Improving the picture for irrigation using SEBAL in Australia to measure evapotranspiration (ET)

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Abstract

This paper discusses remote sensed measurements of evapotranspiration (ET) within the Australian irrigation sector. Sinclair Knight Merz (SKM) and WaterWatch have undertaken a major water resource assessment for the National Water Commission using SEBAL 2009, a remote sensing software application that provides spatial and temporal measurement of evapotranspiration at varying scales, from paddock to basin. The project involved application of the technology at a range of scales and geographic locations, that covered a range of water resource issues including identification of water requirements for groundwater dependent ecosystems, water use in plantations, evaporative losses from storages, and variance within specific agricultural landuse within regional catchments. Outcomes from the project have resulted in a better understanding of the business requirements for satellite based measurements of water use in the agricultural industry.

INTRODUCTION

The question of how much water is being used by different land use types at the catchment scale is the great unknown in the catchment water balance. Estimates of evapotranspiration (ET), or actual water use, have generally been scaled up from field experiments which can be expensive and of limited accuracy for estimating evapotranspiration across landscapes.

An innovative and cost effective application called SEBAL 2009, which is based on the Surface Energy Balance Algorithm for Land (Bastiaanssen et.al. 1998; 2005), uses readily available satellite imagery, for estimating water use by vegetation at large scales. The application has undergone 15 years of extensive development and is an existing operational tool that has been successfully applied across the world and peer reviewed by the international scientific community.

Funding from the National Water Commission has enable SKM in collaboration with WaterWatch, the developers of SEBAL 2009, to evaluate the use of the remote sensing methods to estimate water use across the Australian landscape and to scope out specific applications for water resource managers, which includes irrigation (SKM, 2009).

Evaporation is the volume of water transferred to the atmosphere from the earth’s surface (i.e. soil and water) and canopy interception. Transpiration is the volume of water
Evapotranspiration is calculated as the residual of the surface energy budget equation:

\[ ET = R_n - G - H \]

Where \( ET \) is the latent heat flux (\( W/m^2 \)), \( R_n \) is the net radiation flux at the surface (\( W/m^2 \)), \( G \) is the soil heat flux (\( W/m^2 \)) and \( H \) is the sensible heat flux to the air (\( W/m^2 \)).

The primary input data for SEBAL 2009 is satellite imagery data that consists of spectral radiance in the visible, near infrared and thermal infrared part of the spectrum. Commonly used satellite imagery includes Landsat and MODIS. Satellite imagery data for the area of interest is sourced and models run to calculate the surface radiation (energy in) for each pixel for each individual image. Further models are run to determine intermediate indices including: normalised difference vegetation index (NDVI), leaf area index (LAI) and albedo (light reflectance). All products to this stage are instantaneous for the time and date of the satellite imagery, and are not temporally distributed.

Meteorological data is acquired including solar radiation, atmospheric air temperature, relative humidity and wind speed. This data is sourced as point-based measurements and interpolated to derive a spatially distributed gridded data surface.

Using the interim products in conjunction with the gridded meteorological data, models are run to produce grids of net radiation, soil heat flux and sensible heat flux. The remaining elements of the evapotranspiration calculation are then determined and the SEBAL algorithm solved. The SEBAL results for each image date are integrated over time, using a daily evaporative factor derived from meteorological data to provide daily estimates of ET. The Penman-Monteith equation is used subsequently to compute weekly ET, using the actual bio-physical parameters derived on the satellite overpass day. The daily estimates of ET can be aggregated to provide monthly, quarterly, and annual estimates.

The key output of SEBAL 2009 is gridded output files of spatially and temporally distributed actual and potential evapotranspiration (ET).

COMPARABILITY

To provide confidence in the accuracy of the image processing a comparison with field based evapotranspiration measurements provided by NSW Department of Primary Industries and CSIRO was undertaken. The objective was to determine if there is overlap between the estimates, while acknowledging that all methods include error when comparing results. Aside
of the inherent errors, it is not desirable that SEBAL show bias by consistently over estimating or under estimating compared to other methods.

The Key Sites Project commenced under the NSW Salinity Strategy in 2003, has eight research sites across the NSW tablelands (Mitchell et al. 2006). At these sites, intensive measurements of the Bowen ratio have been used to derive components of the water balance, particularly the amount of water used by plants. The Bowen ratio is the ratio of energy fluxes used for sensible heat (convection) compared to latent heat (evaporation). Because the Bowen ratio is an expression for the energy partitioning at the evaporating surface, it can be used in conjunction with net radiation to estimate evapotranspiration from an area of the land surface.

The Bowen ratio measurement represents the conditions in the atmosphere upwind of the measurement location for an approximate horizontal distance of 100 times the height of the Bowen ratio equipment. For the NSW Key Sites, the height is 2 m, therefore wind rose (speed and direction) data was used to define a “wedge” shape for 200 m upwind of each site on each day of recorded data, using the dominant wind speed and direction(s) through the day. The average evapotranspiration calculated via the SEBAL method within the wedge shaped area was used for comparison with the field ET measurement from the Bowen ratio measurement sites.

The Bowen ratio and SEBAL ET estimates are shown in Figure 1 on a scatter plot, with a 1:1 line also displayed. There is no obvious bias to the data; that is, the distribution of points where SEBAL is higher or lower than the Bowen ratio estimates is quite random and evenly distributed above and below the 1:1 line. For the sake of datapoint reduction, the average ET for each site has been considered. The overall coefficient of efficiency for the entire data set is 0.56 and the overall root mean square (RMS) error in the daily data is 53% of the mean daily evaporation rate. However, the differences between SEBAL and the Bowen Ratio estimates are lowest during the seasons when the evaporation rates are at their highest. For the October 2004 data, when evaporation rates in this data set are relatively high, the SEBAL and Bowen ratio estimates are highly correlated, with a coefficient of efficiency of 0.65, a mean absolute error of 7% and an RMS error of 23%. For the summer 2005 data (Jan-Feb), there is a reasonable correlation between the estimates, with a coefficient of efficiency of 0.34, mean absolute error of 25% and RMS error of 47%.

![Figure 1](image-url)

**Figure 1** Comparison of daily SEBAL and Bowen ratio evapotranspiration estimates for NSW Key Sites Project stations (Data courtesy of NSW DPI)
The results show that when the ET is very low, typically in winter, the percentage differences between the SEBAL and Bowen ratio estimates become more exaggerated. This is likely a result of decreased accuracy of the Bowen ratio energy balance approach at lower evaporative fluxes. This ratio can be accurately measured at relatively high evaporative fluxes when there is a distinct gradient of water vapour, however this method becomes less accurate at lower values. Moreover, the actual evapotranspiration fluxes from the Bowen ratio technique depend on the absolute values of net radiation and soil heat flux. A small mistake in one of these two terms will be translated into an error between the estimate and the true evapotranspiration rate.

Point measurements, at a daily scale, from any measurement technique include a significant amount of measurement uncertainty. Comparing single daily ET values from Bowen ratio measurements with single daily estimates from SEBAL will include measurement uncertainty from both sources and it is reasonable to expect differences between these values of +/- 30%. The comparisons between SEBAL and the Bowen ratio measurements are within this expected range for the spring 2004 and summer 2005 comparisons. Comparisons made using measurements that integrate evapotranspiration over longer periods of time and/or larger spatial domains were found to reduce the differences. Allen et al. (2007) showed a similar behaviour of the deviations from a lysimeters in Idaho (US); the deviation on individual Landsat days was 20 to 30%, but the accumulated ET value for the growing season was only a few percent.

In the south east of South Australia and south west of Victoria, CSIRO has collected measurements of daily transpiration for plantation forests (i.e. blue gum) based on daily sap flow measurements and approximately monthly interception and soil evaporation. The measurement techniques have been described in detail by Benyon and Doody (2004) and Benyon et al. (2006).

The CSIRO data and SEBAL 2009 estimates have been compared over the 2004/05 period on an annual basis. As CSIRO collected only periodic totals of rainfall, throughfall, stem flow and soil evaporation, calculating average daily ET (and consequently monthly) would result in some inaccuracies in individual day and months, however annual totals should be reasonably accurate (pers. comm. Richard Benyon, 2009). The average blue gum ET measured for the 6 sites is 857 mm and SEBAL annual values based on Landsat and MODIS data becomes 789 mm. This is an acceptable difference and comparable to earlier SEBAL validation studies (Bastiaanssen et al., 2005). This allows temporal comparison over a full year, even though the data collection periods are not identical. Site details and annual results are provided in Table 1.

### Table 1 Annual ET estimated using field measurements and SEBAL for CSIRO forestry plantation study sites for 2004/05

<table>
<thead>
<tr>
<th>Site</th>
<th>Approximate Location</th>
<th>Age (yr)</th>
<th>Height (m)</th>
<th>CSIRO Annual ET (mm)</th>
<th>SEBAL Annual ET (mm)</th>
<th>Difference</th>
<th>Percentage Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Approx 10 km north of Mt Gambier, SA</td>
<td>8</td>
<td>22</td>
<td>1094</td>
<td>786</td>
<td>-308</td>
<td>-28%</td>
</tr>
<tr>
<td>4</td>
<td>Approx 20 km west of Penola, SA, Approx. 400 m apart in same plantation</td>
<td>8</td>
<td>21</td>
<td>1054</td>
<td>778</td>
<td>-276</td>
<td>-26%</td>
</tr>
<tr>
<td>5</td>
<td>Approx 30 km west of Penola, SA, Approx. 70 m apart in same plantation</td>
<td>6</td>
<td>18</td>
<td>632</td>
<td>883</td>
<td>+251</td>
<td>+40%</td>
</tr>
<tr>
<td>6</td>
<td>Approx 20 km north-west of Port Fairy, Vic</td>
<td>6</td>
<td>15</td>
<td>683</td>
<td>686</td>
<td>+3</td>
<td>0%</td>
</tr>
</tbody>
</table>
SEBAL 2009 was used to determine total annual and monthly evapotranspiration from the Murray-Darling Basin using MODIS satellite imagery at a resolution of 250 m for the three assessment years being 2002/03, 2004/05 and 2007/08 (Table 2 and Figure 2).

In Figure 3, the temporal variation in ET across the year can be attributed to the variation in climatic conditions. The cumulative monthly totals show 2002/03 as having lower total ET which reflects the lower annual rainfall experienced across the Murray-Darling Basin, compared with other years.

Table 2  Total annual evapotranspiration from the Murray-Darling Basin, estimated using SEBAL 2009

<table>
<thead>
<tr>
<th>Assessment Period</th>
<th>Evapotranspiration rate (mm/year)</th>
<th>Evapotranspiration volume (GL/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002-03</td>
<td>337</td>
<td>366,870</td>
</tr>
<tr>
<td>2004-05</td>
<td>411</td>
<td>448,044</td>
</tr>
<tr>
<td>2007-08</td>
<td>413</td>
<td>450,052</td>
</tr>
</tbody>
</table>

APPLICATIONS

In addition to calculating total ET for a catchment, the SEBAL 2009 gridded output data, when used in conjunction with land use maps, provided information on ET variation between different land use types. In Table 3, annual rates and volumes of ET for various land uses are presented for the Murray Darling Basin and two sub-catchments; Broken River and Murrumbidgee River. The differences between the two sub-catchments reflects the difference in climatic conditions. The Murrumbidgee River Catchment had an annual rainfall of 406 mm in 2004/05, compared with 716 mm in the Broken River Catchment.

Note that the ET from irrigated land is a very small component, and the ET from pastures is dominant. The rate of ET from a particular land use type can vary significantly depending on localised climatic conditions, water availability and vegetation status. To illustrate this variation, evapotranspiration estimates were extracted for six sites (using single pixels of 250 m x 250 m) in close proximity (three within redgum forest and three within dryland farming) along the Murrumbidgee River near Narrandera in NSW. Figure 3 shows the locations of the pixels while Figure 4 shows the pattern of monthly evapotranspiration for each pixel for the 2007/08 water year.
Table 3  Total annual evapotranspiration from different land use types for Murray-Darling Basin and two sub-catchments Broken River and Murrumbidgee River for the 2004-05 water year, estimated using SEBAL 2009

<table>
<thead>
<tr>
<th>Land use type</th>
<th>ET from Murray Darling Basin</th>
<th>ET from Broken River sub-catchment</th>
<th>ET from Murrumbidgee River sub-catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate (mm/year)</td>
<td>Volume (GL/year)</td>
<td>Rate (mm/year)</td>
</tr>
<tr>
<td>Forest and plantations</td>
<td>338</td>
<td>176,374</td>
<td>775</td>
</tr>
<tr>
<td>Irrigated areas</td>
<td>590</td>
<td>10,532</td>
<td>747</td>
</tr>
<tr>
<td>Pasture</td>
<td>482</td>
<td>190,095</td>
<td>705</td>
</tr>
<tr>
<td>Dryland farming</td>
<td>425</td>
<td>56,071</td>
<td>552</td>
</tr>
<tr>
<td>Other</td>
<td>655</td>
<td>14,972</td>
<td>893</td>
</tr>
<tr>
<td>Total</td>
<td>411</td>
<td>448,044</td>
<td>707</td>
</tr>
</tbody>
</table>

The more consistent estimates in Figure 5 for the redgum forest sites reflect the nature of the vegetation and its ability to draw water through deeper penetrating root systems, in comparison to grasses. The typical difference is 100 mm/yr and this difference can be regarded as the soil water and groundwater contribution in cases where the red gum is a groundwater dependent ecosystem.
The results of these applications show that ET rates can vary significantly, not only on a catchment scale but also on a local scale. Such variations when captured using a technique such as SEBAL 2009 can be used to infer information about likely water availability across the landscape (localised and catchment scale) and local climate influences.

At a paddock scale variation in ET can be used to assess irrigation performance. The most commonly applied performance indicators are those which show whether water deliveries meet the water demand of a unit of irrigated land, or for environmental applications, if deliveries to forests or wetlands for environmental watering meet the requirements of the ecosystem.

SEBAL 2009 includes a routine that calculates biomass production, and for most crops the harvestable yield can be computed as a fraction of the total biomass production corrected for the moisture content in the harvestable component. Hence, information on total biomass production for a season and the crop types can be combined to obtain an assessment of crop yield.

Water productivity (defined in this paper as biomass production per unit of water) has been estimated for a section of the Shepparton Irrigation Area, just east of Shepparton (Figure 5). These results show that water productivity is highest along water courses (Goulburn River and Broken Creek) and through the irrigation areas. It is also apparent that water productivity varies considerably between paddocks. This implies that the agricultural sector could become more efficient with irrigation water.

The two applications described above highlight the significant benefit of obtaining ET data at a spatial and temporal scale, which previously has been an onerous and often erroneous task. In a catchment water balance ET is typically described as a bulk number for the entire catchment, and although SEBAL 2009 can provide this number it also provides the spatial distribution of the ET across the catchment. This is a significant progression from typical methods and has the potential to greatly improve management of water resources at both the large catchment scale and also the local scale such as an irrigation district or at the individual farm level. It also has the potential to quantify the contribution of groundwater on the evaporation of phreatophytes.
PROJECT DEVELOPMENT

SEBAL 2009 relies on remotely sensed satellite imagery. There are a considerable number of satellites in orbit which are able to provide imagery. Selecting the right satellite imagery for projects is dependent on the required outcomes and the spatial resolution of end outputs.

The spatial resolution of the imagery defines the level of detail visible. For example Landsat provides imagery of 30 m resolution, which makes it suitable for assessment of water use for areas at sub hectare scale. Whereas MODIS, which provides imagery of 250 m resolution, is suitable for km² size units. Another factor influencing selection of an appropriate resolution is the extent of the area of interest. Having smaller resolution imagery reduces the total coverage available in a single scene. However, subsequent scenes can be merged to reduce processing time and increase the coverage. New imagery such as the British Disaster Monitoring Constellation (DMC) and the Chinese HJ satellites have great potential for operational monitoring due to short repeat cycles (1 to 2 days) and large areal coverage (total swath upto 700 km wide).

Other satellites offer benefits through having alternative resolutions and spectral bands that allow additional processing of the imagery and products to be produced. A more detailed explanation of satellites and sensors commonly used, is available on the Geoscience Australia website (http://www.ga.gov.au/remote-sensing/satellites-sensors/index.jsp). In addition, there are several papers in the literature that compare different satellite imagery and sensors for different application (e.g. Thome et al., 2006). Reviews of applications of remote sensing in water management can be found in Bastiaanssen and Harshadeep (2005) and Allen et al. (2007).

PROJECT DELIVERY MODELS

There are three primary business models that can be developed for delivery of SEBAL 2009 gridded data output files. The first of these is for a suite of regional scale products commissioned by government and made available on demand to a range of users. The second is a cooperative model where regional or local scale interests can be concurrently met by a larger scale project. The third is based on individual commissioned products for specific projects to meet individual user requirements.

Producing a suite of regional scale standard products, for example monthly gridded ET maps on an annual basis, could be funded by Government agencies that have water resource management responsibilities at a State or National scale. Such products would be required to meet both large scale and smaller regional scale applications, making MODIS imagery, which produces output grids at a 250 m to 1000 m resolution, ideal. The 1 km scale is suitable for linkages with land use maps, which are usually available at the same spatial resolution.

For the regional scale standard products, satellite imagery would be analysed using SEBAL 2009 and a catalogue of SEBAL outputs developed covering a large geographic area. This catalogue would be continually updated and expanded as new imagery becomes available (i.e. new years/months of data would be added). This process would occur regardless of specific (commissioned) demands for the data. This delivery model is analogous to the collection of climate and streamflow data in Australia undertaken by organisations such as the Bureau of Meteorology and Water Authorities, which is then made available on request to third parties.

The cooperative delivery model is aimed to meet the requirements of a collective group of users, which enables the cost of the image processing to be distributed across the group. For example, Catchment Management Authorities (CMAs) across south east Australia may commission a MODIS based SEBAL project from which individual CMA regions can be
extracted. The 250 m resolution of gridded outputs would be suitable for catchment scale water balances and other land use water resource studies. The gridded outputs could also be used at the larger scale to provide combined coverage for all of the authorities. Similarly, irrigators within a district may commission a project that provides coverage for the entire district, but the outputs are cookie-cut to the farm boundaries to enable individuals to manage their water resources independently. This type of irrigation district scale project would utilise a higher resolution imagery such as Landsat (30 m resolution), which would enable more accurate estimates of water use at the paddock scale. The FieldLook service described by Bastiaanssen et al. (in these conference proceedings) is an example of that.

Under the 'commissioned projects' delivery model, parties interested in obtaining SEBAL 2009 gridded data outputs would commission delivery of products specific to their own needs. This would generally be one-off type projects undertaken using higher resolution imagery that better suits the user's needs.

The first delivery model has a number of advantages, specifically: development of a valuable information resource in an organised, strategic and centralised manner; short project lead times as the required SEBAL products would be available on demand rather than it being necessary to wait for commissioned work to be undertaken; and would mean relatively low costs per image analysed.

At the other end of the spectrum, the commissioned projects can be tailored to meet the specific needs of the user such as water saving, water productivity or monitoring soil wetness in wetland ecosystems, therefore eliminating the need to compromise on resolution or ideal time periods which may occur if selecting data from a catalogue. Additionally only the required images and period of interest would be analysed, reducing the risk of producing costly data sets which are poorly utilised.

CAPACITY AND KNOWLEDGE BUILDING

The water industry currently has limited operational capability for utilising gridded evapotranspiration data outputs. This is predominantly a result of historically not having access to data of this type in usable forms and not having a clear understanding of its potential application. With respect to capacity building the delivery models discussed above are based on a three tier system, where the top tier is the remote sensing service delivery company which produces the SEBAL based products. The second tier refers to the water resource management consultant that generally commissions and project manages these types of remote sensing works. These consultants understand the remote sensing methodology and its inherent limitations, and the user’s application requirements. They obtain the output data from the remote sensing service provider and apply it to the application requested by the end user, which represents the third tier of the system. The end user funds the project because they require the application of ET data to meet a specific water resource management aspect of their business.

As the availability of gridded ET data increases, and successful applications are completed, the capacity and knowledge of its benefit to the water industry will increase. Projects such as that funded by the National Water Commission, which includes the scoping and delivery of a range of applications, will facilitate the development of this capacity.

The SEBAL technology has, and will continue, to be constantly improved and updated by companies such as WaterWatch and SKM based on research and application by collaborating research organisations both in Australia and internationally.
CONCLUSIONS

SEBAL 2009 has been shown to provide accurate estimates of evapotranspiration at a range of spatial and temporal scales. It has distinct advantages over existing measurements systems that are based on interpolation of point based measurements to provide equivalent spatial coverage. Further, across a lot of Australia field based ET data is scarce or non-existent making even scaling up from points extremely difficult. SEBAL 2009 does not face any spatial limitations and allows ET to be understood with far greater certainty across the continent. The remote sensing methodology is repeatable and with use of archived satellite imagery can allow analysis of time periods back to the late 1980s to current.

Several delivery models for the provision of ET data have been discussed; ranging from centralised systems making available standard products to the more customised commissioned project aimed at meeting the requirements of an individual user. The costs and economic benefits of each model require further development once the industry has a greater understanding of the capability and benefit of applications using ET data.

The irrigation industry is well positioned to take advantage of this technological advance in remote sensing measurement of evapotranspiration, which will result in improved water use efficiency at a range of scales. However, the Government will also need to contribute through continued investment and adoption of applications to ensure potential benefits are maximised.

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