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Technical Memorandum

To: Larry Walker Associates
From: Davids Engineering
Date: January 23, 2020
Subject: **Butte Valley Evapotranspiration and Applied Water Estimates**

1 Summary

The purpose of this effort is to develop time series estimates of agricultural water use for the Butte Valley Basin from January 1989 through December 2018. The approach builds upon estimates of actual evapotranspiration (ETa) developed using remotely sensed information from the Landsat satellite.

The consumptive use of water (i.e., evapotranspiration) is the primary destination of infiltrated precipitation and applied irrigation water within the Basin. Quantification of consumptive use was achieved by performing daily calculations of evapotranspiration (ET) for individual fields for the study period. ET was separated into its evaporation (E) and transpiration (T) components. Transpiration was quantified using a remote sensing approach where Landsat satellite images acquired from USGS were used to calculate the Normalized Difference Vegetation Index (NDVI), which was subsequently translated to a basal crop coefficient and combined with reference ET (ETo) to calculate transpiration over time.

A spatial coverage of field boundaries was developed for the study area, and individual field polygons were assigned cropping and irrigation method information over time based on available data. Field boundaries were delineated by combining polygon coverages in GIS format from the California Department of Water Resources (DWR).

ET was calculated based on a combination of remote sensing data and simulation of irrigation events in a daily root zone water balance model. Due to the remote sensing approach, ET estimates are relatively insensitive to crop or land use type and irrigation method so detailed, accurate assignment of crop types and irrigation methods to each field is not critical to developing relatively reliable estimates of ET. The amount of green vegetation present over time was estimated for each field polygon based on NDVI, which is calculated using a combination of red and near infrared reflectances as measured using multispectral satellite sensors onboard Landsat satellites. Following the preparation of NDVI imagery spanning the analysis period, all images were quality controlled to remove pixels affected by clouds.

Mean daily NDVI values for each field were converted to basal crop coefficients. Daily precipitation was estimated based on assembly and review of data from the PRISM Climate Group at Oregon State University[1]. Daily reference evapotranspiration (ET_o) was estimated based on information from the California Irrigation Management Information System (CIMIS) and from National Oceanic and

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[1] PRISM website: http://prism.oregonstate.edu/

Atmospheric Administration (NOAA) weather stations. Root zone parameters that influence the amount of available soil moisture storage were estimated based on crops and soils present in the study area.

A summary for the analysis period of the annual ET of applied water (ET_{AW}), ET_c (synonymous with ET_a), applied water (AW), deep percolation of applied water (DP_{AW}) and deep percolation of precipitation (DP_{pr}) estimates based on the root zone water balance model is given in the Results section.

Application of remote sensing combined with daily remote sensing-based root zone water balance modeling (RS-RZ model) provides a reliable methodology in the absence of more detailed, ground-based information for estimation of surface interactions with the groundwater system including net groundwater depletion through estimation of ET of applied water and other fluxes.

2 Introduction

The purpose of this effort is to develop time series estimates of agricultural and native vegetation water use for the Butte Valley Basin from 1989 to 2018. Demand has been quantified at the field scale using a remote-sensing based daily root zone water balance model.

3 Methodology

3.1 *Daily Root Zone Simulation Model*

A conceptual diagram of the various surface layer fluxes of water into and out of the crop root zone is provided in Figure 3.1. The consumptive use of water (i.e., evapotranspiration or ET) is the primary destination of infiltrated precipitation and applied irrigation water within the study area. Quantification of consumptive use was achieved by performing daily calculations of ET for individual fields from January 1989 through December 2018. Evapotranspiration was separated into its evaporation (E) and transpiration (T) components. Additionally, each component was separated into the amount of E or T derived from precipitation or applied water.

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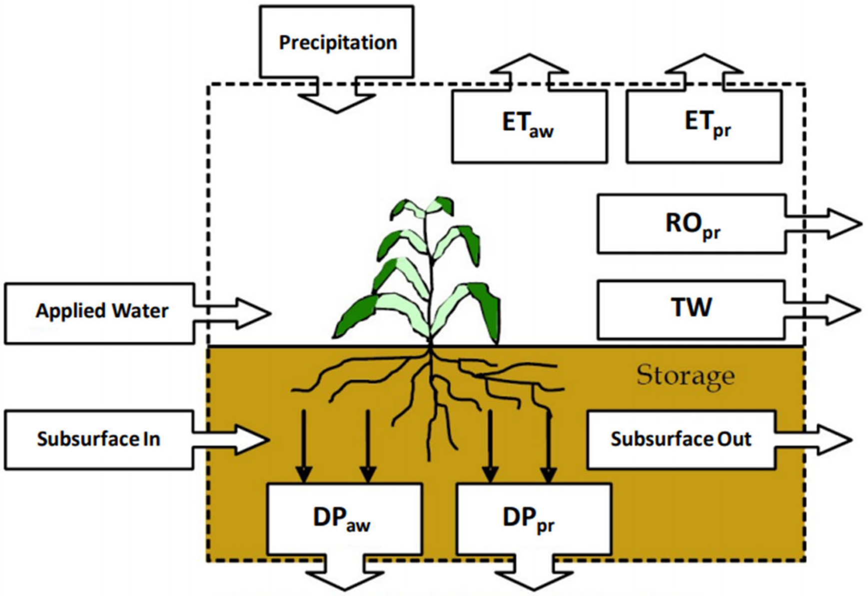

Figure 3.1. Conceptualization of Fluxes of Water Into and Out of the Crop Root Zone

Transpiration was quantified using a remote sensing approach whereby Landsat satellite images acquired from USGS were used to calculate the Normalized Difference Vegetation Index (NDVI), a measure of the amount of green vegetation present. NDVI values were calculated and interpolated for each field over time. NDVI values were then converted to transpiration coefficients that were used to calculate transpiration over time by multiplying daily NDVI by daily reference evapotranspiration (ET_o). Evaporation was quantified by performing a surface layer water balance for the soil based on the dual crop coefficient approach described in FAO Irrigation and Drainage Paper 56 (Allen et al. 1998). On a daily basis, evaporation was calculated based on the most recent wetting event (precipitation or irrigation) and the evaporative demand for the day (ET_o). This methodology is described in greater detail in Davids Engineering (2013).

3.2 Development of Field Boundaries

A spatial coverage of field boundaries was developed for the study area, and individual field polygons were assigned cropping and irrigation method information. For each polygon, daily water balance calculations were performed, and irrigation events were simulated to estimate the amount of water applied to meet crop irrigation demands. This section describes the development of the field polygon coverage and assignment of cropping and irrigation method attributes.

The Study Area includes areas within and immediately surrounding the Butte Valley and Red Rock Valley Basins, and areas along Butte Creek. This technical memorandum summarizes results for the Butte Valley groundwater basin.

Field boundaries in agricultural areas were delineated by combining polygon coverages from the California Department of Water Resources (DWR) in GIS format. Non-agricultural areas were filled using a grid of approximately 40-acre tracts based on the Public Land Survey System (PLSS).

3.3 Assignment of Cropping and Irrigation Method

As described previously, crop evapotranspiration (ET) was calculated based on a combination of remote sensing data, precipitation data, and simulation of irrigation events in a daily root zone water balance model. A result of the remote sensing approach is that crop transpiration was estimated with little influence from the assigned crop type for each field. Additionally, crop transpiration is the dominant component of ET, meaning that ET estimates are likewise largely independent of the assigned crop type.

Crop evapotranspiration is driven to some extent by the characteristics of the irrigation method and its management, including the area wetted during each irrigation event and the frequency of irrigation. Surface irrigation methods typically wet more of the soil surface than micro-irrigation methods; however, surface irrigated fields are typically irrigated less frequently than their micro-irrigated counterparts. As a result, evaporation rates can be similar among surface and micro-irrigated fields and estimates of evaporation are likewise somewhat independent of the assigned irrigation method. Parameters related to irrigation method were assigned based on the predominant irrigation method for each crop, as described by available DWR land and water use surveys.

A key result of the relative insensitivity of the crop ET estimates to crop type or irrigation method (due to the remote sensing approach), is that detailed, accurate assignment of crop types and irrigation methods to each field is not critical to developing reliable estimates of crop ET at the field scale and, more importantly, at coarser scales due to the cancellation of errors in individual field estimates as they are aggregated (Davids Engineering 2013).

Crop types were assigned to each field based on a combination of data from the 2000, 2010, and 2014 DWR land use surveys for Siskiyou County. In years without available survey data, crop type was assigned based on the nearest year in time for which crop data were available.

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3.4 NDVI Analysis

The amount of green vegetation present over time was estimated for each field polygon based on the Normalized Difference Vegetation Index (NDVI), which is calculated using a combination of red and near infrared reflectances, as measured using multispectral satellite sensors onboard Landsat satellites. NDVI can vary from -1 to 1 and typically varies from approximately 0.15 to 0.2 for bare soil to 0.8 for green vegetation with full cover. Negative NDVI values typically represent water surfaces.

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3.4.1 Image Selection

Landsat images are preferred due to their relatively high spatial resolution (30-meter pixels, approx. 0.2 acres in size). A total of 428 raw satellite images were selected and converted to NDVI spanning the study period (Table 3.1). Of the images selected, 217 were from the Landsat 5 satellite, 128 were from the Landsat 7 satellite (first available in 2001), and 83 were from the Landsat 8 satellite (first available in 2013). These images were used to process and download surface reflectance (SR) NDVI from the USGS Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA)[2].

The number of days between image dates ranged from 8 to 160, with an average of 25 days. Generally, there was at least one image selected for each month, with less images available during winter months when cloudy conditions are more likely to occur.

3.4.2 Extraction of NDVI Values by Field and Development of Time Series NDVI Results

Following the preparation of NDVI imagery spanning the analysis period, NDVI for water surfaces (such as lakes or some wetlands) was adjusted to a higher value to more accurately estimate ET. All images were then masked using the Quality Assessment Band (BQA) provided by ESPA to remove pixels affected by snow, clouds and cloud shadows. Then, mean NDVI was extracted from the imagery for each field for each image date. These NDVI values were interpolated across the full analysis period from January 1, 1989 to December 31, 2018 to provide a daily time series of mean NDVI values for each field.

3.4.3 Development of Relationship to Estimate Basal Crop Coefficient from NDVI

Basal crop coefficients (K_{cb}) describe the ratio of crop transpiration to reference evapotranspiration (ET_o) as estimated from a ground-based agronomic weather station. By combining K_{cb}, estimated from NDVI, with an evaporation coefficient (K_e), it is possible to calculate a combined crop coefficient ($K_c = K_{cb} + K_e$) over time[3]. By multiplying K_c by ET_o, crop evapotranspiration (ET_c) can be calculated. For this analysis, ET_o, K_{cb}, K_e, and ET_c (synonymous to actual ET, ET_a) were estimated for each field on a daily time step for the full analysis period.

Mean daily NDVI values for each field were converted to basal crop coefficients using a relationship following Er-Raki (2007) and as described in greater detail by Davids Engineering (2013)[4].

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[2] USGS ESPA website: https://espa.cr.usgs.gov/

[3] The estimation of Ke is based on a daily 2-stage evaporation model described in FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998).

[4] This relationship is developed based on comparison of the combined crop coefficient to NDVI for individual fields but represents only the transpiration component of ET. Thus, the relationship developed predicts the basal crop coefficient, Kcb.

Table 3.1. Landsat Image Selection by Month and Year for Study Period.

Year	Month												Total
	1	2	3	4	5	6	7	8	9	10	11	12	
1989	0	0	1	1	1	2	2	1	2	2	0	2	14
1990	1	1	1	2	1	2	0	1	1	2	0	0	12
1991	0	0	1	2	0	2	0	2	2	2	0	0	11
1992	0	0	1	1	2	1	2	2	2	2	2	1	16
1993	1	1	0	0	2	2	1	1	2	1	1	1	13
1994	2	1	1	2	1	1	2	2	2	1	1	0	16
1995	0	0	0	1	1	2	2	2	2	2	1	1	14
1996	1	1	1	2	2	1	2	2	1	2	1	0	16
1997	1	1	2	2	2	1	1	2	2	2	1	1	18
1998	0	1	2	2	0	2	2	1	2	2	0	2	16
1999	0	0	1	1	1	1	2	1	1	1	1	1	11
2000	0	0	1	0	2	2	1	2	1	1	0	1	11
2001	1	0	1	1	1	1	2	1	1	0	1	0	10
2002	1	1	0	1	1	2	1	1	1	1	1	0	11
2003	1	2	1	0	1	1	1	1	1	1	1	0	11
2004	0	1	1	1	1	1	2	1	1	0	1	1	11
2005	1	0	2	1	2	1	2	1	1	1	1	0	13
2006	0	1	0	1	2	1	2	1	1	1	1	0	11
2007	1	0	2	1	1	2	2	1	1	1	1	0	13
2008	0	0	1	1	1	2	2	2	0	1	1	0	11
2009	1	0	1	2	1	1	2	2	2	0	1	1	14
2010	0	1	1	2	1	1	2	1	2	0	1	0	12
2011	1	0	1	1	1	1	1	1	2	1	0	1	11
2012	1	1	0	1	2	0	1	2	2	0	1	1	12
2013	0	1	0	1	1	2	3	1	2	2	1	0	14
2014	1	0	0	1	1	2	2	1	1	2	0	0	11
2015	3	2	2	2	0	2	2	1	1	2	2	0	19
2016	4	1	4	2	3	2	2	3	3	1	3	2	30
2017	2	2	3	3	3	2	2	2	3	2	1	2	27
2018	1	2	0	1	2	2	2	2	2	2	2	1	19
Total	25	21	32	39	40	45	50	44	47	38	28	19	428

3.5 *Precipitation*

Daily precipitation was estimated based on assembly and review of data from the PRISM Climate Group at Oregon State University. Specifically, each field was assigned estimated daily precipitation from the 4km PRISM grid cell within which its centroid fell. The study area is represented by 99 individual grid cells.

Annual precipitation totals, averaged over the study area for water years 1990 to 2018, are shown in Figure 3.1. Water year precipitation over the study period varied from 7.9 inches in 2001 to 22.1 inches in 1998, with an annual average of 14.0 inches.

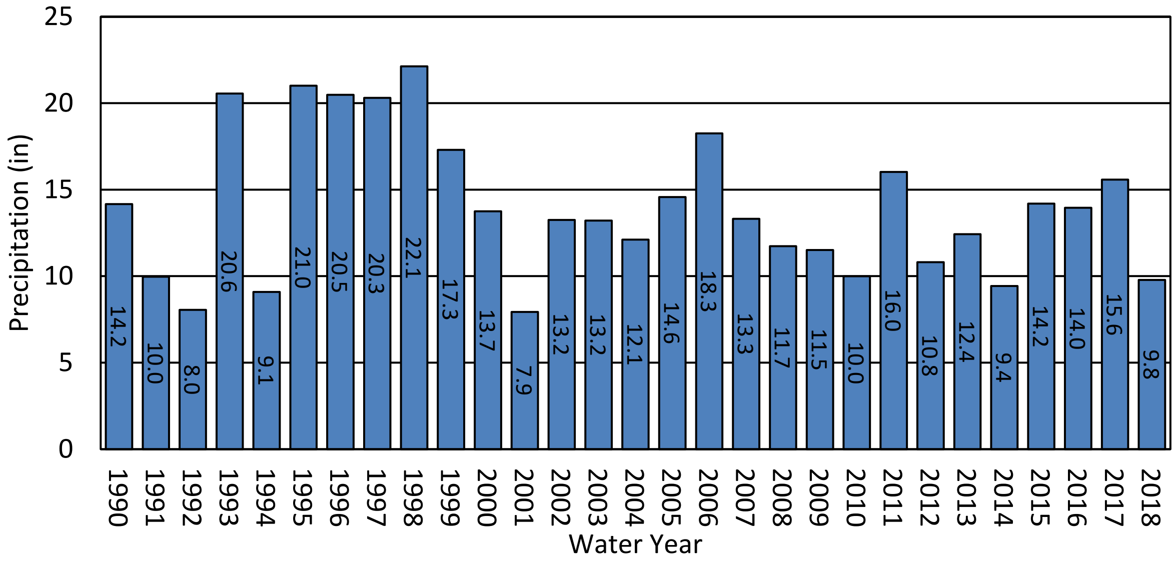

Figure 3.2. Annual Precipitation Totals

3.6 *Reference Evapotranspiration*

Daily reference evapotranspiration (ET_o) was estimated based on information from the MacDoel II CIMIS weather station (Station No. 236) and air temperature at the Juanita Lake NOAA[5] weather station. ET_o provides a means of estimating actual crop evapotranspiration over time for each field. Based on review of nearby weather stations with data available during the period of analysis, the MacDoel II station was selected based on it being located within the Butte Valley Basin, having relatively good fetch, and having available data during part of the analysis period. Since the MacDoel II station only had data available starting in 2015, estimated ET_o data based on temperature at the Juanita Lake station were used to fill in the remaining time period.

Individual parameters from the available CIMIS data including incoming solar radiation, air temperature, relative humidity, and wind speed were quality-controlled according to the procedures of Allen et al. (2005). The quality-controlled data were then used to calculate daily ET_o for the available period of record. Quality controlled NOAA temperature data were used to estimate daily ET_o using the method of Hargreaves and Samani (1985). The estimated Juanita Lake ET_o data were then correlated to the CIMIS data at MacDoel II during the period of overlap. This resulted in an adjustment factor that was applied to the Juanita Lake ET_o for the period during which MacDoel II data were not available.

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[5] https://www.ncdc.noaa.gov/cdo-web/search

ET_o zones were developed to account for the variability in elevation, slope, and aspect (and therefore ET) found in the study area based on long-term average spatialy distributed ETo from Spatial CIMIS[6]. One ET_o zone was created for each PRISM precipitation grid cell, resulting in the creation of 99 ET_o zones. ET values were multiplied by an adjustment factor for each zone to derive an ET time series for each land use and ET zone.

3.7 Root Zone Water Balance Parameters

Root zone parameters that influence the amount of available soil moisture storage were estimated based on crops and soils present in the study area. Crop parameters of interest include root depth, NRCS curve number[7], and management allowable depletion (MAD). Root depth was estimated by crop group based on published values. Curve numbers were estimated based on values published in the NRCS National Engineering Handbook, which provides estimates based on crop type and condition. MAD values by crop were estimated based on values published in FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998).

Soil hydraulic parameters of interest include field capacity (% by vol.), wilting point (% by vol.), saturated hydraulic conductivity (ft/day), total porosity (% by vol.), and the pore size distribution index (λ, dimensionless). These parameters were estimated by first determining the depth-weighted average soil texture (sand, silt, clay, etc.) based on available NRCS soil surveys. Next, the hydraulic parameters were estimated using hydraulic pedotransfer functions developed by Saxton and Rawls (2006). Then, hydraulic parameters were adjusted within reasonable physical ranges for each soil texture so that the modeled time required for water to drain by gravity from saturation to field capacity agreed with typically accepted agronomic values. Unsaturated hydraulic conductivity (e.g. deep percolation) within the root zone was modeled based on the equation developed by Campbell (1974) for unsaturated flow.

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[6] Spatial CIMIS is a gridded ETo product available from DWR. Long-term average gridded ETo was estimated based on daily ETo grids for the years 2004 to 2018.

[7] The curve number runoff estimation method developed the Natural Resources Conservation Service (NRCS) was used to estimate runoff from precipitation in the model. For additional information, see NRCS NEH Chapter 2 (NRCS, 1993).

4 Results

4.1 Evapotranspiration

Estimated annual crop evapotranspiration volumes for agricultural fields in the Study Area are shown in Figure 4.1. Estimated volumes of ET derived from applied water (ETaw) and precipitation (ETpr) are shown in thousands of acre-feet (taf). Annual ETaw ranged from 28 taf to 61 taf, with an average of 41 taf. Annual ETpr ranged from 12 taf to 32 taf, with an average of 21 taf. Total crop ET ranged from 49 taf to 82 taf, with an average of 62 taf.

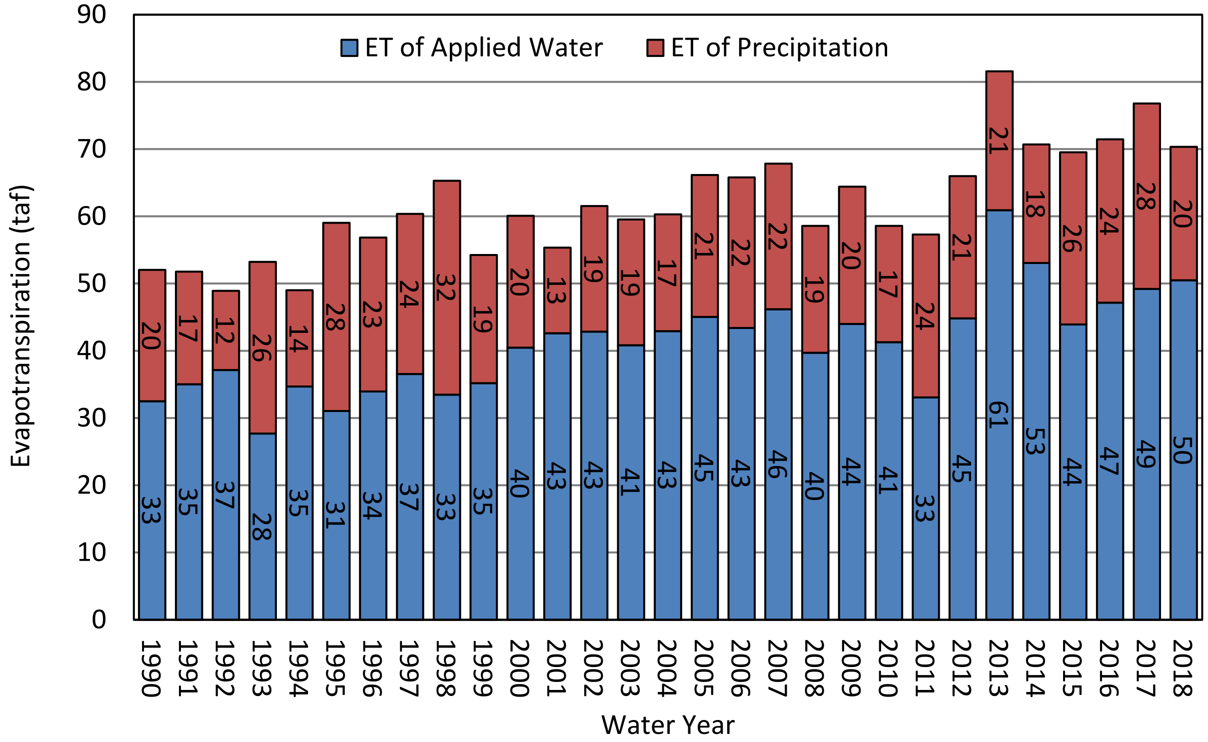

Figure 4.1. Crop ET by Water Year

4.2 Irrigation Demands

Annual estimated irrigation demands for fields in the Study Area are shown in Figure 4.2 in thousands of acre feet. Annual demands ranged from 42 taf to 82 taf, with an average of 59 taf.

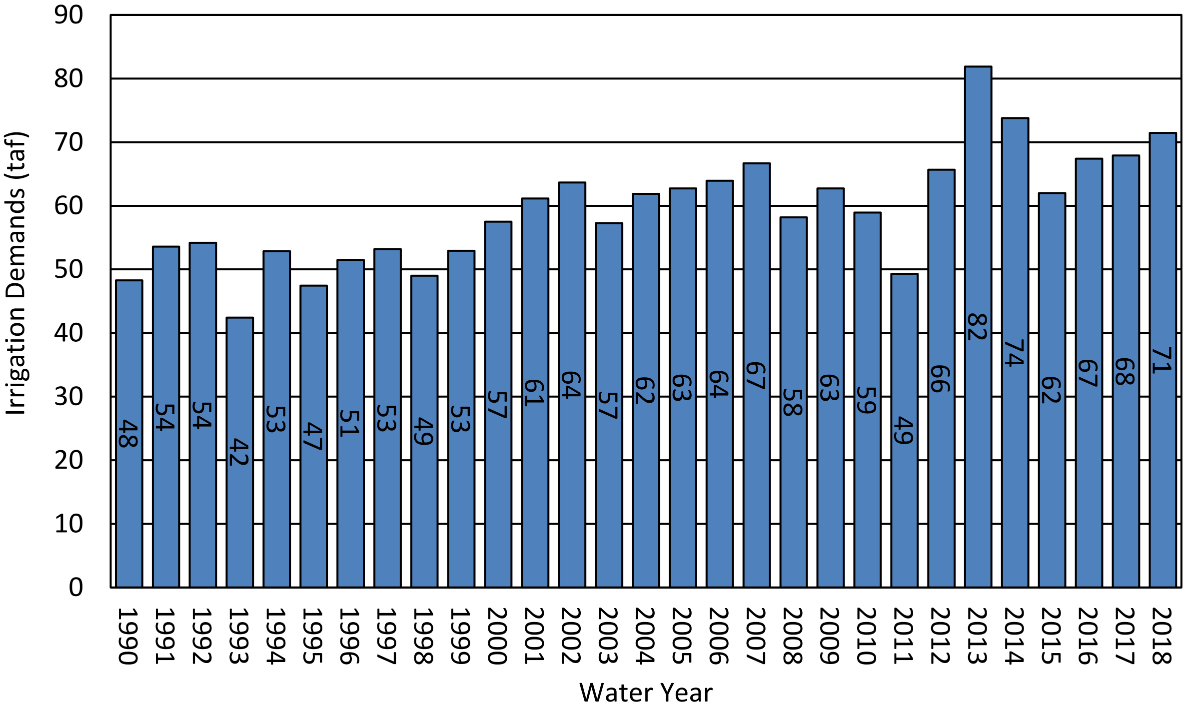

Figure 4.2. Study Area Irrigation Demands by Water Year

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4.3 Deep Percolation

Estimated annual deep percolation volumes for fields in the Study Area are shown in Figure 4.3. Estimated volumes of deep percolation derived from applied water (DPaw) and precipitation (DPpr) are shown in thousands of acre-feet. Annual DPaw ranged from 15 taf to 23 taf, with an average of 18 taf. Annual DPpr ranged from 5 taf to 21 taf, with an average of 12 taf. Total deep percolation ranged from 23 taf to 42 taf, with an average of 30 taf.

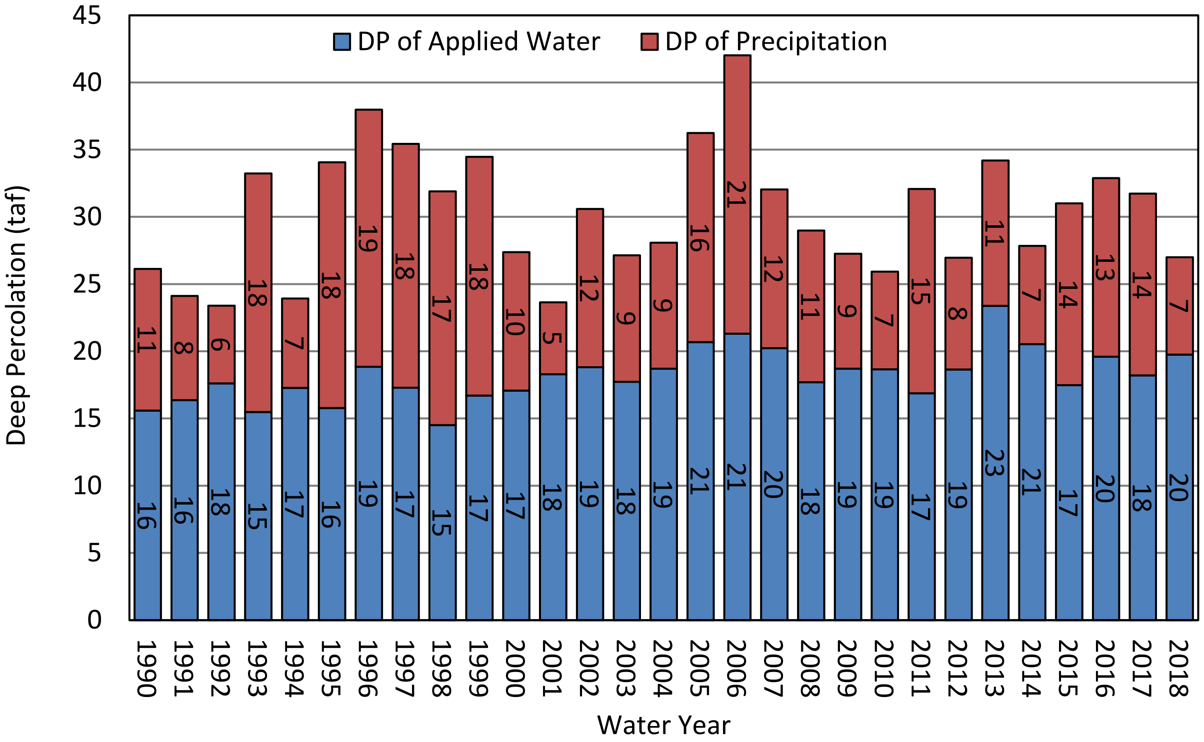

Figure 4.3. Study Area Deep Percolation by Water Year.

4.4 Evapotranspiration by Crop

Average monthly evapotranspiration by crop (ETc) is presented in Figures 4.4 through 4.9 for each year with available DWR land use survey data (2000, 2010, and 2014), along with averages for the three survey years. Additionally, monthly ETo values are shown along with monthly crop coefficients (Kc), calculated as ETc divided by ETo.

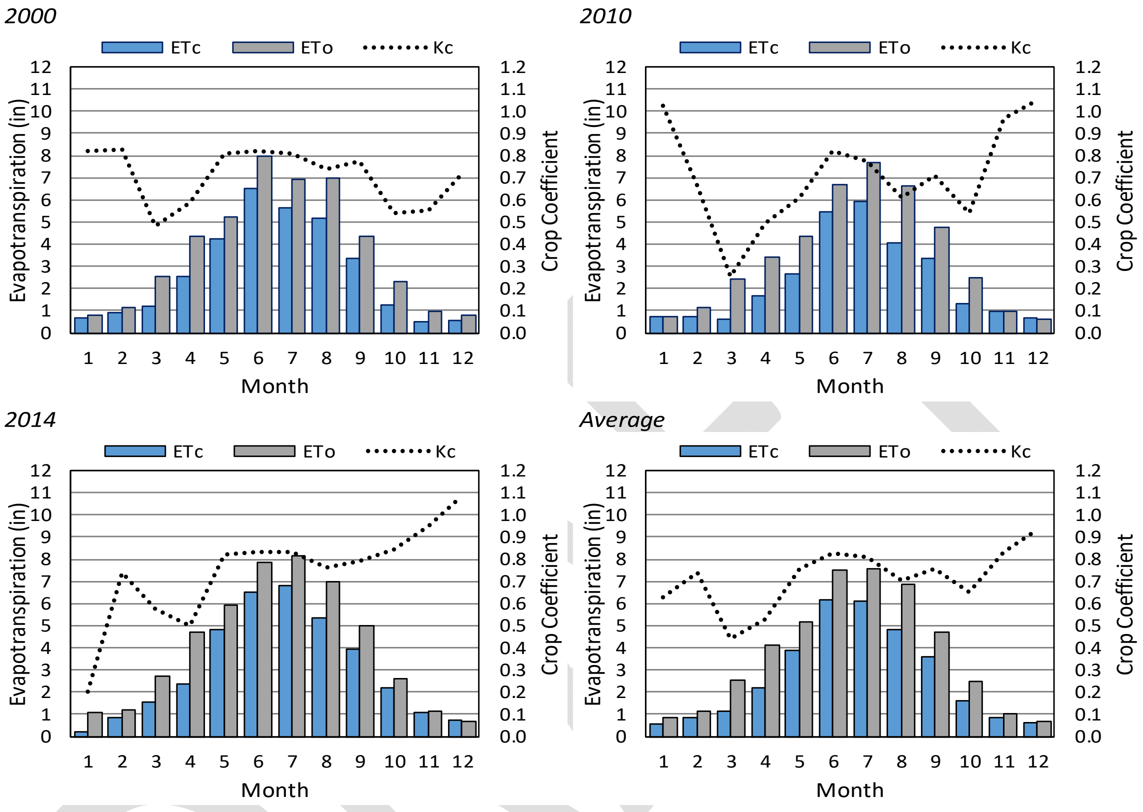

Figure 4.4. Alfalfa Monthly ETc, ETo, and Kc.

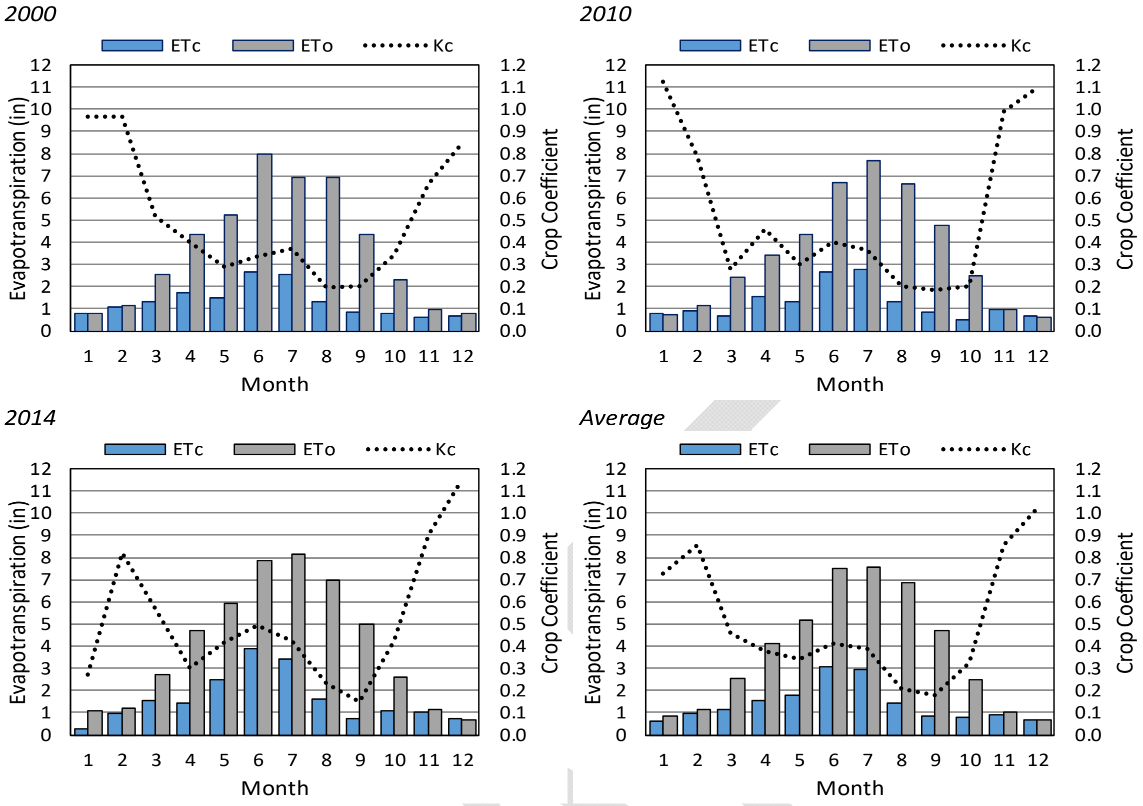

Figure 4.5. Grain and Hay Monthly ETc, ETo, and Kc.

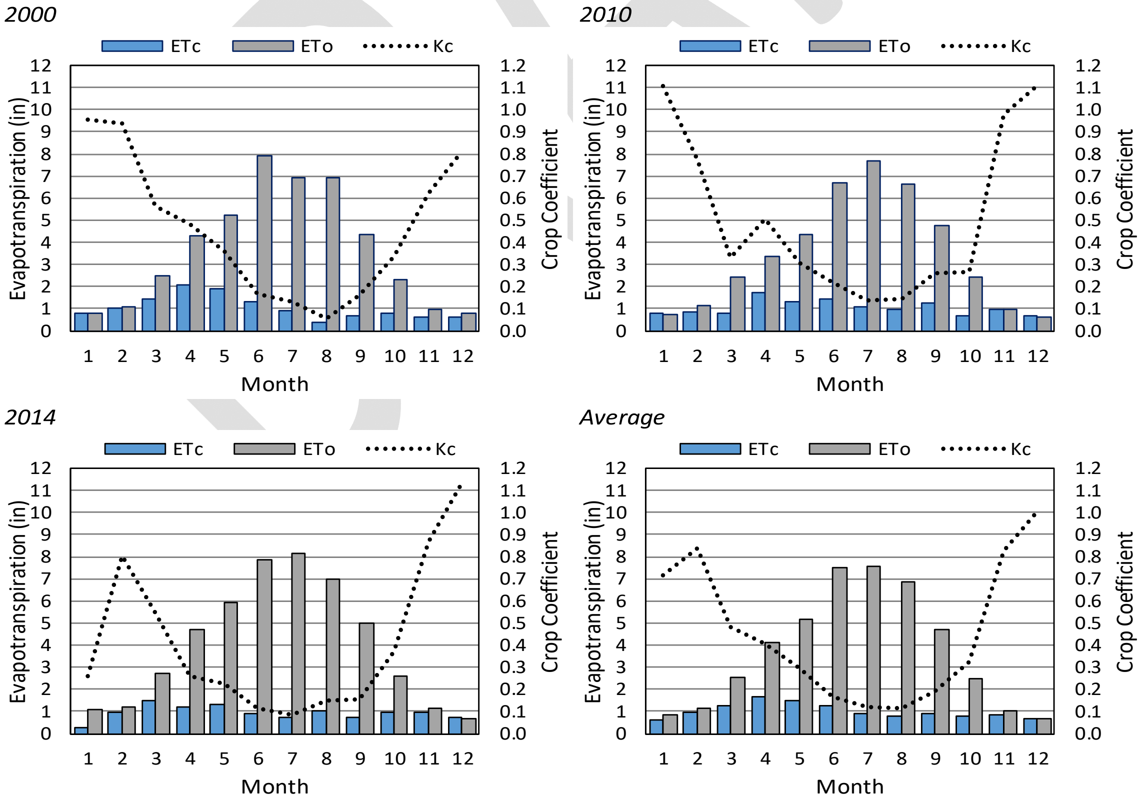

Figure 4.6. Idle Cropland Monthly ETc, ETo, and Kc.

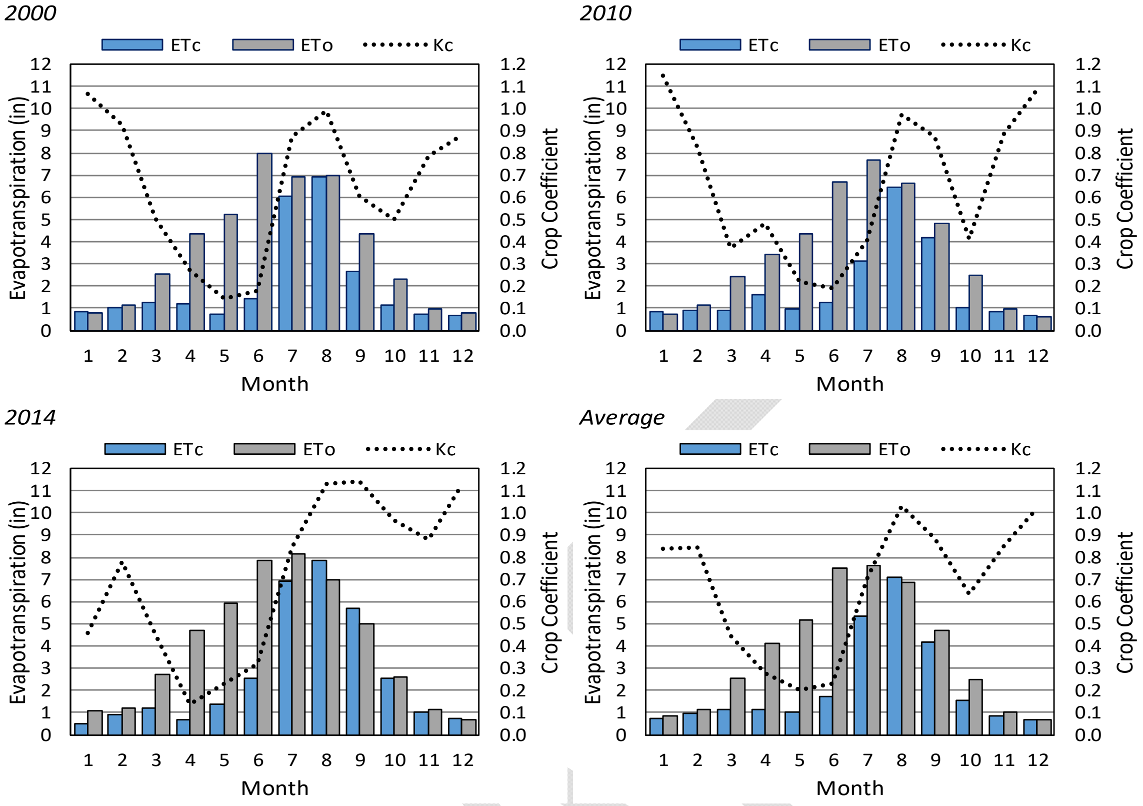

Figure 4.7. Miscellaneous Truck Crop Monthly ETc, ETo, and Kc.

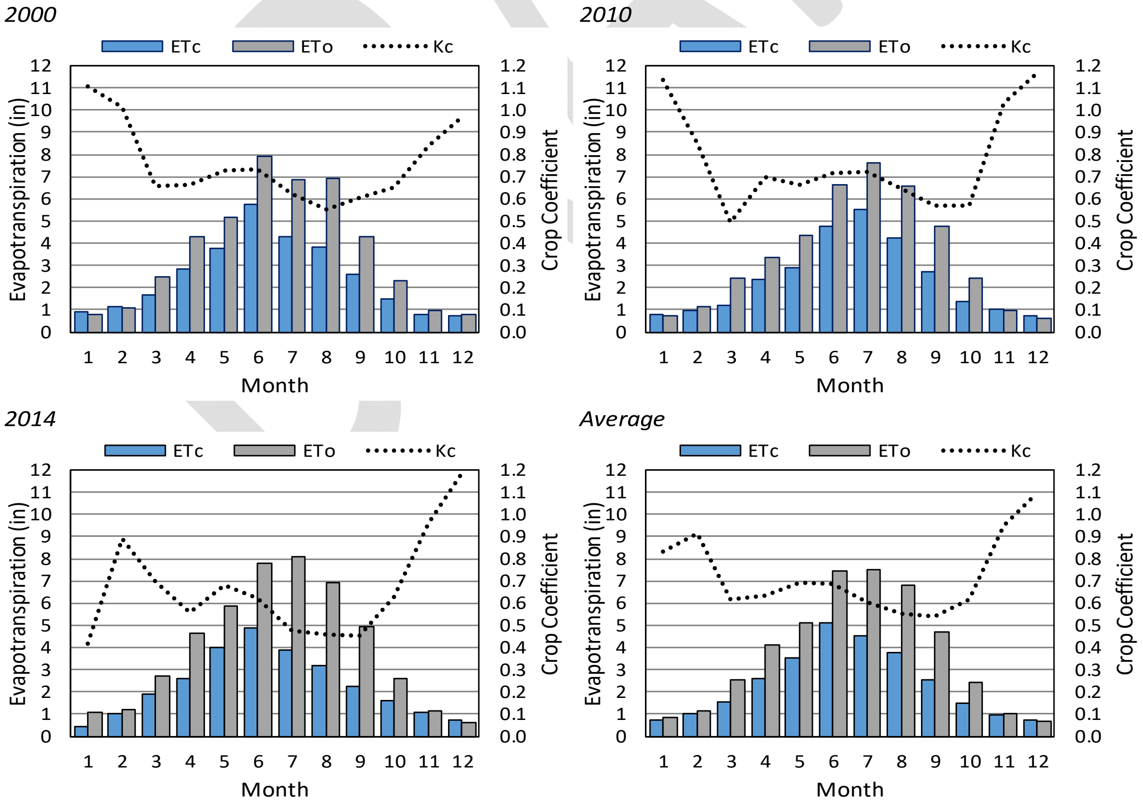

Figure 4.8. Pasture Monthly ETc, ETo, and Kc.

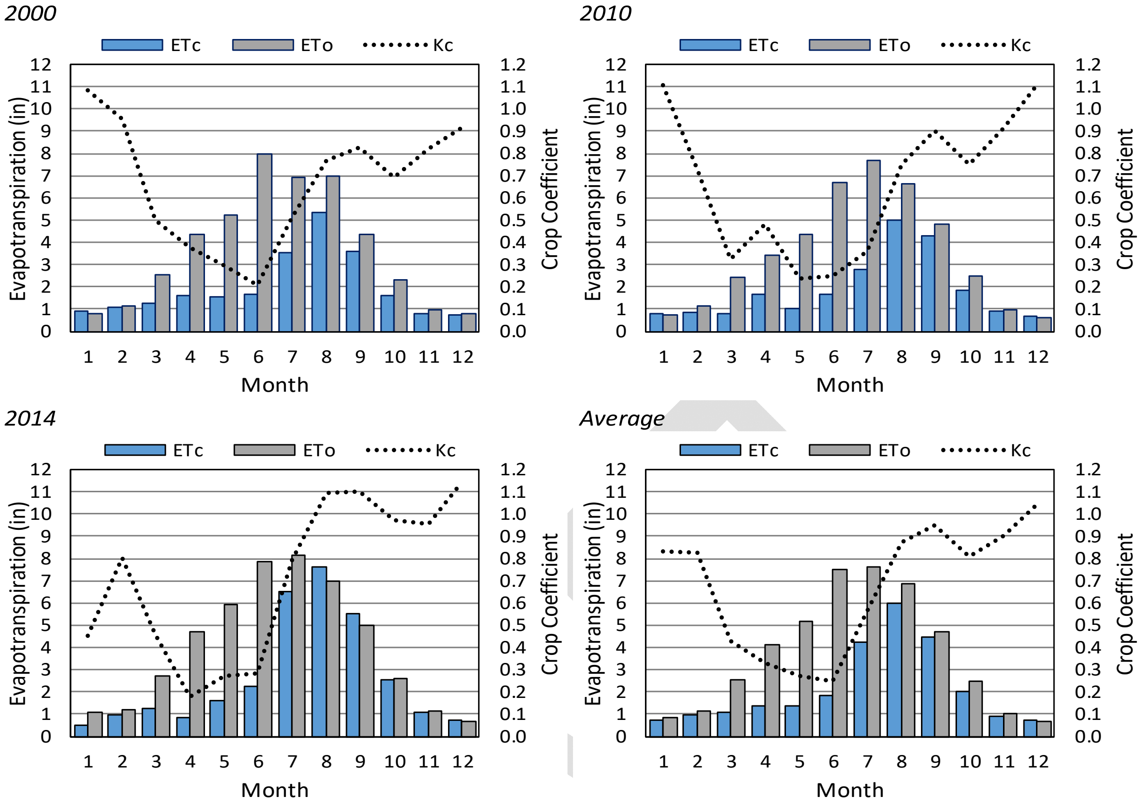

Figure 4.9. Strawberry Monthly ETc, ETo, and Kc.

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