ESTIMATING ACTUAL EVAPOTRANSPIRATION WITHOUT LAND USE CLASSIFICATION

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ABSTRACT

Water resource planning requires knowledge of consumptive water use by crops and natural vegetation. Remote sensing offers the promise of obtaining 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 the energy balance at the earth's surface. Evapotranspiration (ET) is predicted as a residual of the energy balance, without needing to know crop or vegetation type, or other ground-based information, except routine weather data.

Utilizing SEBAL, annual *actual* ET in 2002 for the state of California has been computed from *MODerate-resolution Imaging Spectroradiometer* (MODIS) satellite images for each square kilometer. Annual ET can be summarized spatially using any spatial characteristic for which a GIS overlay is available or can be developed. Annual ET was summarized spatially by land use, county and watersheds. Validation of the SEBAL process is discussed in general and for this specific application. Annual *actual* ET from a MODIS pixel comprised of largely alfalfa fields was found to differ by 0.9 percent from alfalfa annual actual ET measured by a lysimeter maintained by the United States Department of Agriculture, Agriculture Research Service near Fresno, California (Ayars and Soppe, 2003).

INTRODUCTION

Water resource planning requires knowledge of consumptive water use by crops and natural vegetation. The accepted approach to determining consumptive use of

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water by crops and natural vegetation begins with computation of a reference ET using data from nearby weather stations (Jensen, et.al. 1990 and Allen, et.al. 1998). Many computation methods exist for reference ET. However, in the last few years the Penman-Monteith combination equation has gained wide acceptance. Differences in reference ET between locations account for most of the climatic differences between areas. The next step is to select and apply crop coefficients for individual crops and natural vegetation types. The crop coefficients selected must have been developed for use with the selected method for computing reference ET. Crop coefficients are by definition (Allen, et.al. 1998) developed for standard (sometimes called "pristine") conditions. Standard conditions are defined as "disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions and achieving full production under the given climatic conditions." Thus, consumptive use or ET computed in this manner is standard, or "pristine," ET.

Actual ET can be obtained from "pristine" ET in a variety of ways. A simple technique is to discount actual ET by a percentage, such as 7% (Cal Poly, 2001), to account for low crop density, poor fertility conditions, high salinity and other factors that occur in production agriculture and tend to suppress ET. Other more intensive methods include a root zone water balance coupled with water application amounts and dates to estimate soil water stress and ET reduction experienced by crops.

Computation of "pristine" ET requires detailed weather data and crop type and area information. When accurate weather and crop type and area information are available, accurate values are obtained for "pristine" ET. For well managed irrigated areas with sufficient water availability, these values in aggregate are reasonably accurate and can be considered representative of actual ET with a small percentage reduction (Burt, et.al. 2002). However, ET for each crop is considered uniform within and among fields. For water-short or salinity-affected irrigated areas, determination of actual ET becomes much more difficult because these influences tend to be spatially variable.

Remote sensing offers the promise of determining irrigated area and crop ET for large areas with spatial sensitivity. ET can be computed as the residual of the surface energy balance without the need for crop type information and irrigated area is integral to the process. ET computed from the energy balance is the actual ET, as compared to the "pristine ET," and is the total ET of precipitation and applied water.

This paper provides a brief overview of remote sensing and data products derived from remote sensing, presents results from the application of remote sensing to compute ET at a large spatial scale (1 km by 1 km square pixels) for the state of California in the year 2002, and finally compares the results to other ET measurements.

PART 1. OVERVIEW OF REMOTE SENSING ET PRODUCTS

Remote Sensing

Remote sensing can be defined as the collection of information about an object from a distance. In this paper, remote sensing generally refers to measurement of spectral radiances sensed by satellites or airplanes. Remote sensing from aircraft can be flown whenever desired and is generally of higher resolution. However, satellite images (remotely sensed data) are more readily available.

Most satellite remote sensing relies on naturally reflected or emitted radiation from the earth's surface. The imaging systems are designed to take images of visible, near infrared, thermal and microwave energy. Thus, a single satellite "image" is comprised of many (seven in the case of Landsat-7) separate images, or bands, each corresponding to a different wavelength. Image analysis is accomplished by treating each band as a raster layer in GIS. This paper focuses on remote sensing from satellites.

Remote Sensing Applications

A wide variety of individual parameters have been mapped from remote sensing data utilizing many different technical solutions. Some of these individual parameters include: vegetation indices to determine the extent and health of vegetation, thematic classification into crop types, irrigated area and land cover and use (Bastiaanssen, 1998). Other biophysical crop parameters that can be computed from remote sensing measurements include: fractional vegetation cover, leaf area index, photosynthetically active radiation, surface roughness, broadband surface albedo, thermal infrared surface emissivity, surface temperature, surface resistance, crop coefficients, transpiration coefficients, ET and crop yield. Additional information that can be derived from remote sensing includes: soil moisture, soil salinity and soil mineralogy. Remotely sensed ET at sub-field resolution across a large region contributes significantly to improving water resources management. Schultz and Engman (2000) provide a recent overview.

Remotely sensed ET at sub-field resolution across a large region contributes significantly to improving water resources management. Kustas, et. al. (2003) describe two modeling schemes to compute ET from data remotely sensed by the Geosynchronous Operational Environmental Satellite (GOES). A major disadvantage of these two approaches for agricultural applications is the large pixel size of 5 to 10 km^2. ET cannot be evaluated at the sub-field or even field scale due to the coarseness of the spatial resolution. Moreover, these technologies do not provide an accumulated value for ET. SEBAL (Surface Energy Balance Algorithm for Land) combines satellite remote sensed data with weather station data, to solve the energy balance at the earth's surface for the actual ET and

biomass production of agricultural crops and native vegetation. Actual ET can be obtained at field and sub-field scale and for seasonal accumulated values. Since SEBAL computes the energy balance on the basis of spectral radiances, information on crop development is not required. As discussed in Part 3 of this paper, the finer spatial resolution of the SEBAL results enables validation comparisons against lysimeters in many instances. Bastiaanssen et. al. (2004) provides a detailed description of the SEBAL algorithm.

PART 2. CALIFORNIA 2002 ET, BIOMASS PRODUCTION AND WATER USE EFFICIENCY

One MODIS image covering California was processed with the SEBAL algorithm to compute actual ET and biomass production on a scale of 1 km by 1 km for each month of 2002. The processing was completed without land use classification. The CIMIS network of automatic weather stations was used in conjunction with the DAYMET high-resolution climate grid to fill out the days between consecutive MODIS images (Thornton et al., 1997).

The result of this processing was an actual ET value for each square kilometer pixel in California for each month, in the form of an ArcInfo Grid, or raster, coverage. This raster coverage can be converted to 409,616 polygons, each with an area of one square km and a unique computed value of actual ET. The result is 12 of these raster coverages, one for each month in 2002. In GIS, this information can be overlaid with other spatial coverages for analysis. The remainder of this paper provides just a few examples of the analytical possibilities.

The actual ET values for California are at the lower end of the SEBAL accuracy spectrum due primarily to the use of a single image per month and lack of adjustment for surface roughness. The lack of adjustment for the surface roughness results in inaccuracies, particularly for the forest ecosystems. A single surface roughness, selected for greatest accuracy in the agricultural areas, was used in the SEBAL computations. The small differences in surface roughness among agricultural crops allow for the use of a single surface roughness for these areas and ET to be computed without specific crop information. The larger surface roughness difference between agricultural areas and mature forests results in over estimation of ET for the mature forests. A similar over estimation occurs for the bare rock/desert areas. Higher accuracy in the ET estimates could be achieved by processing additional images and by applying appropriate, spatially sensitive refinements to surface roughness.

ET by Land Use

A 1992 statewide land use map was obtained (USGS, 2003) and superimposed on the ET grids from 2002. The USGS National Land Cover Characterization team

made this high-resolution 30 m land use database. The 21 land use classes have been consolidated to reduce the number of classes to 12.

The land use areas that consumed the most water in 2002 in terms of depth of ET were the forest ecosystems and open water (Table 1). The lack of a 2002 land use map introduces some uncertainty in the results. Nevertheless, the potential of evaluating the ET rates and volumes for each land use class is demonstrated. Wetlands followed by orchards/vineyards and agricultural crops come after the forest ecosystems. Built up ("urban") areas consumed only slightly less than agricultural crops. Not surprisingly, bare rock and desert consumed the least amount of water.

Table 1. Annual 2002 ET by Land Use Class in California (1 km^2 resolution)

Land Use	Area, ac	Total, in	Volume, AF	area,%	Volume,%
Mixed forest	3,323,164	54.4	15,065,012	3.3%	5.4%
Open water	1,127,315	53.5	5,025,947	1.1%	1.8%
Deciduous forest	1,888,596	49.7	7,821,936	1.9%	2.8%
Evergreen forest	22,720,724	49.4	93,533,647	22.4%	33.6%
Wetlands	385,449	43.4	1,394,041	0.4%	0.5%
Orchards/Vineyards	2,656,290	41.2	9,119,928	2.6%	3.3%
Agricultural Crops	9,224,304	37.2	28,595,341	9.1%	10.3%
Built-up area	3,017,239	35.5	8,925,997	3.0%	3.2%
Grassland/Herbaceous	15,071,265	33.3	41,822,761	14.9%	15.0%
Perennial ice/snow	9,810	32.3	26,405	0.0%	0.0%
Shrubland	35,641,046	21.1	62,668,840	35.2%	22.5%
Bare rock/desert	6,153,055	9.3	4,768,618	6.1%	1.7%
Totals	101,218,258	33.0	278,768,475	100.0%	100.0%

Figure 1 shows the monthly distribution of ET during 2002 for five of the land use classes. As expected, ET from wetlands is roughly the same as for open water in March and April, however beginning in May the wetland ET begins to be less than the ET of the open water surface, presumably due to insufficient water supplies to support full wetland ET. The agricultural area appears higher than expected in March. The built-up area ET appears lower than expected in May and higher than expected in November. These may be due to climatic or management effects.

ET by County

Figure 2 shows that 40 percent of California counties had an average actual ET of 40 inches or greater. Conversely, 10 percent had an average actual ET of less than 26 inches. (Note: averages are not weighted by county area.)

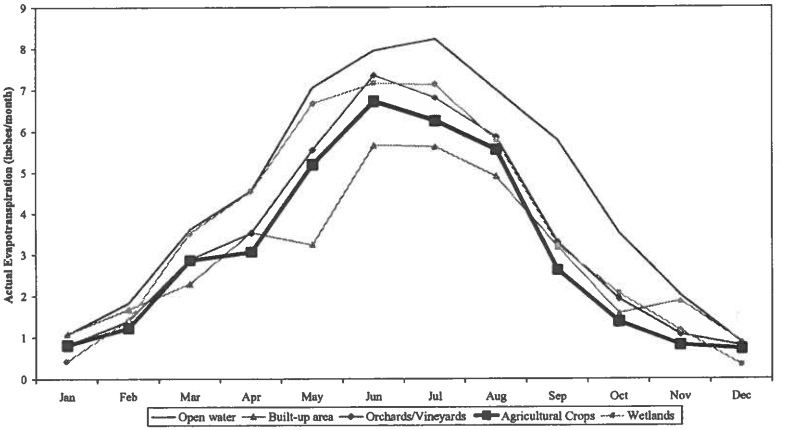

Figure 1. Monthly ET in 2002 computed from MODIS satellite images.

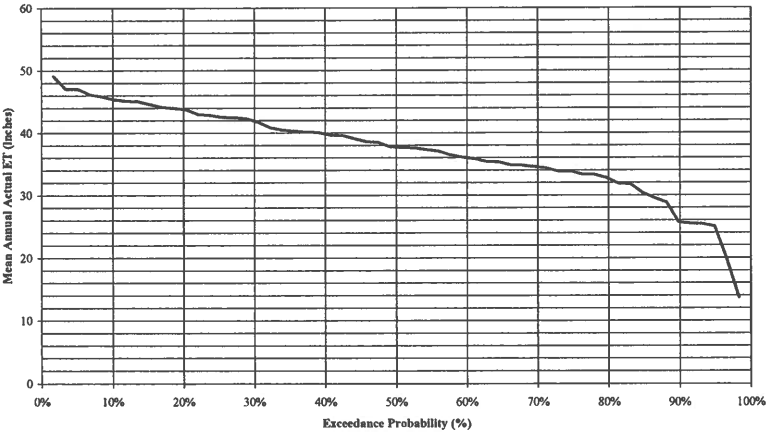

Figure 2. Mean California County 2002 Annual Actual ET Exceedance Probability

Actual ET and biomass production (another SEBAL output) were combined to compute water use efficiency. WUE is defined as the biomass production in dry mass per area divided by the actual ET. It should be emphasized that this is the efficiency per unit of water depleted, i.e. water that has evaporated into the atmosphere and is no longer available for downstream users. Table 2 lists the top

five counties in California in 2002 in WUE. Sonoma County ranks number one in terms of water use efficiency in 2002. This county ranks 14th in biomass production, but only 43rd in actual ET. The county has a significant area in wine grapes and it is likely that the regulated deficit irrigation practiced is a leading factor in the high water use efficiency. The county with the highest annual actual ET, Humboldt county, is ranked fifth in WUE, while Mendocino county has the highest biomass production and is ranked second. As expected, all of the counties in the top five have significant forested area.

Table 2. Top Five California Counties in 2002 in Water Use Efficiency (WUE)

No.	County	Biomass, tons/ac	Actual ET, inches	WUE, lbs/acre-inch of ET
1	Sonoma County	11.1	33.9	655
2	Mendocino County	14.1	43.8	644
3	Santa Cruz County	11.9	38.5	618
4	Del Norte County	12.2	43	567
5	Humboldt County	13.8	49.1	562

ET by Watershed

The California Department of Water Resources (CDWR) has divided California into ten major Hydrologic Regions corresponding to the State's major drainage basins, or watersheds, for the development of the California Water Plan (CDWR, 1998). By overlaying the GIS polygons for these watersheds, the mean actual total ET for 2002 of all the 1 km^2 pixels in each of these watersheds is computed (Table 3). (Here too, annual ET is the total ET of precipitation and irrigation combined.) The land use polygons can now be overlaid on the watersheds and the actual annual ET in each watershed broken down by land use area.

Table 3. Mean Annual Actual ET in 2002 for California's Ten Major Watersheds

No.	Watershed	Area, acres	Mean Annual Actual ET, inches	No. of Sub-watersheds
1	North Coast	12,442,916	42.7	1566
2	San Joaquin	9,800,815	41.1	769
3	Sacramento River	17,409,785	40.3	1454
4	South Coast	7,149,255	38.2	345
5	Central Coast	7,370,731	35.9	842
6	Tulare Lake	10,767,959	35.7	754
7	San Francisco Bay	2,892,803	35.1	274
8	North Lahontan	3,909,887	33.9	354
9	Colorado River	12,711,832	19.2	63
10	South Lahontan	17,572,920	16.3	601

PART 3. COMPARISONS TO OTHER ET ESTIMATES

Comparing ET computed by SEBAL to that determined by other ET estimating techniques presents difficulties in both the temporal and spatial dimensions. Table 4 lists some of the most common ET measurement technologies along with the temporal and spatial scales associated with them.

Table 4. ET Estimating Techniques by Temporal and Spatial Scales

	Scales	
ET Estimating Techniques	Temporal	Spatial
SEBAL	Instantaneous*	0.2 to 250 acres
Lysimeters	Hourly	10-20 sq. ft.
Eddy Correlation	Instantaneous	20-40 acres
Bowen Ratio	Instantaneous	20-40 acres
Scintillometer	Instantaneous	1000 to 2000 acres
Water Balance	Monthly	Thousands of acres

*SEBAL estimates actual ET flux at the moment of satellite image capture. The instantaneous flux can be reliably extrapolated to hourly, daily and longer periods.

Many consider good lysimeter data sets to be the best standard for ET measurements. However, many researchers have indicated the difficulty of maintaining proper lysimeter conditions. One of the challenges is keeping the vegetation within the lysimeter representative of the surrounding field. This is obviously critical for comparisons against SEBAL considering the spatial scales of the two technologies. In a comparison of SEBAL results to lysimeter measurements in the Bear River Basin in Idaho (Allen, et. al. 2002), for July through October for grass, the seasonal ET computed by SEBAL was 4.3% greater than that measured by the lysimeters (15.9 compared to 15.4 inches).

Additional SEBAL validation comparisons across many climates and ET measurement technologies are described in Bastiaanssen, et. al. (2004). These comparisons have indicated that for short-time periods based on a single satellite image, SEBAL results are within 15 to 20 percent of other measurements. For longer time periods, based on a multiple satellite images, up to and beyond a full season, random errors inherent in a process that includes semi-empirical relations cancel. Thus, SEBAL results are typically within five percent of other reliable ET estimates for seasonal and longer periods.

California 2002 Annual ET Comparison to Lysimeter Data

The USDA (Ayars and Soppe, 2003) measured the ET of alfalfa throughout 2002 using a weighing lysimeter in the vicinity of Parlier. The "West" lysimeter was maintained under farmer management conditions, while the "East" lysimeter was maintained under optimal agronomic conditions. Thus, the ET measured by the

East lysimeter is considered to be near potential while that from the "West" lysimeter more closely represents actual ET under commercial farming conditions. The "West" lysimeter field was located on a Landsat image and found to be a few pixels in size and in an area dominated by grapes. Thus, the corresponding MODIS pixel could not be used because the pixel including the "West" lysimeter was mostly grapes and the actual ET for this pixel would be essentially a weighted average of the grape area and the alfalfa area. This obstacle was overcome by using several large fields, recognized as alfalfa fields by their spectral pattern, for the comparison. A MODIS pixel from this area was selected for comparison with the "West" lysimeter data. The actual ET by SEBAL for the satellite image days compares well to the curve of lysimeter-measured crop ET (Figure 3). The difference in the annual crop ET between the lysimeter (45.9 inches) and SEBAL (46.4 inches) is 0.9%.

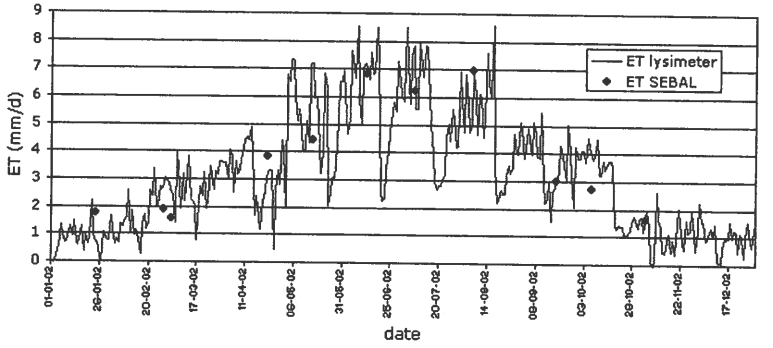

Figure 3. Comparison of Alfalfa ET to lysimeter ET (Ayars and Soppe, 2003)

CONCLUSIONS

Spectral radiances captured by satellites enable estimation of actual ET using energy balance techniques. One of these techniques, SEBAL, is widely tested and validated. It offers the advantages of not needing to know the crop type, computing actual ET directly and providing a spatial view of ET. Once ET is computed by SEBAL and an ArcInfo Grid is generated, this information can be combined with other spatial coverages for a wide variety of hydrologic analyses.

Determining *actual* ET has always been an imposing, if not insurmountable challenge. The promise of remote sensing and estimation of *actual* ET with SEBAL is an easier, more accurate method for all those applications for which an accurate determination of *actual* ET is critical. The method opens up a new era by enabling water managers to "see" the spatial variability in *actual* ET, leading to higher levels of understanding in hydrologic processes.

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