Application of SEBAL for Western US Water Rights Regulation and Planning

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Abstract
Quantifying evapotranspiration (ET) from irrigated projects is important for water rights management, water resources planning and water regulation. Traditionally, ET from agricultural fields has been estimated by multiplying the weather-based reference ET by crop coefficients (Kc) determined according to the crop type and the crop growth stage. However, there is typically some question regarding whether the crops grown compare with the conditions represented by the Kc values, especially in water short areas. In addition, it is difficult to predict the correct crop growth stage dates for large populations of crops and fields. Recent developments in satellite remote sensing ET models have enabled us to accurately estimate ET and Kc for large populations of fields and water users and to quantify net ground-water pumpage in areas where water extraction from underground is not measured.

SEBAL (Surface Energy Balance Algorithm for Land) is an image-processing model comprised of twenty-five submodels for calculating evapotranspiration (ET) as a residual of the surface energy balance. SEBAL was developed in the Netherlands by Bastiaanssen and was extended during Idaho applications for mountainous terrain and with tighter integration with ground-based reference evapotranspiration. SEBAL has been applied with Landsat images in southern Idaho to predict monthly and seasonal ET for water rights accounting and for operation of ground water models. ET “maps” (i.e., images) via SEBAL provide the means to quantify, in terms of both the amount and spatial distribution, the ET on a field by field basis. The ET images generated by SEBAL show a progression of ET during the year as well as distribution in space.

ET from satellite images may ultimately replace current procedures used by state departments of Water Resources and other management entities and ministries 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 inexpensive procedure to predict the actual evaporation fluxes from irrigated lands throughout a growing season.

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Resume

Il est important de mesurer l'évapotranspiration ET de l'agriculture irriguée. ET est employé pour les projets qui impliquent des droites gestion de l'eau, la planification de ressource d'eau, et le règlement de l'eau. Traditionnellement, ET des champs agricoles a été estimé en employant la référence survie-basée ET. La référence ET est multipliée par les coefficients de récolte (Kc). Les coefficients sont calculés pour chaque récolte et pour la quantité de croissance de chaque récolte. Cependant, la croissance de récolte réelle peut ne pas assortir les conditions représentées par les valeurs de Kc, particulièrement s'il n'y a pas assez d'eau. En outre, il est difficile de prévoir correctement la taille de la récolte n'importe quelle date s'il y a beaucoup de champs de la récolte. Les développements récents en utilisant des modèles ET de la télédétection satellite nous permettent d'estimer exactement les les deux ET et le Kc pour de grands secteurs des récoltes.

SEBAL (algorithme extérieur de bilan énergétique pour la terre) est un modèle de télédétection. Il calcule ET comme résiduel du bilan énergétique extérieur. SEBAL a été développé en Hollandes par Bastiaanssen. En Idaho, il a été prolongé au terrain montagneux, et il plus étroitement est intégré avec la référence au sol ET. En Idaho méridional, SEBAL a été employé avec Landsat pour prévoir ET par mois et par saison. ET a été employé pour la comptabilité du permis pour l'usage de l'eau pour des modèles de l'eau souterraine. Les cartes de ET décrivent la quantité et l'endroit ET pour de chaque champ agricole. ET les cartes de SEBAL montrent le changement dans ET au-dessus du temps et de l'espace.

Méthodes courantes pour calculer ET employer des coefficients généraux de récolte, et pour produire des résultats incertains. Les essais initiaux montrent cela ET de la télédétection peut être efficace, précis, et peu coûteux, et ce SEBAL peut prévoir réel ET de la terre irriguée pendant une saison de croissance entière.

Introduction

SEBAL uses digital image data collected by Landsat or other remote-sensing satellites that record thermal infrared radiation in addition to 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. Details are presented in Bastiaanssen et al. (1998), Bastiaanssen (2000) and Tasumi et al., (2003a).

SEBAL applications in Idaho and surrounding areas have been made over a three year period. In year 1, ET maps were created for the Bear River Basin that covers 20,000 km² of the three USA states of Idaho, Utah, and Wyoming and contains about 190,000 ha of crop and pasture land. The purpose of the application was to quantify the amount of irrigation water that is evaporated and transpired by each of the states. Water from the Bear River is divided among the three states according to an apportionment that was agreed upon in the 1950’s. Each state
must determine how many hectares of land to can be developed for irrigation before the net depletion to the river resource exceeds that state’s apportionment. The determination has been difficult to accomplish, and in the past was made using the standard crop coefficient – reference ET procedure. However, differences between ET from cropped land and natural rangeland that is replaced by irrigated agriculture must be considered. River depletions by irrigated agriculture are defined as the differences between diversions and net returns to the river system via ground water. Because the net returns to the river are in diffuse form, they are impossible to measure. Net depletions are therefore predicted using ET from irrigated lands less any ET that would have occurred from natural range conditions in the absence of irrigation. In addition, the type of crops grown impact the total stream depletion. SEBAL was used to provide the integrated total ET from irrigated and natural systems in the Basin.

In years 2 and 3, ET was determined for the Snake River Plain of southeastern Idaho. The Snake River Plain and 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 (Fig. 1). Comparisons of ET predicted by SEBAL with precision weighing lysimeter data at Kimberly, Idaho provided information on the conditions required to obtain maximum accuracy with SEBAL and the best procedure for obtaining ET for monthly and annual time periods. The generated ET maps have 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 an area containing 5,000 to 6,000 wells has been estimated using ET from SEBAL by developing correlations between ET and pump discharge at about 400 measured wells and then extrapolating to the larger area using ET maps from SEBAL (Morse et al, 2001).

In the Idaho applications, we have exclusively used Landsat imagery. The attractiveness of Landsat is the high resolution (30 m in the visible and near infrared bands and 60 to 120 m in the thermal band) so that ET from individual fields can be observed. Field-scale ET is very important for water rights regulation where proof of water consumption on a field by field basis is often required. Field-scale ET also permits using SEBAL to define new crop coefficients for an area.

As mentioned, there are several operational or nearly operational energy-balance based remote sensing models for predicting ET from satellite imagery, including SEBAL. Primary reasons why SEBAL is attractive to our applications include the following:

Fig. 1. State of Idaho showing irrigated areas in the Snake Plain (southern part of state) as bright green.
SEBAL can be configured for each image to predict ET at key locations (pixels) where the real ET is known via ground-based calculations of ET (made using weather data) or via known surface characteristics (Bastiaanssen et al., 1998; Tasumi et al., 2003a). Therefore, the ET map product created by SEBAL is fully compatible with ground-based ET values in which our confidence is high.

Implicit internal calibration of sensible heat computation within SEBAL eliminates the need for atmospheric correction using radiative transfer models for surface temperature and albedo (Tasumi et al., 2003a). The internal calibration also reduces impacts of any bias in aerodynamic stability correction or roughness prediction.

SEBAL relies heavily on theoretical and physical relationships, but provides for the introduction of empirical coefficients and relationships in order to make the process operational and accurate.

Bear River Application

The Bear River meanders from the Uinta Mountains of northern Utah into Wyoming, then to Utah, then west into Idaho, and then back into Utah where it empties into the Great Salt Lake (Fig. 2). The river and its tributaries are used primarily for irrigation. In 1958 the Bear River Compact was developed to establish how the three states of Idaho, Utah and Wyoming would equitably distribute and use water from the Bear River. In February 1980 the Amended Bear River Compact was signed into federal law. The compact assigns a depletion (i.e. ET) allotment to each state and directs the Bear River Commission to develop and implement "approved procedures" to account for and calculate the amount of water depleted. The role of IDWR is to compute depletion 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 Bear River basin to assist in administration of the Bear River Compact.

In year 1 (2000) of our SEBAL applications, ET maps were generated on a monthly basis for a 500 km x 150 km area comprised of 2 Landsat images and encompassing the Bear River basin (Morse et al., 2000). Landsat images were processed for 1985 since 1985 coincided with an ET study using lysimeters (Hill et al., 1989). Lysimeters were located near Montpelier, Idaho, north of Bear Lake. The lysimeters were planted to a native sedge forage crop characteristic of the area. Allen et al., (2002) and Tasumi et al., (2003a) show results of the comparisons of SEBAL with lysimeter. Summary results are shown in Table 1 for monthly ET.
ET information from SEBAL was presented in mm/month and in terms of crop coefficients (Kc). The Kc was defined as ET/ETr, where ETr is reference ET, which in our applications is based on an alfalfa reference crop rather than on grass. The alfalfa reference is preferred in the semi-arid USA because it approximates the upper limit of ET by many crops, thus the upper limit of the Kc is generally 1.0. In addition, use of alfalfa ETr facilitates internal calibration of the SEBAL process (Tasumi, 2003; Trezza, 2002; Tasumi et al., 2003a). In the SEBAL application, Kc’s are computed for each pixel and are used to extrapolate ET from the day of the satellite image to days between images. ETr is computed for each day between images and accounts for changes in ET caused by weather variation from day to day.

Predicted ET for monthly periods averaged +/- 16% as compared to the lysimeter at Montpelier (Table 1). However, seasonal differences between SEBAL and lysimeters were only 4% due to impacts of reduction in the random error components. An image of the final July – October period ET map for 1985 is presented in Fig. 3. The white areas are locations where there was cloud cover on one or more of the images and thus were masked out as white. The monthly and seasonal ET maps for the basin are being studied to provide information on total water consumption. Total net depletion of river flows can be computed by entering the ET maps into a GIS structure and integrating over the irrigated areas. The final depletion is then corrected by subtracting out the ET for the same area that would have occurred by natural vegetation or by dryland farming in the absence of irrigation.

Table 1. Summary of SEBAL- and lysimeter-derived ET values for weekly and monthly periods and the associated error for Bear River application, 1985.

<table>
<thead>
<tr>
<th></th>
<th>Lysimeter ET mm/d</th>
<th>7-day SEBAL ET mm/d</th>
<th>7-day SEBAL Kc</th>
<th>Differences in 7-day ET (SEBAL – Lys) %</th>
<th>Monthly Alfalfa Reference ET mm</th>
<th>Monthly SEBAL Monthly ET mm</th>
<th>Monthly Lysimeter Monthly ET mm</th>
<th>Monthly Kc for Lys.</th>
<th>Monthly ET (SEBAL) – Lys %</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td>5.3</td>
<td>0.98</td>
<td>6.8</td>
<td>28%</td>
<td>202</td>
<td>198</td>
<td>167</td>
<td>0.83</td>
<td>19%</td>
</tr>
<tr>
<td>Aug</td>
<td>3.5</td>
<td>0.59</td>
<td>3.7</td>
<td>6%</td>
<td>201</td>
<td>119</td>
<td>145</td>
<td>0.72</td>
<td>-18%</td>
</tr>
<tr>
<td>Sept</td>
<td>1.9</td>
<td>0.57</td>
<td>2.1</td>
<td>10%</td>
<td>115</td>
<td>66</td>
<td>54</td>
<td>0.47</td>
<td>22%</td>
</tr>
<tr>
<td>Oct</td>
<td>0.7</td>
<td>0.49</td>
<td>0.6</td>
<td>-14%</td>
<td>45</td>
<td>22</td>
<td>23</td>
<td>0.51</td>
<td>-5%</td>
</tr>
<tr>
<td>July–Oct</td>
<td>2.9</td>
<td>0.73</td>
<td>3.3</td>
<td>15%</td>
<td>563</td>
<td>405</td>
<td>388</td>
<td>0.69</td>
<td>4%</td>
</tr>
</tbody>
</table>

Snake River Plain Application

Administering water rights and irrigation on the Snake River Plain and tributary basins presents a challenge to 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 ET, which is the
consumed fraction of diversions, is needed. SEBAL has been used in conjunction with Water Measurement data to provide pumping estimates for large areas inexpensively and efficiently, thereby extending Water Measurement Data in both time and space.

Fig. 3. SEBAL-driven ET “map” of the Bear River Basin area showing cumulative ET for the period July 1 through October 21, 1985.

This combined program offers advantages over present methods. First, it offers the ability to monitor whether or not water has actually stopped being used for irrigation after a water shut-off order has been issued. Second, it can discover if more water has been used than is authorized. Third, it can quantify and be used as proof of beneficial use of a right. Fourth, it can be used as an unbiased, quantitative record of historic use. Fifth, the consumed fraction and return of non-evapotranspired water to the resource can be quantified. Sixth, estimations of yield and productivity (Bastiaanssen et al., 2001) can be made to assess benefits of water development and potential tradeoffs in water management.

The production of ET maps having 30 m resolution for the Eastern Snake River Plain Aquifer (ESPA) for years 2000 and 2002 has been highly successful. ET images were created for 12 dates during year 2000 and were integrated.

Fig. 4. Seasonal ET for Eastern Snake River Plain of Idaho
over the April – October period (Figure 4). Interpolation between image dates was done using $K_c$ from pixels of each image and multiplying these by $ET_r$ computed for each day between images.

![ET map computed by SEBAL for a portion of southern Idaho. Circular areas are 800 m diameter center pivot systems.](image)

Fig. 5. Close up of ET map computed by SEBAL for a portion of southern Idaho. Circular areas are 800 m diameter center pivot systems.

Resulting seasonal ET maps, following import into a GIS system, are utilized by the State of Idaho, University of Idaho, and US Bureau of Reclamation planners, water rights regulators, hydrologists, and irrigation engineers to quantify water consumption. Ground-water modelers are using the maps to predict recharge of irrigation water to the ESPA. IDWR and UI have recalibrated the ESPA ground water model that is used to simulate ground-water levels and movement. The model predicts interactions of the aquifer system with stream-flows of the Snake River and will be used in support of conjunctive management of ground and surface water.

Recharge from both irrigated and non-irrigated lands is a major component in developing the long-term water balance for the ground-water model, and is the amount of water remaining after ET is subtracted from the amount of water diverted from surface-water sources plus precipitation. An improved ET estimate (spatially, temporally and in total magnitude) significantly reduces the uncertainty involved in computing the net recharge input terms. SEBAL allows IDWR to compute the agricultural ET component of the model in an efficient and inexpensive way, and to compute the wildland ET component for the first time.

Images were purchased from both Landsat 5 and Landsat 7 archives to increase the number of images available for the Southern Idaho area. Often, images were available where the dates for adjacent Landsat paths were separated by only one day. This was made possible by
obtaining Landsat 5 images for one path and Landsat 7 images for the adjacent path. We found Landsat 5 images to be of immense value in predicting ET between Landsat 7 dates.

**Validation of SEBAL at Kimberly, Idaho**

The validation of SEBAL on the Snake River Plain centered on the use of two precision weighing lysimeter systems for evapotranspiration measurement that were in place at Kimberly, Idaho from 1968 to 1991 (Wright, 1982, 1996). The lysimeter data sets at Kimberly are extremely valuable in that they represent absolute, continuous measurements of ET fluxes spread over a long period of time. They provided valuable information to verify procedures used to extrapolate SEBAL and other remote sensing algorithms over various time scales and for various types and categories of land cover. The validation results and SEBAL applications are fully described by Tasumi (2003) and Trezza (2002) and are summarized in Allen et al. (2002) and Tasumi et al. (2003a). The validation with the lysimeters at Kimberly guided and supported the use of ET$_r$ to define the evapotranspiration at the “cold” pixel of SEBAL and for extrapolation from the satellite image time to the full day and to days in between image dates.

**Derivation Of Crop Coefficient Curves**

A valuable product of SEBAL applications over a growing season are crop coefficient curves derived by sampling the ET maps for specific fields. This was done for 2000 for the Twin Falls area of Idaho. More than 2500 fields were classified for crop type and ET was sampled (Tasumi et al., 2003b). Results for 717 sampled potato fields are shown in Fig. 6 for K$_c$ and Fig. 7 for NDVI. The distribution and progression of K$_c$ with time is typical of potato growth, and the impact of soil wetness from irrigation on K$_c$ is evident, especially during the period of development (days 120 – 180). NDVI, the normalized difference vegetation index, was computed from the Landsat images and is commonly used to indicate the amount of vegetation. In some studies, NDVI has been used to predict K$_c$ (Neale et al., 1989, Bausch and Neale. 1989, Bausch, 1993, 1995, Choudhury et al., 1994). In fact, similarity between the progression and distribution of K$_c$ and NDVI with time is evident between Figs. 6 and 7. However, primarily because of impacts of soil wetting on K$_c$, the two parameters do not follow a directly predictable relation. This is illustrated in Fig. 8 where the fraction of reference ET (i.e., K$_c$) is plotted against NDVI for the same 717 fields for three image dates.

The first date shown in Fig. 8, in early June, is during plant development when a majority of the soil surface is bare. Impacts of soil wetting on evaporation (and thus ET) for the period of low vegetation cover is quite evident. The second date, in late June, had higher vegetation cover, with less impact from evaporation from soil. The last date, in late July, is a period of maximum crop development when the surface is nearly completely covered by vegetation so that impacts of soil surface wetness on K$_c$ are not pronounced. The relationship between K$_c$ and NDVI is irregular because of the impacts of surface wetting. The illustration of Fig. 8 shows that any relationship between K$_c$ and NDVI (or other vegetation index) will be useful primarily for predicting a baseline (i.e., “basal”) K$_c$ estimate, which is shown as the solid line in Fig. 8 and which represents K$_c$ for a relatively dry soil surface. Fig. 8 illustrates, however,
that a full energy-balance based remote sensing model is necessary to determine total water consumption, including evaporation from the soil surface.

Fig. 6. Crop coefficients determined by SEBAL from 717 potato fields in the Twin Falls area of Idaho for 12 Landsat image dates during 2000 (solid line is the mean).

Fig. 7. Normalized Difference Vegetation Index (NDVI) from 717 potato fields in the Twin Falls area of Idaho from 12 Landsat image dates during 2000.
In addition to impacts of soil surface wetting, $K_c$ can vary from NDVI under conditions of soil water shortage. This impact is not evident in Fig. 8, however, because potatoes fields in southern Idaho are under nearly optimum production and water management. The derived $K_c$ curves, especially the average curve shown in Fig. 6, are useful for characterizing the real, expected $K_c$ curves for a region. Tasumi et al., (2003a,b) show comparisons of $K_c$ derived from SEBAL with $K_c$ curves based on traditional procedures and data.

![Crop Coefficient vs. NDVI for 717 potato fields in the Twin Falls area of Idaho for two Landsat dates during 2000.](image)

**Fig. 8.** Crop coefficient vs. NDVI for 717 potato fields in the Twin Falls area of Idaho for two Landsat dates during 2000.

**Cost Savings**

SEBAL ET data are clearly less expensive to produce for large regions than are ET data produced by the standard methods of crop coefficient and reference ET on a field by field basis. There are several ways to use SEBAL-derived ET products. ET is a component of ground-water models and can be used to estimate net depletion from aquifers. The ET data are also used as a tool in administering water rights. Because IDWR is still integrating
SEBAL data into their operations, a quantitative cost-benefit analysis is premature. Nevertheless, a general cost comparison was performed by Morse et al., (2002) who estimated costs for ground-based monitoring of pumping systems in the eastern Snake River Plain of Idaho to be about $500,000 per year. Costs for providing similar information using SEBAL are estimated to be about $80,000 per year. Thus, there is a very large economic advantage (nearly 6 to 1) for using satellite based ET mapping to replace ground-water pumpage monitoring. The other beneficial products of the ET maps (for calibration of groundwater models and development of $K_c$ curves) increase the ratio even more.

It is recognized that ET mapping from satellite will never completely replace ground-based pump measurements, since some measurement data related to individual water rights are needed to develop regressions against the SEBAL ET data to establish relationships between volumes of water pumped and volumes of ET. However, the developed relationships can be applied to large areas containing non-monitored water rights and associated wells to estimate both aquifer depletion and water use by individual water rights.

Conclusions

ET maps for the Bear River Basin and for the Eastern Snake River Plain were generated using SEBAL on an approximately monthly basis. The maps showed a progression of ET during the year as well as the distribution of ET in space. Predicted ET compared well with ground measurements of ET during the studies that were derived by lysimeter systems.

SEBAL is an emerging technology and has the potential to become widely adopted and used by water resources and irrigation communities. The application and testing of SEBAL in Idaho indicates substantial promise as an efficient, accurate, and relatively inexpensive procedure to predict the actual ET from irrigated lands throughout a growing season. This work supports findings in other parts of the world. 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 and any associated ground-water usage. In particular, the Idaho Department of Water Resources (IDWR) will use results to predict total, net depletion of water from the Bear River system and Snake Plain aquifer systems resulting from irrigation diversions and to regulate irrigators who are consuming more water than their water rights entitle.

Acknowledgements

The authors wish to acknowledge technical and philosophical guidance over the past four years by Dr. Wim Bastiaanssen of WaterWatch, The Netherlands. We also acknowledge precision lysimeter data provided by Dr. J.L. Wright of the USDA-ARS, Kimberly, Idaho and image processing technical advise from Mr. William Kramber, Idaho Department of Water Resources. Funding for the studies and applications reported was from Raytheon, Idaho Dept. Water Resources, and University of Idaho.
References


