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## Technical Memorandum

**To:** GEI Consultants  
**From:** Davids Engineering  
**Date:** November 30, 2018  
**Subject:** **Kaweah Subbasin Development of Evapotranspiration and Applied Water Estimates Using Remote Sensing**

### 1 Summary

The purpose of this effort is to develop time series estimates of agricultural water demands for the Kaweah Subbasin from 1999 through 2017. This effort updates a similar analysis previously completed for the Kaweah Delta Water Conservation District (KDWCD) from 1999 through 2016 to include the areas currently not included in the KDWCD area but lying within the Kaweah Subbasin and to extend the estimates through 2017.

The consumptive use of water (i.e., evapotranspiration) is the primary destination of infiltrated precipitation and applied irrigation water within the Kaweah Subbasin. Quantification of consumptive use was achieved by performing daily calculations of evapotranspiration (ET) for individual fields from October 1998 through December 2017. 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 referent ET to calculate transpiration over time.

A spatial coverage of field boundaries was developed for the Kaweah Subbasin, 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 United States Department of Agriculture (USDA) and the California Department of Water Resources (DWR). The area encompassed by the field boundary GIS coverage includes the Kaweah Subbasin and the area immediately surrounding but outside of the subbasin.

Crop 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 crop 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 crop ET. Crop types and irrigation method were assigned to each field based on a combination of data from DWR and USDA. 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 based on cropping information from the 2007 Tulare County crop survey, combined with an analysis of actual evapotranspiration ( $ET_a$ ) by crop conducted using the Surface Energy Balance Algorithm for Land (SEBAL®) for 2007 (Bastiaanssen et al., 2005; SNA, 2009). Daily precipitation was estimated based on assembly and review of data from the PRISM Climate Group at Oregon State University<sup>1</sup>. Daily reference evapotranspiration ( $ET_o$ ) was estimated based on information from California Irrigation Management Information System (CIMIS) weather stations. Root zone parameters that influence the amount of available soil moisture storage were estimated based on crops and soils present in the Kaweah Subbasin.

A summary for the 1999 to 2017 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 root zone water balance modeling (RS-RZ model) provides an improved methodology 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 water demands for the Kaweah Subbasin from 1999 through 2017. Demand was estimated quantitatively at the field scale using a daily root zone water balance model and aggregated to monthly time steps. It is anticipated that these estimates will be used to support development of an integrated hydrologic model for the Kaweah Subbasin and water budget development for one or more Groundwater Sustainability Plans (GSPs). Crop evapotranspiration (ET), the primary driver of agricultural water demand, was estimated based on a combination of remote sensing and simulation of irrigation events using the water balance model.

This effort updates a similar analysis previously completed for the Kaweah Delta Water Conservation District (KDWCD) from 1999 through 2016 to include the areas currently not included in the KDWCD area but lying within the Kaweah Subbasin. In addition to adding the additional areas within the Kaweah subbasin, this analysis extends the estimates through the end of the 2017 calendar year.

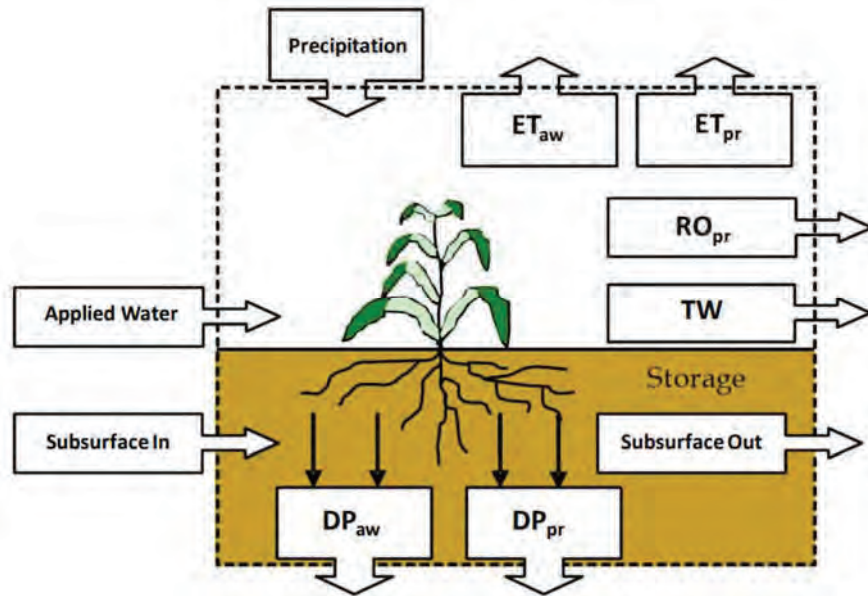
## 3 Methodology

### 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 Kaweah Subbasin. Quantification of consumptive use was achieved by performing daily calculations of ET for individual fields from October 1998 through December 2017. 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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<sup>1</sup> <http://prism.oregonstate.edu/>



**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 by Davids Engineering (Davids Engineering 2013).

### **3.2 Development of Field Boundaries**

A spatial coverage of field boundaries was developed for the Kaweah Subbasin, and individual field polygons were assigned cropping and irrigation method information. For each field polygon, daily water balance calculations were performed for the 1999 to 2017 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.

#### **3.2.1 Development of Field Boundaries**

Field boundaries were delineated by combining publicly available polygon coverages in GIS format from the United States Department of Agriculture (USDA) and the California Department of Water Resources (DWR). For the original KDWCD study area, common land unit (CLU) coverages developed by the USDA Farm Services Administration (FSA) on a county by county basis were combined to develop the base field coverage. Gaps exist in the CLU field coverages for fields not participating in USDA farm programs. These gaps were filled by overlaying the FSA CLU data with field polygons from DWR land use surveys for Kings and Tulare counties.

For the expanded study area encompassing the full Kaweah Subbasin, the original field boundaries were retained, and additional fields were added based on DWR's 2014 statewide spatial cropping dataset.

The area encompassed by the field boundary GIS coverage includes the Kaweah Subbasin and the area immediately surrounding, but outside of, the subbasin. Fields outside of the subbasin were included to provide a more robust dataset for model calibration and validation. Ultimately, results specific to the subbasin as a whole include only those fields with their centroid located within the Kaweah Subbasin.

### ***3.3 Assignment of Cropping and Irrigation Method***

As described previously, crop evapotranspiration (ET) was calculated based on a combination of remote sensing 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 the predominant irrigation method for each crop, as described by recent historical 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.

Crop types were assigned to each field based on a combination of data from DWR and USDA. DWR data consisted of land use data from 2003 and 2014 for Kings County and from 1999, 2007, and 2014 for Tulare County. USDA data consisted of Cropland Data Layer coverages for 2008 to 2013 and 2015 to 2016. The source of land use data for each year is summarized in Table 3.1.

**Table 3.1. Land Use Sources by County and Year.**

| County | Year(s)   | Source     |
|--------|-----------|------------|
| Kings  | 1999-2007 | DWR (2003) |
|        | 2008-2013 | CDL        |
|        | 2014      | DWR (2014) |
|        | 2015-2017 | CDL*       |
| Tulare | 1999-2002 | DWR (1999) |
|        | 2003-2007 | DWR (2007) |
|        | 2008-2013 | CDL        |
|        | 2014      | DWR (2014) |
|        | 2015-2017 | CDL*       |

\* CDL data for 2016 was used for 2017

### **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 is 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 682 raw satellite images were selected and converted to NDVI spanning the period from September 1998 to January 2018. Of the images selected, 230 were from the Landsat 5 satellite, 350 were from the Landsat 7 satellite (first available in 2001), and 102 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)<sup>2</sup>.

An example time series of NDVI imagery for 2010 for the Kaweah Delta Water Conservation District (KDWCD) is shown in Figure 3.1 in Davids Engineering (2013). In the figure, areas with little or no green vegetation present are shown in brown, and areas with green vegetation are shown in green.

There was sufficient cloud-free Landsat imagery available that no cloud gap filling as in Davids Engineering (2013) was necessary. The number of days between image dates ranged from 5 to 56, with an average of 10 days. Generally, there was at least one image selected for each month.

#### **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, all images were masked using the Quality Assessment Band (BQA) provided by ESPA to remove pixels affected by clouds. Then, mean NDVI was extracted from the imagery for each field for each image date. These NDVI values were then interpolated across the full analysis period from October 1, 1998 to December 31, 2017 to provide a daily time series of mean NDVI values for each field.

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<sup>2</sup> USGS ESPA website: <https://espa.cr.usgs.gov/>

Top of Atmosphere (TOA) NDVI was calculated for several image dates and compared to SR NDVI on the same image dates to establish the following relationship ( $R^2=0.99$ ):

$$(\text{TOA NDVI}) = 0.9224 * (\text{SR NDVI}) - 0.0171 \quad [3.1]$$

This regression was applied to all image dates to convert from SR to TOA NDVI to provide consistency with the relationship between NDVI and the transpiration coefficient developed by Davids Engineering (2013) Error! Bookmark not defined..

Landsat 8 bandwidth was adjusted to be consistent with bandwidths from Landsat satellites 5 and 7 using the following empirical relationship:

$$(\text{L7 mean NDVI}) = 0.984 * (\text{L8 mean NDVI}) - 0.0421 \quad [3.2]$$

An example of time varying NDVI for individual fields over time is found in Section 3 of Davids Engineering (2013). Interpolated NDVI values for selected fields are provided for the period 1999 through 2010 on an annual basis, from January 1 to December 31 of each year. These figures illustrate the ability of the remote sensing approach to account for both changes in cropping over time and the presence of double- and triple-cropping.

### 3.4.3 Development of Relationships 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<sup>3</sup>. 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 from October 1, 1998 to December 31, 2017.

Mean daily NDVI values for each field were converted to basal crop coefficients based on cropping information from the 2007 Tulare County crop survey conducted by DWR, combined with an analysis of actual evapotranspiration ( $ET_a$ ) by crop conducted using the Surface Energy Balance Algorithm for Land (SEBAL<sup>®</sup>) for 2007 (Bastiaanssen et al., 2005; SNA, 2009). Specifically, a relationship between actual basal crop coefficients estimated using SEBAL and field-scale mean NDVI values developed by Davids Engineering (2013) was applied to calculate daily basal crop coefficients for each field over time<sup>4</sup>.

## 3.5 Precipitation

Daily precipitation was estimated based on assembly and review of data from the PRISM Climate Group at Oregon State University<sup>5</sup>. Specifically, each field was assigned estimated precipitation from the 4km PRISM grid cell within which its centroid fell. The update generally results in modest increases in estimated precipitation within the study area, with greater increases moving from west to east due to orographic effects.

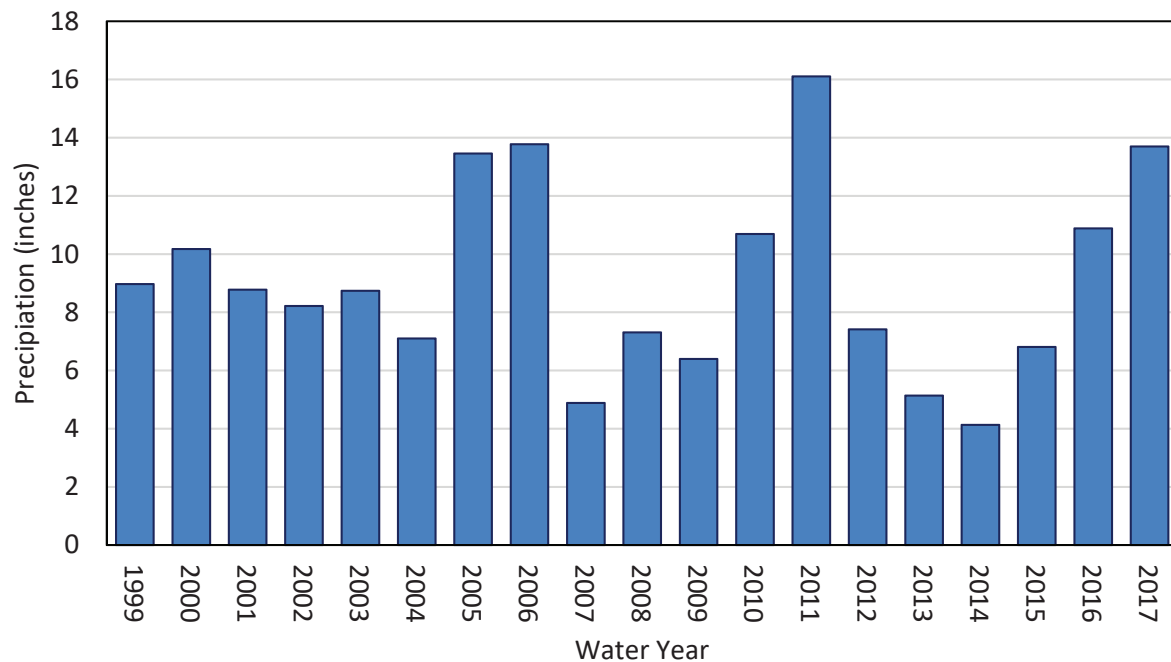
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<sup>3</sup> The estimation of  $K_e$  is based on a daily 2-stage evaporation model presented in FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998).

<sup>4</sup> 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,  $K_{cb}$ .

<sup>5</sup> <http://prism.oregonstate.edu/>

Annual precipitation totals, averaged over the study area for water years 1999 to 2017, are shown in Figure 3.1. Water year precipitation over the study period varied from 4.1 inches in 2014 to 16.1 inches in 2011, with an annual average of 9.1 inches.



**Figure 3.2. Annual Precipitation Totals**

### **3.6 Estimation of Daily Reference Evapotranspiration**

Daily reference evapotranspiration ( $ET_o$ ) was estimated based on information from California Irrigation Management Information System (CIMIS) weather stations.  $ET_o$  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 Porterville station (169) was selected based on it being relatively close to the Kaweah Subbasin, at a similar elevation to the Kaweah Subbasin, having relatively good fetch, and having available data for the majority of the analysis period.

Individual parameters from the available 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.

CIMIS data for Porterville were not available prior to August 2000. As a result, it was necessary to estimate  $ET_o$  for the period from October 1, 1998 to August 1, 2000.  $ET_o$  for Porterville was estimated by developing a linear regression to estimate Porterville  $ET_o$  using quality-controlled data from the Stratford CIMIS station for the period of overlapping data availability.

### **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 crops and soils present in the Kaweah Subbasin. Crop parameters of interest include root

depth, NRCS curve number<sup>6</sup>, and management allowable depletion (MAD). Root depth was estimated by crop group based on published values and a representative mix of individual crops within each crop group for the Kaweah Subbasin. 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 ( $\lambda$ , dimensionless). These parameters were estimated by first determining the depth-weighted average soil texture (sand, silt, clay, etc.) based on available NRCS soil surveys. Then, the hydraulic parameters were estimated using hydraulic pedotransfer functions developed by Saxton and Rawls (2006). Next, 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.

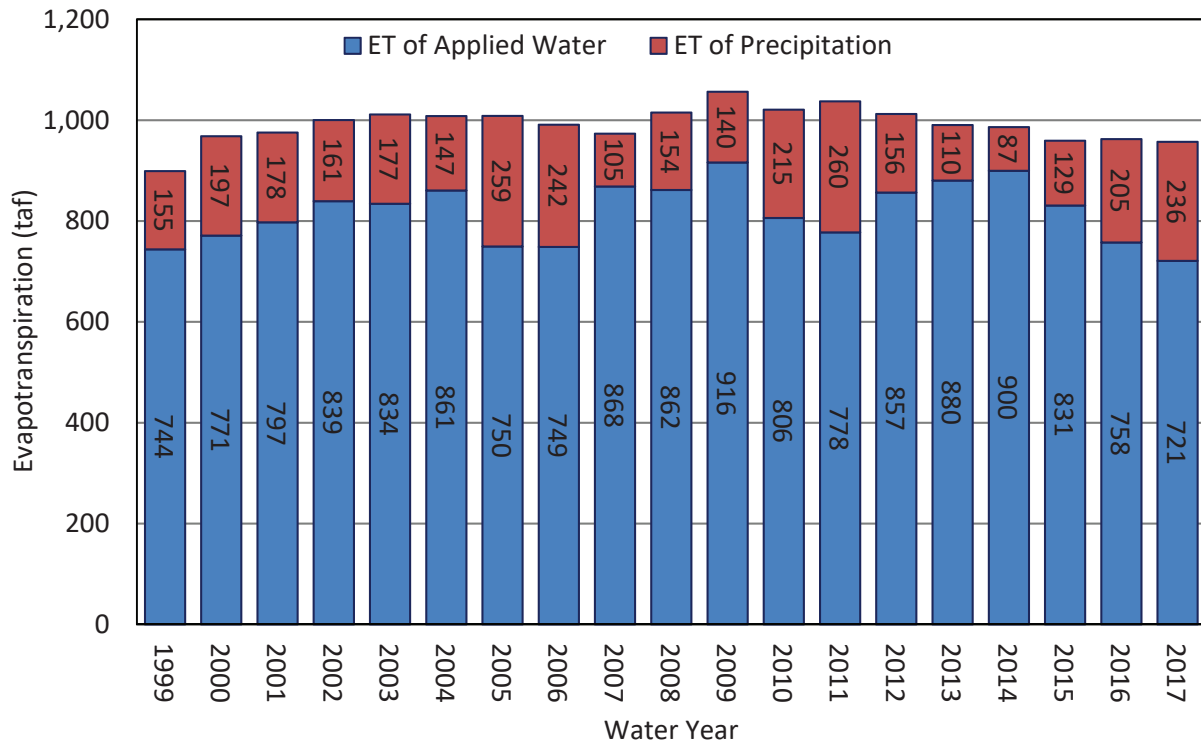
## **4 Results**

### **4.1 Crop Evapotranspiration**

Estimated annual crop evapotranspiration volumes for fields with their centroid within the Kaweah Subbasin are shown in Figure 4.1. Estimated volumes of ET derived from applied water (ET<sub>aw</sub>) and precipitation (ET<sub>pr</sub>) are shown in thousands of acre-feet (taf). Annual ET<sub>aw</sub> ranged from 721 taf to 916 taf, with an average of 817 taf. Annual ET<sub>pr</sub> ranged from 87 taf to 260 taf, with an average of 174 taf. Total crop ET ranged from 899 taf to 1,056 taf, with an average of 991 taf.

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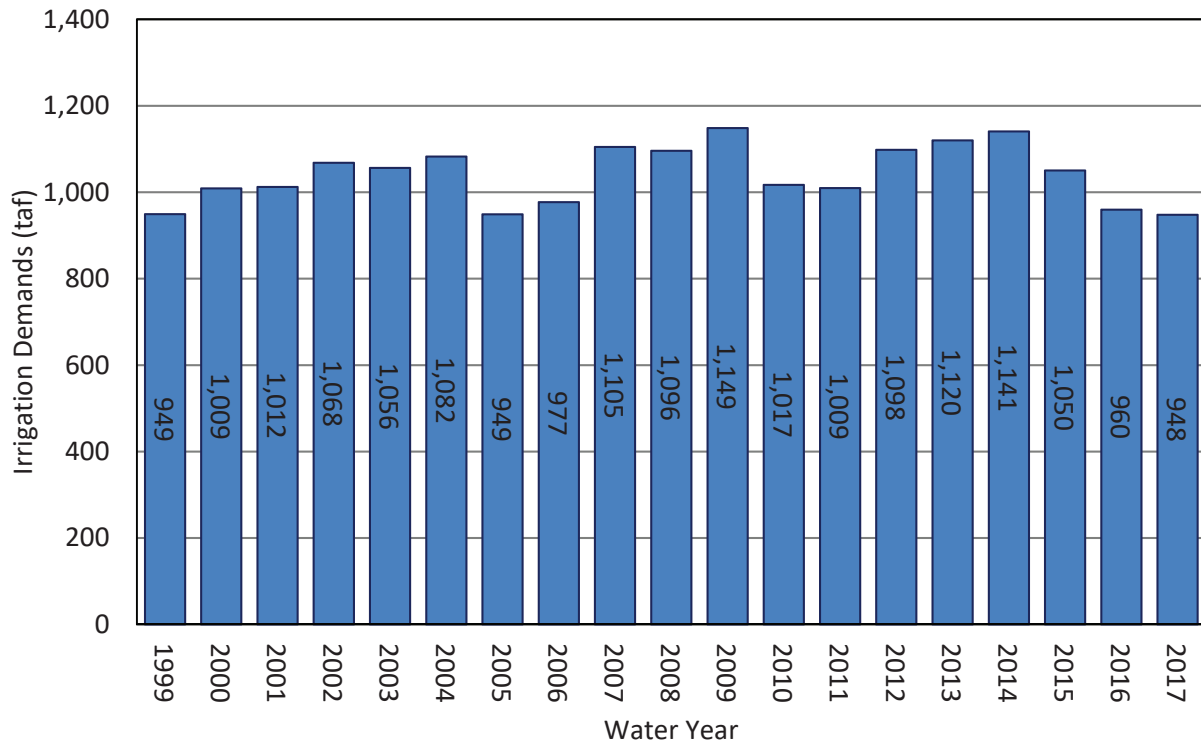
<sup>6</sup> The curve number runoff estimation method developed the Natural Resources Conservation Service (NRCS) was used to estimate runoff from precipitation in the model. For additional information, see NRCS NEH Chapter 2 (NRCS, 1993).



**Figure 4.1. Kaweah Subbasin Crop ET by Water Year**

## 4.2 Irrigation Demands

Annual estimated irrigation demands for fields with their centroid within the Kaweah Subbasin are shown in Figure 4.2 in thousands of acre feet. Annual demands ranged from 948 taf to 1,149 taf, with an average of 1,042 taf.



**Figure 4.2. Kaweah Subbasin Irrigation Demands by Water Year**

### **4.3 Deep Percolation**

Estimated annual deep percolation volumes for fields with their centroid within the Kaweah Subbasin 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 208 taf to 242 taf, with an average of 227 taf. Annual DPpr ranged from 24 taf to 130 taf, with an average of 60 taf. Total deep percolation ranged from 255 taf to 372 taf, with an average of 287 taf.

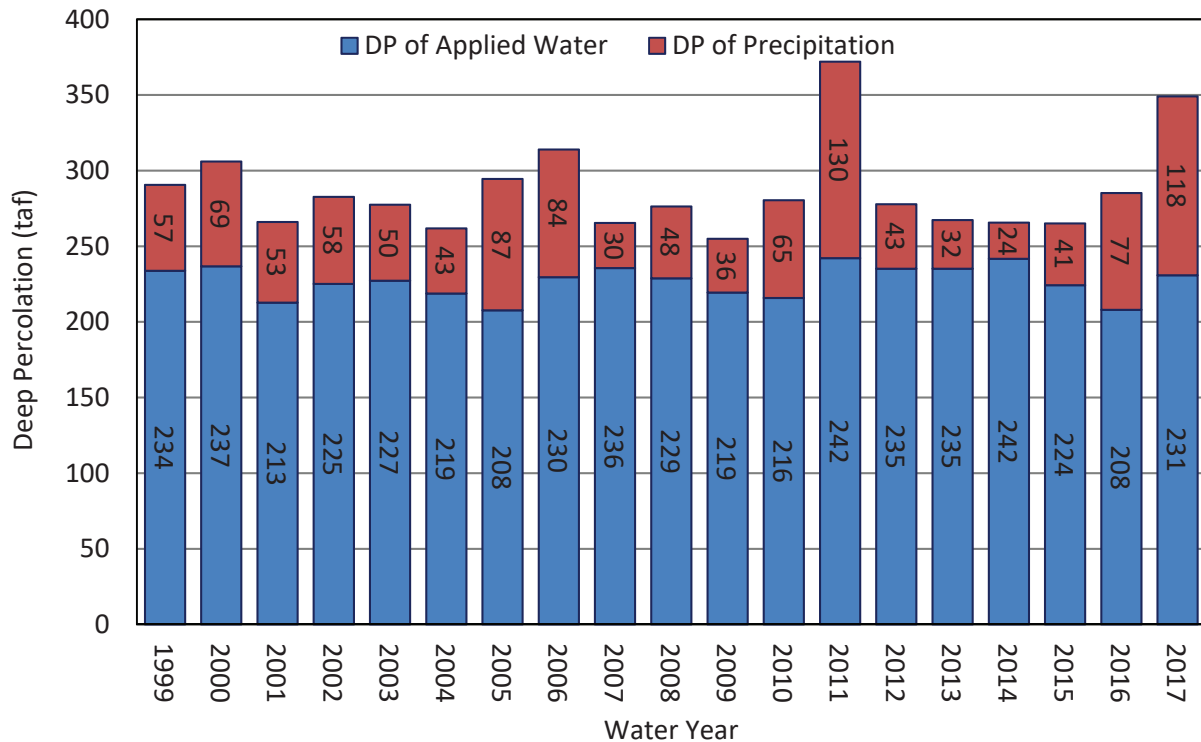
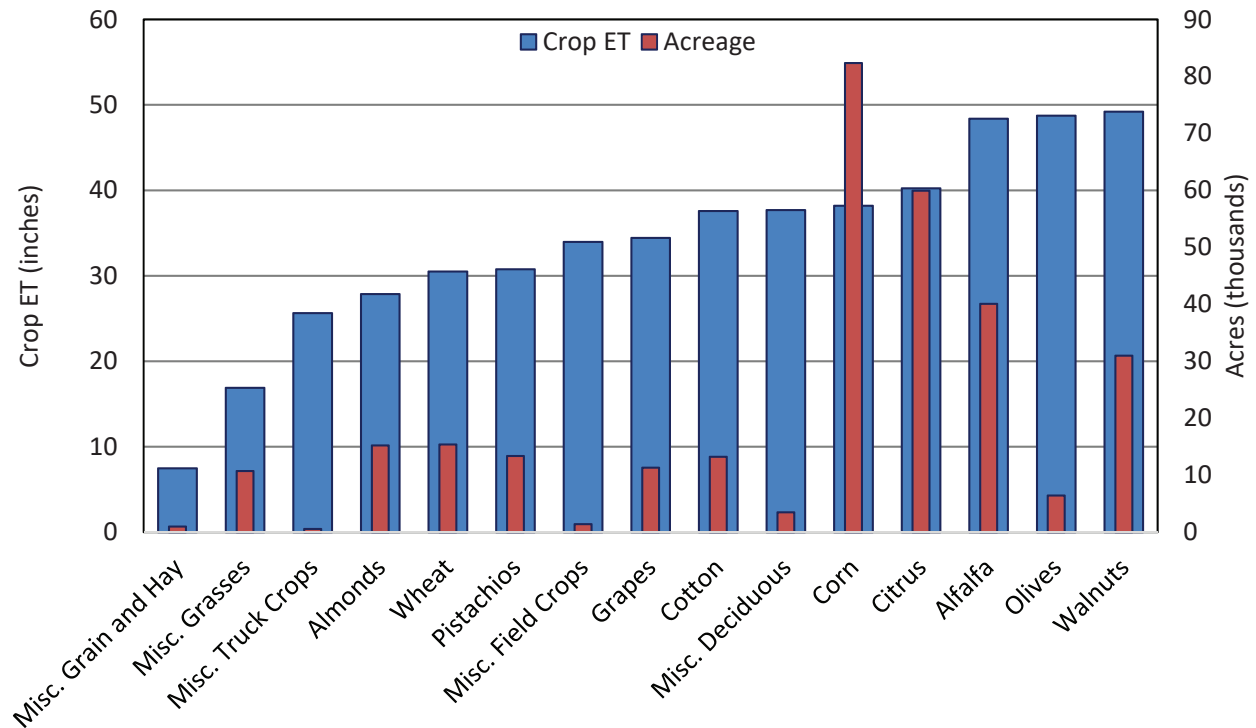


Figure 4.3. Kaweah Subasin Deep Percolation by Water Year

#### 4.4 Annual Evapotranspiration by Crop for 2014

Estimated annual average evapotranspiration by crop is shown in Figure 4.4, along with the estimated acreage for each crop. Figure 4.4 shows the estimated average total ET by crop in inches in 2014. Average ET ranges from 7 inches for miscellaneous grain and hay to 49 inches for walnuts. The primary crops are corn, citrus, alfalfa and walnuts, representing 82, 60, 40, and 31 thousand acres, respectively.



**Figure 4.4. Kaweah Subbasin 2014 Average ET by Crop and Crop Acreage**

Additional monthly plots of  $ET_{of}$ ,  $ET_a$  and AW by crop for 2014 can be found in the appendix.

## 5 References

- Allen, R.G, L.S. Pereira, D. Raes, and M. Smith. 1998. Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. FAO. Rome, Italy.
- Davids Engineering. 2013. Time Series Evapotranspiration and Applied Water Estimates from Remote Sensing. Kaweah Delta Water Conservation District. <http://www.kdwcd.com/wp-content/uploads/2018/07/KDWCD-NDVI-ET-Analysis-FINAL-REPORT-March-2013.pdf>
- NRCS. 1993. Chapter 2 - Watershed Project Evaluation Procedures. National Engineering Handbook Part 630, Hydrology.
- Saxton, K.E. and W.J. Rawls. 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Sci. Soc. Am. J. 70:1569–1578.

## 6 Appendix

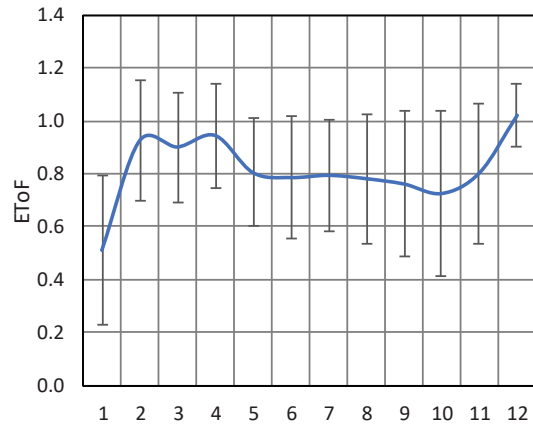
This appendix includes the following figures:

- Average monthly crop water use coefficients or “fraction of reference ET” (EToF) by crop, along with error bars depicting the standard deviation among fields.
- Average monthly crop ET by crop, along with error bars depicting the standard deviation among fields.
- Average monthly applied water by crop, along with error bars depicting the standard deviation among fields.

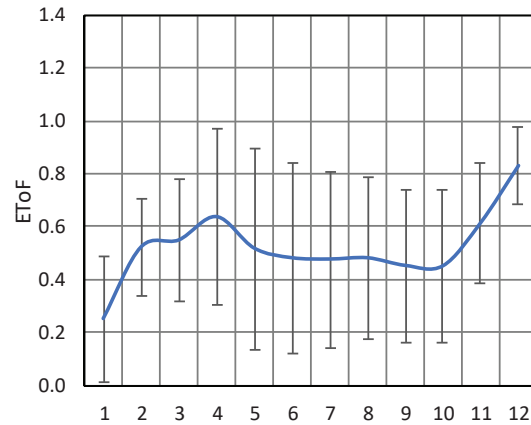
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## EToF 2014

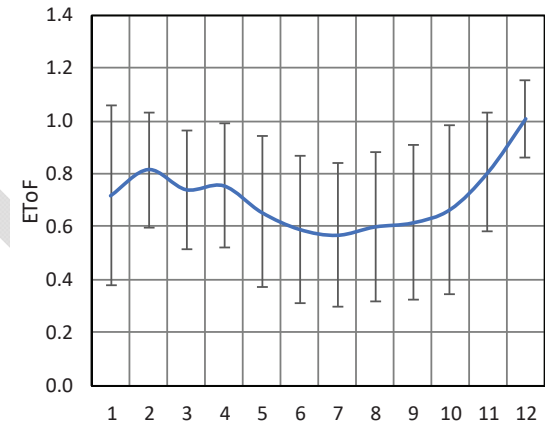
Alfalfa



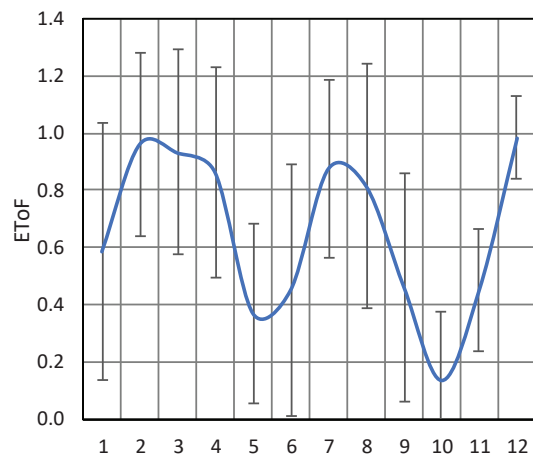
Almonds



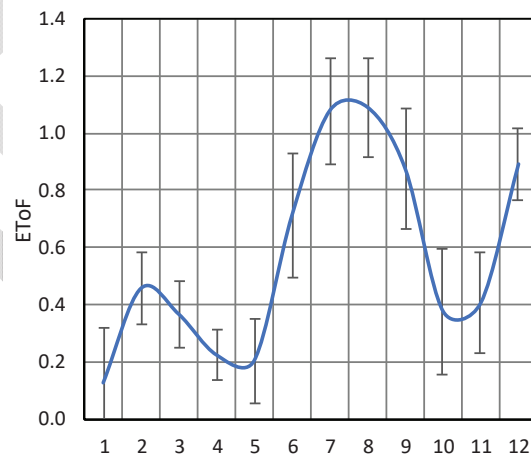
Citrus



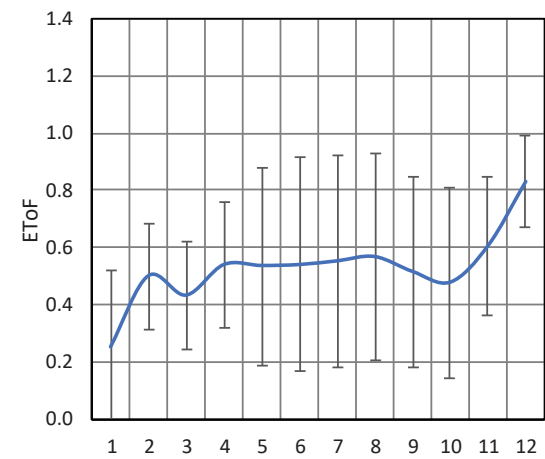
Corn



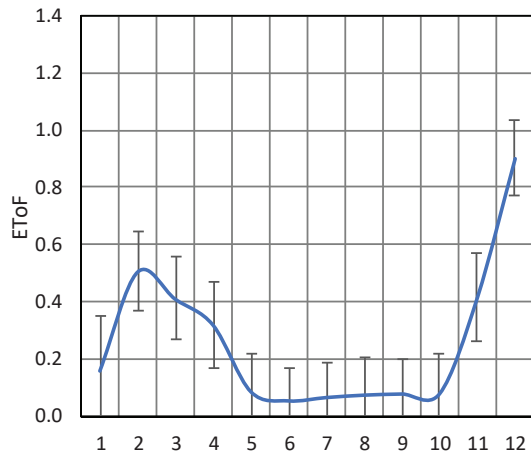
Cotton



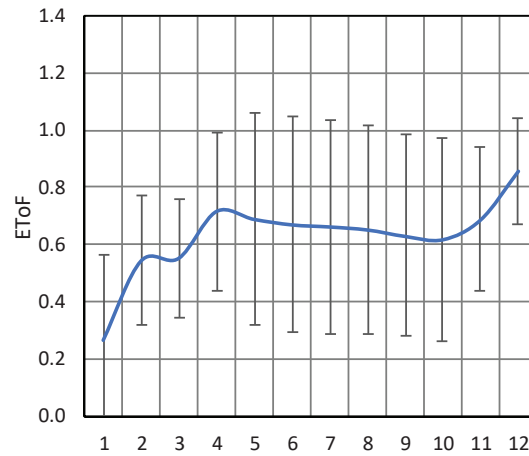
Grapes



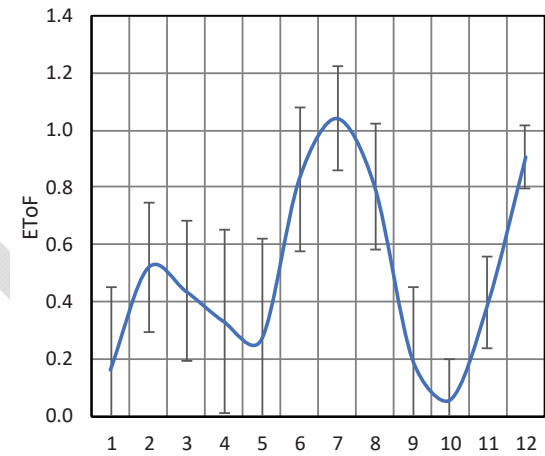
Idle



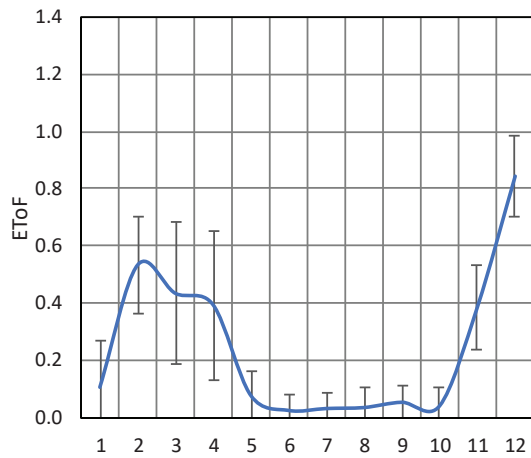
Misc. Deciduous



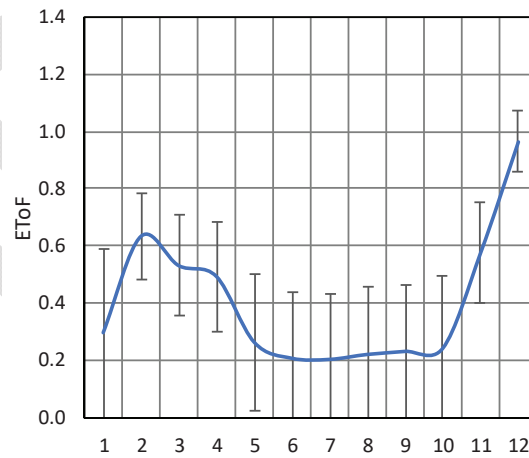
Misc. Field



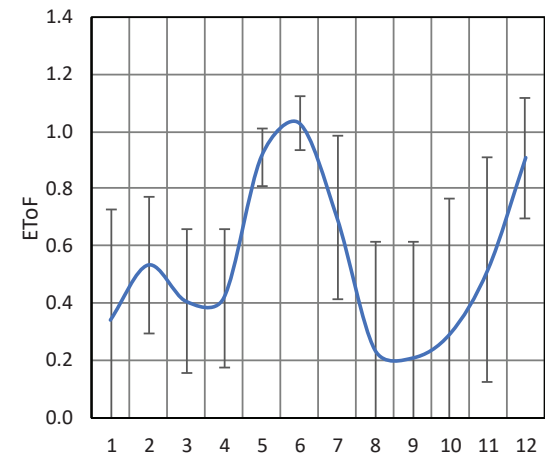
Misc. Grain and Hay



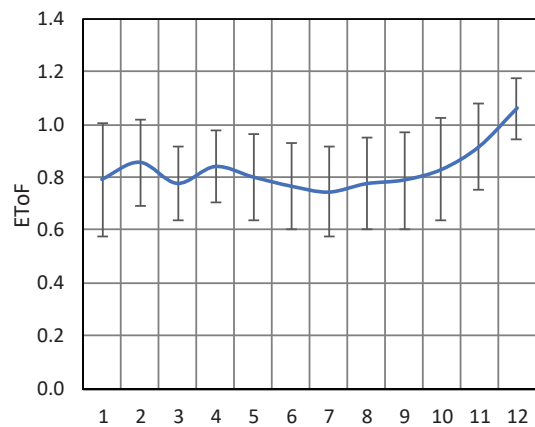
Misc. Grasses



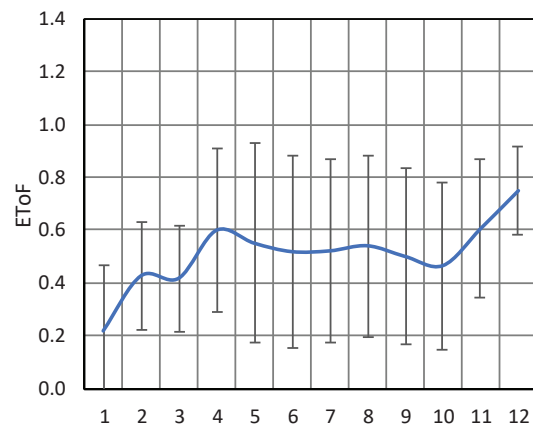
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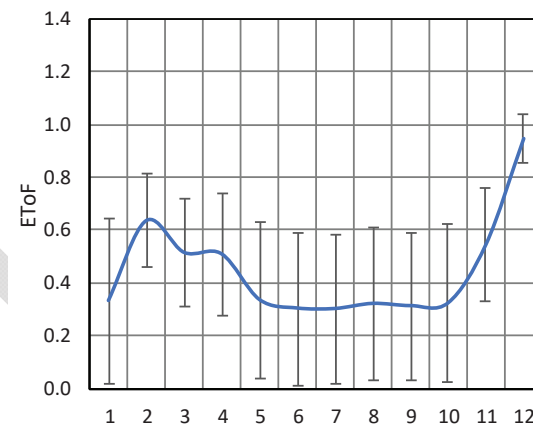
Olives



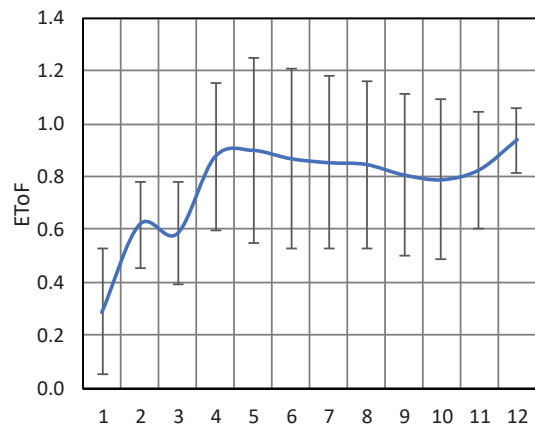
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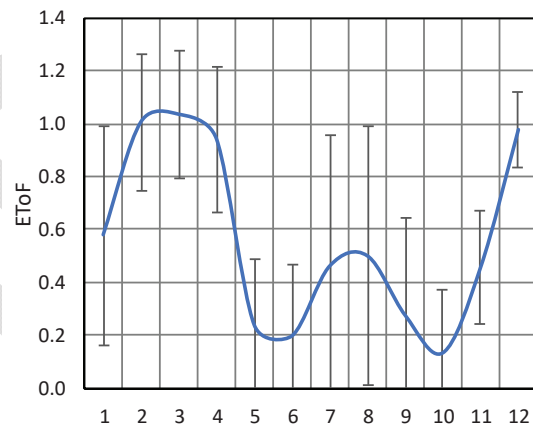
Urban



Walnuts

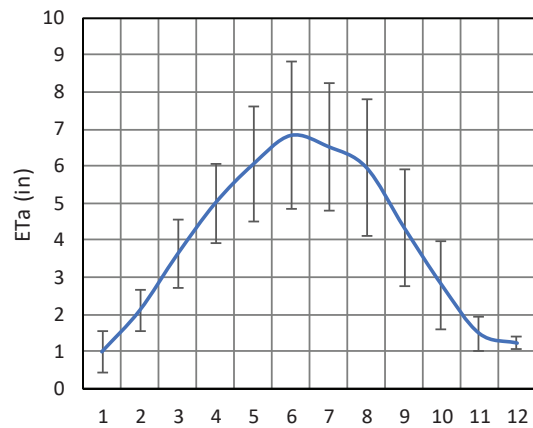


Wheat

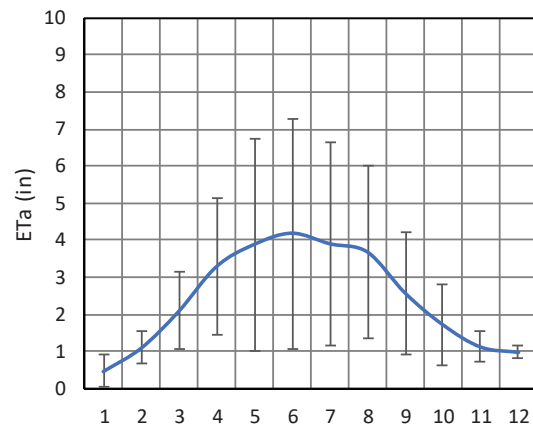


## ETc 2014

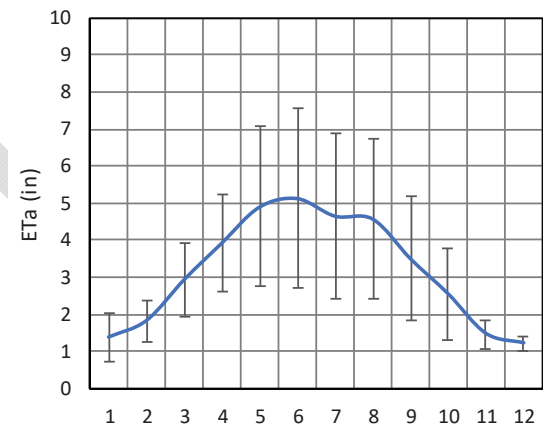
Alfalfa



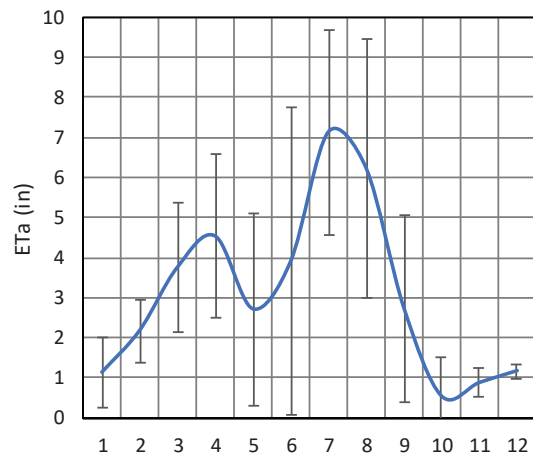
Almonds



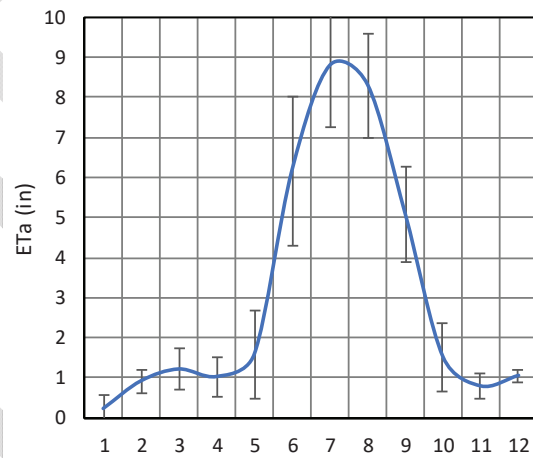
Citrus



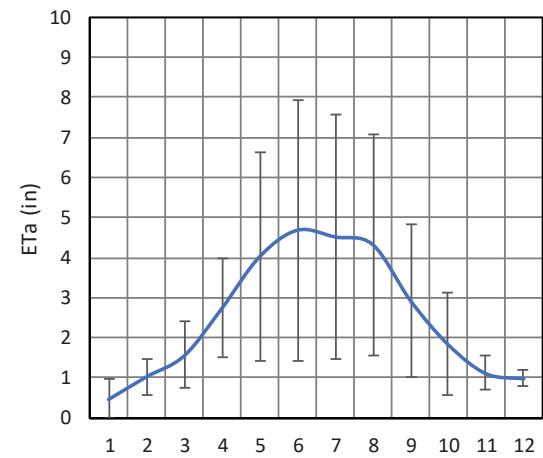
Corn



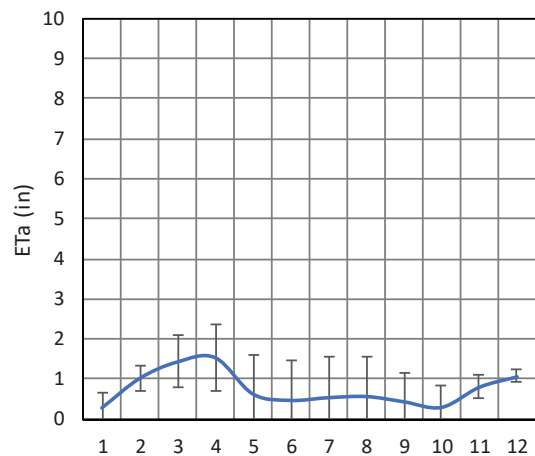
Cotton



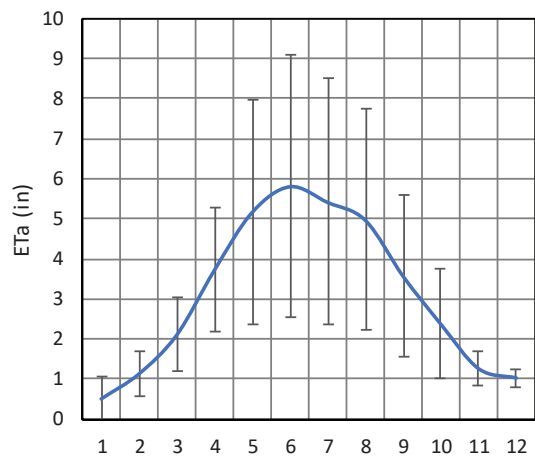
Grapes



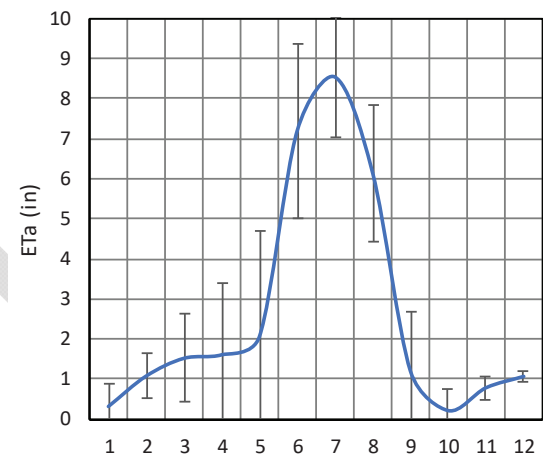
Idle



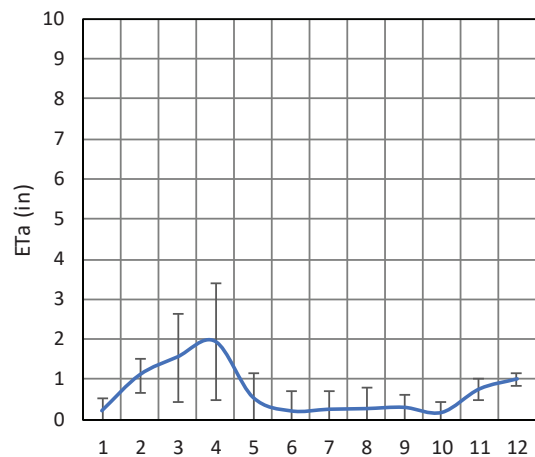
Misc. Deciduous



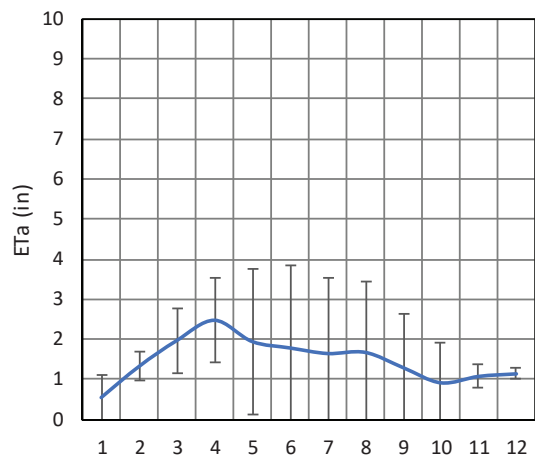
Misc. Field



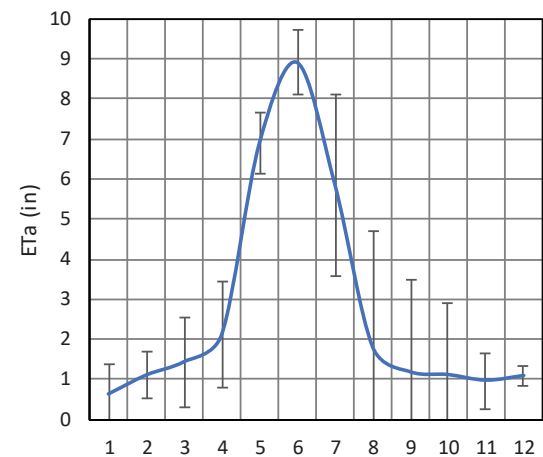
Misc. Grain and Hay



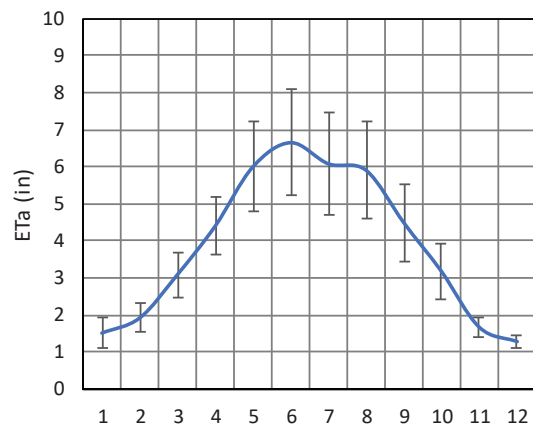
Misc. Grasses



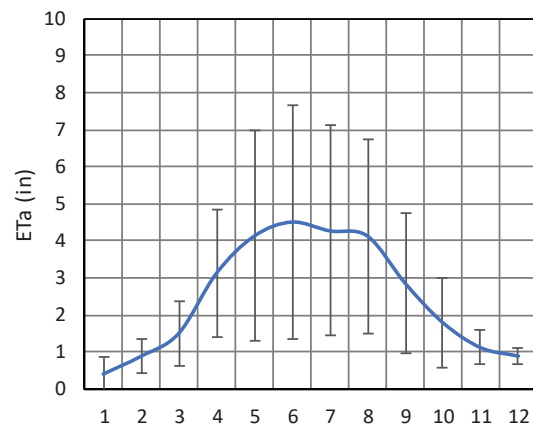
Misc. Truck



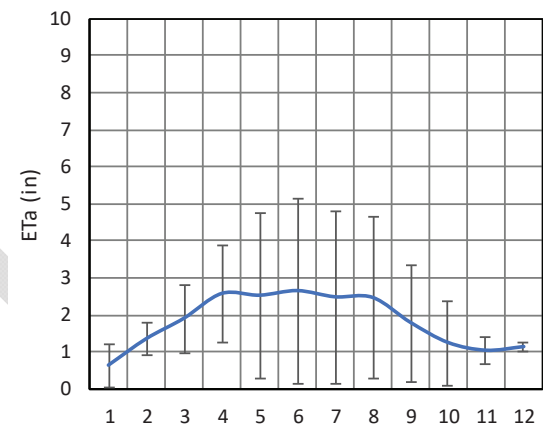
Olives



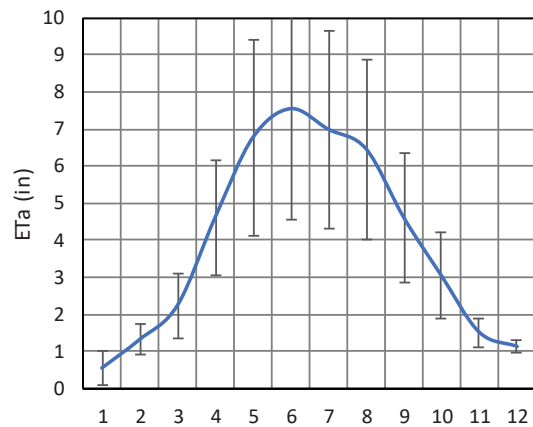
Pistachios



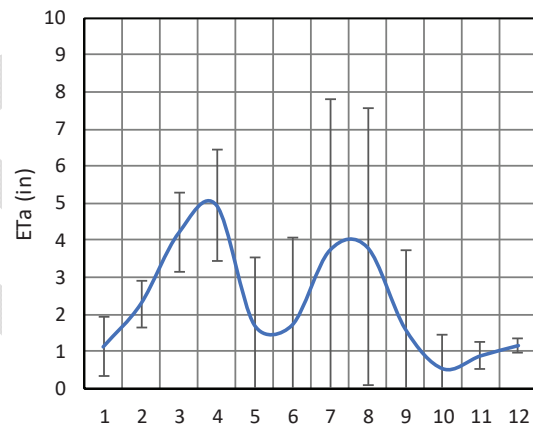
Urban



Walnuts

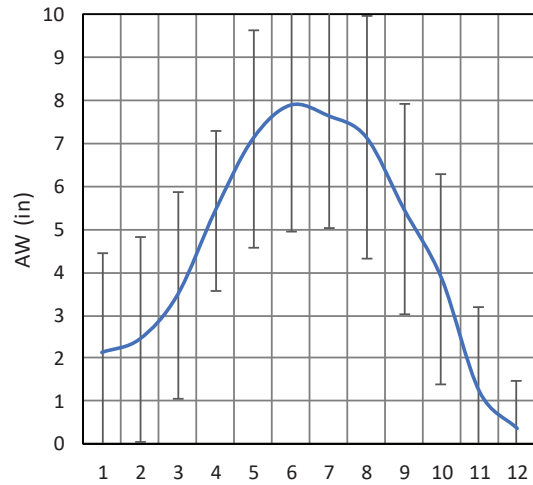


Wheat

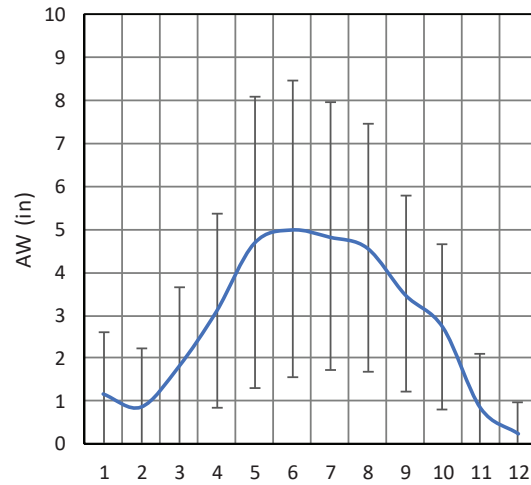


## AW 2014

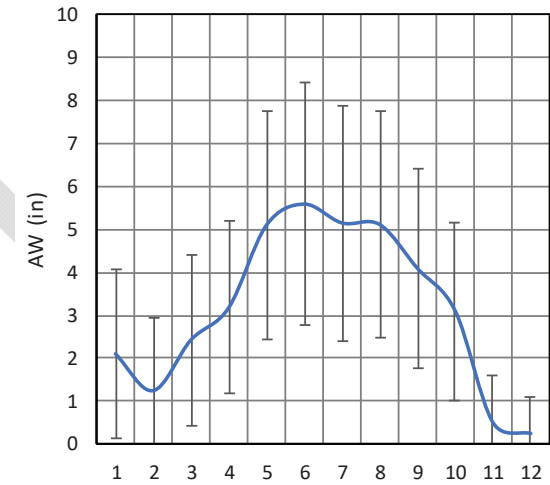
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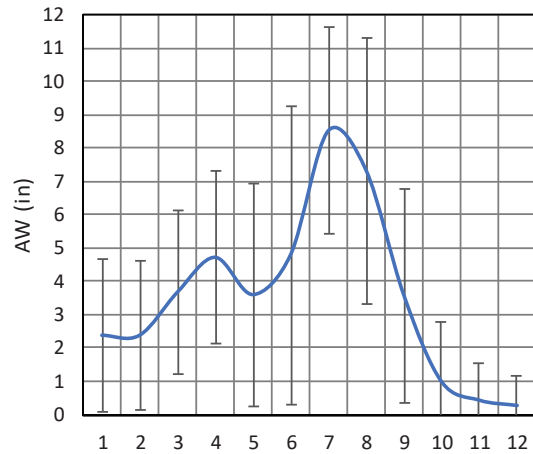
Almonds



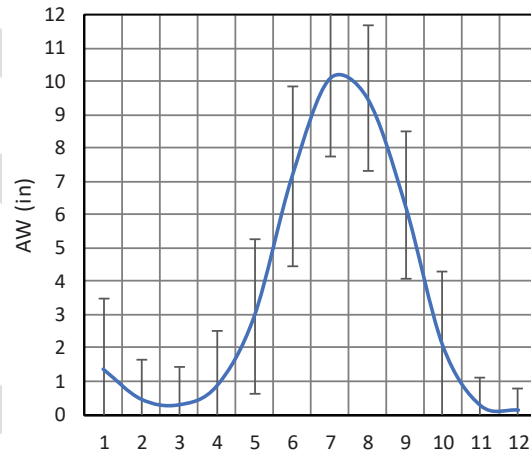
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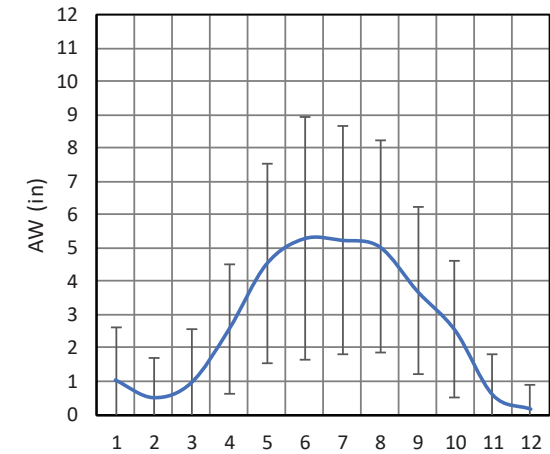
Corn



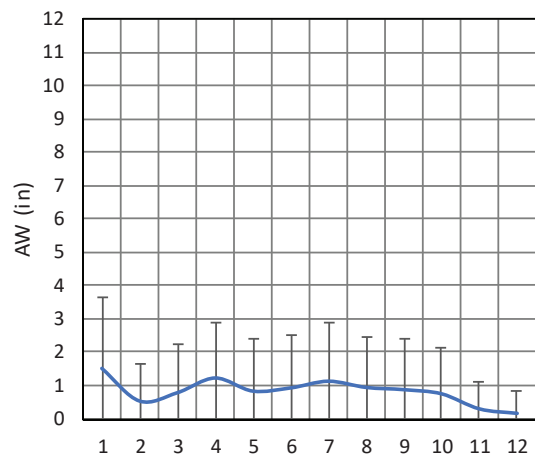
Cotton



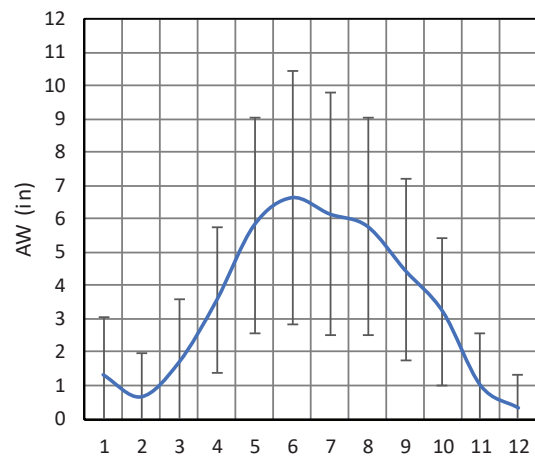
Grapes



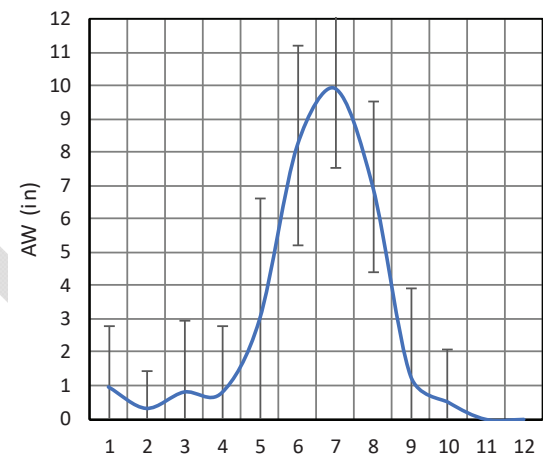
Idle



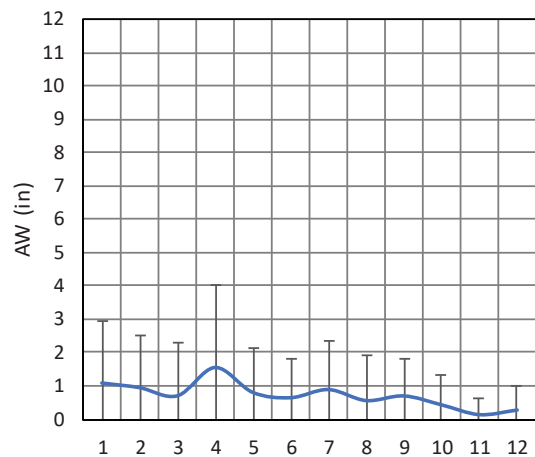
Misc. Deciduous



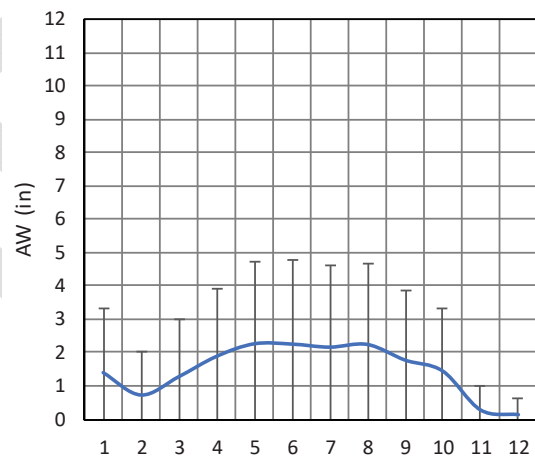
Misc. Field



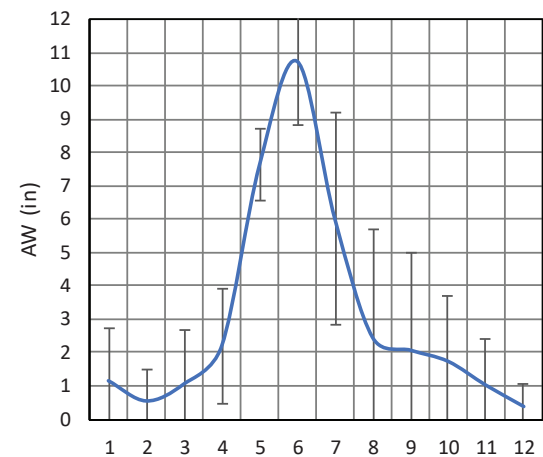
Misc. Grain and Hay



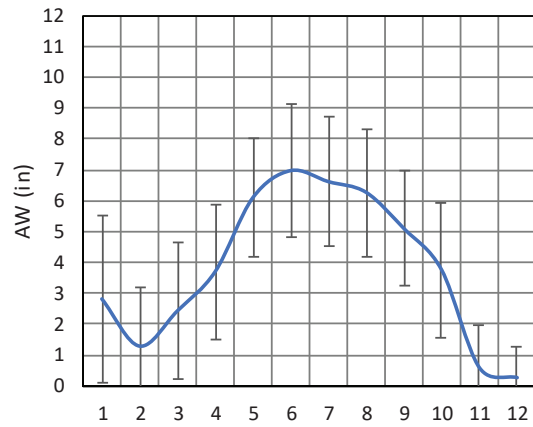
Misc. Grasses



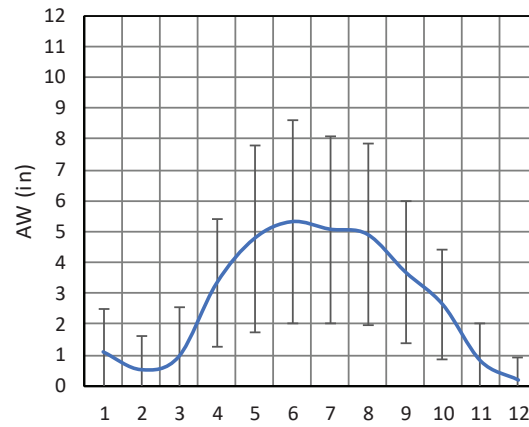
Misc. Truck



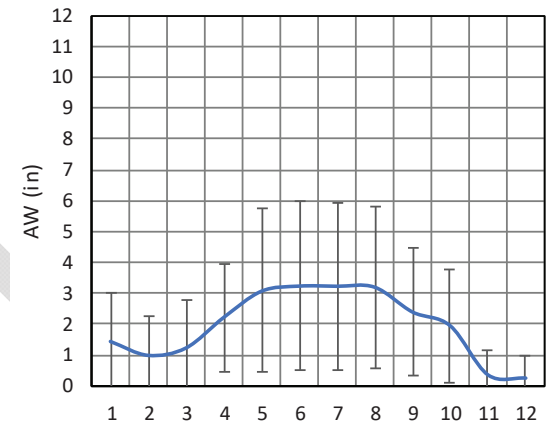
Olives



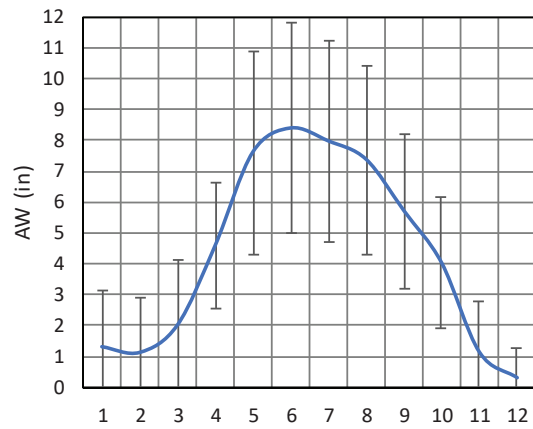
Pistachios



Urban



Walnuts



Wheat

