

## CROP WATER REQUIREMENTS FROM A REMOTE SENSING MODEL FOR THE SNAKE PLAIN AREA IN IDAHO

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### Abstract

SEBAL (Surface Energy Balance Algorithm for Land) is a remote sensing model comprised of twenty-five submodels for calculating crop water requirements or evapotranspiration (ET) for large areas. 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 United States Department of Agricultural Research Center at Kimberly, Idaho. ET maps via SEBAL provide the means to quantify, in terms of both the amount and spatial distribution, the ET on a field-by-field basis. ET from satellite images may ultimately replace current procedures used by management entities that rely on ground-based ET equations and generalized crop coefficients that have substantial uncertainty. Initial application and testing of SEBAL indicates substantial promise as an efficient, accurate, and relatively inexpensive procedure to predict the actual evaporation fluxes from irrigated lands throughout a growing season.

**Keywords:** Evapotranspiration, Remote Sensing, Satellites Images, Water Rights

## REQUERIMIENTOS DE AGUA PARA CULTIVOS USANDO UN MODELO DE SENSORES REMOTO EN EL AREA DE SNAKE PLAIN, IDAHO

### Resumen

SEBAL (Algoritmo para el Balance de Energía Superficial) es un modelo de teledetección compuesto de 25 sub-modelos para calcular las necesidades de agua de los cultivos o evapotranspiración (ET) en áreas extensas. SEBAL fue desarrollado en Holanda por Bastiaanssen y ha sido modificado en Idaho, EE.UU. para ser aplicado en agricultura, terrenos montañosos y lagos en condiciones semi-áridas. SEBAL ha sido aplicado en muchos países en desarrollo y es aplicado actualmente en Idaho para predecir ET mensual y por temporada, para contabilizar derechos de agua y para la operación de modelos de agua subterránea. Los resultados obtenidos con SEBAL fueron validados al compararlos con mediciones en lisímetros de precisión efectuados en el Centro de Investigación del Departamento de Agricultura ubicado en Kimberly, EE.UU. Los mapas de ET generados por SEBAL proveen las herramientas para evaluar el valor de ET en términos cuantitativos, así como su distribución espacial en cada campo. Los valores de ET obtenidos a través de imágenes de satélite permitirán en un futuro reemplazar las metodologías actuales, basadas en mediciones locales y coeficientes de cultivo. Las aplicaciones iniciales y

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evaluaciones de SEBAL han mostrado eficiencia y exactitud para predecir la evapotranspiración real en áreas bajo riego.

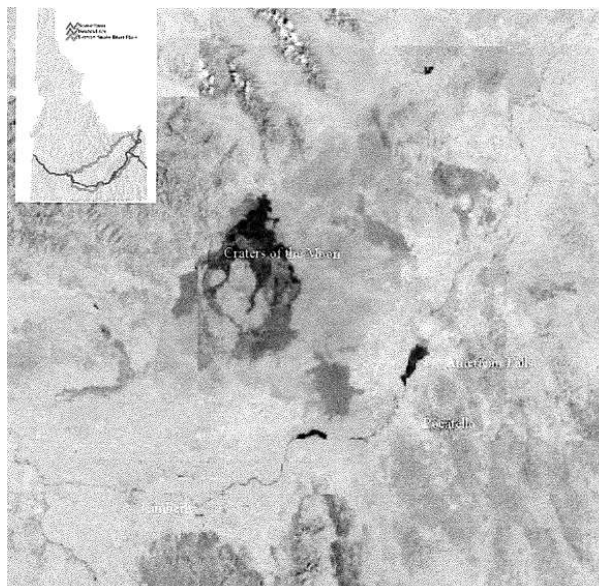
**Palabras claves:** Evapotranspiración, Teledetección, Satélites, Derechos de Agua

### Introduction

SEBAL is an emerging technology that has the potential to become widely adopted and used by water resources communities, both nationally and globally. Evapotranspiration (ET) maps created using SEBAL or similar remote sensing based on 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 being used to generate seasonal ET maps for predicting effects of irrigation on stream flow depletion in the Bear River Basin and within 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 of irrigated farmland. Details of the study area are shown in Figure 1.

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



**Figure 1.** Snake River Plain in Idaho, USA

### *Materials and methods*

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  $ET = R_n - G - H$ ;  $R_n$  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 the Idaho study using the ERDAS Imagine software with modelmaker coding. Modifications to SEBAL, made during the Idaho study, have included the method for selecting anchor points in the energy balance, autocalibration procedure and means for extrapolating ET predicted at the time of the satellite overpass to the encompassing 24-hour period, as well as to the intervening period between satellite images (Trezza, 2002).

The application of the model SEBAL in the State of Idaho involved two stages: 1) the validation of the model by comparing estimates of ET using SEBAL and measurements of ET using lysimeters, and 2) the application of SEBAL to estimate ET in the Snake River Plain in 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 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. In addition, measurements of net radiation, soil heat flux and plant canopy parameters were frequently made at or near the lysimeter site. The lysimeter data sets at Kimberly provide valuable information to verify SEBAL and other remote sensing algorithms over various time scales and for various types and categories of land cover.

Nineteen Landsat 5 satellite image dates were purchased for Kimberly, Idaho, covering the period between 1986 and 1991. These dates were for cloud-free conditions at Kimberly having high quality lysimeter and micrometeorological data. The dates represented a combination of various crop growth stages and times of the year. Eight images processed for 1989 are discussed here. After validating the model, SEBAL was applied for ET estimation in the entire Snake River Plain in Idaho.

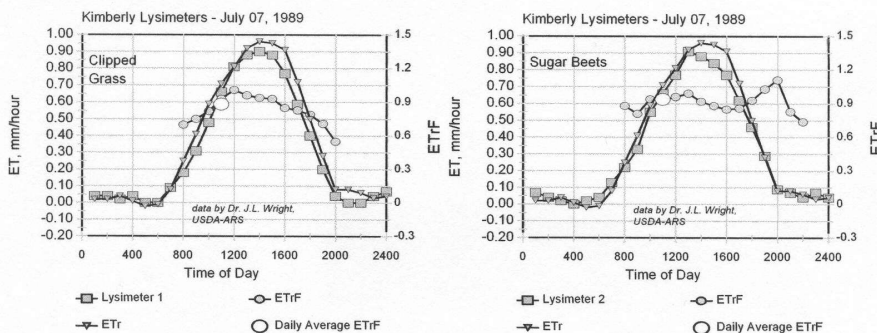
### **Results and discussion**

The Model SEBAL was validated and then applied to the Snake Plain River area in Idaho. The results are commented separately.

#### **Model Validation**

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 time periods. They have also been used to assess the variability in ETrF (the ratio between actual ET and alfalfa reference ETr) over the course of a day. The success of SEBAL is partially predicated on the assumption that ETrF for a 24-hour period can be predicted from the ETrF from the instantaneous satellite image. ETr 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, full-cover alfalfa 0.5 m in height. The denominator  $ET_r$  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. An illustration of  $ET_rF$  for a day in 1989 is given in Figure 2 for clipped grass (fescue) and sugar beets.  $ET_rF$  for many days was even more uniform than shown in the figure. In nearly all cases, the  $ET_rF$  for the 24-hour period was within 5% of the  $ET_rF$  at 1030.



**Figure 2.** Hourly measured ET,  $ET_r$ ,  $ET_rF$  and 24-hour  $ET_rF$  for July 7, 1989 for clipped grass (left) and sugar beets (right) at Kimberly, Idaho.

Table 1 summarizes error between SEBAL and lysimeter measurements of ET during 1989. Absolute error averaged 30% for the eight days. When April 18 was omitted, the average absolute error for a given image date was only 14%. The April 18 date 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, but for more than 30 million individual pixels.

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

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

Image Date	Lys. ET on date (mm d-1)	SEBAL ET on date (mm d-1)	Error on Image Date (%)	ETr on date (mm d-1)	ETr 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						718a	705b	714c
Percent Error						-----	-1.8%	-0.6 %

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

<sup>b</sup> The sum of ET computed for each lysimeter period, computed by multiplying summed ETr during the period by the ETrF for the image date.

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

### Snake River Plain Application

Managing water rights and irrigation on the Snake River Plain and tributary basins presents a challenge to the Idaho Department of Water Resources (IDWR). Water for irrigation comes from both 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 (WMIS) 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 some 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 many advantages over present methods: 1) it offers the ability to monitor the requirement of water by crops; 2) it can discover if more water has been used than is 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 historic 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.

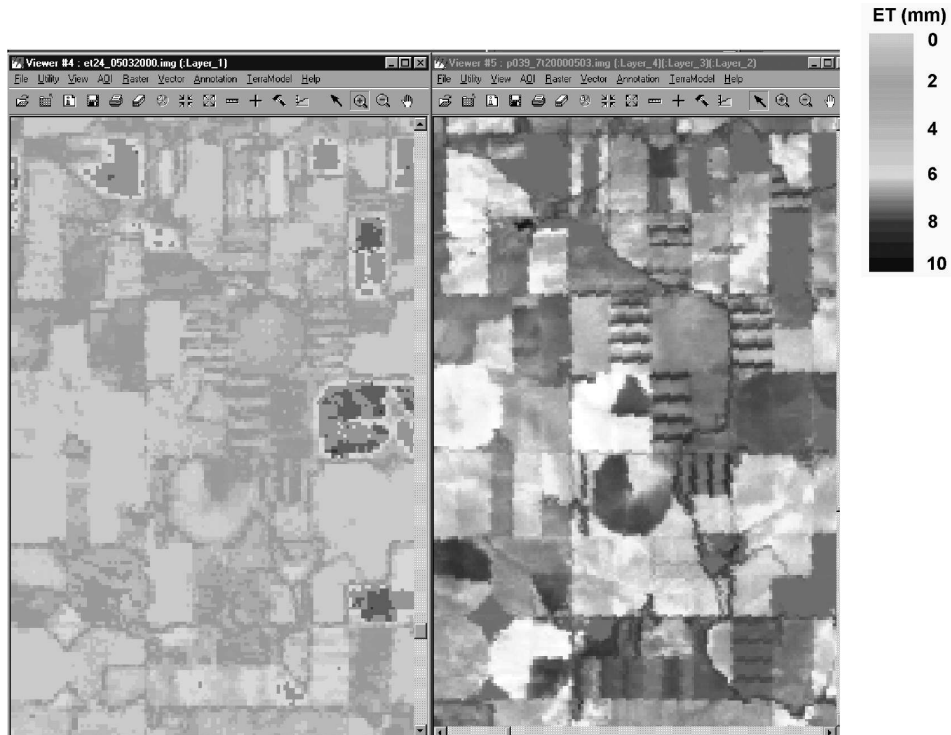
A number of tasks during Phase II (Allen et al., 2001, Trezza, 2002) were directed at improving components of SEBAL to better predict ET for environments found in the western of United States. These included prediction of net radiation and soil heat flux components, improvement in identification and assessment of the energy balance for "indicator" pixels (i.e., the so-called "hot" pixel and "cold" pixels of SEBAL), determination of mean wind speeds in mountain areas, prediction of aerodynamic roughness for various vegetation covers, and development of an ET reference fraction (ET<sub>rF</sub>) 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 (ESPA) was highly successful. ET images were created for 12 dates during year 2000 and were integrated over the March – October period. Interpolation between image dates was done using ET<sub>rF</sub> from pixels of each image and multiplying these by ET<sub>r</sub> computed for each day between images.

Resulting seasonal ET maps are utilized by the State of Idaho, University of Idaho (UI), and US Bureau of Reclamation ground-water modelers to predict recharge of irrigation water to the ESPA. IDWR and UI have begun re-calibrating the Eastern Snake River Plain ground water model to better predict ground-water levels and spring discharge to the Snake River, along with impacts of ground-water pumpage. The re-calibrated model will be used in support of conjunctive management of ground and surface water. A necessary component of recalibration is better estimation of aquifer recharge. Improved ET estimates (spatially, temporally and in total magnitude) will significantly reduce the uncertainty involved in computing the net recharge terms.

Images were purchased from both Landsat 5 and Landsat 7 archives for the year 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.

An illustration of the type of resolution for ET maps generated from Landsat imagery is shown in Figure 3 for a 4 km x 6 km area near American Falls, Idaho.



**Figure 3.** Close-up of ET (left) with false color composite (right) from Landsat 7 showing variation within individual fields May 5, 2000.

### 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  $ET = \text{net radiation} - \text{heat to the soil} - \text{heat to the air}$ .

With regard to the model validation 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 during 2001 have provided valuable information on the conditions required to obtain maximum accuracy with SEBAL and the best procedure for obtaining ET for monthly and annual time periods. ET has been calculated for the entire Snake River Plain of southeastern Idaho, which can improve the calibration of ground-water models by providing better information on ground-water recharge as a component of water balances.

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