Abstract

Evaporation from reservoirs represents a significant component of the water balance, however quantification is often limited. Methods exist to estimate evaporation from reservoirs however they are often extremely data intensive, limiting their application. The most common method for estimating evaporation from reservoirs, the pan coefficient method, is widely recognised to be least accurate.

An innovative and cost effective method called SEBAL (Surface Energy Balance Algorithm for Land) now exists for estimating evapotranspiration from land at large scales from readily available satellite imagery. Whilst SEBAL is designed for land based applications, SKM undertook a study to determine if SEBAL is able to produce accurate estimates of evaporation from reservoirs based on a case study of the Menindee Lakes.

This paper compares SEBAL estimates of evaporation from the Menindee Lakes to estimates of evaporation determined using more traditional (and commonly applied) calculation methods. Results indicate that SEBAL is able to produce accurate estimates of evaporation from the Menindee Lakes. Based on this, the future applications of SEBAL are significant, with the potential to improve the accuracy of water use estimates for supply systems and storages across Australia.

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. Evapotranspiration represents a fundamentally important component of the water balance, with approximately 90% of the total precipitation falling on Australia returning to the atmosphere through evapotranspiration (Wang et al., n.d.).

Evaporation from water storages is an important component of the water balance for resource planning and water accounting, however it is typically calculated as the residual loss from storage or estimated through the use of a surrogate (pan evaporation). Improved measurement of evaporation from storages would increase confidence in available resources for allocation planning and improve the accuracy of water accounting.

An innovative and cost effective method now exist to measure actual water use at large scales called SEBAL 2009 (Surface Energy Balance Algorithm for Land).

As a part of a study funded by the National Water Commission, SKM (2009) investigated the potential to use SEBAL 2009 to measure evaporation from storages based on a trial
application for the Menindee Lakes on the Darling River in New South Wales using Landsat and MODIS satellite imagery. The trial application was based on the 2004/05 water year, and as such investigated only two of the lakes (Lake Wetherell and Lake Pamamaroo, as the other lakes have been dry since 2002). Figure 1 shows a location of the Menindee Lakes.

![Map showing the location of the Menindee Lakes](https://example.com/map.png)

**Figure 1: Map showing the location of the Menindee Lakes (Geoscience Australia, 2009).**

The SEBAL 2009 application developed by WaterWatch, applies complex radiation and energy balance algorithms to derive evapotranspiration or actual water use from satellite imagery. The primary basis of the SEBAL 2009 model is the surface energy balance, developed and reported by Bastiaanssen et al. (1998). 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 SEBAL 2009 application has undergone over 15 years of development and is an existing operational tool that has been successfully applied across the world. Using remotely sensed data minimises uncertainty as it covers the entire area of interest and is not based on extrapolation of point based measurements. A feature of recent development has been the estimation of evaporation from water storages.

Water storages (and other water bodies) can be grouped into three broad categories; shallow, deep and dry. Each category of water storage behaves differently, with different evaporation responses; hence different methods of calculating evaporation should be applied for each category.

For shallow water storages, such as the Menindee Lakes, SEBAL 2009 calculates evaporation using a method based on the Penman-Monteith equation, in which a sinusoidal heat storage function is included in the calculation to account for the energy transfer to or from the water storage. The amplitude and phase of the heat storage term varies with the depth of the water storage and annual variations in air temperature. Climates with stronger amplitudes in air temperature are assumed to have a larger heat storage term.
For deep water bodies, SEBAL 2009 calculates evaporation using a method based on a bulk transfer equation, in which heat storage is calculated as a function of net radiation. The fraction is adjusted to the prevailing annual cycle of net radiation, ensuring the annual heat storage is neutral. Typical values range from 0.5 to 0.6.

The spatial analyst applying the SEBAL 2009 routine normally selects one of the above methods to apply to all water bodies across the assessment area. The decision is made with consideration of the predominant storage characteristics and the overall objectives of the project. For this study of the Menindee Lakes, the shallow lake method was applied.

Dry water bodies are treated as per the surrounding land, and the standard SEBAL 2009 routine for land is applied. The switch between soil and water as the water body fills or empties is made on the basis of a water mask spatial layer, which is created from a gridded data surface of the normalised difference vegetation index (NDVI).

RESULTS

SEBAL 2009 was used to produce gridded data output files of evapotranspiration for the Menindee Lakes area suitable for spatial analysis for the 2004/05 water year based on LandSat and MODIS satellite imagery. Figure 2 shows monthly maps of evapotranspiration for the 2004/05 water year produced from the gridded data output files. Quarterly and annual data sets and maps were also prepared.

The SEBAL 2009 derived gridded data output files of evaporation from the Menindee Lakes were used to calculate the rate and volume of evaporation from Lake Wetherell and Lake Pamamaroo on a monthly basis for the 2004/05 water year (Table 1).
Using Satellite Imagery to Measure Evaporation from Storages

Table 1: Rate and volume of evaporation from Lake Wetherell and Lake Pamamaroo, calculated using SEBAL 2009 gridded data output files.

<table>
<thead>
<tr>
<th>Assessment Period</th>
<th>Lake Wetherell</th>
<th>Lake Pamamaroo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Evaporation Rate (mm/day)</td>
<td>Evaporation Volume (GL)</td>
</tr>
<tr>
<td>July 2004</td>
<td>1.16</td>
<td>3.4</td>
</tr>
<tr>
<td>August 2004</td>
<td>3.03</td>
<td>8.9</td>
</tr>
<tr>
<td>September 2004</td>
<td>4.17</td>
<td>11.4</td>
</tr>
<tr>
<td>October 2004</td>
<td>5.82</td>
<td>15.3</td>
</tr>
<tr>
<td>November 2004</td>
<td>6.31</td>
<td>14.9</td>
</tr>
<tr>
<td>December 2004</td>
<td>8.62</td>
<td>19.1</td>
</tr>
<tr>
<td>January 2005</td>
<td>8.63</td>
<td>25.2</td>
</tr>
<tr>
<td>February 2005</td>
<td>6.92</td>
<td>15.8</td>
</tr>
<tr>
<td>March 2005</td>
<td>5.43</td>
<td>10.4</td>
</tr>
<tr>
<td>April 2005</td>
<td>3.66</td>
<td>5.3</td>
</tr>
<tr>
<td>May 2005</td>
<td>2.07</td>
<td>2.4</td>
</tr>
<tr>
<td>June 2005</td>
<td>1.06</td>
<td>1.1</td>
</tr>
<tr>
<td>Annual 2004/05</td>
<td>133.2</td>
<td></td>
</tr>
</tbody>
</table>

The SEBAL 2009 measurements of evaporation were then compared to estimates of evaporation calculated using a traditional (water balance) method. The results of this comparison, presented in Figure 3, show that provided the appropriate shallow or deep water assessment method is selected, SEBAL 2009 is able to produce accurate estimates of evaporation from water storages.

The traditional water balance method calculated evaporation as the residual of the water balance equation. Surface water inflows and outflows, change in storage volume and evaporation and rainfall were based on recorded data provided by the Department of Water and Energy (NSW). Groundwater recharge was estimated based on an assumed recharge rate of 1 mm/day. Local inflows (from local catchment runoff) were estimated based on recorded rainfall and an assumed local catchment area.

Figure 4 shows the results of the water balance equation for two example months, a winter month: July 2004 and a summer month: December 2004. These figures show that each of the three assessment methods (water balance, pan evaporation and SEBAL) produce similar, but different, estimates of evaporation. Due to the nature of the water balance equation, all error is assumed to be contained within the evaporation component. In reality, there are many sources of uncertainty, particularly relating to the assumed groundwater recharge rate, the volume of local inflows and measurement error for inflows, outflows and storage volume.

Using SEBAL 2009 allows you to more confidently determine one component of the water balance (evaporation) and therefore better identify and quantify the other sources of uncertainty such as local inflows and groundwater recharge.
DISCUSSION

As SEBAL 2009 is able to produce accurate estimates of evaporation from water storages, the potential exists to apply SEBAL 2009 to improve accounting of evaporation from water supply storages (and other open water bodies) across Australia.

This could be achieved in a number of ways including:

1) Update evaporation estimates and calculations (including in water resource assessment models) to use spatially distributed evaporation in place of traditional estimates.
The vast majority of water resource assessments (including the majority of water resource modelling) use pan evaporation data multiplied by a pan factor to estimate evaporation from water storages. This method introduces a number of sources of uncertainty including the following sources identified by Lowe et al (2009):

a) Use of point data to estimate a spatially distributed variable

b) Uncertainty associated with the spatial translation factor applied if the pan measurement site is at a distance to the site of interest, if applied. Often differences between evaporation at the measurement site and the site of interest are not accounted for.

c) Uncertainty associated with the pan factor to account for the difference between evaporation in a small pan and evaporation in a large water body.

d) Uncertainty associated with the use of average surface area over the year, as actual surface area can be highly variable.

SEBAL 2009 can be used to derive time series of monthly or annual evaporation data suitable for inclusion in water resource assessments (including modelling) which eliminates all of the above sources of uncertainty as it is spatially distributed across the whole region of interest and it eliminates the need to apply any adjustment factors. This option would lead to the greatest improvement in evaporation calculations.

2) Use spatially distributed evaporation data to derive or update site specific annual pan factors.

Annual pan factors of between 0.7 and 0.9 are commonly applied across Australia with little verification. These factors are based on studies of a limited number of reference reservoirs, with few studies or substantial reviews in decades.

The accuracy of evaporation estimates for water storages could be significantly improved through the derivation of more accurate (site specific) pan factors. This would be a significant, if not impossible, undertaking using traditional methods to estimate or calculate evaporation data, due to the large volume of high quality data that would be required.

SEBAL 2009 offers a less data intensive approach to determine pan factors for reservoirs across Australia to (a) derive site specific annual pan factors for individual storages or (b) update the recommendations of generic pan factors for Australia on a whole-of-country or regional basis.

3) Use spatially distributed evaporation to derive monthly or seasonal pan factors.

Worse than applying annual pan factors with little verification, it is not uncommon for such annual pan factors to be applied uniformly on a monthly or seasonal basis, which ignores the influence of changes in heat storage on a sub-annual time step.

Determination of seasonal or monthly pan factors (particularly site specific factors) could significantly improve the accuracy of evaporation estimates for water storages. As with the option above, this would be a significant, if not impossible, undertaking using traditional methods.

As an example of this potential application, SEBAL 2009 estimates of evaporation for Lake Wetherell were compared to measured pan evaporation to derive monthly pan factors. Figure 5 shows the comparison between pan evaporation rates and SEBAL 2009
evaporation rates for Lake Wetherell, while Figure 6 shows the derived pan factors for Lake Wetherell (and Lake Pamamaroo).

These results show there is considerable seasonal variation in pan factors, ranging from 0.83 to 0.46 for Lake Wetherell and from 0.86 to 0.52 for Lake Pamamaroo; an overall range of 0.4. Therefore, adopting a uniform pan factor of 0.7 across the year would lead to an overestimation of the volume of evaporation in winter months (April to July) by up to 20%, and underestimate of the volume of evaporation in summer months (December to February) by up to 10%.

Figure 5: Pan evaporation rate compared to SEBAL 2009 derived evaporation rate for Lake Wetherell (2004/05).

Figure 6: Monthly derived pan factors for Lake Wetherell and Lake Pamamaroo.
CONCLUSIONS

SEBAL 2009 determined that 133 GL of water evaporated from Lake Wetherell in 2004/05. Knowing this volume more accurately allows for increased confidence in the assessment of available resources for allocation planning and improved water accounting.

Based on 2004/05 data, using a uniform pan factor of 0.7 across the year would result in winter evaporation being overestimated by up to 20% and summer evaporation being underestimated by up to 10%.

Comparison of SEBAL 2009 estimates of evaporation to water balance estimates of evaporation offers the potential to improve the identification and quantification of the unknown components of the water balance. This may be particularly advantageous for the components of the water balance which are difficult to accurately measure, such as groundwater recharge and inflows.

The application of SEBAL 2009 to derive time-series estimates of evaporation has the greatest potential for locations or reservoirs where evaporation measurements are not recorded in close proximity to the site of interest or are not undertaken on a daily basis. The remote sensing approach allows evaporation to be measured for any period since the mid-1980s. This may also be advantageous where evaporation measurements have not been continuous.

ACKNOWLEDGEMENTS

Funding for the study was provided by the National Water Commission under the Raising National Water Standards Program. The NSW Department of Water and Energy, provided expert insight and the data required to undertake this study.

REFERENCES


