EVAPOTRANSPIRATION FROM A SATELLITE-BASED SURFACE ENERGY BALANCE FOR THE SNAKE PLAIN AQUIFER IN IDAHO

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ABSTRACT

SEBAL (Surface Energy Balance Algorithm for Land) is an image-processing model comprised of 25 submodels for calculating evapotranspiration (ET) as a residual of the surface energy balance. SEBAL was developed in the Netherlands by Bastiaanssen and has been modified during Idaho studies for application to irrigated agriculture, rangeland, mountainous terrain and clear, cold lakes under semiarid conditions. SEBAL has been applied in many developing countries and has now been applied in southern Idaho to predict monthly and seasonal ET for water rights accounting and for operation of ground water models. Results from SEBAL have been compared and validated using precision-weighing lysimeter measurements from the U.S. Department of Agriculture - Agricultural Research Service (USDA-ARS) at Kimberly, Idaho, and from Utah State University for the Bear River. ET for periods between satellite overpasses was computed using ratios of ET from SEBAL to reference ET computed for ground-based weather stations. ET maps via SEBAL provide the means to quantify, in terms of both the amount and spatial distribution, ET from individual fields. The ET images generated by SEBAL show a progression of ET during the year as well as distribution in space.

Initial application and testing of SEBAL indicates substantial promise as an efficient, accurate, and relatively inexpensive procedure to predict the actual

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evaporation fluxes from irrigated lands throughout a growing season. ET from satellite images may replace current procedures used by Idaho Department of Water Resources and other management entities that rely on ground-based ET equations and generalized crop coefficients that have substantial uncertainty.

INTRODUCTION

SEBAL is an emerging technology that has the potential to become widely adopted and used by the world's water resources communities. ET maps created using SEBAL or similar remote-sensing based processing systems will some day be routinely used as input to daily and monthly operational and planning models for reservoir operations, ground-water management, irrigation water supply planning, water rights regulation, and hydrologic studies.

In Idaho, SEBAL is used to generate seasonal ET maps for predicting effects of irrigation on stream flow depletion in the Bear River Basin and the upper Snake River Basin. The ET maps are also used to predict recharge to ground-water systems and to extend pumpage records for ground-water diversions. The Snake River Plain aquifer system is large, spanning more than 30,000 square km (an area larger than the states of Massachusetts, Connecticut, and Rhode Island combined), with over 7,000 square km (1.7 million acres) of irrigated farmland.

Two SEBAL applications have been made in Idaho using funding from Raytheon Company and the National Aeronautics and Space Administration (NASA). The first application, during Phase I of the study, was to the Bear River Basin of southeast Idaho (Morse et al., 2000). The second application, during Phase II, was to the eastern Snake River Plain of southern Idaho, (Morse et al., 2001).

The theoretical and computational approach of SEBAL is well documented in Bastiaanssen et al., (1998), Bastiaanssen (2000) and Morse et al., (2000). Basically, ET for each image pixel is computed for the energy balance where ET = $R_n - G - H$, where R_n is net radiation, G is soil heat flux density, and H is sensible heat flux density. R_n is computed from satellite-measured broad-band reflectances and surface temperature, G is estimated from R_n , surface temperature, and vegetation indices, and H is estimated from surface temperature ranges, surface roughness, and wind speed using buoyancy corrections. The model was applied in Idaho using the ERDAS Imagine software with the Spatial Modeler. Modifications to SEBAL have included the method for selecting anchor pixels in the energy balance computation and the method for extrapolating ET from the time of the satellite overpass to adjoining periods (Allen et al., 2001).

BEAR RIVER APPLICATION

In 1958, the Bear River Compact was developed to establish how Idaho, Utah and Wyoming would equitably distribute and use water from the Bear River. The role of Idaho Department of Water Resources (IDWR) is to compute depletion by irrigated agriculture for the Idaho part of the basin to support Idaho's position in negotiations with the other two states. IDWR will continue to refine and apply SEBAL in the basin to assist in administration of the Bear River Compact.

In Phase I (2000) of our SEBAL study, ET maps were generated monthly for a 500 km x 150 km area (comprised of 2 Landsat images) encompassing the Bear River basin. Images were processed for 1985, coinciding with an ET study using lysimeters (Hill et al., 1989) that allowed for comparison to SEBAL. Lysimeters near Montepelier, Idaho, just north of Bear Lake, had been planted to an irrigated native sedge forage crop characteristic of the area and local surroundings. The lysimeters were measured weekly. ET from the three lysimeters was averaged to reduce random error and uncertainty in the ET measurements. Results for four satellite images during the 1985 growing season (July 14, Aug. 15, Sept. 16, Oct. 18) are summarized in Figure 1 and Table 1. The results compare well to lysimeter data for the last three image dates. The earliest date, July 14, compares well when examined in context of the impact of precipitation preceding the image date and rapidly growing vegetation during that period (Morse et al., 2000).



Figure 1. Comparison of ET_r fractions (i.e., K_c) derived from 7-day lysimeter measurements near Montpelier, Idaho during 1985 and values from SEBAL for four Landsat dates (ETc = crop ET).

The Fraction of Reference ET (ETrF) in Table 1 is defined as ET/ET_r where ET_r is reference ET based on an alfalfa-referenced Penman equation (Hill et al., 1989). ETrF values were computed for each pixel and used to extrapolate ET from the day of the satellite image to days between images. ETrF is synonymous

	mo	nthly peri	ods and the	e associat	ed error t	or Bear R	iver, 1985).
	7-day Lys. ET ave. for image date (mm d ⁻¹)	SEBAL ETrF on image date	7-day SEBAL ET for image date (mm d ⁻¹	Diff. in 7-day ET (SEBAL – Lys) (%)	Monthly Alfalfa ET _r (mm)	SEBAL Monthly ET (mm)	Lys. Monthly ET (mm)	Diff. in Monthly ET (SEBAL – Lys.) (%)
(1) July	(2) 5.3	(3) 0.98	(4) 6.8	(5) 28%	(6) 202	(7) 198	(8) 167	(10) 19%
Aug	3.5	0.59	3.7	6%	201	119	145	-18%
Sept	1.9	0.57	2.1	10%	115	66	54	22%
Oct	0.7	0.49	0.6	-14%	45	22	23	-5%
July- Oct.	2.9	0.73	3.3	15%	563	405	388	4%

with the well-known crop coefficient, K_c . ET_r accounts for changes in ET caused by weather variation between satellite image dates.

Table 1. Summary of SEBAL- and lysimeter-derived ET for weekly and

Predicted monthly ET averaged +/- 16% relative to the lysimeter at Montepelier (Table 1). However, seasonal differences between SEBAL and lysimeters were only 4% due to impacts of reduction in the random error component present in each estimate.

SNAKE RIVER PLAIN APPLICATION

Managing water rights and irrigation on the Snake River Plain and tributary basins presents a challenge to IDWR. Water for irrigation comes from surface and ground sources. For various historical reasons, the use of surface water has been directly measured and regulated by IDWR while the use of ground water has not. This situation began to change in 1995 when the Water Measurement Information System Program was established within IDWR to measure ground-water use. IDWR has dedicated considerable resources to water measurement, including three full-time positions to monitor about 5,000 points of diversion, mostly wells. As useful as these data are, they do not provide all the information necessary for effective management of the resource. Information regarding the ET or consumed fraction of diversions is needed. SEBAL can be used in conjunction with Water Measurement data in an efficient program to help manage water development, use and stewardship. SEBAL covers large areas inexpensively and efficiently, thereby extending Water Measurement data in both time and space, and the Water Measurement data, in turn, can be used to validate or calibrate the SEBAL results. This combined program offers advantages over present methods: 1) it offers the ability to monitor whether water has actually stopped being used for irrigation after a water shut-off order has been issued; 2) it can discover if more water has been used than authorized; 3) it can quantify and be used as proof of beneficial use of a right; 4) it can be used as an unbiased, quantitative record of historical use; 5) the consumed fraction and return of non-evapotranspired water to the resource can be quantified; 6) estimates of yield and productivity can be made to assess benefits of water development and tradeoffs in water management. In addition, resulting seasonal ET maps are utilized by the State of Idaho, University of Idaho, and U.S. Bureau of Reclamation ground-water modelers to predict recharge of irrigation water to the Eastern Snake Plain Aquifer.

A number of tasks during Phase II (2001) were directed at improving components of SEBAL to better predict ET for environments found in the western United States. These include prediction of net radiation and soil heat flux components and identification and assessment of the energy balance for "anchor" pixels used to define the overall energy balance for the image. Other improvements included determination of mean wind speeds in mountain areas, prediction of aerodynamic roughness for various vegetation covers, and development of an ET reference fraction (ETrF) approach for extending ET between images (Allen et al., 2001).

The production of ET maps having 30 m resolution for the Eastern Snake River Plain Aquifer was highly successful. ET images were created for 12 dates during 2000 and were integrated over the March – October period. Interpolation between image dates was done using ETrF from pixels of each image and multiplying these by ET_r computed for each day between images.

Images were purchased from both Landsat 5 and Landsat 7 archives for 2000 to increase the number available for the southern Idaho area. Often, dates for adjacent Landsat 5 and 7 paths were separated by just one day. Landsat 5 images were of immense value in providing ET for similar periods between paths. Algorithms were developed to correct individual reflectance bands of Landsat 5 to coincide with measurements by Landsat 7 to account for sensor deterioration.

Validation of SEBAL at Kimberly, Idaho

The validation of SEBAL on the Snake River Plain has centered on the use of two precision-weighing lysimeter systems for ET measurement in place near Kimberly, Idaho, from 1968 to 1991. The lysimeter system was installed and operated by Dr. James Wright of the USDA-ARS (Wright, 1982, 1996) and measured ET fluxes continuously. ET data are available for a wide range of weather conditions, surface covers, and crop types. Measurements of net radiation, soil heat flux and plant canopy parameters were frequently made near the lysimeter site. The lysimeter data sets provide valuable information to verify SEBAL over various time scales and for various conditions of ground cover.

Ninetcen Landsat 5 satellite image dates were purchased for Kimberly, Idaho, covering the period between 1986 and 1991. These dates had quality lysimeter and cloud-free micrometeorological data and represent a combination of crop growth stages and times of the year. Eight images from 1989 are discussed here.

The lysimeter data for intervening periods between image dates were used to assess the impact of various methods for extending ET maps from a single day to longer periods. They have also been used to assess the variability in ETrF over a day. The success of SEBAL is predicated on the assumption that ETrF for a 24hour period can be predicted from the ETrF from the instantaneous satellite image. ET, was calculated for hourly and 24-hour periods using the ASCE standardized Penman-Monteith method for an alfalfa reference (EWRI, 2001), representing the ET from a well-watered, fully vegetated crop, in this case, fullcover alfalfa 0.5 m in height. The denominator ETr serves as an index representing the maximum energy available for evaporation. Weather data were measured near the lysimeter and included solar radiation, wind speed, air temperature and vapor pressure. Lysimeter data analyses showed ETrF= ET / ET, to be preferable to the evaporative fraction (EF) parameter used in previous applications of SEBAL (Bastiaanssen et al., 1998, Bastiaanssen 2000)), where EF = ET / $(R_n - G)$. The better performance by ETrF was due to its consistency during daytime and agreement between hourly ETrF at satellite overpass time (~1030) and daily average ETrF. An illustration of ETrF for a day in 1989 is given in Figure 2 for clipped grass (alta fescue) and sugar beets. ETrF for many days was even more uniform than shown in the figure. In nearly all cases, the ETrF for the 24-hour period was within 5% of the ETrF at 1030.

T able 2 summarizes error between SEBAL and lysimeter measurements during 1989. Absolute error averaged 30% for the eight days. When April 18 was omitted, the average absolute error was only 14%. April 18 was before planting of the sugar beets and represented a period of drying bare soil following precipitation. The field at this time was nonuniform in wetness due to differential drying, and differences between lysimeter and estimate were only 1 mm. The standard deviation of error between SEBAL and lysimeter for dates from May -September was 13%. In comparison, a commonly quoted standard error for ET prediction equations that are based on weather data, for example, Penman or Penman-Monteith-types of equations, is about 10% for daily estimates. SEBAL was able to obtain close to this level of accuracy for the field surrounding the lysimeter. Results are illustrated in Figure 3, where ET is expressed in the form of ETrF. ETrF was used to normalize results for differences in climatic demand (i.e. ET,). The round symbols and horizontal line segments in Figure 3 represent ETrF determined from lysimeter on the image date. These values are those directly compared with SEBAL predictions in Table 2. The triangular symbols in represent the ETrF predicted by SEBAL for the image date.



Figure 2. Hourly measured ET, ET, ETrF and 24-hour ETrF for July 7, 1989, for clipped grass (top) and sugar beets (bottom) at Kimberly, Idaho.

Table 2 summarizes the extrapolation of ET by SEBAL over the season (April 1 – Sept. 30, 1989). Most periods were 16 days, centered on the image date. April 18 was used to represent April 1 – April 25, July 23 was used to represent July 16 to August 24 and Sept. 25 was used to represent Aug. 25 through Sept. 30. What is surprising is the close agreement for seasonal ET for April 1 – September 30. The difference between SEBAL (714 mm) and the lysimeter measurement (718 mm) was less than 1% for the sugar beet crop. It appears that much of the error occurring on individual dates was randomly distributed, and tended to cancel.

Beets) at Kimberry, Idano.											
Image Date	Lys. ET on date (mm d ⁻¹)	SEBAL ET on date (mm d ⁻¹)	Error on Image Date (%)	ET _r on date (mm d ⁻¹)	ET _r for period (mm)	Lys. ET summed daily for period (mm)	Lys. ET for period based on image date only (mm)	SEBAL ET for period (mm)			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)			
4/18/89	0.73	1.74	139	6.78	147	28	16	38			
5/4/89	6.61	5.09	-23	7.76	94	30	80	62			
5/20/89	1.37	1.34	-2	7.27	90	22	17	17			
6/5/89	1.73	1.78	3	6.68	118	24	30	31			
6/21/89	2.39	2.54	6	6.33	127	62	48	51			
7/7/89	7.96	5.89	-26	8.44	120	116	113	84			
7/23/89	7.64	7.17	-6	7.38	253	266	262	246			
9/25/89	5.51	7.40	34	8.00	201	171	138	186			
4/1 9/30	21					718 ^a	705 ^b	714¢			
Percent Error							-1.8%	-0.6 %			

Table 2. Summary and computation of ET during periods represented by each satellite image and sums for April 1 – September 30, 1989, for Lysimeter 2 (Sugar Parts) at Kimberly, Ideba

^a The sum of daily measurements by lysimeter computed as the sum over all days between April 1 and Sept. 30.

^b The sum of ET computed for each lysimeter period, computed by multiplying summed ET, during the period by the ETrF for the image date.

^c The sum of ET predicted by SEBAL for the lysimeter 2 field, computed by multiplying the summed ET, during the period by the ETrF computed on the image date by SEBAL.

An illustration of the type of resolution for ET maps generated from Landsat imagery is shown in Figure 4 for a 4 km x 6 km area near American Falls, Idaho.

IMPACT

The SEBAL work is evolving. Nevertheless, there have been impacts. IDWR found the results of Phase I and II sufficiently compelling to request additional funding from the Idaho Legislature to include SEBAL as the ET source for recalibration of the Eastern Snake River Plain aquifer model and to generate ET maps to monitor ground-water pumage. The aquifer model uses 5 km grid cells, and aggregating ET up to a 5 km cell is preferable to disaggregating county-averaged data.



Figure 3. Results by SEBAL and ET by Lysimeter as ETrF (top). The thin line is the five-day average ETrF for lysimeter and the thick line is the assumption used in SEBAL to extrapolate between images. The bottom figure shows total ET for the image period.



Figure 4. Close-up of ET (left) with false color composite (right) from Landsat 7 showing variation within individual fields May 5, 2000.

COST SAVINGS

SEBAL ET data are less expensive to generate than are standard ET data. Since IDWR is still developing the SEBAL data, a quantitative cost-benefit analysis is premature. Nevertheless, it is possible to do a cost comparison based on some available figures. Current costs for monitoring water use on the eastern Snake River Plain are estimated to be about \$500,000 per year. We estimate costs for remote sensing to be about \$50,000 per year. This includes costs for 30 TM scenes representing 8 to 10 dates for the whole eastern Snake Plain (Landsat scenes cost about \$400 each for images more recent than 1998 and about \$4,000 each for images older than 1999. Geo-registration of images costs an additional \$400 each, for a total procurement cost of about \$24,000). SEBAL processing requires about 3 days per scene (90 days * 8 hours = 720 hours * \$30.00 per hour = \$22,000). The total for remote sensing is \$46,000. Set-up and time for aggregation of ET results in a GIS structure results in a total remote sensing cost of \$50,000. Using these figures, the estimate cost ratio of remote sensing to the current measurement program is \$50,000/\$500,000 = 0.10, i.e., remote sensing costs about 10% of the measurement costs. Measurement costs are for a subset of the total number of wells, all of which are not measured in a single year, whereas, SEBAL data cover the entire Snake River Plain and all places of use. The use of SEBAL ET will not replace the existing measurement program, per se. Pumpage data that can be related to individual water rights will be needed to regress against the SEBAL ET data for the same water rights to establish the relationship between volume pumped and volume of ET. That relationship can then be applied to all other non-monitored water rights and their associated wells to estimate both aquifer depletion and water use by individual water rights.

SUMMARY AND CONCLUSIONS

SEBAL uses digital image data collected by Landsat and other remote-sensing satellites that record thermal infrared, visible and near-infrared radiation. ET is computed on a pixel-by-pixel basis for the instantaneous time of the satellite image. The process is based on a complete energy balance for each pixel, where ET is predicted from the residual amount of energy remaining from the classical energy balance, where ET = net radiation – heat to the soil – heat to the air.

In Phase 1 for the Bear River Basin, the difference between SEBAL and the lysimeter, total, for the growing season was 4%. For the Phase 2 comparison with precision weighing lysimeters at Kimberly, differences were less than 2%. These comparisons represent a small sample, but are probably typical. Error as high as 10 to 20%, if distributed randomly, could probably be tolerated by IDWR and by the water user communities.

Comparisons of SEBAL predicted ET with precision weighing lysimeter data at Kimberly, Idaho, from 1989 have provided valuable information on the conditions required to obtain maximum accuracy with SEBAL and the best procedure for obtaining ET monthly and annually. ET has been calculated for the entire Snake River Plain of southeastern Idaho and has improved the calibration of ground-water models by providing better information on ground-water recharge as a component of water balances. Ground-water pumpage from over 10,000 wells has been estimated using ET from SEBAL by developing correlations between ET and pump discharge at measured wells and then extrapolating over large areas using ET maps from SEBAL.

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