO})_{Non}]_{After}$	=	Carryover soil moisture from the non-irrigation season for the non-irrigated condition *after* the change (AFY), and
$[(SM_{CO})_{Non}]_{Before}$	=	Carryover soil moisture from the non-irrigation season for the non-irrigated condition *before* the change (AFY).

For all conveyance system changes contemplated in Table 1.1, the non-irrigated condition components of Equations 1.12 and 1.13 can be cancelled because there is no change to the irrigation season length. In these cases:

$$\Delta D_{Conv} = \{[(ET_{Corr})_{Season}]_{After} - [(ET_{Corr})_{Season}]_{Before}\} + \left[\left(E_{Open}\right)_{After} - \left(E_{Open}\right)_{Before}\right] + [(E_{Bed})_{After} - (E_{Bed})_{Before}] \tag{1.14}$$

where:

ΔD_{Conv}	=	Change in depletion from conveyed water from *before* the practice is changed to *after* (AFY),
$[(ET_{Corr})_{Season}]_{After}$	=	Evapotranspiration from vegetation in the

		conveyance corridor during the irrigation season *after* the change (AFY),
$[(ET_{Corr})_{Season}]_{Before}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season *before* the change (AFY),
$(E_{Open})_{After}$	=	Direct evaporation of conveyed water (open water surface evaporation) *after* the change (AFY),
$(E_{Open})_{Before}$	=	Direct evaporation of conveyed water (open water surface evaporation) *before* the change (AFY),
$(E_{Bed})_{After}$	=	Wet canal bed evaporation *after* the change (AFY), and
$(E_{Bed})_{Before}$	=	Wet canal bed evaporation *before* the change (AFY).

Example

A 10,000-ft canal segment has a water surface width of 8.7 ft and bank vegetation extracting water for 4.35 ft on either side of the canal. Open channel plus wet canal bed evaporation is 24.9 in yr^{-1} including offseason evaporation from the canal bed. The canal bank vegetation is grass with 31.7 in yr^{-1} of ET including the offseason. The system is to be piped. After piping, the direct evaporation of water will be eliminated and leaks will be negligible, so bank ET from irrigation water will be negligible. The change in depletion would be:

$$Bank\ Area = \frac{2(10{,}000\ \text{ft})(4.35\ \text{ft})}{43560\ \text{ft acre}^{-1}} = \ 2\ \text{acres}$$

$$Water\ Area = \frac{(10{,}000\ \text{ft})(8.7\ \text{ft})}{43560\ \text{ft acre}^{-1}} = 2\ \text{acres}$$

$$[(ET_{Corr})_{Season}]_{After} = \frac{0\ \text{in y}^{-1}}{12\ \text{in ft}^{-1}} 2\ \text{acres} = 0\ \text{AFY}$$

$$[(ET_{Corr})_{Season}]_{Before} = \frac{31.7\ \text{in y}^{-1}}{12\ \text{in ft}^{-1}} 2\ \text{acres} = 5.3\ \text{AFY}$$

$$\left(E_{Open}\right)_{After} + (E_{Bed})_{After} = \frac{0\ \text{in y}^{-1}}{12\ \text{in ft}^{-1}} 2\ \text{acres} = 0\ \text{AFY}$$

$$\left(E_{Open}\right)_{Before} + (E_{Bed})_{Before} = \frac{24.9\ \text{in y}^{-1}}{12\ \text{in ft}^{-1}} 2\ \text{acres} = 4.1\ \text{AFY}$$

$$\Delta D_{Conv} \approx 0\ \text{AFY} - 5.1\ \text{AFY} + 0\ \text{AFY} - 4.1\ \text{AFY} = -9.2\ \text{AFY}$$

The estimated change in depletion in the conveyance corridor is a reduction of 9.2 AFY.

For other conditions, e.g., forbearing diversion into a conveyance system for a full irrigation season or in a way that would change the length of the irrigation season, the full Equation 1.12 should be used neglecting terms only as appropriate for the specific project.

It should be noted that the above example and equations do not account for changes in depletion associated with consumptive use from return flows (e.g., drainage ditches, or wet areas supplied by runoff or drainage) or changes in ability to provide water to a service area. Changes in these depletions can be estimated using the principles herein, if warranted. Further discussion and detail regarding ΔD_{Conv} is provided in Section *4.2*.

1.4.3 Comparison Methods

Computing the depletion change component pairs for Equations 1.9 through 1.13 requires identifying a comparison basis. For predictive estimates of depletion changes prior to project implementation, data may be available for the *before* condition; however, no data will be available for the *after* condition. For estimates made *after* a project is implemented, there may be data available for the *after* condition. However, there will not be data for the *before* condition for the same period. In both cases, some basis is needed for comparisons. Recommendations are discussed below, and further discussion is provided in Section *4*.

1.4.3.1 Predictive (Pre Facto) Comparisons

For predictive, or pre facto, comparisons, there are no data yet available for the *after* condition. So, there is no means of comparing the *subject* location with data from both *before* and *after*, which would be a time-based comparison. However, comparisons in space, i.e., between the *subject* area and a *comparison* area that has already had the change are possible, as are some indirect methods based on assumptions of the *after* condition.

- **Comparisons in space:** Depletion estimated using data for *subject* area *before* the practice change is compared with depletion from the same period for a similar *comparison* field that has already had the practice applied:

$$\Delta D \approx \left(D_{Comparison}\right)_{Before} - \left(D_{Subject}\right)_{Before} \tag{1.15}$$

where:

ΔD	=	Change in depletion from *before* the practice is changed to *after* (AFY),
$(D_{Comparison})_{Before}$	=	Depletion from a neighboring *comparison* area assumed to represent the *subject* area *after* the change (AFY), $(D_{Comparison})_{Before}$ is from the same period as $(D_{Subject})_{Before}$, and
$(D_{Subject})_{Before}$	=	Depletion from the *subject* area using data from *before* the change (AFY).

Example:

Consider a 100-acre, partial-season-fallowed field. It is 2019 and an estimate of the change in depletion is being made prior to practice change that will occur before the 2020 season. A nearby 40-acre *comparison* field was partial-season fallowed from 2015 through 2017. The average depletion from the *comparison* field in 2015 through 2016 was estimated to be 20 in yr^{-1}. The depletion from the *subject* field from 2015 through 2016 was 31 in yr^{-1}. Therefore:

$$\left(D_{Comparison}\right)_{Before} = \frac{20\ \text{in y}^{-1}}{12\ \text{in ft}^{-1}} 100\ \text{acres} = 167\ \text{AFY}$$

$$\left(D_{Subject}\right)_{Before} = \frac{31\ \text{in y}^{-1}}{12\ \text{in ft}^{-1}} 100\ \text{acres} = 258\ \text{AFY}$$

$$\Delta D_{Field} \approx 167\ \text{AFY} - 258\ \text{AFY} = -91\ \text{AFY}$$

The estimated change in depletion is a reduction of 91 AFY.

- **Indirect comparisons:** Depletion is estimated using data for *subject* area *before* the practice change and is compared with an estimate of what the depletion will be *after* the practice change using the same *before* data period:

$$\Delta D \approx \left(D_{Estimate}\right)_{After} - \left(D_{Subject}\right)_{Before} \tag{1.16}$$

where:

ΔD	=	Change in depletion from *before* the practice is changed to *after* (AFY),
$\left(D_{Estimate}\right)_{After}$	=	Indirect estimate of depletion for the *subject* area *after* the change using data from *before* the change (AFY), and
$\left(D_{Subject}\right)_{Before}$	=	Depletion from the *subject* area using data from *before* the change (AFY).

This method is suitable for use when ET is estimated using the Evaporative Fraction Method for ET (Section *5.1.2.8*) and when estimated changes in different efficiencies are used (Section *5.2* and Section *6*).

Example:

Consider the same 100-acre, partial-season-fallowed field as in the previous example. However, no adequate comparison field is available. So, another means of predicting the change in depletion is needed. The evaporative fraction method (Section *5.1.2.8*) was used to estimate depletion based on partial-season fallowing in another county. The resulting estimate for partial-fallow depletion for the 2014 through 2018 period was 19 in y^{-1}. Recall from

Section *1.4.3.1* that the depletion from the *subject* field from 2014 through 2018 was 250 AFY. Therefore:

$$\left(D_{Subject}\right)_{Before} = 250\text{ AFY}$$

$$\left(D_{Estimate}\right)_{Before} = \frac{19\text{ in y}^{-1}}{12\text{ in ft}^{-1}}100\text{ acres} = 158\text{ AFY}$$

$$\Delta D_{Field} \approx 158\text{ AFY} - 250\text{ AFY} = -92\text{ AFY}$$

The estimated change in depletion is a reduction of 92 AFY. In this example, the estimate was very close (1% different) to the previous comparison in space. Given the accuracy of the various methods used to estimate ET_{Crop} and L_{CU} this error is well within the overall depletion estimation error.

1.4.3.2 Post-Facto Comparisons

To estimate depletion changes *after* a practice change has occurred when sufficient data have been collected in the *after* condition, the following methods are of practical value to consider:

- **Comparisons in space:** Comparisons of depletion in the *subject* area (field or conveyance corridor) *after* a change was implemented are compared with a nearby *baseline* area assumed to represent the *subject* area *before* the change. The comparison is made using data from the same period for both areas to match climate and water supply conditions.

$$\Delta D \approx \left(D_{Subject}\right)_{After} - \left(D_{Baseline}\right)_{After} \tag{1.17}$$

where:

ΔD	=	Change in depletion from *before* the practice is changed to *after* (AFY),
$(D_{Subject})_{After}$	=	Depletion from the *subject* area *after* the change (AFY), and
$(D_{Baseline})_{After}$	=	Depletion from a neighboring *baseline* area assumed to represent the *subject* area *before* the change (AFY), $(D_{Baseline})_{After}$ is for the same period as $(D_{Subject})_{After}$.

Ensuring that the *baseline* area is representative of what the *subject* area would have been had the practice not been changed is difficult. Therefore, this method is generally not recommended. More information on this matter is presented in Section *4.3.1*.

Example:

Consider the same 100-acre, partial-season-fallowed ~~fieled~~field as in the Section *1.4.3.1* comparisons. It is now 2025 and a post-facto analysis is conducted using data from 2020 through 2024. The average depletion from that field was estimated to be 21 in yr^{-1} across those years based on a gridded dataset and additional analysis. A neighboring 80-acre field has similar soils, topographic position, and crop but was irrigated for the entire season. That field had an average estimated depletion of 32 in yr^{-1} from 2020 through 2024 using the same methods as for the *subject* field. Therefore:

$$\left(D_{Subject}\right)_{After} = \frac{21 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 175 \text{ AFY}$$

$$\left(D_{Baseline}\right)_{After} = \frac{32 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 267 \text{ AFY}$$

$$\Delta D_{Field} \approx 175 \text{ AFY} - 267 \text{ AFY} = -92 \text{ AFY}$$

The estimated change in depletion is a reduction of 92 AFY. Notice that the area of *subject* field (100 acres) was used in computing both $(D_{Subject})_{After}$ and $(D_{Baseline})_{After}$. This happens to be similar to the predicted values.

- **Comparisons in time:** Comparisons of depletion in the *subject* area (field or conveyance corridor) using data from *before* a change was implemented are compared with depletion using data from *after* implementation, such that:

$$\Delta D \approx \left(D_{Subject}\right)_{After} - \left(D_{Subject}\right)_{Before} \tag{1.18}$$

where:

ΔD	=	Change in depletion from *before* the practice is changed to *after* (AFY),
$(D_{Subject})_{After}$	=	Depletion from the *subject* area using data from *after* the change (AFY), and
$(D_{Subject})_{Before}$	=	Depletion from the *subject* area using data from *before* the change (AFY).

In this method, the time periods for the comparison data are not the same. The primary challenge in this method is to select *before* and *after* data periods such that factors outside of the practice change itself can be considered similar between the comparison periods. For a field, these factors include crops grown, crop management, weather, and water availability. For a conveyance system, these factors include conveyed flow, weather, and water availability. More information is presented in Section *4.3.2*.

Example:

Consider the same 100-acre, partial-season-fallowed field as the previous example. However, the *before* condition is estimated using data from the *subject* field for the years 2014 through 2018 (2019 had poor data). The average depletion from the field in 2014 through 2018 was estimated to be 30 in yr^{-1}. Therefore:

$$\left(D_{Subject}\right)_{After} = 175 \text{ AFY}$$

$$\left(D_{Subject}\right)_{Before} = \frac{30 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 250 \text{ AFY}$$

$$\Delta D_{Field} \approx 175 \text{ AFY} - 250 \text{ AFY} = -75 \text{ AFY}$$

The estimated change in depletion is a reduction of 75 AFY. This is a 17-AFY smaller reduction than in the previous example (and is less than the predictive estimates in Section *1.4.3.1*). However, both estimates are perhaps equally valid, both methods having strengths and weaknesses.

- **Comparison in time and space:** This method is an attempt to strike a balance between the comparisons in time or space only. It is, therefore, recommended for use in post-facto comparisons, where possible. In this method, the *subject* and *baseline* areas are both compared or the same *before* and *after* periods, with the practice only being changed in the *subject* area. The change in depletion is computed as:

$$\Delta D \approx \left(D_{Subject}\right)_{After} - \left(\frac{\left(D_{Subject}\right)_{Before}}{\left(D_{Baseline}\right)_{Before}}\right)\left(D_{Baseline}\right)_{After} \tag{1.19}$$

where:

ΔD	=	Change in depletion from *before* the practice is changed to *after* (AFY),
$(D_{Subject})_{After}$	=	Depletion from the *subject* area using data from *after* the change (AFY), and
$(D_{Subject})_{Before}$	=	Depletion from the *subject* area using data from *before* the change (AFY),
$(D_{Baseline})_{Before}$	=	Depletion from a neighboring *baseline* area assumed to represent the *subject* area *before* the change (AFY), $(D_{Baseline})_{Before}$ is for the same period as $(D_{Subject})_{Before}$, and
$(D_{Baseline})_{After}$	=	Depletion from a neighboring *baseline* area *after* the change; the *baseline* area is assumed to represent the *subject* area *before* the change (AFY), $(D_{Baseline})_{After}$ is for the same period as $(D_{Subject})_{After}$.

This method still requires the care in selecting a *baseline* area as described for comparisons in space and selection of *before* and *after* data periods as described for comparisons in time. Therefore, the benefits of this method come at the cost of increased complexity.

Example:

Consider the same 100-acre, partial-season-fallowed field as the previous examples and its 80-acre, *baseline* comparison field. The average depletion from the *baseline* field in 2014 through 2018 was estimated to be 33 in yr^{-1}. Therefore:

$$\left(D_{Subject}\right)_{After} = 175 \text{ AFY}$$

$$\left(D_{Subject}\right)_{Before} = 250 \text{ AFY}$$

$$(D_{Baseline})_{Before} = \frac{33 \text{ in y}^{-1}}{12 \text{ in ft}^{-1}} 100 \text{ acres} = 275 \text{ AFY}$$

$$(D_{Baseline})_{After} = 267 \text{ AFY}$$

$$\Delta D_{Field} \approx 175 \text{ AFY} - \left(\frac{275 \text{ AFY}}{267 \text{ AFY}}\right) 250 \text{ AFY} = -82 \text{ AFY}$$

The estimated change in depletion is a reduction of 82 AFY. The ratio of $(D_{Subject})_{After}$ to $(D_{Baseline})_{Before}$ was 275 AFY ÷ 267 AFY = 1.03. It is assumed that under unchanged conditions, the *subject* field depletion would continue to be about 3% greater than the *baseline* field, so the $(D_{Baseline})_{After}$ is effectively adjusted up by Equation 1.19. The estimate in this example happens to lie between the previous two estimates but certainly may not always do so. It is also less than the predictive estimates from Section *1.4.3.1*. Given the accuracy of the various methods used to estimate ET_{Crop} and L_{CU} this error is well within the overall depletion estimation error.

1.4.4 Selecting Comparison Averaging Periods

For all comparison methods in Sections *1.4.3.1* and ***Error! Reference source not found.***, it is prudent to include multiple years in the analysis for both *before* and *after* conditions. This is done to account for interannual variability in depletion. A clear exception would be when considering an *after* condition that is only temporary and, therefore, only exists in one year. Selecting an appropriate averaging period may be challenging.

There is no accepted standard for number of years for *before* or *after* depletions. For example, a 30-year period may match climate normals but is clearly impractical in most cases. A three-year period matches the conventional minimum number for computing means. A five-year period has been used in studies in Utah and Arizona (e.g., Jacobs, 2024; discussion for Mohave Valley Irrigation District in NRCE and Jacobs, 2021b). A seven-year period has been considered for estimating depletion in Utah with the justification being that it matched the seven years associated with non-use forfeiture in Utah water rights (S. Morrison, Jacobs Engineering, Personal Communication, 2024).

The selection of an averaging period is one of a practical nature. Certainly, three years would be the preferred minimum period length, unless fewer years of data are available. The maximum period length should be selected such that field or conveyance practices do not differ from the intended comparison condition. For fields, this includes crop(s) grown and irrigation and cultural practices. For conveyance systems, this includes conveyed flow and conveyance corridor conditions/management. Therefore, the period should not "look" too far back in time. Additionally, the years included should be selected to avoid bias relating to over representation of known wet or dry years. No example of different averaging periods is provided here because this should be made based on local/historic knowledge.

1.5 Depletion from Return Flows

In addition to the depletion from irrigated fields and irrigation conveyance corridors, irrigation water can contribute to depletion through CU from return flows. Return flows include deep percolation and irrigation runoff as these flows work their way back to the source water or another waterbody (including aquifers). Return flows may flow into drainage ditches, where consumptive use may include both open water surface evaporation and ditch corridor vegetation evaporation. For these cases, methods applicable to conveyance systems area applicable for depletion estimates. Return flows may also accumulate in ponds, wetlands, or other areas. Deep percolation may raise a local water table and, thus, provide water for nearby vegetation. In general, field methods including $(ET_{Non})_{Season}$ may be helpful in quantifying depletion from these areas. Depletion from return flows is not considered in more detail herein, but many of the methods provided are applicable to these depletions.

1.6 Depletion Component Estimation Methods

The following are recommendations for methods to estimate components of depletion from Section *1.3*. The primary components involved in many irrigation practice changes include ET, consumptive losses, and open channel evaporation (Section *1.4*). In some cases, it is also necessary to estimate effective precipitation, carryover soil moisture, and groundwater contributions all for the non-irrigated condition. While a summary of recommendations is provided below, further detail and comparisons of methods are provided in Section *4.4.*

1.6.1 Evapotranspiration

The recommended methods for crop and conveyance corridor ET estimation are OpenET's *(**ensemble**)* or Measuring EvapoTRanspiration with Internal Calibration model version for the Google Earth Engine (***eeMETRIC™***) products (e.g., Allen et al., 2007). OpenET is a collaboration and platform that provides satellite-remote-sensing-based ET estimates over an expanding area presently including the Western U.S. (Section *5.1.2.7*). The ensemble product is an average ET from six models used by OpenET excluding outliers, if any. The eeMETRIC™ model is relevant in Utah because it has been adopted for estimating consumptive water use in the Upper Colorado River Basin by a Resolution of the Upper Colorado River Commission (UCRC, 2022).

Regarding these two data products, the OpenET ensemble product has been found to perform statistically better over the U.S. than any of the individual models (Volk et al., 2024). However, Volk et al. (2024) stated that none of the models was a clear or consistent outlier. The OpenET eeMETRIC™ model had less bias but more scatter overall than did the ensemble in Volk et al.'s work. The eeMETRIC™ model has also been found to perform better than the ensemble model in comparison with eddy covariance measurements in the Escalante Valley of Southwestern Utah in 2020 and 2021 (Allen et al., 2022). However, both models underestimated ET relative to the eddy covariance measurements. With underestimation of the advective contribution to ET being a likely factor.

Conversely, in an urban golf course setting in Roy, Utah, USU researchers found that the Atmosphere-Land Exchange Inverse and associated disaggregation model (ALEXI-disALEXI; Anderson et al., 1997, 2007) product from OpenET performed best (K. Meza Capcha and A. Torres Rua, unpublished research). For this reason, until more conclusive evidence is available, no single model is recommended for general use. Selection of an appropriate model is at the discretion of the Division of Water Rights.

OpenET products are also recommended if estimating non-irrigated condition ET directly (as opposed to estimating effective precipitation, carryover soil moisture, etc.). This was done by UCRC and Wilson Water (2024) for the System Conservation Pilot Program in the Upper Colorado River Basin.

Use of an appropriate OpenET model represents a reasonably accurate estimate that is research-based, consistent with efforts throughout the Western U.S., and is being continuously supported and improved. Use of OpenET products is recommended for study areas that are at least 10-acres in size (nominally 930 ft wide and long, which is twice the hypotenuse of a 100-m Landsat thermal infrared pixel; e.g., Section *5.1.2.6.3*). Remote-sensing-based ET products are particularly useful in post-facto analyses.

OpenET products are less suited for smaller areas (smaller than the resolution of the satellite imagery) and hypothetical, or predictive purposes. In such cases, they can be combined with the evaporative fraction method (Section *5.1.2.8*):

$$ET_f = \frac{(ET_a)_{Rep}}{(ET_r)_{Rep}} \tag{1.20}$$

where:

ET_f	=	ET fraction based on a selected representative location/condition (dimensionless),
$(ET_a)_{Rep}$	=	"Actual" ET from a remote-sensing-based model for the selected representative location/condition (in), and

$(ET_r)_{\mathrm{Rep}}$	=	Tall reference evapotranspiration for the selected representative location/condition (in).

To get ET for the subject location:

$$ET_{Subject} = ET_f(ET_r)_{Subject} \tag{1.21}$$

where:

$ET_{Subject}$	=	Estimated ET for the subject location/condition (in),
ET_f	=	ET fraction based on a selected representative location (dimensionless),
$(ET_r)_{Subject}$	=	Tall reference evapotranspiration for the subject location/condition (in).

Example:

You need to estimate ET for a 2-acre pasture and would like to use an OpenET product. The ET for the pasture is 15 inches from Open ET. You are concerned that edge effects are affecting the result. A 20-acre pasture in the same valley has ET = 26 in. You have determined that this is sufficiently representative. The short reference ET (ET_o) from Open ET for the growing season for your field is 34 in. The ET_o for the 20-acre pasture is 36 in. So, the estimated ET for the 2-acre pasture is:

$$(ET_a)_{Rep} = 26 \text{ in}$$

$$(ET_o)_{Rep} = 36 \text{ in}$$

$$ET_f = \frac{26 \text{ in}}{36 \text{ in}} = 0.72$$

$$(ET_r)_{Subject} = 34 \text{ in}$$

$$ET_{Subject} = 0.72(34 \text{ in}) = 24.6 \text{ in}$$

Two things to note: 1) in this example, ET_o was used instead of ET_r (the reference does not matter too much as long as it is consistent, ET_r can be a little more responsive to atmospheric conditions than ET_o), 2) for best results, the representative location should not differ significantly in season length and climate conditions from the subject location.

It may also be appropriate for small areas and predictive analyses to use the crop coefficient method (Section *5.1.2.4*). Often a mean crop coefficient method is appropriate:

$$ET_c = K_c ET_r \tag{1.22}$$

where:

ET_c	=	Crop evapotranspiration, the subscript *c* is used in contemporary literature to refer to ET computed using

		this method (in day^{-1}),
ET_r	=	Tall reference evapotranspiration (short reference ET may be used if the crop coefficients used are for that reference; in day^{-1}), and
K_c	=	Empirical crop coefficient (must match the reference selected; dimensionless).

For Equations 1.20 through 1.22, the ASCE Standardized Reference Evapotranspiration Equation (Section *5.1.2.4.1.1*) should be used when possible. Otherwise, the Hargreaves and Samani Equation (Section *5.1.2.4.1.3*) calibrated to the ASCE Standardized Equation is acceptable.

For improved representation of crop coefficients to actual conditions, reflectance-based crop coefficients (Section *5.1.2.4.2.8*) are recommended. However, these are typically limited to areas 200-ft on a side or larger (two times the hypotenuse of a 30-m Landsat satellite image) and only for post-facto conditions. Otherwise, they can be used to help determine crop growth timing for other crop coefficient methods. When reflectance-based methods are unavailable, suitable tabular or equation-based crop coefficients should be used (see Section *5.1.2.4.2.5 Crop Coefficients Sources*). Care should always be made to get the crop coefficient curve timing correct. Users should be aware that most crop coefficients are developed for ideal conditions and may overestimate actual ET.

1.6.2 Consumptive Losses

The recommended method to compute consumptive losses for surface, subsurface, and drip (including mobile drip on center pivots) irrigation is to assume consumptive losses are zero (Section *5.2*). For sprinkler irrigation, the recommended method depends on the type of sprinkler system:

- For wheel lines, hand lines, solid sets, and micro sprinklers, a reasonable method is the equation of Trimmer (1987), which had notable scatter, but performed well on average in the study by Maroufpoor et al. (2017):

$$f_{WDE} = \frac{\left[1.98{d_{noz}}^{-0.72} + 0.22(e_s - e_a)^{0.63} + 0.00036P^{1.16} + 0.14u^{0.7}\right]^{4.2}}{100} \tag{1.23}$$

where:

f_{WDE}	=	The fraction of sprinkler discharge that is evaporated, here assumed to be wind drift and evaporation (WDE),
d_{noz}	=	Sprinkler nozzle diameter (mm),
e_s	=	Average daytime saturated vapor pressure during the irrigation event (kPa),
e_a	=	Average daytime actual vapor pressure during the irrigation event (kPa),
P	=	Sprinkler nozzle operating pressure (kPa), and

u	=	Average daytime wind speed during the irrigation event ($m\ s^{-1}$).

Yazar (1984) stated that wind drift was 25% of f_{WDE} when wind speed was less than 4 $m\ s^{-1}$ (9 mph) and 47% at greater wind speeds in Eastern Nebraska. More information is provided in Section *5.2.4.1*.

Example:

The average wind speed on a given day is 2.2 $m\ s^{-1}$, the average vapor pressure is 0.55 kPa and the average saturated vapor pressure is 1.19 kPa. A wheel line has sprinklers with 3/16-in = 4.8-mm nozzles (a common size in Utah) and is operated at 60 psi = 410 kPa (a common recommended pressure for wheel lines). Estimate the evaporative losses:

$$\begin{aligned} f_{WDE} = \{[&1.98(4.8\text{ mm})^{-.72} + 0.22(1.19\text{ kPa} - 0.55\text{ kPa})^{0.63} \\ &+ 0.00036(410\text{ kPa})^{1.16} + 0.14(2.2\text{ m s}^{-1})^{0.7}]^{4.2}\} \div 100 \\ &= 0.05 \end{aligned}$$

Applying the 25% wind drift reduction based on Yazar (1984):

$$f_E = 0.75(0.05) = 0.03$$

The estimated evaporation loss fraction for the day is 0.03. Meaning, 3% of the water entering the sprinkler system would be evaporated. This example is based on weather data from May 30, 2024, at the Laketown, UT weather station (Utah Climate Center, 2025). If the calculations are done hourly and then f_E is averaged, the result rounds to 0.04. For many cases, hourly is probably a more appropriate timestep than daily.

- For center pivots and lateral-move systems with mid-elevation sprinklers, the best consumptive loss estimates available are from Eastern Washington (Sarwar et al., 2019):

$$f_{WDE} = 0.01873 + .07042u + 0.02672(e_s - e_a) \tag{1.24}$$

where:

f_{WDE}	=	The fraction of sprinkler discharge that is evaporated, here assumed to be wind drift and evaporation (WDE),
u	=	Average daily wind speed during the irrigation event ($m\ s^{-1}$),
e_s	=	Average daily saturated vapor pressure during the irrigation event (kPa), and
e_a	=	Average daily actual vapor pressure during the irrigation event (kPa).

As done for other sprinklers, Equation 1.21 can be adjusted based on Yazar (1984) to get only the fraction evaporated. The challenge is that Equation 1.21, even with this adjustment produces notably larger evaporation estimates than does Equation 1.20. This is counterintuitive because USU catch-can observations in Utah indicate that wheel lines have greater evaporation losses than do center pivots with mid-elevation sprinklers. Current research is underway to improve f_{WDE} estimates for wheel lines in Utah. More information is provided in Section *5.2.4.2*.

Example:

Consider the same location as for the previous example. Converting the vapor pressures to kPa, e_a = 0.55 kPa and e_s = 1.19 kPa. Estimate the evaporative losses:

$$f_{WDE} = 0.01873 + .07042(2.2 \text{ m s}^{-1}) + 0.02672(1.19 \text{ kPa} - 0.55 \text{ kPa}) = 0.19$$

Applying the 25% reduction based on Yazar (1984):

$$f_E = 0.75(0.19) = 0.14$$

The estimated evaporation loss fraction for the day is 0.14. Meaning, 14% of water entering the sprinkler system would be evaporated. This number matches closer to Utah catch can observations during summer daytime periods, though the 14% in the example was for a 24-hr average.

- Pivots and lateral move systems with low-elevation sprinklers: assume consumptive losses are 10% of applied water. More information is provided in Section *5.2.4.2*.
- Big guns, Equation 1.23 does not represent big guns well, Karney and Podmore (1984) developed a relationship for big guns, but the equation fit was not good (R^2 = 61%), and they did not control for evaporation from their catch cans. Their relationship is:

$$f_{WDE} = \frac{0.0389u + 29.49(e_s - e_a)}{T_K} \qquad (1.25)$$

where:

f_{WDE}	=	The fraction of sprinkler discharge that is evaporated, here assumed to be wind drift and evaporation (WDE),
u	=	Average daytime wind speed during the irrigation event (m s^{-1}),
e_s	=	Average daytime saturated vapor pressure during the irrigation event (kPa),
e_a	=	Average daytime actual vapor pressure during the irrigation event (kPa), and
T_K	=	Absolute air temperature (K).

Yazar's (1984) wind drift reductions should be applied as in Equation 1.24. Though, this is beyond the scope of Yazar's work. Big guns have significantly greater throw and trajectory height than other sprinklers. This effects both wind drift and evaporation, though it is expected that wind drift would be a greater fraction of end gun application than for smaller sprinklers. More information is provided in Section *5.2.4.3*.

Example:

Consider the same location and weather conditions as the previous examples. The air temperature is 8.9 °C = 282 K. Estimate the evaporative losses for a big gun:

$$f_{WDE} = \frac{0.0389(2.2\ \mathrm{m\ s^{-1}}) + 29.49(1.19\ \mathrm{kPa} - 0.55\ \mathrm{kPa})}{282\ \mathrm{K}} = 0.15$$

Applying the 25% reduction based on Yazar (1984):

$$f_E = 0.75(0.152) = 0.11$$

The estimated evaporation loss fraction for the day is 0.11. Meaning, 11% of water entering the sprinkler system would be evaporated.

1.6.3 Canal Open Water Evaporation

The relationship used by Allen and Robison (2009) is recommended for open water evaporation from canals:

$$E_{Open} = 0.6ET_r \tag{1.26}$$

where:

E_{Open}	=	Open water surface evaporation (in) and
ET_r	=	ASCE Standardized Tall Reference ET (in).

Another suitable estimate is to neglect evaporation from canals, particularly when dealing with narrow channels or short reaches. More information is provided in Section *5.3*.

Example:

Consider the same location as in the Section *1.6.1*. ET_r is 0.23 in d^{-1} for the same day as in those examples and 39 in for May through October. Estimate the open water evaporation for both of these conditions:

May 30

$$E_{Open} = 0.6(0.23\ \mathrm{in\ d^{-1}}) = 0.14\ \mathrm{in\ d^{-1}}$$

Full season:

$$E_{Open} = 0.6(39\ \mathrm{in}) = 23\ \mathrm{in}$$

The seasonal E_{Open} is often of a similar magnitude as pasture, turfgrass, or spring grains.

1.6.4 Canal Bed Evaporation

For canals that are intermittently full and empty, E_{Bed} can be estimated. For lined canals, E_{Bed} can usually be neglected. For canals with frequent filling, assuming $E_{Bed} = E_{Open}$ is probably sufficient. Because E_{Bed} is expected to be small, more detailed analyses are likely not often warranted. However, a soil evaporation model (Equation 5.54) can be used if the bed is relatively free of vegetation. If the canal bed has vegetation in it an ET model (Section *1.6.1*) can be employed.

1.6.5 Other Depletion Components

1.6.5.1 Effective Precipitation for the Non-Irrigated Condition

Effective precipitation requires the measurement of precipitation and then an adjustment to account for runoff and deep percolation from precipitation. For irrigation requirements used for system design, effective precipitation is computed for the crop (e.g., Soil Conservation Service, SCS, 1993). This is often done for depletion estimates also. However, as discussed in Sections *1.3.2.1* and *2*, effective precipitation used for depletion estimates should be for the non-irrigated condition.

1.6.5.1.1 Precipitation Measurement

Manual-read, tipping bucket, and weighing rain gauges are all common methods that are recommended for precipitation measurements used in depletion estimation provided the gauges are well-sited, -maintained, and -operated. In general, the nearer to a field the precipitation measurement device is, the better. This is because precipitation can vary significantly over short distances, particularly with summertime thunderstorms. Some gridded weather datasets may also be appropriate, including PRISM (PRISM Climate Group at Oregon State University, Corvallis, OR, https://prism.oregonstate.edu/) or Daymet (Thornton et al., 2021) both of which were found to perform well by Muche et al. (2020) in Kansas. More information is provided in Section *5.1.1.1.2*.

1.6.5.1.2 Effective Precipitation

The recommended method for estimating effective precipitation for depletion changes in Utah is to assume:

$$\left(P_{Eff}\right)_{Non} = P - RO_{Precip} \tag{1.27}$$

where:

$(P_{Eff})_{Non}$	=	Effective precipitation for the non-irrigated condition (in),
P	=	Irrigation season precipitation (in), and
RO_{Precip}	=	Irrigation season runoff from precipitation (in).

Here, any deep percolation from in-season precipitation is neglected because storm events in Utah are usually not sufficiently large or frequent enough to cause significant amounts of deep percolation in lower elevation areas. More information is provided in Section *5.5.2*.

Runoff can be estimated using the United States Soil Conservation Service (SCS) Equation (i.e., the Curve Number Method; Natural Resources Conservation Service, NRCS, 2004b):

$$RO = \begin{cases} 0, & P \le I_a \\ \dfrac{(P - I_a)^2}{P - I_a + S}, & P > I_a \end{cases} \tag{1.28}$$

where:

RO	=	Estimated runoff (in),
P	=	Precipitation (in),
I_a	=	Initial abstractions (in), usually assumed to be 0.2S, and
S	=	Maximum water retention after runoff initiation (in).

and:

$$S = \frac{1000}{CN} - 10 \tag{1.29}$$

Where:

CN	=	The SCS Curve Number (NRCS, 2004a).

Example:

You are estimating effective precipitation for a location across the irrigation season. From the NRCS's WebSoilSurvey (https://websoilsurvey.sc.egov.usda.gov), you have identified that the soils are a classified as Hydrologic Soil Group C. The typical non-irrigated cover is sagebrush desert. The following precipitation values are provided for three days of that record:

Day	Rainfall (in d^{-1})
1	0.0
2	2.1
3	0.9

Estimate the total effective precipitation for the non-irrigated condition for these three days.

First, from Table 5.1, a CN for an assumed "fair" hydrologic condition is 63. So,

$$S = \frac{1000}{63} - 10 = 5.9 \text{ in}$$

$$I_a = 0.2(5.9 \text{ in}) = 1.2 \text{ in}$$

Day 1:

$$0.0 \text{ in} \leq 1.2 \text{ in}, \text{so } RO = 0.0 \text{ in}$$

Day 2:

$$2.1 \text{ in} > 1.2 \text{ in}, \text{so } RO = \frac{(2.1 \text{ in} - 1.2 \text{ in})^2}{2.1 \text{ in} - 1.2 \text{ in} + 5.9 \text{ in}} = 0.1 \text{ in}$$

Day 3:

$$0.9 \text{ in} \leq 1.2 \text{ in}, \text{so } RO = 0.0 \text{ in}$$

Totals:

$$Total\ P = 0 \text{ in} + 2.1 \text{ in} + 0.9 \text{ in} = 3.0 \text{ in}$$

$$Total\ RO = 0 \text{ in} + 0.1 \text{ in} + 0 \text{ in} = 0.1 \text{ in}$$

$$\left(P_{Eff}\right)_{Non} = 3.0 \text{ in} - 0.1 \text{ in} = 2.9 \text{ in}$$

A reasonable estimate of runoff can be achieved running this method on a daily basis (as opposed to a 60-minute or 15-minute hyetograph). This was done in the above example. When using the 24-hour timestep, treat each day as its own storm event. More information on runoff including curve number values is provided in Section *5.1.1.1.5*.

1.6.5.2 Carryover Soil Moisture for the Non-Irrigated Condition

The recommended operational estimation method for carryover soil moisture is:

$$(SM_{CO})_{Non} = \min\left[\left(P_{Inf}\right)_{Off} - E_{Off}, f_{SMD}\ (AWC)(Z_r)\right] \tag{1.30}$$

where:

$(SM_{CO})_{Non}$	=	Carryover soil moisture for the non-irrigated condition (in),
$(P_{Inf})_{Off}$	=	Infiltrated precipitation during the offseason (in),
E_{Off}	=	Soil/surface evaporation during the offseason (in),
f_{SMD}	=	Fraction of soil water storage depleted at the end of the growing season,
AWC	=	Available water capacity of the soil (in in^{-1}), and
Z_r	=	Root zone depth for the non-irrigated condition (in).

For rainfall during the non-irrigation season, Equation 1.27 can be used to estimate $(P_{Inf})_{Off}$. This method is not valid for snowmelt. For reference, Hill et al. (1989) assumed $(P_{Inf})_{Off}$ was 67% of offseason precipitation in the Bear River Basin. E_{Off} can be estimated using the crop coefficient method using coefficients from Allen and Robison (2009) (Table 5.2) or using an Open ET product for a neighboring non-irrigated area (e.g., rangeland) during the non-irrigation season.

The f_{SMD} is a judgement call. Using 0.75 is consistent with Hill et al. (1989). AWC can be obtained from WebSoilSurvey. The user can enter the expected root depth from the non-irrigated condition to retrieve a representative expected average. We recommend using a "Weighted Average" "Aggregation Method" when using the "Soil Properties and Qualities" tab of that website.

Root zone depths should be estimated based on expected non-irrigated vegetation. For example, Sagebrush effective rooting depth (primary water extraction) was 3 ft – 4 ft in a Wyoming study by Sturges (1977). See Section 5.5.3.3 for more information regarding this method for carryover soil moisture.

Example:

You are estimating carryover soil moisture for a location with an offseason from November through April. You estimate that the non-irrigated vegetation has an effective root depth of 3 ft. From WebSoilSurvey, you find the weighted average available water capacity for the subject location is 0.11 $m^3\ m^{-3}$. You have the following data:

Month	Precipitation (in)	Runoff (in)	ET_r (in)
November	1.0	0.0	1.5
December	1.1	0.0	0.5
January	2.1	0.0	0.4
February	1.5	0.0	1.2
March	1.2	0.5	3.0
Total	**6.9**	**0.5**	**6.6**

Estimate the carryover soil moisture for the non-irrigated condition.

$$\left(P_{Inf}\right)_{Off} = 6.9\text{ in} - 0.5\text{ in} = 6.4\text{ in}$$

Using evaporation coefficients from Table 5.2:

Month	ET_r (in)	Evap. Coeff. (-)	E_{Off} (in)
November	1.5	0.39	0.59
December	0.5	0.42	0.21
January	0.4	0.60	0.24
February	1.2	0.49	1.59
March	3.0	0.47	1.41
Total	**6.6**		**3.0**

$$(SM_{CO})_{Non} = \min[6.4\text{ in} - 3.0\text{ in}, 0.75\ (0.11\text{ in in}^{-1})(3\text{ ft})(12\text{ in ft}^{-1})] = 3.0\text{ in}$$

1.6.5.3 Direct Groundwater Contributions

Perhaps the greatest challenge with using Equation 1.4 rather than Equation 1.3 for estimating field depletion or Equation 1.7 Rather than Equation 1.6 for conveyance depletion is the estimation of direct groundwater contributions, when not negligible. The first step is to determine if these contributions are negligible. For this, a simple analysis was performed based on soil type and water table depth (Table 2.1). When those conditions are not met, capillary rise can be estimated using the Upflow model (Raes and Proost, 2003), which is available at: https://iupware.be/?page_id=883. Jensen and Allen (2016) recommend this method.

For conditions where the non-irrigated vegetation would extract water directly from the water table, there is likely no robust model available. If piezometer measurements are available, the White (1932) method can be used (Section *5.1.1.1.4.1*).

1.6.6 Comparisons of Depletion Component Estimation Methods

In Sections *1.6.1* through *1.6.4*, recommended methods for different depletion components were presented. Additional methods are discussed in Section 4.4. A summary based on these above-cited sections is provided in Table 1.2.

Table 1.2. Depletion Component Quantification Method Comparison Summary.

Evapotranspiration

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Reso-lution	Measurement Area	Comments
	Energy Balance Models						
1	OpenET (Ensemble)	$-$$$$$	Download	Medium-High	Daily-Monthly	100's of ft.	Post Facto
1	OpenET eeMETRIC™	$-$$$$$	Download	Medium-High	Daily-Monthly	100's of ft.	Post Facto
1	ET Fraction	$-$$$$$	Download/ Analysis	Medium-High	Daily-Monthly	Field	
3	OpenET geeSEBAL	$-$$$$$	Download	Medium-High	Daily-Monthly	100's of ft.	Post Facto
3	OpenET ReSET	$$$$$	Analysis	Medium-High	Daily-Monthly	100's of ft.	Post Facto
3	OpenET SSEBop	$-$$$$$	Download	Medium-High	Daily-Monthly	100's of ft.	Post Facto
3	OpenET Priestly-Taylor JPL	$-$$$$$	Download	Medium-High	Daily-Monthly	100's of ft.	Post Facto
3	OpenET ALEXI-DisALEXI	$-$$$$$	Download	Medium-High	Daily-Monthly	100's of ft.	Post Facto
4	---TSEB	$$$$$	Analysis	Medium-High	Daily-Monthly	100's of ft.	Post Facto

Table 1.2. Depletion Component Quantification Method Comparison Summary. (Continued)

Evapotranspiration

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Reso-lution	Measurement Area	Comments
	Reference Evapotranspiration and Crop Coefficients: Reference ET Methods						
3	ASCE Standardized Reference ET	$$$	Analysis	Low-High	Daily	Field	
4	Hargreaves and Samani	$$$	Analysis	Low-High	Monthly	Field	
5	Blaney-Criddle	$$$	Analysis	Low-High	Monthly	Field	Of historical value
	Reference Evapotranspiration and Crop Coefficients: Crop Coefficient Methods						
3	Tabulated/Equations	$$$	Analysis	Low-High	Daily	Field	Often for ideal, “potential” conditions
3	GridET	$$$	Analysis	Low-High	Daily	Field	Often for ideal, “potential” conditions
3	Reflectance-Based Crop Coefficients	$$$$	Analysis	Medium-High	Daily	100's of ft.	Often in between ideal and actual conditions
3	---SIMS	$-$$$$	Download	Medium-High	Daily-Monthly	100's of ft.	Post Facto

Canal Water Evaporation

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Reso-lution	Measurement Area	Comments
1	Reference ET and Coefficient	$$$	Analysis	Medium	Daily	Canal Reach	
2	Zero Assumption	$	N/A	Medium	N/A	N/A	

Non-Irrigated Condition Evapotranspiration

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Reso-lution	Measurement Area	Comments
1	ET Fraction w/ OpenET Ensemble or eeMETRIC™	$-$$$$$	Download/ Analysis	Medium-High	Daily-Monthly	Field	

Table 1.2. Depletion Component Quantification Method Comparison Summary. (Continued)

Consumptive Losses

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Resolution	Measurement Area	Comments
1	Surface, drip, subsurface: L_{CU} = 0	$	N/A	High	Per irrigation	Field	
2	Line-source: Eq 1.20	$$$	Analysis	Medium	Per irrigation	Field	
2	Line-source: Eq 5.48	$$$	Analysis	Low-Medium	Per irrigation	Field	
2	LEPA/LESA: Efficiency	$$	Analysis	Medium	Per irrigation	Field	
3	Big Guns: Eq. 1.22	$$$	Analysis	Low-Medium	Per irrigation	Field	
4	All systems: Eq 6.14	$$	Analysis	Low-Medium	Per irrigation	Field	Can be used for quick estimates

Precipitation

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Resolution	Measurement Area	Comments
1	Tipping Bucket	$$$	Sensor mainte-nance	Low-High	Continuous	Point	
1	Weighing Gauge	$$$$	Sensor mainte-nance	Medium-High	Continuous	Point	
2	PRISM	$$-$$$$	Download	Medium-High	Continuous	4 km (800 m for charge)	
2	Daymet	$$	Download	Medium-High	Continuous	1 km	Significant lag before data are available
2	Manual-Read Gauge	$$$	Manual measure-ments	Low-High	Per storm	Point	Accuracy depends on user

Effective Precipitation for the Non-Irrigated Condition

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Resolution	Measurement Area	Comments
1	*P - RO*	$$	Analysis	Low-High	N/A	Same as Precip.	
2	Water Balance	$-$$$$	Analysis	Medium-High	N/A	Same as Precip.	

Table 1.2. Depletion Component Quantification Method Comparison Summary. (Continued)

Runoff from Precipitation

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Resolution	Measurement Area	Comments
1	SCS Equation	$$	Analysis	Low-High	Per storm	Same as Precip.	Better than nothing

Direct Groundwater Contributions for the Non-Irrigated Condition

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Resolution	Measurement Area	Comments
1	Eq 5.8	$$$$$	Field measure-ments	Medium-High	Continuous	Varies	
2	*GW* = 0	$	N/A	Low-High	N/A	Field	

Capillary Rise for the Non-Irrigated Condition

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Resolution	Measurement Area	Comments
2	Upflow	$$$$	Analysis	Medium	Continuous	Field	
2	*CR* = 0	$	N/A	Low-High	N/A	Field	

Deep Percolation for the Non-Irrigated Condition

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Resolution	Measurement Area	Comments
2	*DP* = 0	$	N/A	Low-High	N/A	Field	
2	Water Balance	$$$$	Analysis	Medium-High	Continuous	Field	

Carryover Soil Moisture for the Non-Irrigated Condition

Rank	Method	Estimated Cost	Required Effort	Accuracy	Temporal Resolution	Measurement Area	Comments
1	Available-Water-Capacity-Based	$$$	Analysis	Low-High	N/A	N/A	
3	SM_{CO} = 0	$	Minimal	Low-High	N/A	N/A	Will bias depletion high

1.7 Recommended Operational Methods for Estimating Depletion Changes

Recommended operational methods for quantifying depletion changes from irrigated agriculture are listed in Table 1.3 and Table 1.4. It is also recommended to review Figure 2 in *Exploration of Quantification Methods for Agricultural Water Savings in the Lower Colorado River Basin: Executive Summary* Prepared by NRCE and Jacobs (2021c) and the *Executive Summary: Case Study: Validating Methods for Measuring Evapotranspiration and Accounting for Actual Depletion in Utah* Prepared by Jacobs (2023).

Table 1.3. Depletion Change Estimation Method Decision Matrix for Field Practices.

<table>
<tr><th colspan="6">Changing Irrigation Systems and Same System Automation</th></tr>
<tr><td colspan="6">Predictive Methods</td></tr>
<tr><th colspan="3">ΔET_{Crop}</th><th colspan="2">ΔL_{CU}</th></tr>
<tr><th>Condition</th><th>ET_{Crop}</th><th>Strategy</th><th>System</th><th>L_{CU}</th></tr>
<tr><td>Field is ≥ 10 acres</td><td>Rank 1: OpenET & ET Fraction</td><td>Space</td><td>Drip: Surface, Subsurface, Mobile</td><td>0</td></tr>
<tr><td rowspan="2">Field is < 10 acres</td><td>Rank 2: ASCE Std. ET_{ref} × Table K_c or GridET</td><td rowspan="2">Use Historic Average</td><td>Sprinkler: Big Gun</td><td>Eq 1.23 w/ Wind Loss Reduction</td></tr>
<tr><td>Rank 3: Hargreaves ET_{ref} × Table K_c</td><td>Sprinkler: Pivot/Lateral - LESA/LEPA</td><td>10% w/ Wind Loss Reduction</td></tr>
<tr><td rowspan="7"></td><td rowspan="7"></td><td rowspan="7"></td><td>Sprinkler: Pivot/Lateral - MESA</td><td>Eq. 1.22 w/ Wind Loss Reduction</td></tr>
<tr><td>Sprinkler: Pivot/Lateral - Top of Pipe</td><td>Eq. 1.21 w/ Wind Loss Reduction</td></tr>
<tr><td>Sprinkler: Wheel Line, Hand Line, Solid Set, Micro</td><td>Eq. 1.21 w/ Wind Loss Reduction</td></tr>
<tr><td>Subirrigation</td><td>0</td></tr>
<tr><td>Surface: Blocked Furrow, Border, Basin, Surge</td><td rowspan="3">Negligible, Should be in OpenET Products When Ponding is Long</td></tr>
<tr><td>Surface: Non-Blocked Furrow, Border, Surge</td></tr>
<tr><td>Surface: Wild Flood</td></tr>
</table>

Table 1.3. Depletion Change Estimation Method Decision Matrix for Field Practices. (Continued)

<table>
<tr><th colspan="5">Changing Irrigation Systems and Same System Automation</th></tr>
<tr><td colspan="5">Post-Facto Methods</td></tr>
<tr><th colspan="3">ΔET_{Crop}</th><th colspan="2">ΔL_{CU}</th></tr>
<tr><th>Condition</th><th>ET_{Crop}</th><th>Strategy</th><th>System</th><th>L_{CU}</th></tr>
<tr><td rowspan="4">Field is ≥ 10 acres</td><td>Rank 1: OpenET</td><td rowspan="3">Time and Space</td><td>Drip: Surface, Subsurface, Mobile</td><td>0</td></tr>
<tr><td rowspan="2">Rank 2: OpenET & ET Fraction</td><td>Sprinkler: Big Gun</td><td>Eq 1.23 w/ Wind Loss Reduction</td></tr>
<tr><td>Sprinkler: Pivot/Lateral - LESA/LEPA</td><td>10% w/ Wind Loss Reduction</td></tr>
<tr><td>Rank 3: ASCE Std. ET_{ref} × Reflectance-Based-K_c</td><td>Time</td><td>Sprinkler: Pivot/Lateral - MESA</td><td>Eq. 1.22 w/ Wind Loss Reduction</td></tr>
<tr><td rowspan="3">Field is < 10 acres</td><td>Rank 2: OpenET & ET Fraction</td><td>Time and Space</td><td>Sprinkler: Pivot/Lateral - Top of Pipe</td><td>Eq. 1.21 w/ Wind Loss Reduction</td></tr>
<tr><td>Rank 5: ASCE Std. ET_{ref} × Table K_c or GridET</td><td rowspan="2">Time</td><td>Sprinkler: Wheel Line, Hand Line, Solid Set, Micro</td><td>Eq. 1.21 w/ Wind Loss Reduction</td></tr>
<tr><td>Rank 6: Hargreaves ET_o × Table K_c</td><td>Subirrigation</td><td>0</td></tr>
<tr><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td>Surface: Blocked Furrow, Border, Basin, Surge</td><td rowspan="3">Negligible, Should be in OpenET Products When Ponding is Long</td></tr>
<tr><td>Surface: Non-Blocked Furrow, Border, Surge</td></tr>
<tr><td>Surface: Wild Flood</td></tr>
</table>

Table 1.3. Depletion Change Estimation Method Decision Matrix for Field Practices. (Continued)

Changing Crops, Deficit Irrigation, and Ceasing Irrigation			
Predictive and Post-Facto Methods			
ΔET_{Crop}		**ΔL_{CU}**	
Same as *Changing Irrigation Systems and Same System Automation*		Same as *Changing Irrigation Systems and Same System Automation*	
$\Delta(ET_{Non})_{Seas}$		**$\Delta[(P_{Eff})_{Non}]_{Seas}$**	
ET_{Crop}	**Strategy**	**$(P_{Eff})_{Non}$**	**Strategy**
Rank 1: OpenET & ET Fraction	Time	Rank 1: *P - RO*	All
		P	**Strategy**
		Rank 1: Nearby Rain Gauge	Time/Historic
		Rank 2: Daymet or PRISM	Time/Historic
		RO	**Strategy**
		Rank 1: SCS Eq.	Time/Historic
$\Delta[(SM_{CO})_{Non}]_{Seas}$		**$\Delta(GW_{Non})_{Seas}$**	
$(SM_{CO})_{Non}$	**Strategy**	**GW_{Non}**	**Strategy**
Rank 1: AWC Method	Time/Historic	Rank 1: Assume 0 If Water Table is Deep	All
		Rank 2: Upflow for Capillary Rise	All
		Rank 3: Direct Extraction, No Practical Method	Time/Historic

Table 1.4. Depletion Change Estimation Method Decision Matrix for Conveyance Systems.

Conveyance System Changes			
Predictive Methods and Post-Facto – No Change to Irrigation Season Length			
Δ(ET_{Corr})$_{Seas}$		**Δ(E_{Open})$_{Seas}$**	
ET_{Corr}	**Strategy**	**System**	**E_{Open}**
Rank 1: OpenET & ET Fraction	Space	Canal	0.6 ET_r
Rank 2: ASCE Std. ET_{ref} × Hi-Res Reflectance-Based-K_c	Time/Historic	Pipe	0
Rank 3: ASCE Std. ET_{ref} × Table K_c or GridET			
Rank 4: Hargreaves ET_{ref} × Table K_c			
Predictive and Post-Facto Methods – No Change to Irrigation Season Length			
ΔET_{Corr}		**ΔE**	
Same Methods as No Change to Irrigation Season		*Same Methods as No Change to Irrigation Season*	
Δ(ET_{Non})$_{Seas}$		**Δ[(P_{Eff})$_{Non}$]$_{Seas}$**	
ET_{Crop}	**Strategy**	**(P_{Eff})$_{Non}$**	**Strategy**
Rank 1: OpenET & ET Fraction	Time	Rank 1: P - RO	All
		P	**Strategy**
		Rank 1: Nearby Rain Gauge	Time/Historic
		Rank 2: Daymet or PRISM	Time/Historic
		RO	**Strategy**
		Rank 1: SCS Eq.	Time/Historic
Δ[(SM_{CO})$_{Non}$]$_{Seas}$		**Δ(GW_{Non})$_{Seas}$**	
(SM_{CO})$_{Non}$	**Strategy**	**GW_{Non}**	**Strategy**
Rank 1: AWC Method	Time/Historic	Rank 1: Assume 0 If Water Table is Deep	All
		Rank 2: Upflow for Capillary Rise	All
		Rank 3: Direct Extraction, No Practical Method	Time/Historic

1.8 Conclusion

Depletion from irrigated agriculture is a quantity that is not directly measurable. There are several reasonable methods that can be used to estimate depletion from agricultural fields. Among these, the use of OpenET's ensemble and eeMETRIC™ evapotranspiration products are recommended for quantifying ET for crops for fields greater than 10 acres. For fields less than 10 acres and conveyance corridors, it is recommended to use these two OpenET products for a representative area and then apply them to the subject area using the evaporative fraction method. When this is not possible, appropriate crop coefficient methods are recommended. However, these methods typically provide an idealized ET that an overestimate of actual ET. Consumptive irrigation losses are best quantified using empirical relationships, though simple loss fractions may be appropriate in some cases. Canal evaporation can be estimated as a fraction of reference ET or assumed to be zero for narrow canals and short reaches.

For irrigation practice changes that do not affect the irrigation season length, the above parameters are sufficient for computing a depletion change. For practices that change the irrigation season length, the non-irrigated condition ET must be estimated for the irrigation season period. This can be done using an OpenET product for a representative area (e.g., nearby range) and then applied using the evaporative fraction method to the subject area. If this is unreasonable, effective precipitation, carryover soil moisture, and groundwater contributions can be estimated for the non-irrigated condition for the irrigation season period. In Utah, effective precipitation can be estimated by subtracting runoff from rain gauge, Daymet, or PRISM precipitation. Runoff can be estimated using the SCS runoff equation. Carryover soil moisture can be estimated based on estimates of off-season evaporation and soil available water capacity. If the water table is too shallow to neglect, contributions from groundwater can be estimated using the Upflow model for capillary rise. Direct contributions from groundwater can be estimated using the White method, but this is not practical.

2 Development of a Depletion Definition for Fields

2.1 Definition Development

The two primary components of depletion can be summarized as:

$$D = CU_{Irr} - CU_{Non} \tag{2.1}$$

where:

D	=	Depletion (AFY),
CU_{Irr}	=	Consumptive use under the irrigated condition (AFY), and
CU_{Non}	=	Consumptive use under the non-irrigated condition (AFY).

For most irrigated land, the CU under non-irrigated conditions would only have included evapotranspiration (ET) from the natural or other non-irrigated landcover. For a field, the irrigated CU includes ET from the cropland plus any consumptive losses between the point of delivery to the field and the water reaching the plant/soil surface. Therefore, the D definition becomes:

$$D_{Field} = ET_{Irr} + L_{CU} - ET_{Non} \tag{2.2}$$

where:

D_{Field}	=	Depletion from an irrigated field (AFY),
ET_{Irr}	=	Evapotranspiration of the irrigated cropland (AFY),
L_{CU}	=	Consumptive losses of irrigation water (AFY), and
ET_{Non}	=	Evapotranspiration of the non-irrigated landcover (AFY).

In most cases, consumptive losses are any evaporative losses. That is, the direct evaporation of irrigation water as it is applied to the field. This includes evaporation from sprinkler droplets as they travel through the air; it can also include direct evaporation from water ponded during surface irrigation.

Quantifying ET during the offseason can be particularly difficult. However, during that portion of the year, ET is typically small. Often, it is safe to assume that the ET and sublimation from irrigated cropland is similar in magnitude to the non-irrigated cover (Figure 1.1). This simplification has been employed in Utah for decades (e.g., Hill et al., 2011; Hill, 1994; Hill et al., 1989). Using this simplification, D_{Field} becomes:

$$D_{Field} = (ET_{Irr})_{Season} + L_{CU} - (ET_{Non})_{Season} \tag{2.3}$$

where:

D_{Field}	=	Depletion from an irrigated field (AFY),
$(ET_{Irr})_{Season}$	=	Evapotranspiration of the irrigated cropland during the irrigation season (AFY),

L_{CU} = Consumptive losses of irrigation water (AFY), and
$(ET_{Non})_{Season}$ = Evapotranspiration of the non-irrigated landcover during the irrigation season (AFY).

It is more common to represent $(ET_{Irr})_{Season}$ as ET_{Crop}, resulting in:

$$D_{Field} = ET_{Crop} + L_{CU} - (ET_{Non})_{Season} \tag{2.4}$$

where:

D_{Field} = Depletion from an irrigated field (AFY),
ET_{Crop} = Irrigated crop evapotranspiration (AFY),
L_{CU} = Consumptive losses of irrigation water (AFY), and
$(ET_{Non})_{Season}$ = Evapotranspiration of the non-irrigated landcover during the irrigation season (AFY).

The challenge with quantifying $(ET_{Non})_{Season}$ is that the non-irrigated condition is not observable at the same time and location as the irrigated condition. So, it is sometimes necessary to estimate this component less directly. This can be done because ET is equal to the sum of its contributing water sources:

$$(ET_{Non})_{Season} = \left(P_{Eff}\right)_{Non} + GW_{Non} + \left(SM_{Begin}\right)_{Non} - (SM_{End})_{Non} \tag{2.5}$$

where:

$(ET_{Non})_{Season}$ = Evapotranspiration of the non-irrigated landcover during the irrigation season (AFY).
$(P_{Eff})_{Non}$ = Effective precipitation for the non-irrigated condition during the irrigation season (AFY),
GW_{Non} = Groundwater contributions to the non-irrigated ET during the irrigation season (AFY),
$(SM_{Begin})_{Non}$ = Soil water storage for the non-irrigated condition at the beginning of the irrigation season (AFY), and
$(SM_{End})_{Non}$ = Soil water storage for the non-irrigated condition at the end of the irrigation season (AFY).

The $(P_{Eff})_{Non}$ is the portion of precipitation that contributes to the non-irrigated ET. When shallow groundwater (a high water table) is present, like in many riparian corridors, non-irrigated vegetation is naturally sub-irrigated, which is accounted for using GW_{Non}. The difference between $(SM_{End})_{Non}$ and $(SM_{Begin})_{Non}$ is the amount of water stored in the soil outside of the irrigation season that is available for non-irrigated plant growth.

It is often helpful to consider the available soil water storage from off-season precipitation in terms of water accumulated in the soil between the beginning of the irrigation season and the end of the previous irrigation season. This difference is called carryover soil moisture (e.g., Hill et al., 1989):

$$(SM_{CO})_{Non} = \left(SM_{Begin}\right)_{Non} - \left(SM_{End,Prev}\right)_{Non} \tag{2.6}$$

where:

$(SM_{CO})_{Non}$	=	Carryover soil moisture from the non-irrigation season for the non-irrigated condition (AFY),
$(SM_{Begin})_{Non}$	=	Soil water storage for the non-irrigated condition at the beginning of the irrigation season (AFY), and
$(SM_{End,Prev})_{Non}$	=	Soil water storage for the non-irrigated condition at the end the previous irrigation season (AFY).

Combining Equations 2.4 and 2.5, D_{Field} can be defined as:

$$D_{Field} = ET_{Crop} + L_{CU} - \left(P_{Eff}\right)_{Non} - GW_{Non} + \left(SM_{Begin}\right)_{Non} - (SM_{End})_{Non} \tag{2.7}$$

where:

D_{Field}	=	Depletion from an irrigated field (AFY),
ET_{Crop}	=	Evapotranspiration of the irrigated cropland during the irrigation season (AFY),
L_{CU}	=	Consumptive losses of irrigation water (AFY),
$(P_{Eff})_{Non}$	=	Effective precipitation for the non-irrigated condition during the irrigation season (AFY),
GW_{Non}	=	Groundwater contributions to the non-irrigated ET during the irrigation season (AFY),
$(SM_{Begin})_{Non}$	=	Soil water storage for the non-irrigated condition at the beginning of the irrigation season (AFY), and
$(SM_{End})_{Non}$	=	Soil water storage for the non-irrigated condition at the end of the irrigation season (AFY).

However, the form combining Equations 2.4 and 2.6 is more practical:

$$D_{Field} = ET_{Crop} + L_{CU} - \left(P_{Eff}\right)_{Non} - GW_{Non} - (SM_{CO})_{Non} \tag{2.8}$$

where:

D_{Field}	=	Depletion from an irrigated field (AFY),
ET_{Crop}	=	Irrigated crop evapotranspiration (AFY),
L_{CU}	=	Consumptive losses of irrigation water (AFY),
$(P_{Eff})_{Non}$	=	Effective precipitation for the non-irrigated condition during the irrigation season (AFY),
GW_{Non}	=	Groundwater contributions to the non-irrigated ET during the irrigation season (AFY), and
$(SM_{CO})_{Non}$	=	Carryover soil moisture for the non-irrigation season during the non-irrigated condition (AFY).

The question may be asked why P_{eff}, GW, and SM_{CO} in Equations 2.5, 2.6, and 2.8 are specifically for the non-irrigated condition. In some D_{Field} estimates, these terms are instead defined for the irrigated condition. However, based on Equations 2.4 and 2.5, these must be considered for the non-irrigated condition.

Consider a soil root zone water balance (Figure 2.1). For the non-irrigated condition, some precipitation may infiltrate into the soil, and some may run off. As the pore space in the soil fills, water drains downward driven by gravity and capillary forces. These forces can cause some of the infiltrated water to drain below the plant's roots. This is called deep percolation or deep drainage.

In some cases, the root zone is immediately above the water table, or it may extend into it enabling direct extraction from the groundwater. If the root zone is sufficiently drier than the soil below it, there may be an upward flow of water called capillary rise, which is sometimes included as part of groundwater contributions. Often, one of the largest components of the soil water balance is the extraction and transpiration of water by the plant and evaporation of water from the soil surface.

The soil water balance for the non-irrigated condition can be represented in terms of the volume of water stored in the soil following the assumptions above as:

$$(SM_{End})_{Non} = \left(SM_{Begin}\right)_{Non} + P - RO_{Non} - DP_{Non} + GW_{Non} - ET_{Non} \qquad (2.9)$$

where:

$(SM_{End})_{Non}$	=	Soil water storage for the non-irrigated condition at the end of the period (AFY),
$(SM_{Begin})_{Non}$	=	Soil water storage for the non-irrigated condition at the beginning the period (AFY),
P	=	Precipitation during the period (AFY),
RO_{Non}	=	Runoff for the non-irrigated condition during the period (AFY),
DP_{Non}	=	Deep percolation for the non-irrigated condition during the period (AFY),
GW_{Non}	=	Groundwater contributions for the non-irrigated condition during the period, including capillary rise (AFY), and
ET_{Non}	=	Evapotranspiration for the non-irrigated condition during the period (AFY).

Considering only the gains and losses specific to precipitation, gives:

$$\left(P_{Eff}\right)_{Non} = P - RO_{Non} - DP_{Non} \qquad (2.10)$$

where:

$(P_{Eff})_{Non}$	=	Effective precipitation for the non-irrigated condition

		(AFY),
P	=	Precipitation (AFY)
RO_{Non}	=	Runoff for the non-irrigated condition (AFY), and
DP_{Non}	=	Deep percolation for the non-irrigated condition (AFY).

Substituting Equation 2.10 into Equation 2.9 yields Equation 2.5.

Because the crop root zone in the non-irrigated condition may not be the same depth as in the irrigated condition, deep percolation from rainfall and groundwater contributions are not necessarily the same for the irrigated and non-irrigated conditions. Similarly, the runoff potential for the irrigated and non-irrigated conditions are not necessarily equal.

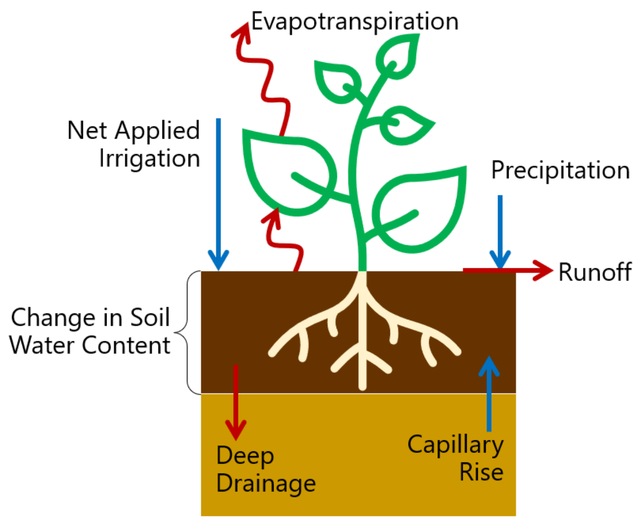

Figure 2.1. Conceptual depiction of a crop rootzone soil water balance. Inflows have blue arrows and outflows have red arrows. Subsurface lateral inflows and outflows are neglected here.

2.2 Possible Simplifications

In some cases, Equation 2.8 (or Equation 2.4) may be simplified. For example, in some cases GW_{Non} can be neglected. To demonstrate this, simple steady-state capillary rise estimates were computed using HYDRUS-1D software (Simunek et al, 2005) for different soil texture classes assuming a matric potential equal to -100 kPa at the bottom of the crop root zone. The minimum depth to water table below the root zone resulting in 1 in of capillary rise or less was computed assuming a 180-day irrigation season. The value ranges from 1 ft to 19 ft (Table 2.1). If these conditions are met, GW_{Non} might safely be neglected, and Equation 2.8 reduces to:

$$D_{Field} = ET_{Crop} + L_{CU} - \left(P_{Eff}\right)_{Non} - (SM_{CO})_{Non} \tag{2.11}$$

where:

D_{Field}	=	Depletion from an irrigated field (AFY),
ET_{Crop}	=	Evapotranspiration of the irrigated cropland during the

		irrigation season (AFY),
L_{CU}	=	Consumptive losses of irrigation water (AFY),
$(P_{Eff})_{Non}$	=	Effective precipitation for the non-irrigated condition during the irrigation season (AFY), and
$(SM_{CO})_{Non}$	=	Carryover soil moisture from the non-irrigation season for the non-irrigated condition (AFY).

If the GW_{Non} = 0 assumption is made incorrectly, the result will be an overestimation of D_{Field}.

In some cases, it may be acceptable to assume that $(SM_{CO})_{Non} = 0$, or $(SM_{End})_{Non} - (SM_{Begin})_{Non} = 0$. While this should not be routinely done (Section 5.5.3.2), this assumption depends heavily on the non-irrigated landcover. For example, sagebrush and other bushes often have deep root zones and transpire late into the year while native cool season grasses often have shallow root systems and rely mostly on spring rain (E. Thacker, Utah State University, Personal Communication, 2024). In cases where $(SM_{CO})_{Non} \approx 0$:

$$D_{Field} \approx ET_{CROP} + L_{CU} - \left(P_{Eff}\right)_{Non} - GW_{Non} \tag{2.12}$$

or (if appropriate):

$$D_{Field} \approx ET_{CROP} + L_{CU} - \left(P_{Eff}\right)_{Non} \tag{2.13}$$

where:

D_{Field}	=	Depletion from an irrigated field (AFY),
ET_{Crop}	=	Evapotranspiration of the irrigated cropland during the irrigation season (AFY),
L_{CU}	=	Consumptive losses of irrigation water (AFY),
$(P_{Eff})_{Non}$	=	Effective precipitation for the non-irrigated condition during the irrigation season (AFY), and
GW_{Non}	=	Groundwater contributions for the non-irrigated condition during the period, including capillary rise (AFY).

If the assumption that $(SM_{CO})_{Non} = 0$ is made in error, D_{Field} will be overestimated. This is most likely to occur in locations with significant winter precipitation.

Table 2.1. Estimated Depth to Water Table Values Resulting in 1 Inch of Capillary Rise Over a 180-Day Irrigation Season.

Soil Texture	**θ^1 ($m^3\ m^{-3}$)**	**DTW[2] (ft)**
Clay	0.32	7
Silty Clay	0.32	3
Sandy Clay	0.23	3
Clay Loam	0.22	13
Silty Clay Loam	0.29	11
Sandy Clay Loam	0.14	4
Silt	0.18	19
Silt Loam	0.18	18
Loam	0.12	11
Sandy Loam	0.07	3
Loamy Sand	0.06	2
Sand (e.g., pure sand)	0.05	1

[1]Volumetric soil water content corresponding to -100 kPa matric potential used in modeling.
[2]Depth to water table **BELOW THE ROOT ZONE** computed using HYDRUS-1D with default soil moisture release curve coefficients based on texture classes.

To demonstrate this concept, an oversimplified analysis was performed using the mean precipitation and reference ET for Utah sites in Hill et al. (2011). Mean $(SM_{CO})_{Non}$ was estimated for non-irrigated vegetation assuming a 4-ft root zone for non-irrigated vegetation depleted to 75% of available water capacity by the end of September for a range of available water capacity values typical of agricultural soils (Hargreaves and Merkley, 1998). Offseason evaporation was estimated using evaporation coefficients from Table 5.2. Potential $(SM_{CO})_{Non}$ was computed using Equation 5.61, assuming 80% of precipitation infiltrated.

The median SM_{CO} for each site and crop was then mapped (Figure 2.2). This analysis is too crude to draw a conclusion regarding where the $(SM_{CO})_{Non} = 0$ is valid but is sufficient to demonstrate that is may not always be valid. When it is not valid, the assumption will result in underestimated D_{Field}.

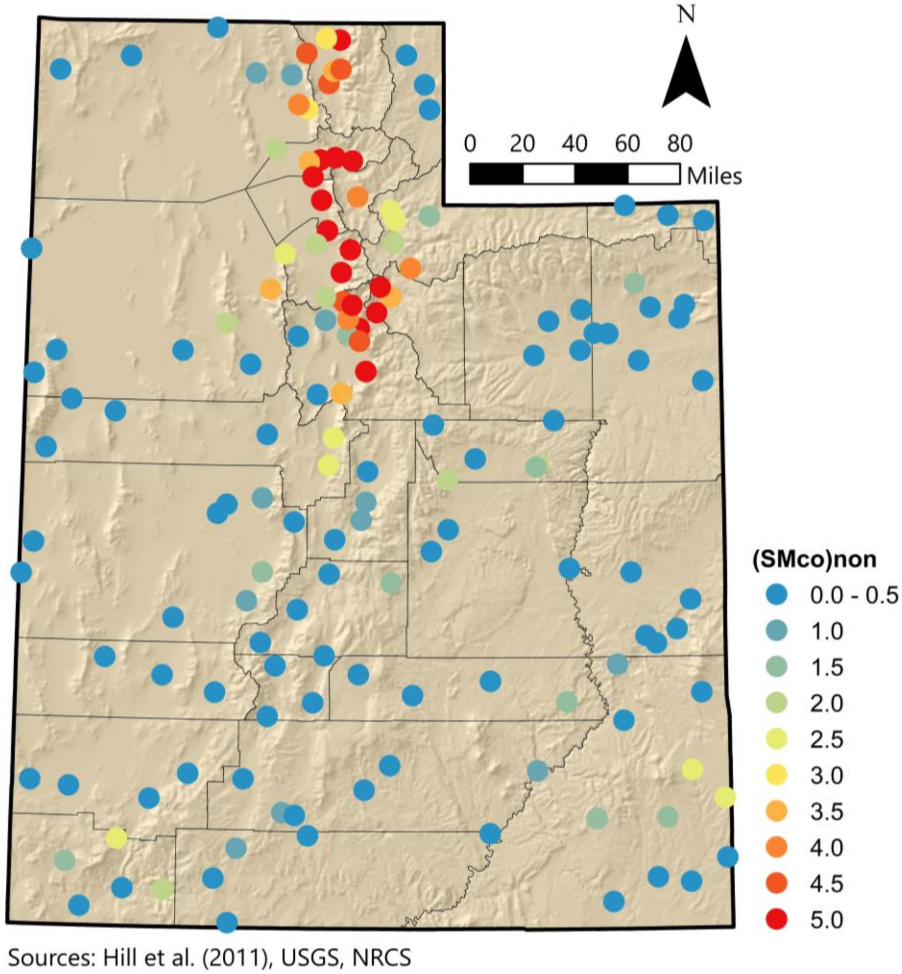

Figure 2.2. Map of estimated mean potential carry-over soil moisture in inches for locations in Utah included in the report of Hill et al. (2011).

3 Development of a Depletion Definition for Conveyance Systems

3.1 Definition Development

Depletion from irrigation conveyance systems is conceptually like that of fields (Section 2). However, instead of crop ET and consumptive losses, there are ET from vegetation that is derived from seeped water from the canal and direct open water surface evaporation.

$$D_{Conv} = ET_{Corr} + E_{Open} + E_{Bed} - ET_{Non} \tag{3.1}$$

where:

D_{Conv}	=	Depletion from conveyed water (AFY),
ET_{Corr}	=	Evapotranspiration from vegetation in the conveyance corridor (AFY),
E_{Open}	=	Direct evaporation from open water surface evaporation (AFY),
E_{Bed}	=	Direct evaporation of wet canal bed evaporation (AFY), and
ET_{Non}	=	Evapotranspiration of the non-irrigated conveyance corridor landcover (AFY).

Again, it is common practice to quantify depletion only for the irrigation/growing season, yielding:

$$D_{Conv} = (ET_{Corr})_{Season} + (E_{Open})_{Season} + (E_{Bed})_{Season} - (ET_{Non})_{Season} \tag{3.2}$$

where:

D_{Conv}	=	Depletion from conveyed water (AFY),
$(ET_{Corr})_{Season}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season (AFY),
$(E_{Open})_{Season}$	=	Direct open water during the irrigation season (AFY),
$(E_{Bed})_{Season}$	=	Wet canal bed evaporation during the irrigation season (AFY), and
$(ET_{Non})_{Season}$	=	Evapotranspiration of the non-irrigated conveyance corridor landcover during the irrigation season (AFY).

Like fields, it may be difficult to quantify $(ET_{Non})_{Season}$. In such situations, it is helpful to consider terms differently. Adapting Equations 2.7 and 2.8 for conveyance systems gives:

$$D_{Conv} = (ET_{Corr})_{Season} + (E_{Open})_{Season} + (E_{Bed})_{Season} - (P_{Eff})_{Non} - GW_{Non} - (SM_{End})_{Non} + (SM_{Begin})_{Non} \tag{3.3}$$

and

$$D_{Conv} = (ET_{Corr})_{Season} + \left(E_{Open}\right)_{Season} + (E_{Bed})_{Season} - \left(P_{Eff}\right)_{Non} - GW_{Non} - (SM_{CO})_{Non} \tag{3.4}$$

respectively, where:

D_{Conv}	=	Depletion from conveyed water (AFY),
$(ET_{Corr})_{Season}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season (AFY),
$(E_{Open})_{Season}$	=	Direct open water during the irrigation season (AFY),
$(E_{Bed})_{Season}$	=	Wet canal bed evaporation during the irrigation season (AFY),
$(P_{Eff})_{Non}$	=	Effective precipitation for the non-irrigated condition during the irrigation season (AFY),
GW_{Non}	=	Groundwater contributions to the non-irrigated ET during the irrigation season (AFY),
$(SM_{End})_{Non}$	=	Soil water storage for the non-irrigated condition at the end of the irrigation season (AFY),
$(SM_{Begin})_{Non}$	=	Soil water storage for the non-irrigated condition at the beginning of the irrigation season (AFY), and
$(SM_{CO})_{Non}$	=	Carryover soil moisture from the non-irrigation season for the non-irrigated condition (AFY).

Recall ET_{Corr} is for vegetation specifically being supplied by the canal through seepage. This vegetation is often grasses, reeds, water loving bushes like willows, and water loving trees like cottonwoods. Therefore, $(P_{Eff})_{Non}$, GW_{Non}, $(SM_{End})_{Non}$, $(SM_{Begin})_{Non}$ and $(SM_{CO})_{Non}$ all apply to the same area that that corridor vegetation occupies plus the open water surface area of the canal. GW_{Non} does not include groundwater contributions to the canal stream itself (i.e., in a gaining canal reach).

3.2 Possible Simplifications

In some cases, Equation 3.4 can be reduced as was done from Equation 2.8 to Equations 2.11 through 2.13. If GW_{Non} can safely be neglected (see Table 2.1), then:

$$D_{Conv} = (ET_{Corr})_{Season} + \left(E_{Open}\right)_{Season} + (E_{Bed})_{Season} - \left(P_{Eff}\right)_{Non} - (SM_{CO})_{Non} \tag{3.5}$$

where:

D_{Conv}	=	Depletion from conveyed water (AFY),
$(ET_{Corr})_{Season}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season (AFY),
$(E_{Open})_{Season}$	=	Direct open water during the irrigation season (AFY),
$(E_{Bed})_{Season}$	=	Wet canal bed evaporation during the irrigation season (AFY),
$(P_{Eff})_{Non}$	=	Effective precipitation for the non-irrigated condition during the irrigation season (AFY), and
$(SM_{CO})_{Non}$	=	Carryover soil moisture from the non-irrigation season

for the non-irrigated condition (AFY).

As with D_{Field} estimates, neglecting GW_{Non} where inappropriate, will lead to an overestimate of D_{Conv}. One consideration for canal conveyance corridors is that, relative to irrigated fields, the overall D_{Conv} is small simply because the area is much smaller in total.

Where it can safely be assumed that $(SM_{CO})_{Non}$ is negligible (see Equations 2.12 and 2.13 and associated discussion), Equation 3.4 simplifies to:

$$D_{Conv} \approx (ET_{Corr})_{Season} + \left(E_{Open}\right)_{Season} + \left(E_{Open}\right)_{Season} - \left(P_{Eff}\right)_{Non} - GW_{Non} \tag{3.6}$$

or (if appropriate):

$$D_{Conv} \approx (ET_{Corr})_{Season} + \left(E_{Open}\right)_{Season} + \left(E_{Open}\right)_{Season} - \left(P_{Eff}\right)_{Non} \tag{3.7}$$

where:

D_{Conv}	=	Depletion from conveyed water (AFY),
$(ET_{Corr})_{Season}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season (AFY),
$(E_{Open})_{Season}$	=	Direct open water during the irrigation season (AFY),
$(E_{Bed})_{Season}$	=	Wet canal bed evaporation during the irrigation season (AFY),
$(P_{Eff})_{Non}$	=	Effective precipitation for the non-irrigated condition during the irrigation season (AFY), and
GW_{Non}	=	Groundwater contributions to the non-irrigated ET during the irrigation season (AFY).

Again, if the assumption of $(SM_{CO})_{Non} = 0$ is made in error, D_{Conv} will be overestimated. This is most likely to occur in locations with significant winter precipitation.

4 Workable Depletion Change Definitions

The specific subject of the present report is estimating changes in depletion. That is:

$$\Delta D = D_{After} - D_{Before} \tag{4.1}$$

where:

ΔD	=	Change in depletion from *before* the practice is changed to *after* (AFY),
D_{After}	=	Depletion *after* the change (AFY), and
D_{Before}	=	Depletion *before* the change (AFY).

The primary complication is that it is impossible to observe both the *before* and *after* conditions for a specific location at the same instant.

4.1 Depletion Change for Field Practices

For field-level irrigation practice changes, Equations 4.1 and 2.3 can be combined, yielding:

$$\begin{aligned}\Delta D_{Field} = \left[\left(ET_{Crop}\right)_{After} - \left(ET_{Crop}\right)_{Before}\right] + \left[(L_{CU})_{After} - (L_{CU})_{Before}\right] \\ - \left\{\left[(ET_{Non})_{Season}\right]_{After} - \left[(ET_{Non})_{Season}\right]_{Before}\right\}\end{aligned} \tag{4.2}$$

where:

ΔD_{Field}	=	Change in field-level depletion from *before* the practice is changed to *after* (AFY),
$(ET_{Crop})_{After}$	=	Irrigated crop evapotranspiration *after* the change (AFY),
$(ET_{Crop})_{Before}$	=	Irrigated crop evapotranspiration *before* the change (AFY),
$(L_{CU})_{After}$	=	Consumptive losses from irrigation water *after* the change (AFY),
$(L_{CU})_{Before}$	=	Consumptive losses from irrigation water *before* the change (AFY),
$[(ET_{Non})_{Season}]_{After}$	=	Evapotranspiration of the non-irrigated landcover during the *after*-condition irrigation season (AFY), and
$[(ET_{Non})_{Season}]_{Before}$	=	Evapotranspiration of the non-irrigated landcover during the *before*-condition irrigation season (AFY).

Where it is not practical to estimate $(ET_{Non})_{Season}$, Equation 4.1 can be combined with Equation 2.8:

$$\Delta D_{Field} = \left[\left(ET_{Crop}\right)_{After} - \left(ET_{Crop}\right)_{Before}\right] + \left[(L_{CU})_{After} - (L_{CU})_{Before}\right] \\ - \left\{\left[\left(P_{Eff}\right)_{Non}\right]_{After} - \left[\left(P_{Eff}\right)_{Non}\right]_{Before}\right\} \\ - \left[(GW_{Non})_{After} - (GW_{Non})_{Before}\right] \\ - \left\{\left[(SM_{CO})_{Non}\right]_{After} - \left[(SM_{CO})_{Non}\right]_{Before}\right\} \tag{4.3}$$

where:

ΔD_{Field}	=	Change in field-level depletion from *before* the practice is changed to *after* (AFY),
$(ET_{Crop})_{After}$	=	Irrigated crop evapotranspiration *after* the change (AFY),
$(ET_{Crop})_{Before}$	=	Irrigated crop evapotranspiration *before* the change (AFY),
$(L_{CU})_{After}$	=	Consumptive losses from irrigation water *after* the change (AFY),
$(L_{CU})_{Before}$	=	Consumptive losses from irrigation water *before* the change (AFY),
$[(P_{Eff})_{Non}]_{After}$	=	Effective precipitation for the non-irrigated condition during the irrigation season *after* the change (AFY),
$[(P_{Eff})_{Non}]_{Before}$	=	Effective precipitation for the non-irrigated condition during the irrigation season *before* the change (AFY),
$(GW_{Non})_{After}$	=	Groundwater contributions to the non-irrigated ET during the irrigation season *after* the change (AFY),
$(GW_{Non})_{Before}$	=	Groundwater contributions to the non-irrigated ET during the irrigation season *before* the change (AFY),
$[(SM_{CO})_{Non}]_{After}$	=	Carryover soil moisture from the non-irrigation season for the non-irrigated condition *after* the change (AFY), and
$[(SM_{CO})_{Non}]_{Before}$	=	Carryover soil moisture from the non-irrigation season for the non-irrigated condition *before* the change (AFY).

Conveniently, when an irrigation practice change does not alter the irrigation season length, the non-irrigated condition does not change, so $[(ET_{Non})_{Season}]_{After} = [(ET_{Non})_{Season}]_{Before}$, $[(P_{Eff})_{Non}]_{After} = [(P_{Eff})_{Non}]_{Before}$, $(GW_{Non})_{After} = (GW_{Non})_{Before}$, and $[(SM_{CO})_{Non}]_{After} = [(SM_{CO})_{Non}]_{Before}$. Therefore,

$$\Delta D_{Field} = \left[\left(ET_{Crop}\right)_{After} - \left(ET_{Crop}\right)_{Before}\right] + \left[(L_{CU})_{After} - (L_{CU})_{Before}\right] \tag{4.4}$$

where:

ΔD_{Field}	=	Change in field-level depletion from *before* the practice is changed to *after* (AFY),
$(ET_{Crop})_{After}$	=	Irrigated crop evapotranspiration *after* the change (AFY),
$(ET_{Crop})_{Before}$	=	Irrigated crop evapotranspiration *before* the change (AFY),
$(L_{CU})_{After}$	=	Consumptive losses from irrigation water *after* the change (AFY), and
$(L_{CU})_{Before}$	=	Consumptive losses from irrigation water *before* the change (AFY).

Changes that do not alter the irrigation season length include:

- Changing irrigation systems,
- Changing irrigation system efficiency,
- Crop changes that do not significantly change the growing season,
- Irrigation system automation,
- Deficit irrigation that does not involve ceasing irrigation prematurely in the season or starting irrigation late in the season, and
- Improved irrigation management.

For changes that do alter the irrigation season, the full version of Equation 4.2 or Equation 4.3 should be used. These practices include:

- Crop changes that result in a change in growing season length,
- Deficit irrigation that results in a change in irrigated growing season,
- Full-season fallowing, and
- Partial-season fallowing.

In these conditions, Equations 4.2 and 4.3 can sometimes be partially simplified following the discussion in Section 2.2.

4.2 Depletion Change for Conveyance Systems

For conveyance system changes, Equation 4.1 can be combined with Equation 3.2:

$$\begin{aligned}\Delta D_{Corr} = &\left\{[(ET_{Corr})_{Season}]_{After} - [(ET_{Corr})_{Season}]_{Before}\right\} \\ &+ \left[\left(E_{Open}\right)_{After} - \left(E_{Open}\right)_{Before}\right] + \left[(E_{Bed})_{After} - (E_{Bed})_{Before}\right] \\ &- \left\{[(ET_{Non})_{Season}]_{After} - [(ET_{Non})_{Season}]_{Before}\right\}\end{aligned} \tag{4.5}$$

where:

ΔD_{Conv}	=	Change in depletion from conveyed water from *before* the practice is changed to *after* (AFY),
$[(ET_{Corr})_{Season}]_{After}$	=	Evapotranspiration from vegetation in the

		conveyance corridor during the irrigation season *after* the change (AFY),
$[(ET_{Corr})_{Season}]_{Before}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season *before* the change (AFY),
$(E_{Open})_{After}$	=	Direct evaporation of conveyed water (open water surface evaporation) *after* the change (AFY),
$(E_{Open})_{Before}$	=	Direct evaporation of conveyed water (open water surface evaporation) *before* the change (AFY),
$(E_{Bed})_{After}$	=	Wet canal bed evaporation *after* the change (AFY),
$(E_{Bed})_{Before}$	=	Wet canal bed evaporation *before* the change (AFY),
$[(ET_{Non})_{Season}]_{After}$	=	Evapotranspiration of the non-irrigated landcover during the *after*-condition irrigation season (AFY), and
$[(ET_{Non})_{Season}]_{Before}$	=	Evapotranspiration of the non-irrigated landcover during the *before*-condition irrigation season (AFY).

Again, for cases where estimating $(SM_{CO})_{Non}$ is not $(ET_{Non})_{Season}$, Equation 4.1 can be combined with Equation 3.4:

$$\begin{aligned}\Delta D_{Corr} = {} & \{[(ET_{Corr})_{Season}]_{After} - [(ET_{Corr})_{Season}]_{Before}\} \\ & + \left[\left(E_{Open}\right)_{After} - \left(E_{Open}\right)_{Before}\right] + [(E_{Bed})_{After} - (E_{Bed})_{Before}] \\ & - \left\{\left[\left(P_{Eff}\right)_{Non}\right]_{After} - \left[\left(P_{Eff}\right)_{Non}\right]_{Before}\right\} \\ & - \left[(GW_{Non})_{After} - (GW_{Non})_{Before}\right] \\ & - \{[(SM_{CO})_{Non}]_{After} - [(SM_{CO})_{Non}]_{Before}\}\end{aligned} \tag{4.6}$$

where:

ΔD_{Conv}	=	Change in depletion from conveyed water from *before* the practice is changed to *after* (AFY),
$[(ET_{Corr})_{Season}]_{After}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season *after* the change (AFY),
$[(ET_{Corr})_{Season}]_{Before}$	=	Evapotranspiration from vegetation in the conveyance corridor during the irrigation season *before* the change (AFY),
$(E_{Open})_{After}$	=	Direct evaporation of conveyed water (open water surface evaporation) *after* the change

(AFY),

$(E_{Open})_{Before}$ = Direct evaporation of conveyed water (open water surface evaporation) *before* the change (AFY),

$(E_{Bed})_{After}$ = Wet canal bed evaporation *after* the change (AFY),

$(E_{Bed})_{Before}$ = Wet canal bed evaporation *before* the change (AFY),

$[(P_{Eff})_{Non}]_{After}$ = Effective precipitation for the non-irrigated condition during the irrigation season *after* the change (AFY),

$[(P_{Eff})_{Non}]_{Before}$ = Effective precipitation for the non-irrigated condition during the irrigation season *before* the change (AFY),

$(GW_{Non})_{After}$ = Groundwater contributions to the non-irrigated ET during the irrigation season *after* the change (AFY),

$(GW_{Non})_{Before}$ = Groundwater contributions to the non-irrigated ET during the irrigation season *before* the change (AFY),

$[(SM_{CO})_{Non}]_{After}$ = Carryover soil moisture from the non-irrigation season for the non-irrigated condition *after* the change (AFY), and

$[(SM_{CO})_{Non}]_{Before}$ = Carryover soil moisture from the non-irrigation season for the non-irrigated condition *before* the change (AFY).

As for ΔD_{Field}, if an irrigation practice change does not affect the irrigation season length, then $[(ET_{Non})_{Season}]_{After} = [(ET_{Non})_{Season}]_{Before}$, $[(P_{Eff})_{Non}]_{After} = [(P_{Eff})_{Non}]_{Before}$, $(GW_{Non})_{After} = (GW_{Non})_{Before}$, and $[(SM_{CO})_{Non}]_{After} = [(SM_{CO})_{Non}]_{Before}$. So,

$$\Delta D_{Corr} = \{[(ET_{Corr})_{Season}]_{After} - [(ET_{Corr})_{Season}]_{Before}\} + \left[\left(E_{Open}\right)_{After} - \left(E_{Open}\right)_{Before}\right] + [(E_{Bed})_{After} - (E_{Bed})_{Before}] \quad (4.7)$$

where:

ΔD_{Conv} = Change in depletion from conveyed water from *before* the practice is changed to *after* (AFY),

$[(ET_{Corr})_{Season}]_{After}$ = Evapotranspiration from vegetation in the conveyance corridor during the irrigation season *after* the change (AFY),

$[(ET_{Corr})_{Season}]_{Before}$ = Evapotranspiration from vegetation in the conveyance corridor during the irrigation season *before* the change (AFY),

$(E_{Open})_{After}$	=	Direct evaporation of conveyed water (open water surface evaporation) *after* the change (AFY),
$(E_{Open})_{Before}$	=	Direct evaporation of conveyed water (open water surface evaporation) *before* the change (AFY),
$(E_{Bed})_{After}$	=	Wet canal bed evaporation *after* the change (AFY), and
$(E_{Bed})_{Before}$	=	Wet canal bed evaporation *before* the change (AFY).

The simplification in Equation 4.7 applies to the conveyance system changes contemplated in Table 1.1. For other conditions, e.g., forbearing diversion into a conveyance system for a full irrigation season or in a way that would change the length of the irrigation season, the full Equation 4.5 or Equation 4.6 should be used neglecting terms only as appropriate for the specific project.

4.3 Comparison Strategies for Post-Facto Analyses

To reduce redundancy in discussing method development, strategies for post-facto comparisons are covered here first, then strategies for predictive analyses in the following section (Section *4.4*). As discussed above in this section, it is impossible to observe the *before* and *after* conditions of an irrigation practice change at the same instant. Therefore, methods are commonly adopted to make these estimates in space OR time (NRCE and Jacobs, 2021a; Figure 4.1). Examples of both methods were provided in the extensive review by Natural Resources Consulting Engineers, Inc. and Jacobs Engineering Group (NRCE and Jacobs, 2021a) including a relevant discussion for the Upper Colorado River Basin based on Allen and Torres-Rua (2018).

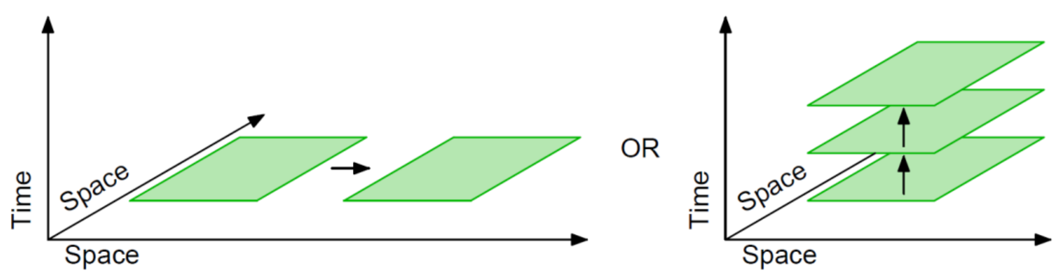

Figure 4.1. Depiction of depletion change estimates being made in space (left) or time (right).

4.3.1 Comparison in Space

Comparisons of depletion in space involve comparing the area where an irrigation practice has changed (the *subject* location) with an area assumed to be like the *subject* before the change (the *baseline* location). These locations may be a field, a group of fields, or conveyance corridors. This comparison takes the form of:

$$\Delta D \approx D_{Subject} - D_{Baseline} \tag{4.8}$$

where:

ΔD	=	Change in depletion from *before* the practice is changed to *after* (AFY),
$D_{Subject}$	=	Depletion from the new or changed condition in the *subject* location (AFY), and
$D_{Baseline}$	=	Depletion from the reference, or *baseline* location during the same period used for the *subject* location (AFY).

Some of the challenges arising from this assumption include the fact that the conditions of the *subject* location had it not been modified cannot be exactly known. Other challenges relating to the differences between the *subject* and *baseline* locations include:

- Size (canal or field),
- Soils,
- Crop varieties (strains within the same specie),
- Irrigation type,
- Irrigation or water management,
- Tillage,
- Fertility management,
- Topography and elevation,
- Climate and microclimate (e.g., precipitation, advective energy from arid surroundings, air drainage)
- Crop age (e.g., alfalfa stand age),
- Weed pressure,
- Pest (insect, disease) stress,
- Presence and type of vegetation in a conveyance corridor,
- Measurement method or accuracy, and
- Access to groundwater or capillary rise.

There are other differences that may exist, but this list is sufficient for discussion purposes. The challenge for the individual making comparisons in space is to select the *baseline* location to minimize any differences as much as possible. At a minimum, a justification relating to the items in the above list should be included in the analysis.

Comparisons in space are particularly appealing when remote-sensing-based methods are used to estimate depletion (Section *5.1.2.8*) and/or data periods of record are short.

4.3.2 Comparison in Time

Comparisons of depletion in time involve comparing the *subject* area *after* an irrigation practice has been changed with the same area *before* the change. The comparison periods may include one or more *after* and *before* years. Some of these conditions are discussed for the Palo Verde Irrigation District by NRCE and Jacobs (2021a), see also PVID et al (2020):

$$\Delta D \approx D_{After} - D_{Before} \tag{4.9}$$

where:

ΔD	=	Change in depletion from *before* the practice is changed to *after* (AFY),
D_{After}	=	Depletion from the *subject* area *after* irrigation practice change (AFY), and
D_{Before}	=	Depletion from the *subject* area *before* the irrigation practice change (AFY).

Allen and Torres-Rua (2018) and NRCE and Jacobs (2021a) discussed challenges including the fact that the conditions of the subject location had it not been modified cannot be exactly known. Other challenges relating to comparison in time include:

- Weather,
- Crop varieties (strains within the same specie),
- Irrigation type,
- Irrigation or water management,
- Tillage,
- Fertility management,
- Crop age (e.g., alfalfa stand age),
- Weed pressure,
- Pest (insect, disease) stress,
- Presence and type of vegetation in a conveyance corridor,
- Measurement method or accuracy, and
- Access to groundwater or capillary rise.

Again, there are other differences that may exist, but this list is sufficient for the present discussion. The challenge for the individual making comparisons in time is to select an averaging period (the number of years to include in the analysis) and a *before* period to minimize any differences unrelated to the irrigation practice change as much as possible. At a minimum, a justification relating to the items in the above list should be included in the analysis.

4.3.3 Comparison in Time with Weather Scaling

A third type of comparison method was recommended by Allen and Torres-Rua (2018) in the Upper Colorado River Basin. This type of method can be generalized as:

$$\Delta D \approx D_{After} - A_W D_{Before} \tag{4.10}$$

where:

ΔD	=	Change in depletion from *before* the practice is changed to *after* (AFY),
D_{After}	=	Depletion from the *subject* area *after* implementing the irrigation practice change (AFY),
D_{Before}	=	Depletion from the *subject* area *before* implementing the

		irrigation practice change (AFY), and
A_W	=	Weather adjustment between the comparison periods (dimensionless).

Allen and Torres-Rua (2018) used the reasonable concept of scaling based on differences in reference evapotranspiration:

$$A_W = \frac{ET_{ref,After}}{ET_{ref,Before}} \tag{4.11}$$

where:

A_W	=	Weather adjustment between the *before* and *after* periods (dimensionless),
$ET_{ref,After}$	=	Reference ET for the *after* period (in), and
$ET_{ref,Before}$	=	Reference ET for the *before* period (in).

This method builds on the concept of a crop coefficient, which is discussed in Section *5.1.2.4*. This method does not address all the challenges with time-based comparisons, but it does help address differences related to weather. Furthermore, scaling by ET_{ref} alone does not account for differences in water available for crop growth including precipitation, groundwater contributions, carryover soil moisture, and irrigation water supply, all of which would be assumed to be proportional to reference ET. Of these, irrigation water supply is the value most likely to have significant impacts on *D*. Following the recommendation of S. McGettigan, Utah Division of Water Resources (personal communication, 2024), this could take the form of:

$$A_W = \frac{WS_{After}}{WS_{Before}} \tag{4.12}$$

where:

A_W	=	Weather adjustment between the comparison periods,
WS_{After}	=	Irrigation water supply for the *after* period, and
WS_{Before}	=	Irrigation water supply for the *before* period.

4.3.4 A Combined Method

Comparison methods can also include a combination of time and space comparisons. For example, with satellite remote sensing products, comparisons can be made between the *subject* and *baseline* areas *before* implementation of the irrigation practice change and then again *after*. This should also include comparisons of each of the two areas between their respective *before* and *after* conditions (Figure 4.2).

Mathematically, the baseline field is used to represent the weather adjustment, A_W. So:

$$A_W = \frac{D_{Baseline}^{After}}{D_{Baseline}^{Before}} \tag{4.13}$$

where:

A_W	=	Weather adjustment between the comparison periods (dimensionless),
$D_{Baseline}^{After}$	=	Depletion from the *baseline* subject area *after* implementing the irrigation practice change in the *subject* area, and
$D_{Baseline}^{Before}$	=	Depletion from the *baseline* area *before* implementing the irrigation practice change in the *subject* area.

When Equation 4.13 is inserted into Equation 4.10 (with ΔD being for the subject area):

$$\Delta D \approx D_{Subject}^{After} - \left(\frac{D_{Subject}^{Before}}{D_{Baseline}^{Before}}\right) D_{Baseline}^{After} \tag{4.14}$$

where:

ΔD	=	Change in depletion from *before* the practice is changed to *after* (AFY),
$D_{Subject}^{After}$	=	Depletion from the *subject* area *after* implementing the irrigation practice change (AFY),
$D_{Subject}^{Before}$	=	Depletion from the *subject* area *before* implementing the irrigation practice change (AFY),
$D_{Baseline}^{Before}$	=	Depletion from the *baseline* area *before* implementing the irrigation practice change in the *subject* area (AFY), and
$D_{Baseline}^{After}$	=	Depletion from the *baseline* subject area *after* implementing the irrigation practice change in the *subject* area (AFY).

This method has the benefit of implicitly accounting for some weather and water supply conditions. This method is recommended, where possible, for post-facto estimations.

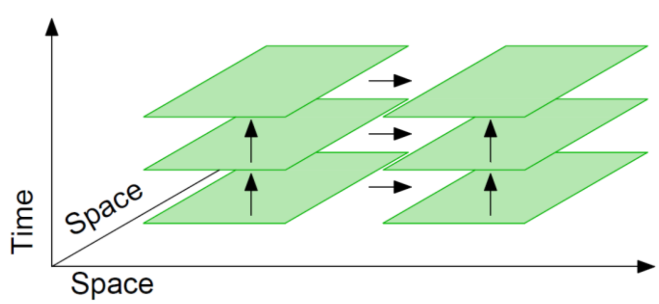

Figure 4.2. Depiction of depletion change estimates with both space and time comparisons.

4.4 Comparison Strategies for Prediction

Of the four comparison strategies listed for post-facto analyses in Section *4.3*, the most reasonable for predictive estimates is comparison in space (Section *4.3.1*) likely using the Evapotranspiration Fraction fraction for ET (Section *5.1.2.8*). In predictive analyses, an average over multiple previous years would be used for this comparison. The selection of an averaging period is a matter of judgment as discussed in Section *1.4.4*. This type of method is most suitable for fallowing, partial season fallowing, deficit irrigation, and crop changes where spatial datasets (i.e., remote sensing ET) can be used.

A second comparison method for prediction for conditions where spatial data are unavailable or inappropriate is to use historic weather data for the *subject* field for both the *before* and *after* estimates. This is appropriate, for example when estimating L_{CU} (Section *1.6.2*) or assumed efficiency changes (Section *6*), though the latter method is prone to significant uncertainty. For ET changes where the evaporative fraction method is not possible, a crop coefficient (Section *5.1.2.4*) can be used, though, this method is often prone to overestimations of actual ET.

5 Estimating Components of Depletion

Depletion is computed from multiple component estimates. Methods to quantify these components that are relevant to Utah are discussed below. Special attention is paid to methods relevant when computing changes in depletion, including evapotranspiration (ET), open water evaporation, and consumptive losses.

5.1 Evapotranspiration

Many methods have been developed over the last century to estimate crop ET. The methods can be grouped into two groups: observation and modeling.

Some observation methods include:

- Soil water balance,
- Lysimetry, and
- Micrometeorology.

Lysimetry and micrometeorology are discussed only briefly because they are not practical outside of carefully managed research settings.

Common current modeling methods can be divided into two primary groups:

- Reference evapotranspiration methods and
- Energy balance methods.

Remote-sensing-based methods typically fit within one of these two modeling groups.

5.1.1 Observation Methods

5.1.1.1 Water Balance Methods

ET can be estimated by measuring or otherwise quantifying components of the root zone water balance (Figure 2.1) and finding ET as:

$$ET = SM_{Begin} - SM_{End} + P - RO + I_{Gross} - DP + GW - L_{CU} \tag{5.1}$$

where:

ET	=	Evapotranspiration during the period (in),
SM_{Begin}	=	Soil moisture or soil water storage at the beginning the period (in),
SM_{End}	=	Soil moisture or soil water storage at the end of the period (in),
P	=	Precipitation during the period (in),
RO	=	Runoff during the period (in),
I_{Gross}	=	Gross applied irrigation during the period (in),
DP	=	Deep percolation during the period (in),
GW	=	Groundwater contributions during the period, including capillary rise (in), and

L_{CU}	=	Consumptive losses of irrigation water during the period (in).

Some challenges are that RO is difficult to measure and, therefore, typically modeled, and DP and GW can only be estimated indirectly. When estimating components of Equation 5.1, it is sometimes helpful to clearly split contributions of precipitation and irrigation:

$$ET = SM_{Begin} - SM_{End} + P + I_{Gross} + GW - DP_{Precip} - DP_{Irr} - RO_{Precip} - RO_{Irr} - L_{CU} \quad (5.2)$$

where:

ET	=	Evapotranspiration during the period (in),
SM_{Begin}	=	Soil moisture or soil water storage at the beginning the period (in),
SM_{End}	=	Soil moisture or soil water storage at the end of the period (in),
P	=	Precipitation during the period (in),
I_{Gross}	=	Gross applied irrigation during the period (in),
GW	=	Groundwater contributions during the period,
L_{CU}	=	Consumptive losses of irrigation water during the period (in),
DP_{Precip}	=	Deep percolation derived from precipitation during the period,
DP_{Irr}	=	Deep percolation derived from irrigation during the period,
RO_{Precip}	=	Runoff derived from precipitation during the period (in), and
RO_{Irr}	=	Runoff derived from irrigation during the period (in).

This breakdown is important because it makes quantifying many of the terms simpler.

5.1.1.1.1 Changes in Soil Moisture

5.1.1.1.1.1 Root Zone Total Water Storage

Water balance estimates should be based on soil water content measurements for the entire crop root zone. For best results, measurements should extend below the root zone (Evett et al., 2012). Estimates of managed crop root zone depth can be obtained from The Food and Agriculture Organization of the United Nations Irrigation and Drainage Paper No. 56 *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements* by Allen et al. (1998; FAO 56). In most cases, the average of the range provided in that reference should be the maximum depth considered for water balance work. Generally, measurements (or sensors) should be installed in a vertical profile with spacing between sensors not exceeding 12 in on center with the shallowest sensor being no more than 6 in from the soil surface (Figure 5.1). For shallow rooted crops, larger distances can be used below the top 2 to 3 ft, where the crop will have most of its root mass.

Root zone total soil water storage can be computed as:

$$SM = \sum_{i=1}^{n} \theta_{v,i} \Delta d_i \tag{5.3}$$

where:

SM	=	Total root zone soil moisture or soil water storage (in),
θ_i	=	Measured volumetric water content for depth i ($in^3\ in^{-3}$), and
Δd_i	=	Thickness of root zone that measurement i represents (in), usually the distance between the midpoints between sensor i and its two adjacent sensors; for the sensor nearest the surface, it can often be assumed to be representative of the soil from the surface to the midpoint between the first and second sensors.

There are other methods to aggregate individual sensor data, but typically a simple mean is not recommended unless soil moisture sensors each represent an equal thickness of the rootzone. For a full irrigation season water balance, the beginning of season should be collected at planting/bud break or start of irrigation, whichever comes first, and end of season soil moisture measurements should be collected at harvest/killing frost or end of the irrigation season, whichever is later.

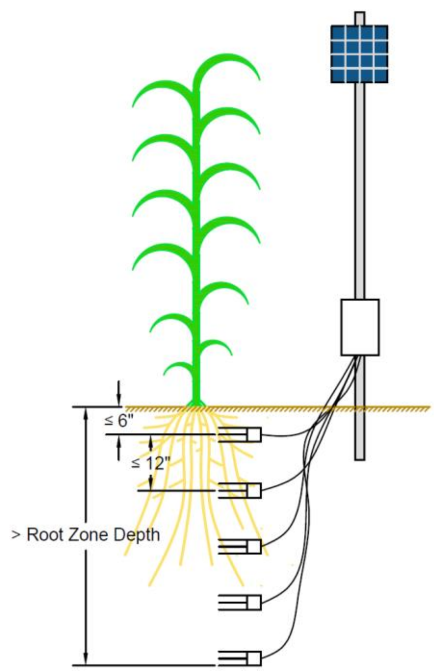

Figure 5.1. Example soil water content sensor profile. Recommended practical profile constraints are shown.

5.1.1.1.1.2 Measuring Volumetric Water Content

Volumetric water content can be measured gravimetrically by collecting and drying soil samples, or by using one of several sensor technologies including neutron probe, time-domain reflectometry, and capacitance probes.

5.1.1.1.1.2.1 Gravimetric Soil Water Content

Gravimetric soil sampling, as described in the American Society of Civil Engineers Manuals and Reports on Engineering Practice No. 70 *Evaporation, Evapotranspiration, and Irrigation Water Requirements,* 2nd Ed. Edited by Jensen and Allen (2016; MOP 70) and Evett et al. (2012), involves the collection and weighing of wet soil samples. Soil samples are collected, placed in sealed containers, weighed wet, dried at 105°C for 48 hours or until there is no change in mass and then weighed again. The difference in weight is the mass-based gravimetric water content:

$$\theta_w = \frac{W_{moist} - W_{dry}}{W_{dry}} \tag{5.4}$$

where:

θ_w	=	Gravimetric water content (g g^{-1}),
m_{wet}	=	Mass of wet soil sample (g), and
m_{dry}	=	Mass of dry soil sample (g).

It is necessary to adjust these measurements to represent the density of the bulk soil, or bulk density. Therefore, accurate measurements of bulk density are needed for this method. This density is the mass of dry soil particles in a known volume of soil as it is in the field:

$$\theta_v = \theta_w \frac{\rho_b}{\rho_w} \tag{5.5}$$

where:

θ_v	=	Volumetric water content (volume of water per bulk volume of soil; cm^3 cm^{-3} = in^3 in^{-3}),
θ_w	=	Gravimetric water content (g g^{-1}),
ρ_b	=	Bulk density of the soil (g cm^3), and
ρ_w	=	Density of water (g cm^3).

Gravimetric sampling is the gold standard volumetric water content measurement. Because of the labor requirements, this method is often limited to calibration exercises and measurement frequency is often limited.

5.1.1.1.1.2.2 Neutron Attenuation Probes

Neutron attenuation probes have a radioactive source that emits high energy neutrons. As these neutrons collide with the nuclei of atoms in the soil, they ricochet off, losing little energy. However, when they collide with hydrogen nuclei, which are the same mass as a neutron, they lose some of their energy. When this happens enough times, the neutrons' energy level is reduced. A neutron probe includes a sensing device that can detect these lower energy neutrons (Figure 5.2). Their relative count is related to the amount of water in the soil.

After site-specific calibration, the neutron probe is one of the most accurate methods of measuring soil water content (Evett et al. 2012). However, probes must be manually attended to when being used and are subject to state and Federal regulations. This often limits their use to research or use by consultants. The authors are unaware of any consultants in Utah operating neutron probes for agricultural purposes. Measurement frequency is often limited to weekly observations.

Figure 5.2. Photo of a neutron attenuation probe sitting on an access tube that has been installed to a depth of about seven feet into the soil of this corn field.

5.1.1.1.1.2.3 *Time Domain Reflectometry (TDR)*

TDR sensors send a high frequency electric pulse down thin metal rods, which make up the bulk of the sensor (Figure 5.3). The wave hits the ends of the rods and reflects back to the sensor head. The sensor records the reflected wave and can interpret it to estimate the soil electrical permittivity and subsequently the volumetric soil water content. When done properly, this is one of the most accurate methods for measuring soil water content (Evett et al. 2012). Datta et al. (2018) tested several soil water content sensors in Oklahoma including the Model TDR 315 (Acclima, Inc., Meridian, Boise, ID). That sensor was found to be accurate in all but a highly saline soil.

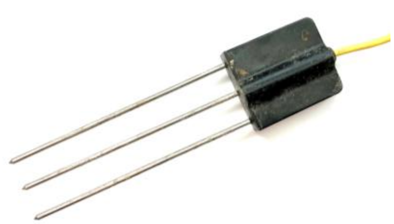

Figure 5.3. Photo of time-domain reflectometry (TDR) probe. The metal guides on this probe are six inches long.

There are also sensors that can be considered pseudo-TDR, or TDR-like. These sensors do not interpret the data the same way that TDR sensors do. These sensors should not be considered equivalent to true TDR technologies. However, Datta et al. (2018) did find one such sensor, the Campbell Scientific (Logan, Utah) Model CS655 sensor to be suitable for water balance work. Beyond this, any true TDR is herein recommended as a first choice for operational measurement of volumetric soil water content with the caveat that site-specific calibration is necessary in saline soils.

5.1.1.1.1.2.4 Capacitance Sensors

Capacitance sensors use an electromagnetic field to sense soil electrical permittivity and subsequently the volumetric soil water content. These sensors typically require local calibration. Many configurations of these sensors are available including individual sensors with guide probes like a TDR sensor and single tubular profile sensors that rely on inductance coils (Figure 5.4). Generally, profile sensors have a small sensing volume making them less suited for water balance work. Though technology has advanced since their paper was published, Evett et al. (2012) did not recommend capacitance probes for water balance work. Datta et al. (2018) found that the METER Group (Pullman, WA) Model GS1 sensor performed satisfactorily for water balance work. This sensor is similar in technology to the GS3, TEROS 10, 11, and 12 sensors also from METER.

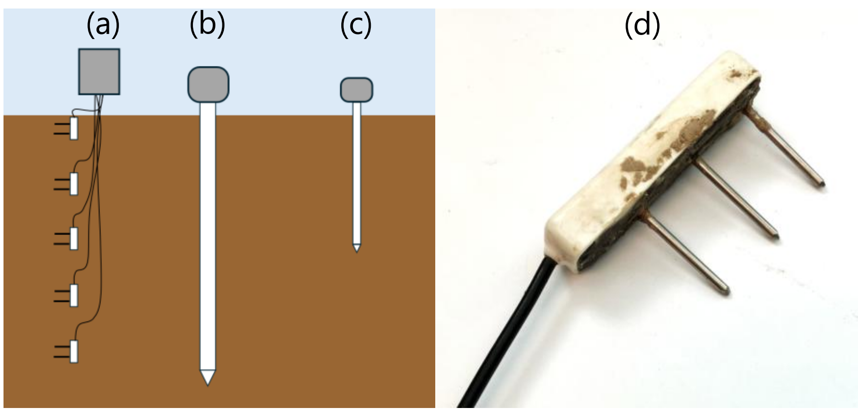

Figure 5.4. Depiction of a profile of (a) individual prong-type capacitance sensors, (b) long profile, (c) short profile capacitance sensors, and (d) photo of an individual capacitance sensor. Prong-type sensors are typically better suited to water balance work.

5.1.1.1.1.2.5 Satellite Remote Sensing

Satellite remote sensing can be used to estimate surface soil moisture. These sensors are intended for hydrologic modeling applications including estimation of soil evaporation. At present, it is not recommended to use these products for irrigation depletion estimation. These products have large spatial scales and are sensitive only to surface soil moisture (A. Torres-Rua, personal communication, 2024). The utility of remote sensing for soil water balance may improve in the future.

5.1.1.1.1.2.6 Recommendations
It is recommended that gravimetric water content and site-calibrated neutron probes be considered acceptable volumetric water content methods. For continuous measurement, true TDR technologies are recommended, with site-specific calibration in saline soils. Based on the literature, the Campbell Scientific Model CS655 and the METER TEROS 10, 11, and 12 sensors should be considered acceptable except in saline soils.

It is recommended that any other sensors have a site-specific calibration or provide third-party results from a replicated study in a similar condition demonstrating that the sensors in question can produce soil water measurements within 1 inch over the crop root zone. This is computed by multiplying the sensor accuracy percentage by the depth of the measurement profile. A sensor with ±3% water content accuracy in a profile measuring 5 ft of soil will have $\pm 0.03 \times 5$ ft $\times 12$ in ft^{-1} = ±1.8 in, which may be greater than desired.

5.1.1.1.1.3 Other Measures of Soil Water Status
In addition to volumetric soil water content, soil water status can be measured in terms of soil matric potential. Hand-feel estimates of soil water content can also be used to estimate soil water content.

5.1.1.1.1.3.1 Matric Potential Sensors
Soil matric potential sensors measure the force holding water in the soil. There are three primary types of these sensors including tensiometers, gypsum-based sensors, and capacitance sensors (Figure 5.5). While estimates of volumetric water content can be made from these measurements, it is not recommended to use these sensors to estimate changes in soil water storage for water balance work. These sensors are typically better suited to other applications including irrigation management. Matric potential can be used to model deep drainage and capillary rise.

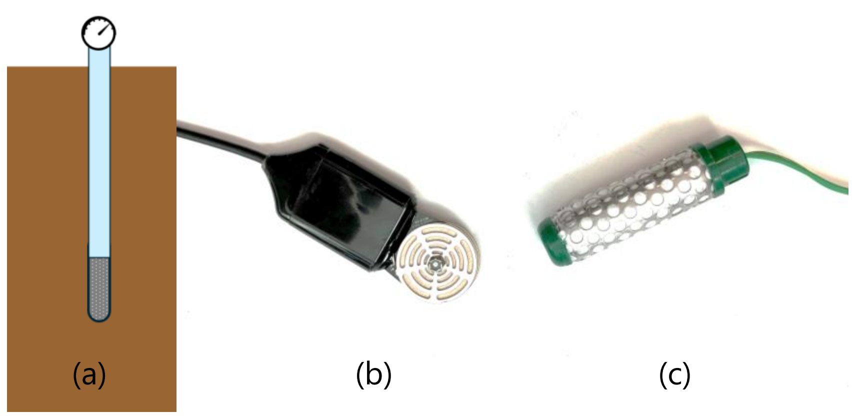

Figure 5.5. Depiction of (a) a tensiometer, and photos of (b) a capacitance-based matric potential sensor, and (c) a gypsum-based matric potential sensor.

5.1.1.1.1.3.2 Hand-Feel Estimates
Soil water content can be estimated by feeling the soil by hand (NRCS, 1998). This is sometimes done in irrigation management. These estimates are not sufficiently accurate for water balance work.

5.1.1.1.1.4 Soil Variability and Location and Quantities of Monitoring Locations
One challenge with measuring soil water content for a field water balance is ensuring that the measurement location represents the average condition of the field. Often, the sites that represent the average condition in a field change throughout a growing season (e.g., Barker et al., 2017). Barker et al. (2017) looked at a principle called variance reduction to determine the number of soil monitoring locations needed to accurately represent the field mean in a corn field in Nebraska. For their conditions, in relatively uniformly textured soils, a minimum of three measurement locations were needed for any field from 0.5 acres to 60 acres (the range of their study).

For practical applications, it may be difficult to monitor three locations in a field. However, the uncertainty associated with using only a single monitoring location should be acknowledged. Placing sensors in areas with typical crop cover and health is best practice. The need for multiple measurement locations is particularly important when there is notable soil variability.

5.1.1.1.2 Precipitation
There are many technologies to measure precipitation. The three most common devices include manual-read, tipping bucket, and weighing rain gauges. For the purposes of quantifying irrigation season precipitation, rain gauges for rainfall (not snow) are typically sufficient. These are the devices discussed here.

Rain gauges are more accurate the nearer they are to the ground surface. Typically, having the top being about 24 to 60 in is best (CoCoRAHS, 2024). The higher above the ground a gauge is mounted, the less accurate the gauge will be. All rain gauges should be mounted so that the top of the funnel is level. The top of the gauge should be four times the distance of any obstacle away from the obstacle (ASABE, 2015).

In general, the proximity of the rain gauge to the subject field is more important than the gauge technology. Rainfall varies significantly in space. While many weather variables may be representative over large areas, like most of a valley, rainfall is best measured near the subject field.

5.1.1.1.2.1 Manual-Read Rain Gauges
Manual-read rain gauges are the simplest rain measurement devices (Figure 5.6). They are also usually the least expensive. Manual-read gauges should be kept clean and should be read and emptied after each rainfall event to avoid algae growth in the device and loss of water through evaporation. Larger rain gauges, those with openings four inches or larger, are more accurate than rain gauges with small openings.

Figure 5.6. Photo of a good-quality, manual-read rain gauge.

5.1.1.1.2.2 Tipping Bucket and Incremental Rain Gauges

Tipping bucket rain gauges, use a funnel to guide water into a device like a seesaw with small containers on a balance (Figure 5.7). When enough water pools in the container, the bucket tips, dumping the water and triggering a small switch to close, recording an increment of rainfall (typically, 0.01 in). The largest challenge with these devices is interference with the measurement device by bugs and insects like spider webs and wasp nests or clogging by bird droppings. All these interferences have the effect of reducing the measurement. Tipping buckets also do not perform well in high-intensity rainfall as occurs in some monsoon events, where they tend to tip without fully filling or emptying.

Figure 5.7. Photo of an incremental-measure rain gauge that is part of a mini weather station.

5.1.1.1.2.3 Weighing Rain Gauges

Weighing rain gauges use a weight sensor to measure the mass of water that is collected by a funnel on top of the gauge (Figure 5.8). These are the most accurate class of rain gauge but also the most expensive. Weighing gauges are most suitable for public weather networks.

Figure 5.8. Photo of a Utah Climate Center Agricultural Weather Network weather station with a weighing rain gauge (large white cylinder).

5.1.1.1.2.4 Solid State Measurements

There are some options for measuring precipitation without moving parts. One option is hotplate rain gauges (Pond Engineering Labs, 2020; Rasmussen et al., 2011). The authors have no direct experience with this technology. However, power requirements may limit use far from electrical infrastructure. The sensors accuracy likely decreases in high intensity storms (Pond Engineering Labs, 2020). A second type of technology is based on acoustics (Arable, 2021). These sensors are intended for rainfall measurement and are purported to be a significant benefit over traditional rainfall measurement technologies. It is the authors' understanding that the Mark 3 version of this device is accurate enough for rainfall measurement for depletion estimation (Arable, San Francisco, CA, personal communication, 2024).

5.1.1.1.2.5 Radar

Radar precipitation products can be useful but may be less accurate in areas like Utah with orographic effects (impacts of mountains on precipitation). These products should be calibrated against reliable ground-based data. Federally produced RADAR products are described by NOAA (2024).

5.1.1.1.2.6 Gridded Datasets

Gridded weather datasets often include precipitation. Some of these are suitable for depletion estimation. One easily accessible dataset that is of use is the PRISM climate dataset produced by the PRISM Climate Group at Oregon State University, Corvallis, OR (https://prism.oregonstate.edu/). This product is available in 4-km and 800-m grids for daily and monthly products. Because the dataset is sensitive to topography, care must be taken when applying it near the foothills of mountains, etc., so that precipitation for the field of interest is representative of its actual elevation.

Another gridded dataset of interest is Daymet (Thornton et al., 2021). This product is available at a 1-km resolution, but has a significant delay in product generation, so it is not suitable for near-real-time analyses. Both PRISM and Daymet were found to perform well in Kansas by Muche et al. (2020).

5.1.1.1.3 Applied Irrigation

Applied irrigation is the portion of irrigation water that reaches the field. This could be water turned out from a field head gate, water entering a field head ditch or gated pipe system, or water supplied to a sprinkler or drip irrigation system.

5.1.1.1.3.1 Flow Measurement

The best practice for quantifying applied irrigation is by using accurate flow measurement.

5.1.1.1.3.2 Quantifying Applied Irrigation

Applied irrigation can be quantified by measuring the flow rate and duration of irrigation.

$$V = Qt \tag{5.6}$$

where:

V	=	Volume of water applied (cubic feet, ft^3),
Q	=	Volumetric flow rate of water applied (cubic feet per second, cfs), and
t	=	Duration of water application (s).

For this method, accurate measures of both time and flow rate are needed. Some flow measurement devices automatically compute or otherwise produce volume measurements. These are preferred over instantaneous or even averaged flow rates.

When depletion estimates are needed in terms of depths of water rather than volumes:

$$I_{GROSS} = \frac{V}{A_i} \tag{5.7}$$

where:

I_{GROSS}	=	Gross applied irrigation during the given period (ft),
V	=	Volume of water applied (ft^{-3}), and
A_i	=	Area irrigated (ft^2).

5.1.1.1.3.3 Irrigated Area

Of the quantities in Equation 5.7, the irrigated area may be the most nuanced (see NRCE and Jacobs, 2021b). This area must be defined for the purposes of the respective analysis being performed. Some examples include:

- The area within the bulk boundary of the field,
- The area associated with a water right,
- The total area wetted by the irrigation event,
- The area within a certain field boundary wetted during an irrigation event,

- The total cropped area within a certain field boundary,
- The total cropped area wetted by the irrigation event, and
- The total cropped area within a certain field boundary wetted during an irrigation event.

The irrigated area may include access roads within the field if they are irrigated (e.g., an access road to the middle of a center pivot). However, other access roads or areas may not be appropriate to count. (For example, roads and portions of dikes or berms not wetted during surface irrigation events). With irrigation methods that do not apply water to an entire field (e.g., drip irrigation, furrow irrigation, micro irrigation), the cropped areas not directly wetted during water application (e.g., interrows and alleyways) should typically be included as part of the irrigated area. Judgement must be used when considering areas that are not irrigated within a surface irrigated field because of flow paths or local high points (Figure 5.9).

A further consideration when determining the irrigated area is the time period in consideration. Some irrigation methods, surface methods in particular, may not wet the exact same area in each irrigation event. So, the irrigated area could be an average, it could be the total area including any area receiving irrigation water at least once during the irrigation season. Or some other criterion could be used.

Perhaps more important than the definition of the application area is consistency in defining irrigated area and clarity in explaining that definition.

Figure 5.9. Photo of dry areas in a field irrigated with surface irrigation.

5.1.1.1.3.4 Pipe Flow Measurement

For pressurized systems, a flow meter should be used to measure flow. Guidelines provided in the USU Publication *Accurate Irrigation Water Flow Measurement in Pipes* can be followed (Barker et al., 2023). This reference should be used until such time as the State of Utah adopts its own approved resource. It is best practice to use a flow meter that has been tested and verified by an independent laboratory. The Utah Water Research Laboratory (UWRL) is one such facility. UWRL personnel have tested many flow meters. A list of meters that have been tested at the UWRL and approved by the Idaho Department of Water Resources is available in Idaho's regularly updated *List of Approved Closed Conduit Flow Meters* (IDWR, 2023). These meters are recommended for quantifying applied irrigation water in Utah until the State of Utah adopts its own list.

5.1.1.1.3.5 Open Channel Flow Measurement

For irrigation systems supplied by a canal, it is recommended to use a properly installed and maintained flow structure. For new installations, a long-throated flume, like a ramp flume should be considered. Though, other structures, including Parshall and cutthroat flumes, sharp crested weirs, orifices, and calibrated gates can also be accurate. Generally, using stage-discharge relationships for flow measurement in canals is discouraged. Measurement structures should be installed and maintained in adherence with the U.S. Bureau of Reclamation's *Water Measurement Manual* 3rd Ed. (USBR, 2001) until the State of Utah adopts its own approved resource.

In some locations, it may be appropriate to use doppler velocity meters to monitor flow, though they should be verified using current metering. Periodic verification of all open channel flow measurement devices using current metering is recommended. The U.S. Bureau of Reclamation's *Water Measurement Manual* includes guidelines for current metering using wading rods as does the U.S. Geological Survey's *Discharge Measurements at Gaging Stations* (Turnipseed and Sauer, 2010).

In some cases, a profiling area Dopler current profiler (ADCP) device may be used to validate discharge measurements. Extreme care should be exercised when using an ADCP to ensure accurate measurement. Current metering with wading rods or ADCPs requires time, and care, these measurements should not be rushed and often should be replicated.

5.1.1.1.3.6 Irrigation Duration

In some cases, total applied irrigation can be determined accurately using Equation 5.6 by tracking the total duration of irrigation if the irrigation application rate is known. The primary challenge with this method is having a good understanding of the flow rate. For this reason, this method may be suitable for some types of pressurized irrigation and should not be used for surface irrigation or subirrigation.

Cases where this method may be accurate include situations where system discharge is consistent. These may include:

- A center pivot or lateral-move system with properly functioning and positioned sprinklers having properly rated and performing pressure regulators and sufficient system pressure. The system should be free of leaks. The irrigation duration method is discouraged when end guns are used. Worn sprinklers or improper sprinkler placement (nozzles not matching the location on the machine) will cause errors. Worn or malfunctioning pressure regulators will also cause errors. The method should not be used when pressure regulators are not present unless the field is level, and a pressure control valve or pressure-based pump control is positioned at the pivot inlet. If pressure anywhere in the center pivot drops below 5 psi greater than the pressure regulator rating, discharge will not be consistent, and this method will be inaccurate (Nelson, 2008).

A wheel line, hand line, solid set, or other sprinkler system with flow-control nozzles operated at a consistent pressure. The plots in Figure 5.10 were produced to illustrate this point. A flow control nozzle has much less discharge variability as pressure changes than does a conventional tapered bore nozzle. The flow control nozzle here is rated at 5.5 gallons per minute, the actual discharge is closer to 5.7 gallons per minute over much of the plotted range. The flow control nozzle had about a 3% range of flow rates over the plotted range. This is comparable to a 28% range for each of the conventional nozzles, which is unacceptable for quantifying applied irrigation. The standard nozzles would need to be used with pressure regulators or with tightly controlled system inlet pressure on a field of uniform topography to be usable for quantifying applied irrigation. Finally, the system should be free of leaks.

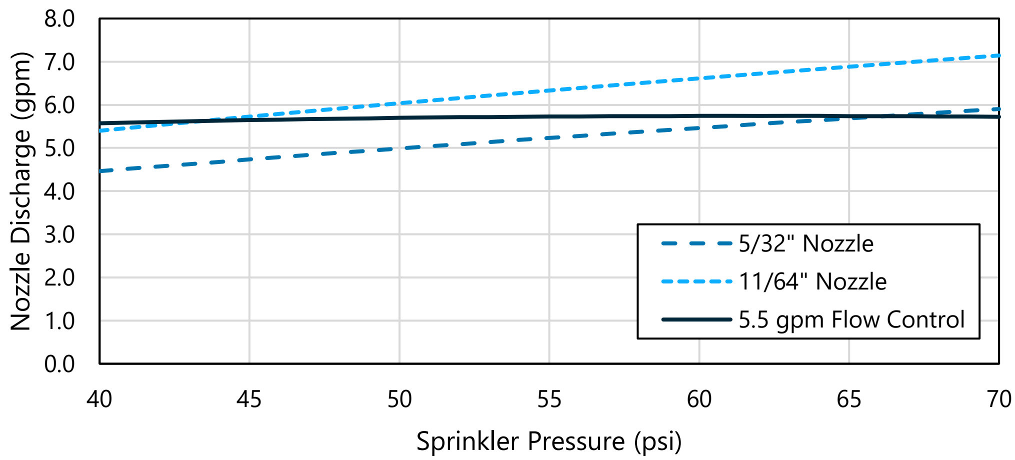

Figure 5.10. Plot of sprinkler nozzle discharge (gallons per minute) with sprinkler pressure (pounds per square inch) for two conventional, tapered-bore nozzle sizes, 5/32-inch and 11/64-inch and one flow control nozzle with a nominal discharge of 5.5 gpm. The two standard nozzles have discharge ranges of 28% of their respective means between 40 and 70 psi. The flow control nozzle has a discharge range of 3% of the mean. The mean discharge for the flow control nozzle is 5.7 gpm over this range. Flow control nozzle performance from Nelson (2001).

- Drip irrigation with carefully controlled inlet pressures and no leaks, regular flushing, and no drip emitter clogging or wear. Drip irrigation systems meeting these requirements have consistent discharge. However, leaks, clogging, and changes in supply pressure can cause significant differences in system discharge like those illustrated for wheel lines and other line-source sprinklers (Figure 5.10).

5.1.1.1.4 Groundwater Contributions, Deep Percolation and Capillary Rise

The largest challenge with a root zone water balance is quantifying deep percolation, capillary rise, and/or groundwater contributions. For the purposes of quantifying depletion, deep percolation is of no concern unless a full water balance is used to estimate ET. However, capillary rise can be an important contribution to crop ET, which reduces the depletion. Capillary rise can be a challenge to approximate. For this reason, the most common and defensible means of dealing with these flows in a research experiment is to select site conditions where deep percolation and capillary rise can be guaranteed to be small (Evett et al., 2012). Selecting a site like this is not possible in production farming conditions.

5.1.1.1.4.1 Capillary Rise and Direct Contributions of Groundwater

One of the most defensible methods for quantifying capillary rise or deep percolation is through unsaturated soil flow modeling using measured matric potential as an input like Gibbson (2018) did. One modeling option is to use the numerical model HYDRUS-1D, which is a public domain software package available from PC Progress (Prague, Czech Republic). However, this is impractical for operational estimates of capillary rise.

Other, simpler methods exist for estimating capillary rise. One example is using the UPFLOW model (Raes and Deproost, 2003) as demonstrated in MOP 70. Use of a capillary rise model is only recommended if the water table is near the root zone (see Table 2.1).

Groundwater contributions can also include root water uptake in the saturated zone and are likely common in areas of shallow water tables including near rivers and streams. These non-capillary contributions of groundwater are more difficult to quantify. One method that can be used to quantify total GW is to use the White (1932) method:

$$GW = Y(\overline{r_{24}} + s) \tag{5.8}$$

where:

GW	=	Groundwater contributions to depletion (in),
Y	=	Aquifer specific yield (dimensionless),
$\overline{r_{24}}$	=	Average daily rise in water table (in, based on daily cycles of decline and recovery caused by plant uptake during the day and groundwater recovery at night, and
s	=	Seasonal water drawdown (in, + for decline, - for increase).

This method was developed for the Escalante Valley in Iron and Washington Counties, Utah and relies on groundwater elevation observations. This method is based on monitoring groundwater levels to determine water depletion. The amount of water depletion is estimated by examining decreases in groundwater level changes during the day and recovery during the night.

Taghvaeian (2011) used this method to produce estimates of ET for riparian vegetation along the Lower Colorado River and compared it with a remote sensing ET model. While the White method is sensitive to the specific yield of the study aquifer (Taghvaeian, 2011), it may be useful to distinguish between *GW* and irrigation contributions to ET.

This method could be used for case studies, but it is impractical for operational estimates of depletion.

5.1.1.1.4.2 Deep Percolation

As an alternative to using unsaturated flow modeling, some researchers use a secondary water balance with modeled ET to estimate deep percolation (e.g., Barker et al., 2018a; Djaman and Irmak, 2012). Barker et al. (2018a) estimated ET using a water balance method based on neutron probe soil water content measurements. Between measurements, they ran a water balance model based on FAO 56 and MOP 70. This model is based on the crop-coefficient method of modeling ET and is widely used in irrigation science (see Section *5.1.2.4*). The challenge is that the "measured" ET then becomes dependent upon the quality of the ET model in the water balance.

This method is impractical for operational depletion estimates. It is valuable to consider here because the effective precipitation method being developed by the Desert Research Institute for *OpenET* will, of necessity, include some estimate of deep percolation. Though their effective precipitation estimates will be for the actual (i.e., irrigated) condition.

5.1.1.1.5 Runoff from Precipitation

It is difficult to measure runoff at the field scale. For this reason, runoff is typically either neglected in a field water balance or modeled. Justification should be provided if the runoff is neglected. Runoff is less likely when growing season precipitation is small and low intensity (gentle), the soil is coarse (sands), slope is small or level, tillage is minimal, and crops are close seeded. High intensity rainfall like summer monsoons is more likely to produce runoff. Fields that have diked ends (blocked border strips or basins) will rarely have runoff.

If a field does not have a diked end, it is more appropriate to model runoff. Modeling runoff is a primary subject of the hydrologic sciences. Such efforts are beyond the practical scope of estimating depletion. One simple method that has credibility in depletion work is the SCS runoff equation (NRCS, 2004b):

$$RO = \begin{cases} 0, & P \le I_a \\ \dfrac{(P - I_a)^2}{P - I_a + S}, & P > I_a \end{cases} \tag{5.9}$$

where:

RO	=	Estimated runoff (in),
P	=	Precipitation (in),
I_a	=	Initial abstractions (in), usually assumed to be 0.2S, and

S = Maximum water retention after runoff initiation (in).

and:

$$S = \frac{1000}{CN} - 10 \tag{5.10}$$

Where:

CN = The SCS Curve Number (dimensionless, NRCS, 2004a).

This method has been employed by researchers in estimated plot runoff (Barker et al., 2018a). The SCS runoff equation is intended to be implemented using hourly or more frequent data. However, reasonable results have been achieved assuming that the total precipitation for each day represents a separate 24-hour storm (e.g., Barker et al., 2018a).

There is considerable uncertainty with this method as with all runoff models. MOP 70 includes a method where the CN is related to the modeled surface soil water content. This water content is used to estimate the antecedent moisture condition adjustment, which influences the CN. However, Hjelmfelt (1991) suggested that the antecedent moisture conditions represented more of a range of possible CNs for a given condition rather than a direct response to surface soil water conditions (NRCS, 2004b).

Based on Hjelmfelt's work, the three antecedent moisture conditions (I, II, and III) can represent the 10th, 50th, and 90th percentile probability values of the CN. If desired, the user can estimate the uncertainty of runoff estimates using this information (see Figure 5.11).

The primary challenge with the SCS equation is to identify a reasonable CN, which can be obtained from the literature.

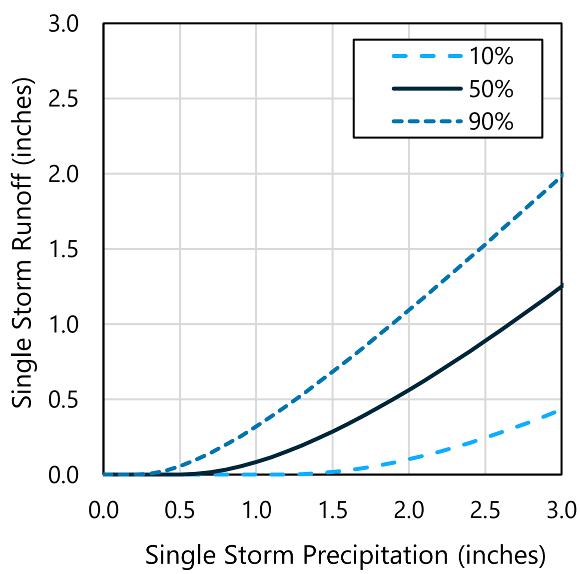

Figure 5.11. Plot of potential rainfall runoff variation assuming a curve number of 80 with antecedent moisture conditions I, II, and III representing the 10%, 50%, and 90% values presented.

While there is much uncertainty with the SCS method, it provides an acknowledgment of the runoff process in the water balance. Furthermore, RO_{Precip} is typically a small component of the water balance during the irrigation season in Utah.

5.1.1.1.6 Runoff from Irrigation

Runoff can result when irrigation exceeds the infiltration capacity of the soil. In sprinkler irrigation, systems should be designed and operated to avoid runoff. This is sometimes difficult with center pivots but is typically achievable. There is no well-accepted means of estimating runoff from sprinkler irrigation systems when it is not zero. Runoff is infrequent in drip irrigation systems in Utah, though it can occur (Burt and Styles, 2016).

Runoff from surface irrigation systems, however, is common, often by design. Blocked furrow and border systems and enclosed basins have a dike at the tail of the field to prevent runoff. For other surface irrigation systems, water is allowed to run off the tail of the field or the irrigated area is effectively defined by the frontier of the area where water can spread during irrigation. In some cases, the runoff is collected in a ditch or is concentrated in a small area at the tail of the field. In these cases, it may be possible to employ open channel flow measurement techniques to measure runoff. Otherwise, the most practical method for estimating runoff is through surface irrigation water balance and simulation (Strelkoff and Clemmens, 2007; Clemmens et al., 2007). The U.S. Department of Agriculture's WinSRFR program may be helpful for this purpose.

5.1.1.1.7 Consumptive Irrigation Losses

Because L_{CU} is included directly in change in depletion estimates (Equation 4.3), methods for quantifying it are discussed in Section *5.2*.

5.1.1.2 Modified Water Balance Methods

Only one modified soil water balance method is considered here. The Soil Moisture and Evapotranspiration (SMET) method was developed by Hargreaves (2023) as part of a M.S. thesis at USU that contributed to a depletion estimation case study funded by the Utah Agricultural Water Optimization Task Force (Jacobs, 2023). SMET is a method used to estimate ET by continuously monitoring soil moisture and weather. The model is:

$$ET = \begin{cases} \alpha(ET_r - \Delta SM), & \Delta SM < 0 \\ 2\alpha ET_r, & \Delta SM \geq 0 \end{cases} \tag{5.11}$$

where:

ET	=	Crop evapotranspiration, (in),
α	=	Empirical coefficient (dimensionless),
ET_r	=	Tall reference crop evapotranspiration (in, Section *5.1.2.4*), and
ΔSM	=	Change in root zone soil water storage (in).

This model has an empirical fit coefficient, α, which means that it is dependent on the calibration dataset. The model is still under development (A. Torres-Rua, Personal Communication, 2024). The α is not dissimilar to a crop coefficient (Section *5.1.2.4*).

5.1.1.2.1 Complicating Factors for Water Balances

It is important to understand that many of the methods described above for estimating water balance components are only appropriate when all the water in the system is liquid. That is, not snow or ice, melting snow, or frozen ground. Small, quick melting snow falls when the soil is thawed are a possible exception. When the ground is frozen, electromagnetic soil moisture sensors (Section *5.1.1.1.1.2*) do not accurately quantify root zone total water storage. Furthermore, water flow in frozen soil is more difficult to predict than for thawed soil.

5.1.1.2.2 Available Software

Some packaged software programs like the Soil-Plant-Atmosphere-Water (SPAW) model are available for certain aspects of a water balance analysis (Saxton, 2017). Another example is the Water-Use, Irrigation, Nitrogen, Drainage, and Salinity (WINDS) model (Waller and Yitayew, 2016).

5.1.1.3 Lysimetry

Lysimetry is a controlled type of water balance method used to quantify ET in research settings. The method is relevant here because of the models that have been calibrated against lysimeter data. A lysimeter is a container (typically a large, steel, rectangular container) of soil in which plants are grown (MOP 70). The lysimeter is placed in the ground so that the plants are subject to similar growing conditions as adjacent plants outside of the lysimeter. The lysimeter prevents runoff, run-on, subsurface lateral flows, and capillary rise. Any drainage in the lysimeter is removed and measured. Weighing lysimeters use electronic load cells to measure the change in mass of the lysimeter as water is removed via ET. Well-constructed and managed weighing lysimeters are considered a gold standard of ET measurement. However, these systems require significant resources to design, construct, and maintain.

5.1.1.4 Micrometeorology

Micrometeorology is the study of near-land-surface weather to understand the interactions between the land and the lower atmosphere. ET is an exchange of water vapor between the land/plant surface and the lower atmosphere. Therefore, micrometeorological theory can be employed to estimate ET using any of several methods. Micrometeorology is limited to research and validation studies. These methods rely on the principles of a surface energy balance. Since ET involves the vaporization of water, which requires significant amounts of energy to overcome the latent heat of vaporization, ET can be estimated if this energy can be accurately quantified. The simplified surface energy balance is:

$$R_n = LE + H + G \tag{5.12}$$

where:

R_n	=	Net radiation flux, incoming solar radiation minus reflected solar radiation plus radiation emitted by the sky minus radiation emitted from the land surface (W m^{-2}),
LE	=	Latent heat flux, water vapor flux times the latent heat of vaporization (W m^{-2}),
H	=	Sensible heat flux, energy heating the air (W m^{-2}), and
G	=	Soil heat flux, energy moving into or out of the soil (W m^{-2}).

Energy storage at the land surface (e.g., within the crop) and energy used in photosynthesis are neglected. The energy used for photosynthesis is a small fraction of the total energy balance.

Because there is uncertainty when measuring any of the four primary energy balance components, it is best practice to measure each of them. Micrometeorological methods differ in how they measure H and LE, or what are called the aerodynamic fluxes. The current general state of the science is to use the eddy covariance method to measure H and LE. This, again, is limited to research settings.

5.1.2 Modeling Methods

Because of the challenges associated with measuring ET, many ET models have been developed. Models vary from entirely empirical to theoretical. Some empirical models were developed to make use of limited weather datasets, e.g., including only air temperature.

5.1.2.1 The Penman Equation

One theoretical ET model important in modern modeling was developed by Penman (1948). This model was helpful because it combined the concepts of energy and mass transfer to solve for ET. A form of this equation is presented in MOP 70:

$$ET = \frac{\Delta(R_n - G) + \gamma(e_s - e_a)W}{\rho_w \lambda(\Delta + \gamma)} \tag{5.13}$$

where:

ET	=	Evapotranspiration (m d^{-1}),
Δ	=	Slope of the vapor pressure-air temperature curve (kPa K^{-1}),
γ	=	Psychrometric constant (kPa K^{-1}),
R_n	=	Net radiation energy flux (e.g., MJ m^{-2} d^{-1}),
G	=	Soil heat (energy) flux (e.g., MJ m^{-2} d^{-1}),
ρ_w	=	Density of water (kg m^{-3}),
λ	=	Latent heat of vaporization of water (MJ kg^{-1}),
e_s	=	Saturated vapor pressure (kPa),
e_a	=	Actual vapor pressure (kPa), and

W	=	The wind function (kPa^{-1}).

The wind function requires empirical calibration. This makes the model difficult to employ for conditions differing from the calibration location. Alone, the Penman Equation is limited in its ability to be used to estimate ET. It was historically used as a reference evapotranspiration equation (see Section *5.1.2.4*), but that use is discouraged in favor of more modern methods.

5.1.2.2 The Penman-Monteith Equation

In 1965, Monteith expanded on the Penman equation to included terms to represent a crop canopy. The combined method is referred to as the Penman-Montieth equation (MOP 70):

$$ET = \frac{\Delta(R_n - G) + \frac{\rho_a c_p \gamma (e_s - e_a)}{r_{ah}}}{\rho_w \lambda \left[\Delta + \gamma\left(1 + \frac{r_s}{r_{ah}}\right)\right]} \tag{5.14}$$

where:

ET	=	Evapotranspiration ($m\ d^{-1}$),
Δ	=	Slope of the vapor pressure-air temperature curve ($kPa\ K^{-1}$),
R_n	=	Net radiation energy flux (e.g., $MJ\ m^{-2}\ d^{-1}$),
G	=	Soil heat (energy) flux (e.g., $MJ\ m^{-2}\ d^{-1}$),
ρ_a	=	Density of air ($kg\ m^{-3}$),
c_p	=	Specific heat of air at constant pressure, ($MJ\ kg^{-1}\ K^{-1}$)
γ	=	Psychrometric constant ($kPa\ K^{-1}$),
e_s	=	Saturated vapor pressure (kPa),
e_a	=	Actual vapor pressure (kPa), and
r_{ah}	=	Aerodynamic resistance to heat transfer ($d\ m^{-1}$),
ρ_w	=	Density of water ($kg\ m^3$),
λ	=	Latent heat of vaporization of water ($MJ\ kg^{-1}$),
r_s	=	Stomatal resistance ($d\ m^{-1}$).

The Penman-Monteith equation is a foundational equation in many ET models. However, the largest challenge with the equation is quantifying the resistance terms.

5.1.2.3 The Priestly-Taylor Equation

While Monteith expanded upon the Penman Equation, Priestly and Taylor (1972) developed a model that represents a simplification by effectively neglecting the influence of mass transfer:

$$ET = \frac{\alpha\Delta(R_n - G)}{\rho_w \lambda(\Delta + \gamma)} \tag{5.15}$$

where:

ET	=	Evapotranspiration ($m\ d^{-1}$),

α	=	Empirical adjustment coefficient (dimensionless),
Δ	=	Slope of the vapor pressure-air temperature curve (kPa K^{-1}),
R_n	=	Net radiation energy flux (e.g., MJ m^{-2} d^{-1}),
G	=	Soil heat (energy) flux (e.g., MJ m^{-2} d^{-1}),
γ	=	Psychrometric constant (kPa K^{-1}),
ρ_w	=	Density of water (kg m^3), and
λ	=	Latent heat of vaporization of water (MJ kg^{-1}).

Because the impacts of wind and vapor pressure deficit on mass transport are significant in semi-arid areas like Utah, use of the Priestly-Taylor method is not recommended for depletion calculations except for its use in some remote sensing models.

5.1.2.4 Reference Evapotranspiration and Crop Coefficients

The Penman, Penman-Monteith, and Priestly-Taylor methods all share a common shortcoming, they require some adjustment depending on the land surface conditions. E.g., the Penman wind function, the Penman-Monteith resistances, and the Priestly-Taylor α. All these factors change based on vegetation conditions (cover, height, physiology, water stress) and surface soil moisture, among other factors.

For several decades, the most widespread practice to account for all these factors has been to use a model, like those listed here or others, for a given, well-defined, uniform land surface and then to adjust the resulting ET by some empirical factor. The ET for this well-defined surface is called reference ET, because it represents some reference surface condition. Crop-specific ET is computed as:

$$ET_c = K_c ET_{ref} \tag{5.16}$$

where:

ET_c	=	Crop evapotranspiration (in), the subscript *c* is used in contemporary literature to refer to ET computed using this method,
ET_{ref}	=	Reference evapotranspiration (in), and
K_c	=	Empirical crop coefficient (dimensionless).

Two common land surface conditions have been adopted in current practice. One is well-watered, short grass and the other is actively growing, well-watered, full-cover alfalfa. The former is used more widely globally, while the latter is used in much of the Western U.S. (outside of California and Arizona) including Utah. Lysimeter data for both surface types have been used to develop and calibrate reference ET models (e.g., ASCE, 2005). Notably, for Utah, Wright (1982) used lysimeter data from Kimberly, ID to develop the Kimberly Penman equation, which was frequently used in the state in the past.

The standard acceptable nomenclature is to refer to short reference (grass) ET_{ref} as ET_o and tall reference (alfalfa) ET_{ref} as ET_r (ASCE, 2005). The use of the term "potential ET" when referring to reference ET is ambiguous and should be avoided. Because ET_o and ET_r are not equal for the same weather conditions (ET_r is often about 20% greater than ET_o; ASCE, 2005), K_c values for the two references are not equal for the same crop and growth conditions. Therefore, it can be helpful to refer to the K_c as being either K_{cr}, for tall reference, or K_{co}, for short reference (MOP 70):

$$ET_c = K_{cr}ET_r = K_{co}ET_o \tag{5.17}$$

where:

ET_c	=	Crop evapotranspiration (in),
K_{cr}	=	Tall reference crop coefficient (dimensionless),
ET_r	=	Tall reference evapotranspiration (in),
K_{co}	=	Short reference crop coefficient (dimensionless), and
ET_o	=	Short reference evapotranspiration (in).

5.1.2.4.1 Reference Evapotranspiration Equations

Many reference ET equations have been developed. Here, only the equations most relevant to Utah are considered.

5.1.2.4.1.1 The ASCE Standardized Reference Evapotranspiration Equation

A task force from the American Society of Civil Engineers (ASCE) standardized recommended reference ET computation in 2005 (ASCE, 2005). The result was a single recommended equation, the ASCE Standardized Reference ET Equation. This is the Penman-Monteith (Equation 5.14) with specified relationships for the resistance terms and prescribed methods for intermediate calculations. The Standardized Equation is:

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \frac{\gamma C_n u_2}{T}(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{5.18}$$

where:

ET_{ref}	=	Reference evapotranspiration (mm d^{-1} or mm hr^{-1}),
Δ	=	Slope of the vapor pressure-air temperature curve (kPa K^{-1}),
R_n	=	Net radiation energy flux (MJ m^{-2} d^{-1} or MJ m^{-2} hr^{-1}),
G	=	Soil heat (energy) flux (MJ m^{-2} d^{-1} or MJ m^{-2} hr^{-1}),
γ	=	Psychrometric constant (kPa K^{-1}),
C_n	=	Numerator constant,
u_2	=	Wind speed at 2 m above ground surface (m s^{-1}),
e_s	=	Saturated vapor pressure (kPa),
e_a	=	Actual vapor pressure (kPa), and
C_d	=	Denominator constant.

The numerator and denominator constants differ based on the calculation time interval and the reference type (tall or short). The ET_o version of this equation is effectively the same as the FAO Penman-Monteith Equation (FAO 56). However, it is recommended that the ASCE (2005) be used as a reference when computing ET_{ref} until such time as FAO 56 is replaced (a process that is currently in progress). Please note that MOP 70 includes an extensive discussion of the Standardized Reference ET Equation, but the method is easier to follow in ASCE (2005).

The ASCE Standardized equation is the state of practice for reference ET and is recommended for use in all cases where reference ET is used, and sufficient data exist. This is supported by the large comparative analysis presented in ASCE (2005). In Utah, where possible, it is recommended that ET_{ref} be computed based on hourly intervals and summed to daily values rather than using daily calculations (see Irmak et al., 2003). This is based on observations at the Logan Golf and Country Club in Utah where high morning winds result in erroneously high daily ET when calculated using a daily timestep.

It is also recommended to use the humidity-based, clear-day solar radiation model presented in ASCE (2005) rather than the elevation-based method, but significant differences are not expected. Care should be taken when adjusting wind speed based on measurement height, particularly if measured over vegetation taller than short grass (MOP 70).

5.1.2.4.1.2 The 1982 Kimberly Penman Equation

The 1982 Kimberly Penman Equation (Wright, 1982) was commonly used in Utah before the release of the ASCE Standardized Reference ET Equation. The equation is Equation 5.13 with the following wind function:

$$W = \left\{0.4 + 1.4\exp\left[-\left(\frac{DOY - 173}{58}\right)^2\right]\right\} + \left\{0.605 + 0.345\exp\left[-\left(\frac{DOY - 243}{80}\right)^2\right]\right\} u_2 \tag{5.19}$$

where:

W	=	The wind function (kPa^{-1}),
DOY	=	The day of year, and
u_2	=	The wind speed at 2 m above ground surface (m s^{-1}).

This is a tall reference equation. However, it is not equivalent to the ASCE Standardized Equation. The 1982 Kimberly Penman is no longer recommended for use in Utah.

5.1.2.4.1.3 Hargreaves and Samani Equation

When there are insufficient data to compute ET_{ref} using the ASCE Standardized Equation, it is recommended that the Hargreaves and Samani (1985) Equation be used (ASCE, 2005; MOP 70):

$$ET_o = \frac{0.0023(T_{max} - T_{min})^{0.5}\left(\frac{T_{max} - T_{min}}{2} + 17.8\right)R_a}{\rho_w \lambda} \tag{5.20}$$

where:

ET_o	=	Short reference evapotranspiration (mm d^{-1}),
T_{max}	=	Maximum daily air temperature (°C),
T_{min}	=	Minimum daily air temperature (°C),
R_a	=	Extraterrestrial solar radiation (MJ m^{-2} d^{-1}),
ρ_w	=	Density of water (kg m^{-3}), and
λ	=	Latent heat of vaporization for water (MJ kg^{-1}).

This equation can be calibrated for a specific location based on comparisons with the ASCE Standardized Equation by adjusting the leading coefficient. R_a is computed based on latitude and day of year (MOP 70). This model should not be used for depletion estimation purposes in Utah without calibration.

5.1.2.4.1.4 Blaney-Criddle Equation

The Blaney-Criddle equation (e.g., Blaney and Criddle, 1950) was developed (MOP 70). In time, two common forms were developed: 1) the SCS form and 2) the FAO form.

5.1.2.4.1.4.1 SCS Blaney-Criddle

The SCS Blaney-Criddle for monthly values of ET is (SCS, 1993):

$$ET = \frac{kT_M P_D}{100} \tag{5.21}$$

where:

ET	=	Evapotranspiration (in. d^{-1}),
k	=	Empirical crop factor, and
P_D	=	The percentage of annual daylight hours occurring in that month (%),

and

$$k = \max(0.0173T_M - 0.314, 0.30)K_c \tag{5.22}$$

where:

T_M	=	Mean monthly air temperature (°F) and
K_c	=	Empirical crop coefficient based on the crop and growth Stage (dimensionless).

Notice that the crop coefficient is tied into the ET equation and that such crop coefficients are SCS-Blaney-Criddle-Specific. The SCS Blaney-Criddle is of particular interest in Utah because of its use by Hill (1994) in estimating ET and net irrigation values for many crops. It should understood that Hill did not use the SCS Blaney-Criddle equation directly but calibrated the equation using the 1982 Kimberly Penman Equation.

5.1.2.4.1.4.2 FAO Blaney-Criddle

The FAO Blaney-Criddle (Doorenbos and Pruitt, 1975; SCS, 1993) for monthly values of ET is:

$$ET_o = c_e[a_t + (b_n + b_u)P_D T_M] \quad (5.23)$$

where:

ET_o	=	Short reference evapotranspiration (in. d^{-1}),
c_e	=	Empirical elevation factor, and
a_t	=	Empirical coefficient,
b_n	=	Empirical coefficient,
b_u	=	Empirical coefficient,
P_D	=	The percentage of annual daylight hours occurring in during the calculation interval (e.g., month), and
T_M	=	Mean monthly air temperature (°F).

and

$$c_e = 0.01 + 3.049 \times 10^{-7} z \quad (5.24)$$

where:

z	=	elevation above mean sea level (ft),

and

$$a_t = 3.937\left(0.0043 RH_{min} - \frac{n}{N} - 1.41\right) \quad (5.25)$$

where:

RH_{min}	=	Mean daily minimum relative humidity (%),
n	=	Sunshine hours, and
N	=	Possible sunshine hours,

and

$$b_n = 0.82 - 0.0041 RH_{min} + 1.07\frac{n}{N} - 0.006 RH_{min}\frac{n}{N} \quad (5.26)$$

and

$$b_u = \frac{(1.23 - 0.0112 RH_{min})u_2}{1000} \quad (5.27)$$

where:

u_2	=	Mean daily wind speed (miles d^{-2}).

The FAO Blaney-Criddle Equation is not recommended for estimating depletion in Utah.

5.1.2.4.2 Crop Coefficients

Crop coefficients are determined empirically from research experiments. Crop coefficients typically change in magnitude with crop growth stage. For many crops, the K_c is low at planting or green-up, increases to some peak value at full cover (when crop leaf area is sufficient to transpire at peak rates relative to ET_{ref}), and then eventually decreases during crop senescence (Figure 5.12). For a hay crop, like alfalfa, this cycle would be repeated multiple times during the growing season.

The shape of the resulting K_c curve depends on the experimental data. These data are typically scattered and do not form uniform lines as represented by published K_c curves. Rather, the curve is fit to the data. This fit is one source of error in this method. Therefore, the K_c method is least accurate at a daily time scale (the shortest time scale appropriate for this method) and accuracy increases with increasing timescales (e.g., weekly, monthly, seasonal).

Because crop coefficients are empirical, their accuracy is dependent upon how similar the application conditions are to those of the development study. The crop coefficient may not just be dependent upon the crop, but also the variety, climate, soil, and cultural practices (cultivation, planting, irrigation, nutrient, and pest management). The use of ET_{ref} is intended to account for some climate and weather differences. Some crop coefficients are developed to allow for adjustment in development timing of the crop (see MOP 70). Crop coefficients must be applied so that they properly align with crop growth at the location.

Care is needed when applying a crop coefficient. For example, in Figure 5.13, three crop coefficients for corn are presented. Each curve was employed using assumptions that may be reasonable. The three curves cannot all be equally accurate for the same situation.

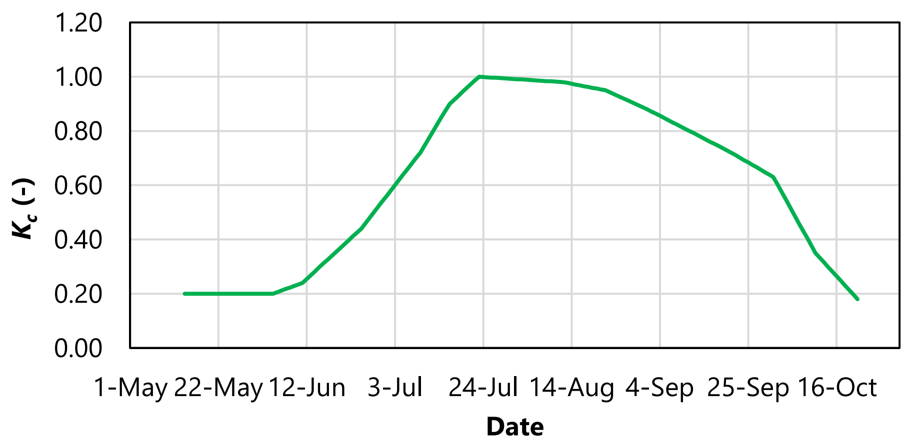

Figure 5.12. Example crop coefficient for corn under assumed conditions for Cache Valley, Utah (MOP 70).

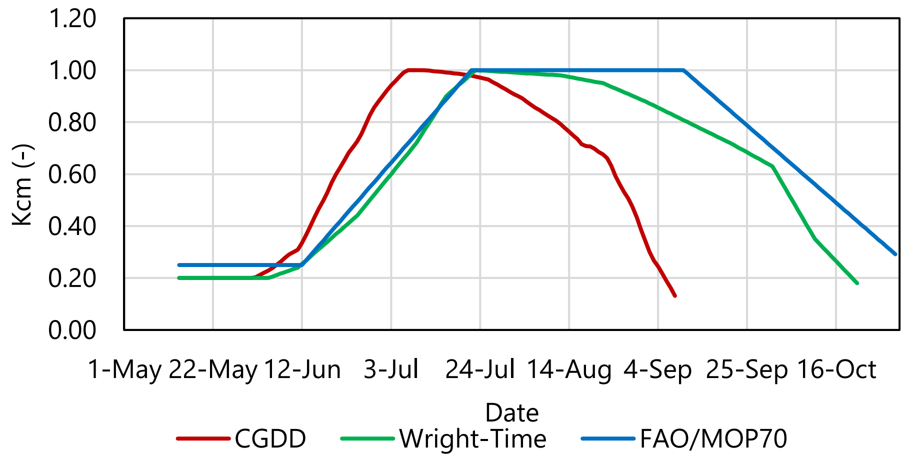

Figure 5.13. Crop coefficients based on MOP 70 and Hill et al. (2011) all for corn.

5.1.2.4.2.1 Reference Type

As indicated in Section *5.1.2.4.1*, crop coefficients are dependent on the ET_{ref} type for which they were developed. For example, ET_o crop coefficients cannot be used with ET_r. Furthermore, crop coefficients developed for use with Blaney-Criddle, or Kimberly Penman cannot be used with Standardized Reference ET Equation ET_{ref}. In some cases, crop coefficients can be converted from one reference to another, but this is best done using the original study data (e.g., MOP 70).

Users should avoid converting a K_c from short reference to tall reference and vice versa. It is best practice to use the reference for which the K_c was developed (ET_r or ET_o) even if this means using both reference types for the same study.

5.1.2.4.2.2 Crop Coefficient Type

There are two primary K_c methods: 1) mean, or single, K_c and 2) dual K_c. The former combines the entire ET process, evaporation from the soil and transpiration from the crop, into a single coefficient and is applied as (MOP 70):

$$K_c = K_{cm} \tag{5.28}$$

where:

K_c	=	The crop coefficient (dimensionless) and
K_{cm}	=	The mean crop coefficient (dimensionless).

Values for K_{cm} are determined from published tables and functions. Evaporation from wet soil is dependent on the extent and frequency of soil wetting. For example, sprinkler, border, and basin irrigation typically wet the entire soil surface, while drip and furrow irrigation do not. Drip and center pivot irrigation events are usually frequent, while surface irrigation and wheel line irrigation events are typically not. If irrigation and precipitation frequency was different in the K_c development study than in the application condition, the K_{cm} may not be representative.

The dual K_c method (Wright, 1982; FAO 56; MOP 70) was developed to make the K_c method more adaptable:

$$K_c = K_{cb} + K_e \quad (5.29)$$

where:

K_c	=	The crop coefficient (dimensionless),
K_{cb}	=	The basal crop coefficient, primarily representing plant Transpiration (dimensionless), and
K_e	=	The soil evaporation coefficient (dimensionless).

Values for K_{cb} are determined from published tables and functions. The present recommended method for obtaining K_e is through a water balance of the top layer of the soil, the evaporation layer, as detailed in MOP 70.

Experience has proven that accurately parameterizing this model can be difficult, and it is easy to get erroneous estimates of soil evaporation. Including such things as root water extraction from the evaporation layer and crop residue adjustments together with site-specific calibration can help improve the accuracy (Barker et al., 2018b).

5.1.2.4.2.3 Ideal Conditions

Crop coefficients are often developed under low-crop-stress conditions. Meaning, nutrients and water are not limiting, and pests are carefully controlled. This often results in plant transpiration being greater than is realized in many production conditions. For this reason, ET_c modeled in this way is sometimes referred to as "potential ET," though this term is generally discouraged by contemporary scientists because it is ambiguous.

Methods have been developed to adjust crop coefficients based on water and salinity stress. These methods are well documented in FAO 56 and MOP 70. When using the crop coefficient method to estimate actual depletion, these methods are recommended. The K_c including water stress is (MOP 70; Figure 5.14):

$$K_c = K_s K_{cm} \quad (5.30)$$

where:

K_c	=	The crop coefficient (dimensionless),
K_s	=	The water stress coefficient (dimensionless), and
K_{cm}	=	The mean crop coefficient (dimensionless),

and

$$K_c = K_s K_{cb} + K_e \quad (5.31)$$

where:

K_{cb}	=	The basal crop coefficient, primarily representing plant transpiration (dimensionless),
K_s	=	The water stress coefficient (dimensionless), and

K_e = The soil evaporation coefficient (dimensionless).

Because the K_s applies truly to transpiration, it is best applied to the dual crop coefficient method. Estimating K_s requires accurately parameterizing and modeling the crop root zone water balance (MOP 70). For this, it is necessary to accurately identify soil AWC, root zone depth, soil evaporation layer depth, initial soil water content, deep drainage rates, precipitation, runoff, soil residue cover, and infiltrated irrigation, in addition to accurate application of the K_c. Because of this, K_c methods are best employed for planning purposes, prediction, and hypothetical analyses rather than accurate depletion estimation.

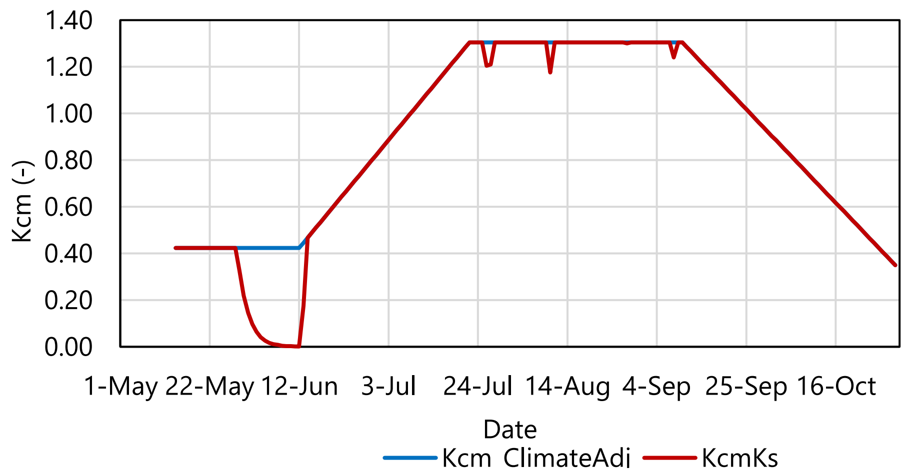

Figure 5.14. Mean crop coefficient for corn with and without water stress adjustments (MOP 70).

5.1.2.4.2.4 Climate Adjustments

Short reference crop coefficients published in FAO 56, MOP 70, and related literature require climate adjustments. Proper short reference crop coefficients for use with the Standardized Reference ET Equation should be provided for conditions of mean wind speeds equal to 2 m s^{-1} (4.5 miles h^{-1}) and mean daily minimum relative humidity equaling 45% (Pereira et al. 2021a). These conditions are uncommon in Utah. So, climate adjustments are necessary. The adjustment procedure presented in MOP 70 should be followed whenever using short reference crop coefficients in Utah. An example of a climate adjustment for a corn crop coefficient for Cache Valley, Utah is shown in Figure 5.15.

Climate adjustments are not needed for tall reference crop coefficients because the tall reference is more responsive to climate differences than the short reference is. ET_r and tall reference crop coefficients are recommended for use in Utah, when possible.

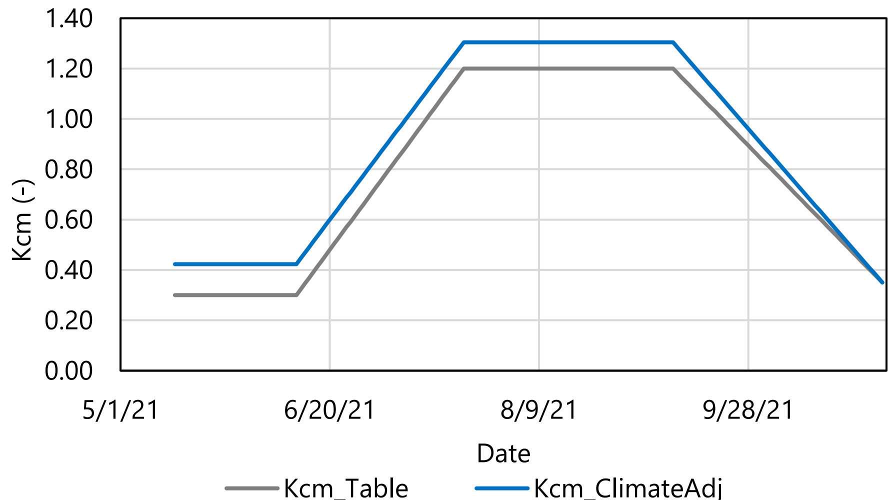

Figure 5.15. Climate adjusted crop coefficient for corn for Cache Valley, Utah (MOP 70).

5.1.2.4.2.5 Crop Coefficients Sources

Two primary sources for crop coefficients for the Standardized Reference ET Equation are FAO 56 and MOP 70. Useful sources for updated crop coefficients for vegetable and fruit crops are Periera et al. (2021a,b). Some additional sources that may be applicable in Utah include Allen and Robison (2007) and Allen et al. (2020), though, the latter is not a direct source. The mean crop coefficients used by Hill et al. (2011) were deemed appropriate for planning purposes in Utah. However, care should be exercised when applying them beyond that study. For example, the K_c timing for corn is known to the present authors to result in low estimates of ET_c.

5.1.2.4.2.6 Crop Coefficient Method Applications

Crop coefficients are conventionally applied for a single field using ground-based weather data. A variation of this method was applied by Hill et al. (2011) for Utah, Allen and Robison (2007) for Idaho, Huntington and Allen (2010) for Nevada, and Huntington et al. (2015, 2016) for areas of the Western U.S. using generalized crop timing for regions based on local, ground-based, weather data. However, these studies have relied on engineering judgement with little ground truthing.

Hill et al. (2011), for example, provided perhaps the most complete ground truthing by comparing modeled alfalfa ET_c with ET estimated based on alfalfa yield in different areas of Utah. They adjusted ET_r accordingly to reconcile the two estimates. While this method may have improved the ET_c estimates for alfalfa, the implicit assumption was that similar differences would occur for all crops and landcovers.

Of the studies cited above, Hill et al. was the only one in which mean crop coefficients were used, the others all used dual crop coefficients. For planning purposes, both methods may be valid. However, none of these studies provided estimates of ET_c for different irrigation management scenarios or irrigation system types. This is a capability of the dual K_c method.

5.1.2.4.2.7 Gridded Weather Data and Crop Survey Methods

Another method of applying the crop coefficient method for depletion estimates was employed for the Mohave Valley Irrigation District in the Lower Colorado River Basin of Arizona as described in NRCE and Jacobs (2021b). In this, a spatial crop survey was used to determine crops for each field in the study. ET was then modeled for each field using ground-based weather data. The accuracy of this method is highly dependent upon the proper selection and employment of crop coefficients.

Lewis and Allen (2017), expanded on the methods of Hill et al. (2011) by using gridded weather data instead of point-based data. They eliminated the ET_r adjustment based on alfalfa yield and eliminated weather-based growing season initiation in favor of a fixed date. Their product, GridET, is used and updated by the Utah Division of Water Resources for depletion estimates. However, the method is still subject to errors related to selection of crop coefficients, timing of crop growth conditions, and non-ideal growing conditions.

5.1.2.4.2.8 Reflectance-Based Crop Coefficients

One method that was developed starting in the 1980's to improve K_c application is the reflectance-based crop coefficient (e.g., Bausch and Neale, 1987). These are crop coefficients based on relationships with remote sensing vegetation indices. Actively growing vegetation reflects little red light, but it is highly reflective of longer wavelength light in the near-infrared range. Soil, on the other hand, typically reflects more red and less near-infrared light than vegetation. These behaviors have allowed remote sensing scientists to develop ratio indices (called vegetation indices) based on the portion of light in these two bands that is reflected (reflectance, ranging from 0 to 1) to estimate green vegetation cover.

5.1.2.4.2.8.1 General Concept

One common vegetation index is the Normalized Difference Vegetation Index (NDVI; Rouse, 1974):

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}} \tag{5.32}$$

where:

$NDVI$	=	The Normalized Difference Vegetation Index (dimensionless),
ρ_{NIR}	=	Near-infrared light reflectance (dimensionless, 0 – 1), and
ρ_{Red}	=	Red light reflectance (dimensionless, 0 – 1).

Researchers have observed that K_{cb} tends to be linearly related to NDVI and other vegetation indices. Crop coefficients obtained this way are called reflectance-based crop coefficients (Neale et al., 1989):

$$K_{cbrf} = aVI + b \tag{5.33}$$

where:

K_{cbrf}	=	The reflectance-based basal crop coefficient (dimensionless),
a	=	Empirical, crop-specific, slope coefficient (dimensionless),
VI	=	Vegetation index, e.g., the NDVI (dimensionless), and
b	=	Empirical, crop-specific, intercept coefficient (dimensionless).

The K_{cbrf} method holds distinct advantages over conventional crop coefficient methods when determining depletion. Advantages include improved accuracy in the timing of the crop coefficient. Because the vegetation index responds directly to green vegetation cover and leaf area, any differences in crop development from those of the original K_{cb} study conditions are accounted for. Furthermore, this method implicitly accounts for many growth restrictions caused by biotic and abiotic stress on crops.

Proper employment of this method still requires modeling the water stress term (K_s) and soil evaporation (see Barker et al., 2018b). The method is, therefore, subject to the same challenges as described earlier in Sections *5.1.2.4.2.2* and *5.1.2.4.2.3*. Site-specific validation is still the best practice.

The reflectance-based crop coefficient method is the simplest of remote-sensing-based methods for modeling ET. There are many sources of K_{cbrf} relationships. It is important that they be applied using climate adjustments (if used with ET_o), using the same remote sensing platform (e.g., Landsat) that they were developed for, and using the proper vegetation index (not all are for NDVI). Furthermore, it should be noted that the NDVI is sensitive to reflectance characteristics of the site soil. It is, therefore, less transferable than other indices, like the Soil Adjusted Vegetation Index (Huete, 1988; Bausch, 1993). The following sources may be helpful in Utah: Campos et al. (2017) for grain corn and Melton et al. (2012). The latter is of interest because it is the reference for the Satellite Irrigation Management System (SIMS) model.

5.1.2.4.2.8.2 The Satellite Irrigation Management System (SIMS) Model

The SIMS model (Melton et al., 2012), is a reflectance-based crop coefficient model developed by the National Aeronautics and Space Administration (NASA) and originally employed in California. It is included as one of six remote-sensing-based models in the OpenET platform (Section *5.1.2.7*) and is distinguishable as being the only crop-coefficient-based method in OpenET.

5.1.2.5 Energy Balance Evapotranspiration Models

Remote sensing can be used to model ET in other ways beyond being used to estimate crop coefficients. The primary method for such use is the surface energy balance (Equation 5.12). Remote sensing data (land surface temperature, and multispectral reflectance) are typically used to model R_n, G, and H with LE computed using the energy balance.

Because LE is modeled for observed conditions, ET from energy balance models is typically considered to be representative of actual ET, rather than some idealized value as is common in K_c methods.

In energy balance models, R_n is typically modeled using shortwave reflectance and a measurement of total incoming solar radiation (e.g., Brest and Goward, 1987). Radiation flux in the longwave (thermal) bands can be estimated using land surface and air temperatures by applying the Stephan-Boltzmann Law. The specifics of the R_n models vary between ET models, but well-parameterized models typically estimate R_n well.

Different methods are used to model G, including some as simple as assuming G is a constant fraction of R_n or of the R_n associated with the soil surface (e.g., Norman et al., 1995). It is common for G to be modeled poorly, but it is often small relative to R_n and LE.

The premise of many remote sensing energy balance models is the fact that sensible heat flux can be defined based on the temperature difference between the land surface and the air at some known height:

$$H = \frac{\rho_a c_p (T_{Aero} - T_{Air})}{R_{ah}} \quad (5.34)$$

where:

H	=	Sensible heat (energy) flux (W m^{-2}),
ρ_a	=	Density of air (kg m^{-3}),
c_p	=	Specific heat of air at constant pressure (J kg^{-1} K^{-1}),
T_{Aero}	=	Aerodynamic surface temperature (K),
T_{Air}	=	Air temperature (K), and
R_{ah}	=	Aerodynamic resistance to heat transfer (s m^{-1}).

The T_{Aero} is akin to the surface temperature, which can be measured with an infrared radiometer, a thermal infrared camera, or a satellite thermal infrared instrument. The challenge is that T_{Aero} itself is not a measurable quantity. It is a theoretical quantity based on Equation 5.34. Remote sensing energy balance models vary fundamentally on how they handle this theoretical obstacle so they can employ land surface temperature measurements to estimate ET.

There are many energy-balance ET models. Some that are relevant to Utah are briefly described below. Additional comparisons of ET models are provided by Jacobs (2023) and Medellin-Azuara (2018).

5.1.2.5.1 Surface Energy Balance Algorithm for Land (SEBAL)

The Surface Energy Balance Algorithm for Land (SEBAL) model was developed in the Netherlands by Bastiaanssen et al. (1998a,b). This model overcame two challenges with satellite remote sensing: 1) the T_{Aero} problem and 2) the need for accurate land surface temperature corrections. In SEBAL, this is done by taking a land surface temperature map and expertly selecting one pixel in the map to represent full LE ($R_n - G = LE$) and one to represent full *H* ($R_n - G = H$). The remainder of the temperatures in the image are scaled accordingly and then used to compute *H* and then *LE* for each pixel.

Because a pixel that is dominated by *LE* will be cooler than one dominated by *H* for otherwise similar conditions, the *LE* pixel is called the "cool" pixel, and the *H* pixel is called the "hot" pixel. Consider a simplified image with only 25 pixels (Figure 5.16). An expert has determined that Pixel 7 meets the criteria for a cold pixel and Pixel 18 meets the criteria for a hot pixel. The remaining temperatures are used to compute *H* based on energy balance assumptions for these two pixels.

One challenge with this method is that it requires comparisons between pixels in each image or scene. Another challenge with the SEBAL method is that it originally required manual expertise to select the hot and cold pixels. Finally, If the energy balance assumptions for the hot and cold pixels are not valid, the method will result in erroneous values.

SEBAL is of particular interest in Utah because a version of the model, Google Earth Engine SEBAL (geeSEBAL, Laipelt, 2021) with automated hot and cold pixel selection is included on the OpenET platform (Section *5.1.2.7*).

T_1	T_2	T_3	T_4	T_5
T_6	T_7	T_8	T_9	T_{10}
T_{11}	T_{12}	T_{13}	T_{14}	T_{15}
T_{16}	T_{17}	T_{18}	T_{19}	T_{20}
T_{21}	T_{22}	T_{23}	T_{24}	T_{25}

Figure 5.16. Simplified temperature map to illustrate SEBAL method.

5.1.2.5.2 Measuring EvapoTRanspiration with Internal Calibration (METRIC™)

The METRIC™ model was developed in Southern Idaho by Allen et al. (2007) based on the principles of SEBAL. A key difference between METRIC and SEBAL is the assumed condition for the cold pixel. In METRIC, the cold pixel was originally assumed to have *LE* that matched ASCE Standardized Tall Reference ET.

METRIC is of particular interest in Utah because a version of METRIC for Google Earth Engine (eeMETRIC) with automated selection of hot and cold pixels (Allen et al., 2013; 2015) has been adopted for estimating consumptive water use in the Upper Colorado River Basin by a Resolution of the Upper Colorado River Commission (UCRC, 2022) and is also included in the OpenET platform. METRIC is also of note because of its regional popularity, meaning that finding qualified modelers may be less difficult than some other models.

5.1.2.5.3 Atmosphere-Land Exchange Inverse (ALEXI)

The Atmosphere-Land Exchange Inverse (ALEXI) model was developed by the U.S. Department of Agriculture (Anderson et al., 1997, 2007). This model uses the Two-Source Energy Balance (TSEB) model (Norman et al., 1995) to model ET as part of a larger ecosystem model.

The TSEB was developed in Wisconsin. When employed with satellite data, measured land surface temperature is divided into component plant canopy and soil components:

$$T_{Surf}^4 = f_c T_c^4 + (1 - f_c) T_s^4 \tag{5.35}$$

where:

T_{Surf}	=	Surface temperature (K),
f_c	=	Fraction of the soil covered by vegetation (dimensionless, 0 – 1),
T_c	=	Canopy temperature (K), and
T_s	=	Soil temperature (K).

Partitioning the surface temperature allows for the energy balance to be solved at once for both the soil and the canopy and avoids the need to quantify the combined T_{Aero}. However, Equation 5.28 introduces a new challenge: it has two unknowns (note, f_c can be found using a vegetation index; Choudhury et al., 1994). To alleviate this problem, Norman et al. provided a method wherein the canopy *LE* is initially assumed to match ET from the Priestly-Taylor Equation (Colaizzi et al., 2014 adapted the model to use the Penman-Monteith Equation). This allows for a canopy *H* to be estimated, then canopy temperature, then soil temperature, then a soil *H*, then soil *LE*, by the energy balance. The model includes an iteration should either *LE* term be negative. The PyTSEB model (https://github.com/hectornieto/pyTSEB) by H. Nieto, is a freely available code for the TSEB model.

The primary factor that differentiates the ALEXI model from the general TSEB is the fact that ALEXI was developed to be operated over large areas with limited weather data. ALEXI operates using geostationary satellites or polar orbiting satellites with frequent overpasses. Using these data, ALEXI solves the TSEB model twice daily (originally, mid and late morning). From these measurements, the model can estimate air temperature for use in computing ET, thus eliminating the need for measured air temperature.

Because geostationary and high-frequency polar orbiting satellites have large ground resolutions (1 km +; see Section *5.1.2.4.1.1*), Anderson et al. (2012) developed a method to downscale the results to a 30-m ground resolution. This downscaling uses less-frequent Landsat data in a disaggregation routine called DisALEXI. This model uses the air temperature and atmospheric layering information modeled by ALEXI to model ET using Landsat imagery.

The ALEXI-DisALEXI model combination is of interest in Utah because of the inclusion of the pair in the Open ET platform (Section *5.1.2.7*). ALEXI data are also available for some areas of the world through the Global Daily EvapoTranspiration (GloDET) website operated by the University of Nebraska (https://glodet.nebraska.edu/#/).

5.1.2.5.4 Remote Sensing of EvapoTranspiration (ReSET)

The Remote Sensing of EvapoTranspiration (ReSET) model was developed in Colorado by Elhaddad and Garcia (2008). This model shares principles with SEBAL and METRIC where conditions for two extreme pixels, a wet pixel where $LE = R_n - G$ and a dry pixel where $H = R_n - G$. ReSET uses these data to eliminate the need for measured air temperature in the model. This is done using the wet and dry pixels rather than two times of day as in ALEXI. Elhaddad and Garcia (2011) modified the model to use gridded weather data products, but the general principles remain the same. ReSET is noteworthy for Utah because, having been developed in Colorado, it may be used for regional ET studies.

5.1.2.5.5 Operational Simplified Surface Energy Balance (SSEBop)

The Operational Simplified Surface Energy Balance (SSEBop) model was developed by the U.S. Geological Survey (USGS; Senay et al., 2013). The premise of SSEBop is like that of SEBAL and METRIC in that comparison temperatures are necessary to obtain ET estimates. However, in SSEBop, the hot and cold temperature values are obtained based on weather conditions rather than neighboring pixels. SSEBop does not directly model ET, but rather the fraction of ET to reference ET (Senay et al., 2013):

$$ET = ET_f k ET_o \tag{5.36}$$

where:

ET	=	Evapotranspiration (in),
ET_f	=	ET fraction (dimensionless),
k	=	ET adjustment factor (in), and
ET_o	=	Short reference evapotranspiration (in).

Note that the coefficient, k, behaves like a crop coefficient, but it is meant to adjust ET_o upward and takes on values like the ratio of ET_r/ET_o (Senay, 2018), suggesting that the use of ET_r may be appropriate here.

The ET_f is found as:

$$ET_f = \frac{T_{Hot} - T_{Surf}}{T_{Hot} - T_{Cold}} \tag{5.37}$$

where:

ET_f	=	ET fraction (dimensionless),
T_{Hot}	=	“Hot” temperature (no latent heat flux; K),
T_{Cold}	=	“Cold” temperature (no sensible heat flux; K), and
T_{Surf}	=	Surface temperature (K).

The model uses measured air temperature to obtain T_{Cold} and an energy balance model, including an R_n model, to estimate T_{Hot} from T_{Cold}. It should be noted that under some conditions, T_{Surf} is adjusted (Senay, 2013). Senay (2018) provided an alternate formulation for the model based on psychrometrics.

The SSEBop model is of interest in Utah because it is included on the *OpenET* platform.

5.1.2.5.6 Jet Propulsion Laboratory's Priestly-Taylor

NASA's Jet Propulsion Laboratory's Priestly-Taylor (Priestly-Taylor JPL; Fisher et al., 2008) uses The Priestly-Taylor Equation to find LE. This is done by breaking LE into components:

$$LE = LE_C + LE_S + LE_I \tag{5.38}$$

where:

LE	=	Total latent heat (energy) flux (W m^{-2}),
LE_C	=	Canopy latent heat flux (W m^{-2}),
LE_S	=	Soil latent heat flux (W m^{-2}), and
LE_I	=	Intercepted water latent heat flux (W m^{-2}).

R_n and G are model inputs and, so, are modeled separately. The Priestly-Taylor JPL model does not rely on thermal infrared imagery, unless used to model R_n and/or G. However, since the Priestly-Taylor equation is derived from the energy balance, it is included here as an energy balance equation.

The remote sensing inputs for the model are two vegetation indices, the NDVI and SAVI. NDVI loses sensitivity to green vegetation as the vegetation cover increases. SAVI maintains sensitivity to increases in vegetation longer than NDVI. Together, they are used to help determine the LE_c based on the Priestly-Taylor Equation (Section *5.1.2.3*). Other inputs include air temperature and relative humidity along with parameters like the optimal plant growth temperature.

The Priestly-Taylor JPL model is intended for large, regional, analyses. The model is of interest in Utah because it is included on the OpenET platform (Section *5.1.2.7*).

5.1.2.5.7 Temporal Scaling

A common challenge for many energy balance models is that of temporal scaling. Models like SEBAL, METRIC, ALEXI, ReSET, and SSEBop, natively produce an instantaneous value of ET for the moment that input imagery was collected. This value is of limited use unless it can be scaled up to a daily value. There are several common methods for temporal scaling and each model typically incorporates one of them. For example, a form used for ALEXI is (Anderson et al., 2007):

$$ET_{Day} = \frac{1.1 ET_{Inst}\left(R_{n,Day} - G_{Day}\right)}{\left(R_{n,Inst} - G_{Inst}\right)} \tag{5.39}$$

where:

ET_{Day} = Daily ET (in d^{-1}),
ET_{Inst} = Instantaneous ET from the model (in d^{-1}),
$R_{n,Day}$ = Daily net radiation (W m^{-2}),
G_{Day} = Daily soil heat flux (W m^{-2}),
$R_{n,Inst}$ = Instantaneous net radiation (W m^{-2}), and
G_{Inst} = Instantaneous soil heat flux (W m^{-2}),

Here, the 1.1 factor is to account for the ratio of ET to $R_n - G$ at the time of the model image being less than the daily average.

For geeSEBAL, a method like Equation 5.39 is used (Laipelt et al, 2021):

$$ET_{Day} = \frac{ET_{Inst} R_{n,Day}}{\left(R_{n,Inst} - G_{Inst}\right)} \tag{5.40}$$

where:

ET_{Day} = Daily ET (in d^{-1}),
ET_{Inst} = Instantaneous ET from the model (in d^{-1}),
$R_{n,Day}$ = Daily net radiation (W m^{-2}),
$R_{n,Inst}$ = Instantaneous net radiation (W m^{-2}), and
G_{Inst} = Instantaneous soil heat flux (W m^{-2}).

Here, G_{Day} is assumed to be zero, which is a common assumption (ASCE, 2005), and no adjustment is made like the additional 10% in Equation 5.39.

METRIC uses a similar relationship based on ET_r rather than available energy ($R_n - G$) (Allen et al., 2007):

$$ET_{Day} = \frac{ET_{Inst} ET_{r,Day}}{ET_{r,Inst}} \tag{5.41}$$

where:

ET_{Day} = Daily ET (in d^{-1}),
ET_{Inst} = Instantaneous ET from the model (in h^{-1}),
$ET_{r,Day}$ = Daily tall reference ET (in d^{-1}), and
$ET_{r,Inst}$ = Instantaneous tall reference ET (in h^{-1}).

There is some discussion related to the ReSET model regarding how models like SEBAL, which make the cold pixel assumption of $LE = R_n - G$ use relationships like Equations 5.39 and 5.40 verses models like METRIC, which use ET_{ref} to define the cold pixel conditions that use something like Equation 5.41 (Elhaddad and Garcia, 2011). This makes sense based on the fundamental differences in model assumptions.

There are other methods, like those above, including Equation 5.40 omitting G_{Inst}, Equation 5.40 using incoming solar radiation instead of R_n and omitting G_{Inst} and Equation 5.41. with

ET_o in place of ET_r. Chávez et al. (2008) compared these different methods using their own energy balance model and found that the Equation 5.39 and 5.40 method was best in their conditions and suggest that Equation 5.41 is better for non-stressed conditions. Colaizzi et al. (2006) performed an extensive comparison of scaling methods and recommended using Equation 5.41 using ET_o. Their study was based on ET measurements only and so individual model performance may differ.

In practice, it is important to be aware of the temporal scaling methods because they have significant impact on model performance. However, well-calibrated models should be developed with a temporal scaling method appropriate for the respective model.

5.1.2.5.8 The Advection Problem

Remote sensing energy balance models operate on the implied assumption that energy transfer at the land surface is vertical. Solar radiation comes down, heats the land surface, some energy moves down into the soil, the warmed surface heats the air above it, energy evaporates water in the soil surface or in plants. However, in areas like Utah, where there are large regions of dry land around the irrigated areas, wind can import energy horizontally into irrigated areas. This process is called advection.

In advective conditions, the dry areas have less LE and more H, so the air gets warmer. Wind blows this warm, dry air into an area with more water (e.g., irrigated lands), the energy from this warm, dry air increases LE beyond what would occur from R_n and G alone. This process is difficult to account for in models that are built upon the assumption of vertical energy transfer.

Models, like SEBAL, METRIC, SSEBop, and ReSET rely on the vertical energy transfer assumption when making comparisons between pixels. Though, there is evidence (Jacobs, 2023; Torres-Rua, personal communication, 2024) that METRIC responds better to advection than do other OpenET models. For models like the Priestly-Taylor JPL, ET is directly related to $R_n - G$ and horizontal energy movement can be problematic because it shows up as increased temperatures and decreased humidity, which are not included in the Priestly Taylor equation. ALEXI relies on the assumption of vertical energy transfer to obtain air temperature estimates. Furthermore, the scale at which ALEXI is computed can result in significant smoothing at the edge of irrigated areas. It is noted that these assumptions, which may at first seem like weaknesses, are what have allowed these models to bet operational at large spatial scales.

All the remote sensing models in OpenET have some dependence on ground or gridded weather data. Ground-based weather data can, theoretically, be sensitive to some advective effects. That is, the temperature and humidity of the air, combined with the wind speed. For some models, like the TSEB, which do not rely on spatial relations, accurate weather data corresponding to the modeled point may allow the model to respond to advection (e.g., this has been observed in advective conditions in Texas, P. Colaizzi, personal communication, 2023).

Gridded weather data products have two challenges: 1) some of these products represent regional conditions, often without irrigation, and 2) sometimes gridded weather products are adjusted to represent well-irrigated conditions (R.G. Allen, personal communication, ca. 2016). Reality can sometimes be in between these conditions, which is difficult to accomplish for large, regional models.

The net effect of models being unable to respond to advection is a systematic low bias. In time, models will become better at responding to advection. At present, the advection question should not be used as a hobble to prevent using the best, reasonable method to estimate depletion understanding that the methods will improve in the future.

5.1.2.6 Remote Sensing Platforms

Functionality and accuracy of remote-sensing-based ET models depend on the source of input data including remotely sensed land surface temperature and surface reflectance data. Operationally, it is most convenient to use satellite remote sensing imagery, though aerial platforms (including unmanned aerial vehicles, UAVs), and ground-based systems are also available.

5.1.2.6.1 Landsat

One of the most used satellite platforms for ET models is Landsat, operated by NASA and the USGS. There are currently two active Landsat satellites: Landsat 8 and Landsat 9. Previous Landsat satellites of note include Landsat 5 (1984 - 2013) and Landsat 7 (1999 - 2022) (NASA, 2024a). However, Landsat 7 had a sensor problem that caused it to skip substantial amounts of data making it less useful for many purposes than some of the other Landsat missions. Each of these satellites has an overpass recurrence interval of 16 days. Landsat 8 and 9 are offset from each other in a way so that there are 8 days between overpasses. Landsat satellites overpass Utah around 11:00 am Mountain Standard Time.

These satellites measure reflected shortwave radiation at a ground resolution of 30 m. Thermal infrared radiation (for land surface temperature) is measured at 100 m and then sharpened to 30 m (Figure 5.17). Because of the scale that these data are collected at, there are edge effects, like blurring, caused by edge pixels containing data both within and without an area of interest. Small irrigated areas, smaller than the thermal pixels, may not be well represented.

Landsat is a particularly important dataset for Utah because of its wide use and inclusion in the OpenET platform.

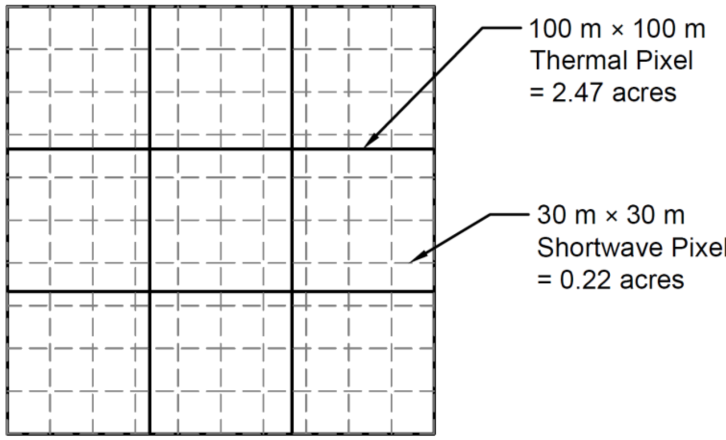

Figure 5.17. Representation of Landsat shortwave and thermal band horizontal scales.

5.1.2.6.2 Sentinel

The European Space Agency (ESA) operates the Sentinel satellite constellation. For ET applications, Sentinel 2, which currently includes two satellites, measures shortwave reflectance at a ground resolution of 10 m. Sentinel 3 will include shortwave reflectance at a 500-m resolution and thermal infrared imaging at a 1,000-m resolution in the coming years (ESA, 2025).

5.1.2.6.3 Moderate Resolution Imaging Spectroradiometer (MODIS)

The Moderate Resolution Imaging Spectroradiometer (MODIS) mission includes two satellites Aqua (intended for ocean observation) and Terra (intended for land observation). The two satellites cover the earth every day or two with Terra passing in the late morning and Aqua in the early afternoon (NASA, 2024b). The satellites have both surface reflectance data (500 m) and thermal data (1,000 m). The frequency of these satellite measurements makes them helpful for data continuity. However, this is done at the expense of spatial resolution (Figure 5.18). The MODIS pixels by themselves are too coarse for field-level ET estimates in Utah.

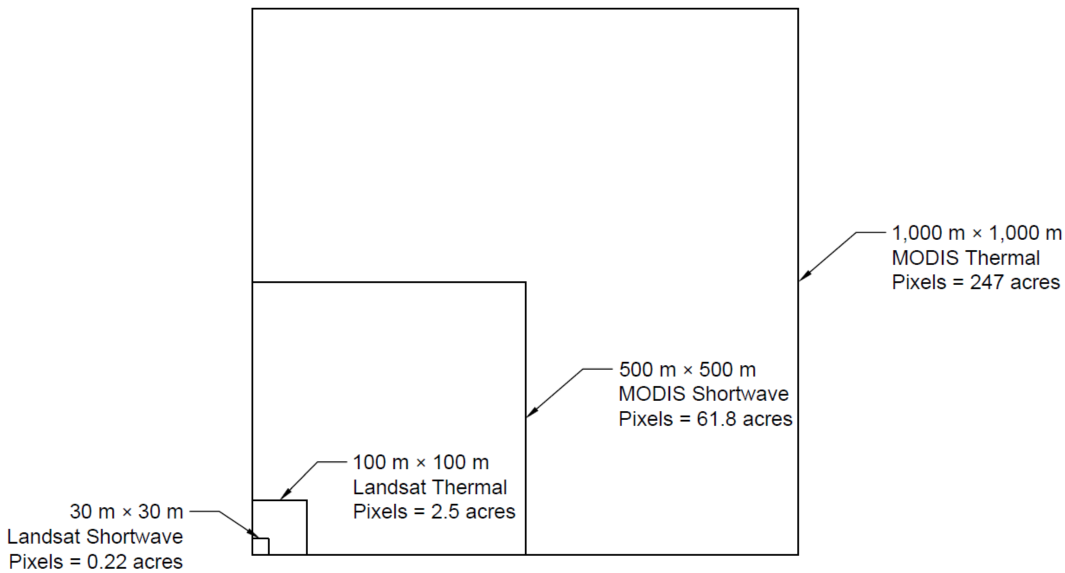

Figure 5.18. Comparison of Landsat and MODIS pixel sizes.

5.1.2.6.4 Visible Infrared Imaging Radiometer Suite (VIIRS)

NASA operates the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite. The Satellite has a 750-m ground resolution for both shortwave and thermal bands. The satellite has daily coverage of any given location (NASA, 2024c).

5.1.2.6.5 CubeSats and Planet™

Until recently, satellite remote sensing was fairly limited to using datasets from government-sponsored satellite platforms. However, some commercial satellite providers now produce high resolution remote sensing products that can be used to model ET. One example is the use of CubeSats, small cubic satellites, which are much less expensive than the typical government-sponsored platform. The utility of CubeSats for ET modeling at a small spatial scale (e.g., 3 m) was demonstrated by Aragon et al. (2021).

CubeSat data are available through the company Planet (www.planet.com). However, the data are not all free of charge and may require processing that is sometimes otherwise provided by government agencies to make the data products suitable for ET estimation.

5.1.2.6.6 Unmanned Aerial Vehicles (UAVs)

Unmanned Aerial Vehicles (UAVs) are small, autonomous aircraft, or drones, which are widely marketed to agricultural producers. UAVs can be equipped with scientific-grade remote sensing cameras including multispectral cameras and thermal infrared imagers. However, not all camera systems are suitable for collecting scientific-grade data products necessary to estimate ET. Furthermore, proper image collection conditions and data processing are needed to produce suitable imagery. At present, UAVs are not recommended for depletion quantification.

5.1.2.6.7 Ground-Based Sensors

Reflectance-based crop coefficients and some energy balance models can be used with ground-based remote sensing platforms. These sensors can be mobile, mounted to a center pivot or to some other platform (Colaizzi et al., 2017). These sensors can also be stationary. Development of stationary sensing platforms for estimating ET at small spatial scales is a current topic of research at USU (Stewart, 2024). These methods have been used successfully for dry bean in Nebraska (Liang et al., 2021), corn in Nebraska (Katimbo et al., 2022), and cotton, corn, and sorghum in Texas (Colaizzi et al., 2017). Ground-based systems including on-site weather data have the potential to overcome the advection problem (Section *5.1.2.5.8*). Though, the ground-based stations are not ready for general deployment at present.

5.1.2.7 OpenET

OpenET is a collaboration providing modeled ET from six models (*SIMS*, *geeSEBAL*, *eeMETRIC*, *ALEXI-DisALEXI*, *SSEBop*, and *Priestly-Taylor JPL*) at a 30-m ground resolution (OpenET, 2024). The advent of OpenET has improved the practicality of using remote sensing for operational quantification of depletion. OpenET can provide monthly ET estimates for each of the included models. It also includes an ensemble mean ET estimate, which is an arithmetic mean, excluding outliers (OpenET, 2024). Some of the ET estimates are provided free of charge. However, large requisitions require a fee.

OpenET estimates are subject to the same temporal scaling, pixel scale and edge-effect issues (Section *5.1.2.6*) described for the individual component models and the advection problem (Section *5.1.2.5.8*).

For the present, OpenET represents the best general, remote-sensing-based ET dataset for routine use in estimating depletion in Utah. The primary justification for this statement is the reasonable performance of the ET products from this platform (e.g., Volk et al., 2024) and the continued development, improvements, and support that OpenET is receiving and will receive in the future.

Because of the modeling scales, OpenET is not recommended for areas less than two times the hypotenuse of a Landsat thermal infrared pixel hypotenuse across. Landsat thermal pixels are 100 m × 100 m. This gives a hypotenuse of 141 m = 464 ft. Double this value is about 930 ft.

5.1.2.8 Evapotranspiration Fraction

A final ET estimation method that is considered here is the ET fraction. This was defined previously in Equation 5.36 and the temporal scaling methods (Section *5.1.2.5.7*). However, here, the concept is for comparison purposes and is analogous to a crop coefficient:

$$ET_f = \frac{(ET_a)_{Rep}}{(ET_r)_{Rep}} \tag{5.42}$$

where:

ET_f	=	ET fraction based on a selected representative location/condition (dimensionless),
$(ET_a)_{Rep}$	=	"Actual" ET from a remote-sensing-based model for the selected representative location/condition (in), and
$(ET_r)_{\text{Rep}}$	=	Tall reference evapotranspiration for the selected representative location/condition (in).

To get ET for the subject location/condition:

$$ET_{Subject} = ET_f (ET_r)_{Subject} \tag{5.43}$$

where:

$ET_{Subject}$	=	Estimated ET for the subject location/condition (in),
ET_f	=	ET fraction based on a selected representative location,
$(ET_r)_{Subject}$	=	Tall reference evapotranspiration for the subject location/condition (in).

The ET_f can be computed for areas representative of a location of interest where a specific crop or management practice has not yet occurred. This method allows for the expanded use of remote-sensing-based models for the purposes of prediction, not just post-facto analysis. ET_o can be used in place of ET_o based on data availability or user preference.

5.2 Consumptive Losses

Consumptive losses include any evaporation of irrigation water before it infiltrates into the soil. Direct evaporation of applied irrigation water depends upon the irrigation method.

5.2.1 Surface Irrigation

In border, basin, and wild flood irrigation, water is spread across the entire surface of the irrigated area. Consumptive losses only include direct evaporation from the ponded water before it infiltrates. This evaporation is often small relative to the total applied irrigation and is well within the uncertainties of the water balance. This evaporation should typically be neglected (Strelkoff and Clemmens, 2007). In furrow irrigation, water is only ponded in furrows resulting in even less direct evaporation. In some cases, water is ponded for multiple days, this occurs typically in systems with low levels of design or management. For example, this has been observed by the authors in the Beaver and Bear Lake Valleys of Utah. In these cases, if energy balance ET methods are used, they should pick up on some of this evaporation, negating the need to further account for it. In other cases, open surface evaporation can be estimated as in (Section *5.3.1*) and then added to the crop ET. However, the sum of those two should not exceed tall reference ET (ET_r) for the day.

5.2.2 Drip Irrigation

Drip irrigation typically does not result in water being ponded on the soil surface. Therefore, direct evaporation from ponded water does not occur. Drip droplets spend little time traveling between drip lines and the soil surface even when drip lines are suspended a short distance above the soil surface. Subsurface drip irrigation has no direct evaporation because the system is buried. Consumptive losses should be neglected in all forms of drip irrigation. This does not include micro spray or mini sprinkler irrigation.

5.2.3 Subirrigation

Subirrigation involves purposely raising the water table into the crop's root zone. This may be done by running water through ditches along the field. If this is done, there may be some evaporation from the diches. However, consumptive losses can typically be neglected from subirrigation.

5.2.4 Sprinkler and Micro Irrigation

Sprinkler irrigation, including micro sprays and mini sprinklers, is the most susceptible of all farm irrigation methods to consumptive losses. When a water droplet travels through the air, there is an opportunity for water to evaporate from the droplet. Smaller droplets are more susceptible to evaporation than large droplets because their surface-area-to-mass-ratio is larger. Droplet travel time in the air also effects evaporation with droplet evaporation increasing with increasing time between leaving the sprinkler and reaching the ground.

Weather affects droplet evaporation. The two weather variables that matter most to water evaporation are humidity and wind speed (Sarwar et al., 2019). Dry air will cause more evaporation than moist air. Nighttime evaporation is often smaller than daytime evaporation for this reason. High wind brings new dry air in contact with the water droplets, and it can also cause droplets to break apart into smaller drops. Wind can cause wind drift, forcing droplets away from their intended application area. Wind drift is not strictly a consumptive use. However, it is difficult to separate from evaporation. Yazar (1987) was able to differentiate between evaporation and wind drift using a salt balance. He found under wind conditions less than 4 m s^{-1} (9 mph), wind drift was about 25% of wind drift and evaporation and 47% for higher winds in his Eastern Nebraska study.

Wind drift and evaporation are typically measured together in research studies using catch cans. There is no practical method to directly measure consumptive losses for extended periods of time. Instead, empirical relationships are developed relating wind drift and evaporation losses to weather variables.

5.2.4.1 Line-Source Sprinklers and Big Guns

Line-source sprinklers involve a pipeline with sprinklers at even intervals along the line. Wheel lines, hand lines, and solid set systems are types of line-source sprinklers. Conventionally, these systems have used tapered-bore, brass impact sprinklers (Figure 5.19). One relationship for conventional impact sprinklers was developed in the form of a nomograph by Frost and Schwalen (1955) and Frost (1963). Trimmer (1987) converted the Frost nomograph into the following equation:

$$f_{WDE} = \frac{\left[1.98{d_{noz}}^{-.72} + 0.22(e_s - e_a)^{0.63} + 0.00036P^{1.16} + 0.14u^{0.7}\right]^{4.2}}{100} \tag{5.44}$$

where:

f_{WDE} = The fraction of sprinkler discharge that is evaporated, here assumed to be wind drift and evaporation (WDE),

d_{noz} = Sprinkler nozzle diameter (mm),

e_s = Average daytime saturated vapor pressure during the irrigation event (kPa),

e_a = Average daytime actual vapor pressure during the irrigation event (kPa),

P = Sprinkler nozzle operating pressure (kPa), and

u = Average daytime wind speed during the irrigation event (m s^{-1}).

Common design pressures for wheel line sprinklers are in the 50 to 60 pounds per square-inch (psi) (345 kPa – 415 kPa) range. Many systems operate lower than this. The Frost nomograph covers a vapor pressure deficit range from 0 kPa to 6.9 kPa, a nozzle diameter range from 1/8 inch to 1 inch, a nozzle pressure range from 20 psi to 80 psi (140 kPa – 550 kPa), and wind speeds from 0 mph (0 m s^{-1}) to 15 mph (6.7 m s^{-1}).

According to Frost (1963), nighttime wind drift and evaporation losses should be neglected. So, for irrigation events including nighttime application:

$$f_{WDE} = \frac{f_{WDE}^{Day} t_{Day}}{t_{Total}} \tag{5.45}$$

Figure 5.19. Conventional, tapered-bore, brass impact sprinkler on a hand line irrigation system.

where:

f_{WDE}	=	The fraction of sprinkler discharge that is evaporated, here assumed to be wind drift and evaporation (WDE),
f_{WDE}^{Day}	=	The fraction of sprinkler discharge that is evaporated based on Equation 42 (-),
t_{Day}	=	The total time irrigated during the day during the irrigation event (hours), and
t_{Total}	=	The total time both day and night during the irrigation event (hours).

However, with the ability to model using nighttime data, where the vapor pressure is usually near zero, it is recommended herein to use Equation 5.44 without the Equation 4.45 adjustment.

One difficulty with Equation 5.44 is the inclusion of the sprinkler nozzle diameter and operating pressure (which are used as surrogates for water droplet size distribution). A simpler equation was developed by Yazar (1984). He conducted his own study in Eastern Nebraska using fewer measurements than Frost and Schwalen (1955). However, he attempted to measure evaporation and wind drift separately using a clever salt balance. He included two nozzle sizes (13/64 inch and 7/32 inch) and three pressures (30 psi, 40 psi, and 45 psi). He developed the following relationship for evaporation only:

$$f_E = 0.00389\exp(0.18u)(e_s - e_a)^{0.70} \tag{5.46}$$

where:

f_E	=	The fraction of sprinkler discharge that is <u>evaporated</u>,
u	=	Average wind speed at 2 m above ground surface during the irrigation event (m s^{-1}), tests were conducted for one hour,
e_s	=	Average saturated vapor pressure during the irrigation event (mbar), tests were conducted for one hour and
e_a	=	Average actual vapor pressure during the irrigation event (mbar), tests were conducted for one hour.

Because Yazar's tests were conducted for one hour and his function is non-linear, it is recommended to use this function with hourly data (Figure 5.20).

Yazar also developed a separate relationship for wind drift measured at two distances from the sprinkler, depending on the distance away from the sprinkler that wind drift is considered a loss:

$$f_{WD} = \begin{cases} 0.0027u^{2.15}, & \text{70 ft from sprinkler} \\ 0.0010u^{2.39}, & \text{85 ft from sprinkler} \end{cases} \tag{5.47}$$

where:

f_{WD}	=	The fraction of sprinkler discharge that is "lost" to wind drift (dimensionless), and
u	=	Average wind speed during the irrigation event, tests were conducted for 1 – 2 minutes (m s^{-1}).

Yazar concluded that for wind speeds above 4 m s^{-1} (9 mph), wind drift was about 47% of f_{WDE} and for wind speeds below this threshold, wind drift was 25% of f_{WDE}, on average.

For comparison of Equations 5.44 and 5.46, Yazar's f_E relationship was plotted against the Trimmer's f_{WDE} relationship for the extreme conditions of Yazar's data (High: 13/64-inch nozzle at 45 psi and Low: 7/32-inch nozzle at 30 psi). In General, Yazar's equation fits between the estimates from Frost's nomograph (Figure 5.21). However, Equation 5.44 seems to give values closer to observations by the authors in Utah.

For the present, Equation 5.44 based on Frost and Schwalen's work represent a consistent method for estimating evaporation loss from line-source sprinklers in Utah. This relationship is intended for traditional, tapered-nozzle, brass, impact sprinklers. More research is needed to refine estimates for newer technologies, like wobbling and rotating sprinklers. Some of these sprinklers likely have less WDE losses than conventional sprinklers. This is the subject of current and ongoing USU research for wheel line sprinklers.

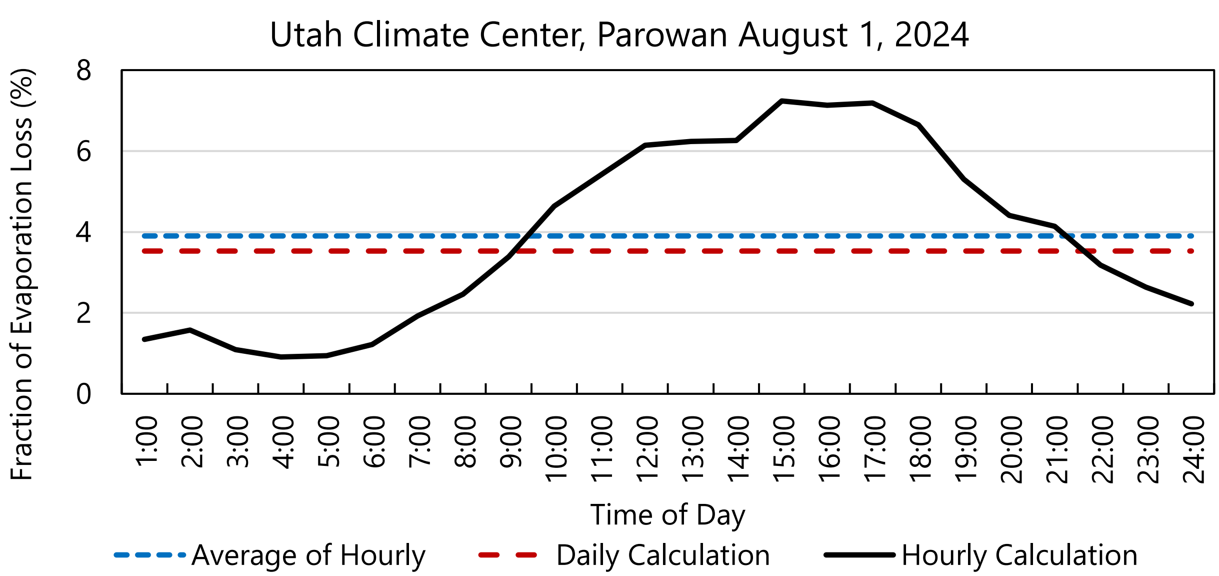

Figure 5.20. Example difference in estimated sprinkler evaporation loss using Yazar's (1987) equation using hourly and daily time steps.

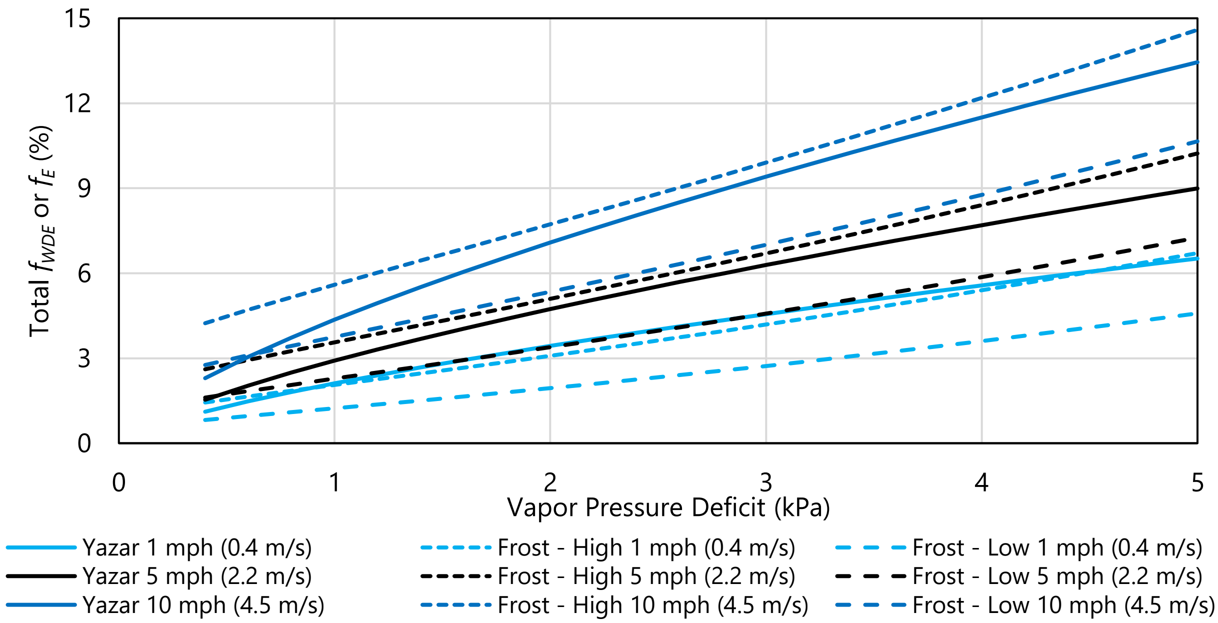

Figure 5.21. Comparison of Yazar's (1985) evaporation loss fraction (f_E) and Trimmer's (1987) wind drift and evaporation (f_{WDE}) equation for Frost's (1963) nomograph for the high and low range of Yazar's data.

5.2.4.2 Center Pivots and Lateral-Move Systems

WDE losses are not the same for mechanized irrigation systems like center pivots and lateral-move systems as they are for impact sprinklers. There are five common sprinkler configurations for mechanized irrigation systems: 1) top-of-lateral, 2) mid-elevation, e.g., mid-elevation spray application (MESA), 3) low-elevation, e.g., low-elevation spray application (LESA), 4) low-energy precision application (LEPA), and 5) mobile drip irrigation (MDI), which is not a sprinkler, but a drip system. Top-of-lateral sprinklers are uncommon in Utah because of WDE. These systems were once common and used brass-impact sprinklers. Should such be encountered, the best estimates at present is Equation 5.44.

Sarwar et al. (2019) developed a relationship for mid-elevation spray application (MESA) sprinklers (conventional drops) on center pivots and lateral-move systems in Eastern Washington:

$$f_{WDE} = 0.01873 + .07042u + 0.02672(e_s - e_a) \tag{5.50}$$

where:

f_{WDE}	=	The fraction of sprinkler discharge that is evaporated, here assumed to be wind drift and evaporation (WDE),
u	=	Average daily wind speed during the irrigation event (m s^{-1}),
e_s	=	Average daily saturated vapor pressure during the irrigation event (kPa), and

e_a = Average daily actual vapor pressure during the irrigation event (kPa).

This relationship has provided reasonable estimates compared to mid-day observations for some irrigation evaluations in Utah. However, it may provide an overestimate when considering that center pivots and lateral-move systems operate around the clock. This may give an overestimate of f_{WDE}. For the present, this is still preferred over a constant fraction. To demonstrate this, a simple analysis was performed using the monthly average weather data published in Hill et al. (2011). Weighted mean annual f_{WDE} values were computed for sites throughout Utah (Figure 5.22). Values ranged from 14% to 28% with lower values generally in the wetter portions of the state (northern Utah) and greater values in dryer areas, like the southeast corner. One anomaly occurred near St. George, which is unexpected and may be an artifact of the weather adjustments applied by Hill et al. (2011).

To adjust the f_{WDE} values from Equation 5.48 to account only for evaporation losses, the values can be reduced by Yazar's (1987) 25% for wind speeds less than 4 m s^{-1} (9 mph) and 47% for wind speeds above this level.

Sarwar et al. also provided a relationship for low-elevation spray application (LESA) devices. However, their relationship has an unexpected response to the vapor pressure deficit (efficiency increasing with drier air). This reportedly matches the data (R.T. Peters, personal communication, c.a. 2022), which must have had notable scatter and low values of wind drift and evaporation losses. USU's *Irrigation Conversion Water Savings Destination Calculator* (Calculator; https://extension.usu.edu/crops/tools/conversion-calculator) includes first approximations of WDE losses for several sprinkler systems. The f_{WDE} for LESA is 10% in the Calculator, which is in the 6% – 18% range for annual values reported by Sarwar et al. This value is recommended herein for LESA f_{WDE} and can be reduced using Yazar's (1984) percentages from the previous paragraph.

LEPA systems can be considered to have WDE losses equal to or less than LESA. The Calculator f_{WDE} for LEPA is 13%, which is high compared to LESA. For the present, the method recommended for LESA should suffice. Mobile drip irrigation (drip lines attached to a center pivot) has negligible WDE losses.

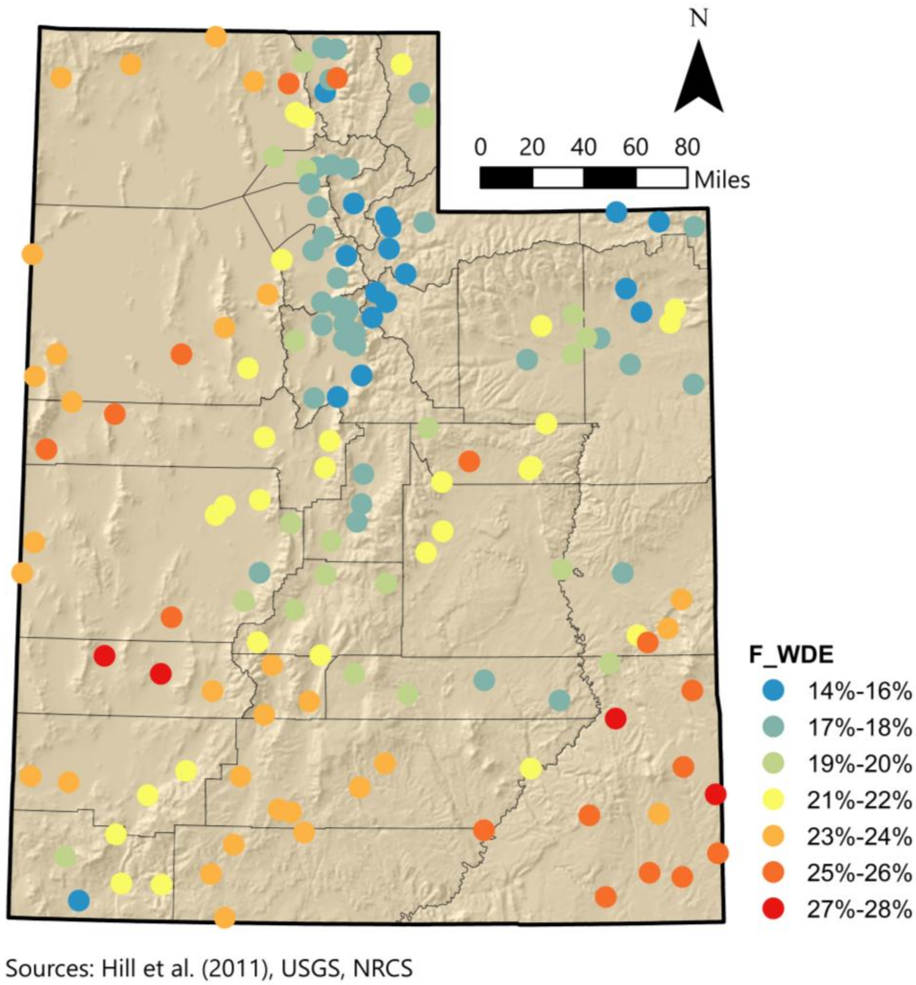

Figure 5.22. Map of estimated wind drift and evaporation fractions estimated using weather data reported in Hill et al. (2011).

5.2.4.3 Big Gun Systems

Equation 4.44 does not represent big guns well. Karney and Podmore (1984) developed a relationship for big guns, but the equation fit was not good (R^2 = 61%), and they did not control for evaporation from their catch cans. Their relationship is:

$$f_{WDE} = \frac{0.0389u + 29.49(e_s - e_a)}{T_K} \tag{5.51}$$

where:

f_{WDE}	=	The fraction of sprinkler discharge that is evaporated, here assumed to be wind drift and evaporation (WDE),
u	=	Average daytime wind speed during the irrigation event (m s^{-1}),
e_s	=	Average daytime saturated vapor pressure during the irrigation event (kPa),

e_a	=	Average daytime actual vapor pressure during the irrigation event (kPa), and
T_K	=	Absolute air temperature (K).

To adjust the f_{WDE} values from Equation 5.51 to account only for evaporation losses, the values can be reduced by Yazar's (1987) 25% for wind speeds less than 4 m s^{-1} (9 mph) and 47% for wind speeds above this level.

5.3 Open Water Evaporation

For canal evaporation, it may be necessary to estimate open water surface evaporation. This is a difficult quantity to measure because, in conditions common in Utah, it is often negligible compared to flow measurement error and seepage.

5.3.1 Modeling

Hill et al. (2011) adopted two methods for modeling open water evaporation for shallow systems in Utah. For shallow water, like stock ponds, open water evaporation, following Allen and Robison (2009), evaporation was:

$$E_{Open} = 0.7ET_r \tag{5.52}$$

where:

E_{Open}	=	Open water surface evaporation (in), and
ET_r	=	ASCE Standardized Tall Reference ET (in).

For shallow water, deeper than stock ponds and less than 13 ft (4 m), open water evaporation, following Allen and Robison (2009), was assumed to be:

$$E_{Open} = 0.6ET_r \tag{5.53}$$

where:

E_{Open}	=	Open water surface evaporation (in) and
ET_r	=	ASCE Standardized Tall Reference ET (in).

Equation 5.53 may be more suitable than Equation 5.52 for most canals. Equation 5.52 is for use in turbid, shallow water and where water can warm up from solar radiation. This does not happen in canals. We recommend using Equation 5.53. However, this is a judgement call. In either case, E_{Open} from a canal will typically be small or negligible.

5.3.2 Zero Evaporation Assumption

It is reasonable to assume that open water surface evaporation is negligible relative to canal flow and seepage for many canals in Utah. This is particularly true for narrow canals and short reaches.

5.4 Canal Bed Evaporation

For canals that are intermittently full and empty, E_{Open} only applies while the canal has water in it. For lined canals, there is usually negligible evaporation from the canal bed when empty. For earthen canals, during periods when the canal is empty, water will continue to evaporate from the wet canal bed. If these periods are short, it is reasonable to estimate E_{Bed} the same as E_{Open}, for simplicity purposes. This is justified because the magnitude of $E_{Open} + E_{Bed}$ is expected to be small compared to the volume of conveyed water for many systems in Utah.

For other cases, it may be desirable to use an evaporation model. The model used for the dual crop coefficient method (Section *5.1.2.4.2.2*) is a reasonable model. In this,

$$E_{Bed} = K_e ET_{ref} \tag{5.54}$$

where:

E_{Bed}	=	Evaporation from wet canal bed (similar to evaporation from wet soil; in),
K_e	=	Evaporation coefficient (dimensionless), and
ET_{ref}	=	Reference evapotranspiration (in).

Determining K_e requires modeling the water balance of the evaporation layer of the soil/canal bed (typically the top 4 to 6 inches). Methods for estimating K_e are presented in MOP 70 and FAO 56. They are not detailed further here because they are not expected to be employed often.

For intermittently wet canals that have significant vegetation in the canal bed, an ET method should be used (Section 5.1).

5.5 Estimating Other Components of Absolute Depletion

The methods in the above sections are presented in the context of estimating changes in depletion from irrigation practice changes. For situations where it is necessary to compute depletion itself, the following methods for estimating effective precipitation and carryover soil moisture for the non-irrigated condition are discussed below.

5.5.1 Evapotranspiration for the Non-Irrigated Condition

An example of how to estimate $(ET_{Non})_{Season}$ is provided by the Upper Colorado River Commission and Wilson Water (2024), who, for the System Conservation Pilot Program in the Upper Colorado River Basin, used ET from nearby non-irrigated areas (e.g., range) to estimate this value.

5.5.2 Effective Precipitation for the Non-Irrigated Condition

Effective precipitation can be estimated in several ways, however most of these are intended for estimating effective precipitation for the **irrigated condition**. Some of these methods relevant to Utah are described below.

5.5.2.1 Bear River Depletion Method

One common effective precipitation method for the **irrigated condition** relevant to Utah is the assumption that:

$$P_{Eff} = 0.8P \tag{5.55}$$

where:

P_{Eff}	=	Effective precipitation (in), and
P	=	Irrigation season precipitation (in).

This assumption is published in Hill et al. (1989) and has been used for the Bear River Compact. Hill (1994) and Hill et al. (2011) used the same assumption for consumptive use estimates in Utah. This method was based on a judgement call made by several people, probably in connection with the Bear River depletion verification work (R. Hill, personal communication, ca. 2010).

5.5.2.2 Soil Conservation Service Method

The SCS developed an effective precipitation method for the **irrigated condition** for use in monthly calculations that has been used for decades (SCS, 1993):

$$P_{EFF} = SF(0.70917P_{month}^{0.82416} - 0.11556)(10^{0.02426ET_{month}}) \tag{5.56}$$

where:

P_{Eff}	=	Effective precipitation (in mo^{-1}),
d	=	Useable soil water storage (in), depends on irrigation management,
P_{month}	=	Monthly total precipitation (in mo^{-1}), and
ET_{month}	=	Monthly total ET (in mo^{-1}).

where:

$$SF = 0.531747 + 0.295164d - 0.057697d^2 + 0.003804d^3 \tag{5.57}$$

where:

SF	=	Effective precipitation (in mo^{-1}) and
d	=	Useable soil water storage (in).

Making a reasonable estimate for d depends on the irrigation system and management. For surface irrigation, a reasonable upper estimate is:

$$d = (MAD)(AWC)(Z_r) \tag{5.58}$$

where:

d	=	Useable soil water storage (in).
MAD	=	Management allowable depletion (dimensionless, 0 – 1),
AWC	=	Available water capacity of the soil (field capacity minus permanent wilting point, in in^{-1}), and
Z_r	=	Root zone depth (in).

MAD and Z_r can be approximated using references like FAO 56. Z_r for this purpose should not be allowed to extend into bedrock or the water table. Soil survey data (e.g., NRCS's Soil Survey Graphical Database, SSURGO, accessed through https://websoilsurvey.nrcs.usda.gov/app/) should be sufficient for reasonable estimates of AWC.

A version of this method is used by the Utah Division of Water Resources in their GridET software.

5.5.2.3 Water Balance

One method that can work for both the irrigated and **non-irrigated condition** for determining effective precipitation is to simulate a soil water balance (e.g., following Allen et al., 1998, MOP 70, or SCS, 1993). Equation 5.2 without the irrigation-related terms can be used for the non-irrigated condition. In using a water balance, the SCS runoff equation could be used to model runoff (see Section *5.1.1.1.5*). Deep percolation associated with rainfall can be approximated through the water balance. If ET is being determined by a method other than a full water balance, the ET estimate can be input directly into the water balance.

The Desert Research Institute at the University of Nevada, Reno is developing an effective precipitation product based on a soil water balance that is intended for use with OpenET (Section *5.1.2.7*). However, this product will likely represent the **irrigated condition**, if employed over an irrigated field. Under most conditions, using a water balance to estimate effective precipitation for the non-irrigated condition is not practical.

5.5.2.4 Precipitation Less Runoff

A simplification of a full water balance is to assume:

$$P_{Eff} = P - RO \tag{5.59}$$

where:

P_{Eff}	=	Effective precipitation (in),
P	=	Irrigation season precipitation (in), and
RO	=	Irrigation season runoff from precipitation (in).

When most rainfall events during the non-irrigated growing season are small (e.g., < 1 to 2 in), which is common in Utah during the warm months, this may be a reasonable assumption because deep percolation from rainfall will be small. Runoff for Equation 5.59 can be computed using the SCS runoff equation (Section *5.1.1.1.5*). Equation 5.59 should only be used for rainfall, runoff from snowmelt is more complicated.

When employing this method for the non-irrigated condition, curve number values presented in Table 5.1 should be adequate for estimating RO_{Precip} for depletion estimates.

Table 5.1. Curve Numbers for Average Conditions (Antecedent Soil Moisture Condition II) for Different Non-Irrigated Conditions from NRCS (2004a).

Non-Irrigated Cropland and Pastureland						
Landcover	**Land Treatment[1]**	**Hydrologic Condition[2]**	**CN by Hydrologic Soil Group**			
			A	**B**	**C**	**D**
No Crop	Bare Soil	--	77	86	91	94
	Crop Residue Cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Small Grain (e.g., wheat, barley, oats, triticale, rye, and 2-way, 3-way, 4-way combinations, raised for grain or forage)	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T + CR	Poor	60	71	78	81
		Good	58	69	77	80
Pasture - for continuous grazing (i.e., naturally well-watered pasture)[3]		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
Meadow Hay-continuous grass, not grazed (i.e., naturally well-watered meadow hay)		Good	30	58	71	78

Table 5.1. Curve Numbers for Average Conditions (Antecedent Soil Moisture Condition II) for Different Non-Irrigated Conditions from NRCS (2004a). ***Error! Reference source not found.*** *(Continued)*

Natural Covers and Range						
Landcover	**Hydrologic Condition[4]**	**CN by Hydrologic Soil Group**				
		A[5]	**B**	**C**	**D**
Herbaceous—mixture of grass, weeds and low-growing brush, with brush the minor element	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon-juniper—pinyon, juniper, or both; grass understory	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sage-grass—sage with an understory of grass	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub—major plants include saltbush, greasewood, creosote bush, blackbrush, bursage, paloverde, mesquite, and cactus	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

[1]Crop residue cover applies only if residue is on at least 5 percent of the surface throughout the year.

[2]Hydrologic condition is based on combinations of factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good >20%), and (e) degree of surface toughness. Poor: Factors impair infiltration and tend to increase runoff. Good: Factors encourage average and better then average infiltration and tend to decrease runoff. For conservation tillage poor hydrologic condition, 5 to 20 percent of the surface is covered with residue (less than 750 pounds per acre for row crops or 300 pounds per acre for small grain). For conservation tillage good hydrologic condition, more than 20 percent of the surface is covered with residue (greater than 750 pounds per acre for row crops or 300 pounds per acre for small grain).

[3]Poor:< 50% ground cover or heavily grazed with no mulch. Fair: 50 to 75% ground cover and not heavily grazed. Good: > 75% ground cover and lightly or only occasionally grazed.

Curve numbers for group A have been developed only for desert shrub.

Poor: <30% ground cover (litter, grass, and brush overstory); Fair: 30 to 70% ground cover; Good: >70% ground cover.

5.5.3 Carryover Soil Moisture

Carry-over soil moisture (SM_{CO}) can be estimated using several methods. However, most are intended for the **irrigated condition**.

5.5.3.1 Bear River Depletion Method

In the Bear River depletion validation work, Hill et al. (1989) employed the following method for computing carryover soil moisture, for the **irrigated condition**:

$$SM_{CO} = \min\left\{0.67\left[\max\left(P_{Off} - 1.25ET_{Off}, 0\right)\right], 0.75(AWC)(Z_r)\right\} \tag{5.60}$$

where:

SM_{CO}	=	Carryover soil moisture (in),
P_{Off}	=	Measured precipitation during the offseason (in),
ET_{Off}	=	Evapotranspiration during the offseason, intended to be crop evapotranspiration during the offseason (in),
AWC	=	Available water capacity of the soil (field capacity minus permanent wilting point; $in^3\ in^{-3}$), and
Z_r	=	Root zone depth (in).

Hill et al. (1989) considered the offseason moisture accumulation to occur between October 1 and April 30 of each year.

This method was based on judgement and some evidence from some of the project's validation sites. Implicit in this method is the assumption that the soil water will be depleted to 75% of available water at the end of the growing season and will be refilled to field capacity by the start of the next season.

5.5.3.2 The Zero Carryover Assumption

Assuming that carryover soil moisture is zero means that the soil water content for the **non-irrigated condition** would be the same in the spring as it was at the end of the previous growing season. In northern Utah, winter precipitation is sufficient to make this assumption invalid unless the vegetation's root zone is full of water (at field capacity) at the end of the growing season. Non-irrigated vegetation type matters also. For example, sagebrush and other bushes often have deep root zones and transpire late into the year while native cool season grasses often have shallow root systems and rely mostly on spring rain (E. Thacker, Utah State University, Personal Communication, 2024). The result of incorrectly assuming that there is zero carryover soil moisture is an overestimation of depletion.

5.5.3.3 Available Water Capacity Method

Like the inclusion of soil AWC in the Bear River Depletion Method above, one can make assumptions about non-irrigated condition root depths and soil moisture depletion at the end of the growing season and infiltrated winter precipitation to estimate carryover soil moisture, such that:

$$SM_{CO} = \min\left[P_{Inf,Off} - E_{Off}, (f_{SMD})(AWC)(Z_r)\right] \tag{5.61}$$

where:

SM_{CO}	=	Carryover soil moisture (in),
$P_{Inf,Off}$	=	Infiltrated precipitation during the offseason (in),
E_{Off}	=	Soil evaporation during the offseason (in),
f_{SMD}	=	Fraction of soil water storage depleted at the end of the growing season (in),
AWC	=	Available water capacity of the soil (field capacity minus permanent wilting point; $in^3\ in^{-3}$), and
Z_r	=	Root zone depth (in).

Here, assumptions must be justified for the estimation of $P_{Inf,Off}$, E_{Off}, and f_{SMD}. $P_{Inf,Off}$ could be estimated using Equation 5.59 for offseason rainfall and a rough assumption of 100% of snowmelt. E_{Off} is more difficult to estimate but could be roughly estimated using *OpenET* during the offseason. In absence of that data, a simple constant offseason crop coefficient can be used (see Section *5.1.2.4*). The mean, tall-reference crop coefficients from lysimeter measurements in Kimberly, Idaho from 1985-1991 may be appropriate (Allen and Robison, 2007; Table 5.2). These measurements included disked fields, winter wheat, and dormant alfalfa. These should be reasonable rough estimates for use in computing carryover soil moisture. For the purposes of computing SM_{CO}, f_{SMD} = 0.75 for non-irrigated conditions following Hill et al. (1989) is reasonable unless the end of the irrigation season has significant precipitation.

Soil survey data (e.g., NRCS's Soil Survey Graphical Database, SSURGO, accessed through https://websoilsurvey.nrcs.usda.gov/app/) should be sufficient for reasonable estimates of *AWC*. Estimates of managed Z_r should be based on expected non-irrigated landcover (e.g., Table 5.3).

For practical purposes, this *AWC* method for SM_{CO} is recommended when computing depletion.

Table 5.2. Tall Reference Mean Crop Coefficients for Dormant Crop/Bare Soil in Kimberly Idaho (Allen and Robison, 2007).

Month	$K_{cm,r}$
Oct	0.33
Nov	0.39
Dec	0.42
Jan	0.60
Feb	0.49
Mar	0.47

Table 5.3. Published Rooting Depths for Some Utah Range Vegetation.

Plant	Root Depth (ft)	Source
Indian Ricegrass, Max	4.9	Reynolds and Fraley (1988)
Crested Wheatgrass, Max	4.9	Reynolds and Fraley (1988)
Birdbeak, Max	4.9	Reynolds and Fraley (1988)
Squirreltail, Max	3.3	Reynolds and Fraley (1988)
Basin Wildrye, Max	6.6	Reynolds and Fraley (1988)
Rabbitbrush, Max	6.6	Reynolds and Fraley (1988)
Big Sagebrush, Max	7.4	Reynolds and Fraley (1988)
Big Sagebrush, Max	7	Struges (1977)
Big Sagebrush, Effective	3-4	Struges (1977)

5.5.4 Direct Groundwater Contributions

Perhaps the most difficult component of depletion estimates to quantify is the direct groundwater contributions to non-irrigated ET. Groundwater contributions can be neglected when the water table is sufficiently deep (Table 2.1). Otherwise, estimates of groundwater contributions are difficult requiring measurements and modeling and are discussed in Section *5.1.1.1.4*.

6 Estimating Consumptive Use Differences Using Efficiencies

6.1 Introduction

In Section *4.4*, methods for estimating depletion components are described and recommended. However, sometimes, the information needed to use those methods, or the time needed to make the calculations are not available and a simpler estimate, perhaps sacrificing accuracy, may be desired.

In these cases, some of the components of depletion may be estimated based on the principles of irrigation efficiency.

6.2 Irrigation Efficiency

Irrigation efficiency is commonly defined in three ways:

- Application efficiency
- Conveyance efficiency
- Total irrigation efficiency

6.2.1 Application Efficiency

Application efficiency is a field-level term. It can be defined as the amount of irrigation water that infiltrates into the soil but does not drain below the crop's roots divided by the amount of water applied to the field:

$$E_{App} = \frac{I_{stored}}{I_{App}} \tag{6.1}$$

where

E_{App}	=	Application efficiency (fraction),
I_{stored}	=	Amount of irrigation water infiltrated and stored in the crop root zone of the soil (in), and
I_{App}	=	Amount of irrigation water applied to the field (in).

E_{App} depends on the design and management of the field's irrigation system and may also depend on other factors like soil properties and weather.

6.2.2 Conveyance Efficiency

Conveyance efficiency relates to delivery or conveyance systems, like supply canals. It can be defined as the amount of irrigation water delivered to the field(s) divided by the diversion amount:

$$E_{Conv} = \frac{I_{App}}{I_{Div}} \tag{6.2}$$

where

E_{Conv}	=	Conveyance efficiency (fraction),
I_{App}	=	Amount of irrigation water applied to the field (in), and
I_{Div}	=	Amount of water diverted (in).

6.2.3 Total Irrigation Efficiency

Total irrigation efficiency, or simply irrigation efficiency, is the combination of application and conveyance efficiencies. In other words, it is the amount of water stored and usable by the plants divided by the diverted amount:

$$E_{Irr} = E_{App}E_{Conv} \tag{6.3}$$

where

E_{Irr} = Irrigation efficiency (fraction),
E_{App} = Application efficiency (fraction), and
E_{Conv} = Conveyance efficiency (fraction).

6.3 Using Efficiencies to Estimate Irrigation Water Use

The most appropriate way to use irrigation efficiencies is in the design of irrigation systems. However, these concepts are sometimes inverted to estimate irrigation water use including total diverted water, total applied water, and consumptive use. In this practice, there are three reasonable starting points: 1) an estimate of crop ET, 2) measured applied irrigation (e.g., from a flow meter), 3) diversion measurements.

6.3.1 Estimating Irrigation Water Use from Crop Evapotranspiration

When crop ET is used as the starting point, the ET is usually based on a model. In many locations, precipitation provides some of the water used by the plants. To get the net irrigation requirement, analogous to depletion, the effective precipitation must be subtracted out:

$$NIR = ET - P_{Eff} \tag{6.4}$$

where

NIR = Net irrigation requirement (AFY),
ET = Crop evapotranspiration (AFY), and
P_{Eff} = Effective precipitation for the **irrigated condition** (AFY)**.**

For depletion purposes, neglecting other contributions, like carryover soil moisture or groundwater contributions must be justified (see Section *1.3.2.1*).

In addition to meeting crop ET, it is often necessary to apply additional irrigation water to flush salt out of the soil. The fraction of total irrigation water used for this purpose is called the leaching fraction. In cases where salt leaching is necessary, the *NIR* includes that water also as (SCS, 1993):

$$NIR = \frac{ET}{1 - LF} - P_{Eff} \tag{6.5}$$

where

NIR = Net irrigation requirement (AFY),
ET = Crop evapotranspiration (AFY),
P_{Eff} = Effective precipitation for the **irrigated condition** (AFY), and
LF = Leaching fraction (fraction, typically between 0.0 and 0.3).

In irrigation design, the *NIR* is the same as the depth of water that infiltrates and is stored in the root zone. So, the gross irrigation requirement, or that portion that should be applied to the field is:

$$GIR = \frac{NIR}{E_{App}} \tag{6.6}$$

where

GIR	=	Gross irrigation requirement (AFY),
NIR	=	Net irrigation requirement (AFY), and
E_{App}	=	Application efficiency (fraction).

To estimate the diversion requirement:

$$DIR = \frac{GIR}{E_{Conv}} \tag{6.7}$$

where

DIR	=	Diverted irrigation requirement (AFY),
GIR	=	Gross irrigation requirement (AFY), and
E_{Conv}	=	Conveyance efficiency (fraction).

Because this method is being used for water use estimates rather than design, the irrigation requirement values could be called <u>estimated</u> net, gross, and diverted irrigation water use, respectively. To reduce complication, the requirement terms will be used here.

6.3.1.1 Estimating Irrigation Water Use from Measured Application Irrigation

The benefit of starting irrigation water use estimates with measured *applied irrigation* is that the starting point is a measurable value, rather than a modeled value like ET. However, a challenge is that the measured value gives no information about the consumptive use of irrigation water. The estimated net irrigation water requirement may be computed by rearranging Equation 6.6:

$$NIR = GIR\left(E_{App}\right) \tag{6.8}$$

where

NIR	=	Estimated net irrigation requirement (AFY),
GIR	=	Gross irrigation requirement (in; here, this is measured irrigation application), and
E_{App}	=	Application efficiency (fraction).

Using an assumed E_{App} is not as appropriate in this type of estimate as it is in irrigation system design. E_{App} can have large variability for a given type of irrigation. E_{App} is highly dependent on system design, maintenance, management, soils, and climate. If the *LF* can be estimated, then the *NIR* gives an estimate of the portion of consumptive irrigation water use associated with crop ET. The estimated *DIR* is computed using Equation 6.7.

6.3.1.2 Estimating Irrigation Water Use from Measured Diversion

Starting with measured diversion also has the benefit of starting with a measurement. However, the separation of this value from the crop ET and depletion is larger. In addition to dependence upon E_{App} assumptions, this method is also highly dependent on the E_{Conv}, which for canal systems requires seepage studies to determine with any accuracy. With these caveats in mind:

$$GIR = DIR(E_{Conv}) \tag{6.9}$$

where

GIR	=	Gross irrigation requirement (AFY),
DIR	=	Diverted irrigation requirement (AFY), and
E_{Conv}	=	Conveyance efficiency (fraction).

Then, Equation 6.8 is employed.

6.3.2 Further Partitioning Irrigation Water Use

One area where irrigation efficiencies can be employed is in further subdividing irrigation water use estimates beyond what was discussed above. For example, some application and conveyance inefficiencies (or losses) are consumptive while other inefficiencies are not. Examples of consumptive losses include evaporation from sprinkler water droplets or from water intercepted by the plants themselves or ET from vegetation on canal banks. Examples of non-consumptive losses include runoff from a field, drainage of irrigation water below crop roots, and canal seepage. Non-consumptive losses are considered return flows.

In partitioning irrigation losses, it is helpful to consider these inefficiencies as portions of the total loss fraction. Application losses can be considered as a fraction of the applied irrigation or gross irrigation requirement, so:

$$L_{App} = GIR - NIR \tag{6.10}$$

where

L_{App}	=	Application losses (AFY),
GIR	=	Gross irrigation requirement (AFY), and
NIR	=	Net irrigation requirement (AFY).

The application loss as a fraction of GIR is:

$$f_{Loss,App} = 1 - E_{App} \tag{6.11}$$

where

$f_{Loss,App}$	=	Application loss fraction (fraction)
E_{App}	=	Application Efficiency (fraction)

The $f_{Loss,App}$ can be comprised of three components, runoff, deep drainage (deep percolation), and the evaporative or consumptive component, here represented using wind drift and evaporation (see Section 1.6.2):

$$f_{Loss,App} = f_{RO} + f_{DP} + f_{WDE} \tag{6.12}$$

where

$f_{Loss,App}$ = Application loss fraction (fraction),
f_{RO} = Runoff fraction of applied losses (fraction),
f_{DP} = Deep percolation fraction of applied losses (fraction), and
f_{WDE} = Wind drift and evaporation loss fraction (fraction).

The f_{WDE} can be partitioned into its components:

$$f_{WDE} = f_{WD} + f_E \tag{6.13}$$

where

f_{WDE} = Wind drift and evaporation loss fraction (fraction),
f_{WD} = Wind drift fraction (fraction), and
f_E = Evaporation fraction (fraction).

Based on Yazar (1984), f_E may be about 53% to 75% of f_{WDE} (Section *5.1.1.1.7*). Using these fractions, the total consumptive use can be estimated from applied water as:

$$CU = ET_{Crop} + GIR\left(1 - E_{App}\right)(f_E) \tag{6.14}$$

where

CU = Irrigated condition consumptive use (AFY),
GIR = Applied irrigation or gross irrigation requirement (AFY),
E_{App} = Application efficiency (fraction), and
f_E = Evaporation loss fraction (fraction).

For conveyance losses, the loss fractions are similar. With the conveyance loss based on the *DIR* and *GIR*:

$$L_{Conv} = DIR - GIR \tag{6.15}$$

where

L_{Conv} = Conveyance losses (AFY),
DIR = Diverted irrigation requirement (AFY), and
GIR = Gross irrigation requirement (AFY).

The conveyance loss as a fraction of *DIR* is:

$$f_{Loss,Conv} = 1 - E_{Conv} \tag{6.16}$$

where

$f_{Loss,Conv}$= Conveyance loss fraction (fraction) and
E_{Conv} = Conveyance efficiency (fraction).

The $f_{Loss,Conv}$ is comprised of three components, spill, seepage, and consumptive losses. So:

$$f_{Loss,Conv} = f_{Spill} + f_{Seep} + f_{CU,Conv} \tag{6.17}$$

where

$f_{Loss,Conv}$ = Conveyance loss fraction (fraction),
f_{Spill} = Spill fraction of conveyance losses (fraction),
f_{Seep} = Seepage fraction of conveyance losses (fraction), and
$f_{CU,Conv}$ = Consumptive use fraction of conveyance losses (fraction).

The total *CU* from conveyance can be estimated using these fractions:

$$CU = DIR(1 - E_{Conv})(f_{CU,Conv}) \tag{6.18}$$

where

CU = Consumptive use during conveyance (AFY),
DIR = Diverted irrigation requirement (AFY),
E_{Conv} = Conveyance efficiency (fraction), and
$f_{CU,Conv}$ = Consumptive use fraction of conveyance losses (fraction).

6.4 Other Considerations

Care must be taken when applying irrigation efficiency assumptions to compare diversion, applied irrigation, or consumptive use between irrigation systems or methods. First, there is significant uncertainty in assumed efficiencies. Remember, these methods are more appropriate for design than depletion estimations. Furthermore, different irrigation practices do not necessarily have similar crop ET. For example, drip irrigation systems may result in less ET than sprinkler irrigation systems because of less evaporation from the soil. Center pivots often irrigate very frequently and may have more evaporation from the soil than other irrigation systems like surface irrigation or wheel lines. Furthermore, increased irrigation efficiency often leads to increased crop production, which in turn leads to increased crop transpiration, often meaning an increase in total consumptive use. These considerations are not accounted for in efficiency terms as they are part of crop ET itself. It is also important to note that irrigation efficiencies also change for a given field or canal during a growing season or depending on the weather.

6.5 Application

Understanding the caveats and limitations of the methods, irrigation efficiencies can still be used to provide estimates of irrigation water use (accepting the inaccuracies and uncertainty) for comparison or predictive estimates.

Jacobs et al. (2024) did such in their *Quantifying the Possible* work. In their method, they neglected carryover soil moisture and groundwater contributions (they selected sites where groundwater contributions could be assumed small), such that Equation 6.4 was a reasonable assumption. They obtained *ET* from *OpenET* and estimated effective precipitation. Then, they considered consumptive losses by estimating *GIR* using Equation 6.6 and total field-level depletion using Equation 6.13. In their analysis, they adjusted crop ET based on assumed yield changes and wet soil evaporation differences.

One tool that uses similar methods as Jacobs et al. (2024) is the *Irrigation Conversion Water Savings Destination Calculator*, developed by T. Peters at Washington State University (*https://extension.usu.edu/crops/tools/conversion-calculator*) in collaboration with USU Extension. The tool was developed to help Utah growers estimate potential water savings. It has the following embedded assumptions for application efficiencies and loss fractions (Table 6.1). These assumptions are ballpark estimates for comparison purposes only and extreme care should be taken when applying them. There is a need to verify these values with data from Utah. In time, datasets being actively collected by USU researchers will help improve these numbers.

Table 6.1. Assumed Default Efficiencies Included in the Utah State University Extension Irrigation System Conversion Water Savings Calculator.

Type	Irrigation System	Reasonable Application Efficiency[1]	Typical Losses as Portion of Application[1]			
			WDE[2]	RO[2]	DP[2]	RO+DP
Drip	Subsurface drip	98%	0%	0%	2%	0%
	Surface Drip	95%	0%	0%	5%	0%
	Mobile Drip Irrigation	96%	0%	0%	4%	0%
Sprinkle	Pivot/Linear LEPA	86%	13%	0%	1%	0%
	Pivot/Linear LESA	90%	10%	0%	1%	0%
	Microsprinkler	74%	22%	0%	4%	1%
	Under-tree Orchard	80%	19%	0%	1%	0%
	Pivot/Linear MESA	78%	21%	0%	1%	0%
	Solid Set Sprinklers	71%	28%	0%	1%	0%
	Hand move	67%	31%	0%	2%	1%
	Wheel Line	67%	31%	0%	2%	1%
	Big Gun	57%	41%	0%	2%	1%
	Pivot/Linear (Top of Pipe)	57%	41%	0%	2%	1%
Surface	Basin	80%	0%	0%	20%	4%
	Border	78%	0%	2%	20%	5%
	Graded Furrow	78%	0%	3%	19%	5%
	Contour Border	78%	0%	2%	20%	5%
	Furrow	70%	0%	6%	24%	9%
	Corrugation	68%	0%	6%	26%	10%
	Wild Flood	50%	0%	5%	45%	25%

[1]Sources: Barber et al. (2020); Keller and Bliesner (2000), Hoffman et al. (2007), Waller and Yitayew (2016), Sarwar et al. (2019), and data an experience from Utah State University and Washington State University.
[2]WDE = wind drift and evaporation, RO = runoff, DP = deep percolation.

It should be noted that the efficiencies in Table 6.1 were determined through a combination of literature review, personal experience, and professional judgement. The efficiencies for drip irrigation were intended to help to account for changes in crop ET from reduced evaporation, but none of the efficiencies were intended to account for potential increases or decreases in yield and associated changes in transpiration. That is, crop transpiration (and yield) is assumed to be constant in the values in Table 6.1.

6.6 Conditions When Evapotranspiration Changes

The methods in this appendix can be used for conditions where the crop ET changes in addition to efficiency changes only. For example, a change in crop or a change to an irrigation method that might change ET (e.g., better production increasing transpiration or reduced soil wetting reducing evaporation). One example of how these methods might be used to approximate total consumptive water use is illustrated in Table 6.2.

Table 6.2. Example of Depletion Change Based on Assumed Efficiencies and a Change in Crop Evapotranspiration.

Description	Condition 1	Condition 2	Comment
Crop Evapotranspiration, ET_{Crop} (in/yr)	36	32	
Effective Precip. for the **irrigated condition**, P_{eff} (in/yr)	3	3	
Net Irrigation Req., *NIR* (in/yr)	33	29	Eq 6.4
Application Efficiency, E_{App} (%)	70%	85%	
Gross Irrigation Req., *GIR* (in/yr)	47.1	34.1	Eq 6.6
Consumptive Loss Fraction (%)	15%	5%	
Consumptive Losses, L_{CU} (%)	7.1	1.7	Eqs 6.10 – 6.13
Total Consumptive Use, ET_{Crop} + L_{CU} (in/yr)	43.1	33.7	Eq 6.14
Change in Depletion, *ΔD* (in/yr)		**-9.4**	Eq 4.4

7 Conclusion

Depletion from irrigated agriculture is a quantity that is not directly measurable. There are several reasonable methods that can be used to estimate depletion from agricultural fields. Among these, the use of OpenET's ensemble and eeMETRIC™ evapotranspiration products are recommended for quantifying ET for crops for fields greater than 10 acres. For fields less than 10 acres and conveyance corridors, it is recommended to use these two OpenET products for a representative area and then apply them to the subject area using the evaporative fraction method. When this is not possible, appropriate crop coefficient methods are recommended. However, these methods typically provide an idealized ET that an overestimate of actual ET. Consumptive irrigation losses are best quantified using empirical relationships, though simple loss fractions may be appropriate in some cases. Canal evaporation can be estimated as a fraction of reference ET or assumed to be zero for narrow canals and short reaches.

For irrigation practice changes that do not affect the irrigation season length, the above parameters are sufficient for computing a depletion change. For practices that change the irrigation season length, the non-irrigated condition ET must be estimated for the irrigation season period. This can be done using an OpenET product for a representative area (e.g., nearby range) and then applied using the evaporative fraction method to the subject area. If this is unreasonable, effective precipitation, carryover soil moisture, and groundwater contributions can be estimated for the non-irrigated condition for the irrigation season period. In Utah, effective precipitation can be estimated by subtracting runoff from rain gauge, Daymet, or PRISM precipitation. Runoff can be estimated using the SCS runoff equation. Carryover soil moisture can be estimated based on estimates of off-season evaporation and soil available water capacity. If the water table is too shallow to neglect, contributions from groundwater can be estimated using the Upflow model for capillary rise. Direct contributions from groundwater can be estimated using the White method, but this is not practical.

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