ENERGY BALANCE EVAPOTRANSPIRATION ESTIMATES OVER TIME FOR THE SOUTHERN SAN JOAQUIN VALLEY

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ABSTRACT

Water resource planning requires knowledge of changes in consumptive water use by crops and natural vegetation over time. Remote sensing offers the promise of a consistent methodology to obtain consumptive use and other water resource data over large areas at regular intervals. SEBAL® (Surface Energy Balance Algorithm for Land) uses data gathered by satellite-based sensors to compute evapotranspiration (ET) and biomass production. ET is computed as the residual of the energy balance at the Earth's surface.

Growing season ET (April through October) was computed for 2002 and 2005 using SEBAL for the area covered by Landsat Path/Row 42/35 of the Southern San Joaquin Valley in California. Growing season ET for this area, selected smaller areas within it and selected crops, where reliable cropping records were available, was compared to annual and seasonal precipitation.

INTRODUCTION

Hanson (1991) estimated that about 67 percent of the precipitation falling on the United States, returns to the atmosphere through evapotranspiration (ET). After precipitation, ET is the most significant term in the water cycle. ET varies according to weather and water availability conditions in discernable regional and seasonal patterns. Quantifying ET is important to develop a thorough understanding of the hydrologic process and knowledge about the spatial and temporal rates of water movement. This understanding and knowledge is critically important for water resources planning and management. Matyac (2005) also stresses that improving our understanding of evapotranspiration is the key to improved water management. Further indicative of the need for evapotranspiration data, Hutson, et. al (2005) asserts that many individuals and organizations require reliable water use data to support research and policy decisions.

The objective of this paper is to further the knowledge and understanding of the spatial and temporal variations in ET by examining regional and seasonal patterns in ET.

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Regional ET computations are extremely data intensive and time consuming. To obtain regional ET estimates in a convenient and cost-effective manner, ET was computed as the residue of a surface energy balance utilizing satellite-based remotely sensed data together with ground-based weather station data. The SEBAL® (Surface Energy Balance Algorithm for Land) model, the most extensively used and validated surface energy balance model, was used to estimate ET for this analysis.

SEBAL THEORY

The sun's net radiation reaching the Earth's surface balances with soil, sensible, and latent heat fluxes according to conservation of energy at the Earth's surface. Taking into account the latent heat of vaporization and density of water, latent heat flux can be converted into ET flux (volume of water per unit area per unit time). ET flux can be estimated as a closure term from estimates of the remaining fluxes (Equation 1).

$$ET_a = \frac{1}{\lambda \rho_w}\left[R_n - (G + H)\right] \qquad [1]$$

where λ is the latent heat of vaporization of water, ρ_w is the density of water, ET_a is the actual crop ET, R_n is the net radiation flux at the Earth's surface, G is the soil heat flux, and H is the sensible heat flux.

The SEBAL model estimates actual crop ET (ET_a) from the energy balance by applying radiative, aerodynamic, and energy balance physics in 25 computational steps. Multispectral satellite imagery with a thermal band is used to calculate ET_a at the pixel-scale. Required input data include radiances in the visible, near infrared, and thermal infrared regions sensed by earth observing satellites; spatially interpolated ground based weather data from agricultural or other weather stations; and land use data describing general vegetation types, when available. Knowledge of specific crop types is not needed to solve the energy balance. SEBAL avoids the need for absolute calibration of the surface temperature of each pixel by utilizing a unique internal calibration for each image to estimate sensible heat flux between the surface and the atmosphere. A detailed explanation of the algorithm is provided by Bastiaanssen et al. (1998). Continuing refinements to the model include the use of digital elevation models for radiation balances in mountains (Allen et al., 2001), an improved albedo function (Tasumi et al., 2005), advection corrections, an improved soil heat flux relation, and an improved relation for surface roughness for momentum transport.

Recent validations of SEBAL, summarized by Bastiaanssen et al. (2005), have shown seasonal ET_a results generally fall within five percent of seasonal ET_a determined from reliable ground-based measurements. ET_a results from the 2002 SEBAL analysis used in this paper were compared to lysimeter measurements on alfalfa and peaches (Cassel, 2006) and surface renewal measurements on tomatoes (Roberson, 2006). In each comparison, the difference between the SEBAL ET_a and the ground-based estimates was five percent or less (Figure 1).

Input Data

A combination of satellite, ground based-meteorological, topographic, and land cover classification data are utilized to quantify spatially distributed ET_a. For this study, these datasets were obtained from the U.S. Geological Survey (USGS) and CIMIS. These data are described in greater detail in the following paragraphs.

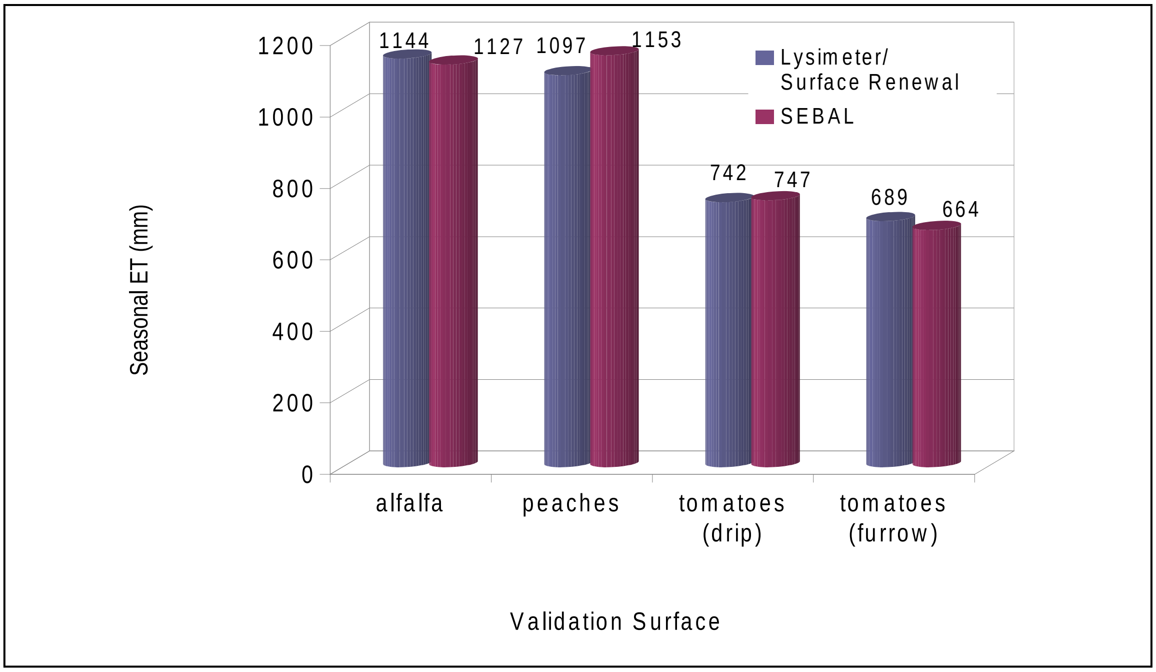

Figure 1. Seasonal SEBAL ET_a Results Compared to Lysimeter and Surface Renewal Results

Satellite Images. Seven Landsat 7 ETM and seven Landsat 5TM multispectral images encompassing the period from April to October for Path 35/Row 42 were obtained from USGS for 2002 and 2005, respectively (Table 1). Cloud-free images were selected to achieve a temporal frequency of one image per month for each growing season.

Table 1. SEBAL Datasets Used for Growing Season ET Analysis

Region	Satellite Platform	Row/ Path	Thermal Resolution	Image Dates	Images
Southern San Joaquin Valley (2002 season)	Landsat 7 ETM	42/35	60 m	4/12, 5/14, 6/15, 7/17, 8/2, 9/3, 10/5/2002	7
Southern San Joaquin Valley (2005 season)	Landsat 5	42/35	120 m	4/12, 5/14, 6/15, 7/17, 8/18, 9/19, 10/5/2005	7

Meteorological Data. Measurements of incoming solar radiation (R_s), relative humidity (RH), air temperature (T_a) and wind speed (WS) were available as hourly averages for the time of image acquisition. Daily (average for the image date), and period (average for the days represented by an individual image) measurements were also available. Twenty-three CIMIS stations falling within or on the edge of the study area were used to develop a weather surface prior to the SEBAL image processing. Weather data were quality checked according to the guidelines specified in Appendix-D of the ASCE Task Committee Report on the Standardized Reference Evapotranspiration Equation (Allen et al., 2005).

Weather data were spatially interpolated using MeteoLook, a collection of algorithms developed to interpolate point weather observations based on the surface and terrain characteristics coupled with physically-based models (Voogt, M.P., 2006). Processes that influence surface weather conditions such as elevation, surface roughness, albedo, incoming radiation, land wetness, and distance to water bodies are represented in MeteoLook. This improved spatial distribution of weather data improves the ability to estimate surface conditions influencing the surface energy balance and the ability to estimate spatially distributed reference ET.

Landuse Data and Digital Elevation Model (DEM). A generalized landuse map from the National Land Cover Dataset (NLCD) for 1992 was obtained from USGS and combined with available land use data from the California Department of Water Resources (CDWR) and Kern County to estimate obstacle heights for different surfaces within the study area. These data have been developed by various means including analysis of Landsat images along with inspection of aerial photographs and ground-surveys.

A DEM of one arc-second resolution (approximately 30 meter resolution) was obtained from USGS and was used in SEBAL to incorporate the effects of the slope, aspect and elevation into the energy balance.

RAINFALL AND REFERENCE ET

As general indicators of surface water supply availability, the California Department of Water Resources (CDWR) defines San Joaquin River Basin water years types based on the measured unimpaired runoff of four rivers. The four rivers are Stanislaus River inflow to New Melones, Tuolumne River inflow to New Don Pedro, Merced River inflow to New Exchequer and San Joaquin River inflow to Millerton. The water year type was below normal and wet for 2002 and 2005, respectively. The precipitation during the water year in 2002 was less than half the precipitation in 2005 (Table 2). The CIMIS reference ET ranged from four to nine percent greater for the April through October growing season and the water year (October through September), respectively for 2002 compared to 2005. These data indicate that 2002 was a year with less available soil moisture and a greater ET demand compared to 2005.

Table 2. Rainfall and Reference ET (Average of Selected CIMIS Stations in the Landsat Scene) in 2002 and 2005

Time Period	Precipitation (in)		Reference ET (in)	
	2002	2005	2002	2005
Water Year (Oct - Sept)	6.1	14.0	58.90	53.96
Annual (Jan - Dec)	6.1	11.0	58.80	55.24
April - Oct	1.0	2.5	48.03	46.04

ET COMPARISONS

The Landsat scene encompasses all of Kings County and parts of Kern, Tulare and Fresno Counties (Figure 2). The mean ET across the agricultural area of the Landsat image was about four inches higher in 2002 compared to 2005 (Table 3). The standard deviation was also higher indicating greater variation in ET across the agricultural areas of the image. Although all of the agricultural area requires irrigation to be productive, every year some area is not irrigated. These non-irrigated areas would be expected to have ET roughly equal to or slightly less than the precipitation in both images, on average. On the other hand, the irrigated areas will have close to the crop water requirements in both images unless water availability becomes a factor. Given the greater rainfall in 2005, the difference between the irrigated areas and the non-irrigated areas is greater in the 2002 image leading to a greater variation in ET as indicated by the greater standard deviation. The portion of Tulare County is on the eastern side of the San

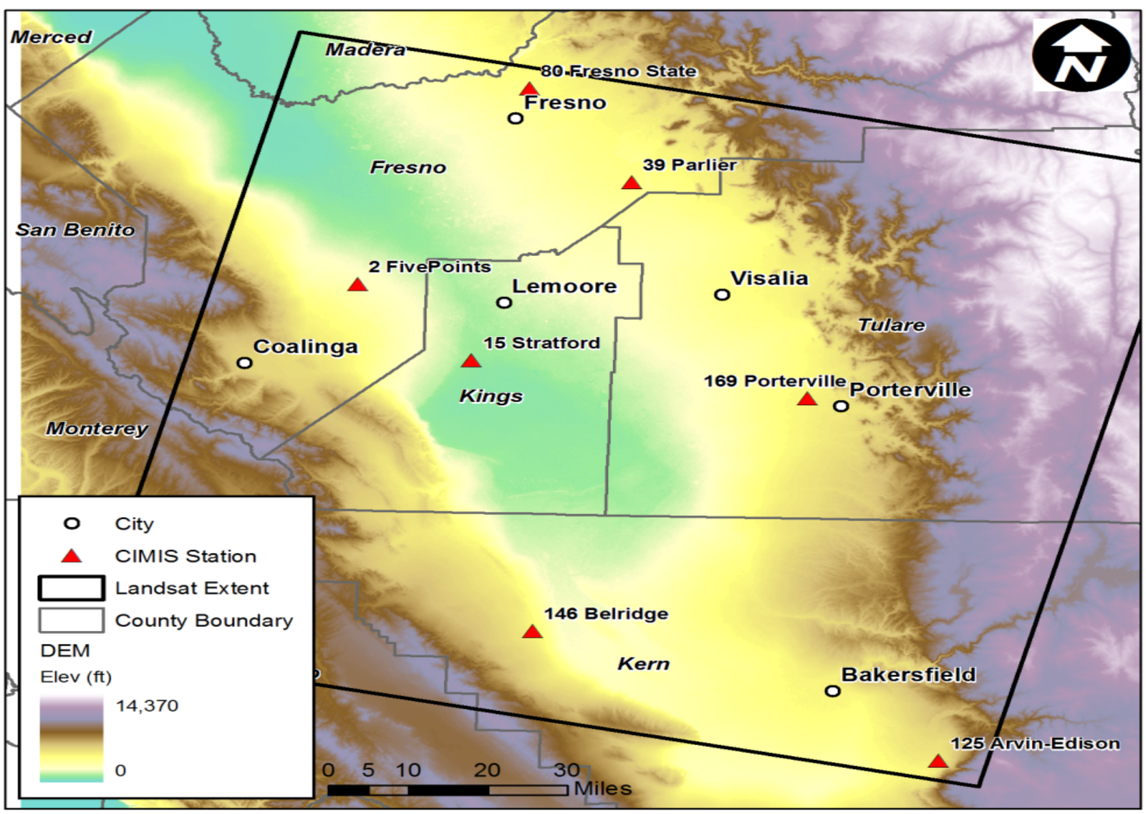

Figure 2. Southern San Joaquin Counties Encompassed within the Landsat Scene

Table 3. Seasonal (April through October) ET Statistics for the Agricultural Area within the Landsat Scene

Region	Area (ac)	Mean ET (in)		Difference in Mean ET (in)	Std. Dev. (in)	
		2002	2005	2002 & 2005	2002	2005
Landsat Image	2,889,645	31.39	27.17	4.22	13.96	11.66
Kings County	630,642	29.93	25.52	4.41	14.56	10.83
Part of Kern County	757,299	28.06	27.34	0.72	15.11	13.62
Part of Tulare County	687,967	36.99	31.18	5.81	12.02	9.61
Part of Fresno County	736,211	31.46	25.05	6.41	11.84	10.87

Joaquin Valley and has the highest average ET. Kings County, west of Tulare County on the western side of the San Joaquin Valley has much lower ET. The portion of Kern County has the lowest ET in the image.

Agricultural areas not irrigated during the study period are expected to have ET less than the total precipitation (Table 4). Using this criteria to identify land that was not irrigated in 2002 and 2005 indicated that non-irrigated area in 2005 was about 148,000 acres (five percent) more than in 2002. Most of this area was located on the west side of the Valley.

Table 4. Agricultural Area with ET Less Than Precipitation

Region	Area (ac)	Area in 2002 with ET < 6 in (ac)	Area in 2005 with ET < 11 in (ac)	Area in 2002 with ET < 6 in (%)	Area in 2005 with ET < 11 in (%)
Landsat Image	2,889,645	174,813	322,892	6.05	11.18
Kings County	630,642	57,248	79,388	9.08	12.59
Part of Kern County	757,299	71,045	115,987	9.38	15.32
Part of Tulare County	687,967	2,013	17,978	0.29	2.61
Part of Fresno County	736,211	30,848	94,789	4.19	12.88

Field boundaries and crops were obtained for Kern County from the County Agricultural Commissioner's office for 2002. The top five crops produced in terms of acreage were almonds on about 132,000 acres, followed by cotton on 92,000 acres, alfalfa and alfalfa mixtures on 75,000 acres, pistachios on about 54,000 acres and wheat on about 51,000 acres (Table 5). Alfalfa and alfalfa mixtures had the highest April through October average ET at just over 39 inches followed by almonds at about 34 inches. All crops, except alfalfa which was about the same, had slightly higher average ET in 2002 compared to 2005.

Given the ET_a computed by the SEBAL model, a "lumped" crop coefficient can be computed as ET_a divided by the reference ET. The SEBAL model computes a reference ET for each pixel in the image based on the FAO 56 (reference) Penman-Montieth equation and spatially interpolated weather parameters. This "lumped" crop coefficient combines the pristine crop coefficient (K_c) and the stress coefficient (K_s) into a single

Table 5. Seasonal (April – October) ET for the Five Crops Covering the Most Area in Kern County

Top Five Crops by Area in Kern County	Area (ac)	Mean ET (in)		Std. Dev. ET (in)	
		2002	2005	2002	2005
Almonds	131,967	34.58	33.97	12.89	16.29
Cotton	92,018	35.71	32.49	11.12	6.99
Alfalfa & Alfalfa mixtures	75,155	39.16	39.17	12.66	8.56
Pistachios	54,124	25.73	25.31	14.10	15.45
Wheat	50,825	28.52	26.24	14.97	9.64

term (K_{cs}). The mean seasonal K_{cs} for almonds, cotton and pistachios is essentially the same for both 2002 and 2005, indicating that the level of average water stress was about the same for the two years. Conversely, the mean K_{cs} is 14 and 9 percent lower for alfalfa and alfalfa mixtures and wheat, respectively in 2002. This represents increased water stress on alfalfa and wheat crops in 2002, the dry year.

Four alfalfa and four almond fields were selected as an example of intra-field, inter-field and inter-year ET (Figures 3, 4 and 5). At the time the aerial photo (Figure 3) was taken in June 2005, it appears that the two north alfalfa fields were fallow. However, the 2002 ET results indicate that these two fields had more ET than the south fields in 2002 (Figure 4).

Figure 3. Aerial Photo of Selected Alfalfa and Almond Fields near Wasco, California

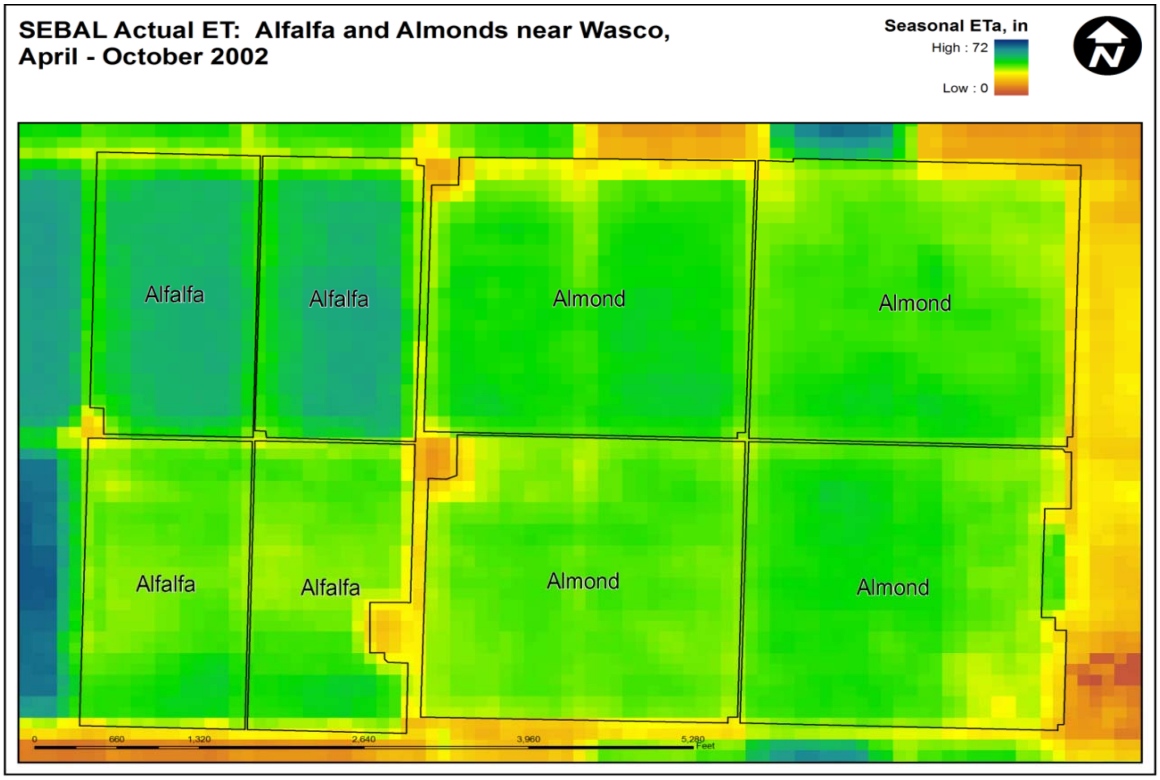

Figure 4. ET of Selected Alfalfa and Almond Fields near Wasco, California

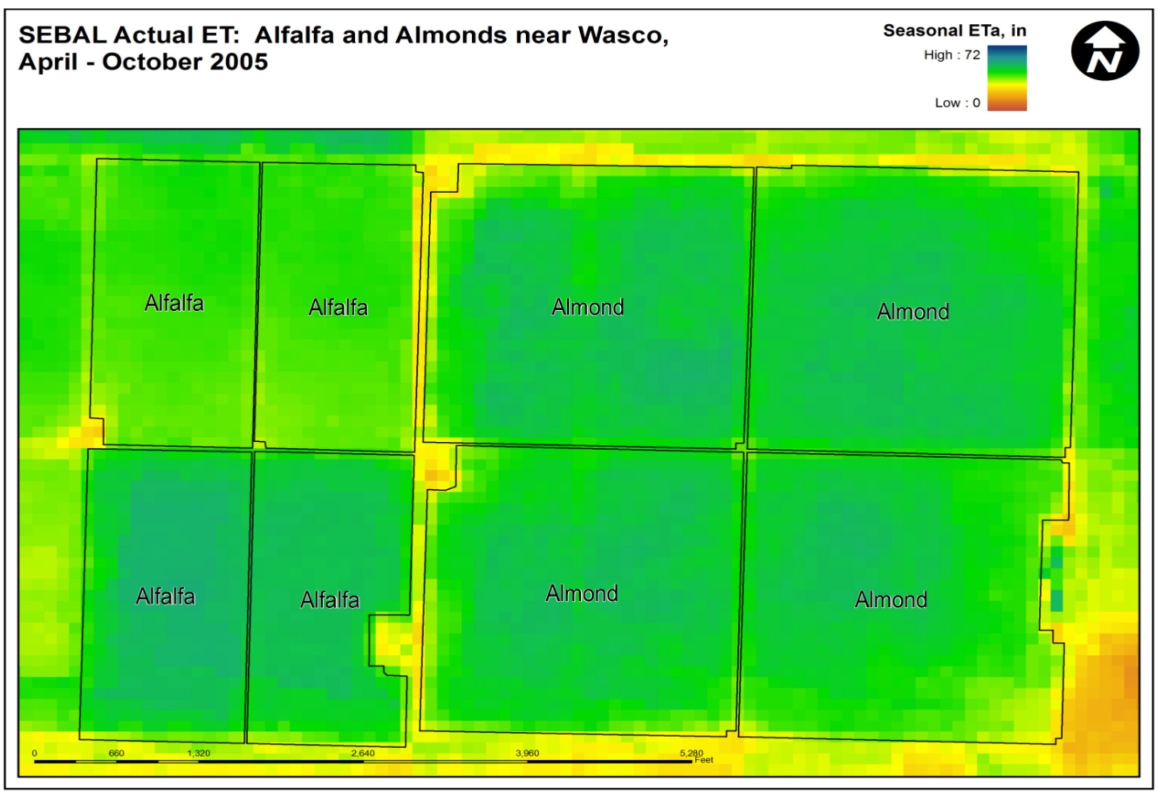

Figure 5. ET of Selected Alfalfa and Almond Fields near Wasco, California

However, the 2005 ET results (Figure 5) show greater ET in the south two alfalfa fields as one would expect based on the aerial photo. All four almond fields consumed more water in 2005 than in 2002.

COMPARISONS TO OTHER REGIONAL WATER USE ESTIMATES

The USGS compiles and publishes nation-wide estimates of water use every five years. For the 2000 report, the most recent available, water use was defined as water withdrawals (Hutson, et al., 2005). Water withdrawal is defined as "water removed from the ground or diverted from a surface-water source for use." The report acknowledges that a portion of these water withdrawals is "released" from the point of use and thus becomes available for further use.

In 2000, irrigation water withdrawals for irrigation in Kings County were estimated to total 1.66 million acre-feet (3.25 acre-feet per acre) (Hutson, et al., 2005). The CDWR estimates a total crop ET of 1.31 million acre-feet (2.56 acre-feet per acre) (CDWR, 2009). The SEBAL model results estimate a total crop ET of 1.57 and 1.34 million acre-feet for the April through October growing season in 2002 and 2005, respectively.

CONCLUSIONS

Total ET in 2002 and 2005, respectively dry and wet years with regard to surface water supplies, was essentially the same for agricultural lands in the southern San Joaquin Valley. For the year 2002, the increased evaporative demand, as indicated by the higher reference ET, and the lower available soil moisture resulted in increased water stress on lower value crops. This increased water stress was indicated by the lower seasonal K_{cs} as compared to the 2005 year. Accurate quantification of ET is extremely important because water consumed as ET is not available for reuse. The SEBAL model provides extensive data sets quantifying spatial and temporal patterns in ET, greatly increasing knowledge and understanding of the consumptive use of water to support more informed water resources planning and management

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