

# Spatio-temporal distribution of near-surface and root zone soil moisture at the catchment scale

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## Abstract:

Soil moisture is highly variable both spatially and temporally. It is widely recognized that improving the knowledge and understanding of soil moisture and the processes underpinning its spatial and temporal distribution is critical. This paper addresses the relationship between near-surface and root zone soil moisture, the way in which they vary spatially and temporally, and the effect of sampling design for determining catchment scale soil moisture dynamics. In this study, catchment scale near-surface (0–50 mm) and root zone (0–300 mm) soil moisture were monitored over a four-week period. Measurements of near-surface soil moisture were recorded at various resolutions, and near-surface and root zone soil moisture data were also monitored continuously within a network of recording sensors. Catchment average near-surface soil moisture derived from detailed spatial measurements and continuous observations at fixed points were found to be significantly correlated ( $r^2 = 0.96$ ;  $P = 0.0063$ ;  $n = 4$ ). Root zone soil moisture was also found to be highly correlated with catchment average near-surface, continuously monitored ( $r^2 = 0.81$ ;  $P < 0.0001$ ;  $n = 26$ ) and with detailed spatial measurements of near-surface soil moisture ( $r^2 = 0.84$ ). The weaker relationship observed between near-surface and root zone soil moisture is considered to be caused by the different responses to rainfall and the different factors controlling soil moisture for the soil depths of 0–50 mm and 0–300 mm. Aspect is considered to be the main factor influencing the spatial and temporal distribution of near-surface soil moisture, while topography and soil type are considered important for root zone soil moisture. The ability of a limited number of monitoring stations to provide accurate estimates of catchment scale average soil moisture for both near-surface and root zone is thus demonstrated, as opposed to high resolution spatial measurements. Similarly, the use of near-surface soil moisture measurements to obtain a reliable estimate of deeper soil moisture levels at the small catchment scale was demonstrated. Copyright © 2007 John Wiley & Sons, Ltd.

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## INTRODUCTION

Soil moisture is a key variable within earth system dynamics (Famiglietti *et al.*, 1998). It exerts considerable influence on many hydrological (e.g. runoff and flood forecasting) and pedogenic processes (Western *et al.*, 2004), and on the water and energy balances of land surfaces (Qui *et al.*, 2001; Di Domenico *et al.*, 2006). The spatial distribution of soil moisture has received increasing attention over recent decades (Famiglietti *et al.*, 1998; Starks *et al.*, 2006) because it is widely recognized that improving our knowledge and understanding of soil moisture and the processes underpinning its spatial and temporal distribution is critical (Wilson *et al.*, 2003).

Soil moisture content is highly variable, spatially and temporally (Famiglietti *et al.*, 1998; Qui *et al.*, 2001; Cosh *et al.*, 2004; Western *et al.*, 2004; Hebrard *et al.*, 2006). Near-surface soil moisture (i.e. in the top 50 mm of the soil profile) is particularly complex and highly variable (Svetlitchnyi *et al.*, 2003). Many authors have investigated the main factors controlling the spatial and

temporal dynamics of soil moisture, including topography (slope gradient, curvature, relative elevation), soil properties (clay content, albedo, organic matter), aspect, land use, vegetation, solar radiation, upslope or specific contributing area, and mean soil moisture (Famiglietti *et al.*, 1998; Western *et al.*, 1999; Qui *et al.*, 2001; Svetlitchnyi *et al.*, 2003; Canton *et al.*, 2004; Wilson *et al.*, 2005; Hebrard *et al.*, 2006). Conflicting opinions over which of these factors are most important are widespread. Many of these factors are interrelated, making it difficult to isolate and quantify the relative importance of individual factors (Qui *et al.*, 2001; Canton *et al.*, 2004). Furthermore, Famiglietti *et al.* (1998) suggest the reason for the contradictory findings within the literature can be attributed to under-sampling in space or time, or both. Further research is therefore required at a range of scales (hillslope and catchment) and soil depths, for different environments and time scales.

Present methods for measuring and estimating soil moisture can be classified into three main groups: (1) ground-based measurement; (2) estimation based on remote sensing; and (3) estimation via simulation models (Grayson and Western, 1998). Ground-based measurements can be direct (e.g. gravimetric soil sampling) or

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indirect (e.g. Theta probes) and can be made at various spatial and temporal scales. In recent years hand held instruments, such as the Theta probe, have allowed the quick and easy measurement of soil moisture in the near-surface (0–50 mm). Use of these probes provides a simple and reliable method of obtaining an instantaneous measure of soil moisture at the hillslope and catchment scale (Wilson *et al.*, 2003). Nevertheless, while it has been shown that this data can provide information on surface soil moisture, little work has been done to address the variability of soil moisture at a range of different scales to ensure that point based measurements of soil moisture can provide reliable data at the field, hillslope and catchment scale.

In this study we compare two different approaches to examine the spatial and temporal distribution of near-surface (0–50 mm) and root zone (0–300 mm) soil moisture. Ground-based data collected during the four-week National Airborne Field Experiment (NAFE) (Walker *et al.*, 2005) in November 2005 (high spatial, low temporal resolution) is compared with continuously recorded data obtained over the same period as part of the Scaling and Assimilation of Soil Moisture and Streamflow (SASMAS) project (low spatial, high temporal resolution) (Rudiger *et al.*, 2007, in press). Together, these projects add two unique datasets to the limited number available which can be employed to investigate the spatio-temporal patterns of soil moisture (De Lannoy *et al.*, 2006). This study is based within the 150 ha Stanley catchment in the Upper Hunter region of New South Wales, Australia, an area which is of particular interest as it is the focus of a study to examine the spatial and temporal dynamics of soil carbon at the hillslope and catchment scale (Martinez *et al.*, 2006). Soil moisture exerts control over the spatial distribution of vegetation, regulates soil temperature and the decomposition of organic matter by microbial activity, and is therefore an important variable influencing the spatial and temporal distribution of soil carbon within the landscape. This study is focused on obtaining estimates of catchment-scale average soil moisture (both near-surface and root zone) which, according to

Grayson and Western (1998), are required for a variety of hydrologic applications. This research aims to address the following questions:

- How does soil moisture (near-surface and root zone) vary spatially and temporally at the small catchment scale?
- What are the main factors controlling the spatial and temporal distribution of near-surface and root zone soil moisture at the small catchment scale?
- What is the relationship between near-surface and root zone soil moisture?
- Can near-surface soil moisture measurements provide data on soil moisture at greater depths?
- What is the effect of sampling design (i.e. low spatial, high temporal resolution [SASMAS] versus high spatial, low temporal resolution [NAFE]) for the determination of catchment scale soil moisture dynamics?

## STUDY SITE

The 150 ha Stanley catchment (150°07'00"E and 32°05'32"S) is a tributary of the 562 km<sup>2</sup> Krui River catchment, located in the Upper Hunter Valley of New South Wales, Australia (Figure 1). The catchment has seven permanent soil moisture monitoring stations, labelled S1–S7 (Figure 1), one of which, S2, doubles as a weather station. S2–S4 and S5–S7 are positioned on south-west and north-west facing hillslopes, respectively (Figure 2), while S1 is located on the relatively flat area alongside the main drainage line leading to the catchment outlet. Soil moisture and soil temperature are continuously recorded at each of these sites (20-min intervals) at a number of depths (0–50 mm, 0–300 mm, 300–600 mm, and 600–900 mm).

The catchment is underlain with Tertiary Basalt of the Liverpool Range beds (McInnes-Clarke, 2003) and forms part of the Merriwa Plateau (Story *et al.*, 1963). Three soil landscapes have been identified, including the Ant Hill (**ah**) and landscape variant **aha**), Bow

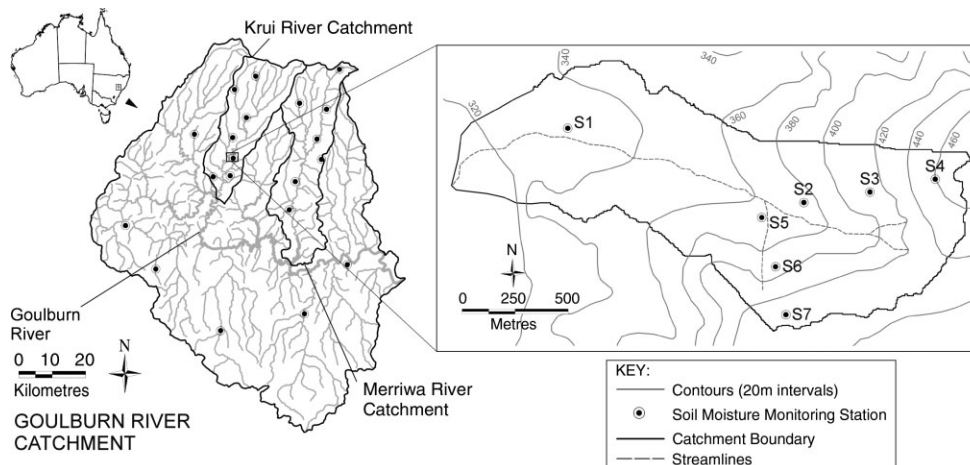


Figure 1. Location map showing Goulburn, Krui and Merriwa River catchments and the Stanley study catchment (including location of SASMAS soil moisture monitoring sites)

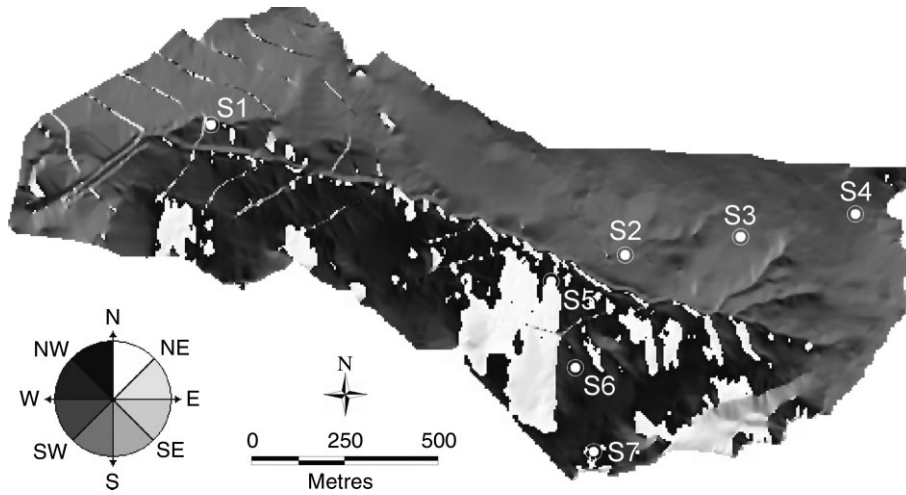


Figure 2. Aspect map for the Stanley micro-catchment

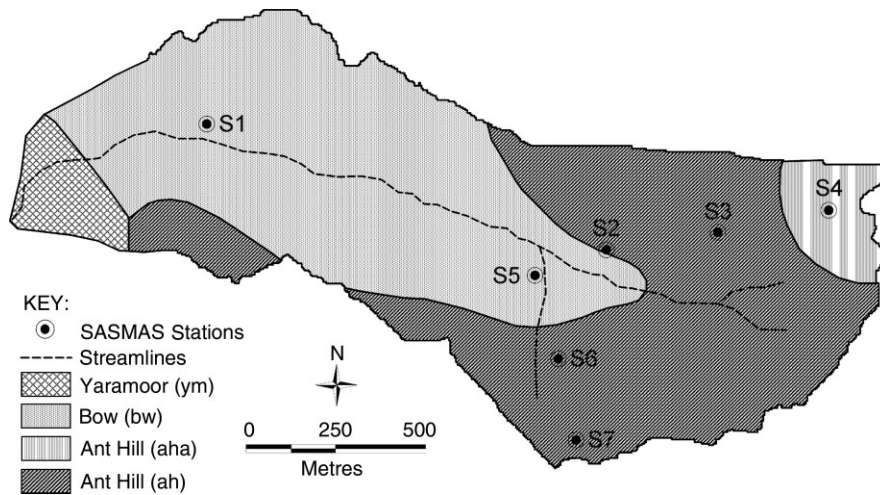


Figure 3. Soil landscape map for the Stanley micro-catchment

(**bw**) and Yarramoor (**ym**) (Figure 3) (McInnes-Clarke, 2003). The catchment consists of undulating hillslopes with gradients between 15–30% (**ah**) and 2–10% (**bw**) (McInnes-Clarke, 2003). The dominant soils of the Ant Hill soil landscape include Red and Black Dermosols (Chocolate soils and Euchrozems) and Red Vertisols (Red Clays). Soils in the Bow soil landscape are predominantly Black Vertisols and Black Dermosols (Black Earths and Chocolate soils) (Kovac and Lawrie, 1991).

The site is located in the temperate zone of eastern Australia. Climate in the region is dominated by a continental influence, although topography, elevation and proximity to the ocean are also considered important (Kovac and Lawrie, 1991). Average annual rainfall for Stanley is  $412 \pm 84$  mm, as recorded at S2 (2003–2006). Monthly rainfall figures for the region are 50–60 mm in summer and 30–40 mm in winter, where winter rainfall is least variable, and rainfall in late summer–autumn most variable (Kovac and Lawrie, 1991). The mean monthly minimum and maximum temperatures are 4 °C (winter) and 16 °C (summer), and 17 °C (winter) and 31 °C (summer), respectively, as recorded at S2 (2003–2006) (Figure 4).

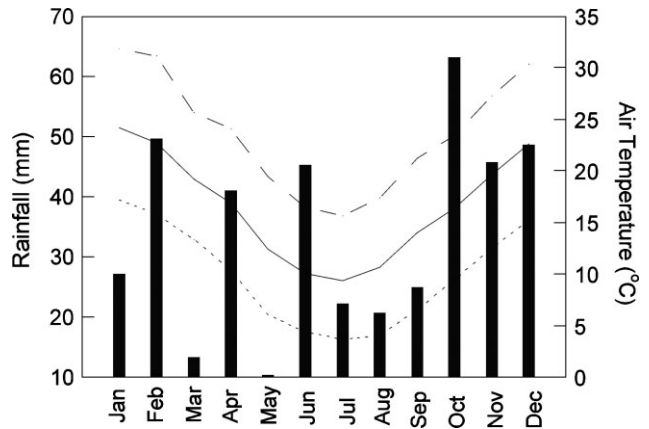


Figure 4. Monthly average rainfall (mm) [bars] and mean monthly [unbroken], minimum [dotted], and maximum [dashed] air temperature recorded at S2 between 2003 and 2006

The catchment is dominated by native grasses with scattered eucalypt species. Dominant grass species include plains grass (*Austrostipa aristiglumis*), wiregrass (*Aristida ramosa*), wallaby grasses (*Danthonia spp.*), red grass (*Bothriochloa macra*) and blue grass (*Dicanthium*

spp.) (Mitchell, 2002). Kovac and Lawrie (1991) classify the region's vegetation as eucalypt tree savannah, with sparse tree cover. Dominant tree species include White Box (*E. albens*) and Yellow Box (*E. melliodora*), Blakelys Red Gum (*E. blakelyi*), Kurrajong (*Brachychiton populneus*), Rough-barked Apple (*Angophora floribunda*) and Fuzzy Box (*E. conica*).

The Stanley catchment is currently a biodynamic (organic) beef cattle grazing property. Portions of the catchment were once cropped (along the lower flats of the catchment). Cropping on the property began in the late 1960s. Cereal crops (e.g. wheat and oats) dominated initially and were later followed by improved pasture crops (primarily lucerne). Cropping continued until the 1980s for the southern part of the catchment, until the 1990s on the flats towards the catchment outlet and 2003 for the northern half of the catchment. These areas were subsequently allowed to return to native pastures to be used for cattle grazing. Currently, cell grazing and time-controlled grazing activities are practised on the property, whereby cattle are routinely moved around from paddock to paddock, so as to reduce grazing pressure on any one area for extended periods.

A high-quality 5 m digital elevation model (DEM) of the Stanley catchment was created from measurements made during a three-day field campaign in November 2004, using a Trimble 4700 base station and rover (Differential Global Positioning System). The catchment was systematically walked with the rover, which was set to automatically record coordinate data at 5 m intervals. This produced a data set of approximately 16 000 points, which equates to approximately 1 data point for every 100 m<sup>2</sup> of the 150 ha catchment. The data was gridded using triangulation with smoothing (*Vertical Mapper v. 2.6*) to produce a high resolution 5 m DEM. The accuracy of the system was approximately 50 mm in X and Y directions (horizontal) and in the Z direction (vertical). Before use, the data was pit filled using the Tarboton *et al.* (1989) method. Aspect and slope gradient were derived from the 5 m DEM and are shown in Figures 2 and 5, respectively.

## DATA COLLECTION METHODS

This study examines data collected at various spatial and temporal scales during the National Airborne Field Experiment (NAFE) (Walker *et al.*, 2005) and as part of the Scaling and Assimilation of Soil Moisture and Streamflow (SASMAS) project (Hemakumara *et al.*, 2004; Rudiger *et al.*, 2007, in press).

### National Airborne Field Experiment (NAFE'05)

The National Airborne Field Experiment (NAFE) was a four-week field study conducted between 31 October and 25 November 2005, in the Goulburn River catchment, New South Wales, Australia (Walker *et al.*, 2005). The primary objective of the NAFE project was to map near-surface soil moisture at a range of resolutions, making use of ground measurements and airborne and satellite-based remote sensors. The ground-based data are presented and included in the current analysis. Eight farms within the Krui (562 km<sup>2</sup>) and Merriwa (651 km<sup>2</sup>) River catchments were selected as part of this project, including the Stanley catchment (Figure 1). A portion of each farm was selected and multi-resolution soil moisture measurements taken four times at weekly intervals throughout the four-week campaign (3 November, 10 November, 17 November and 24 November).

Ground-based soil moisture measurements for the Stanley catchment were made on a regular grid at a number of nested spatial scales – 6.25 m, 12.5 m, 62.5 m and 250 m (Figure 6). Soil moisture was recorded using Stevens Water HydraProbe® sensors. The cylindrical sensing volume is 40.3 cm<sup>3</sup> (3 cm diameter and 5.7 cm length) and the reported accuracy is  $\pm 0.03$  water fraction by volume in typical soils (Stevens Vitel Inc., 1994). The HydraProbe measures both the dielectric constant and the conductivity of soils, which provides a direct measurement of soil moisture and salinity. The multi-resolution near-surface soil moisture measurements were taken as quickly as possible over the course of a day, so that any temporal variability was kept to a minimum. One team took catchment-wide measurements at 62.5 m and

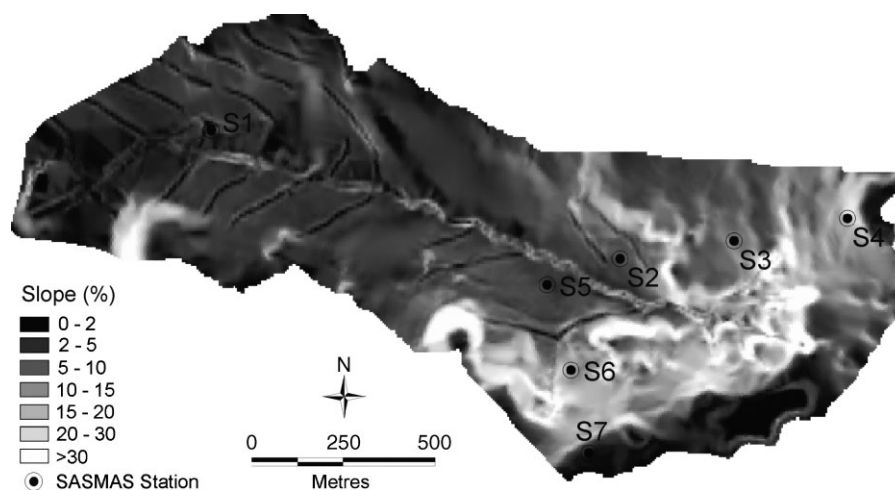


Figure 5. Slope gradient (%) map for the Stanley micro-catchment

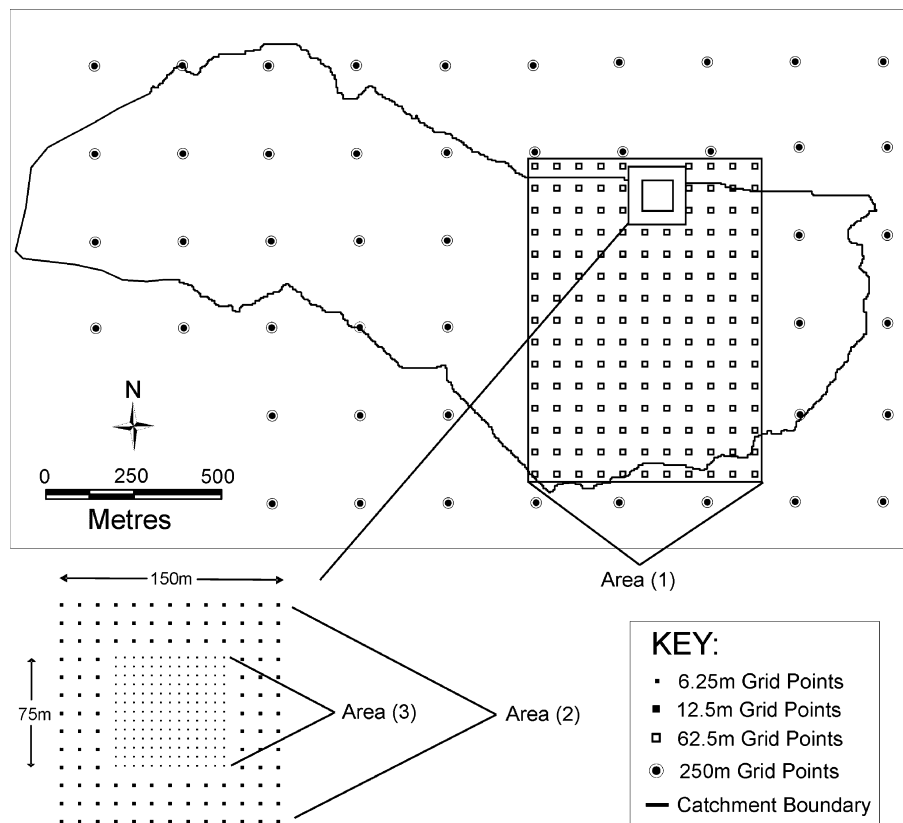


Figure 6. Schematic of ground-based soil moisture sampling strategy for the Stanley catchment during NAFE'05

250 m grid spacings (Figure 6) with sampling locations identified from a predefined grid using Global Positioning System (GPS) technology. This was achieved by using a unique GPS, hand-held computer (iPAQ), and HydraProbe setup which provided an automated means of making repeated soil moisture measurements at the same locations at different times. In addition, a small area 150 m  $\times$  150 m in size ('high resolution area'), was the focus of very intensive near-surface soil moisture measurements taken simultaneously by another team at 6.25 m and 12.5 m grid spacings (Figure 6) using Theta probes. These measurements were taken with the aid of a permanent grid setup in the field. Overall, approximately 500 points were sampled catchment-wide with the HydraProbes and Theta probes at the previously discussed resolutions (week 1–479; week 2–505; week 3–506; week 4–508). Catchment average near-surface soil moisture was calculated by averaging all measurements taken with the HydraProbes (i.e. 250 m and 62.5 m resolution measurements) for each sampling occasion. The repeatability and consistency of sampling locations afforded by the technology and sampling design during the NAFE campaign provided a unique data set with which to investigate soil moisture dynamics.

The output of the Theta probes was calibrated using a gravimetric procedure employing multiple soil samples collected from the Stanley sites. The soil samples were first dried at 105 °C, ground to break up any peds and a known weight placed in a cylindrical container. The collective weight of the soil and container was also

recorded. Water was added until the soil sample was saturated and left for one day to homogenize after which the preweighed Theta probe was inserted. The Theta probe reading was then recorded for the saturated soil at 20 °C. The soil sample was then partially dried at 45 °C, allowed to cool to 20 °C and the weight of the assembly and the Theta probe reading were once again recorded. The drying of the sample and recording of data was repeated until the sample was once again dry. The gravimetric water content–Theta probe calibration curve generated was, with knowledge of the bulk density of the soil, then converted to a volumetric calibration curve. HydraProbes are claimed to have an accuracy of  $\pm 0.03$  v/v if the soil type is unknown. However, if a crude classification of the soil type is made (sand, silt or clay), as was the case in this study, the uncertainty reduces to  $\pm 0.015$ – $0.020$  v/v (Stevens Vitel Inc., 1994). Given this level of accuracy no further site specific calibration of the HydraProbes was undertaken.

#### *Scaling and Assimilation of Soil Moisture and Streamflow (SASMAS)*

The Scaling and Assimilation of Soil Moisture and Streamflow (SASMAS) project is based in the Goulburn River catchment, New South Wales, Australia. The catchment has been instrumented since September 2001, with equipment monitoring near-surface and root zone soil moisture, soil temperature, meteorological data and streamflow (Rudiger *et al.*, 2007, in press).

A series of 26 soil moisture and temperature monitoring sites are located throughout the Goulburn catchment, with seven of these located in the Stanley micro-catchment (S1–S7) (Figure 1). At each of these sites, soil moisture and temperature are continuously recorded at 20-min intervals. Up to three vertically inserted water content reflectometers (Campbell Scientific CS616; Campbell Scientific, 2002) are installed at these sites at a number of soil depths (0–300 mm, 300–600 mm and 600–900 mm). The number of soil moisture sensors, and therefore the depth to which the soil moisture profile is monitored at these sites, is dependent upon soil depth to bedrock, which is less than 900 mm in some cases. HydraProbes are also installed vertically at each of the sites (excluding S2) to continuously monitor surface soil moisture (top 50 mm). Surface soil temperatures were monitored with a thermistor at a depth of 25 mm. One of these sites (S2) is also a weather station. For the purposes of consistency, only the 0–50 mm and 0–300 mm continuously monitored soil moisture data are presented in this study. Further details of the SASMAS project and associated infrastructure are available from Rudiger *et al.* (2007, in press).

The sensitivity of the CS616 sensor output to soil type necessitated the separate calibration of the probes to soil taken from each micro-catchment site. A summary of the calibration procedure follows (for a more complete description, see Rüdiger (2006)). Oven dried soil samples from each site were carefully loaded into cylindrical containers 150 mm in diameter and 400 mm deep and a CS616 probe located vertically along the container axis. A thermocouple was also positioned close to the container axis at 150 mm depth. The containers were suspended from load cells to enable gravimetric changes in soil moisture to be recorded. Commencing with the dry material the response of the probe was recorded for a range of temperatures once the temperature of the unit had stabilized. A small volume of water was then added to the top of the container and allowed to infiltrate down through the soil column. Once the CS616 and thermocouple output stabilized a new set of responses was recorded for a range of temperatures. This process was repeated until the soil column was saturated.

The CS616 calibration data was fitted to a modified version of the standardized calibration equations proposed for CS615 probes by Western and Seyfried (2005). First, the CS616 response was corrected for temperature in the following manner:

$$P_{25} = \frac{P_{obs} - o(T - 25)}{1 + s(T - 25)} \quad (1)$$

where  $P_{obs}$  is the raw CS616 response (ms), for the given soil moisture and temperature conditions ( $T$ , °C);  $o$  and  $s$  are calibration constants that are dependent on soil type and  $P_{25}$  is the CS616 output corrected to 25 °C.

The volumetric water content,  $\theta$  (v/v), of the soil was then calculated using the following:

$$\theta = \alpha N \quad N \leq 0.5 \quad (2)$$

$$\theta = 0.5\alpha + \left( \frac{0.4 - 0.5\alpha}{0.5^\beta} \right) (N - 0.5)^\beta \quad N > 0.5 \quad (3)$$

where  $N$  is the normalized sensor output calculated using Equation (4):

$$N = \frac{P_{25} - P_{0.0}}{P_{0.4} - P_{0.0}} \quad (4)$$

and  $\alpha$ ,  $\beta$  are calibration constants (independent of soil type).  $P_{0.0}$  and  $P_{0.4}$  are the average sensor outputs for dried soil (soil independent) and the optimized soil specific sensor output for soil of 0.4 v/v content respectively.

## RESULTS

### *Near-surface soil moisture—detailed spatial measurements (NAFE)*

The spatial distribution of near-surface soil moisture at four different resolutions (6.25 m, 12.5 m, 62.5 m and 250 m) for the Stanley catchment recorded during the four-week NAFE campaign is illustrated in Figure 7. Daily rainfall recorded during this period at S2 is also shown, with total rainfall for the week preceding each of the sampling occasions indicated (Figure 7). Rainfall appears to be well correlated with the observed temporal soil moisture trends, with wet conditions at the start of the campaign, followed by a drying period after 10 November, before a final wetting towards the end of the campaign. Figure 7 and Table I indicate that 3 November (Week 1) was the wettest sampling occasion, closely followed by 10 November (Week 2), while 17 November (Week 3) was the driest.

Factors such as aspect, topography and soil type are likely to influence the distribution of near-surface soil moisture. A visual assessment of the catchment indicates that areas in the upper reaches of the catchment and along the drainage divide (i.e. greatest slope values) with a north-facing aspect (Figures 2 and 5) appear to be consistently drier relative to the rest of the catchment (Figure 7). Conversely, the region towards the catchment outlet, along the flats, is consistently among the wettest areas of the catchment. Higher levels of clay-sized particles associated with the Bow (**bw**) soil landscape, found in the lower reaches of the catchment, may also help to explain the higher soil moisture values in those areas (Figure 3).

Nevertheless, no statistically significant relationships were observed between near-surface soil moisture and the factors investigated (i.e. slope gradient, elevation and soil type), excluding aspect (Figure 8). Weak, yet significant, relationships were observed for aspect on two sampling occasions. Sampling sites were grouped into two categories: 0–180° ( $N > S$ ) or 180–360° ( $S > N$ ). This was designed to assess whether soil moisture values decreased as aspect moved from a northern to southern orientation and vice versa. Results for the four sampling occasions were mixed. The strongest

CATCHMENT-SCALE SOIL MOISTURE PATTERNS

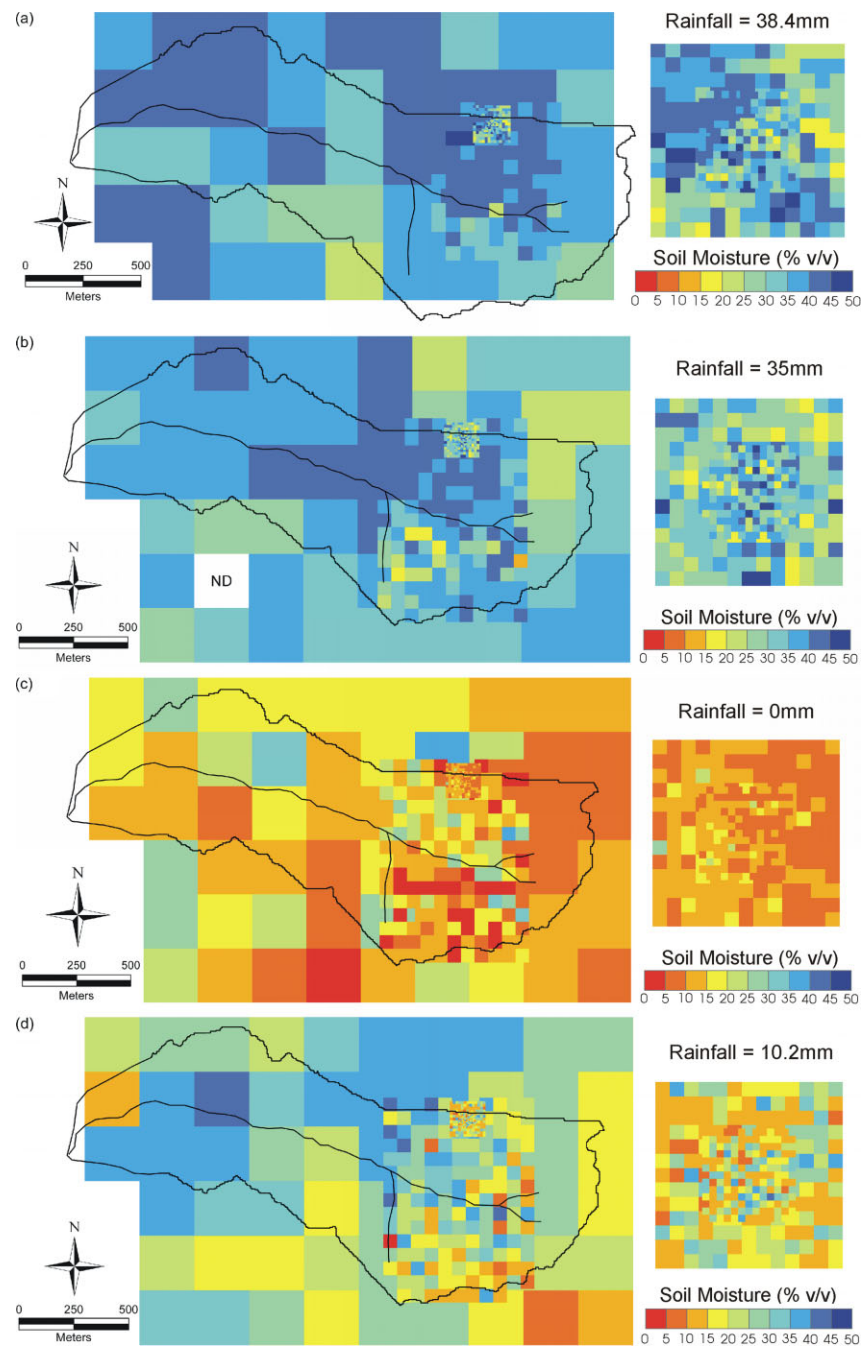


Figure 7. Spatial and temporal near-surface soil moisture patterns at various sampling resolutions for the Stanley catchment during NAFE'05 (a) 3 November; (b) 10 November; (c) 17 November; and (d) 24 November (ND = no measurement collected at point). High-resolution data is enlarged and shown on the right (Areas 2 and 3 in Figure 6). Rainfall for the week preceding the sampling is also shown (mm)

correlations were apparent when conditions were more stable (i.e. very wet or very dry conditions). For the wettest sampling occasion (3 November), there was a positive relationship ( $r^2 = 0.19$ ) for sites with aspect values between  $0^\circ$  and  $180^\circ$  (i.e. moving from north to south), while a significant negative correlation ( $r^2 = 0.13$ ;  $P < 0.0001$ ;  $n = 138$ ) was found for sites with aspect values between  $180$  and  $360^\circ$  (i.e. moving from south to north). That is, soil moisture values increased as sampling sites became increasingly dominated by southerly aspects, and soil moisture values decreased as sampling sites were increasingly dominated by northerly

aspects. Similar trends were observed for 17 November, which coincided with a sustained drying-out period for the catchment. A significant positive relationship ( $r^2 = 0.33$ ;  $P = 0.0007$ ;  $n = 31$ ) was observed for soil moisture values with aspect between  $0^\circ$  and  $180^\circ$ , while a significant negative correlation ( $r^2 = 0.10$ ;  $P = 0.0002$ ;  $n = 129$ ) was recorded for sites with aspects ranging between  $180^\circ$  and  $360^\circ$  (Figure 8). The inclusion of the slope and elevation variables in the regression analysis produced only a marginal improvement in the regression ( $r^2 = 0.37$ ;  $P = 0.0003$  for the relationship between soil moisture and slope, elevation and aspect ( $0^\circ - 180^\circ$ ) and

Table I. NAFE'05 multi-resolution near-surface soil moisture (v/v) summary statistics

Statistics	Area (1)		Area (2)		Area (3)		
	250 m	62.5 m	62.5 m	12.5 m	12.5 m	6.25 m	
Week 1 (3 Nov)*	Mean	0.40	0.39	0.30	0.33	0.35	0.34
	Standard Deviation	0.01	0.04	0.09	0.08	0.07	0.07
	Sample Variance	0.0001	0.001	0.008	0.006	0.005	0.005
	Range	0.03	0.24	0.27	0.35	0.30	0.32
	Minimum	0.38	0.22	0.17	0.17	0.17	0.17
	Maximum	0.41	0.46	0.44	0.52	0.47	0.49
	Count ( <i>n</i> )	6	97	6	171	49	171
Week 2 (10 Nov)	Mean	0.39	0.36	0.34	0.31	0.33	0.33
	Standard Deviation	0.02	0.06	0.05	0.07	0.07	0.07
	Sample Variance	0.0004	0.004	0.003	0.005	0.005	0.005
	Range	0.07	0.32	0.16	0.33	0.33	0.33
	Minimum	0.35	0.13	0.25	0.16	0.16	0.16
	Maximum	0.42	0.45	0.41	0.49	0.49	0.49
	Count ( <i>n</i> )	9	157	6	169	49	169
Week 3 (17 Nov)	Mean	0.16	0.13	0.11	0.11	0.11	0.11
	Standard Deviation	0.07	0.07	0.02	0.03	0.03	0.03
	Sample Variance	0.005	0.006	0.0003	0.001	0.001	0.001
	Range	0.24	0.35	0.05	0.19	0.15	0.17
	Minimum	0.03	0	0.09	0.07	0.07	0.07
	Maximum	0.27	0.35	0.14	0.26	0.22	0.24
	Count ( <i>n</i> )	9	158	6	169	49	169
Week 4 (24 Nov)	Mean	0.26	0.25	0.18	0.19	0.19	0.20
	Standard Deviation	0.09	0.09	0.06	0.08	0.08	0.08
	Sample Variance	0.008	0.009	0.003	0.06	0.007	0.007
	Range	0.33	0.39	0.18	0.31	0.31	0.32
	Minimum	0.07	0.02	0.10	0.08	0.08	0.08
	Maximum	0.40	0.41	0.28	0.39	0.39	0.40
	Count ( <i>n</i> )	9	157	6	170	49	169

\* 250 m and 62.5 m grid measurements for Week 1 covered slightly smaller area (hence only 6 and 97 points included, respectively).

$r^2 = 0.18$ ;  $P < 0.0001$  for slope, elevation and aspect ( $180^\circ - 360^\circ$ )).

The effect of sampling resolution (which is relevant for studies involving ground-based soil moisture measurements) was addressed by comparing the observations made at the various grid sizes (6.25 m, 12.5 m, 62.5 m and 250 m) on all four sampling occasions (Table I). Overlapping measurements taken at these different grid sizes over corresponding areas of the catchment were used for this comparison. For example, 250 m (nine points) and 62.5 m (~160 points) resolution measurements covering grid area (1) were compared (Figure 6). The results suggest that there are no significant differences (mean  $\pm 2\sigma$ ) among the different resolutions over the four sampling events. The data therefore suggest that the spatial patterns of near-surface soil moisture found at small scales is similar to that found at larger scales. It also questions the need for such high resolution ground-based measurements of soil moisture, which are labour intensive and time consuming (Famiglietti *et al.*, 1998).

#### Near-surface and root zone soil moisture—continuous monitoring (SASMAS)

**Near-surface soil moisture (0–50 mm).** Near-surface soil moisture (0–50 mm) was continuously recorded at 20-min intervals at all SASMAS sites, excluding S2, at which no HydraProbe was installed. Data at S1 was

not included in this study, however, because spurious readings indicated that the near-surface probe had not adequately bedded in. Daily average near-surface soil moisture was calculated for each of the monitoring sites by averaging the 20-min data. All sites experienced similar near-surface soil moisture trends, with obvious wetting and drying phases corresponding to periods of rainfall observed (Figure 9a). Sites S6 and S7 were among the wettest sites throughout the recorded period, while S3 was the driest.

Statistical analyses were used to evaluate which factors were influencing near-surface soil moisture at these monitoring sites. Daily average near-surface soil moisture at each of the monitoring sites was regressed with aspect, slope gradient (%), elevation, and soil type properties at each respective site. Results indicate that there were no statistically significant relationships between these factors and the continuously monitored near-surface soil moisture data.

**Root zone soil moisture (0–300 mm).** Root zone soil moisture (0–300 mm) was also recorded continuously at 20-min intervals (average of values taken every minute over 20-min periods) for all SASMAS sites. Data at S6 was not included in this study, however, because the soil moisture data reported by the probe indicated that cracks in the soil had opened up around the probes



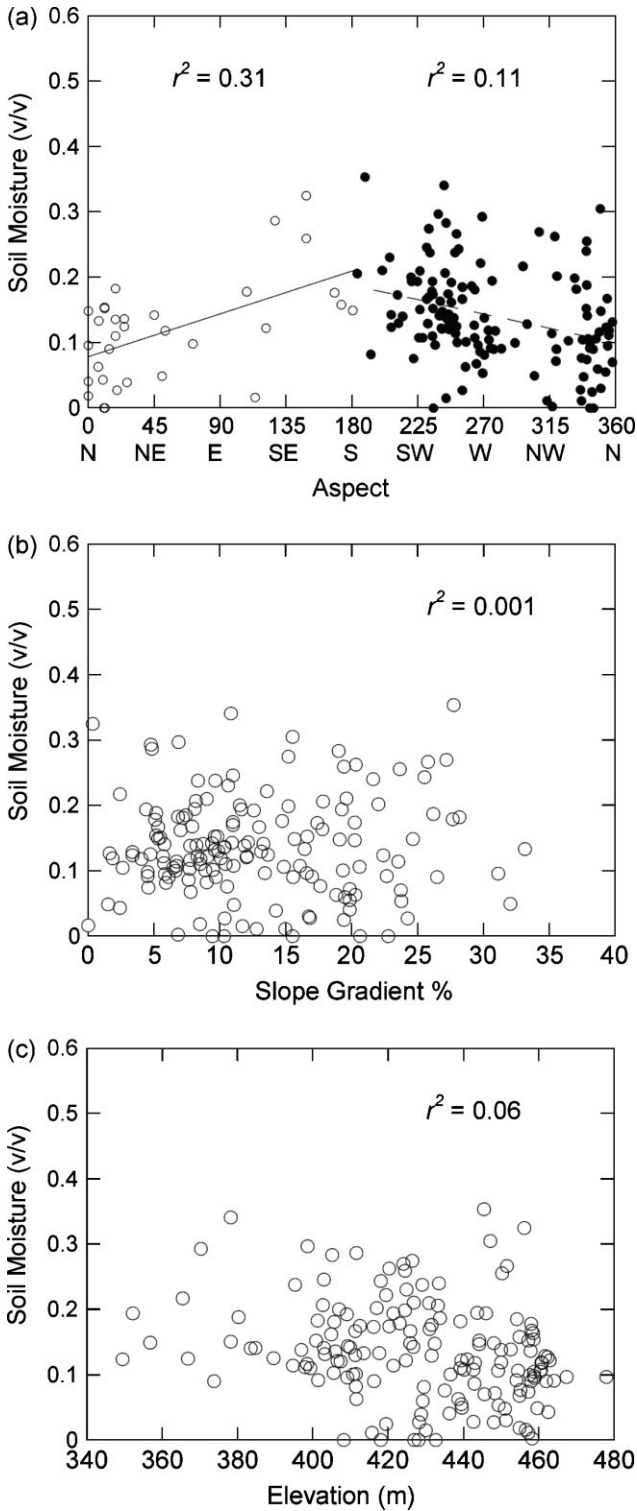


Figure 8. Near-surface soil moisture versus (a) aspect (open circles indicate points with aspect values between 0° and 180° [i.e. N > S]; shaded circles indicate points with aspect values between 180° and 360° [i.e. S > N]); (b) slope gradient (%); and (c) elevation (m) for 17 November (i.e. Week 3)

waveguides. The trends observed for the 0–300 mm data are not as uniform as seen in the near-surface (0–50 mm) soil moisture data described above (Figure 9b). S4 and S7 (two sites located at the highest elevations in the catchment (Figure 1)) display similar trends during the

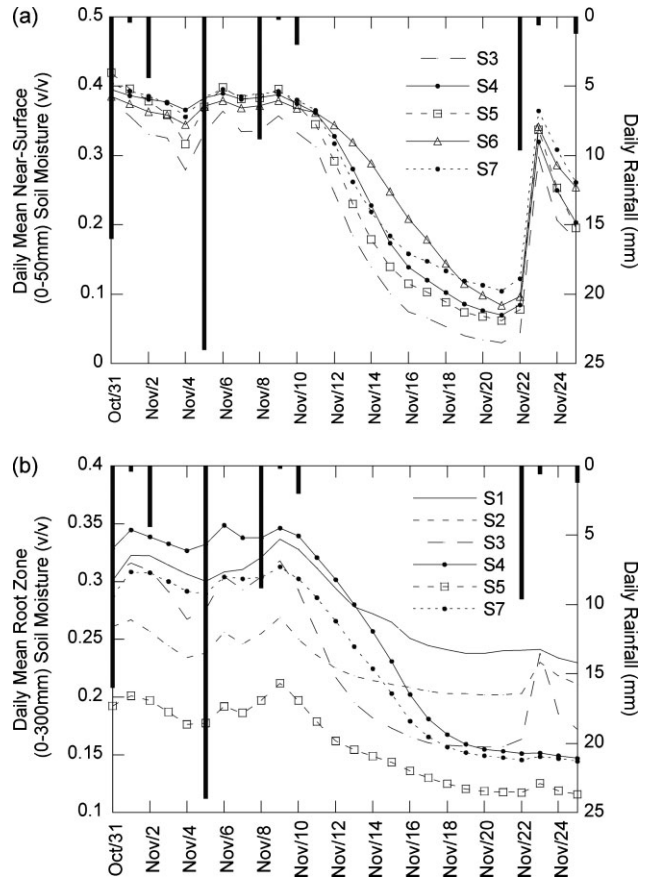


Figure 9. SASMAS daily rainfall (S2) and daily average soil moisture during the period 31 October to 25 November 2005 (a) near-surface (0–50 mm); and (b) root zone (0–300 mm). Note no near-surface (0–50 mm) soil moisture data available for S1 (unreliable data) and S2 (no HydraProbe installed at site), and no root zone (0–300 mm) soil moisture data available for S6 (unreliable data)

period, capturing the initial wet conditions, followed by a substantial drying off phase. S3 approximates this trend as well, the primary difference being its response to the rainfall event on 22 November (Figure 9b). S1, S2 and S5, while having different levels of soil moisture content (S1—wettest; S5—driest), also have very similar responses to rainfall over this period (Figure 9b). The different magnitudes in root zone soil moisture among these three sites are likely to be a result of their positions within the catchment, with S1 located within the Bow soil landscape, with predominantly black clay soils, while S5 is found on the red soils of the Ant Hill soil landscape group, and has a north-east facing aspect.

Despite these observed trends, no statistically significant relationships between root zone soil moisture and aspect, slope, elevation, and soil type were found. Daily average root zone soil moisture, calculated by averaging the 20-min data from the monitoring stations, was regressed against aspect, slope gradient (%), elevation, and soil type at those sites, for which no statistically significant relationships were found.

*Near-surface (0–50 mm) versus root zone (0–300 mm) soil moisture.* Catchment daily mean near-surface (0–50 mm) and root zone (0–300 mm) soil moisture were

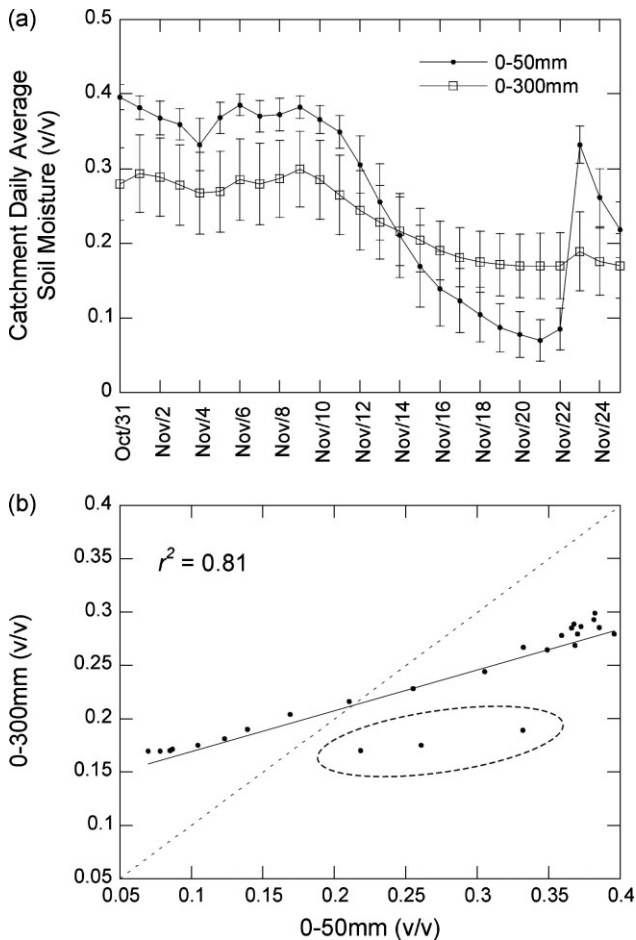


Figure 10. SASMAS catchment daily average ( $\pm 1$  SD) near-surface (0–50 mm) versus root zone (0–300 mm) soil moisture (a) temporal trends during period 31 October to 25 November 2005; and (b) scatter plot. Circled data points indicate outliers. Thin dashed line indicates 1:1 line

calculated by combining data recorded on each sampling occasion over the four-week period at all SASMAS sites (excluding 0–50 mm, S2—as no HydraProbe is installed at this site; 0–50 mm, S1 and 0–300 mm, S6—due to unreliable data). Catchment average near-surface soil moisture (0–50 mm) is consistently higher than root zone soil moisture (0–300 mm) under wet conditions (Figure 10a). In the absence of rainfall (i.e. dry conditions) however, near-surface soil moisture falls below that of the root zone, before rising again following rainfall at the end of November. During high rainfall events, the top few centimetres of the soil become saturated. Surface soil moisture thus exceeds that found in deeper soil layers, due to the lag time involved as surface water infiltrates through the soil profile to deeper layers. Conversely, when rainfall ceases, the surface layers of the soil are exposed to incoming solar radiation and are subject to evaporation, so that drying out of the surface soil layers dominates. Deeper soil layers meanwhile, are protected from such processes and therefore able to maintain moisture more effectively for longer periods of time. Figures 10a and b suggest that a threshold value exists, where below a certain near-surface soil moisture level, the root zone moisture is higher. Figure 10b shows

this threshold value to be where the best fit line cuts the 1:1 line at approximately 0.21 v/v. Thus below near-surface soil moisture values of 0.21 v/v, root zone moisture is higher than near-surface soil moisture.

The relationship between catchment average near-surface and root zone soil moisture was also investigated for the continuously monitored data. A statistically significant relationship was established between these two data sets ( $r^2 = 0.81$ ;  $P < 0.0001$ ;  $n = 26$ ) (Figure 10b). It should be noted that the three data points which appear circled, correspond to the final three days of the monitoring period. The 0–50 mm responds immediately to the rain event on November 22, while the response from the 0–300 mm data is much slower, attenuated and less obvious. When these three data points are removed, the relationship between the near-surface (0–50 mm) and root zone (0–300 mm) soil moisture data is much stronger ( $r^2 = 0.98$ ;  $P < 0.0001$ ;  $n = 23$ ).

The continuously monitored near-surface and root zone soil moisture data collected at the SASMAS sites indicate that a lower level of spatial variability exists between the sites in the near-surface than in the root zone (Figure 10). That is, soil moisture trends observed for the Stanley catchment indicate that the cross-correlation between different points in the landscape decreased with increasing soil depth and was more variable in the root zone. In addition, Figure 10b indicates that the variability of soil moisture increased with increased mean moisture content, a result which is consistent with findings reported throughout the literature (Famiglietti *et al.*, 1998; Mohanty *et al.*, 2000; De Lannoy *et al.*, 2006).

#### Detailed spatial measurements (NAFE) versus continuous monitoring network (SASMAS)

On four occasions during the study period, detailed spatial measurements of near-surface soil moisture were made (NAFE), while similar measurements were simultaneously being recorded on a continuous basis at fixed points in the landscape (SASMAS). Catchment average soil moisture was calculated for the two data sets. For the detailed spatial near-surface soil moisture measurements, the 250 m and 62.5 m grid data was used, while for the continuously monitored near-surface and root zone soil moisture data, all measurements taken at 20-min averages during the entire day at all SASMAS stations were averaged to obtain the daily catchment average. Despite the obvious spatial and temporal differences between these two data sets, overall trends in catchment average near-surface soil moisture were similar. A minor discrepancy was found between the data sets, with 10 November (Week 2) recorded as the wettest sampling occasion, closely followed by 3 November (Week 1) for the continuously monitored sites (i.e. the reverse of what was observed for the NAFE data). 17 November (Week 3) was, however, the driest sampling event recorded for both data sets. Strong statistical relationships were established between the detailed spatial

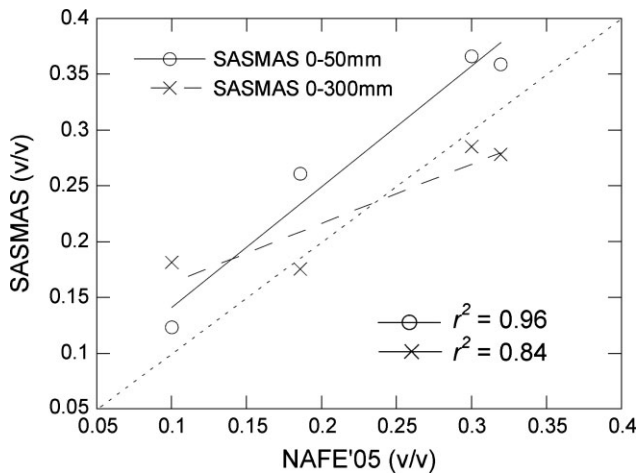


Figure 11. Catchment daily average soil moisture values based on detailed spatial measurements made during NAFE'05 for the near surface (0–50 mm) versus averages based on continuously monitored near-surface (0–50 mm) and root zone (0–300 mm) measurements at the SASMAS sites. Thin dashed line indicates 1 : 1 line

measurements of near-surface soil moisture and continuously monitored near-surface and root zone soil moisture (Figure 11). Near-surface soil moisture was significantly correlated ( $r^2 = 0.96$ ;  $P = 0.0063$ ;  $n = 4$ ), while a strong, although not significant, relationship between root zone soil moisture continuously recorded at the permanent monitoring sites and the detailed near-surface measurements was also established ( $r^2 = 0.84$ ;  $P > 0.05$ ;  $n = 4$ ) (Figure 11). In addition, the line of best fit (near-surface soil moisture) was observed to run parallel with the 1 : 1 line (Figure 11). The SASMAS 0–50 mm is consistently higher than the NAFE'05 data set, however a correction factor can be applied to account for this discrepancy.

Near-surface soil moisture measurements recorded over the entire catchment were also compared to continuously monitored data recorded in the near-surface layer and root zone at the individual SASMAS sites (Figure 12). Results suggest that S3, S4 and S7 exhibit mean near-surface soil moisture patterns that are significantly correlated with catchment average near-surface soil moisture ( $r^2 = 0.99$ ,  $P < 0.01$ ;  $r^2 = 0.99$ ,  $P < 0.001$ ;  $r^2 = 0.95$ ,  $P < 0.05$ , respectively). Apart from the strong statistical relationships, the trends observed at these sites indicate that these sites either fall almost entirely on (S4) or parallel (S3 and S7) to the 1 : 1, or  $x = y$ , line (Figure 12c, d and g). S3 and S7, while running parallel with the 1 : 1 line, consistently underestimate (S3) or overestimate (S7) catchment average near-surface soil moisture. This, however, can easily be resolved by applying an appropriate correction factor. S3 was also identified as displaying mean root zone soil moisture patterns that were significantly correlated with catchment average near-surface soil moisture ( $r^2 = 0.92$ ;  $P < 0.05$ ). Unlike for the previous section, the trend in mean root zone soil moisture at S3 did not fall on or approximate the 1 : 1 line. Rather, during drier conditions, root zone soil moisture would slightly overestimate catchment

average moisture conditions in the near-surface, while at the wetter end of the spectrum, this trend is reversed and it underestimates moisture conditions present in the near-surface. This result is not surprising given the different response times associated with near-surface and root zone soil moisture, highlighted previously in this paper (Figure 10).

## DISCUSSION

Detailed spatial measurements taken during the four-week NAFE field campaign provide a useful data set with which to examine the spatial patterns of near-surface soil moisture at the catchment scale. The results suggest that of the factors examined in this paper, aspect is the dominant factor controlling the spatial distribution of near-surface soil moisture on the Stanley catchment. This finding supports Western *et al.* (1999), who found that aspect, expressed in terms of a potential radiation index, exerts significant control over the spatial distribution of soil moisture. In the present study, hillslopes with a north-facing aspect were consistently among the driest areas of the catchment over the 4-week study, while areas along the drainage divide in the upper reaches of the catchment with the highest slope gradients were also among the driest. Similarly, the lower, flatter areas of the catchment, dominated by the Bow (**bw**) soil landscape with higher clay contents, were among the wettest areas.

The primary mechanisms controlling the spatial and temporal distribution of root zone soil moisture were believed to be topography (i.e. slope gradient and elevation) and soil type. Figure 9b illustrates the influence of topography. Sites S4 and S7 (and S3 to a slightly lesser extent), located at the highest points of their respective hillslopes, are characterized by their similar responses to periods of wetting and drying. The rapid depletion of soil moisture at these sites, particularly in times of low rainfall (transported away as surface and subsurface runoff), in comparison with the other measuring sites (located on relatively flat surfaces), suggests lateral subsurface flow is possibly controlling water movement. Elevation, slope gradient, and shallow soil depth to bedrock, which acts as an impermeable barrier to the movement of moisture vertically through the profile, at these sites, support this observation. Furthermore, the discrepancy among sites can be explained by the fact that soil moisture along the catchment divide is largely supplied by rainfall alone, while further down the hillslope moisture is supplied not only by rainfall but also by the surface and sub-surface flow from upslope areas. During an extended drying off period, as observed in this study, sites located further down the hillslope do not dry out as quickly as areas positioned in the upper reaches of the catchment. Similarly, soil type is thought to be contributing to the higher soil moisture values in the lower reaches of the catchment, where soils with high clay contents dominate.

Near-surface soil moisture data collected with detailed catchment-wide spatial measurements and those continuously monitored at fixed points in the landscape (S1–S7)

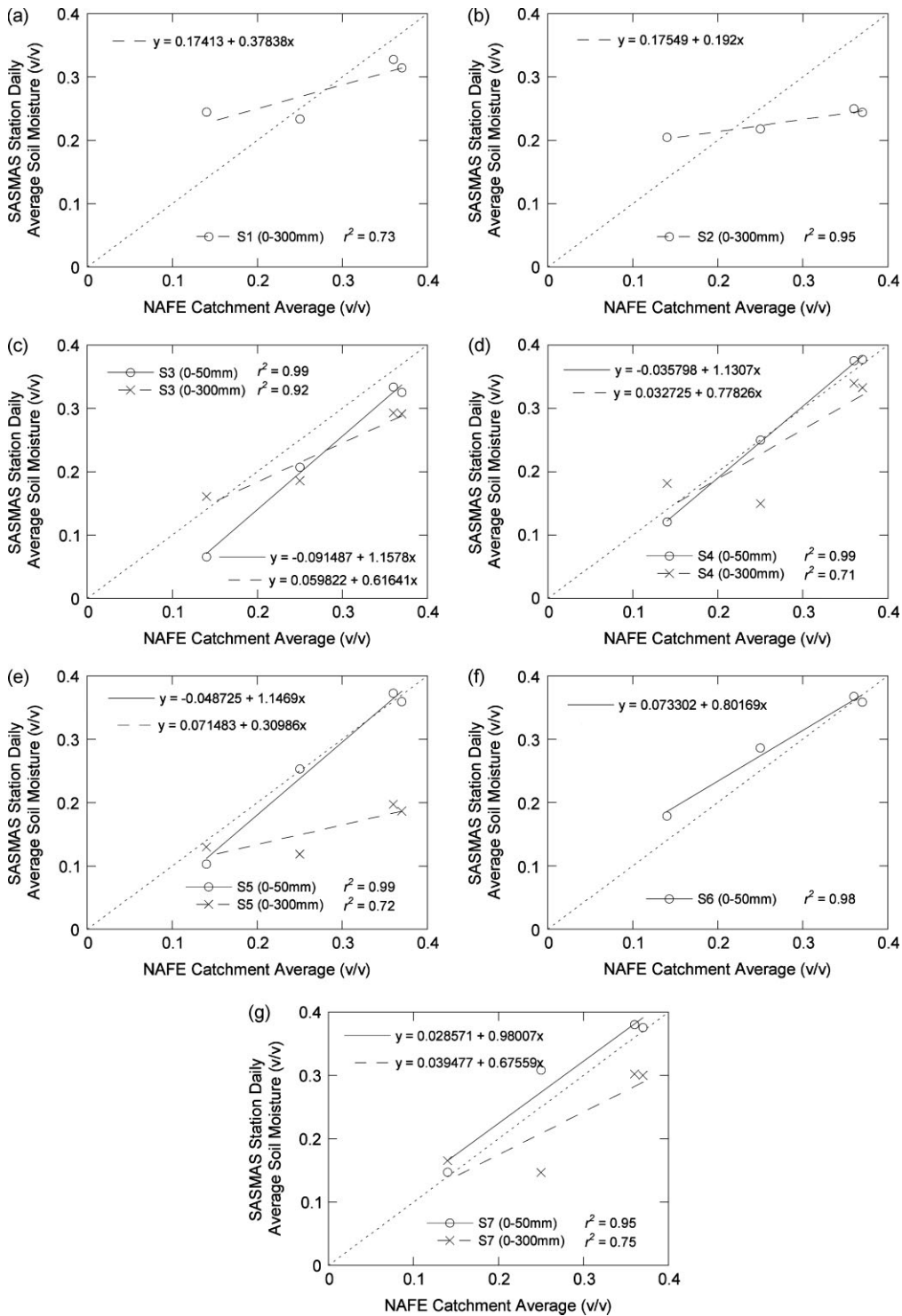


Figure 12. Continuously monitored near-surface and root zone soil moisture (daily average) versus catchment average soil moisture derived from detailed spatial measurements (a) S1; (b) S2; (c) S3; (d) S4; (e) S5; (f) S6 and (g) S7. Thin dashed lines indicate 1 : 1 line

were compared. These two data sets, although measuring soil moisture at different spatial and temporal scales, were found to be significantly correlated ( $r^2 = 0.96$ ) when catchment daily mean soil moisture was calculated. The strong relationship found between these two data sets suggests catchment average near-surface soil moisture estimates can be derived from the limited number of continuously recording moisture stations located at fixed points throughout the catchment. Such a finding

signals the potential for estimates of catchment average soil moisture levels in the near-surface to be derived on a daily basis without the need for labour intensive and time consuming catchment-wide measurements. Such information at the catchment scale is invaluable, particularly given the key influence of soil moisture on hydrological and pedogenic processes, and vegetation dynamics. In the latter case, there is the potential for remotely sensed spectral vegetation indices (e.g. Landsat derived NDVI)

to be used in conjunction with the high resolution soil moisture data afforded by the SASMAS sites to provide further insights into the spatial and temporal dynamics of vegetation patterns at the catchment scale, which are central to both hydrological and biogeochemical cycles (e.g. carbon cycle). In addition, this information may then be used to monitor, and perhaps predict, the spatial and temporal distribution of soil carbon, given the influence of soil moisture on organic matter decomposition, and vegetation dynamics, both above- and below-ground. The soil carbon pool is widely recognized as being a key element within the global carbon cycle, and is reportedly more than three times the size of the atmospheric pool, and approximately 4.5 times that of the biotic pool (Lal, 2004). Soil thus has the potential to be a significant reservoir for the storage of carbon, through the process of carbon sequestration. Increasing the amount of carbon stored in the soil will therefore help to reduce atmospheric concentrations of CO<sub>2</sub>, as well as provide significant benefits to the physical, chemical and biological properties of soils (Lal *et al.*, 1998). Despite its significance, there remains a lack of understanding of the spatial and temporal dynamics of soil carbon at regional and sub-regional (e.g. catchment and hillslope) scales. The SASMAS data set therefore offers a unique opportunity to investigate the influence of soil moisture dynamics on the spatial and temporal distribution of soil carbon at the catchment scale.

Catchment average near-surface (continuously monitored and intensively sampled) and root zone soil moisture were also found to be correlated in this study, however this relationship was not as strong as that found for near-surface soil moisture alone. Continuously monitored near-surface and root zone soil moisture were significantly correlated ( $r^2 = 0.81$ ), while the detailed spatial measurements of near-surface soil moisture were also closely related to the continuously monitored root zone data ( $r^2 = 0.84$ ). While no independent measures of root zone soil moisture were available at the catchment scale to assess the reliability of the continuously monitored root zone soil moisture, these findings suggest that estimates of root zone soil moisture can be inferred from near-surface measurements with a reasonable amount of confidence. The discrepancy between near-surface and root zone soil moisture data is likely to have two causes: (1) near-surface layers will respond faster to wetting events and will dry out more quickly in the absence of rainfall; and (2) different mechanisms control the spatial and temporal distribution of soil moisture at different depths.

Different response times to rainfall events for the two soil depths examined were observed in this study. When wet conditions prevailed, the top few centimetres of the soil became saturated. Soil moisture levels thus exceeded those found in deeper soil layers, due to the lag time involved with water moving down through the soil profile. Conversely, under dry conditions, near-surface soil moisture fell below that of the root zone. In the absence of rainfall, surface soil layers were exposed

to incoming solar radiation and subject to evaporation, so that drying of the surface soil layers dominated. Deeper soil layers meanwhile, were protected from such processes and were therefore able to maintain moisture more effectively for longer periods of time. The threshold value at which root zone soil moisture exceeded that of the near-surface was 0.21 v/v during the drying off period (Figures 10a and b). That is, in the absence of rainfall, and as near-surface soil moisture levels fell below 0.21 v/v, moisture conditions were higher in the root zone. However, when moisture conditions were rising (i.e. in the presence of rainfall), the intersection with the 1 : 1 line was lower (i.e. approx. 0.15 v/v) than when the soil was drying out (Figures 10a and b). This finding seems to suggest that there is a hysteretic effect, and leads to the conclusion that soil moisture trends at different soil depths are occurring at different time scales. This supports the work of Tromp-van Meerveld and McDonnell (2006) and Starks *et al.* (2006) who note that soil moisture is depleted at much faster rates in the near-surface layer than in deeper soils, where more water is stored. Similarly, Wilson *et al.* (2003) found no correlation between 0–6 cm and 0–30 cm soil moisture for a number of sites in New Zealand, and suggested that one of the reasons for this was the rapid wetting after a storm of the 0–6 cm soil layer compared with the 0–30 cm layer. Furthermore, Wilson *et al.* (2003) observed a decoupling of moisture content responses when sites were measured on days following a storm.

This study also provides evidence to support the claim by Wilson *et al.* (2003) for the decoupling of moisture content responses. Figure 9 demonstrates this to be the case for the final three days of the study period. Approximately 10 mm of rainfall fell over the catchment on 22 November. The response of soil moisture in the near-surface layer to this rain event was immediate and significant. Conversely, the response within the root zone was much more subdued, lagging behind that of the near-surface. This observation was not apparent following rainfall events during the first half of the study period, which were more frequent. It is thought that the extended drying off period that took place between rainfall events on the 10 November and 22 November exacerbated the time lag in soil moisture responses between the two soil depths. The statistical implications of this decoupling effect are shown in Figure 10b. Greater levels of variability among the various permanent monitoring sites were observed for moisture levels in the root zone as opposed to the near-surface. That is, the cross-correlation between time series of soil moisture at the seven sites across the landscape decreased with soil depth and was more variable in the root zone. This can be explained by the fact that soil moisture in the near-surface is strongly influenced by precipitation input (De Lannoy *et al.*, 2006), which could be reasonably assumed to be relatively uniform over the 150 ha study catchment, as opposed to deeper soil layers, which are subject to much more variable conditions in space (e.g. soil depth to bedrock, slope gradient, soil texture).

Examination of the detailed near-surface soil moisture measurements indicate that the spatial resolution at which soil moisture measurements were made (250 m, 62.5 m, 12.5 m and 6.25 m) did not have a significant impact on the average levels recorded. This suggests that the variability in near-surface soil moisture found at small scales is similar to that found at larger scales. Furthermore, it questions the need for high resolution ground-based soil moisture measurements, which are both labour intensive and time consuming (Famiglietti *et al.*, 1998). This is further supported in this study by the significant relationships established between the detailed spatial measurements and continuously monitored soil moisture data at a limited number of fixed points. While researchers continue to investigate the use of remote sensing and modelling type approaches, ground-based, essentially point scale, measurements appear to be the most accurate and viable methods for measuring and monitoring soil moisture at the present time. Given this situation, attention should be focused on developing sampling strategies that will provide the most efficient, yet accurate, method by which to obtain areal estimates of soil moisture (Grayson and Western, 1998).

Catchment average soil moisture monitoring (CASMM) sites, a term introduced by Grayson and Western (1998), are based on the concept of time stability, defined as the temporal persistence of a spatial pattern (Vachaud *et al.*, 1985; Kachanoski and de Jong, 1988). Essentially, CASMM sites are those areas within a catchment, which, regardless of the overall patterns or moisture levels, consistently exhibit mean behaviour (Grayson and Western, 1998). In this study, S3 was identified as a potential CASMM site for both near-surface and root zone soil moisture, with significant  $r^2$  values of 0.99 and 0.92 respectively (Figure 12). Similarly, daily averages of continuously monitored near-surface soil moisture at sites S4 ( $r^2 = 0.99$ ) and S7 ( $r^2 = 0.95$ ) were also significantly correlated with catchment average moisture values derived from the detailed spatial measurements obtained across the study site.

The results of this study have implications for the prediction of soil moisture patterns in other catchments, particularly ungauged basins, using methods other than ground-based, essentially point-scale, measurements, such as remote sensing platforms and topographic wetness indices. The lack of relationships observed in the current study between soil moisture and topographic factors (elevation, slope gradient, and aspect) raises doubts over the ability of topographic wetness indices to provide accurate estimates of moisture spatial patterns. Remote sensing platforms also provide an opportunity to predict soil moisture patterns over large areas, within both gauged and ungauged basins. Remote sensing estimates, however, are limited to the top few centimetres of the soil, and therefore the amount of information that can be obtained for soil moisture at depth is limited. Given the results of this study, which have shown that moisture trends in the near-surface and root zone occur at different scales and are influenced by different factors, further

research is required to accurately extrapolate remotely sensed near-surface soil moisture estimates to deeper soil layers.

## CONCLUSION

Soil moisture, in particular near-surface soil moisture, is highly variable both spatially and temporally. Previous studies have shown that there are many possible, and frequently interrelated, factors controlling the spatial and temporal distribution of surface and sub-surface soil moisture content. Their mutual and multiple influences on soil moisture often make it difficult to isolate and quantify the relative importance of any individual factor, thus contributing to the contradictory findings found in the literature.

In this study, near-surface (0–50 mm) and root zone (0–300 mm) soil moisture were monitored over a four-week period in a 150 ha catchment. Ground-based near-surface (0–50 mm) soil moisture measurements were collected once a week at a number of grid sizes. In addition, near-surface (0–50 mm) and root zone (0–300 mm) soil moisture were continuously recorded at seven permanent, monitoring stations. A range of moisture conditions were captured during this period, with both wetting and drying phases observed. Catchment-scale soil moisture dynamics were thus observed for a range of moisture conditions.

Near-surface and root zone soil moisture were found to be quite variable both spatially and temporally. Near-surface soil moisture was less variable spatially than root zone soil moisture due to the more uniform response to precipitation input among the monitoring sites. Root zone soil moisture lagged behind the near-surface values in both wetting and drying and the near-surface was more responsive to rainfall. This was due to the longer distance over which infiltration occurs in the root zone, which was also more variable because deeper soil layers are subject to more variable conditions in space. Conversely, the influence of rainfall on near-surface soil moisture meant that it was more variable temporally than soil moisture in the root zone.

Although no statistically significant relationships were established, aspect was identified as the primary factor influencing the spatial distribution of near-surface soil moisture. Meanwhile, root zone soil moisture was likely to be influenced by factors such as topography (i.e. slope gradient and elevation) and soil type.

Despite the differences in response to rainfall input, and the different factors influencing soil moisture dynamics at these two soil depths, catchment average near-surface and root zone soil moisture estimates were found to be closely related. This study established that near-surface soil moisture measurements could be used to provide estimates of soil moisture levels at greater depths (i.e. root zone).

The effect of sampling design for the determination of catchment scale soil moisture dynamics was also

investigated. The network of continuously monitoring sensors was shown to be able to provide accurate estimates of catchment average near-surface and root zone soil moisture content for a range of moisture conditions as assessed by comparison with detailed spatial measurements obtained over a few hours. In addition, potential CASMM sites were identified among the continuously monitoring stations. The findings of this study have shown that the network of monitoring stations established on the study catchment provide reliable estimates of average soil moisture, both in the near-surface and root zone. This provides a unique opportunity for such an extensive data set to improve our understanding of additional catchment-scale processes, including vegetation dynamics and nutrient cycling, for which soil moisture is a key factor.

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