Using Passive Microwave Response to Soil Moisture Change for Soil Mapping: A Case Study for the Livingstone Creek Catchment

G. Summerell, V. Shoemark, S. Grant, and J. P. Walker

***Abstract*—The 46-km^2 Livingstone Creek Catchment in southeastern Australia was flown with a passive microwave airborne remote sensor four times throughout the three-week National Airborne Field Experiment in 2006, with a spatial resolution of ∼200 m. Both continuous and discrete measurements of soil moisture were taken to help with interpretation of results. The catchment was experiencing extreme drought conditions leading up to the experiment, and as a result, ground cover in the catchment was minimal with many paddocks consisting of sparse dry stubble and grass. During the experiment period of November 2006, 30 mm of rainfall occurred, with the catchment going from parched dry conditions to surface wet conditions and back to dry conditions again in a short period of time. Changes in moisture responses observed by the airborne passive microwave sensor were field verified to reflect the different geology, soil, and landform elements of the catchment. Consequently, this study suggests that passive microwave remote sensing has potential as a tool to assist with soil mapping, through detecting changes in soil moisture spatial and temporal patterns.**

***Index Terms*—National Airborne Field Experiment (NAFE), Polarimetric L-band Multibeam Radiometer (PLMR), remote sensing, soil moisture.**

I. Introduction

UNDERSTANDING soil distribution patterns allows for the different water storage characteristics of catchments to be identified and modeled, increasing our understanding of process connectivity for water balance studies. Current methods for mapping soils use multiple techniques as no individual technique can adequately identify all the processes that lead to soil formation and distribution processes. These methods usually consist of sourcing existing surrogate information such as geological maps, utilizing aerial photography and remote sensing techniques, and field mapping. Remote sensing techniques for mapping soils range from multispectral scanning, airborne gamma-ray spectrometry, hyperspectral remote sensing, gravity, electromagnetics, and radiometrics [13]. All these methods measure different physical characteristics of the regolith, from mineralogy to reflectance and conductance properties. Previous studies have demonstrated the benefits of using passive microwave data for estimating soil hydraulic properties as the method is sensitive to moisture variations [4], [5], [7]. With additional surrogate information on terrain, soil properties, rainfall patterns, and vegetation cover, downscaling of the original data is possible [6], allowing for increased application potential at catchment scales. This study builds on the existing knowledge by demonstrating that passive microwave data from the Polarimetric L-band Multibeam Radiometer (PLMR) can detect landscape soil moisture variations corresponding to different soil types that are influenced by landform controls.

II. Study Area

The Kyeamba Creek catchment is southeast of Wagga Wagga in central New South Wales, Australia. It covers an area of 600 km^2 and flows into the Murrumbidgee River. The major surface drainage features are Kyeamba, O'Briens, and Livingstone Creeks. Average annual rainfall is 650 mm, with a gradient decreasing from the highlands in the south to the confluence with the Murrumbidgee River in the north. Land use is dominated by cattle grazing, limited sheep grazing, and some pasture irrigation. The geology of the area is characterized by granitoids in the higher regions of the catchment and deformed metasediments in the lower regions.

III. Data

The data used in this study were the medium-resolution scale PLMR flights, flown onboard a small aircraft during the National Airborne Field Experiment in 2006 [11] and coincident ground data collection of soil moisture. The focus study area for this letter is the subcatchment Livingstone Creek (see Fig. 1), which covers an area of 46 km^2. The landforms, geology, vegetation, and land use in Livingstone Creek are reflective of the whole Kyeamba Creek catchment.

Four Kyeamba flights were conducted during NAFE'06 one week apart. Airborne measurements used in this study were from the PLMR which measured both vertical (v) and horizontal (h) polarizations at incidence angles of $\pm 7^\circ$, $\pm 21.5^\circ$, and $\pm 38.5^\circ$ in across-track configuration. For this study, the (h) polarization was used as it is best suited to soil moisture sensing [12]. As the flights occurred within a 2-h period during the day when temperature variation was minimal, there was no need to correct for temporal variations in temperature.

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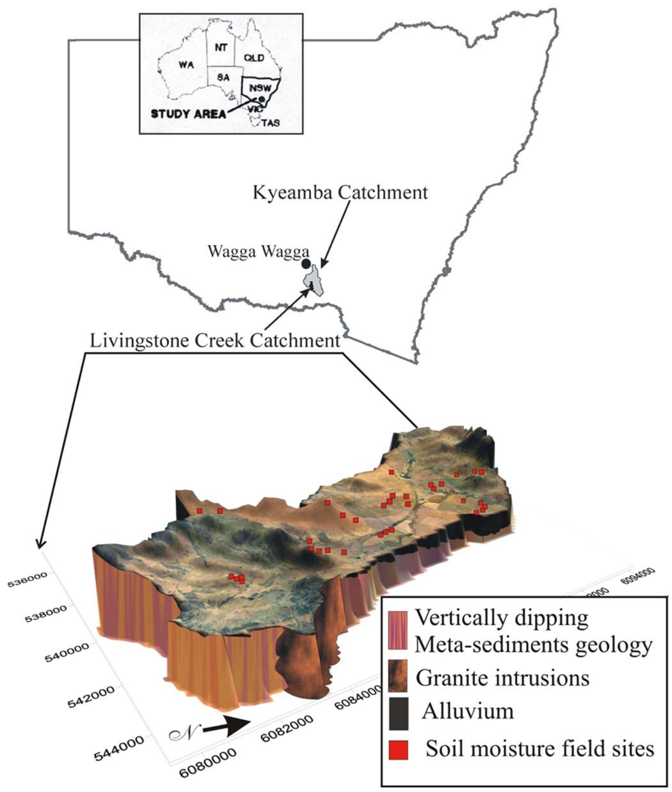

Fig. 1. Location of the Kyeamba Creek and Livingstone Creek catchments showing the major geologies and soil moisture field-site locations.

The Livingstone Creek monitoring network for soil moisture consists of eight continuous near-surface instrumented stations [9]. These stations were installed at eight strategic locations to represent the main landform elements within the study area. The aim of this monitoring was to capture the trend in soil moisture conditions for the duration of the experiment.

To get spatial coverage for the whole catchment, additional discrete soil moisture samples were taken throughout the catchment concurrently with the airborne PLMR data capture. The discrete field soil moisture sample points were determined based on a soil classification [1], combined with a representation of major landform elements from within the catchment. Landforms differentiate the major soil types often expressed as a soil catena sequence (i.e., ridge tops, upper slopes, lower slopes, and flats). The method for deriving the landforms followed [8]. Twenty-seven discrete soil moisture sampling points within the Livingstone Creek catchment were identified. At each site, three soil moisture readings were taken with a Delta-T ML2 Theta Probe and then averaged [3].

IV. Methods

Data acquired by PLMR were processed for the whole of the Livingstone Creek catchment to create a spatial PLMR image. Data were converted to a common incidence angle by using the ratio of each PLMR beam average to the beam 1 average (7°) multiplied by the actual beam observation.

Discrete field soil moisture samples were compared to the angle-corrected PLMR data for each day of the flights through linear regressions. PLMR brightness temperature data were also

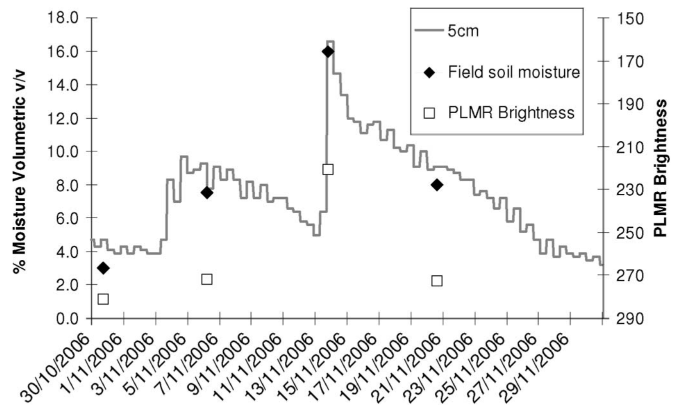

Fig. 2. PLMR brightness of the nearest pixel compared to discrete and 5-cm continuous soil moisture measurements.

compared against continuous field monitoring sites to compare how the readings are representing field moisture conditions.

The strength of using remote sensing technologies is the ability to obtain large spatial coverages. When mapping soils, one of the first delineations is geology, followed by major landscapes (i.e., rolling hills on the same geology as areas of steep hilly landscapes), down to individual toposequences of soil facets within a landscape (i.e., ridge tops, upper and lower slope soils). The spatial patterns of angle-corrected brightness temperature from the PLMR were compared to known geological and soil landscape features in the catchment. Topographic map grid references of 1 km^2 were used to compare percentage presence or absence between observed and PLMR-predicted features of interest.

V. Results and Discussion

During the field campaign, 8 and 22 mm of rainfall were received on the 6th and 13th of November, respectively. Measured rainfall at various locations indicated that precipitation patterns were uniform across the catchment. Fig. 2 shows a continuous trace of soil moisture at 5 cm responding to the rainfall events. Deeper soil moisture measurements showed no observable response, demonstrating that the rainfall only penetrated the near surface. Fig. 2 also shows the discrete soil moisture sample readings taken at the continuous "Soil Moisture 5" station and the PLMR brightness temperatures.

The PLMR images of the study area have shown perceptible wetting and drying patterns (Fig. 3). On November 6, 2006, the PLMR responded to the small amount of rainfall received, and on November 13, 2006, it shows considerable wetting-up followed by a drying of the catchment on November 20, 2006.

Comparisons against the discrete soil moisture data $(n=27)$ to the PLMR soil moisture brightness indicated that, on October 30, 2006, when the catchment was extremely dry, no obvious trends were observed against the PLMR with a linear r^2 of 0.15. Once rainfall was received, the relationship between discrete soil moisture and PLMR brightness temperature established an r^2 around 0.3–0.4. These low relationships are expected, given the errors associated with comparing a point sample to an average signal across a 200-m PLMR pixel.

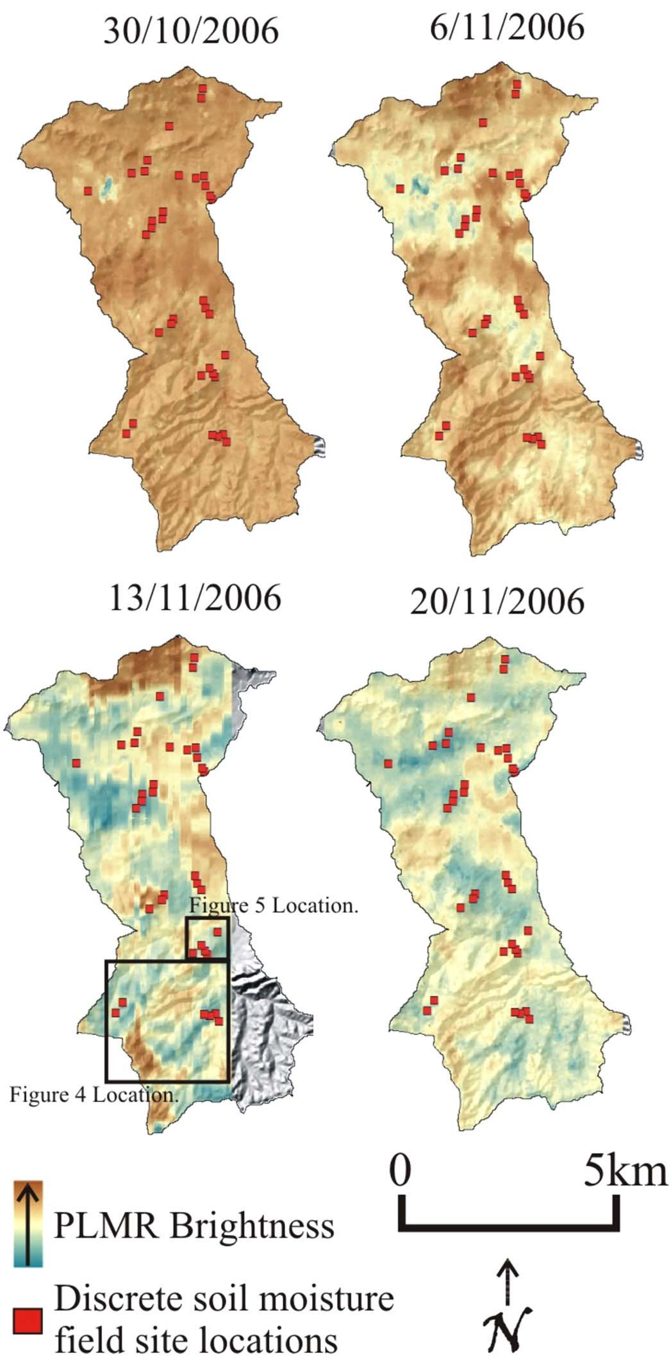

Fig. 3. PLMR images over Livingstone Creek during the four overpass dates of the campaign with discrete field sampling locations shown as red squares. Gray areas are the hill-shaded DEM that is used to help give relief perspective to the images.

Spatial patterns in the images and actual features in the landscape were then compared. Major geological features were observable in the PLMR images, particularly between the granite and metasediment geologies which would be due to the very different textured soils that form over these different geological types, and hence water retention capacities.

More subtle differences were also detected within the same geological types. Fig. 4 shows an area of metasediment geology where Chen and McKain [1] mapped out two separate soil landscapes during field surveying and aerial photo interpretation.

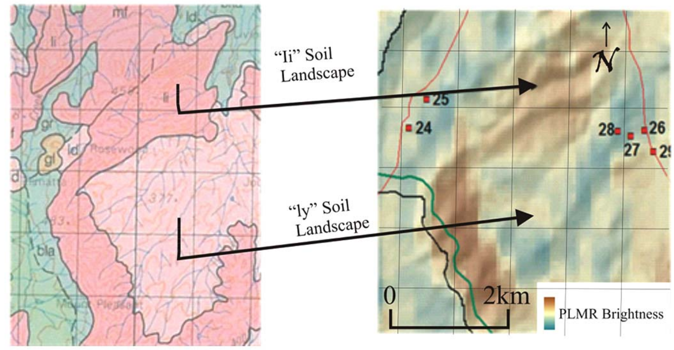

Fig. 4. Different soil landscapes within the same metasediment geology are reflecting soil moisture and temperature differences. Image to the left is from the soil landscapes of the Wagga Wagga 1 : 100 000 map sheet [1]. Image to the right is the PLMR brightness temperature on November 13, 2006. Red and green lines are roads, and the black line is the catchment boundary. Grids are 1 km^2. Location is shown in Fig. 3.

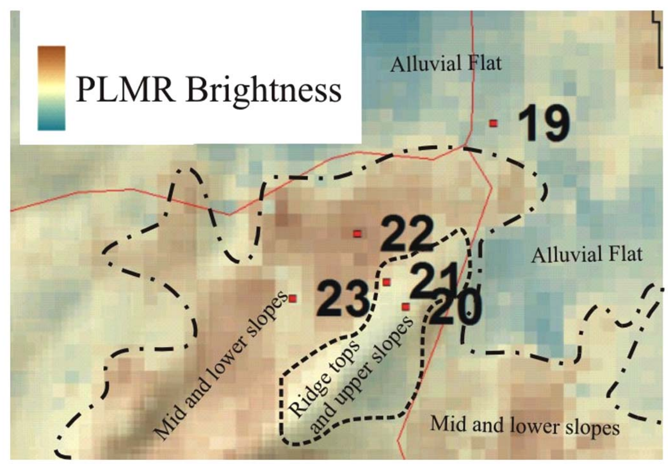

Fig. 5. PLMR image showing spatial correspondence to major landform features. Field sites and roads are marked in red.

These are "li" the Livingstone landscape and "ly" the Lloyd landscape. The "li" soil landscape is typically more weather resistant with a lot more quartz material and shallower soils, while the "ly" is more weathered with deeper soils. The PLMR brightness temperature pattern has reflected these soil landscapes with the "li" soil landscape unit, showing a drier signal than the "ly" unit which is reflective of the soil types and their water retention properties. The "li" soil landscape unit in Fig. 4 crossed into thirteen 1-km^2 topographic map grid cells (grid cells marked on Fig. 4). Within these grid cells, 40% were observed as the "li" unit while ~58% coverage was estimated from the PLMR image. Nine 1-km^2 grids were identified for the "ly" unit with an observed coverage of 70%, while the PLMR prediction of this unit was 67%.

Differences between upper and lower slopes within the same soil landscape were also observed. Fig. 5 shows how the ridge tops of a metasediment hill that consists of porous fractured rock (shales) and very shallow soils are slightly wetter (sites 20, 21) than the mid to lower slopes where the soils are very hard setting and clayeyer (sites 22, 23). At the lower slopes, the soils are deep and derived from colluvial and alluvial soil formation processes, and here, the soil moisture is much wetter as represented in the field at site 19. These observations align with stages 1 and 2 of the soil moisture distribution over time as described by Gwangseob and Barros [2]. They indicated the following: 1) topography appeared to be the dominant spatial structure of soil moisture during and immediately after rainfall; 2) followed by the soil moisture evolving into patterns that reflected soil hydrological properties; and then finally, 3) vegetation dominating the soil moisture patterns through evapotranspiration as the landscapes dry down.

VI. Conclusion

The medium resolution (200 m) flights of PLMR over the Livingstone Creek catchment have shown strong spatial relationships with major geological features within the catchment, down to individual soil landscapes within a geology class, to the landforms within the soil landscape that reflect individual soil types. This study concurs with the landscape soil moisture stages of the study in [2], with stages 1 and 2 being observed, but the drought conditions causing low vegetation cover didn't allow for the processes of three to be expressed. The wetting-up and drying-out characteristics of the different soil types spatially throughout a catchment could potentially be used to define catchment soil moisture retention characteristics. In countries, like Australia, that are experiencing increased drought effects from climate change, better mapping of soil water availability will significantly improve scientific development for natural resource management such as catchment water balance and soil and wind erosion modeling. Passive microwave is a remote sensing technique that is capable of this task and is becoming more widely available on various satellite platforms.

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