

Comparison of Evapotranspiration Estimates from Remote Sensing (SEBAL), Water Balance, and Crop Coefficient Approaches

Bryan Thoreson, Ph.D., P.E.¹, Byron Clark, P.E.¹, Richard Soppe², Andy Keller, Ph.D., P.E.³, Wim Bastiaanssen, Ph. D.², and John Eckhardt, Ph.D., P.E.⁴

¹ Davids Engineering, Inc., 1772 Picasso Avenue, Suite A, Davis, CA 95618, www.sebal.us.

² WaterWatch, Generaal Foulkesweg 28A, 6703 BS Wageningen, The Netherlands, www.waterwatch.nl.

³ Keller-Bliesner Engineering, LLC, Vice President, 78 East Center, Logan, UT 84321, 435-753-5651; akeller@kelbli.com.

⁴ Imperial Irrigation District, Executive Program Manager, QSA-IID/SDCWA Water Transfer, 333 East Barioni Boulevard, Imperial, CA 92251, 760-339-9736 JREckhardt@IID.com.

ABSTRACT

Three independent approaches were applied to estimate annual evapotranspiration (ET) for the Imperial Irrigation District of Southern California for the 1998 water year (October 1997 to September 1998). These approaches included remote sensing (Surface Energy Balance Algorithm for Land, SEBAL[®]), a district-wide water balance with ET as the closure term, and a dual crop coefficient approach based on the procedures of FAO Irrigation and Drainage Paper No. 56 with refinements to account for field-specific irrigation frequency. Differences between annual ET from each independent ET estimation approach are evaluated relative to estimated confidence intervals.

INTRODUCTION

To grow and produce food, plants must release water through the process of transpiration. When the soil surface is wet due to rainfall or irrigation, evaporation also occurs. These two processes together are termed evapotranspiration (ET). In irrigated areas, evapotranspiration is usually the largest consumer of water. Thus, accurate determination of evapotranspiration is important for water resources planning. This paper describes the methodology and compares the results of three independent methods to determine annual evapotranspiration from the Imperial Irrigation District (IID), a large irrigated area in the Southwestern United States.

The three approaches were an energy balance based on remote sensing, a water balance utilizing 15-minute flow measurements and a dual crop coefficient procedure (Allen, 1998 and Allen, et al 2005). The energy balance used was the Surface Energy Balance Algorithm for Land (SEBAL[®]) utilizing Landsat satellite images and the California Irrigation Management Information System (CIMIS). The water balance utilized 15-minute flow data collected by the Imperial Irrigation District. The dual crop coefficient procedure utilized crop areas and plant and harvest dates collected by the Imperial Irrigation District, reference ET obtained from CIMIS and crop coefficients from the Food and Agricultural Organization (FAO) (Allen, 1998) adjusted for local conditions as appropriate (Allen et al, 2005a).

This paper briefly outlines the physical setting, describes the input data and methodology used for each method, reports the results of each method and concludes with a discussion comparing and contrasting the results.

PHYSICAL AND INSTITUTIONAL SETTING

Established in 1911, IID is the nation's largest irrigation district, providing water to about 475,000 acres of diverse crops. The agricultural area lies in the Imperial Valley with much of the area below sea level. The lowest fields are just above the Salton Sea standing at 230 feet below sea level. The land slopes gradually northward from the Mexican border to the south shore of the Salton Sea. A shallow saline groundwater aquifer underlies the agricultural area. The four months of June through September have average high temperatures above 110 degrees Fahrenheit. Annual reference ET (ET_0) has averaged 74 inches ranging from 64 to 83 inches over the last 22 years. Annual precipitation has averaged 2.75 inches ranging from 0.2 to just over 5 inches over the last hundred years. ET_0 was 71 inches and rainfall was 2.13 inches for the water year 1998 studied.

Soils underlying eighty-five percent of the cropped area contain a high percentage of clay with low infiltration rates and high water holding capacities. Annually about 100,000 acres of vegetable crops are grown throughout the area. Carrots, onions and lettuce are the most widely cultivated vegetable crops. The most common field crops include alfalfa, Bermuda grass, wheat, sugar beets and Sudan grass. Most of the vegetable area is double cropped, and roughly 350,000 acres is cropped year-round. In this climate, eight alfalfa cuttings are obtained in a typical year.

ET ESTIMATION METHODOLOGY

Three independent approaches were applied to estimate annual ET for the Imperial Irrigation District of Southern California for the 1998 water year (October 1997 to September 1998). These approaches included the remotely sensed energy balance SEBAL[®], a district-wide water balance with ET as the closure term, and a dual crop coefficient approach based on the procedures of FAO Irrigation and Drainage Paper No. 56 with refinements to account for field-specific irrigation frequency. Input data and methods used are described in the following sections.

Remote Sensing Estimate of ET with SEBAL

The sun's net radiation reaching the Earth's surface balances with soil, sensible, and latent heat fluxes to conserve 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).

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

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; 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.

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), CIMIS, and IID. These data are described in greater detail in the following paragraphs.

Satellite Images. Twelve Landsat 5TM multispectral images encompassing the period from October 1997 to September 1998 (Water Year 1998 or "WY 1998") for Path 37/Row 39 were obtained from USGS. Cloud-free images were selected to achieve a temporal frequency of one image per month for the WY 1998 period.

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. Five stations falling within or on the edge of the study area were used during image processing. The stations selected were Salton Sea West (Station 127), Salton Sea East (Station 128), Calipatria/Mulberry (Station 41), Meloland (Station 87), and Seeley (Station 68). 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).

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 used to estimate obstacle heights for different surfaces within the study area. The NLCD data has been developed at a 30 meter pixel resolution using a series of Landsat images along with aerial photographs and ground-surveys.

A DEM of 1 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.

District-wide Water Balance Estimate of ET

IID's physical and climatic situation results in a unique opportunity to measure inflows and outflows accurately and develop a water balance that closes on ET with high accuracy. IID is unique in that a water balance can be performed based on measured surface flows (Figure 1) that solves for ET of the command area with a high degree of confidence. This is due to the following factors:

1. Location in an extremely arid environment with little annual rainfall,
2. Accurately measured single source of all surface water used for irrigation in the command area,
3. Accurate measurement of all surface water flows out of the command area (about 35 locations) ,
4. Tile drains convey deep percolation from about 95 percent of the command area into surface drains that are tributary to the 35 outflows,
5. Deep percolation not captured by the tile drains, enters the groundwater and is discharged into surface drains,
6. Groundwater is saline and unusable for irrigation (no pumping), and
7. Subsurface natural flows across the area boundaries into and out of groundwater are negligible.

Input Data

A water balance summarizes all the flows entering and leaving a defined area, specified by a closed boundary, within a defined time period. Water balances can be performed at various scales and for various time periods and are defined by equation 2.

$$\sum \text{Inflows} - \sum \text{Outflows} = \Delta \text{Storage} \quad [2]$$

The next sections describe the boundaries and the flow measurements

Boundaries. The study area chosen for comparison is defined by the water balance boundaries. With the exception of small areas on the east and west, this area

is bounded by the All American Canal (AAC) on the south, the Westside Main Canal (WMC) on the west, the Salton Sea on the north and the East highline Canal on the east (Figure 1). These boundaries can be considered vertical planes and all subsurface and surface flows crossing the planes are considered in the water balance. ET flux and precipitation cross a horizontal plane imagined just above the crops within the vertical planes.



Figure 1. IID Water Balance Boundaries and Boundary Flow Measurements.

Inflows and Outflows. The inflows shown in Figure 2 include the AAC, Alamo and New Rivers from Mexico, rainfall, Mesa storm flows and subsurface inflows. The outflows going to the Salton Sea include the New and Alamo Rivers, drain flows to the Salton Sea (termed Direct to Sea flows) and subsurface outflow. Flows from the AAC and Direct to Sea measurement locations are transmitted to a central location at 15-minute intervals. The 15-minute data is loaded into a large database

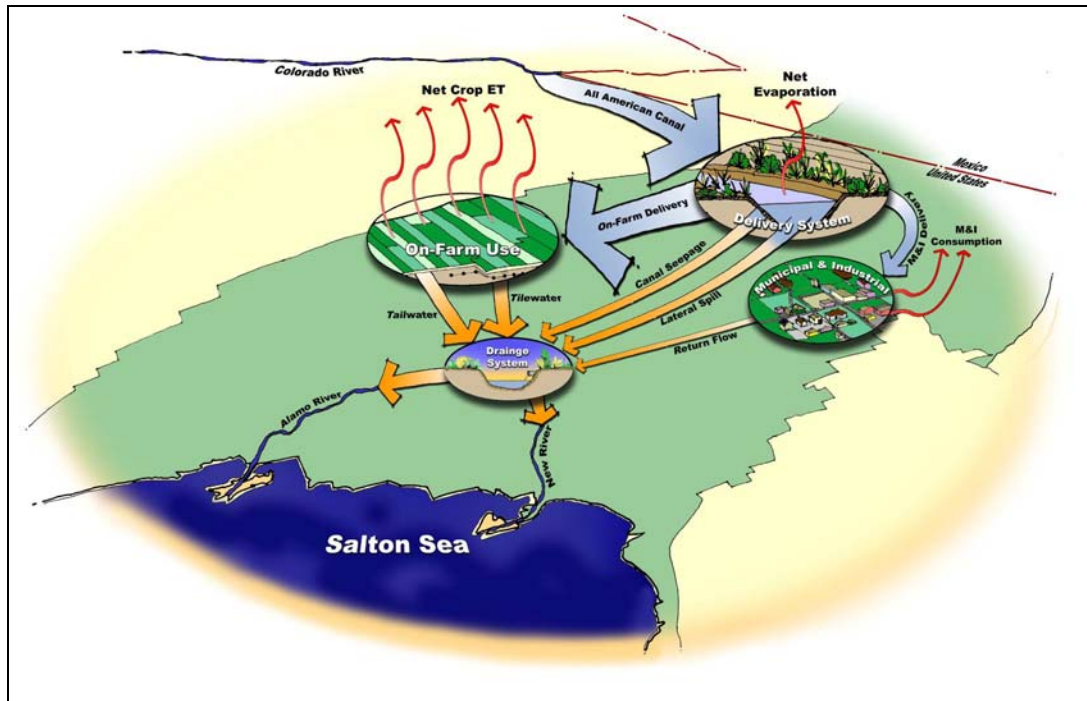


Figure 2. IID Water Balance Components and Flow Paths.

called the IID Water Information System (IID-WIS). In the WIS, the flow data is reviewed on daily, monthly and annual intervals. The 15-minute flows are summarized and reported as daily values. The New and Alamo River inflow and outflow measurements are conducted by the United States Geological Survey (USGS). Daily values from the USGS were used in this study. Rainfall is estimated based on the rainfall measured at three CIMIS stations (Calipatria/Mulberry, Meloland, and Seeley) within the water balance boundaries. Mesa storm inflows are estimated based on rainfall measurements. Small subsurface inflows and outflows estimated by groundwater studies are also included in the water balance.

Water Balance

A water balance was performed to determine total consumptive use (ET_a) within IID. The change in storage component of the water balance was limited to 50% of the available water content of the soils within the study area and estimated as a function of the monthly measured drain outflows relative to farm water deliveries. Given the factors listed above and the measurement accuracy of the surface inflows and outflows, the 95 percent confidence interval on ET_a , as the water balance closure term, was estimated to be 4.4 percent following the methodology of Clemmens and Burt (1997).

Crop Coefficient Estimate of ET

Potential crop evapotranspiration (ET_p) represents the total ET of a crop expected to occur under non-stressed growing conditions. Potential ET was estimated for each field-season by using the standardized dual crop coefficient approach described in FAO56 with planting and harvest dates recorded by IID. Total potential ET was

disaggregated into ET derived from precipitation and from applied irrigation water using a daily root zone water balance model (Allen et al, 2005a).

Input Data

Meteorological Data. The model uses daily weather data (relative humidity, wind speed, reference ET (ET_o), and precipitation) and crop and soil information for each identified field-crop season. Weather data parameters are calculated as a weighted average of quality controlled values from the Calipatria/Mulberry, Meloland, and Seeley CIMIS stations based on the area represented by each station determined using Thiessen polygons.

Crop Planting and Harvest Dates and Areas. IID zanjeros (ditch tenders) deliver water to growers and also record the crop plant and harvest dates and irrigated areas. This data is entered into IID's water order entry database and transferred to the IID-WIS.

Crop Coefficients. The crop coefficients used in the computations were based on FAO 56 and University of California Extension Leaflets 21427 and 21428 (Snyder et al., 1989a, 1989b). These crop coefficients were adjusted for local weather conditions using the FAO 56 recommended adjustment for extreme wind and humidity values.

Crop Water Use Computations

Effective (net) precipitation was estimated using a daily root zone water balance model developed in QuickBasic. Specified field-crop seasons were parameterized based on crop type, planting date, harvest date, and soil type (light or heavy).

The daily root zone water balance model was used to simulate the timing of irrigation applications, with irrigation triggered once the soil moisture depletion reached a crop and soil specific management allowed depletion. The model computes total potential ET (from both applied water and precipitation) by applying the standard dual crop coefficient approach described in FAO 56 (Allen, 1998). Daily values of reference evapotranspiration (ET_o) and precipitation were inputs to the root zone water balance.

The planting time period for many crops can span months due to the mild winters. For example, wheat can be planted anytime between October and January with a few plantings in February. To capture the variability in seasonal ET resulting from highly variable planting dates and resulting season length, root zone model runs were made for unique field-crop season plant and harvest date combinations.

ET ESTIMATION RESULTS

Remotely Sensed Surface Energy Balance Estimate of ET with SEBAL

The ET within the study area was estimated to be 2.010 million acre-feet by the remote sensing approach using SEBAL. The variation of ET across the study area is shown in Figure 3. The average ET for cropped areas within the IID is shown in Figure 4. Peak water consumption for the irrigated areas occurs in June. The average monthly actual ET (ET_a) is always less than the CIMIS reference ET.

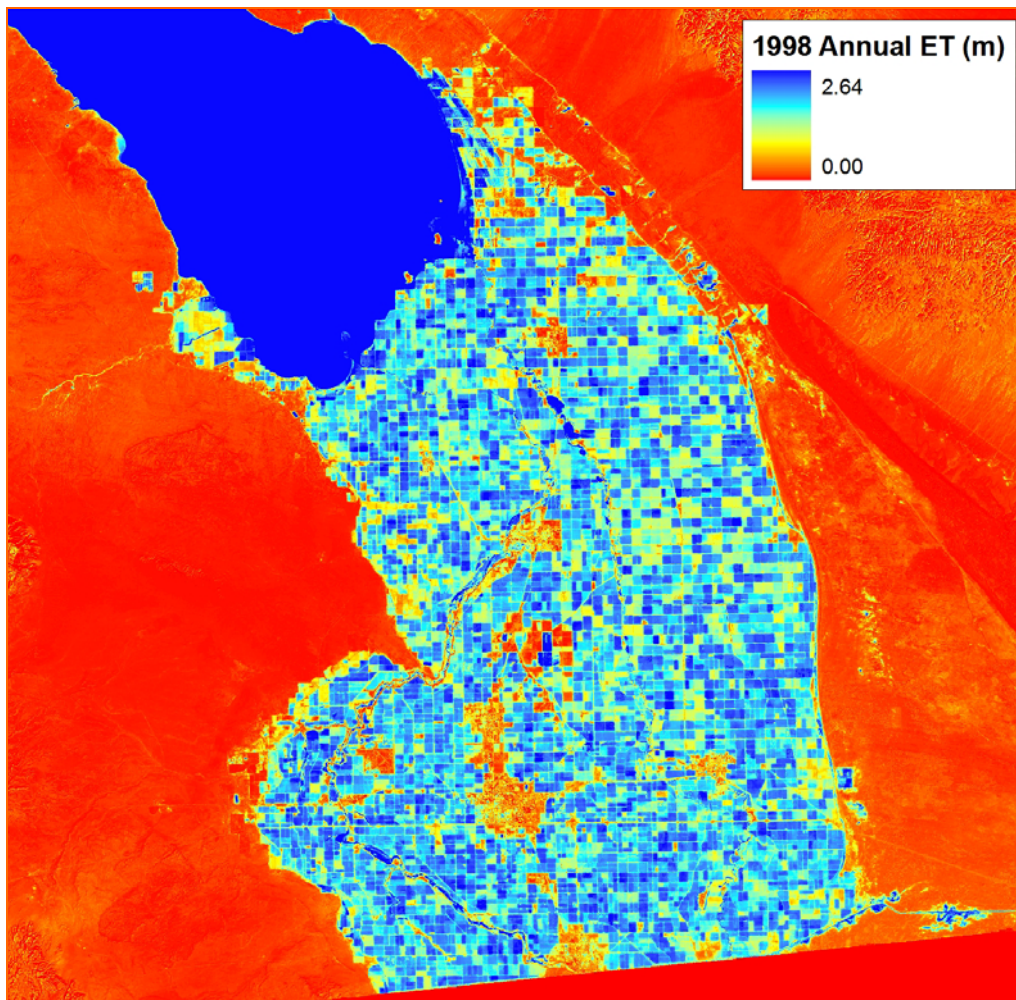


Figure 3. Water Year 1998 Seasonal ET_a Variation across IID Irrigated Area.

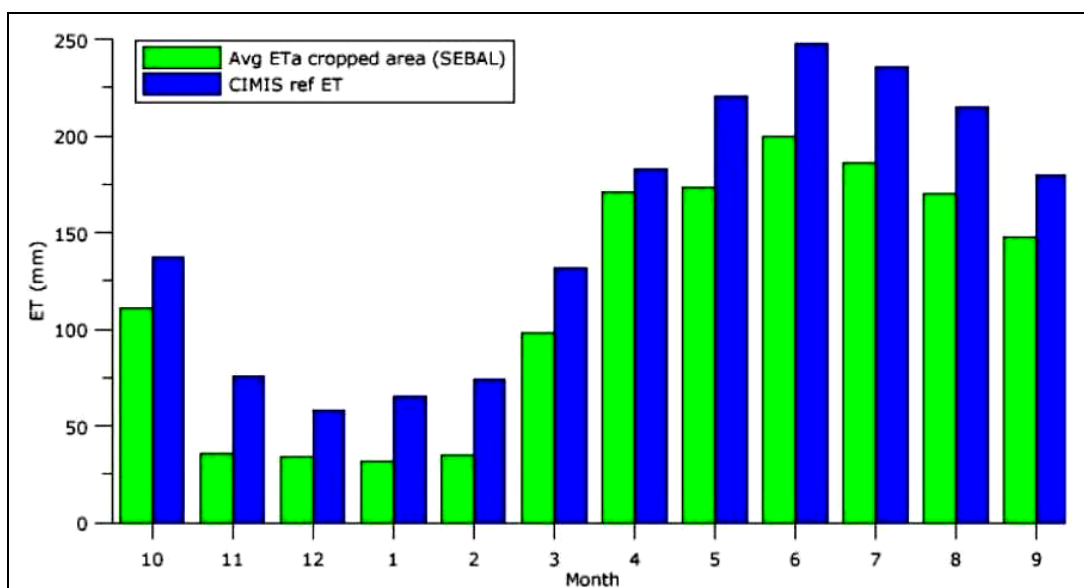


Figure 4. Average ET_a for Cropped Area in IID Compared with Average ET_0 .

District-wide Water Balance Estimate of ET

The total inflow to the area from the AAC was 2.9197 million acre-feet. All the other inflows combined totaled 0.3116 million acre-feet. Outflows totaled 1.2327 million acre-feet, including a net depletion in soil water storage over the course of the year of 102 thousand acre-feet. The resulting estimate of ET within the study area is 1.9985 million acre-feet (Table 1).

The water balance quantifies all primary flow paths and associated water volumes within the study area. This improved understanding is important for water resources planning and management. However, the water balance itself provides no information on the variation of ET across the study area.

Table 1. Water Year 1998 IID Study Area Water Balance.

		Volume (1000 ac-ft)	
Location	Data	1998	CI
Total Inflows			
AAC Inflow at Mesa Lat. 5	Input	2,919.7	2.4%
Alamo River from Mexico	Input	1.5	2.0%
New River from Mexico	Input	181.0	2.0%
Total Rainfall	Calc.	103.2	22.4%
Mesa Storm Inflows	Calc.	5.9	100.0%
External Subsurface	Input	20.0	100.0%
Total Inflows	Calc.	3,231.2	2.5%
Total Outflows			
Alamo River to Salton Sea	Input	665.6	2.3%
New River to Salton Sea	Input	564.0	2.0%
Direct to Sea Drains	Input	104.1	20.0%
Subsurface to Sea	Input	1.0	100.0%
Change in Soil Storage	Input	-102.0	50.0%
Total Consumptive Use	Close	1,998.5	4.4%
Total Outflows	Calc.	3,231.2	2.9%

Crop Coefficient Estimate of ET

Computing ET for each field in the study area using a root zone water balance program with inputs of soil type, recorded plant and harvest dates, ET_o, rainfall, crop coefficients and related irrigation management parameters and summing the total across all fields resulted in a total ET of 2.280 million acre-feet. The climate in the study area allows for crops to be produced year-round and results in a wide range of possible plant and harvest dates for crops. For example, wheat can be planted any time from October through January and sometimes even in February and March. This results in a wide variation of seasonal ET totals for wheat as the later plantings extend into warmer weather before maturing (Figure 5).

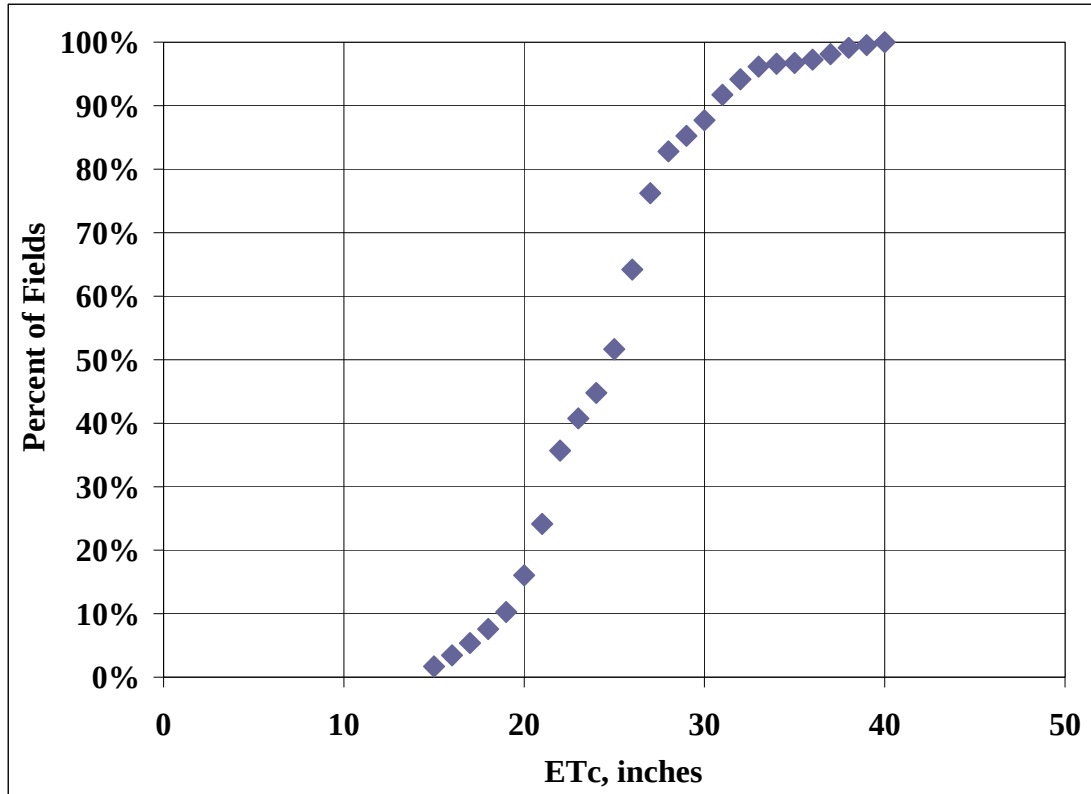


Figure 5. Cumulative Distribution of Wheat ET_c on Heavy Soil Using Reported Plant and Harvest Dates.

DISCUSSION

Annual ET in the study area was estimated using water balance closure, remote sensing energy balance and the FAO 56 crop coefficient approaches. Annual ET estimates varied from 1.999 million acre-feet to 2.280 million acre-feet for the water balance and FAO 56 crop coefficient approaches, respectively. The SEBAL remote sensing ET was very close to the water balance results at 2.010 million acre-feet. For this unique study area, the water balance estimate of ET was estimated to have a confidence interval of 4.4 percent based on the sum of variances method (Clemmens and Burt, 1997). The FAO 56 crop coefficient approach was expected to result in higher ET estimate than the other approaches due to unavoidable ET reducing heat and water stress experienced by crops during the extremely hot summers that is not accounted for in the crop coefficient approach. All estimates agreed within 15 percent (Table 2); however, the water balance and SEBAL approaches were within one percent of each other while the crop coefficient approach estimate was just over 14 percent greater than the water balance results.

Table 2. Comparison of the Three Approaches over the 1998 Water Year.

ET Estimation Approach	Water Year 1998 Total, kaf	Percent Difference (SEBAL-WB)/WB
Water Balance	1998.5	0.0%
SEBAL	2010.4	0.6%
Crop Coefficient	2280.2	14.1%

The monthly percent difference between the water balance and the SEBAL results varied from -2.7 percent to just over 30 percent in one month (Figure 6 and Table 3). Most of the difference is attributed to likely error in estimating the monthly change in soil water storage within the water balance computation. The annual estimate of change in soil water storage error is less error prone. Allen et al. (2005) discusses the month to month storage change and uncertainties in some detail.

The 30-m by 30-m pixel spatial resolution of the SEBAL results allow for a more complete understanding of ET among fields. Only a few alfalfa fields in the study area approach the potential ET computed by the FAO 56 crop coefficient procedures (Figure 7).

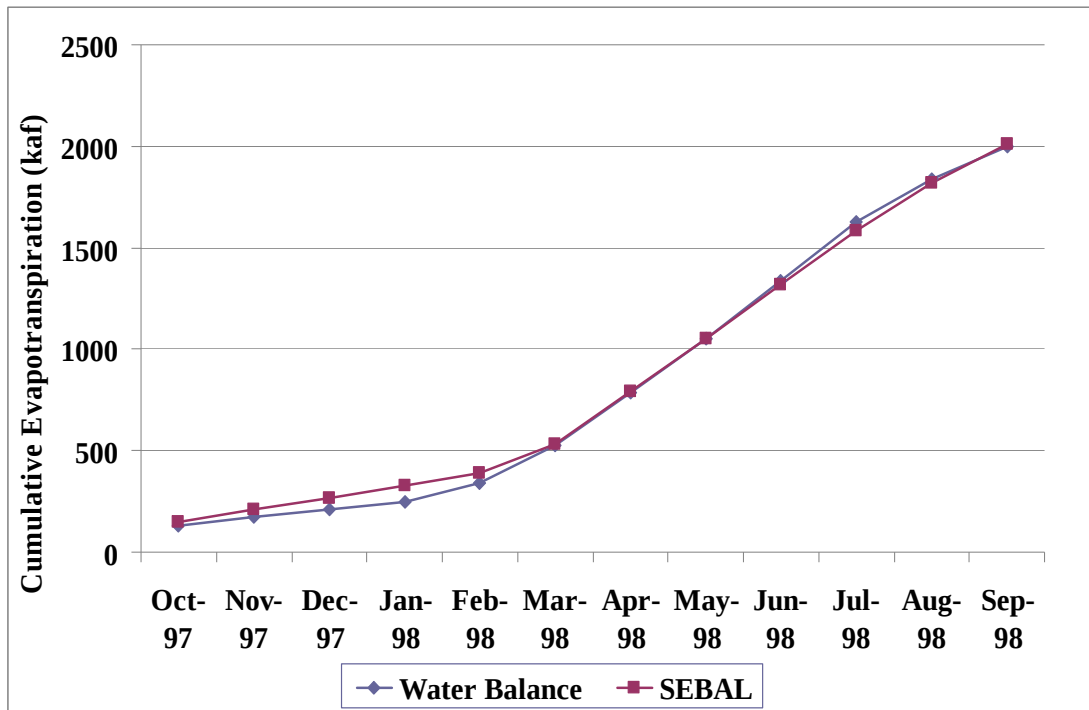


Figure 6. Cumulative ET from Water Balance and SEBAL Results.

Table 3. Comparison of Water Balance and SEBAL Cumulative Monthly Volumes.

Month	Cumulative, kaf		
	Water Balance	SEBAL	Percent Difference (SEBAL-WB)/WB
Oct-97	132.1	147.8	11.9%
Nov-97	173.0	208.6	20.6%
Dec-97	209.2	268.2	28.2%
Jan-98	249.5	326.1	30.7%
Feb-98	339.6	390.6	15.0%
Mar-98	525.8	531.7	1.1%
Apr-98	785.3	790.8	0.7%
May-98	1050.8	1049.4	-0.1%
Jun-98	1337.0	1316.2	-1.6%
Jul-98	1630.5	1585.7	-2.7%
Aug-98	1837.9	1820.9	-0.9%
Sep-98	1998.5	2010.4	0.6%

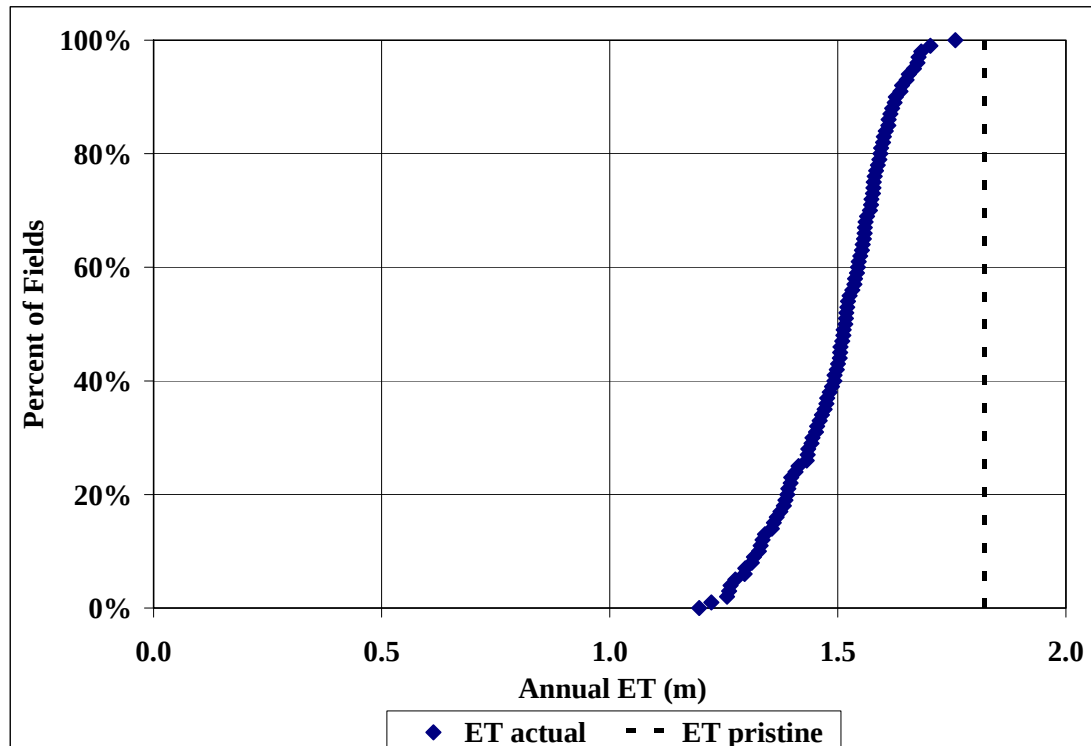


Figure 7. Cumulative Distribution of Water Year 1998 Field Scale ET for Flood Irrigated Alfalfa on Cracking Soils.

The SEBAL results allow for a more complete understanding of ET across time. Although a few fields exceed the monthly pristine ET in some months, the average monthly ET_a from the alfalfa fields in the study area is below the monthly pristine ET computed by the FAO 56 crop coefficient procedures (Figure 8). The low ET in the winter months is likely due to: 1) sheep grazing on some alfalfa fields lowers the averages and 2) 30-60 day periods in the winter when many alfalfa fields are not irrigated, remaining dormant for a couple months in the cooler part of the year.

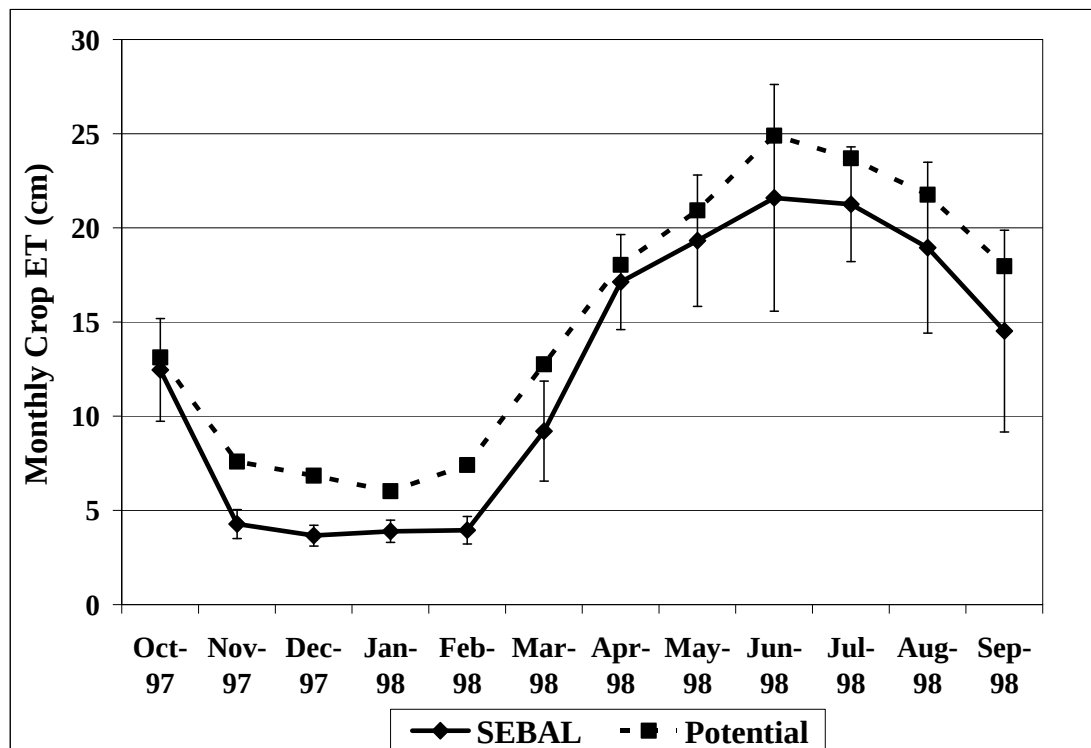


Figure 8. Comparison of Monthly Actual and Pristine ET for Flood Irrigated Alfalfa on Cracking Soils.

The SEBAL results allow for a more complete understanding of ET variation within fields. Six fields with boundaries superimposed on the July 98 SEBAL results are shown illustrating ET variability within fields (Figure 9). The largest field is ½ mile by ½ mile, 160 acres, 65 hectares, 720 pixels. Reduced ET often occurs uniformly and in concentrated areas. Fields with low uniformity may benefit from improved irrigation management to achieve ET (and yield) increases.

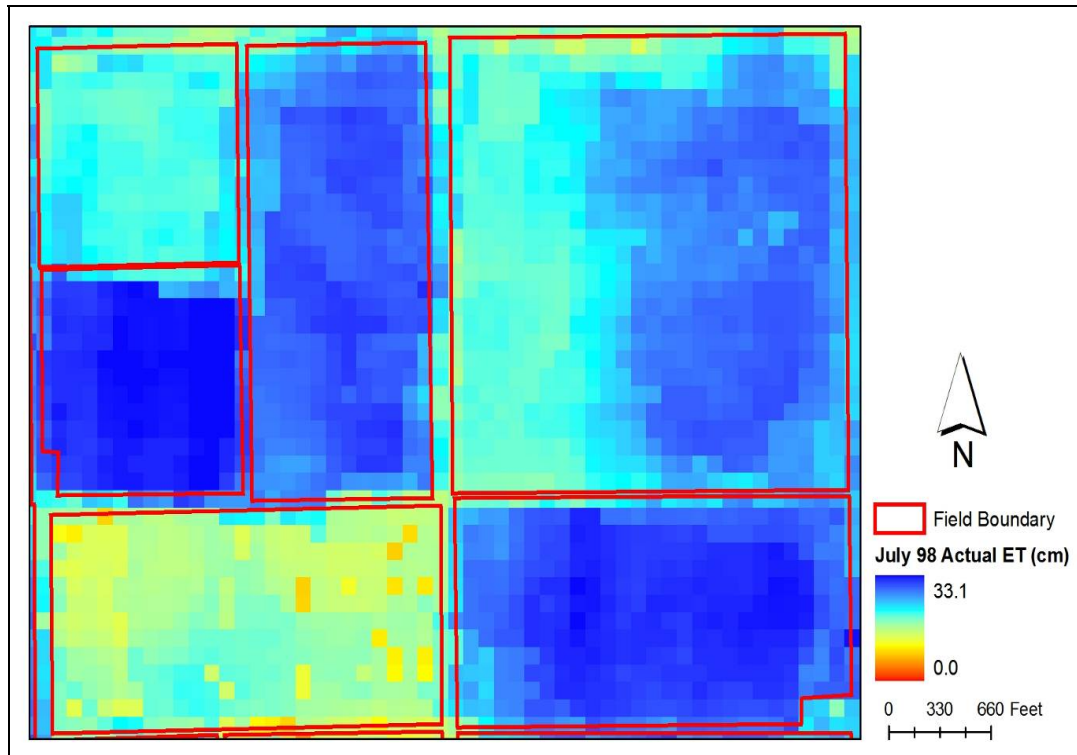


Figure 9. Example of ET Variation between Fields Identified through Remote Sensing.

CONCLUSIONS

Results of the district-wide water balance were compared to corresponding results from the remote sensing approach utilizing SEBAL for the 1998 water year (October 1997 to September 1998), resulting in a difference of less than one percent, providing a strong validation of SEBAL in arid, advective environments. The ET computed from the crop coefficient approach was 14 percent higher than the ET computed by the water balance approach.

The following additional conclusions are evident:

1. The 30-m by 30-m pixel spatial resolution of the remote sensing approach results allow for a more complete understanding of ET within and among fields.
2. The remote sensing approach results allow for a more complete understanding of ET across time.
3. Remote sensing of ET using thermal imagery plays an important role in the IID/SDCWA water transfer and, more broadly, water management in the West.
4. Remote sensing of ET provides opportunities for improved agricultural water management at field, farm, district, basin, state, and regional scales.

REFERENCES

- Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. (1998). Crop Evapotranspiration. *Irrigation and Drainage Paper No. 56. Food and Agriculture Organization of the United Nations*. Rome, Italy.
- Allen, R.G., Bastiaanssen, W.G.M, Tasumi, M., and Morse, A. (2001). Evapotranspiration on the Watershed Scale Using the SEBAL Model and Landsat Images. ASAE Annual International Meeting, Sacramento, CA, 2001.
- Allen, R.A., Walter, I.A., Elliot, R., Howell, T., Itenfisu, D. and Jensen, M. 2005. The ASCE Standardized Reference Evapotranspiration Equation. ASCE, Reston, VA.
- Allen, R.A., Clemmens, A.J., Burt, C.M., Solomon, K. and O'Halloran, T. 2005. Prediction Accuracy for Projectwide Evapotranspiration Using Crop Coefficients and Reference Evapotranspiration. *Journal of Irrigation and Drainage Engineering*. 131(1), 24-36.
- Bastiaanssen, W.G.M., Menenti, M., Feddes, R.A., and Holtslag, A.A.M. (1998). A Remote Sensing Surface Energy Balance Algorithm for Land (SEBAL): 1. Formulation. *Journal of Hydrology*, 212-213: 198-212.
- Bastiaanssen, W.G.M., Noordman, E.J.M., Pelgrum, H., Davids, G., and Allen, R.G. (2005). SEBAL Model with Remotely Sensed Data to Improve Water Resources Management Under Actual Field Conditions. *Journal of Irrigation and Drainage Engineering*. 131(1), 85-93.
- Clemmens, A.J. and Burt, C.M. (1997). Accuracy of Irrigation Efficiency Estimates. *Journal of Irrigation and Drainage Engineering*. 123(6), 443-453.
- Snyder, R.L., Lanini, B.J., Shaw, D.A., and Pruitt, W.O. (1989a). Using Reference Evapotranspiration (ET_o) and Crop Coefficients to Estimate Crop Evapotranspiration (ET_c) for Agronomic Crops, Grasses and Vegetable Crops. *Leaflet No. 21427*, Cooperative Extension, University of California. Berkeley, California.
- Snyder, R.L., Lanini, B.J., Shaw, D.A., and Pruitt, W.O. (1989b). Using Reference Evapotranspiration (ET_o) and Crop Coefficients to Estimate Crop Evapotranspiration (ET_c) for Trees and Vines. *Leaflet No. 21428*, Cooperative Extension, University of California. Berkeley, California.
- Tasumi, M., Trezza, R., Allen, R.G., and Wright, J.L. (2005b). Operational aspects of satellite-based energy balance models for irrigated crops in the semi-arid U.S. *Irrig. Drain. Syst.*, 19, 355-376.