Catchment Monitoring for Scaling and Assimilation of Soil Moisture and Streamflow

C. Rüdiger[a], R.E. Davidson[b], H.M. Hemakumara[b], J.P. Walker[a], J.D. Kalma[b], G.R. Willgoose[c], and P.R. Houser[d]

[a]Department of Civil and Environmental Engineering, University of Melbourne, Parkville, Australia.
c.ruediger@civenv.unimelb.edu.au

[b]Faculty of Engineering and Built Environment, School of Engineering, University of Newcastle, Callaghan, Australia.

[c]School of Geography, University of Leeds, Leeds, United Kingdom.

[d]Hydrological Sciences Branch, NASA Goddard Space Flight Center, Beltsville, USA.

Abstract: The aim of this research is to provide meaningful estimates of the spatial distribution and temporal variation of soil moisture content in the root zone through a combination of modelling and observations using data assimilation. The field work component includes the validation of remotely sensed near-surface soil moisture data (25km ? 25km spatial resolution) from the Advanced Microwave Scanning Radiometer for the Earth observing system (AMSR-E), collection of near-surface soil moisture and stream flow data for assimilation, and monitoring of point soil moisture profiles for validation purposes. The monitoring includes 26 soil moisture profile monitoring sites, 9 stream gauges, 5 weather stations, and numerous rain gauges throughout the 7 000 km^2 Goulburn River catchment in New South Wales, Australia. Monitoring is concentrated in the northern more open cropping and grazing half of the catchment, with less intensive monitoring in the southern more forested southern half of the catchment. This study has three major components. The *scaling* component of this research is developing techniques for downscaling the large-scale satellite measurements to the point-scale, while the *soil moisture assimilation* component is investigating the best way to use both the large- and point- scale near-surface soil moisture data to better estimate the root zone soil moisture content in areas of low vegetation. The *streamflow assimilation* component is investigating how streamflow data may be used to better estimate the root zone soil moisture content in areas of dense vegetation (where remote sensing data is not available), and how it may be used to further constrain soil moisture estimates in areas of low vegetation.

Keywords: *Soil moisture; Streamflow; Data assimilation; Remote Sensing; Scaling*

1. INTRODUCTION

Soil moisture is a significant factor in climatic and hydrologic behaviour. It influences the infiltration capacity of the soils (and therefore runoff), water availability for evapotranspiration and thus cloud formation due to latent and sensible heat flux (e.g. Friedrich and Mölders, 2000), and it plays an important role in land surface modelling (e.g. Jackson et al., 1982) for global climate prediction (e.g. Koster and Suarez, 1995). It is therefore important to understand and model the processes that drive temporal and spatial variability in soil moisture.

Satellite remote sensing offers a great opportunity to retrieve large scale near surface soil moisture data on a sufficiently regular temporal basis (i.e. 1 to 2 days). However, data from passive microwave sensors is not ideally suited for catchment scale hydrological applications, due to its coarse spatial resolution. Additionally, passive microwave remote sensing only provides information on soil moisture content in the first few centimetres of soil (Njoku, 1994). Finally, information on soil moisture content can only be retrieved for areas with low vegetation biomass (e.g. Jackson et al., 1982; Schmugge et al., 2002). Thus it is important that methods be developed for: i) the downscaling of these low spatial resolution measurements; ii) estimation of the deeper root zone soil moisture content from these shallow surface measurements; and iii) estimation of soil moisture content under areas of dense vegetation where remotely sensed soil moisture data is not available.

Several approaches to determine soil moisture content at a range of spatial and temporal scales will be undertaken as part of the project “Scaling and Assimilation of Soil Moisture and Streamflow” (SASMAS), jointly undertaken by

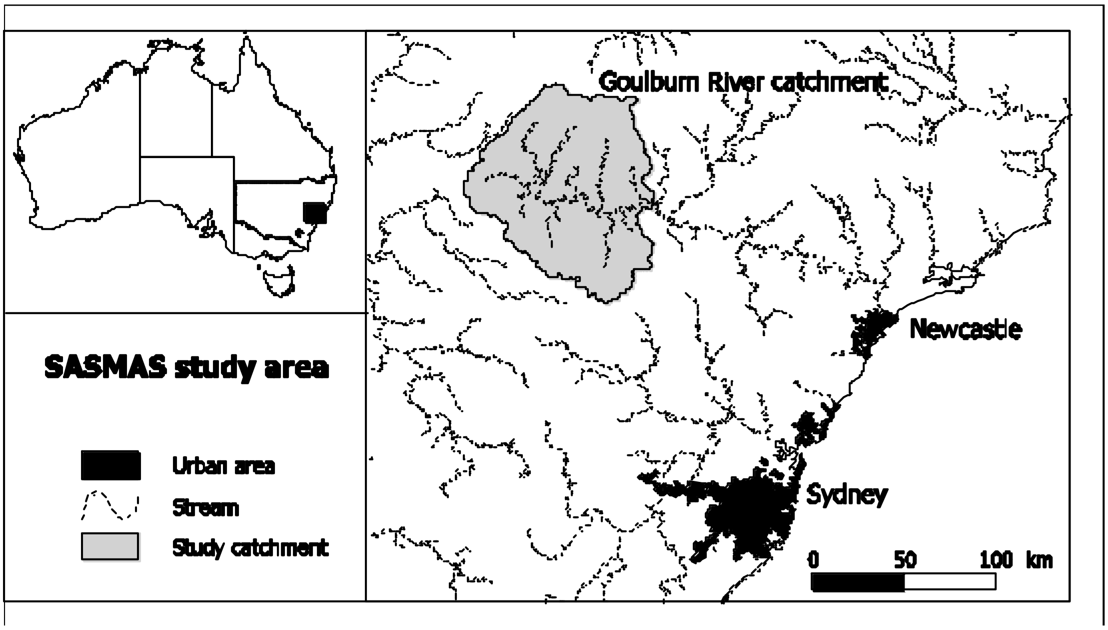

Figure 1. Location of the Goulburn River study catchment.

the Universities of Melbourne and Newcastle (see also http://www.civenv.unimelb.edu.au/~jwalker/data/sasmas). A study region has been selected in the semi-arid Goulburn River catchment (Figure 1) near Newcastle, New South Wales, Australia, for the purpose of validating these approaches. The study region will also be used to verify the remotely sensed soil moisture data from the Advanced Microwave Scanning Radiometer for the Earth observing system (AMSR-E).

2. SATELLITE DATA

The passive microwave data used during the project will be from the AMSR-E sensor onboard the Aqua satellite, which was launched in May 2002. The satellite orbits the earth in a sun-synchronous orbit, having ascending orbits at 1.30pm and descending orbits at 1.30am. The rate of overpasses for a region varies depending on latitude, with polar regions having several overpasses per day and equatorial regions having only one overpass every two days. Our study catchment will have two am and pm overpasses every three days.

The swath width of the AMSR-E sensor at C-band (6.9GHz; the lowest frequency for this sensor) is 1445km and the resolution of one footprint is 74km ? 43km. Due to over-sampling at an interval of 10km ? 10km, the coarse resolution of the footprint is interpolated to provide a 25km ? 25km soil moisture product (Crow et al., 2001).

3. STUDY REGION

3.1. Location

There are several aspects that influenced the choice of the Goulburn River catchment as the primary study region, with the most important reasons being its distance from the ocean and its vegetation cover. A field site too close to the ocean or other large water bodies will undergo a mixed pixel response within the satellite footprint. This is particularly important due to the large size of the AMSR-E footprint. Water surfaces have a significantly different radiobrightness response to that of soil, and affected pixels generally indicate soil moisture levels much higher than reality. The Goulburn River catchment is more than 100km from the coast, meaning that it should be unaffected by coastal influences. Moreover, there are no large water storages in the Goulburn River catchment. Secondly, the northern part of the catchment comprises a cleared area which is sufficiently large for AMSR-E validation (Figure 2).

3.2. Description of the Goulburn River Catchment

The Goulburn River catchment, located in a semi-arid area of south-eastern Australia, has a size of approximately $7000km^2$ and consists of two distinct parts. The northern part of the catchment having dominantly undulating hills with average elevations between 300 and 500m is mainly cleared for cropping and grazing purposes, and the soils are mostly derived from basalt. The northern boundary of the catchment is defined by

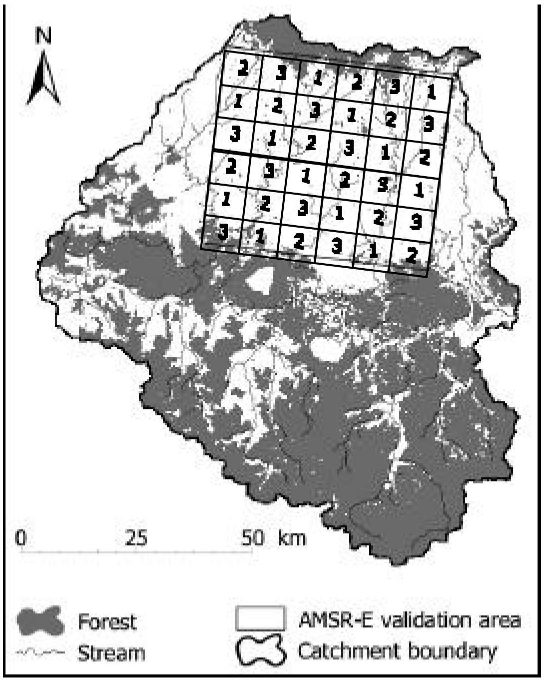

Figure 2. Map showing vegetation cover and AMSR-E validation site in the Goulburn River catchment. Numbers indicate sampling days.

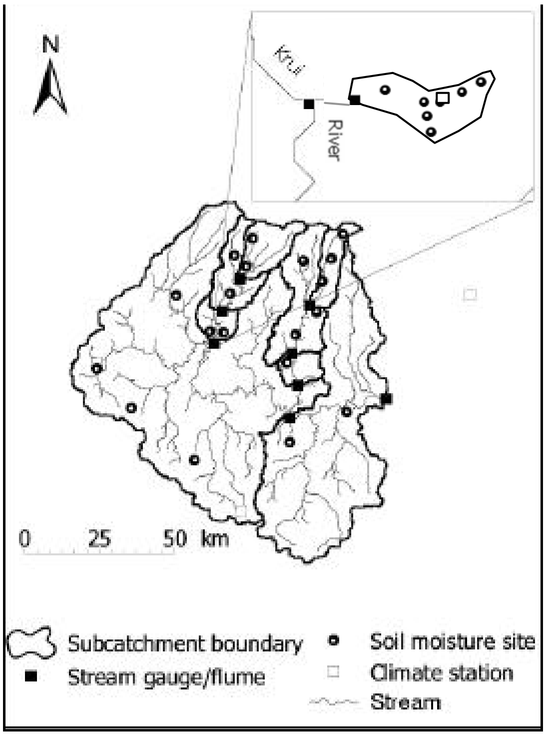

Figure 3. Location of monitoring sites and subcatchment boundaries.

the Liverpool Ranges, which rise to an elevation of more than 1100m. The southern part of the catchment has significantly different surface conditions with steep hills, cliffs and gorges, particularly along the southern boundary. It is also highly forested with sandstone derived soils (Northcote, 1960). Soil depths vary significantly from several metres deep near the Goulburn River to about 30cm on hilltops. The Goulburn River flows in an easterly direction, while its tributaries are aligned in north-south directions. The overall aspect of the Goulburn valley is easterly, with an elevation of about 600m in the western part, declining to 120m at the outlet. The slopes in the subcatchments are mainly facing in east or west directions. The catchment only contains one town with a population of more than 100; Merriwa having a population of 1100.

The annual rainfall within the catchment varies significantly. Average annual rainfall in most of the catchment is approximately 700mm, but can vary from 500mm to 1100mm in higher altitudes. Generally, major rainfall events occur in October and November, while the monthly average precipitation in July is 40mm. The average annual class A pan evaporation for the study region is about 1800mm. The minimum monthly average is reached in July with 75mm and the maximum can be observed in January reaching 250mm (Australian Bureau of Meteorology, 1975).

Monthly mean maximum temperatures reach 30°C in summer and approximately 17°C in winter, with minimum values of 16°C and 3°C, respectively (Australian Bureau of Meteorology, 1975). Except for areas of high altitude, frost is unlikely to occur during daytime during winter, meaning that daytime AMSR-E data may be used throughout the entire year. Care has to be taken during nighttime in winter when temperatures can reach less than 0°C.

There are two focus catchments in the northern half of the Goulburn River catchment: the Krui River catchment and the Merriwa River catchment (Figure 3, small western and eastern subcatchments, respectively). Each of these focus catchments are divided into three further subcatchments. Within the downstream sub-catchment of the Krui catchment is a small 728ha microcatchment. The microcatchment has seven soil moisture monitoring sites, one weather station and a flume for streamflow measurements.

A total of 26 soil moisture monitoring sites are distributed across the Goulburn catchment (Figure 3). The Krui River catchment ($500km^2$) contains 6 monitoring sites in addition to those in the microcatchment, giving a total of 7 sites, presuming the microcatchment is equivalent to a single monitoring site within the larger subcatchment. The neighbouring Merriwa River catchment ($600km^2$) contains a further 7 sites, and the remaining 6 sites are evenly distributed over the remainder of the Goulburn River catchment.

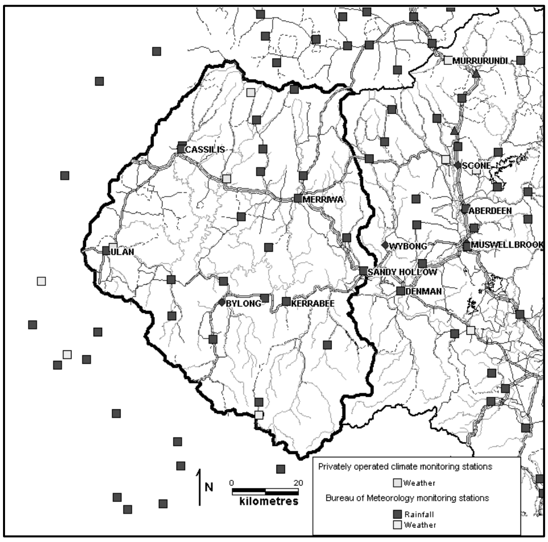

Figure 4. Location of weather stations and collecting rain gauges throughout the Goulburn River catchment and district.

The set ups of a typical soil moisture monitoring site and a weather station are described in detail in a subsequent section.

Stream gauges are located at the outlet of each subcatchment. In addition to the 3 existing Dept. of Land and Water Conservation (DLWC) gauging stations, 5 stream gauging sites and a flume have been installed (Figure 3). Additionally, 2 weather stations have been added to the 3 existing weather stations (Figures 3 and 4) and there are numerous collecting rain gauges located throughout the Goulburn River catchment (Figure 4).

4. INSTRUMENTATION AND SAMPLING

4.1. Soil Moisture Profiles

Two different kinds of soil moisture probes have been installed for soil moisture profile retrieval. Where soil depth permits, three Campbell Scientific CS616 reflectometers and three TRASE® Time Domain Reflectometry (TDR) waveguides have been installed in the top 90cm (Figure 5). The CS616 reflectometers were installed at depths of 0-30cm, 30-60cm, and 60-90cm (through 15cm wide access holes), while the TDR probes reach from the surface to the respective depth (30, 60, and 90cm). Each sensor type yields a measurement of the average soil moisture content over the length of the probe. One Campbell Scientific CS T107 soil temperature sensor has been installed at a depth of 12-18cm (ie. the centre of the T107 being at the centre of the top CS616 soil moisture probe), to allow for temperature correction to the CS616 measurements. While the TDR probes are read manually on a monthly basis, the CS616 and CS T107 sensors are read every minute and the averages over periods of ten minutes logged. Even though the TDR probes have different lengths, comparison with the CS616 data is possible by comparing the aggregate of the different CS616s to the respective TDR measurements. These TDR measurements will be used in the calibration of the CS616 sensors.

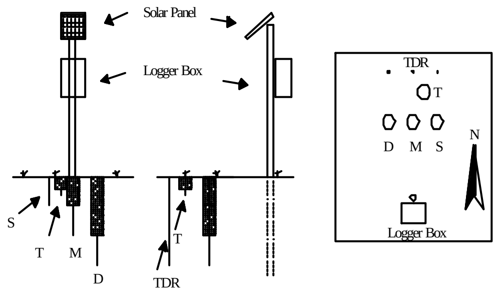

Figure 5. Typical setup of a soil moisture monitoring site (front view, side view and top view); showing shallow (S), medium (M), and deep (D) CS616 and the CS T107 (T) sensors.

It is particularly important for soil moisture monitoring sites to be representative of their surrounding landscape in a catchment, especially given the constraints in the number of sites that can be adequately monitored. Such catchment average soil moisture sites (Grayson and Western, 1998) are obtained by choosing midslope locations with representative vegetation, soil type, terrain slope, elevation, aspect etc. A significant amount of time was spent prior to the installation in order to determine the appropriate locations for soil moisture sites. The soil moisture monitoring sites in the microcatchment were installed in the pattern shown to determine the representativeness of the locations in regard to location in the hillslope. To achieve this and to prove the applicability of the findings of Grayson and Western (1998) to the catchment, sites have been installed in lower, middle, and upper slopes. Moreover, transects using handheld 30cm TDR probes will be made in the area of each monitoring site to give an overview of the spatial variability in soil moisture content and verify that the chosen sites are representative of the surrounding area.

4.2. Climate Stations

The Bureau of Meteorology operates two weather stations near and within the catchment, one in the east and one at the southern end of the catchment. A further private weather station is located in the west. Two supplementary weather stations (Figure 6) have been installed within the Krui

River catchment, one located at the northern end of the catchment, the other within the microcatchment. The supplementary weather stations measure air temperature and relative humidity at 2m, wind speed at 3m, precipitation using pluviometers at 0.5m, soil moisture at 3 depths (same as for the soil moisture profiles), and temperature sensors. Further measurements at the microcatchment weather station include atmospheric pressure, solar radiation at 2.89m, wind direction at 3m, and a net radiometer at 1m. There are also 8 CS T107 temperature sensors at different depths (2.5, 5, 10, 15, 30, 45, 60, and 75cm), and two heat flux plates at 5cm. All measurements are made every minute and averages logged every ten minutes. The two supplementary weather stations are located at different elevations (~200m and ~800m), with the aim of capturing the spatial variation in climate which is strongly linked to orography.

Collecting rain gauges have been installed at four locations in the microcatchment in order to assess the importance of rainfall spatial variability. Additional collecting rain gauge information across the Goulburn catchment (Figure 4) is available from the Bureau of Meteorology. This is in addition to their weather stations. Two supplementary pluviometers have also been connected to soil moisture sites.

4.3. Stream Gauging

Three different kinds of streamflow measurements are being made. Additionally to the three existing DLWC stream gauges, the stream flow is being monitored at five locations using water level pressure sensors (Solinst Model 3001 Levelogger). Measurements of the pressure sensors are logged when changes in the water level of more than 5mm occur. Additionally, a 1ft 6in partial Parshall flume has been installed near the outlet of the microcatchment. The pressure sensor at the flume is an Innovonics MD4W water level logger. Due to its specifications, only measurements on a regular basis are possible. The logger is set to measure the water level at ten minute intervals.

4.4. AMSR-E Validation Procedure

The AMSR-E validation site is located in the northern half of the Goulburn River catchment (Figure 2). In order to accommodate a full 25km ? 25km satellite measurement an area of approximately 50km ? 40km will be monitored. Due to the size and accessibility of the catchment, complete coverage can not be undertaken in a single day. The area will be divided into four sections and assigned to four groups of two

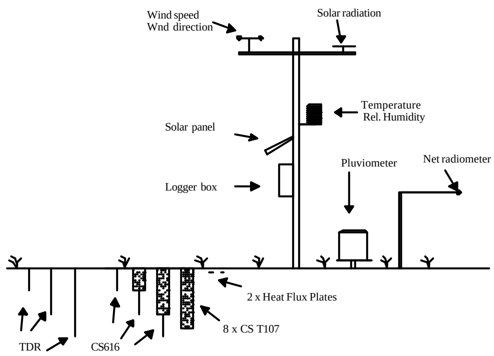

Figure 6. Typical setup for the climate stations.

people, each equipped with GPS for site location. A further subgrid will subdivide the cells into smaller units that will be measured across a three-day period, as indicated by the numbers on Figure 2. A three-day field campaign can be justified on the basis that soil moisture content does not undergo significant changes during the course of a few days under typical periods of exfiltration. The field trips will be scheduled in such a way so that there is at least one overpass, with it being on the second day.

The supplementary data consists of a total of 10-15 measurements within each cell in the subgrid, resulting in 360-450 measurements for each field campaign. This number and their random coverage throughout the catchment should provide a sufficient base to allow for validation of the satellite soil moisture product, and development of a procedure for downscaling of the low resolution satellite measurements.

Three types of point measurements will be taken. Firstly, a volumetric soil sample will be taken from the top 1cm in order to determine its soil moisture content and soil properties. Secondly, Theta® probes will be used to measure the average soil moisture content over a depth of 6cm. Thirdly, a vegetation biomass sample will be taken for determining vegetation water content and dry biomass.

4.5. Instrument Calibration

The CS616 reflectometers used at the soil moisture monitoring sites throughout the catchment are highly sensitive to soil type, salinity, and temperature. The manufacturer only provides calibration charts for a particular soil type under specific conditions, making individual calibrations necessary. Western et al. (2001) have conducted extensive research on temperature correction for the CS615 reflectometer, and have provided a good guideline on how to conduct these calibrations. Their work has shown that the variations from calibration can be significant.

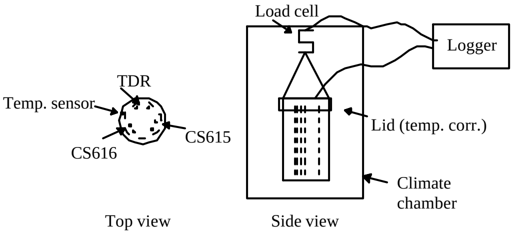

Figure 7. Calibration set up.

Calibration of CS616s will be done at two levels, i) in situ calibration with the TRASE® TDR measurements and ii) a more comprehensive laboratory analysis. Laboratory calibration will involve placing soil samples from the field sites into cylinders of 35cm length and 18cm diameter. The soil samples will be repacked to the approximate density of that in the field and saturated with water before the moisture probes are inserted (Figure 7). The soil will be dried under constant environmental conditions (25° and 10% relative humidity) in a climate chamber for several days during the first run of the experiment. Gravimetric measurements will be continuously recorded using load cells attached to the top of the climate chamber, allowing an estimate of the volumetric soil moisture content in the soil sample. This will allow establishment of a proper calibration for the different soils.

The laboratory set up will include temperature sensors, TDR probes, CS616 and CS615, which will be used in a parallel set up within the same soil sample (Figure 7). This will enable the determination of a precise calibration curve for the CS616 reflectometers as a function of soil temperature, soil type and soil salinity. Due to the small size of the soil samples, care has to be taken to avoid interference from the different sensors and any effects from the surface of the sample container. In order to achieve this, the signals have to be temporally offset, in addition to a distance of at least 5cm between the individual probes and 2cm to the surface of the sample container, as specified by the manufacturer (Campbell Scientific Inc., 2002). The results from the CS616 and CS615 probes will be compared to the TDR measurements and to the results from the gravimetric method.

A second run will be necessary to establish a temperature correction factor. The same soil sample will be sealed and the measurements made under different temperatures for constant moisture content.

Only the CS616 and TDR probes are necessary for calibration purposes. The additional CS615 probes will be placed into the soil samples in order to determine a relationship between the CS616 and its predecessor the CS615, especially under different temperature conditions. This will be done to test whether the CS615 temperature correction developed by Western et al. (2001) can be applied to the CS616.

The determination of salinity will take place before and after the second run of the experiment, to determine any changes in salinity. A soil classification based on particle size will be undertaken after the runs.

5. ACKNOWLEDGMENT

This project is sponsored by ARC Discovery Project DP 0209724. The authors wish to thank Stephen Wealands at the University of Melbourne for his help to produce some of the figures.

6. REFERENCES

Australian Bureau of Meteorology, Climatic atlas of Australia, Australian Publishing Services, Canberra, 1975.

Campbell Scientific Inc., CS616 Water Content Reflectometer Instruction Manual, Campbell Scientific Inc., Logan, USA, 23pp., 2002.

Crow, W.T., M. Drusch, and E.F. Wood, An observation system simulation experiment for the impact of land surface heterogeneity on AMSR-E soil moisture retrieval, *IEEE Transactions on Geoscience and Remote Sensing*, 39(8), 1622-1631, 2001.

Northcote, K.H., Atlas of Australian Soils, Sheet 3, CSIRO and Melbourne University Press, 1960.

Grayson, R.B. and A.W. Western, Towards areal estimation of soil water content from point measurements; time and space stability of mean response, *Journal of Hydrology*, 207(1-2), 68-82, 1998.

Jackson, T.J., T.J. Schmugge and J.R. Wang, Passive microwave sensing of soil moisture under vegetation canopies, *Water Resources Research*, 18(4), 1137-1142, 1982.

Koster, R. D. and M. J. Suarez, Relative contributions of land and ocean processes to precipitation variability, *Journal of Geophysical Research*, 100(D7), 13775-13790, 1995.

Njoku, E.G., Surface temperature estimation over land using satellite microwave radiometry, *Passive Microwave Remote Sensing of Land-Atmosphere Interactions*, Choudhury, B.J., Y. Kerr, E.G. Njoku and P. Pampaloni, eds., VSP, 509-530, 1994.

Schmugge, T.J., W.P. Kustas, J.C. Ritchie, T.J. Jackson, and A. Rango, Remote sensing in hydrology, *Advances in Water Resources*, 25(8-12), 1367-1385, 2002.

Western, A, C. Olszak, T. Anderson, J. Thompson, M. Duncan, R. Grayson, D. Wilson, R. Young, Soil moisture instrument calibration and reliability assessment for MARVEX, Tarrawarra and Point Nepean experimental sites, Centre for Applied Hydrology (CEAH) report 04/01, Melbourne, 2001.