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Technical Memorandum

To: Larry Walker Associates

From: Davids Engineering

Date: January 23, 2020; revised October 20, 2021

Subject: **Shasta Valley Basin Evapotranspiration and Applied Water Estimates**

1 Summary

The purpose of this effort is to develop time series estimates of agricultural water use for the Shasta Valley groundwater 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 Valley. 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 Basin, and agricultural fields (primarily pasture) were identified based on available data. Field boundaries were delineated primarily based on 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, crop ET estimates are relatively insensitive to specific crop type and irrigation method. As a result, detailed, accurate assignment of crop types and irrigation methods to each field is not critical to developing relatively reliable estimates of crop ET. For purposes of this study, irrigated pasture was assigned as a representative crop type for agricultural lands.

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 California Irrigation Management Information System (CIMIS) and from National Oceanic and Atmospheric Administration (NOAA) weather stations. Root zone parameters that influence the amount of available soil moisture storage were estimated based on soils present in the Shasta Valley.

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, urban, and native vegetation water use for the Shasta Valley groundwater basin from 1989 to 2018. Demand has been quantified at the field scale using a remote-sensing based daily root zone water balance model. This effort is primarily focused on agricultural water use, and as such, only results for this are presented. Although results for urban and native vegetation are also available through the model, they have not been quality-controlled or reviewed as extensively as the agricultural water use results.

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 water for irrigation within the Shasta Valley. 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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[1] PRISM website: http://prism.oregonstate.edu/

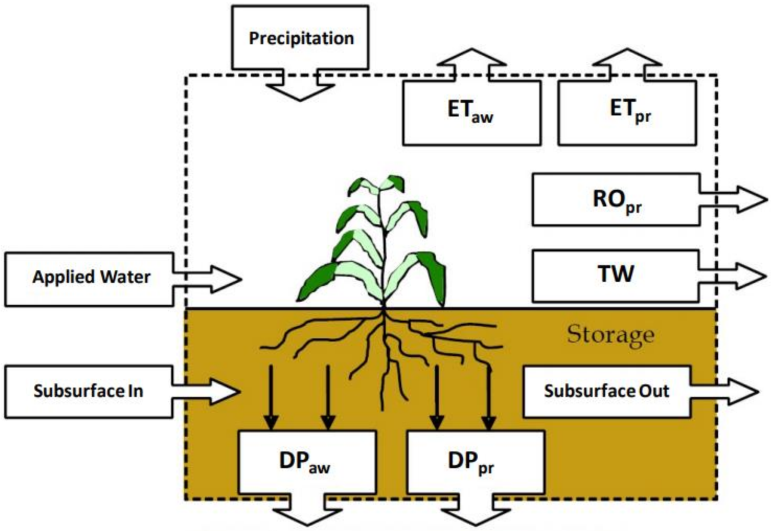

Figure 3.1. Conceptualization of Fluxes of Water Into and Out of the Crop Root Zone.

In estimating applied water for irrigation, the daily root zone simulation model simulates individual irrigation events on a field-by-field basis to meet ET demands in excess of what can be met by precipitation. While the large majority of this demand is truly met through applied irrigation water, some of the demand may also be met by other water sources such as shallow groundwater or seepage from nearby canals. The model does not differentiate between these potential sources of water but designates all demands as met through applied water. An estimated 10% of applied irrigation water is assumed as tailwater, flowing to a nearby stream and leaving the model area[2]. This percentage was based on a review of prior studies in the Shasta Valley and professional judgment regarding tailwater outflows in this context.

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 analysis area, and individual agricultural field polygons were identified. For each polygon, daily water balance calculations were performed for the analysis period, 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. Field boundaries were delineated based on a polygon coverage in GIS format from the California Department of Water Resources (DWR) from 2009.

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[2] This tailwater estimate does not include tailwater that may be recaptured and reused, either on the same field or a downstream field in the model area.

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 Land Use Type 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 assumption that most irrigated lands in the Shasta Valley are irrigated using surface irrigation methods as indicated by the 2009 DWR land and water use survey.

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).

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.

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)[3].

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[4].

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

[4] The winter months have lower evapotranspiration, greater precipitation, and very low to negligible irrigation demands. As a result, they are not as influential for model results as the summer months during the irrigation season.

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[5]. 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 et al. (2007) And as described in greater detail by Davids Engineering (2013)[6].

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[5] 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).

[6] 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.

	Month												
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
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 90 individual grid cells.

Annual precipitation totals, averaged over the agricultural fields in the study area for water years 1990 to 2018, are shown in Figure 3.2. Water year precipitation over the study period varied from 66 taf in 1994 to 184 taf in 2006, with an annual average of 120 taf.

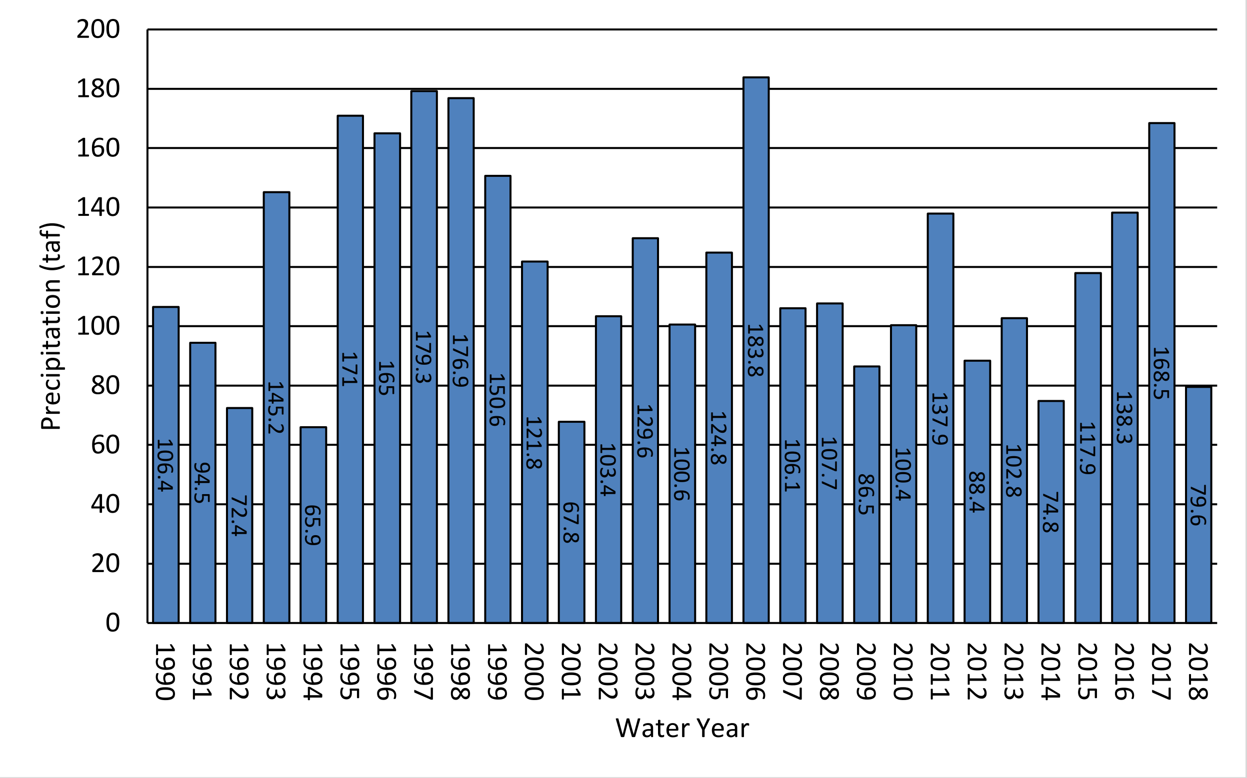

Figure 3.2. Annual Precipitation Totals.

3.6 Estimation of Daily Reference Evapotranspiration

Daily reference evapotranspiration (ET_o) was estimated based on information from the McArthur CIMIS weather station (Station No. 43) and air temperature at the Yreka NOAA[7] station location. 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 McArthur station was selected based on it being located relatively near the Shasta Valley, having relatively good fetch, and having available data during the analysis period. The Yreka NOAA station was selected based on it being within the Shasta Valley.

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. The resulting daily ET_o and quality controlled NOAA temperature data were used to estimate the final time series of daily ET_o at Yreka using the method of Hargreaves and Samani (1985).

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[7] 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 spatially distributed ETo from Spatial CIMIS[8]. One ET_o zone was created for each PRISM precipitation grid cell, resulting in the creation of 90 ET_o zones. Daily ETo values for Yreka were multiplied by an adjustment factor for each zone to derive a spatially distributed ETo time series for each zone.

3.7 Estimation of Root Zone Water Balance Parameters

Root zone parameters that influence the amount of available soil moisture storage were estimated based on soils present in the Shasta Valley. Crop parameters of interest include root depth, NRCS curve number[9], and management allowable depletion (MAD). Root depth was estimated 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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[8] 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.

[9] 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 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 103 taf to 147 taf, with an average of 128 taf. Annual ETpr ranged from 46 taf to 107 taf, with an average of 70 taf. Total ET ranged from 167 taf to 219 taf, with an average of 198 taf.

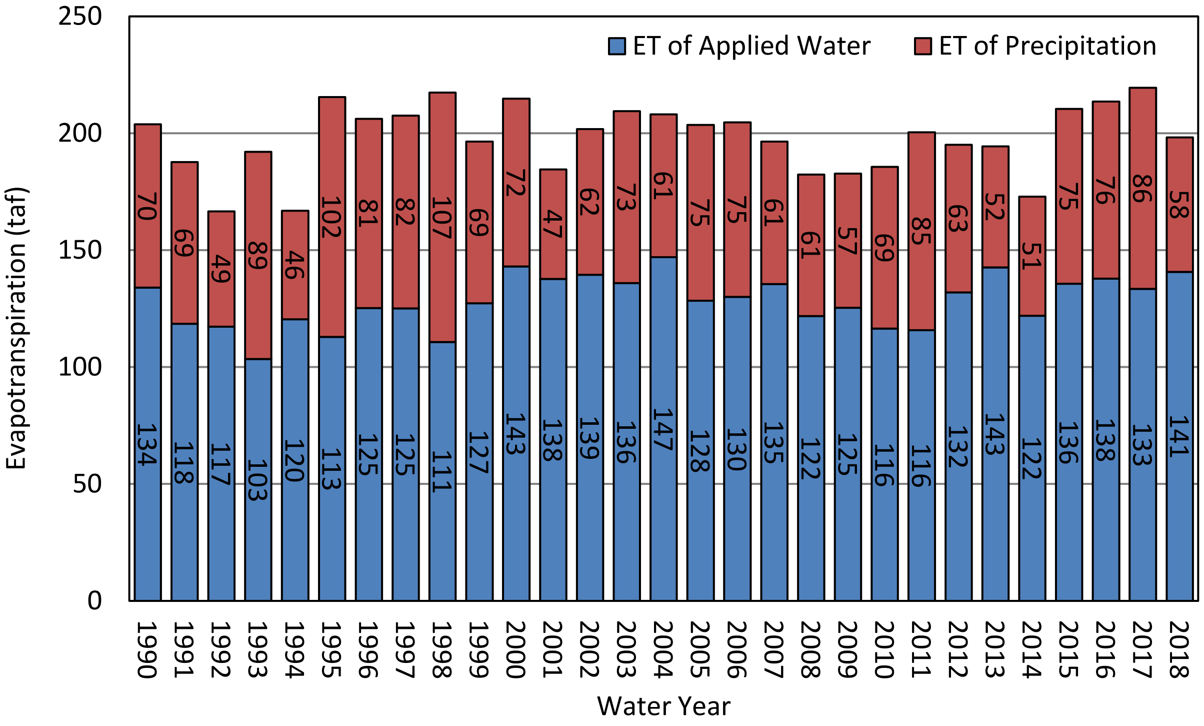

Figure 4.1. Total ET by Water Year.

4.2 Irrigation Demands

Annual estimated irrigation demands for agricultural fields within the study area are shown in Figure 4.2 in thousands of acre feet. Annual demands ranged from 168 taf to 229 taf, with an average of 199 taf.

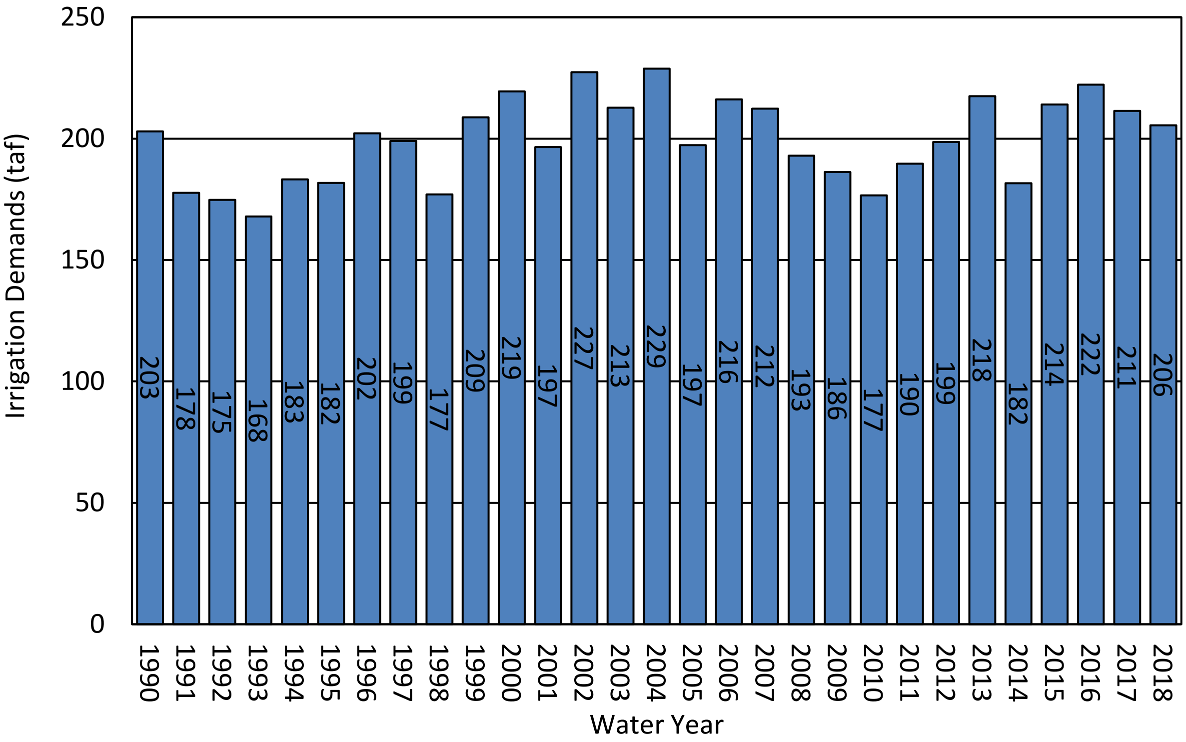

Figure 4.2. Irrigation Demands by Water Year.

4.3 *Deep Percolation*

Estimated annual deep percolation volumes for agricultural fields within 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 40 taf to 62 taf, with an average of 51 taf. Annual DPpr ranged from 15 taf to 82 taf, with an average of 40 taf. Total deep percolation ranged from 60 taf to 144 taf, with an average of 191 taf.

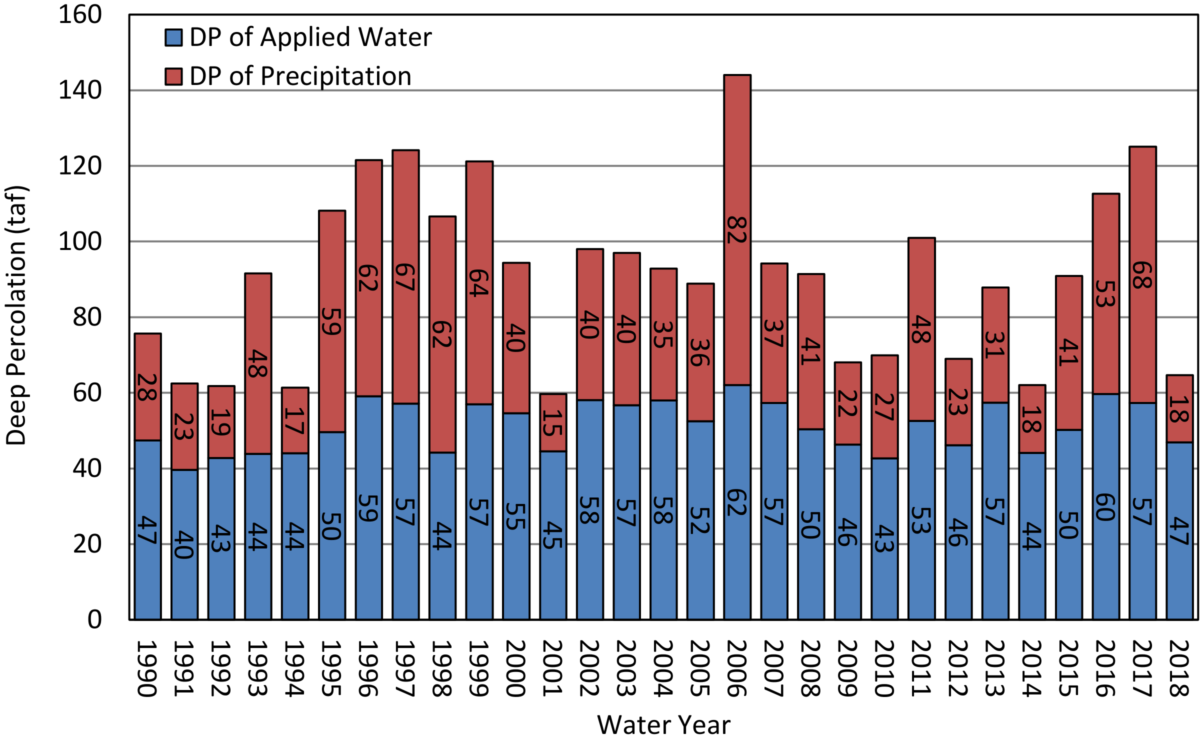

Figure 4.3. Deep Percolation by Water Year.

5 References

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