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Remote Sensing Analysis of Crop Water Use in the Macalister Irrigation District

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Abstract

Irrigation has a significant impact on regional water resources in south-eastern Australia. It is therefore important that objective assessments of the current use of water are undertaken on a routine basis. New remote sensing technologies now provide an opportunity to assess and monitor water use at farm and regional scales. This study demonstrates the use of satellite-based estimates of evapotranspiration (ET) and NDVI (Normalised Difference Vegetation Index) in irrigation performance indicators that relate crop water use to crop water requirement (CWR) in the Macalister Irrigation District of south-eastern Australia. The METRIC energy balance algorithm (Allen et al 2007) was used to derive ET estimates from Landsat 7 ETM+ data. ASTER imagery was used to complement the spatial coverage of the Landsat 7 imagery due to the gaps in the scene acquired.

Key words: Crop water requirement, evapotranspiration, irrigation performance.

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Introduction

Current modernisation programs across irrigation areas in the State of Victoria, Australia, have a key objective to improve the level of services to irrigators through stable flow rates and enhanced ordering systems. This will, in return, provide irrigators with the opportunity to improve irrigation infrastructure and on-farm practices, leading to more efficient use of irrigation water, and a reduced impact on the environment and community. An appraisal of these achievements requires the objective assessment of irrigation performance on an on-going basis.

This study demonstrates the use of Satellite Remote Sensing to support comprehensive and affordable irrigation water use assessments, as well as improved irrigation management in the Macalister Irrigation District (MID) in south-eastern Australia.

There has been a long tradition of measuring crop water use and ‘crop water requirement’ (CWR) in the field of agriculture. The understanding of CWR, defined as the minimum water required to maintain crop growth in stress-free conditions, advanced greatly with the accelerated technological developments in mid 1990’s. Use of technologies, including lysimeters, Bowen ratio and eddy correlation, established the importance of crop type, crop cover, weather conditions, and soil water availability as the major determinants of crop water use.

Doorenbos and Pruitt (1977) related the water use of crops to reference evapotranspiration (ETo) and crop coefficient (Kc), which accounted for all crop-specific variables that contribute to differences in crop water use and crop water requirement. Traditional approaches to Kc values found in literature represent average to optimum agricultural management under stress-free conditions. In reality situations may be very different. The coefficients in literature are generally determined by point-based data and do not

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consider within- and across field variations. Recent approaches to the estimation of actual evapotranspiration by using satellite data overcome the shortcomings of traditional Kc estimations (Tasumi et al 2005)

Satellite images provide vital information on the understanding of water use and vegetation status. A Normalised Difference Vegetation Index (NDVI) derived from satellite data is a measure of the amount of vegetation present at one point of time. Thermal sensors on satellite provide surface temperature, which is a useful indicator of surface water. NDVI and temperature from satellite are widely used as key inputs in the current algorithms to estimate evapotranspiration (Allen et al 2007). This study demonstrated how the measures of NDVI, surface temperature and evapotranspiration (ET) were derived from the available satellite images for the Macalister Irrigation District (MID), used to estimate CWR, and then used to compare CWR estimates with the available crop water (irrigation and rainfall) as an assessment of irrigation performance.

Methods

The study area is MID which is located around the Macalister River in the Gippsland region and covers an area of approximately 53,000 ha, of which more than 95% is under irrigation, dominated by pastures.

This study was conducted for the period Dec 2011 – Mar 2012.

Crop water supply data:

The total crop water supply calculated for this study was derived from two sources. Firstly, the measures of water supplied to farms were sourced from the Victorian Water Register (VWR), maintained by DSE (http://www.waterregister.vic.gov.au/). The VWR records within-season water use which enables matching of water supply to a particular part of the irrigation season. Water use licences (WUL), which authorise the water use for irrigation, have been spatially tagged to land parcels through the standard parcel identifier. The most important requirement for enabling the assessment of WUL land units is the spatial and temporal alignment of the data. The temporal alignment of data to provide the best window to match estimates of crop water requirement against crop water supply is dependent on the frequency of water readings undertaken in the MID and the seasonal conditions being experienced.

The second source of crop water supply is rainfall. Daily estimates of rainfall (mm) were acquired from the SILO web site (http://www.longpaddock.qld.gov.au/silo) for a weather station (East Sale, 38.12°S, 147.13°E) located within the study area. Rainfall figures were aggregated to the designated time window and converted to ML. The general conversion formula used was: 100 mm = 1 ML / ha.

Satellite images:

In this study, the satellite images were used to calculate NDVI and ET, necessary to estimate CWR. Two satellite images were collected for this study: Landsat 7 ETM+ and ASTER captured on 26 January 2012. Both images have certain limitations. Current Landsat 7 images are deficient in spatial coverage, particularly towards the edges. This is due to the scan line correction (SLC) issue. However Landsat 7 images have sufficient detail required to calculate NDVI and ET estimates, and evaluate the ET-NDVI relationship for the region, which is necessary for the calculation of CWR as described later in this Section. The current ASTER images have the advantage of full coverage but their mid-infrared bands are saturated, making them suitable only for NDVI and temperature. ASTER image has been used for the complete coverage of NDVI only.

In this study, the NDVI-ET relationship was evaluated using Landsat 7 imagery. That relationship was then applied to ASTER NDVI in order to achieve the full spatial coverage of CWR estimates. ASTER NDVI was re-sampled to 30 m resolution and adjusted to be comparable to Landsat NDVI. The adjustment factor was derived by using linear regression ($p < 0.0001$):

$$NDVI_{Landsat\text{-}7} = 0.06 + 0.97 NDVI_{ASTER} \quad (1)$$

Estimates of Normalised Difference Vegetation Index (NDVI)

NDVI was calculated using the following equation for ETM+ and ASTER images:

$$NDVI = (NIR - R) / (NIR + R) \quad (2)$$

Here, NIR refers to the near-infrared spectral band and R is the red spectral band of the satellite. Values of NDVI generally vary between 0 (no vegetation) and 1 (full vegetation cover). Negative NDVI values indicate surface water.

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Estimates of evapotranspiration (ET)

ET was estimated using the modified form of SEBAL and METRIC algorithms (Allen et al 2007) implemented at the Victorian Department of Primary Industries (DPI) in Australia (Whitfield et al 2010). The following standard surface energy balance equation is the basis of the algorithm:

$$Rn = LE + H + G \tag{3}$$

The net energy flux (Rn) is distributed between soil heat flux (G) and convective fluxes (sensible heat flux, H, and latent heat flux, LE). LE is determined as a residual energy when the other fluxes are known, measured or modelled. The modification to METRIC, as implemented at DPI, included the empirical relationship of Teixeira et al. (2009) to describe surface roughness as a function of NDVI and surface albedo.

Estimating crop coefficients

Measures of the relative rate of ET (ET ratios) were calculated pixel-wise using Landsat image. Pixel-wise values of ET ratios were computed as the instantaneous satellite-derived ET estimates divided by an image-appropriate measure of on-ground reference ET (REFET): ET ratios = ET / REFET

For image analyses, on-ground measures of REFET were calculated from hourly records of temperature, humidity and wind speed acquired from www.weatherzone.com.au for a weather station (located in East Sale) sited within the image at the time of satellite overpass. Instantaneous and daily measures of REFET were calculated according to Allen et al (2006):

$$REFET = (0.408D \cdot (Rn - G) + g \cdot Cn \cdot u2(es\text{-}ea)/(T+273)\ ) / (D + g\ (1 + Cd \cdot u2)) \tag{4}$$

Here, Cn and Cd are constants appropriate to ‘tall’ or ‘short’ reference crop/grass and time span (hourly, daily data). D is the slope of the saturated vapour pressure curve with respect to temperature, T is air temperature and g is the psychrometric constant. Net radiation (Rn), soil heat flux (G), D and g were calculated according to methods described by Allen et al (1998).

Daily weather data appropriate to the calculation of REFET (mm/day) were acquired from the SILO web site. This site provides measures of ‘short’ crop reference crop evaporation, ETo, based on the assumption of constant wind speed, u2 = 2 m/s. Those data were re-computed to provide measures of ‘tall’ crop reference evapotranspiration by an appropriate choice of constants, Cn and Cd, for tall crop REFET.

Estimating crop water requirement

Pixel-scale estimates of ‘crop water requirement’ (CWR_P) were derived from the standard equation:

$$CWR_P = \Sigma\ Kc\ ETo \tag{5}$$

Here Kc is the crop- and field-specific ‘crop coefficient’ appropriate to the irrigated field, and ETo is reference crop evapotranspiration (Allen et al 2007). The summation in this equation is extended over the seasonal duration of active irrigation of a crop.

The Kc values in this study depended on a triangular irrigated crop response framework (TICRF), derived from the results of Tasumi et al (2005) and implemented for Australian conditions by Whitfield et al (2010, 2012). ET and NDVI calculated for this study were used to validate the TICRF. For the calculation of Kc, the following equation was used based on the validated TICRF:

$$Kc = 1.33\ (NDVI - 0.1),\ NDVI > 0.1 \tag{6}$$

Pixels with NDVI below 0.1 were considered as non-active crops. The equation 6 was applied to the adjusted NDVI values from ASTER sensor.

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Results

Crop water requirement (CWR)

CWR is the quantity of water that is evaporated by the crop (as transpiration, by crop plants, plus evaporation, from soil surface) in order to match water use capability of crop. Figure 1 shows the per pixel distribution of CWR measures based on Eq. 5. The pixel-level CWR values varied between 0 and greater than 500 mm. However, within irrigation areas, CWR was in excess of 200 mm. Notable variations were observed within managed land units.

For the purpose of comparison of CWR with water supply, the pixel-level measures of CWR were converted into ML and aggregated to the WUL units. The distribution of the aggregated CWR per WUL is shown in Figure 2. The aggregated CWR varied considerably, largely in proportion to the area of WUL land units.

Total crop water supply

Total crop water supply (Irrigation plus Rainfall) is shown Figure 3. Irrigation water supply information was unavailable for some WUL units. Nevertheless, the distribution of total water supply showed a similar pattern as for CWR (Fig. 2). Similarly, the variations in total water supply were largely in proportion to the area of WUL land units.

Comparison of water supply with crop water requirement

There were 727 out of 1164 WUL land units that had comparable CWR and water supply estimates. The scatter plot of CWR versus total water supply (Fig. 4) shows a strong correlation between the two measures. The spread of the points in relation to the 1:1 diagonal line indicates a slightly higher water supply compared to CWR. A large number of WUL units had total water supply less than 500 ML.

Discussion

Water use analysis in this study demonstrated the broad application of remotely sensed information in an irrigation area. Here, CWR estimates per pixel attempted to quantify the water required by specified vegetation in a given period of time for normal growth under field conditions. No consideration was given to root-zone soil condition. Comparison of CWR with TCWS provided an assessment of irrigation performance and demonstrated the feasibility of using such assessment indicators in the context of Australian irrigated crops. The use of Satellite Remote Sensing for the estimates of ET and CWR is relatively new (Santos et al 2010) compared to the more traditional FAO methodology (Allen et al, 1998). A remote sensing approach has the advantage of providing a continuous coverage of ET (actual) and CWR, in contrast to point estimates used by the traditional method.

The study area is dominated by irrigated pastures. The key assumption about irrigated pasture, unlike dryland situation, is that the greenness is maintained throughout the season to almost a uniform level, by applying irrigation as required. It is therefore sufficient to use one satellite image to represent an irrigation season as done in this study. However, minor temporal fluctuations in vegetation in such a system are possible due to factors like over-grazing. Severe cases of temporal fluctuations, which may occur in dryland pastures, may need more than one image for the type of analysis presented here.

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Figure 1: Crop water requirement (CWR) estimates at pixel level for the duration of Dec 2011 – Mar 2012 in the Macalister Irrigation District.

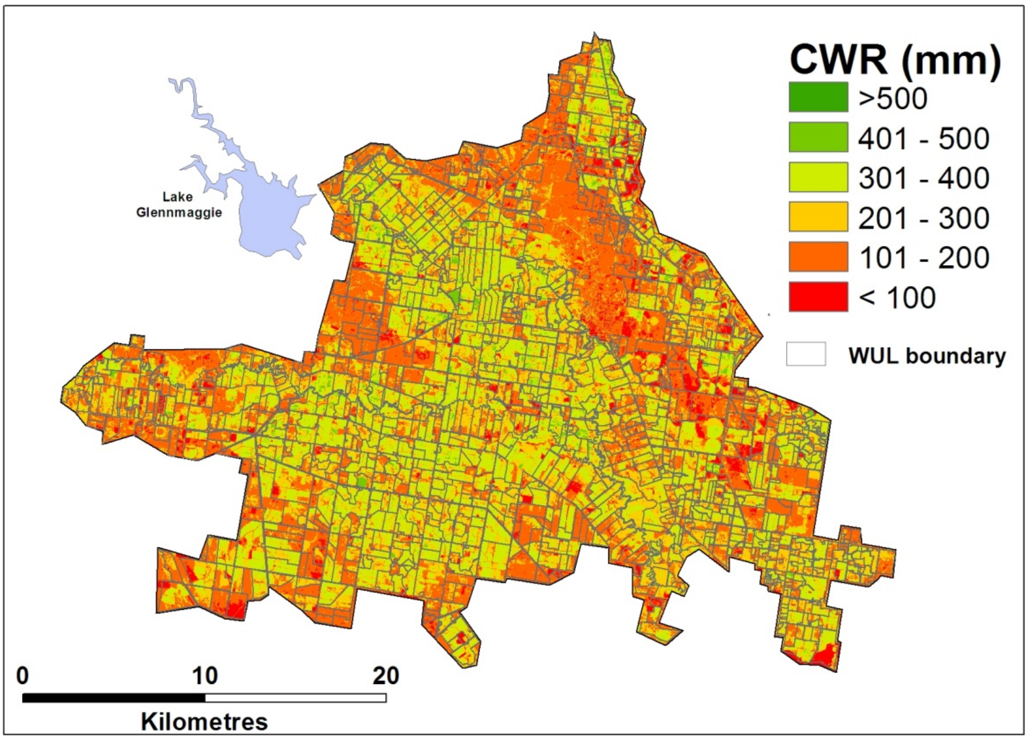

Figure 2: Crop water requirement estimates per WUL unit for the duration of Dec 2011 – Mar 2012 in the Macalister Irrigation District

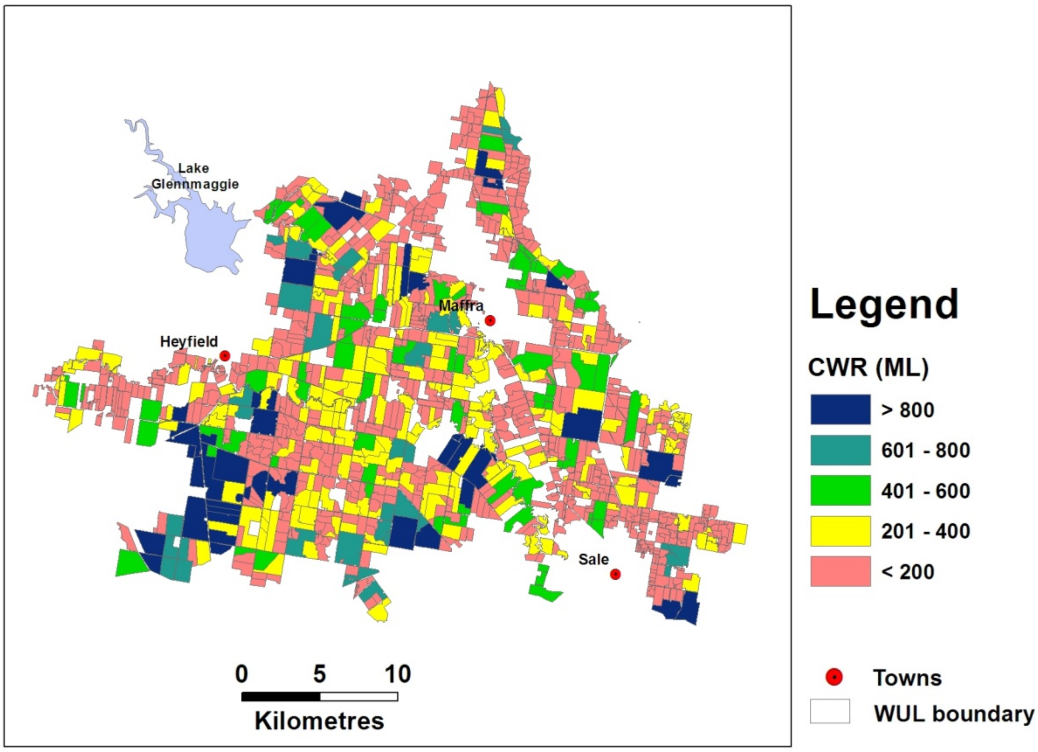

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Figure 3: Total crop water supply (irrigation and rainfall) for the duration of Dec 2011 – Mar 2012 in the Macalister Irrigation District.

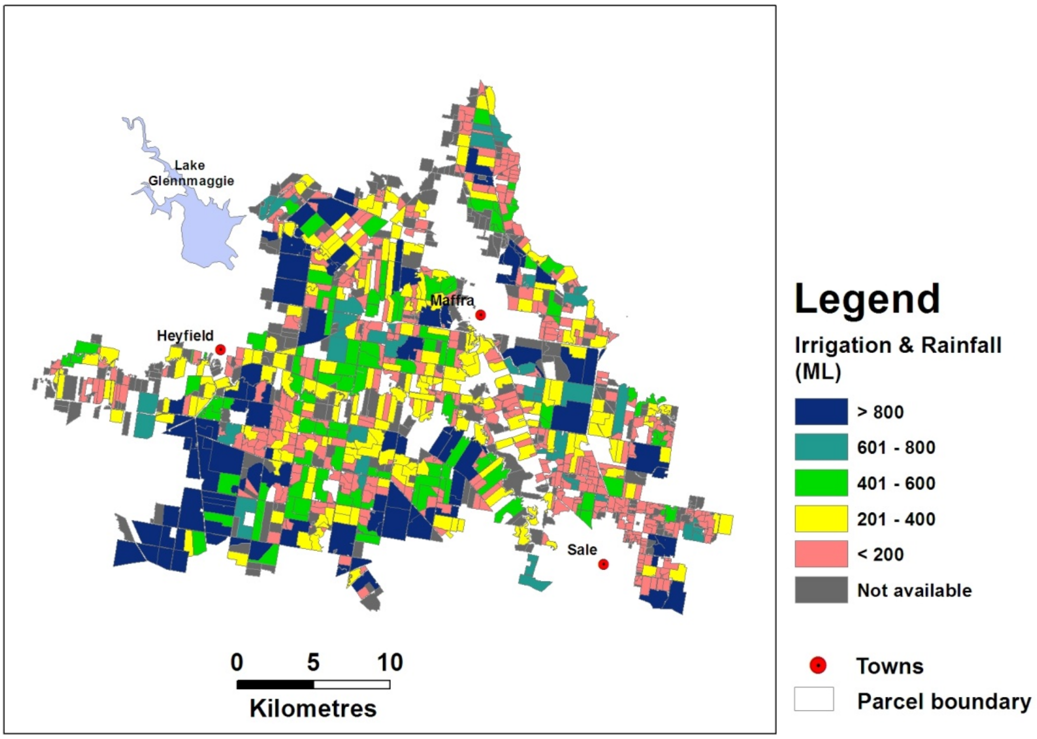
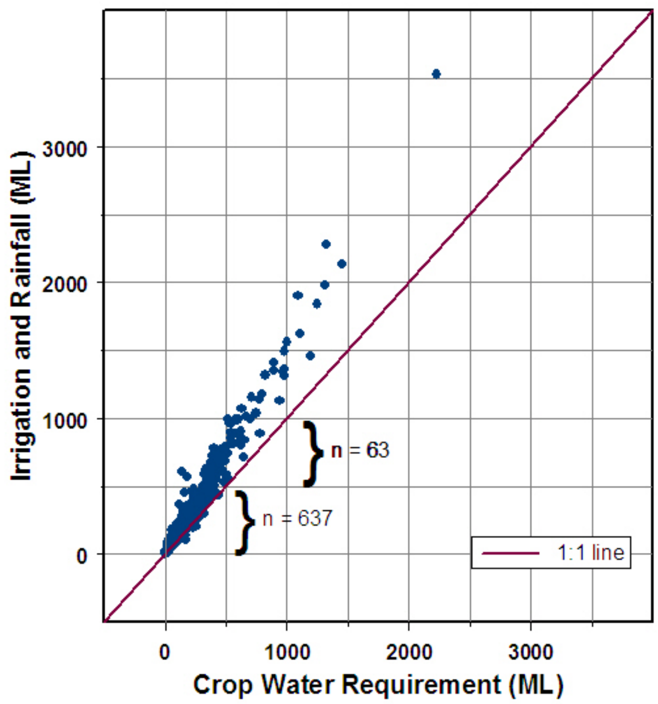


Figure 4: Comparison of water supply (irrigation plus rainfall) with crop water requirement in the Macalister Irrigation District. Each dot represents a WUL unit (n = 727).



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Conclusions

This study demonstrated how the measures of NDVI and ET were derived from the available satellite images for the Macalister Irrigation District (MID). By using these satellite-based measures, this study explored the estimation of ‘crop water requirement’ (CWR). The results also show that the satellite-based measures are vital in the analysis of water use, by creating a comprehensive spatial coverage.

Satellite-derived measurements, in combination with water supply information from the Victorian Water Register, provide the capacity to customise irrigation performance indicators to suit a specified time period and particular crops. The approach demonstrates the ability to report water use in a spatial context, which is potentially scalable from the farm to a regional level. The results of this study will be used to support an irrigation water use appraisal system and the reporting of water use efficiency, as part of the evaluation process for modernisation in MID.

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