RICE EVAPOTRANSPIRATION ESTIMATES AND CROP COEFFICIENTS IN GLENN-COLUSA IRRIGATION DISTRICT, SACRAMENTO VALLEY, CALIFORNIA

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ABSTRACT

The Surface Energy Balance Algorithm for Land (SEBAL®) was applied to estimate remotely sensed evapotranspiration (ET) in the Sacramento Valley (California) for the 2001 crop growing season. The ET estimated by SEBAL was compared to ground-based Surface Renewal ET estimates for a rice field near Nicolaus at daily, monthly and seasonal time scales. For June through September (the period of coincident ET estimates), the SEBAL ET estimate of 33.0 inches was 5 percent more than the Surface Renewal estimate of 31.4 inches. The April 1 through September 30 rice ET estimated by SEBAL was 42.9 inches for this field.

Additionally, district-wide rice crop coefficients were developed for Glenn-Colusa Irrigation District (GCID). GCID is the largest irrigation district in the Sacramento Valley, serving 138,800 irrigated acres. The primary crop grown in GCID is rice. The SEBAL ET results for rice fields in GCID were used to compute average crop coefficient values for each image date and for the months of April through September for the 2001 growing season. The crop coefficients developed from remotely sensed ET were compared to published crop coefficients for rice ET. For the 2,060 rice fields identified for the crop coefficient analysis, the average full April 1 through September 30 rice ET estimate by SEBAL was 39.0 inches.

INTRODUCTION

Satellite based remote sensing techniques have been employed to monitor vegetative growth and to estimate evapotranspiration (ET) for well over two decades (Seguin et. al., 1983, 1989 & 1991). Remote sensing techniques are useful for the estimation of crop ET on a regional scale, particularly when minimal ground-based data such as cropping records are available. Additionally, with the availability of well over twenty years of Landsat imagery, ET can be estimated retrospectively over a range of water supply and cropping conditions. This information can provide useful insights into changes in

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consumptive use relative to urbanization and other factors and aids in modeling of future changes in demands for surface and ground water supplies.

One of the earliest and most thoroughly validated models in the field of remote sensing for estimation of ET is the Surface Energy Balance Algorithm for Land (SEBAL®). SEBAL is a remote sensing based model which applies energy balance physics to estimate actual ET (ET_a) using satellite imagery and ground-based weather data (Bastiaanssen et al.,1998a and 1998b). SEBAL® has been used widely to estimate ET at field and regional scales for multiple crops and land use types (Bastiaanssen, et. al., 2005). Recently, SEBAL has been also used to generate near-real time weekly ET, crop coefficient, and biomass production estimates for the California's Central Valley (Lal, et. al., 2010). SEBAL ET estimates have been compared to and validated by reliable ground-based ET estimates from various methods including eddy covariance, lysimeter, water balance, and surface renewal techniques. These validations have shown that estimates of ET from SEBAL, when applied by an experienced energy balance specialist, typically agree within 5 percent of reliable ground-based ET estimates over the course of a growing season (Bastiaanssen, et. al., 2005).

This paper presents results from an application of SEBAL to estimate ET in the Sacramento Valley of California for the 2001 crop growing season. First, ET estimates obtained from SEBAL for a rice field in the Valley are compared with concurrent ground-based ET estimates from the Surface Renewal (SR) method. Then, crop coefficients developed from the 2001 SEBAL results for approximately 90,000 acres of rice grown in the Glenn-Colusa Irrigation District (GCID) are presented and compared with published values. GCID is the Sacramento Valley's largest agricultural water purveyor, serving a total of 138,800 irrigated acres. Rice in GCID is typically planted in early May and harvested in late September, representing an irrigation season of approximately 150 days.

METHODOLOGY

SEBAL Model

A detailed explanation of the SEBAL model, its applications and validations can be found in Bastiaanssen et al. (2005). A brief conceptual summary is provided herein. SEBAL is a remote sensing model that applies the energy balance at the Earth's surface to estimate actual ET. The energy balance at the Earth's surface is described by:

$$R_n = H + G + LE \tag{1}$$

Where R_n is the net solar radiation available to drive ET, G is the soil heat flux, H is the sensible heat flux, and LE is the latent heat flux.

In SEBAL, the net radiation flux (R_n) is estimated from incoming solar radiation, after accounting for various gains and losses in short and long wave radiation in the atmosphere and at the Earth's surface. The soil heat flux is estimated as a function of R_n, surface temperature and the Normalized Difference Vegetation Index (NDVI), which provides a relative measure of the amount of vegetation cover present. The sensible heat flux (H) in SEBAL is estimated using a unique 'internal calibration' procedure. H is first estimated at two extremes and is then scaled between these two extreme temperatures for all pixels within the satellite image. For accurate results, the two extremes, termed "hot" and "cold" pixels, must be selected by an experienced energy balance specialist.

The latent heat flux (LE), which is the amount of R_n consumed to vaporize available water as ET, is estimated as a residual of the energy balance based on the principle that energy can neither be created nor destroyed. The latent heat flux is converted into an equivalent depth of water consumed during the process of evapotranspiration using the following relation:

$$ET_a = \frac{1}{\lambda \rho_w}\left[R_n - (G + H)\right], \tag{2}$$

where ET_a is the actual evapotranspiration at the instant of satellite overpass, λ is the latent heat of vaporization of water, and ρ_w is the density of water.

Instantaneous ET_a is extrapolated to daily and longer periods by combining spatially distributed weather conditions from ground-based meteorological stations, evaporative fraction ($\Lambda = \frac{LE}{R_n - G}$), and net available energy ($R_n - G$).

SEBAL Application: Sacramento Valley, CA

A total of eight Landsat 7 ETM+ images (Path 44, Row 33) along with meteorological and ancillary data were processed using SEBAL to estimate remotely sensed actual ET in the Sacramento Valley for the 2001 irrigation season. ET_a from SEBAL was obtained at three time scales: (1) for the day of the Landsat image, (2) for the monthly or semi-monthly period represented by an individual image, and (3) for the accumulated irrigation season from April 1 to September 30, 2001. The specific image dates and periods represented by the individual images are provided in Table 1.

Table 1. Satellite Image Dates for 2001 and Periods Represented

Image Date	Period	No. of Days
April 23rd	April 1 – 30	30
May 25th	May 1 – 31	31
June 10th	June 1 – 30	30
July 12th	July 1 – 15	15
July 28th	July 16 – 31	16
August 13th	August 1 –15	15
August 29th	August 16 – 31	16
September 14th	September 1 – 30	30

Surface Renewal Estimate of Rice Evapotranspiration

A detailed description of the surface renewal techniques of estimating ET can be found in Paw et al. (1995) and Snyder et al. (1996, 1997). Briefly, SR estimates sensible heat flux from high frequency air temperature measurements taken at known heights within the canopy using exposed and naturally-ventilated fine wired thermocouples. The SR methodology is based on the theory that heat transfer takes place when an air parcel from the above comes into contact with the canopy and following the heat exchange, it gets replaced or ‘renewed’ by another air parcel. The increase or decrease in the temperature of these individual air parcels during the heat exchange with the canopy provides the measure of sensible heat transferred to or from the canopy. The sensible heat flux estimates from Surface Renewal are then used with the net radiation and soil heat flux estimates to calculate the latent heat flux or actual ET through closure of the energy balance. The rice field studied is located approximately 3.5 miles southeast of Nicolaus in Sutter County, California and is approximately 140 acres in size (Figure 1).

SEBAL and Surface Renewal ET Comparison

ET estimated by SEBAL was compared to the ET estimated by the SR method for the rice field near Nicolaus at daily, monthly or semi-monthly, and seasonal time scales for the 2001 growing season.

SEBAL ET estimates for the field, were determined for a polygon that was digitized using high resolution imagery representing the approximate boundary of the field, and buffered inward by 30 meters to avoid the potential effects of satellite image pixels overlapping the field boundary. Mean SEBAL ET values were extracted from the rice field at daily, period and seasonal time scales to compare with concurrent SR ET estimates.

Remotely Sensed Lumped Crop Coefficeints (K_{cs})

Remotely sensed lumped crop coefficients (K_{cs}) were developed for the rice grown in Glenn-Colusa Irrigation District (GCID). The lumped crop coefficient is equivalent to a standard published crop coefficient, such as the single crop coefficient (K_c) presented in FAO Irrigation and Drainage Paper No. 56, multiplied by a stress coefficient (K_s), which incorporates various reductions in ET that occur under actual growing conditions.
The remotely sensed crop coefficients for rice grown within GCID were calculated as follows (Equation 3):

$$K_{cs} = \frac{ET_a}{ET_o}, \qquad (3)$$

where ET_o is the reference ET, and ET_a is the actual ET estimated by SEBAL. The reference ET (ET_o) estimates were obtained from quality controlled weather data from a California Irrigation Management Information System (CIMIS) station at Orland.

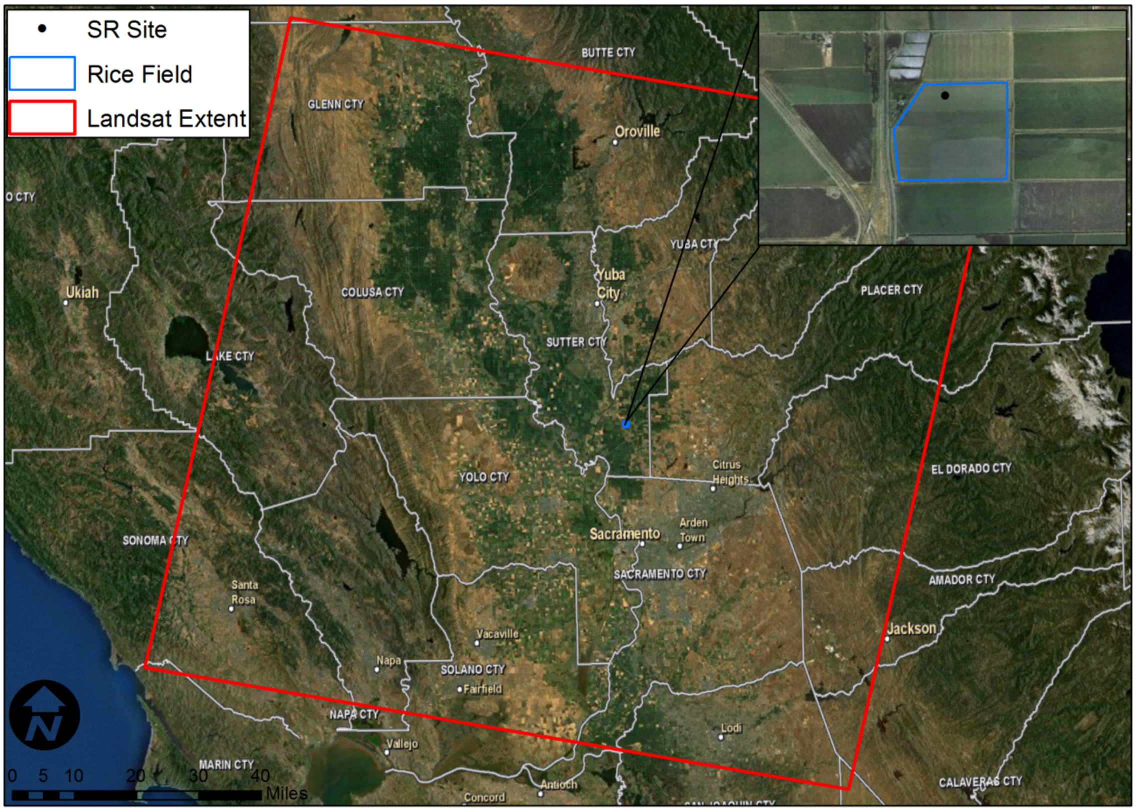

Figure 1. Landsat Image Extent (Path 44, Row 33) and Location of Rice Field for Surface Renewal Comparison

The rice fields within GCID were identified using a GIS coverage of field polygons developed by GCID and linked to the District's 2001 tabular cropping data. In total, 2,060 rice fields encompassing 87,828 acres were identified based on the GCID cropping data.

Prior to extracting ET_a for individual rice fields, the field boundaries were buffered inward by 30 meters to reduce the risk of ET_a for a given field being influenced by ET_a from the neighboring surfaces outside of the field due to satellite image pixels overlapping the field boundary.

Daily SEBAL ET_a estimates for each field were divided by reference ET (ET_o) from CIMIS on a field by field basis to yield a lumped crop coefficient, K_{cs} on the images dates. Additionally, average monthly rice K_{cs} values for the 2001 irrigation season were calculated based on monthly SEBAL ET estimates and cumulative ET_o for the respective months.

RESULTS AND DISCUSSION

SEBAL and Surface Renewal ET Comparison

ET_a estimates for the Nicolaus rice field from SR and SEBAL were compared for the full period of coincident data (May 16 through September 30, 2001), individual satellite image dates, and for periods represented by each satellite image. Daily SR ET data were available from May 16 to September 30, 2001. Daily ET estimates from SEBAL were available for individual satellite overpass dates for which SEBAL was applied as well as for months represented by each image.

The SR estimate of rice ET for June 1 through September 30, 2001 was 798 mm (31.4 inches) compared to 838 mm (33.0 inches) estimated by SEBAL (Figure 2). This 5 percent difference in ET between SEBAL and SR method is similar to differences seen for seasonal ET estimates in other SEBAL applications with reliable ground-based data (Bastiaanssen et al., 2005). This close agreement is important as many uses of ET estimates focus primarily on total seasonal volume.

The SEBAL daily ET_a estimates agree closely with the SR estimates for the main part of the irrigation season (Figure 3). The SEBAL daily ETa estimate for the May 25 image date is 10 to 15 percent less than the SR estimate. The SR equipment started collecting data on May 16th; thus, SR data is not available for comparison to the April 23 image date.

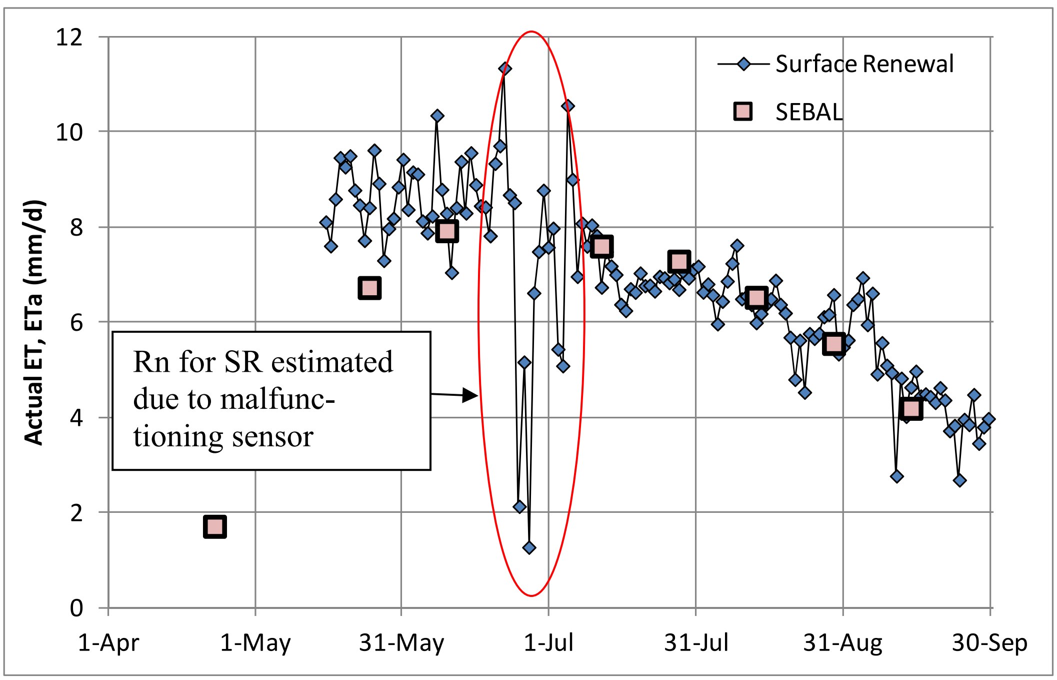

Figure 2. Daily Surface Renewal and SEBAL ET_a Estimates for Study Rice Field, 2001

Figure 3 and Table 2 provide the SEBAL and SR ET comparison for selected individual months for the rice field. This comparison was made only for June - September where SR ET data was available for the entire length of each individual month. April and May were excluded in the monthly ET comparison since the SR ET measurements began on May 16th. The absolute differences between monthly SEBAL and concurrent SR ET estimates ET varied from 6 - 20 percent with an average difference of 13 percent across the four months compared. The overall average 13 percent difference between SEBAL and SR monthly ET is consistent with past comparisons of SEBAL ET_a estimates on a monthly

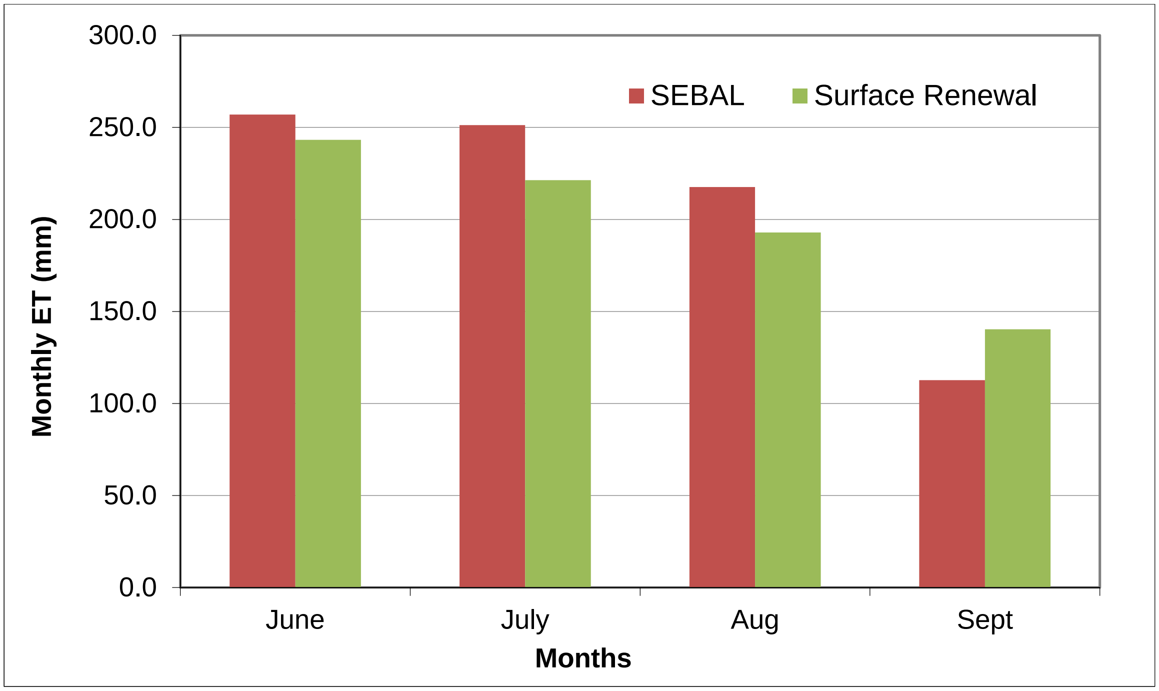

Figure 3. Monthly SEBAL and Surface Renewal ET comparison for the Rice Field

Table 2. Monthly SEBAL and Surface Renewal ET Estimates

Months	SEBAL ET (mm)	SR ET (mm)	Difference
June	256.9	243.2	6%
July	251.2	221.3	14%
August	217.6	192.9	13%
September	112.7	140.3	-20%

basis to reliable ground-based estimates where an average deviation of up to 20 percent was found when SEBAL ET estimates for individual periods/months were compared with the concurrent ground-based ET estimates (Bastiaanssen et al., 2005).

The full growing season rice ET estimated by SEBAL was 42.9 inches, or 3.57 acre-feet per acre, for this field. For the 2,060 rice fields identified for the subsequent crop coefficient analysis, the average full April 1 through September 30 rice ET estimate by SEBAL was 39.0 inches. Ninety percent of the rice fields in GCID had a full season rice ETa between 35.0 and 42.6 inches (Figure 4). This relatively uniform ET_a is indicative of the relatively uniform crop season timing, water supply reliability, and equitable distribution of that water supply throughout GCID. The SEBAL and Surface Renewal estimates of rice ET, or consumptive water use, do not include water that may be required for cultural practices.

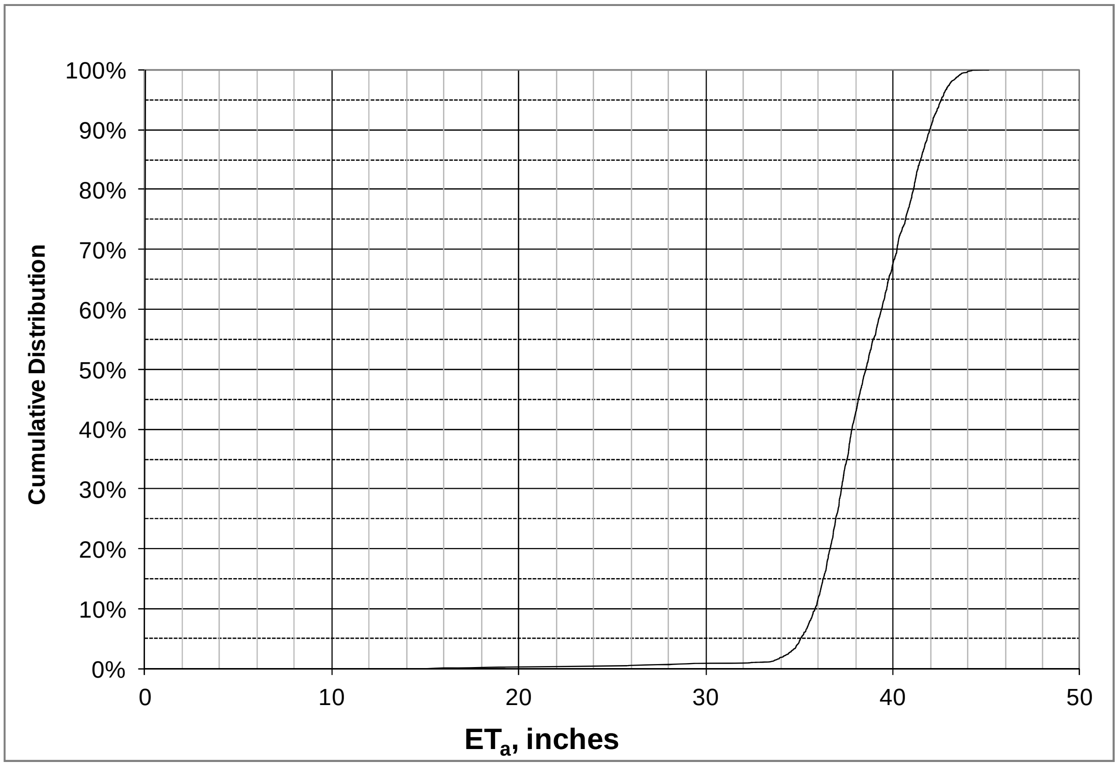

Figure 4. Cumulative Distribution of Seasonal (April – September) ET_a for 2060 Rice Fields in GCID

Remotely Sensed Lumped Crop Coefficeints (K_{cs}) for Rice Fields in GCID

The mean, 10^{th} and 90^{th} percentiles of K_{cs} for all the 2,060 rice fields identified within GCID are shown in Figure 5 for each satellite image date. Additionally, the relative frequency distribution of the field average K_{cs} values on each individual day is shown. A smoothed K_{cs} function based on the Surface Renewal estimates of the single field near Nicolaus generally falls within the frequency distribution of the SEBAL field average K_{cs} values.

Wide variability, particularly early and late in the season is apparent in the K_{cs} distribution for the selected rice fields. The greatest variability in K_{cs} distributions across all the image dates was observed in the April 23^{rd} image (standard deviation of 0.48, Table 3). The relative frequency distribution of K_{cs} on April 23^{rd} suggests that not all the rice fields were flooded by this date. This resulted in a bi-modal distribution of K_{cs} values, with non-flooded fields having K_{cs} in the 0.0 to 0.4 range, and the flooded fields having K_{cs} in the 1.2 to 1.4 range.

A steep increase in K_{cs} is apparent between April 23^{rd} and June 10^{th} during which the average K_{cs} changes from approximately 0.5 to 1.23 reflecting flooding of those fields not flooded by April 23^{rd} and the rapid growth of rice.

In addition to K_{cs} developed for the individual image dates, monthly Kcs values were also developed for the selected rice fields by dividing individual SEBAL monthly ET_a

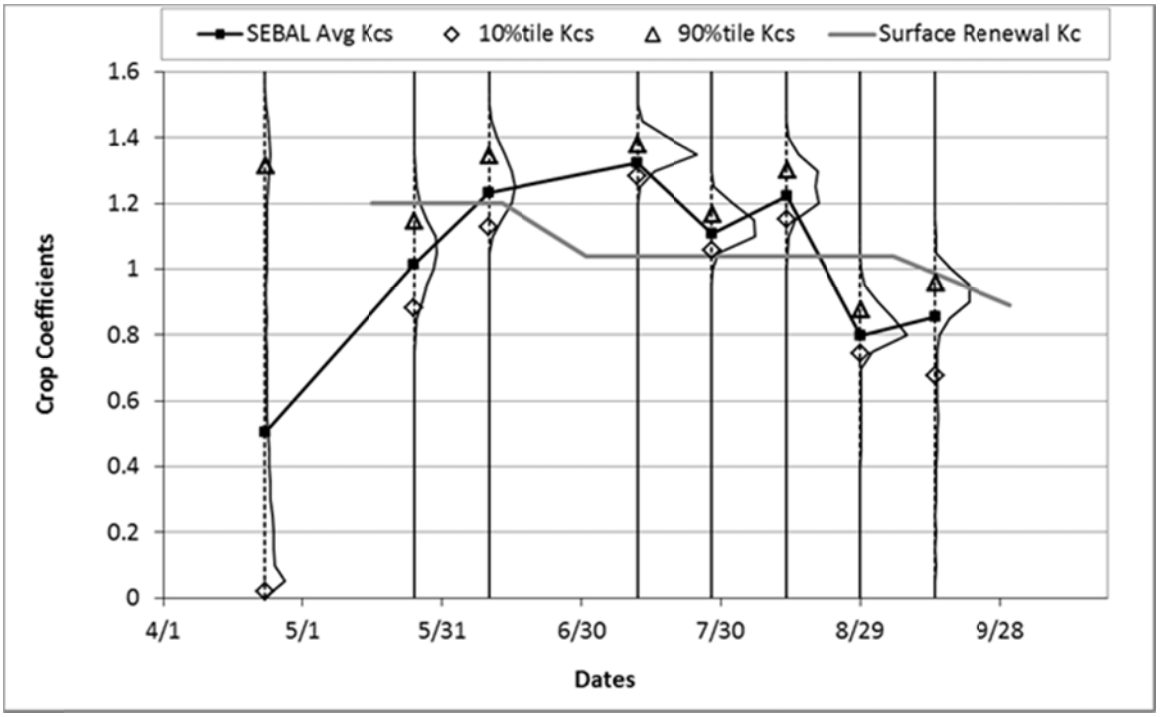

Figure 5. Daily Crop Coefficient Distribution for GCID Rice

Table 3. Summary Statistics of Lumped Crop Coefficient (Kcs) for 2,060 Rice Fields within GCID

Image Dates	10%tile	Mean	90%tile	Std. Dev.
23-Apr-01	0.02	0.50	1.32	0.48
25-May-01	0.88	1.01	1.15	0.14
10-Jun-01	1.13	1.23	1.35	0.09
12-Jul-01	1.29	1.32	1.38	0.10
28-Jul-01	1.06	1.11	1.17	0.07
13-Aug-01	1.15	1.22	1.30	0.08
29-Aug-01	0.74	0.80	0.88	0.06
14-Sep-01	0.68	0.86	0.96	0.13

estimates with monthly ET_o from CIMIS (Figure 6 and Table 4). Monthly K_{cs} estimates are useful in water balance studies performed on a monthly time step and are less impacted by diurnal changes and possible inaccuracies in ET_a and/or ET_o estimates that may occur on a given day. In certain cases diurnal changes and/or inaccuracies in ET_a or ET_o on a given day may result in dramatic changes in the subsequent daily K_{cs} that may not necessarily represent the actual water use trends for the given crop.

The monthly K_{cs} values estimated for rice were compared with the crop coefficient (K_c) values provided in University of California Cooperative Extension Leaflet 21427 (UCCE, 1998) for rice grown in Sacramento Valley (Figure 6). Additionally, K_{cs} estimates (mean, 10^{th} and 90^{th} percentiles) on the individual satellite image dates are included in the figure.

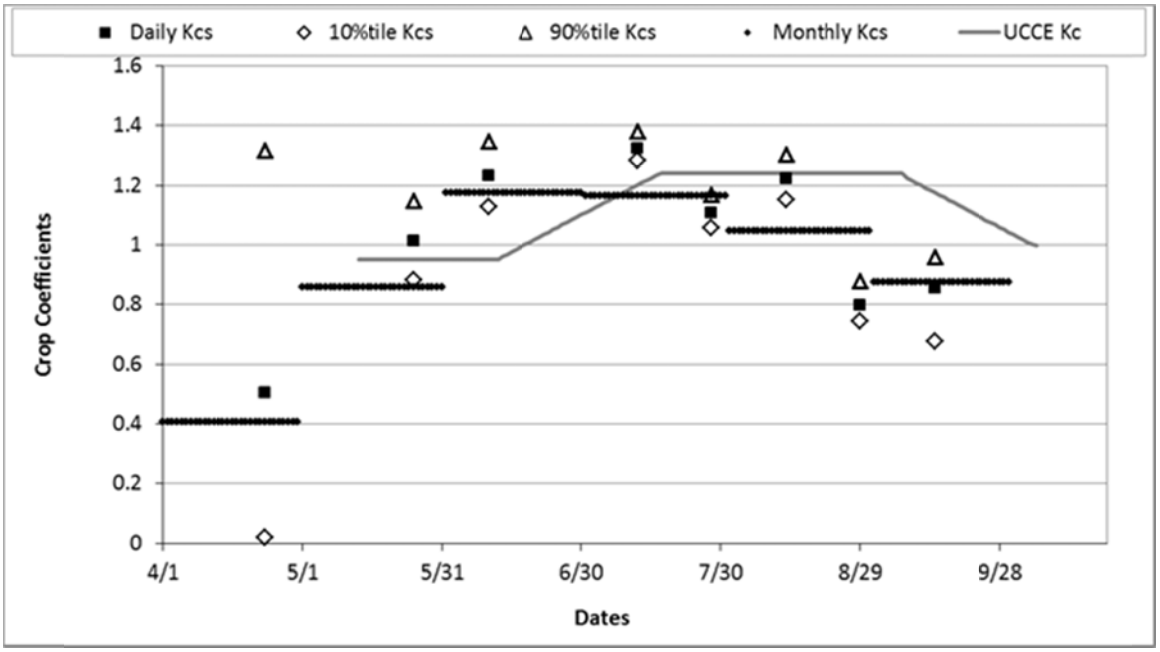

Figure 6. Daily and Monthly Crop Coefficients for Rice

Table 4. Monthly Lumped Crop Coefficients

Months	April	May	June	July	August	September
Average Kcs	0.40	0.86	1.17	1.16	1.04	0.87

The K_{cs} values developed for individual months are generally lower than the K_c values reported 23 years ago by UCCE for the various growth stages of rice. The UCCE crop coefficients were developed for the rice varieties in use at that time and should be updated for more modern varieties. The average Kcs of 0.86 estimated for May is less than the reported Kc value of 0.95 for the initial growth period of rice. The mid-season K_{cs} values of 1.17 and 1.16 for the months of June and July respectively were also lower that reported K_c value of 1.24. Additionally, K_{cs} of 0.87 for September was lower than the K_c of 1.0 reported for the late season.

The differences between estimated and reported crop coefficients for rice may be attributed to differences between actual field conditions and ideal conditions for which the standard K_c values were developed, different rice varieties and different growing season lengths. Additionally, differences early in the season may occur due to differences in the timing of the initial flooding of the rice fields early in the season for a given year relative to the conditions for which the published K_c values were delveloped. Finally, differences between K_{cs} values estimated for this study and K_c values reported in previous studies could be due to differences in the estimation of ET_o from which the crop coefficients are calculated.

SUMMARY AND CONCLUSIONS

The overall objective of this paper was to compare remotely sensed SEBAL ET estimates to ET estimated by the SR method for a rice field. Additionally, the full season ET of rice for the field with the SR equipment and the fields for which crop coefficients were developed are reported. Remotely sensed crop coefficients were developed for rice grown in GCID for the individual image dates and months of the 2001 growing season.

The SEBAL and SR cumulative ET estimates for June 1 to September 30, 2001 were 838 (33.0 inches) and 798 (31.4 inches) millimeters respectively with a difference 5 percent for the four month period. The 5 percent difference between the seasonal SEBAL and SR ET estimates provides a validation of SEBAL at field level for rice based on reliable ground-based data. The absolute difference between SEBAL and SR ET for the individual months (June – September) ranged from six percent to minus 20 percent with an average absolute difference of 13 percent across all the four months. The full growing season rice ET estimated by SEBAL was 42.9 inches, or 3.57 acre-feet per acre, for this field.

For the 2,060 rice fields identified for the subsequent crop coefficient analysis, the average full April 1 through September 30 rice ET estimate by SEBAL was 39.0 inches. Ninety percent of the rice fields in GCID had a full season rice ETa between 35.0 and 42.6 inches. The SEBAL and Surface Renewal estimates of rice ET, or consumptive water use, do not include water that may be required for cultural practices.

Remotely sensed crop coefficients were developed for rice grown in GCID. Wide variability in K_{cs} was observed early and late in the growing season. This variability may result from a variety of factors, including differences in the timing of flooding during the pre-planting preparations, crop physiological responses among rice varieties, or other management related factors. Differences between remotely sensed crop coefficients and published value likely result from differences between conditions for which the published K_c values were developed and actual field conditions for fields evaluated as part of this study.

California is among the major rice producing states in U.S. and more than 95 percent of California's rice is grown in Sacramento Valley. The five percent difference between the SR and SEBAL estimates of seasonal ET_a demonstrates the capability of SEBAL to estimate actual rice ET in the Sacramento Valley, but also suggests that differences between actual field conditions and conditions under which published crop coefficients were developed are substantial and warrant more careful estimation of actual crop coefficients for estimation of rice ET_a in a given year or area. SEBAL ET_a estimates can be utilized to develop remotely-sensed crop coefficients that are more representative of actual growing conditions.

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