

MONITORING EVAPOTRANSPIRATION FOR TERRESTRIAL GROUNDWATER DEPENDANT ECOSYSTEMS USING SATELLITE-BASED ENERGY BALANCE MODEL

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ABSTRACT:

Understanding and mitigating against the impact of land use change and groundwater extraction on groundwater dependant ecosystems (GDE) requires information on the distribution and environmental water needs of these ecosystems. Conventional field based techniques for determining plant water use and plant stress are very labour intensive and time consuming. In this study, we proposed an alternative method using multi-temporal satellite images and the application of the Surface Energy Balance Algorithm for Land (SEBAL). Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) images were used to derive land surface temperatures and evapotranspiration (ET) for the targeting ecosystems and species. The radiative transfer model (MODTRAN 4.1) was used with atmospheric profile data to atmospherically correct the Landsat data. Vegetation indices and surface temperature were derived from the satellite images and used to estimate fractional vegetation cover, leaf area index (LAI), emissivity and net radiation. These data, along with meteorological data, provided inputs for the SEBAL model which was in turn used to determine the actual ET, pixel by pixel, for selected groundwater management areas in the central west of New South Wales, Australia. The remote sensing estimated ET was imported into geographic information systems (GIS) for further spatial analysis and mapping, in combination with land use and other ancillary data. The estimated ET results were evaluated using a Vegetation Index/Temperature Trapezoid (VITT) model and field measurements. Ancillary GIS data were also used in the quality control process to ensure accepted accuracy. It is expected that this technique and the resulting ET maps will assist us to monitor the effects of groundwater management on the water uses and the indicative health of these terrestrial groundwater ecosystems.

1. INTRODUCTION

A Water Management Act was introduced in New South Wales (NSW), Australia in 2000 by the NSW Government as part of on-going major reforms of water resource management. A major component of this reform was the requirement under the Act to prepare Water Sharing Plans (WSP) for regulated and unregulated rivers as well as groundwater. An important focus of these WSP is to ensure that the water needs of ecological assets such as rivers wetlands and groundwater dependant ecosystems (GDE) are identified and the protection of the ecological integrity of these assets balanced with the socio-economic benefits of water extraction and use. As such, WSP provides the framework and rules for managing shares and extraction under an access license.

Groundwater is a relatively small but increasingly important component of water supply within NSW, and for some areas a major and critical component of urban water supplies. Across NSW there are 108 groundwater sources from which approximately 330 GL of groundwater is extracted annually. This is roughly equivalent to 15% of the agricultural and urban water supply demand for the whole State.

Understanding and mitigating against the impact of land use change and groundwater extraction on GDEs requires information on the distribution and environmental water needs of these ecosystems. In an attempt to deal with this issue the

NSW Government has developed an assessment procedure which is based on an iterative, interdisciplinary, risked based approach (Bish *et al.* 2006, personal comm.). One of the key assumptions, of this approach, is that if groundwater is within the potential rooting zone of these woodland species then those species are highly likely to be somewhat groundwater dependant (Eamus *et al.*, 2006). To test this approach we have established a pilot project in the sub-humid woodlands in the Lower Macquarie Groundwater Management Area (GWMA) of central western NSW. The pilot study is to determine if the growth of tree species within the groundwater drawdown radius are different to those outside of these affected areas. If the growth patterns within in the zones are less than that of the trees outside of the drawdown radius then we can be confident that the groundwater pumping is having an effect on these ecosystems. Field based techniques can be used for determining plant water use and plant stress, but these processes are very labour intensive and time consuming, not applicable for large areas. Additionally they also have severe spatial limitations in that the measurements for one tree within one woodland patch are not readily transferable to woodland patches that may be some distance apart.

We therefore propose that as an alternative to using field based measurements of plant water use, we adopt remote sensing based techniques using multi temporal Landsat images and the application of the Surface Energy Balance Algorithms for Land

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(SEBAL, Bastiaanssen *et al.*, 1998a). SEBAL uses spectral radiances recorded by satellite-based sensors and meteorological data, to determine the energy balance for a point on the earth's surface. Using SEBAL we are able to determine the actual evapotranspiration (ET) and biomass production of agricultural crops and native vegetation, pixel by pixel (Bastiaanssen *et al.*, 1998a and 1998b). This will allow us to compare the actual water use of woodlands within the pumping zones and similar woodlands in areas unaffected by the pumping regime. If we find that the water use within the pumping zones is less than those of the same type of woodland in areas unaffected they we can assume that the pumping regime is having an impact on those woodlands. The advantage of this technique for planning process such as the WSPs is the resulting digital ET and biomass growth images can be imported into GIS for spatial analysis, in combination with land use and other data.

This paper will describe how Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) images are used to derive land surface temperatures and ET for the targeting ecosystems and species. Two methods have been tested in this study, one is based on the well-known surface energy balance equations (SEBAL and METRIC), another on the Vegetation Index/Temperature Trapezoid (VITT) concept. Both methods have been implemented in a GIS environment using automated scripts so that these processes are automated and repeatable.

2. THE STUDY AREA

The pilot study area is located at Lower Macquarie Groundwater Management Area (GWMA), which lies west from Dubbo in central western New South Wales (Figure 1). The study area is fully covered by a full scene of Landsat image (Path/Row 92/82, about 130 km by 130 km with a scene centre of -32.0834, 147.95).

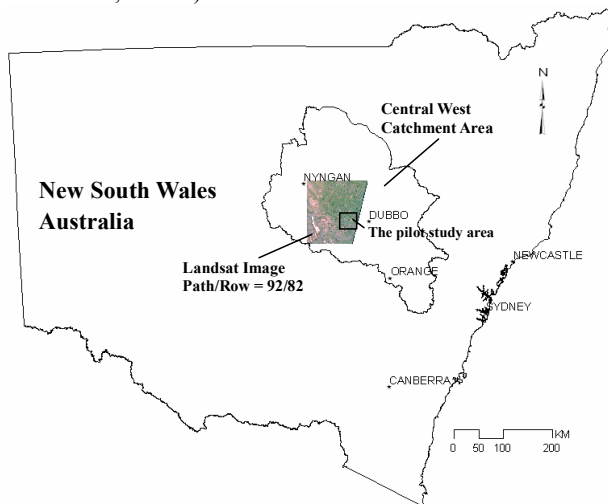


Figure 1. The pilot study area at central west of New South Wales, Australia.

In the study area, the groundwater is primarily used for irrigation of cotton but also for town water supply purposes. The native vegetation consists of Poplar Box (*Eucalyptus populnea*) woodlands on the flats and drainage depressions and White Cypress Pine (*Callitris glaucophylla*) woodlands on the low rises and small areas of aeolian dunes. Along the major water courses and grey cracking clay soils are River Red Gum (*E. camaldulensis*) forests and woodlands and the steeper hills

and ridges tend to be dominated by Dwyer's Red Gum (*E. dwyeri*) and Iron Bark (*E. sideroxylon*) woodlands. The water table occurs at depths of less than 30 m in most areas. Drawdowns from pumping are in the order of 3-4 m over the 4 month pumping season (November to February). Due to the good hydraulic connection between groundwater and the river, groundwater levels are expected to recover rapidly to pre-pumping levels with a month after the cessation of pumping. The study area is a tableland area with elevation ranging from 217 to 420 m. Agriculture includes irrigated cotton and pasture at lower elevations. The climate is sub-humid with mean annual precipitation of about 500 mm.

3. SATELLITE IMAGES AND DATASETS

We obtained seven full-scene Landsat images, five TM and two ETM+ images, which cover different seasons between 2002 and 2005 (refer Table 1). There are four summer images (February/March) when groundwater usage expected to high, and three images in late winter or early spring (August to October). The reason to choose Landsat images is because that they have adequate spatial (30 m) and radiometric resolutions (NIR and thermal bands) needed for vegetation and surface temperature related studies, and they are widely available.

Date	19/10/02	24/02/03	27/08/03	19/02/04	14/09/04	21/02/05	17/03/08
Day of Year	292	55	239	50	257	52	77
Sensor	ETM+	ETM+	TM	TM	TM	TM	TM
Time	09:45:00	09:45:00	09:38:26	09:40:36	09:44:53	09:48:08	09:51:00
Sun azimuth	64.25	70.36	46.16	70.51	49.61	67.62	55.25
Sun Altitud	50.16	44.55	34.99	47.65	41.65	48.61	44.66
T _a (°C)	23.6	25.1	11	33.4	14	25.2	25.0
Wind speed	5	7.8	4.7	2.5	3.6	2.5	2.5

Table 1. Details of Landsat Images obtained for this study and ground weather conditions at the time of the Satellite overpass.

Land cover data are not directly necessary for SEBAL, but it does improve estimates of surface roughness, soil heat flux, and surface emissivity (Allen *et al.* 2007). Land use maps at 1:25,000 were used in this study and the land use classes are grouped into two broad classes as woody and nonwoody for further analysis and sampling purposes. Weather data were obtained from the Bureau of Meteorology at the nearby station (Station ID 51049) including wind speed, solar radiation, air temperature, humidity and reference ET data. These climate data are used as inputs to the SEBAL model and for image radiometric correction. A Digital Elevation Model (DEM) was also used in this project to account for temperature differences in slope, aspect, and elevation. The DEM used was obtained from the Department of Lands at a ground resolution of 25 m. The DEM were processed to remove any gaps and artefacts. In addition, field measurements were carried out at 32 woodland sites within the study areas. The measurements included tree species, canopy heights (m), crown cover (%) and surface temperatures of various targets (trees, soils, litter, grass and rocks) and air temperature. These measurements are useful in the calculation and validation of the surface energy balance.

4. METHODOLOGY

Two methods have been tested in this study, one is based the surface energy balance model (namely SEBAL or METRIC), another is based on the VITT concept (Moran *et al.*, 1994 and Yang *et al.*, 1997). For surface energy balance based calculation, ET is generally determined from satellite imagery by applying an energy balance at the surface, where energy consumed by the ET process is calculated as a residual of the surface energy equation. In the absence of horizontally advective energy, the surface energy balance of the land surface can be expresses as

$$LE = R_n - H - G \tag{1}$$

where LE = the latent or moisture flux (the energy used to evaporate water, Wm^{-2})

R_n = the net radiation at the surface (Wm^{-2})

H = the sensible heat flux to the air (Wm^{-2})

G = the soil heat flux (the energy flux into ground, Wm^{-2}).

The SEBAL (a one-source energy balance model) and the two-source energy balance (TSEB; Norman *et al.*, 1995) models solve Equation (1) by estimating the different components separately using satellite images and weather data (Li and Kustas, 2005). Theoretical and computational basis of SEBAL is described in Bastiaanssen *et al.* (1998a and 1998b). An improved SEBAL model, Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC) is described by Allen *et al.* (2007).

The characteristics of this well-known equation shall not be discussed further, but the emphasis is put on how to make use of this equation for ET estimation for GDEs and how to obtain the energy balance components from remotely sensed data. The following text outlines the application of the energy balance equation and VITT model for regional woodland ET estimation. Specific details and equations for applications of SEBAL, METRIC and VITT are contained in Bastiaanssen *et al.* (1998a, 1998b), Allen *et al.* (2007) and Yang *et al.* (1997). The computation details are not repeated here, but only the general computation process is illustrated (Figure 2).

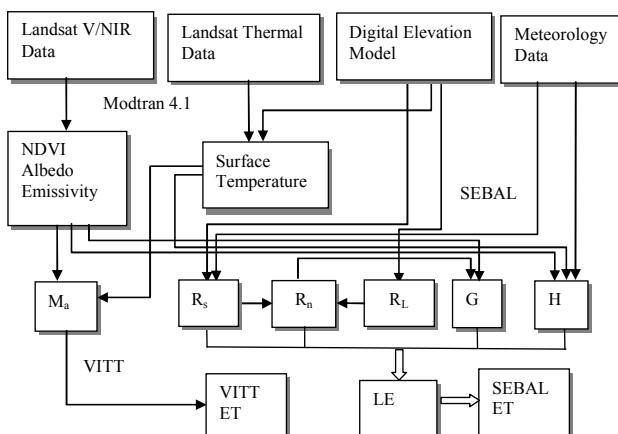


Figure 2. General computation procedures for SEBAL and VITT based evapotranspiration.

First, the radioactive transfer model MODTRAIN (4.1) was used with atmospheric profile data to atmospherically correct the Landsat data (the red, NIR and thermal bands for this study). Then, the vegetation indices (NDVI, SAVI and LAI) were

calculated from the radiometrically corrected surface reflectance from the red and near-infrared (NIR) bands (Band 3 and 4). The surface temperature was calculated from the thermal infrared band (Band 6) after radiometric correction (e.g. Li *et al.*, 2004). The radiation balance for each pixel of the image was calculated from surface temperature, short wave reflectance, atmospheric transmissivity and emittance. Soil heat flux (G) is predicted as a ratio of net radiation (R_n) as a function of soil adjusted vegetation index (SAVI, Huete, 1988), an improved normalized difference vegetation index (NDVI). Sensible heat (H) is calculated following Bastiaanssen *et al.* (1998a) where the near surface aerodynamic resistance is computed using a measurement of wind speed at the time of the image that is representative of the area of interest, and surface roughness is determined as an empirical function of NDVI following Bastiaanssen *et al.* (1998a) and Allen *et al.* (2007). Last, the remote sensing derived instantaneous latent flux (LE) for each pixel was converted to daily value ($mmday^{-1}$) following Jackson *et al.* (1983) which assumed that the daily course of ET would generally follow the trend of solar irradiation throughout the daylight period.

The VITT based ET was calculated based on Moran *et al.* (1994) and Yang *et al.* (1997). The method is based on widely observed negative correlation between T_s and remotely-sensed measurements of actively transpiring vegetation, such as NDVI (Moran *et al.*, 1994) (Figure 4). One hypothesis to explain this correlation is that the relationship between T_s and NDVI is an indicator of evaporative cooling by plant transpiration. With a measurement of $T_s - T_a$ at point C, it would be possible to equate the ratio of actual to potential ET with the ratio of distance CB and AB (Figure 3a). Using physical energy balance equations, it is possible to compute the values of the four vertices of the trapezoid for a specific time and vegetation. More practically, the VITT shape can be constructed from field or remote sensing measurements, and empirical equation can be established to calculate $T_s - T_a$ from NDVI (Figure 3b).

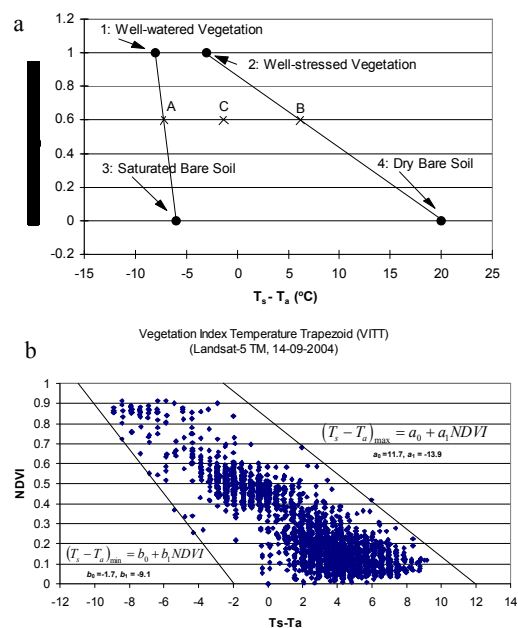


Figure 3. The hypothetical trapezoidal shape that would result from the relation between $(T_s - T_a)$ and the fractional vegetation cover (a); and the trapezoidal shape resulted from the actual calculation from Landsat image (b).

Based on the VITT concept, a water availability index (M_a) can be defined here as:

$$M_a = 1 - WDI = \frac{(T_s - T_a)_{\max} - (T_s - T_a)_r}{(T_s - T_a)_{\max} - (T_s - T_a)_{\min}} = \frac{\lambda E_t}{\lambda E_p} \quad (2)$$

where WDI = the water deficit index (Moran *et al.*, 1994)

λE_t = the surface ET rate (mm hr^{-1})

λE_p = the potential surface ET rate (mm hr^{-1})

r = the subscript refers to the measured value.

The potential ET rate (λE_p) at a specific time and location can be computed using standard methods (Allen *et al.*, 1998; FAO, 1998). Thus, at a given time, if surface temperature is known, then M_a and subsequently can be calculated using Equation 2. The actual ET rate estimated using Equation 2 is also an instantaneous value at the time of satellite overpasses, and it was converted to a daily value using the same methods described by Jackson *et al.* (1983).

The above processes on ET estimation using energy balance and VITT methods were implemented into an Arc Macro Language (AML) program which runs in an Arc/Info GIS (GRID module) environment. The program also generates sampling files in ASCII format which list all estimated energy balance components and final ET results for statistical analysis. The sampling points were 5000 random points evenly distributed in and outside the groundwater drawdown zones.

5. RESULTS AND DISCUSSION

Application of SEBAL and VITT to the NSW central west woodlands produced 25 m resolution ET maps (daily average) from all seven Landsat images for an area of 130 km by 130 km (full scene images). An example ET map for the pilot study area is presented in Figure 4.

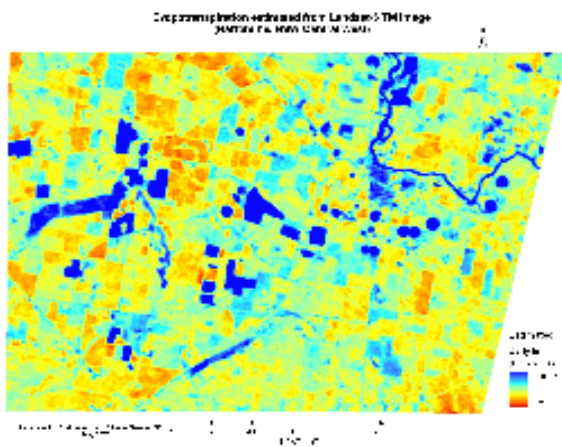


Figure 4. An example map of spatially distributed ET (mm/day) estimated from Landsat TM image on 19/02/2004.

Figure 5 presents the time-series ET maps at various seasons and their average ET value estimated from the selected Landsat images. Despite the relatively sparse temporal resolution (16 days), Landsat images can be used to produce continuous ET maps with useful information on water usage and the seasonal changes. Further, it is possible that the remote sensing estimated ET is linked with the time-series (e.g. daily) ET based on water

balance model to provide continuous measurements of ET in both spatial and temporal contexts at higher resolutions.

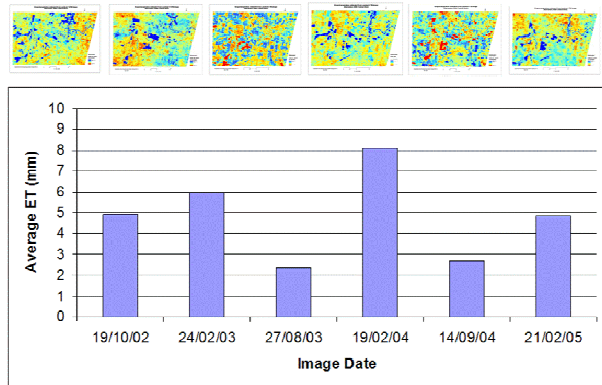


Figure 5. Time series plot of ET from selected satellite images and the corresponding average daily ET values.

Major SEBAL components and the resulting ET values have been sampled randomly (5000 points) across the study area for statistical analysis. Comparisons of predicted ET by SEBAL to VITT model indicate relatively good agreement ($R^2 = 0.91$) and promise for use in groundwater management. The average woodland ET within the pumping area appears less than that outside the pumping area, particularly in summer images (Figure 6) which demonstrates that the pumping regime has an impact on those woodlands. Through it is insufficient for a thorough validation, it shows consistencies and provides a sign that the data is likely useful.

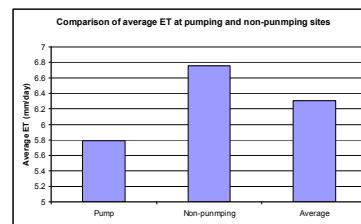


Figure 6. Comparison of average daily ET (mm/day) at pumping and non-pumping zone (a: summer images, b: other images).

Due to the lack of field data on actual ET measurements, we were unable to assess the absolute accuracy of the final ET product by remote sensing methods. However, we measured the spectral reflectance (with ADS FieldSpec® HandHeld spectrometer) and surface temperature (IR thermometer), at the same time of the satellite overpass, for ground targets at the pilot study area in Narromine, central west of NSW. The field measurements were used to compare those values such as NDVI and surface temperature estimated from satellite images, as a measure to validate and improve the remote sensing estimation. The remotely sensed vegetation indices and surface temperature are in good agreement with the measured values, though on average there was an underestimation on NDVI and overestimation of surface temperature (Figure 7).

In most cases, the spectral reflectance of groundwater dependant ecosystems (or woodlands) were easily distinguishable from the background objects such as grass and bare soils, particularly in the NIR wavelength area (Figure 8). Such difference helped to accurately classify GDEs and apply appropriate coefficients in the computation of energy balance components and ET. Land use layer was also useful as ancillary data in the GDE identification and quality control processes.

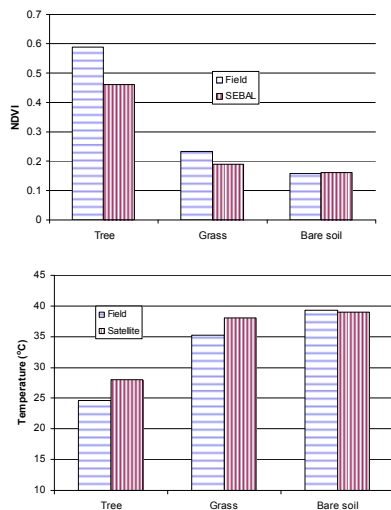


Figure 7. Comparison of average NDVI (top) and temperature (bottom) values of ground targets between field measurements at the time of satellite overpass and calculation from satellite images.

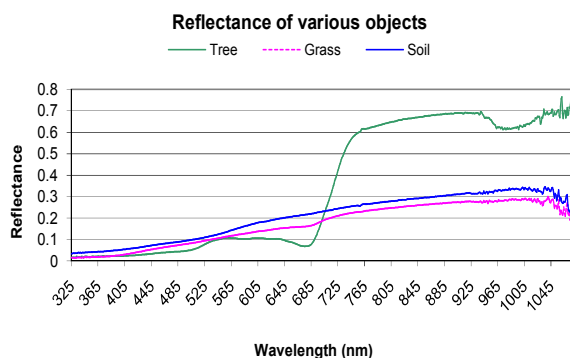


Figure 8. Spectral reflectance of groundwater dependent ecosystem and background objects.

SEBAL and METRIC are emerging technologies and have the potential to become widely adopted and used in groundwater management. However, the computation and implementation of these energy balance based models are rather difficult and not practicable without automated programming. VITT method is much simpler and easier to implement which indicates substantial promise as an alternative procedure to predict the actual ET from GDEs.

6. CONCLUSION AND FURTHER STUDIES

This paper evaluated two methods on ET estimation using satellite images. The successful implement of SEBAL and VITT methods in an ArcGIS environment demonstrated an alternative approach that can estimate ET distribution for GDEs.

This initial application and testing of SEBAL/METRIC in NSW indicates substantial promise as an efficient and inexpensive procedure to predict the actual evapotranspiration fluxes from

different GDEs at different seasons. Predicted ET has been compared with modelled ET by VITT method with good agreement. Though the estimated ET is a relative value, it provides adequate information to assist us for monitoring the effects of groundwater management on the water uses and the indicative health of these terrestrial groundwater ecosystems. The pilot study also demonstrates that Landsat images can be used to effectively quantify, in terms of both the amount and spatial distribution, the ET on a pixel by pixel basis over a region or catchment area.

The methods are still to be fully assessed using field measurements. Once the methods have been validated, we will use it to predict total, net depletion of water from the groundwater system resulting from pumping for all GWMA in the State. While the remotely sensed data currently used are Landsat TM/ETM+, the methodology is applicable to any sensor with both thermal and reflective capacity, such as MODIS (MODerate Resolution Imaging Spectroradiometer), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and CBERS-03/04 (China-Brazil Earth Resources Satellite).

It is a significant milestone to demonstrate SEBAL's operational capabilities to support water user community for informative decision making. The successful implement of SEBAL algorithms in an ArcGIS environment using automated scripts enables that SEBAL be incorporated as an institutional tool for operational water resource administration, such as the groundwater management for terrestrial GDEs at NSW Department of Environment and Climate Change (DECC) and NSW Department of Water and Energy (DWE).

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