Evapotranspiration from Natural Vegetation in the Central Valley of California: Monthly Grass Reference-Based Vegetation Coefficients and the Dual Crop Coefficient Approach

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Abstract: Restoration activities in the Central Valley of California and elsewhere require accurate evapotranspiration information, which can then be used for a wide variety of surface and subsurface hydrologic evaluations. However, directly measuring evapotranspiration can be difficult or impossible depending on the evaluation's time frame. Transferability of measured evapotranspiration in time and space is also necessary but typically requires a weather-based reference. For nonagricultural vegetation, there is at present time no standard reference, which makes the evaluation of a variety of vegetation types from different sources difficult and time-consuming. This paper examines several methods used to estimate evapotranspiration from native vegetation, including the use of vegetation coefficients (K_v). Vegetation coefficients are based on a standardized reference and are computed as the ratio of vegetation evapotranspiration (ET_v) to the grass reference evapotranspiration (ET_o). These monthly K_v values are used to compute the long-term (for this study, 1922–2009) average ET_v for vegetation types documented to exist in California's Central Valley prior to the arrival of the first European settlers in the mid-18th century. For vegetation that relies on precipitation and soil moisture storage, a calibrated daily soil–water balance with a dual crop coefficient approach was used to compute evapotranspiration regionally over the time frame. **DOI: 10.1061/(ASCE)HE.1943-5584.0001162.**

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Introduction

As competition for fresh water supplies intensifies, it becomes increasingly important to accurately track fresh water supply destinations through hydrologic evaluations. In many cases, these groundwater and surface water hydrologic evaluations are used to create models to estimate water distribution under historical conditions or to predict future conditions based on assumed changes in landscape, climate, management, etc. For the hydrologic evaluations to be accurate, however, the assumptions and measurements of inflows and outflows upon which they are based must also be accurate. In arid and semiarid environments, the largest percentage of fresh water is generally expended by evapotranspiration, which is notoriously difficult to measure directly. Therefore, it is crucial that procedures be developed that can accurately estimate evapotranspiration (Milly and Dunne 2010; Zhao et al. 2013).

The current trend of restoring native vegetation and habitats requires a good understanding of these habitats' water demands. For example, the current Bay Delta Conservation Plan includes over 85,000 acres of natural habitat restoration in the California Central Valley over the next 40 years (BDCP 2013). Planners require accurate estimates of evapotranspiration demands from vegetation throughout the year to properly design the habitats so as not to exceed available water supplies. Evapotranspiration demands are also needed by engineers to design new infrastructure to distribute water to these areas or examine if existing infrastructure can supply the additional habitat.

In this study, evapotranspiration estimates from vegetation that existed in the Central Valley of California are developed using standard procedures similar to those used for agriculture. For non-water-stressed vegetation such as riparian forests and permanent wetlands, monthly vegetation coefficients were generated from a detailed review of literature. These coefficients were developed to be used with a reference evapotranspiration computed from regional climate data. Alternative procedures are described for vegetation that relies primarily on rainfall, where evapotranspiration rates are dependent on moisture availability in the soil.

Current Measurement and Estimation Techniques

Techniques to measure and estimate evapotranspiration directly are available but have limitations. Common measurement techniques for actual evapotranspiration include weighing lysimeters, inflow–outflow tanks, Bowen ratio, eddy covariance, surface renewal, and remote sensing using a surface energy balance. There is consensus among researchers that if measurements are made using a localized measurement technique (techniques other than remote sensing using a surface energy balance), the measurement locations should be surrounded by vegetation of the same type, health, and size of the reference vegetation (i.e., "fetch") (Allen et al. 2011). Without the

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proper fetch, warmer, dryer air can move more easily through the vegetation, causing what is termed the clothesline effect, whereby the resulting evapotranspiration estimates are unreasonably high (Blaney et al. 1933; Allen et al. 1998, 2011). Care must be taken when setting up the studies and when examining the results, because published data still exist that report these unusually high values.

Direct measurements of evapotranspiration are often not feasible in hydrologic evaluations. Using remote sensing to compute actual evapotranspiration [Surface Energy Balance Algorithm for Land (SEBAL), Mapping of Evapotranspiration at High Resolution with Internal Calibration (METRIC), etc.] has become popular over the last decade (Allen et al. 2007a). However, this method is time-intensive, and data may only be available for a limited period. Further, remote sensing has limitations when long-term evaluations are required, future predictions are needed, or where the vegetation types are not currently growing in the area of interest.

As a case in point, the California Central Valley has changed significantly since development began in the mid-18th century when the first European settlers arrived. Early maps and eyewitness accounts indicate that the Central Valley was formerly home to vast areas of wetland, riparian forest, and grassland habitats that no longer exist (Thompson 1961; Küchler 1977; California State University Chico 2003). It is estimated that wetland acreage in the Central Valley has declined from over 4 million acres to approximately 379,000 acres (Garone 2011).

In this study, evapotranspiration occurring in a variety of aquatic and terrestrial habitats was estimated for the portion of California's Central Valley that drains to the San Francisco Bay, referred to here as the "Valley Floor." California's Central Valley has a single surface water outlet (not counting evaporation and transpiration): through the San Francisco Bay-Delta, which drains the Sacramento Basin Valley from the north and the San Joaquin Basin Valley from the south. The southern part of the San Joaquin Valley (Tulare Lake Basin) is a closed basin that rarely drains to the Delta. Water that is not consumed through evaporation or transpiration flows through the Delta and is discharged into San Francisco Bay. This is commonly referred to as Delta outflow.

Past Studies

Two studies have estimated evapotranspiration by natural vegetation within the Central Valley (Fox 1987; Shelton 1987). Fox (1987) estimated long-term annual average Delta outflow from a water balance based on unimpaired rim inflows, precipitation on the Valley Floor, and evapotranspiration from native vegetation. Shelton (1987) compared predevelopment evapotranspiration within the Central Valley with current agricultural evapotranspiration. Fox (1987) and Shelton (1987) relied on annual estimates of natural vegetation evapotranspiration from studies throughout the western United States. In some cases, these evapotranspiration measurements were conducted in the early to mid-1900s.

Bolger et al. (2011) used a 3D numerical model (HydroGeoSphere) to assess the hydraulic and hydrologic conditions in the northern San Joaquin Valley from the Kings River (south of Fresno) to Sacramento. Evapotranspiration was estimated within the model based on computed root zone soil moisture along with input information on leaf-area index, soil properties, and potential evapotranspiration (ET) (which was assumed to equal the grass reference evapotranspiration for that study). The potential ET was estimated from long-term averaged data and did not vary from year to year. Bolger acknowledges that ET was a major outflow component; however, he did not report actual evapotranspiration for each vegetation type.

With all of the past studies, a major issue in estimating evapotranspiration from natural vegetation stems from somewhat limited research of varying quality and a lack of standardization on transferability in these measurements to different locations and time frames.

K_v and Water Balance Approaches

In this study, evapotranspiration estimates were made by native vegetation type within each Planning Area [California Department of Water Resources (CDWR) 2005] in the portion of the Valley Floor that historically drained to the San Francisco Bay (Fig. 1).

The new estimation approach presented in this paper is based on studies that measured evapotranspiration from vegetation similar to that found in the predeveloped Central Valley of California. Measured evapotranspiration was used to develop transferable grass reference-based vegetation coefficients (K_v's). These K_v values were used to compute local evapotranspiration on a monthly or daily basis using a standardized approach assuming similar conditions. Two methods were employed to estimate evapotranspiration: (1) K_v method for vegetation with a continuous water supply throughout the growing season, and (2) water balance method for vegetation that depends solely on precipitation. Some estimated vegetation K_v values (for permanent wetlands and riparian forest) are compared to actual evapotranspiration measured using remote sensing. Meteorological conditions of water years 1922 through 2009 (an 88-year period) were used to compute annual average evapotranspiration (depth) for vegetation types in predeveloped California. Studies, currently underway, to simulate hydrologic conditions in predeveloped California (based on the 1922–2009 meteorological conditions) will use the monthly and annual evapotranspiration values developed in this study. The long-term average ET depths by region could be used for planning and design of restoration activities for similar vegetation. The K_v values and soil water balance procedures could be used with local climatic data from other regions around the world for a variety of ET evaluations.

Methods

Several studies have examined the composition of the vegetation in the Central Valley prior to development or early in the development of the region (Thompson 1957, 1961; Küchler 1977; Fox 1987; TBI 1998; California State University Chico 2003). This study relied on the California State University Chico (2003) research, supplemented by Küchler (1977) as discussed in Fox and Sears (2014). A more comprehensive list of historical studies can be found in the reference section of CSU Chico (2003) which is, for the most part, information compiled from many earlier sources used to create a spatial distribution of vegetation categories. The vegetation habitat types in the study area (Fig. 1) include wetlands, riparian forest, grasslands, valley oak/foothill hardwoods, chaparral, and other floodplain habitats. The latter category was subdivided based on the work of Küchler (1977).

The general categories identified in CSU Chico would likely have included vegetation within different ecosystems. Grassland habitat would include perennial grasses with access to moisture in the high water table as well as perennial and annual grasses that relied on precipitation stored in the root zone through winter rains. The other floodplain habitat category was stated as a mixture of riparian, wetland, and grassland vegetation (California State University Chico 2003), which was classified using the technique of Küchler (1977).

The water table in predeveloped California was at or less than 10 feet below ground surface throughout much of the Valley Floor,

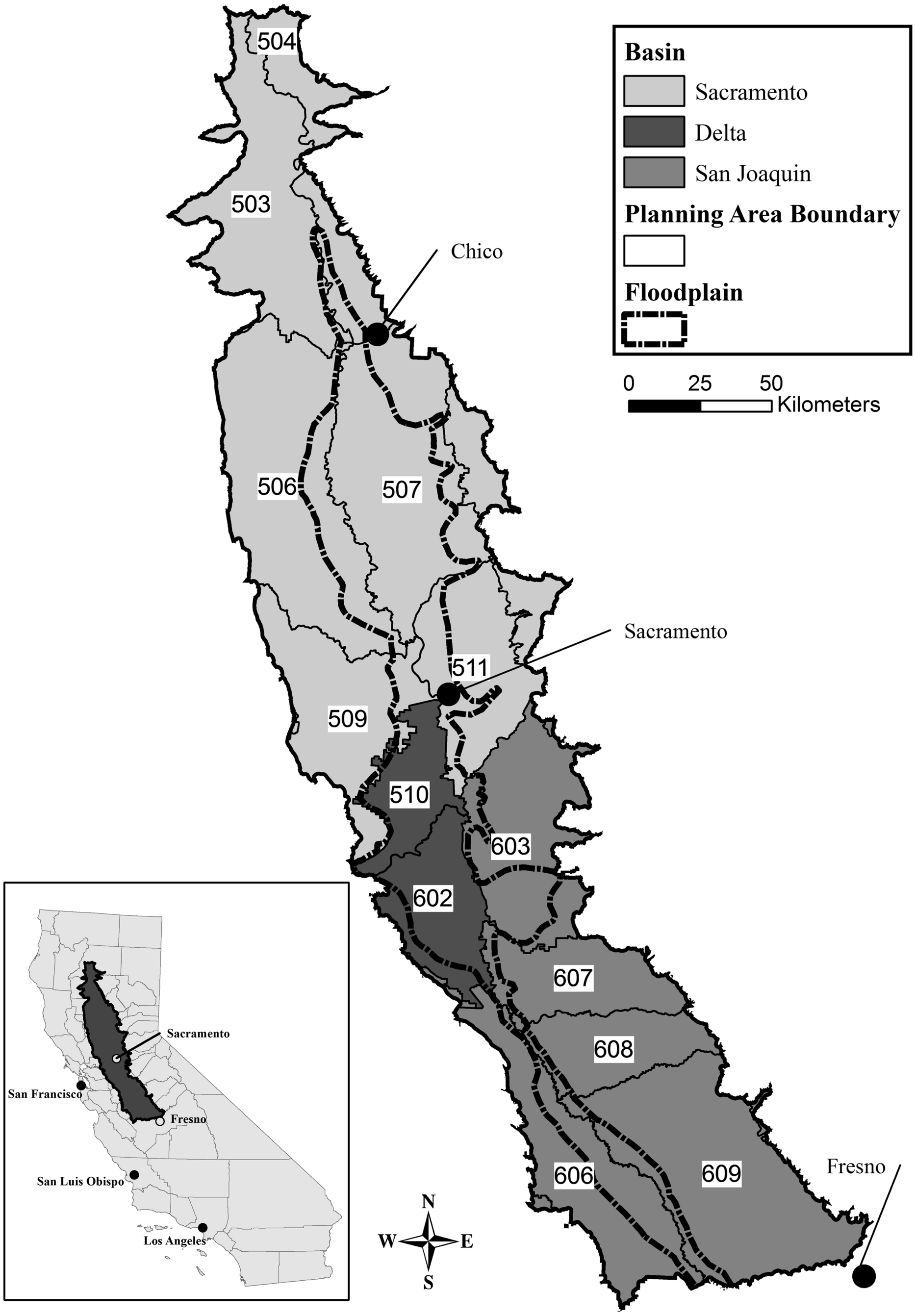

Fig. 1. Planning Areas shown with the Valley Floor and floodplain areas used for this evaluation; Planning Area 601 within the Valley Floor is too small to show on this map

and artesian conditions were widespread (Williamson et al. 1989). This shallow groundwater extended from Sutter Butte to south of the Stanislaus River, covering approximately 8,000 mi^2. In this region, grasslands were likely made up of perennial bunchgrass with year-round access to water from the water table (Küchler 1977; Heady 1988; Bartolome et al. 2007). As the depth to the groundwater table increased away from this region, the grasslands were likely more seasonal, relying on precipitation stored in the root zone. However, in some locations, a perched water table caused by a shallow clay layer or impermeable subsoil layers caused vernal pools to form. In these regions, some of the grasses and other vegetation would have access to water for a longer timeframe compared to the rainfed grasslands.

Similarly, some of the wetland habitat around the periphery of the floodplains, away from areas with high water tables would have relied on seasonal rainfall and flooding as the primary source of moisture. Once the floodwaters receded and the winter and spring precipitation ended, some of the wetlands would dry down until the next fall and winter when rainfalls and floods again occurred. Seasonal wetlands are another wetland classification within the Central Valley along with permanent wetlands and vernal pool wetlands (Garone 2011). The permanent and some vernal pool wetlands would have access to water for a majority of or the entire year.

The determination of K_v and ultimately the evapotranspiration rate from natural vegetation was split into two categories:

evapotranspiration without water deficit (nonstressed), which comprises permanent wetlands, riparian forest, and permanent perennial grasslands; and evapotranspiration under water-stressed conditions once the source water was no longer available (e.g., rainfed grasslands, valley oak/hardwoods split into foothill hardwoods and valley oak savannas, and seasonal wetlands). Vernal pools were examined differently because of the lack of reported evapotranspiration. Once the K_v values were determined for each category, the long-term average ET_v was computed for each Planning Area shown in Fig. 1.

Monthly Non-Water-Stressed K_v

An intensive review of natural vegetation evapotranspiration literature was conducted to examine studies that investigated wetland, riparian, open water evaporation, and native grasslands that had access to water throughout the growing period. There have been several reviews conducted for different native vegetation types (Johns 1989; Drexler et al. 2004; Moore et al. 2004) and it is not the intent to repeat that information here. The available reviews provided information such as who conducted the study, the vegetation type, etc. In most cases, actual results were limited to annual depth of evapotranspiration, if any results were discussed at all.

Specific information was sought for this study to develop useful, reliable K_v values. A main criterion for selection was that the study had to include at least monthly data. The authors only examined data from investigations that measured evapotranspiration from vegetation (ET_v) surrounded by similar vegetation on all sides (i.e., with sufficient fetch) using a lysimeter/tank, Bowen ratio, eddy correlation, surface renewal, or remote sensing of actual evapotranspiration using an energy balance. In one case, estimates of ET_v using porometer measurements were included because of the lack of alternative estimates. ET_v estimates using a larger scale (field or watershed) water balance were avoided due to the inaccuracies associated with measuring inflows, outflows, and changes in internal water storage. ET_v assessments using vegetative indices with empirical coefficients were also avoided since this is not an actual measurement. Several early studies were found in which ET_v was measured without proper fetch, which caused significant overestimation ET_v due to the aforementioned clothesline effect. The data gathered from the literature review focused on ET_v investigations after 1945 unless the site conditions and experimental methods were explained in sufficient detail and the researcher had sufficient experience to provide confidence in the measurements. A majority of the studies used in this paper were conducted in the western United States, although some information from Florida was used.

Computation of Non-Water-Stressed K_v

Transferring and adjusting evapotranspiration estimates made during a specific time frame in one location to a different location during a different time frame is commonly done using a reference based on local weather conditions and an adjustment coefficient based on the vegetation and growth stage (Allen et al. 1998). Weather Bureau Class A Pan evaporation was originally used as the reference for natural vegetation. Starting in the early 1970s, the Priestley-Taylor method became popular for estimating natural vegetation ET because it required less input data. The Jensen-Haise and Blaney-Criddle methods have also been used as references (Jensen et al. 1990). However, without a standard reference, different adjustment coefficients are needed for each reference equation. Attempting to compare coefficients based on different references can be challenging and has been identified as a major drawback of reference-based computations for natural vegetation (Drexler et al. 2004).

The standard approach for agricultural crops is to use a reference crop evapotranspiration (ET_o) computed from specialized weather station networks along with a crop coefficient (K_c) that was developed through research for specific stages of the crop cycle. Crop evapotranspiration (ET_c) can be computed using Eq. (1)

$$\mathrm{ET}_c = \mathrm{ET}_o \times K_c \quad (1)$$

The reference crop used is generally grass (short crop) or alfalfa (tall crop). The 2005 ASCE Standardized Penman-Monteith (ASCE ET_o) equation is the current standard for computation for either a grass or alfalfa reference evapotranspiration (Allen et al. 2005a). Over the past several decades, specialized reference evapotranspiration weather stations have been installed throughout the western United States. This provides a great resource for weather data and reference evapotranspiration at high temporal resolution (hourly and daily values).

This study applied this standard approach to the type of natural vegetation found in California's Central Valley predevelopment. As natural vegetation is of interest, the term crop coefficient is replaced in this work by a more general vegetation coefficient (K_v), and crop evapotranspiration (ET_c) is replaced with vegetation evapotranspiration (ET_v). There is debate on which reference crop, grass or alfalfa, is more appropriate. However, the authors believe that it is more important to define which reference crop was used to develop K_v or K_c values. Generally, regional decisions are made to use a particular reference crop with weather station networks. In California, grass reference evapotranspiration is used in the California Irrigation Management Information System (CIMIS) weather station network. Spatial, long-term daily ET_o information from locations throughout California has also been developed by the California Department of Water Resources (CDWR) Cal-SIMETAW program (Orang et al. 2013). For these reasons, grass reference evapotranspiration (ET_o) was selected for this study.

The grass reference is a hypothetical green surface with an assumed height, and fixed surface resistance and albedo (Allen et al. 1998). The reference crop is not intended to mimic the vegetation for which ET_v is to be estimated. The properties of the hypothetical reference crop are used in the ASCE ET_o equation along with weather information to account for regional climatic variability. The K_v values incorporate vegetation characteristics that influence evapotranspiration such as development, canopy properties, aerodynamic resistances, water availability, and ground cover. For natural vegetation, Eq. (1) can be rewritten as Eq. (2)

$$\mathrm{ET}_v = \mathrm{ET}_o \times K_v \quad (2)$$

Using Eq. (2), the monthly K_v values were developed from the monthly ET_v measurements obtained from the literature review and documented or estimated ET_o using Eq. (3)

$$K_v = \frac{\mathrm{ET}_v}{\mathrm{ET}_{o\_\mathrm{Study}}} \quad (3)$$

Data from some studies were rejected based on methodological issues or conditions that were not representative of the vegetation conditions within the predeveloped Central Valley. Drexler et al. (2004), for example, points out that for wetlands, a drawback to the K_v approach stems from inaccurate methodologies employed during the measurement of ET_v. As previously mentioned, studies conducted without appropriate fetch (isolated stands creating a clothesline effect) were not used in this study. However, elevated ET_v values for vegetation reported to be small stand (as opposed to isolated stands) are valid. As small-stand wetland areas were present along numerous sloughs and lakes within the floodplain, separate K_v values were developed for small-stand wetlands.

Grass Reference ET_{o_Study} to Compute K_v

In several recent studies, K_v was computed based on a Penman-Monteith equation for ET_o (grass reference) or ET_r (alfalfa reference). Some of these studies were conducted prior to the publication of the ASCE Standardized Reference Evapotranspiration Equation, but used similar equations and standards. If the K_v was developed using a grass reference, it is reported here without modification. If the K_v was based on an alfalfa reference, it was modified to convert it to a grass-reference-based K_v. These modifications will be discussed.

In some cases, the standard grass-reference equation could not be used to compute K_v. The ET_{o_Study}, for example, had to be estimated on a monthly basis for the time frame and the location that the study was conducted. As most ET_o weather stations were not installed in the western United States until the 1980s or later, it was not possible to use the standardized reference evapotranspiration equation for some datasets. Alternatively, the Hargreaves ET_o equation was used in cases where the full set of weather parameters was not available. The Hargreaves equation has been shown to provide relatively accurate ET_o estimates with limited data (maximum and minimum temperature only) in arid regions (Jensen et al. 1990; Allen et al. 1998). Hargreaves ET_o is computed based on temperature and extraterrestrial radiation (R_a) as Eq. (4)

$$\text{Hargreaves\_ET}_o = 0.0023(T_{\text{mean}} + 17.8)(T_{\max} - T_{\min})^{0.5} R_a \quad (4)$$

where temperatures are in degrees Celsius, and R_a and ET_o are in millimeters per unit time. The Hargreaves equation does not include direct information on wind speed or relative humidity, which can cause inaccuracies associated with the Hargreaves ET_o. Allen et al. (1998) discusses a calibration method to improve the accuracy of the Hargreaves ET_o estimate on a monthly or annual basis by comparing it to the standardized Penman-Monteith ET_o for years with overlapping data.

ET_{o_Study} was determined for each study site depending on the data availability. The list below is used to identify the method used to compute ET_o for each study summarized in the results section. The methods used for determining ET_o were as follows:

1. In cases where the vegetation coefficient was provided and ET_{o_Study} was not needed, if the K_v provided was based on an alfalfa reference crop (ET_r), these alfalfa-reference-based K_v values were multiplied by 1.15 (estimated ratio of ET_r/ET_o) to estimate K_v based on a grass reference. However, when possible, a conversion factor was computed on a monthly basis as actual ET_r/ET_o over a period of two or more years. The ratio of ET_r/ET_o was then averaged by month to account for seasonal variability improving the accuracy of the monthly grass-reference-based K_v;
2. If an ET_o weather station existed near the study location during the study period, ASCE ET_o was used;
3. If an ET_o weather station was placed near the location (within 10–20 mi depending on the climate variability and terrain) of the study site after the study was conducted, a monthly calibrated Hargreaves ET_o was used. Calibration was conducted based on years when weather station ET_o was available;
4. If no ET_o weather station was near the study location but monthly temperature data were provided with the study data, Hargreaves ET_o was used based on these temperature data; and
5. If no ET_o weather station was near the study location and monthly temperature data for the study period were not provided, Hargreaves ET_o was used based on PRISM data for the location and time frame of the study.

If methods (4) or (5) were used to estimate ET_{o_Study}, these ET_o values were checked against the long-term (10-year) average ASCE ET_o on an annual basis. The long-term average ASCE ET_o used for the check was either from weather stations within 20–30 miles with similar climate conditions or, for studies in California, from Spatial CIMIS data for the location of the study site (Hart et al. 2009). The difference between the annual ET_o values was set at a threshold of $\pm 15\%$. This reality check ensured that gross errors in the ET_{o_Study} were avoided. If the Hargreaves ET_o was outside of this threshold, alternative means of computing ET_o were attempted or the dataset was abandoned. The alternative method for computing ET_o was to find a nearby NCDC weather station with temperature data for the study's time frame and use the Hargreaves equation to compute the ET_o based on these data.

The PRISM (Parameter-elevation Regressions on Independent Slopes Model) system maintained by Oregon State University provides a grid of monthly temperatures (minimum and maximum) from 1895 to the present covering the United States (Daly et al. 2002, 2008). PRISM temperature data are computed based on surface weather station data and are interpolated based on factors such as location, coastal proximity, elevation, and topography (Daly et al. 2000).

Comparison of Nonstressed K_v Values from Previous Studies to Measured Values from Remote Sensing

As part of an unrelated, D. J. Howes, unpublished data, 2013, the primary author measured actual evapotranspiration from riparian and wetland habitats in Kern County, CA using a surface energy balance with remote sensing data. Monthly K_v values were computed based on computed ET_o in these investigations and compared to the monthly K_v values from literature. To develop the actual evapotranspiration from the riparian and wetland vegetation, LandSAT 5 images were processed over a two-year period for each site using modified METRIC procedures (Allen et al. 2007a). The primary author has modified the original METRIC procedure to use a grass-reference evapotranspiration and use a semiautomated internal calibration procedure. The values obtained from this separate study proved useful to the research discussed here, and a comparison of the data appears in the "Results and Discussion" section of this paper.

The wetland area that was examined for the comparison is within Kern Wildlife Refuge in northern Kern County, California. The wetland vegetation consists of tules, timothy, and cattails. LandSAT 5 images (Path 42/Row 35) were processed from March through October 2011, which was an unusually wet year that resulted in a portion of the wetland within the refuge having water all season. Because of limited water supplies during the summer, in most years the Kern Wildlife Refuge wetlands are seasonal with limited water supplies during the summer months.

K_v values were computed for each image processed (one per month) using Eq. (2) where the ET_v was the instantaneous value at the time of image acquisition computed with METRIC and ET_o was the instantaneous grass-reference evapotranspiration. The instantaneous ET_o was interpolated from hourly data collected at the CIMIS weather station near Lost Hills, California (Belridge Station, Number 146).

Riparian vegetation in the Central Valley no longer exists in large quantities. However, one of the most significant remaining cottonwood–willow forests in California is located along the Kern River east of Lake Isabella, California in the southern Sierra Nevada mountain range. LandSAT 5 images (Path 41/Row 35) from March through September 2011 and October and

November 2010 were used to compute actual evapotranspiration for the riparian forest near Lake Isabella. At least one image per month was used for the evaluation. K_v values were computed as previously described; however, the instantaneous ET_o was computed using the 2005 ASCE Standardized ET_o equation with weather data collected at a Remote Automatic Weather Station (RAWS) near Kernville, California (MesoWest Station KRNC1). Weather data were quality controlled prior to computing ET_o based on procedures of Allen et al. (1998).

Evapotranspiration from Rainfed Vegetation

A portion of the grasslands and valley/foothill hardwood habitats and all of the chaparral along the perimeter of the predeveloped Valley Floor would have relied on precipitation because the water table was generally deeper along the higher elevation areas. The native grasslands contained primarily perennial bunchgrasses that have deeper roots than the current annual grasses and in some cases would have had access to groundwater from the high water table (Reever Morghan et al. 2007). Grasslands that have access to groundwater would not have been water stressed, and the K_v would therefore be represented by the natural grass K_v discussed in the previous section. Special consideration was given to oak savannas that had access to groundwater (termed "valley oak savannas") as will be discussed later. However, a portion of the grasslands and valley/foothill hardwoods identified by the CSU Chico study would have relied principally on precipitation (termed "rainfed grassland" and "foothill hardwoods," respectively).

The standard relationship shown in Eqs. (1) and (2) assumes a full water supply. Thus, it cannot be used for vegetation that depends on precipitation as the only water supply. K_v values measured during a particular year would not necessarily be representative of K_v values for a different year with different precipitation rates or in areas with different soil types. Accounting for variable precipitation both from year to year and spatially requires examining root-zone soil moisture and the plant development over the period of interest. For this evaluation, a daily soil–water balance using the dual-crop coefficient method (Allen et al. 1998) was used for the 88-year period for rainfed vegetation.

The ET_v for rainfed grasslands and foothill hardwoods was estimated for this study using the soil water balance approach calibrated using data measured near Ione, CA using the eddy covariance technique (Baldocchi et al. 2004). The subject study area is within managed ranches in which brush has been removed and cattle graze the grasses and herbs. Furthermore, it no longer contains native perennial bunchgrasses believed to have once been dominant. In this oak savanna ecosystem, trees covered about 40% of the landscape, predominately blue oaks (*Quercus douglasii*) with occasional grey pines (*Pinus sabiniana*) (Miller et al. 2010). This ecosystem is used to represent "foothill hardwoods," a subset of Chico's (2003) "valley foothill/hardwood." The perennial blue oaks that dominate the site have limited access to groundwater, unlike the deciduous valley oaks that dominated the Central Valley Floor prior to development. Finally, its soils and elevation are not representative of the Valley Floor study area (Fig. 1). Thus, the soil–water balance approach based on Ione data likely underestimates the evapotranspiration that would have occurred from grassland and foothill hardwood areas under natural conditions. However, it is currently the best source of data available.

The following sections discuss soil–water balance model calibration and the use of the calibrated model to examine rainfed vegetation throughout the Valley Floor. Once the soil–water balance model was calibrated, soil type and root-zone depth (for the oaks) were modified to be more representative of conditions on the Valley Floor, as will be discussed. The third section discusses special consideration for the valley oaks that had access to groundwater but were in rainfed grasslands.

Soil–Water Balance Model Calibration

The soil–water balance model requires inputs related to plant development, soil-available water-holding capacity, root-zone depth, daily grass reference evapotranspiration, daily precipitation, and basal K_v (K_v for vegetation that is nonstressed with no surface evaporation) during different development periods. While many inputs into the model could be estimated for the Valley Floor based on weather measurements and soil reports, vegetation parameters including basal K_v and plant development timing are unknown. To estimate the vegetation parameters for the grasslands and foothill hardwoods, these parameters were adjusted manually until the modeled ET_v matched the measured ET_v. Because only two parameters were modified during the calibration, namely vegetation development and basal K_v, manual calibration was used. However, this was a time-consuming process and in the future, an automated calibration tool may be more appropriate.

Daily grass reference evapotranspiration data were obtained from CDWR Cal-SIMETAW program for the Planning Area that included Ione, California based on the spatially averaged ET_o (Orang et al. 2013). Estimated daily precipitation was also provided with ET_o. However, the annual precipitation in Valley Floor Planning Area was significantly lower during that year than reported by Baldocchi et al. (2004). This is likely due to the fact that Ione, California is at a higher elevation along the Sierra Nevada foothills and receives more precipitation than other portions of the Planning Area (Planning Area #603). However, daily precipitation data from the original study were not available. To make the adjustment, on days of precipitation in the dataset, the precipitation was increased until the annual precipitation amounts matched those of Baldocchi et al. (2004). In this way, the seasonal precipitation variability was maintained.

For model calibration, the soil-available water-holding capacity (AWHC) was based on the soil retention curves measured by Baldocchi et al. (2004). The reported soil textures were silt loam to rocky silt loam (Miller et al. 2010). The AWHC was computed to be 350 mm/m for the oak savanna and 190 mm/m for the grassland based on the soil–water retention curves. The maximum root-zone depth used for the annual grassland was 0.6 m (Reever Morghan et al. 2007).

For the foothill oak savanna, used as a surrogate for foothill hardwoods, the depth of the root zone was assumed to be 1 m, which is equivalent to the depth of the surface soil (Miller et al. 2010). Both Baldocchi et al. (2004) and Miller et al. (2010) reported that the oaks used groundwater in the summer and fall when soil moisture was limited. While the overall ET_v was significantly lower when soil moisture levels were low, a high percentage of ET_v during this time can be attributed to groundwater (Miller et al. 2010). Oak roots can extend through fractured rock to depths in excess of 24 m (Lewis and Burgy 1964). The lower ET_v during the summer and fall is due to the fact that a relatively shallow soil layer overlaid a fractured rock aquifer that was accessible to a smaller portion of roots. Miller et al. (2012) estimates that groundwater supplies account for approximately 20% of the annual evapotranspiration in the foothill oak savanna. The soil–water balance model did not include contributions from the groundwater in the summer and fall, thus underestimating evapotranspiration for foothill oak savanna. Therefore, the summer evapotranspiration comparison shown in Fig. 2(a) is higher for the measured values than the modeled values. In July and August 2002, the difference between measured and modeled ET was 14 mm and 16 mm,

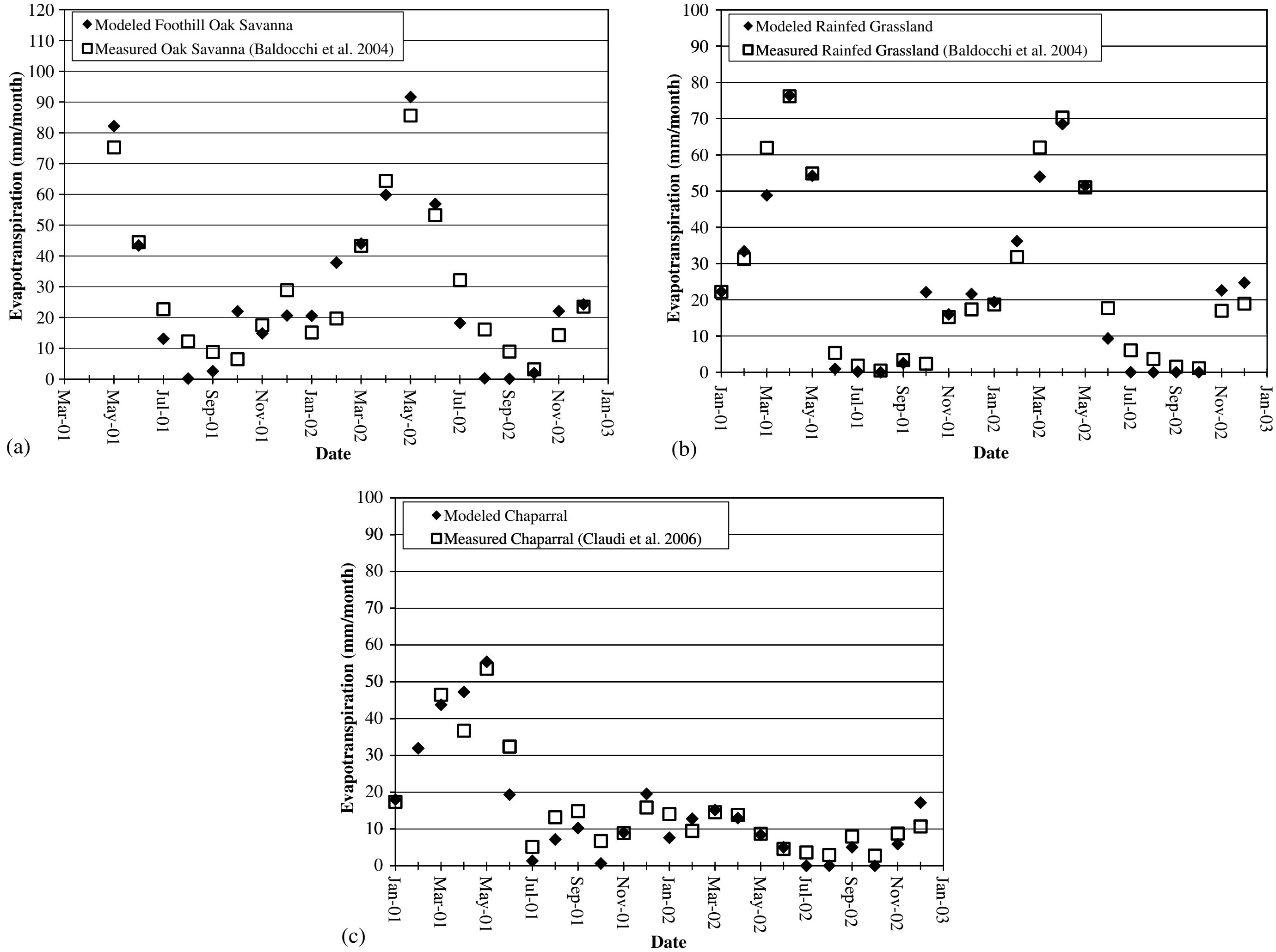

Fig. 2. Measured evapotranspiration from eddy covariance compared to calibrated soil–water balance model results for foothill oak savanna and rainfed grasslands with measured values from Baldocchi et al. (2004) and chaparral with measured values from Claudi et al. (2006)

respectively. For the valley oak savanna category, groundwater availability during the summer was assumed.

Vegetation development and basal K_v were calibrated by comparing reported ET_v data from the eddy covariance stations (Baldocchi et al. 2004) to modeled ET_v. The processed data for the years reported in the study were obtained from FLUXNET (ORNL DAAC 2013). The development stages and basal K_v were manually adjusted until the modeled and measured monthly average ET_v followed similar patterns and had similar magnitudes, as will be discussed in more detail. The basal K_v is the potential transpiration without water stress and is generally a function of leaf area and vegetation type. The actual K_v is computed using the dual-crop coefficient method in the soil–water balance model, which accounts for vegetation stress due to limited water availability and soil evaporation from a wet soil surface. This is because basal K_v values are not available for these vegetation types and would be dependent on the vegetation cover and health. Vegetation development could be predicted initially through visual examination of the ET_v from the covariance stations. Initial adjustments to the vegetation development were made until the early year trends (not magnitude) in monthly ET_v agreed. The basal K_v required more adjustment during the calibration procedure and were adjusted until the magnitude of monthly modeled and measured ET_v correlated. Additional fine tuning adjustments were made to the vegetative development timing but basal K_v seemed to be the most important for calibration. The root mean square error (RMSE) and normalized RMSE (NRMSE) for rainfed grassland were 6.1 mm and 8%, respectively. The RMSE and NRMSE for foothill oak savanna were 9.1 mm and 11%, respectively. The higher RMSE and NRMSE for the foothill oak savanna is in part due to the model underpredicting ET_v because it was conservatively assumed that the vegetation type did not have access to groundwater. Calibrated values used for the long-term modeling are shown in Table 1. A comparison between the measured and calibration results are shown in Fig. 2.

Evapotranspiration from chaparral vegetation was calibrated using a similar procedure previously discussed based on data used by Claudio et al. (2006). The chaparral leaf area and height were assumed constant throughout the year and therefore the only calibration parameter was basal K_v. This assumption, which simplified the calibration procedure, resulted in a best fit between modeled and measured data with a constant basal K_v throughout the year. This indicates that chaparral vegetation is capable of utilizing water if it becomes available and regulates its use as soil moisture depletion increases. Processed eddy covariance data from 2001 through 2002 obtained from FLUXNET (ORNL DAAC 2013) at the Sky Oaks field station located in northern San Diego County were used for the calibration. Grass reference ET_o was obtained

Table 1. Final Calibrated Parameters for the Dual Crop Coefficient Modeling of Grassland and Foothill Oak Savanna Vegetation

Parameter	Rainfed grasslands	Foothill oak savanna	Chaparral
Basal K_v initial	0.1	0.1	0.25
Basal K_v full	0.65	0.5	0.25
Initial period length (days)	70	75	n/a
Development period length (days)	75	90	n/a
Date for start of initial period	December 1	December 1	January 1
Soil moisture depletion at onset of stress (%)	55	55	55

from the CIMIS Station #137 near Temecula, California (CIMIS 2013). Calibrated values used for the long-term modeling of chaparral are shown in Table 1. The RMSE and NRMSE for chaparral modeled values were 4.9 mm and 10%, respectively. A comparison between measured and calibrated-modeled ET_v for chaparral is shown in Fig. 2(c).

Soil–Water Balance Model for Valley Floor ET_v Computations

Once the vegetation parameters were calibrated, the other model inputs were modified to represent average conditions on the Valley Floor (as opposed to the upper foothills). The calibrated model for the rainfed grasslands, chaparral, and foothill hardwoods was used as the basis of the long-term modeling of these vegetative types for the Valley Floor. However, modifications were made to the rooting depth and soil AWHC to account for differing characteristics near the Valley Floor. A root-zone depth of 1.5 m was used for the foothill hardwood, which coincides with the measured root-zone depth of older blue oaks (Millikin and Bledsoe 1999). Oak roots in the Valley Floor can be much deeper to tap into the groundwater, but because the grassland and foothill hardwoods oaks are modeled as a system (as opposed to independently), a deeper root zone would lead to overestimation of ET from the grasslands within the foothill hardwood, while underestimating ET from the hardwood themselves. In the foothill regions on the edge of the Valley Floor, Millikin and Bledsoe (1999) found that the majority of the blue oak root biomass was in the top 0.5 to 1 m of soil, and a smaller percentage below that reached to a depth of 1.5 m. However, Miller et al. (2010) found that blue oaks reach and rely on stores of groundwater more than 10 m below the surface. Thus, the approach used here would underestimate ET_v from foothill hardwoods.

The rainfed grasslands' root zone was maintained at 0.6 m based on field studies of annual and perennial bunchgrass on the Valley Floor (Holmes and Rice 1996). Major soil types covering the grassland and valley/foothill hardwood habitat were examined in GIS by overlaying the vegetation types with a large-scale soils map of California (Soil Survey Staff 2006). The major soil texture in both vegetative categories was silt loam, covering 28% of the valley/foothill hardwood and 18% of the grassland areas. Other major soil textures in these regions included gravelly loam, sandy loam, loam, and clay loam. General published values of AWHC for these soil types range from 110 to 200 mm/m (Allen et al. 1998). An average value of 150 mm/m was used for the modeling of both vegetation types.

Soil–Water Balance Model for Valley Oak Savanna ET_v with Contribution from Groundwater

Urbanization and agriculture have replaced the valley oak savannas that once covered a significant area within the Central Valley. Unlike the blue oaks that make up the majority of the foothill hardwood savannas, valley oaks are not as drought tolerant and studies have indicated that they have deep roots that tap into groundwater reserves (Griffin 1973; Knops and Koenig 1994). Valley oaks tend to grow in bottomlands where groundwater is available. Because the water table was much higher predevelopment, it is reasonable to assume that the valley oaks had unrestricted access to groundwater in a significant portion of the Valley Floor. However, no information on evapotranspiration for natural valley oak savannas was found during this investigation. Valley oaks are dormant from December to approximately March in California (Pavlik et al. 1991). During this time frame, the grass and scrub understory would continue to use water (rainfed). It was assumed that the evapotranspiration on the Valley Floor would be similar to the foothill hardwoods during the winter and spring until the soil moisture was depleted in the primary understory root zone. After this period, a K_v value of 0.4 was used throughout the summer and fall to account for groundwater use by the valley oaks. The value of 0.4 was selected to account for a medium density overstory with a shallower rooted understory that either senesces or has significantly reduced evapotranspiration during the summer and early fall. The tree density of the valley oaks during predevelopment was likely mixed, as it is today (Pavlik et al. 1991), having higher densities on the fringe of the riparian forests to wider spacing towards the foothills on the edge of the Valley Floor. An estimated minimum summer and fall K_v of 0.4 represents an average tree density that would underestimate the evapotranspiration in the dense oak forests. However, the distribution of valley oak tree densities throughout the Valley Floor predevelopment is currently unknown so an average density was assumed.

Seasonal Wetlands and Vernal Pools

In contrast to permanent wetlands, seasonal wetlands undergo periods of high water availability starting in late fall with the first precipitation events, through midsummer when the flooding ceases and the water table drops below the ground surface (Garone 2011). The seasonal wetland habitat would have been found in some vernal pools and between permanent wetlands and the margin of the floodplain along the rivers in the Central Valley (Whipple et al. 2012).

The U.S. Geological Survey examined the evapotranspiration from seasonal wetlands near Upper Klamath Lake, Oregon from 2008 through 2010 using eddy covariance (Stannard 2013). In this study, the water table dropped below the soil surface between mid-July and early August each year and returned to standing water conditions in late winter/early spring. On average, the water table dropped approximately 0.5 m below the ground surface for each year and each site by late September to mid-October. On the Valley Floor of California prior to development, the standing water and water table in seasonal wetlands would likely begin to drop as the river and stream flows began to recede in the late spring and summer. The standing water and water table recession in the Upper Klamath Lake coincides with the long-term average drop-off in estimated valley historical rim inflows from the peak flow occurring generally in May (Tanaka et al. 2006). The combination of surface and subsurface outflow and evapotranspiration from the seasonal wetlands would cause a drop in the water table, resulting in reduced ET_v due to water stress.

Because vernal pools are found nestled within grassland areas, they have historically been classified as grasslands. However, vernal pools are functionally similar to seasonal wetlands. The literature review revealed no information on measurement of actual evapotranspiration from vernal pools. Rains et al. (2006) and Williamson et al. (2005) used potential evapotranspiration (equal to grass reference ET_o) to evaluate the likelihood of seepage from vernal pools. With the lack of monthly (or annual) or more frequent evapotranspiration measurements for vernal pools, estimates were made for K_v values based on typical conditions found in existing vernal pools in California. Vernal pools have a hardpan or low permeability layer at a relatively shallow depth below the ground surface. Rainfall from within the watershed as well as streams and overland runoff feed these vernal pools through surface and subsurface flows. The pools generally fill during the rainy season and in most cases, the pools fill before the vegetation emerges. A variety of vegetation grows within and around the vernal pools. During the summer, evapotranspiration and subsurface outflow drains the pools and some of the vegetation likely senesces. The water available to the plant during the rainy season is similar to wetlands or perennial grasses with access to a high water table. During the summer, evapotranspiration would likely drop significantly because of the lack of available water. This is similar to what occurs with rainfed grasslands, but later into the summer.

Due to the lack of evapotranspiration estimates and a variety of conditions that would be inherently difficult to estimate on a daily basis, it was infeasible to use the daily soil–water balance to estimate evapotranspiration. Estimates for monthly vernal pool K_v values were made based upon reported values from Williamson et al. (2005) on pool stage and soil moisture for vernal pools in California. Williamson et al. (2005) examined the conditions at three vernal pool sites from November through May for a single year. By April–May, the pool levels were dropping. Soil moisture measurements showed further reduction in soil moisture after the pool levels declined to surface. While the soil moisture measurements in the study ended in early June, the soil moisture was still declining, indicating continued evapotranspiration.

The vernal pool K_v was estimated based on aquatic (open water) areas in the winter (December through February) and large-stand wetlands in the spring (March through May). The K_v values in early summer to midsummer during the pool and soil moisture dry-down period were estimated based on data collected by Williamson et al. (2005) and photos taken over a period of several years of vernal pool filling to vegetation senescence (Chester 2003). The K_v is assumed to drop to 0.1–0.15 in late summer and early fall until the next rainy season.

Long-Term Average ET_v

The ET_v for vegetation types other than rainfed grasslands, foothill hardwoods, and valley oak savannas were computed on a monthly basis using K_v values found in or computed from published studies and monthly ET_o by Planning Area (Fig. 1). Thirteen Planning Areas (CDWR 2005) were examined covering the Valley Floor from the westward San Joaquin River in the south to Shasta Lake in the north. Because the majority of Planning Area 504 lies outside of the Valley Floor, ET_o and precipitation from detailed analysis Units 143 and 144 (areas within 504 and the Valley Floor) were used for this area. Daily ET_o data for each planning area were averaged by month for each year from January 1922 through December 2009. The ET_v was computed using Eq. (2) for each month during this time period.

The ET_v for rainfed grasslands, foothill hardwood, and valley oak savannas was computed on a daily basis using a daily soil–water balance model from 1922 through 2009. Daily ET_o and precipitation data were developed from the CDWR Cal-SIMETAW program on a daily basis by Planning Area using procedures described in Orang et al. (2013).

Results and Discussion

Table 2 summarizes key information from the studies used to compute K_v, including occurrence of long-term winter freeze events, water table depth, location, and ET_v measurement method. Table 3 shows the K_v values from each study by month, the average monthly K_v from all studies for each vegetation type, and the K_v used to compute ET_v in this study. The K_v values used to compute ET_v were adjusted to account for conditions that are not representative of the study area. Thus, K_v used to compute ET_v differs from the average of the studies summarized in Table 3 for the reasons explained below.

First, some measurements were taken in climate conditions that were different than those in California. For example, long-term events where average temperatures are below freezing are not common in the Central Valley of California. The criteria for long-term winter freeze generally refer to multiple consecutive days with temperatures below freezing, which could result in severely reduced transpiration even into the early spring because of vegetation dormancy. K_v values from studies that did not have long-term winter freeze were used to compute ET_v in this study during the winter and spring time frames. This was the case for all wetland categories and was a consideration with large-stand riparian forest. For large-stand riparian forest, more weight was given to the Young and Blaney (1942) study results during the spring and summer (through August) because the other study was conducted in New Mexico with long-term winter freeze events.

Second, for permanent grass, measurements taken where the water table was greater than 0.6 m were not used to compute ET_v for this study. The perennial grasses in predeveloped California had deeper roots than the annual grasses examined in these studies. Therefore, inclusion of K_v values for studies with deeper groundwater levels would underestimate evapotranspiration. For other vegetation categories, no other adjustments were made based on water table depth. Water table depth in Table 2 is referenced from the ground surface where reported and is provided for informational purposes. A water table depth identified as "variable" was used for large-scale evapotranspiration assessments using remote sensing (surface energy balance using satellites). A water table depth referred to as "high" indicates that the actual depth was not provided but it was noted that there was the existence of a high water table.

Finally, special cases were considered that only apply to a subset of the measurements (e.g., monthly K_v values with outliers). If a study differed significantly from other studies, it was not used as significantly in the development of the K_v used to compute ET_v. For example, small-stand wetland K_v values in October and November from Young and Blaney (1942) were unusually high compared to other months and studies. In addition, more recent research from reputable sources was often weighted more heavily when deciding what monthly K_v values should be used. However, the factors previously discussed, such as water table depth and absence of long-term freeze events, were given preference when applicable.

Clarification on terminology in the measurement method category is necessary. Many of the earlier studies used inflow/outflow tanks placed within vegetation. These are sometimes referred to as "lysimeters" in literature, but that term was not used here, to differentiate tank measurements with weighing lysimeters often used for measurement of evapotranspiration. The SEB/METRIC measurement method refers to a surface energy balance using remotely sensed data that were processed using the Mapping of Evapotranspiration at High Resolution with Internal Calibration procedure (Allen et al. 2007b).

Table 2. Studies Where Monthly ET_v Data was Obtained for Different Vegetation Types under a Variety of Conditions

Category	Identifier	Vegetation	Long-term winter freeze	Water table depth	Location	Measurement method	ET_o method	Source
Large-stand wetland	1	Cattails	No	Standing	Fort Drum, Florida	Tank within vegetation	1	Mao et al. (2002)
	2	Cattails	No	Standing	Southern Florida	Tank within vegetation	1	Abtew and Obeysekera (1995)[a]
	3	Tules and Cattails	No	Standing	Twitchell Island, California	Surface renewal	1	Drexler et al. (2008)
	4	Tules/Bulrush	No	Standing	Bonsall, California	Tank within vegetation	5	Muckel and Blaney (1945)
	5	Cattails	Yes	Standing	Logan, Utah	Bowen ratio	1	Allen (1998)
Seasonal large-stand wetland	6	Tules, Cattails, Wocus Lilly	Yes	Standing to 0.8 m	Upper Klamath NWR, Oregon	Eddy covariance	1	Stannard (2013)
	7	Tules/Bulrush	Yes	Standing to 0.8 m	Upper Klamath NWR, Oregon	Eddy covariance	1	Stannard (2013)
Small-stand wetland	8	Cattails	No	Standing	King Island, California	Tank within vegetation	5	Young and Blaney (1942)
	9	Tules/Bulrush	No	Standing	King Island, California	Tank within vegetation	5	Young and Blaney (1942)
	10	Tules/Bulrush	No	Standing	Victorville, California	Tank within vegetation	5	Young and Blaney (1942)
	11	Cattails	Yes	Standing	Logan, Utah	Bowen Ratio	1	Allen (1998)
	12	Tules/Bulrush	Yes	Standing	Logan, Utah	Bowen Ratio	1	Allen (1998)
Large-stand riparian	13	Willow	No	High	Santa Ana, California	Tank within vegetation	4	Young and Blaney (1942)
	14	Cottonwood	Yes	Variable	Middle Rio Grande, New Mexico	SEB/METRIC	1	Allen et al. (2005b)
	15	R.Olive	Yes	Variable	Middle Rio Grande, New Mexico	SEB/METRIC	1	Allen et al. (2005b)
	16	Willow	Yes	Variable	Middle Rio Grande, New Mexico	SEB/METRIC	1	Allen et al. (2005b)
Smaller-stand riparian (508 m by 120 m)	17	Reed, Willow, Cottonwood	Yes	0.9 m	Central City, Nebraska	Bowen ratio	1	Irmak et al. (2013)
Large-stand perennial grassland	18	Native pasture	Yes	High	Alturas, California	Tank within vegetation	5	MacGillivray (1975)
	19	Native pasture	Yes	High	Shasta County, California	Tank within vegetation	5	MacGillivray (1975)
	20	Irrigated pasture	Yes	0-0.6 m	Carson Valley, Nevada	Eddy covariance	5	Maurer et al. (2006)
	21	Irrigated pasture	Yes	0.6-1.5 m	Carson Valley, Nevada	Bowen ratio	5	Maurer et al. (2006)
	22	Meadow pasture	Yes	0.3-1.2 m	Upper Green River, Wyoming	Tank within vegetation	1	Pochop and Burman (1987)
Large-stand saltbush	23	Saltbush	Minor	.2-.8 m	Owens Valley, California	Stomatal conductance	1	Steinwand et al. (2001)
	24	Saltbush	Minor	0.4-0.7 m	Owens Valley, California	Eddy covariance	2	Duell (1990)
	25	Saltbush	No	1.6 m	Yuma, Arizona	Tank within vegetation	4	McDonald and Hughes (1968)
	26	Saltbush	No	1.1 m	Yuma, Arizona	Tank within vegetation	4	McDonald and Hughes (1968)
Aquatic surface	27	Shallow open water	No		Fort Drum, Florida	Tank	1	Mao et al. (2002)
	28	Shallow open water	No		Delta Region, California	Tank	5	Matthew (1931)
	29	Shallow open water	No		Lake Elsinore, California	Water balance	5	Young (1947)
Rainfed vegetation	30	Oak-grass savanna	No	No	Near Iona, California	Eddy covariance	2	Baldocchi et al. (2004)
	31	Chaparral—old stand	No	N/A	Near Warner Springs, California	Eddy covariance	2	Claudio et al. (2006)
	32	Chaparral—young stand	No	N/A	Near Warner Springs, California	Eddy covariance	2	Ichii et al. (2009)
	33	Chaparral	Yes	N/A	Sierra Ancha Forest, Arizona	Tank within vegetation	5	Rich (1951)

[a]Presented in (Allen 1998).

Table 3. Monthly K_v (for Grass Reference Evapotranspiration) from Monthly Measured ET_v for Different Vegetation Types and Site Conditions

			K_v for grass reference ET_o											
Category	Identifier	Vegetation	January	February	March	April	May	June	July	August	September	October	November	December
Large-stand permanent wetland	1	Cattails	0.51	0.61	0.64	0.73	0.87	0.87	0.78	0.76	0.86	0.78	0.65	0.56
	2	Cattails		0.69	0.73	1.00	1.15	1.15	1.15	1.15	1.09			
	3	Mixed					0.80	0.92	1.02	1.09	1.01	0.90		
	4	Tules/Bulrush	0.36	0.61	0.76	1.09	1.21	1.20	1.21	1.16	1.15	1.33	0.98	0.78
	4	Tules/Bulrush	0.83	0.61	0.94	1.11	1.24	1.24	1.14	1.14	1.12	1.06	0.78	0.97
	4	Tules/Bulrush	0.98	0.77	0.66	0.83	0.99	1.22	1.27	1.37	1.25	1.23	1.20	0.70
	5	Cattails				0.35[a]	0.75	1.27	1.30	1.30	0.73			
		Average	0.67	0.66	0.75	0.85	1.00	1.12	1.12	1.14	1.03	1.06	0.90	0.75
		Non-Florida average	0.73	0.66	0.79	0.84	1.00	1.17	1.19	1.21	1.05	1.13	0.99	0.82
		Used to compute ET_v	0.70	0.70	0.80	1.00	1.05	1.20	1.20	1.20	1.05	1.10	1.00	0.75
Large-stand seasonal wetland	6	Mixed					0.92	1.06	1.10	1.12	0.72	0.80		
	7	Tules/Bulrush					0.97	1.08	1.09	1.20	0.83	0.85		
		Average					0.94	1.07	1.09	1.16	0.78	0.83		
		Used to compute ET_v[b]	0.70	0.70	0.80	1.00	1.05	1.10	1.10	1.15	0.75	0.80	0.80	0.75
Small-stand permanent wetland	8	Cattails	1.28	1.47	1.61	1.18	1.79	1.46	1.87	1.43	1.52	1.70	1.97	1.36
	9	Tules/Bulrush	0.75	1.09	1.80	1.96	2.64	1.85	1.88	1.40	1.59	2.38	1.97	0.60
	10	Tules/Bulrush	0.46	0.56	0.75	0.81	1.08	1.33	1.39	1.42	1.58	1.26	0.89	0.73
	11	Cattails				0.35	0.96	1.76	1.81	1.81	0.97			
	12	Tules/Bulrush				0.35	0.82	1.60	2.03	1.54	0.52			
		Average	1.02	1.28	1.70	0.96	1.55	1.67	1.90	1.54	1.15	2.04	1.97	0.98
		Used to compute ET_v[c]	1.00	1.10	1.50	1.50	1.60	1.70	1.90	1.60	1.50	1.20	1.15	1.00
Large-stand riparian	13	Willow		0.68	0.78	1.05	0.82	0.90	1.13	1.20	1.43	1.21	1.09	0.80
	14	Cottonwood	0.81	0.72	0.61	0.66	0.82	0.94	1.02	1.02	1.07	1.08	0.88	0.89
	15	R.Olive	0.83	0.74	0.64	0.70	0.86	0.99	1.06	1.06	1.12	1.12	0.92	0.92
	16	Willow	0.81	0.67	0.55	0.59	0.74	0.86	0.93	0.95	1.07	1.05	0.86	0.89
		Average	0.82	0.70	0.65	0.75	0.81	0.93	1.03	1.06	1.17	1.11	0.94	0.87
		Used to compute ET_v[d]	0.80	0.80	0.80	0.80	0.90	1.00	1.10	1.20	1.20	1.15	1.00	0.85
Smaller-stand riparian (508 m by 120 m)	17	Reed, Willow, Cottonwood					0.80	1.24	1.40	1.50	1.13	0.91		
	17	Reed, Willow, Cottonwood					1.00	1.69	1.75	1.79	1.97	1.66		
		Average[e]					0.90	1.46	1.57	1.64	1.55	1.28		
Perennial grassland	18	Native Pasture	0.46	0.43	0.51	0.97	0.97	1.13	1.21	1.28	1.20	1.07	0.69	
	19	Native Pasture	0.29	0.29	0.38	0.90	0.95	1.02	1.09	1.12	1.10	0.99	0.93	0.86
	20	Irrigated Pasture	0.82	0.82	0.90	1.23	1.17	0.93	0.99	0.98	1.09	0.86		
	21	Irrigated Pasture	0.75	0.70	0.63	0.76	1.00	0.84	0.77	0.56	0.50	0.48		
	22	Meadow Pasture					0.63	0.92	0.97	0.78	0.62			
		Average	0.58	0.56	0.60	0.96	0.94	0.97	1.01	0.94	0.90	0.85	0.81	0.86
		Used to compute ET_v[f]	0.55	0.55	0.60	0.95	1.00	1.05	1.10	1.15	1.10	1.00	0.85	0.85
Large-stand saltbush	23	Saltbush			0.04	0.13	0.25	0.35	0.34	0.22	0.10	0.03		
	24	Saltbush	0.39	0.45	0.36	0.41	0.54	0.62	0.75	0.82	0.55	0.32	0.62	0.69
	25	Saltbush	0.20	0.27	0.21	0.42	0.49	0.38	0.49	0.46	0.39	0.35	0.50	0.19
	26	Saltbush		0.50	0.40	0.28	0.61	0.46	0.68	0.69	0.56	0.44	0.42	
	26	Saltbush		0.09	0.20	0.43	0.58	0.60	0.70	0.72	0.64	0.46	0.68	0.72
		Average	0.29	0.33	0.24	0.33	0.49	0.48	0.59	0.58	0.45	0.32	0.56	0.53
		Used to compute ET_v	0.30	0.30	0.30	0.35	0.45	0.50	0.60	0.55	0.45	0.35	0.40	0.35

Table 3. (*Continued.*)

Category	Identifier	Vegetation	K_v for grass reference ET_o											
			January	February	March	April	May	June	July	August	September	October	November	December
Aquatic surface	27	Shallow Water	0.68	0.74	0.78	0.77	0.85	0.85	0.76	0.79	0.70	0.79	0.57	0.53
	28	Shallow Water	0.60	0.71	0.75	0.80	1.05	1.17	1.16	1.20	1.27	0.98	0.79	0.60
	29	Shallow Water	0.70	0.72	0.86	0.79	0.97	1.01	1.12	1.09	1.11	1.20	0.95	0.80
		Average	0.66	0.72	0.80	0.79	0.96	1.01	1.02	1.03	1.03	0.99	0.77	0.64
		Used to compute ET_v	0.65	0.70	0.75	0.80	1.05	1.05	1.05	1.05	1.05	1.00	0.80	0.60
Rainfed vegetation[g]	30	Oak-Grass	0.54	0.39	0.49	0.59	0.55	0.30	0.18	0.11	0.07	0.04	0.36	1.06
	31	Grassland	0.66	0.64	0.70	0.64	0.33	0.10	0.03	0.02	0.01	0.01	0.43	0.86
	31	Chaparral	0.31		0.45	0.28	0.29	0.16	0.03	0.07	0.10	0.06	0.14	0.32
	31	Chaparral	0.23	0.10	0.13	0.11	0.05	0.02	0.02	0.02	0.06	0.03	0.11	0.22
	31	Chaparral	0.19	0.32	0.27	0.25	0.30	0.31						
	32	Chaparral—Young			0.12	0.16	0.17	0.06	0.04	0.04	0.05	0.03	0.14	0.35
	32	Chaparral—Young	0.23	0.35	0.35	0.29	0.37	0.40	0.22					
	32	Chaparral—Young	0.98	0.51	0.55	0.42	0.32	0.20	0.15	0.08	0.21	0.38	0.22	0.18
	32	Chaparral—Young	0.44	0.27	0.59	0.46	0.37	0.30	0.23	0.11	0.10	0.09	0.14	0.34
	33	Chaparral	0.30	0.32	0.26	0.34	0.35	0.04	0.21	0.33	0.30	0.21	0.34	0.40
	Est[h]	Vernal pools	0.65	0.70	0.80	1.00	1.05	0.85	0.50	0.15	0.10	0.10	0.25	0.60

[a]Low K_v value was likely due to low evapotranspiration from postdormant vegetation after significant winter freezing, which is typical in Utah. This value was not used to compute ET_v in this study.

[b]The authors noted errors in measured winter ET_v. Data from permanent wetlands was used for December through January K_v values to compute ET_v for seasonal wetlands in this study. It was assumed that the November K_v was the same as the October K_v for seasonal wetlands.

[c]Low K_v values in April and September for the studies in Utah were likely due to colder temperatures later in the spring and earlier in the fall in addition to the significant winter freeze events causing vegetation dormancy. There was a significant amount of variability in ET_v and K_v from January through May and September through December. The K_v values used to compute ET_v for this study were assumed to increase and decrease relatively smoothly from January to July and July to December, respectively.

[d]Greater weight was given to the K_v values developed for the Young and Blaney (1942) study when developing the K_v values used to compute ET_v in this study especially from January through June and November and December. The other studies examined large-stand riparian forests in New Mexico, which experiences more significant winter freeze than the Central Valley of California.

[e]It was assumed that all riparian forests on the predeveloped Valley Floor were large stand. Therefore, there are no K_v values used to compute ET_v for smaller-stand riparian forests.

[f]K_v values used to compute ET_v for this study were based on studies that examined shallow water table depths within 0.6 m from the surface, as previously described.

[g]K_v values for rainfed vegetation, other than those for vernal pools, were not used to compute ET_v. They are provided here as a reference.

[h]Vernal pool K_v used to compute ET_v in this study was estimated assuming open water from December through February, permanent wetlands from March through May, and decreasing K_v from June through August as the vernal pools soil moisture dries. In November, K_v begins to increase as the rainy season begins.

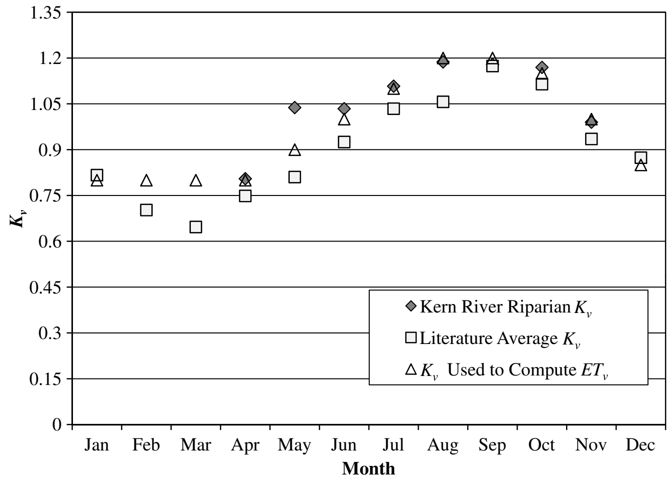

Fig. 3. Comparison of large-stand riparian forest K_v from literature and computed using surface energy balance (METRIC) with LandSAT 5 images for an area along the Kern River near Lake Isabella (March through September 2011 and October and November 2010)

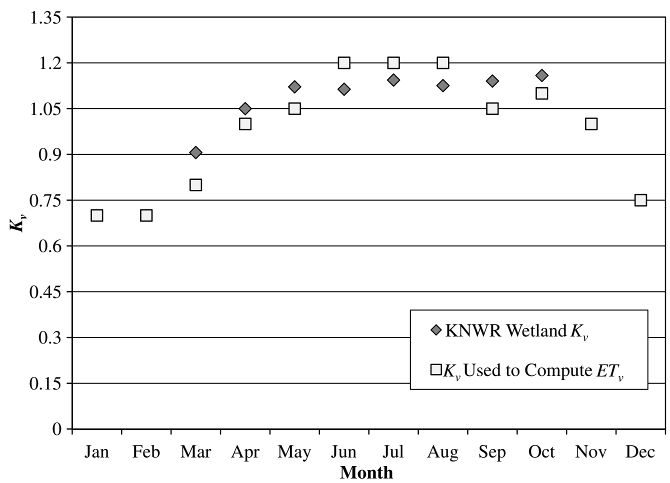

Fig. 4. Comparison of large-stand wetland vegetation K_v from literature and computed using the surface energy balance (METRIC) with LandSAT 5 images for wetlands within Kern National Wildlife Refuge from March 2011 through October 2011

Validation of Large Stand Wetland and Riparian K_v Values

Monthly K_v values for large-stand riparian forest and wetlands from Table 3 were compared to measured values using a surface energy balance (METRIC) with LandSAT 5 for similar vegetation types in California. Figs. 3 and 4 show the comparison of monthly K_v values for riparian forest and wetland vegetation, respectively.

In Figure 3, the average literature K_v values for riparian forest in Table 3 (□) were lower than those measured along the Kern River (◆) from April through August. The majority of the investigations in this category were from the Middle Rio Grande region in New Mexico (Allen et al. 2005b), which experiences winter freezes and thus are not representative of Central Valley riparian forest. Thus, more weight was given to K_v values developed in California, which does not experience winter freezes. The K_v values measured along the Kern River for this comparison were well within the variability seen in Allen et al. (2005b). The K_v used to compute ET_v in this study (Δ) closely matched the values measured at the Kern River site for the April through November analysis period except for May, when the measured K_v was higher.

A comparison of large-stand wetland habitat in Fig. 4 shows the K_v values used in this study (□) were below the measured values at Kern National Wildlife Refuge during the spring and fall (◆). In the summer, the K_v values used in the study were slightly higher than the measured. The lower values measured in the summer months could be due to various issues impacting vegetation health including existing soil conditions such as salinity and alkalinity.

Long-Term Average ET_v of Predevelopment Native Vegetation

The mean annual evapotranspiration (mm/year) from 1922 through 2009 for each vegetation category by Planning Area is shown in Table 4. The coefficient of variation (standard deviation divided by the mean) between years is shown below the annual average ET_v (in italics and parentheses). As expected, the coefficient of variation is similar for vegetation categories where the same set of K_v values were used each year. This would indicate variability due only to ET_o variation. These are not exactly the same for all vegetation types that use the same set of monthly K_v values (e.g., non-water-stressed) due to the fact that the K_v values were not the same each month for different vegetation types. If a K_v is higher in a month that tends to have higher variability in monthly ET_o, the annual coefficient of variation would be slightly higher. An increase in the coefficient of variation, for the vegetation categories that used the daily soil–water balance to determine ET_v, can be attributed to the variability in precipitation as well as ET_o.

The K_v variability within each vegetation category in Table 3 is evident. If one was to select a different set of K_v values to compute ET_v on the predeveloped Valley Floor, the resulting evapotranspiration depth would be different. To examine this, the lowest and highest reported K_v values (on an annual basis) from Table 3 were used to compute the long-term average ET_v over the Valley Floor. The ratios of Valley Floor average ET_v to the Valley Floor average ET_o are shown in Fig. 5. This evaluation was focused on the K_v values that remained constant from year to year (i.e., vegetation with full access to water) since K_v is automatically adjusted on a daily basis for the rainfed vegetation. Therefore, the rainfed vegetation categories that were modeled on a daily basis were not included in Fig. 5. These averages have not been weighted based on the size of the Planning Areas.

Fig. 5 shows that the K_v values used to compute ET_v from Table 4 were between the highest and lowest K_v values, as expected. In some cases, the difference between the ET_v/ET_o for the K_v used in this study and the lowest K_v was greater than the difference with the highest K_v. This can be attributed to several factors. For perennial grasslands, the K_v used in this evaluation was selected for water table depths that did not exceed 0.6 m below ground surface. In other cases, one set of measurements was significantly lower than others (not normally distributed). For example, the K_v used for saltbush was an average; McDonald and Hughes (1968) examined ET_v with the water table reaching 1.6 m in depth below the soil surface (lowest K_v). Therefore, the average ET_v/ET_o was skewed to the higher end because the majority of the studies had water tables closer to the soil surface. Similarly, in other cases such as large-stand riparian, wetlands, and open water evaporation, the studies resulting in the lowest K_v values over the year were outnumbered by higher values, resulting in a higher K_v used to compute ET_v in this study.

Table 4. Results of the Long-Term (1922–2009) Mean Annual Evapotranspiration (mm/year) and Coefficient of Variation between Years (Shown in Parenthesis and Italics) for Each Vegetation Category

Planning area[a]	Rainfed grassland	Perennial grasses	Vernal pools	Large-stand riparian	Large-stand wetland	Small-stand wetland	Seasonal wetland	Foothill hardwood	Valley oak savanna	Saltbush	Chaparral	Aquatic surface
503	391	1,305	755	1,341	1,413	2,043	1,288	451	685	602	295	1,274
	(0.19)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.13)*	*(0.06)*	*(0.03)*	*(0.17)*	*(0.03)*
504[b]	340	1,289	741	1,325	1,395	2,017	1,271	402	640	596	288	1,258
	(0.17)	*(0.04)*	*(0.05)*	*(0.03)*	*(0.04)*	*(0.04)*	*(0.04)*	*(0.11)*	*(0.04)*	*(0.03)*	*(0.17)*	*(0.04)*
506	324	1,350	779	1,387	1,461	2,113	1,331	398	672	623	250	1,317
	(0.21)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.16)*	*(0.06)*	*(0.03)*	*(0.20)*	*(0.03)*
507	352	1,392	803	1,430	1,506	2,179	1,373	427	702	643	269	1,358
	(0.19)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.14)*	*(0.05)*	*(0.03)*	*(0.19)*	*(0.03)*
509	328	1,359	781	1,396	1,469	2,125	1,339	402	679	627	247	1,325
	(0.19)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.14)*	*(0.06)*	*(0.03)*	*(0.20)*	*(0.03)*
510	312	1,368	787	1,404	1,478	2,138	1,347	386	673	631	232	1,333
	(0.20)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.15)*	*(0.06)*	*(0.03)*	*(0.22)*	*(0.03)*
511	348	1,433	820	1,471	1,549	2,241	1,412	426	717	662	264	1,397
	(0.18)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.14)*	*(0.05)*	*(0.03)*	*(0.18)*	*(0.03)*
601	274	1,135	657	1,166	1,227	1,774	1,118	323	560	523	190	1,106
	(0.20)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.04)*	*(0.14)*	*(0.05)*	*(0.03)*	*(0.21)*	*(0.03)*
602	272	1,213	705	1,246	1,312	1,898	1,196	333	590	559	193	1,183
	(0.22)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.16)*	*(0.06)*	*(0.03)*	*(0.24)*	*(0.03)*
603	337	1,427	821	1,464	1,543	2,233	1,407	415	710	659	255	1,391
	(0.20)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.15)*	*(0.06)*	*(0.03)*	*(0.21)*	*(0.03)*
606	240	1,356	786	1,392	1,466	2,121	1,337	312	625	626	174	1,322
	(0.26)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.19)*	*(0.07)*	*(0.03)*	*(0.29)*	*(0.03)*
607	293	1,402	812	1,438	1,516	2,195	1,383	368	673	647	216	1,367
	(0.23)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.18)*	*(0.07)*	*(0.03)*	*(0.26)*	*(0.03)*
608	289	1,446	841	1,482	1,564	2,264	1,427	366	686	667	215	1,410
	(0.24)	*(0.03)*	*(0.04)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.03)*	*(0.19)*	*(0.07)*	*(0.03)*	*(0.28)*	*(0.03)*
609	290	1,521	879	1,558	1,644	2,380	1,499	372	715	702	220	1,482
	(0.25)	*(0.04)*	*(0.04)*	*(0.03)*	*(0.04)*	*(0.04)*	*(0.04)*	*(0.20)*	*(0.07)*	*(0.04)*	*(0.28)*	*(0.04)*

[a]Small portions of additional planning areas fell within the Valley Floor and are not shown in this table. Since the majority of those planning areas fell outside of the Valley Floor, the average ET_o and precipitation would not have been representative of the areas within our investigation boundaries. As a surrogate, ET_v from a neighboring planning area was used. Planning Areas 502, 505, 508, 604, and 610 were assumed to have the same depth of ET_v as 503, 509, 511, 510, and 609, respectively.

[b]Grass reference evapotranspiration and precipitation for Detailed Analysis Unit (DAU) 143 and 144 was used in place of Planning Area 504 since a significant portion of 504 lies outside of the Central Valley Floor. DAU 143 and 144 cover the Valley Floor portion of Planning Area 504.

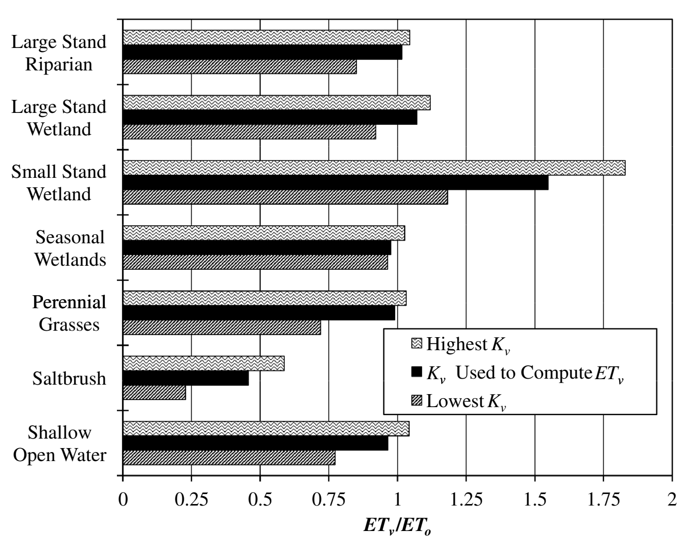

Fig. 5. Comparison of average annual ET_v/ET_o using the highest and lowest K_v to the K_v used to compute ET_v in this study for each vegetation category. The large-stand wetland habitat only considers non-Florida studies from Table 3

The evaporation from shallow open water using the highest K_v matches closely, on an annual basis, with the standard value of 1.05 (grass reference based) for this category reported by Allen et al. (1998). The ET_v/ET_o for K_v used to compute the evaporation from shallow open water was closer to 0.95, which indicates that there may be a slight underestimation in evaporation. However, in some cases the open water (termed "aquatic" in the land use classifications) could be deeper than the 2 m reported for the high ET_v/ET_o; therefore, the lower K_v value is justified.

The most significant variation in ET_v/ET_o was for small-stand wetlands. This also has the highest ratio because of the clothesline effect discussed previously. It is not unexpected that there would be a significant difference in the ET_v/ET_o for this vegetation category since variable stand size will influence ET_v due to the ability of air to move through the vegetation.

It is important to note that the annual ET_v/ET_o ratios shown in Fig. 5 are not transferable. Because the K_v varies by month, the annual ET_v/ET_o ratio will vary in regions that have higher or lower differences between winter and summer ET_o than in the Central Valley of California. Monthly K_v values are generally transferable to other regions as long as vegetative conditions are similar (i.e., no water stress, similar water table depths, similar vegetation characteristics, etc.).

Conclusion

Grass reference evapotranspiration-based vegetation coefficients, K_v, for a variety of natural vegetation categories reported to exist in the Central Valley of California prior to its development have been computed. Two methods were developed to estimate K_v, depending upon the available water supply. For nonstressed vegetation, K_v was estimated assuming a full year-round water supply (e.g., root systems that accessed groundwater). This method was used for permanent wetlands, riparian forest, perennial grassland, saltbush, and shallow open water. For stressed vegetation that relied on available soil moisture, the vegetation coefficients were reduced using a root-zone water balance or estimated based on vegetation characteristics to reduce ET_v below the potential rate due to lack of soil moisture. This method was used for foothill hardwoods, valley oak savanna, rainfed grasslands, vernal pools, seasonal grassland, and chaparral.

The resulting K_v values can be extrapolated to other climates and geographic areas by incorporating locally measured weather parameters to compute the ASCE standardized grass reference ET_o (or equivalent) using Eq. (2). These K_v values are being used by the authors as input to water balances and hydraulic models to estimate natural flows from the Valley Floor (Fig. 1). The K_v values reported here could also be used to estimate evapotranspiration demands in other applications including: to evaluate the impact of climate change on water resources; to determine the effect of vegetation harvesting on stream flows; and to estimate water supplies for habitat restoration activities, just to name a few. As restoration of native vegetation and habitat continue, planners need to be able to estimate water demands from this vegetation. Planners, managers, and policy makers should be aware of the implications of increased water demands associated with potential restoration efforts in areas that may already experience water shortages. Having accurate water consumption estimates can provide insights into which type of vegetation may be most appropriate for restoration efforts. The methods developed in this work could also be extended to other types of vegetation.

This study also highlighted the importance of data made available through networks maintained by local researchers around the world such as FLUXNET. This type of information can be a great benefit to professionals as well as researchers, provided that the data are accurate, well-maintained, and presented in a useable format. Increasing this network of evapotranspiration measurement will be of considerable benefit into the future.

This work highlights areas requiring additional research. This includes: (1) field measurements of evapotranspiration of vernal pools, valley oak savannas, and woodlands, similar to the work reported by Baldocchi et al. (2004) and Miller et al. (2010); (2) validation of small-scale measurements (such as most summarized in Table 3) using surface-energy balance methods with remote-sensing data such as LandSAT; (3) field evaluations of evapotranspiration from similar vegetation but with variable density (riparian and hardwood forests) to develop relationships between density and evapotranspiration; and (4) additional measurements of open water evaporation under variable depths and climate conditions to improve estimates using remote sensing data.

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