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Journal of Hydrology 276 (2003) 254–274
Journal of Hydrology
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Spatial distribution of soil moisture over 6 and 30 cm depth, Mahurangi river catchment, New Zealand

David J. Wilson[a,*], Andrew W. Western[a], Rodger B. Grayson[a], Aaron A. Berg[b], Mary S. Lear[c], Matthew Rodell[d], James S. Famiglietti[b], Ross A. Woods[e], Thomas A. McMahon[a]

[a]*Centre for Environmental Applied Hydrology and Cooperative Research Centre for Catchment Hydrology, Department of Civil and Environmental Engineering, The University of Melbourne, Melbourne, Victoria 3010, Australia*
[b]*Department of Earth System Science, University of California, Irvine, CL 92697-3100, USA*
[c]*University of Texas at Austin, Department of Geological Sciences, Austin, TX 78712, USA*
[d]*Hydrological Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA*
[e]*National Institute for Water and Atmospheric Research (NIWA), P.O. Box 8602, Christchurch 8004, New Zealand*

Received 7 February 2002; accepted 31 January 2003

Abstract

Ground-based measurement of the spatial distribution of soil moisture can be difficult because sampling is essentially made at a point and the choice of both sample depth and sample spacing affects the interpretation of the measurements.

Hydrological interest has generally been in soil moisture of the root zone. Microwave Remote Sensing methods are now available that allow the interpretation of spatial distributions of soil moisture, however, their signals respond to moisture in the upper few centimetres of soil. These instruments are still being developed, but one of the questions surrounding their application is how to interpret the surface moisture in a hydrological context. In this study we compare measurements of soil moisture in 0–30 cm of soil with those in 0–6 cm to examine how representative this surface measure is with regard to the root zone.

Detailed spatial measurements of soil moisture were conducted at three pasture sites in the 50 km^2 Mahurangi River catchment of northern New Zealand as part of a comprehensive hydrology project; MARVEX (MAhurangi River Variability EXperiment). In three field sites, on each of three occasions, field measurements were made using both 30 and 6 cm dielectric-based instruments. Spatial grids of several hundred moisture measurements were collected over 0–30 cm and compared with those collected simultaneously over 0–6 cm.

Results indicate that temporal and spatial issues interfere with correlation of the two sets of series. Rapid wetting of 0–6 cm compared with 0–30 cm is seen following storm activity. Some evidence of the decoupling of moisture content response is also evident when sites are measured on days following a storm. Rapid, but not unrealistic, response to intense rainfall was also observed.

Implications are that detailed and accurate knowledge of local soil conditions and a sound model of soil water redistribution are required before surface soil moisture measurements can be used to infer root zone behaviour. Such knowledge was not available in this study, from either published data or field observation. In this study, without suitable a priori knowledge, soil property information was found via calibration.

* Corresponding author. Fax: +61-3-8344-6215.
E-mail address: d.wilson@civenv.unimelb.edu.au (D.J. Wilson).

0022-1694/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0022-1694(03)00060-X

Keywords: Soil moisture; Spatial patterns; Correlation

1. Introduction

Soil moisture is of critical importance to hydrological processes at a variety of scales (Bárdossy and Lehmann 1998; Western et al., 2002). Processes including surface and subsurface runoff generation, the formation of zones of saturation, and evapotranspiration all depend heavily on the moisture content in the root zone and the entire soil profile. Knowledge of the spatial distribution of soil moisture is also important (Grayson et al., 1999; Bronstert and Bárdossy 1999). Previous studies have highlighted spatial organisation at 0–30 cm depth at some times of the year and a more random pattern at other times (Grayson et al., 1997; Western and Grayson 1998). Such variation has implications for runoff generation and the scale characteristics applied to spatial averaging of processes such as evapotranspiration.

Ground-based measurement of the spatial distribution of soil moisture remains difficult, as current methods of measuring soil moisture at field scales are limited to point measurements. The only method for directly determining soil moisture is gravimetric sampling, however, this is time consuming to undertake and therefore difficult to use for the estimation of spatial patterns. All other methods measure a surrogate (such as dielectric properties or neutron scattering), and must therefore be calibrated against gravimetric samples. One of the most reliable and portable methods of measuring for soil moisture content is time-domain reflectometry (TDR) (Topp et al., 1980; Roth et al., 1992; Western et al., 2001b).

TDR has proven a reliable and accurate method of collecting non-destructive soil moisture values in numerous recent studies (e.g. Grayson et al., 1999; Bárdossy and Lehmann 1998; Walker et al., 2001a), however it remains a point measurement technique. Measurements of the spatial distribution of soil moisture have been made via TDR by making many point measurements within an area, but still only relatively small areas can be sampled (Western and Grayson 1998).

Recent advances in remote sensing methods have pointed to an exciting potential for spatial measurement of soil moisture content. Active microwave remote sensing via Synthetic Aperture Radar (SAR) offers the potential to map soil moisture at high resolution over large areas (Verhoest et al., 1998; Troch et al., 1997; Western et al., in review). The use of SAR to measure soil moisture depends on interpreting the backscatter signal to obtain the component due to variations in the soil dielectric constant. Microwave remote sensing can provide measurements of soil moisture in the surface few centimetres of the soil. Both passive (radiometers measuring microwave emission) and active (synthetic aperture radar) systems have been used. However, these systems respond not only to soil moisture, but also to soil surface roughness and vegetation cover, and are dependent on the look angle of the observations (Dobson and Ulaby, 1998; Jackson and Le Vine, 1996). In broad terms, of the instruments presently on board satellites, passive systems have low spatial resolution (tens of kilometres) but high temporal resolution (daily), while active systems have high spatial resolution (tens of metres) but low temporal resolution (fortnightly). It is possible for active systems to be spatially coarser and more frequently measured. Satellite sensors of both types are currently limited in their soil moisture remote sensing by wavelength and polarisation configurations; however, this situation is likely to change with time.

While microwave remote sensing of soil moisture to date has been applicable, at most, to only the top few centimetres of soil, we are typically interested in moisture content over the root zone of a soil profile. Difficulties in measuring sub-surface properties hinder remote sensing, yet moisture in the root zone is the control on transpiration.

Field investigation of moisture variability within 0–6 cm was carried out using point sampling during the Southern Great Plains Experiment of 1997 (Famiglietti et al., 1998), and relations made to soil moisture variability within remote sensing footprints (Famiglietti et al., 1999). Current research is focussing on the use of remotely sensed images to constrain and/or update models of the soil moisture profile (e.g.

Li and Islam 1999; Walker et al., 2001b). Results from recent laboratory experiments, combining surface measurements with numerical modelling of the unsaturated zone, have indicated a potential for retrieval of moisture information for the soil profile, using only skin surface observations. Various studies have suggested that the accuracy of active microwave surface soil moisture estimation for bare soil at C and L band may be within 5%V/V (Dubois et al., 1995; Mancini et al., 1999; Hoeben and Troch 2000), although it may be difficult to achieve this level of accuracy for vegetated systems. Other experiments have been conducted using data assimilation methods to update and constrain the soil moisture component of hydrological models and propagate the effects to different depths (e.g. Callies et al., 1998). Data assimilation is suggested as the best method of estimating profile soil moisture using remotely sensed surface moisture data (Kostov and Jackson 1993; Walker et al., 2001).

In order for data assimilation methods to be successful, the models used must be able to reproduce the observed relationship between surface soil moisture and that in the deeper layers, particularly the root zone. In this study we measure patterns of soil moisture in 0–6 cm, approximately the depth coverage of remotely sensed values, coincident with measurements in the 0–30 cm, approximately the root zone at these sites, over three pasture-covered sites on each of three occasions. The sites are in the Mahurangi River catchment of the north island of New Zealand. This research is part of a comprehensive study of spatial and temporal hydrological response known as the MAhurangi River Variability EXperiment (MARVEX) (Woods et al., 2001).

Specifically, we aim to compare soil moisture content in 0–6 cm with that of 0–30 cm by examining the different statistical and geostatistical properties of measured field data. We thereby gain some understanding of the changes in soil wetness and its variability through space and time and address whether observed relationships (or lack thereof) are consistent with our understanding of water flow. We then address the extent to which the observed relationships between surface and root zone soil moisture are consistent with hydrologic behaviour as embodied in the type of unsaturated zone models used with data assimilation approaches.

2. Field site description

The Mahurangi River catchment drains 46 km^2 of steep hills and gently rolling lowlands and is located 70 km north of Auckland, New Zealand (Fig. 1). This part of New Zealand experiences a warm, humid climate, with typical annual rainfalls of 1600 mm; maximum rainfall is usually in July, the middle of the austral winter (Fig. 2). Annual pan evaporation is approximately 1300 mm; solar influences are distributed such that both maximum pan evaporation and monthly temperature occur in January or February (Woods et al., 2001).

Intensive measurements of soil moisture were undertaken at four field sites within the Mahurangi catchment: Satellite Station, Clayden's, Carran's (all pasture sites) and Marine Road (pine plantation) (Fig. 1). This study focuses on measurements made at the pasture sites at times when 0–6 cm and 0–30 cm soil moisture were both sampled (Fig. 3). Key aspects of the pasture field sites are listed in Table 1. Details of the sampling methods are provided in Section 3.

2.1. Satellite Station

Satellite Station field site (Fig. 4) comprises part of a dairy cattle property lying in the central lowlands of Mahurangi catchment, and receives its name due to the close proximity of a New Zealand telecommunications satellite dish. The field area captures two subcatchments within a small valley of approximately 60 ha. Ridges, drainage lines and a variety of aspects are contained in the sample area, which is representative of the Mahurangi lowland environment. Undulating terrain is common for this region. Elevation ranges from about 55 to 105 m ASL. Hillslopes generally of gradient 1:8 comprise 80% of the sampling area, though several steeper slopes exist. The remaining 20% of the sampling area is lowland valley flat land, with local topography quite pronounced on the flats. Two streams drain the catchment; one from the east (Satellite Left) and one from the north (Satellite Right). A clear distinction can be drawn between hillslope soils and lowland valley soils. Hillslopes are of silty clay loam soil (27% clay, 51% silt, 0–30 cm depth), and flat valleys comprise alluvial fill with a relatively deep profile and high clay content (58% clay, 34% silt, 0–30 cm depth). Both

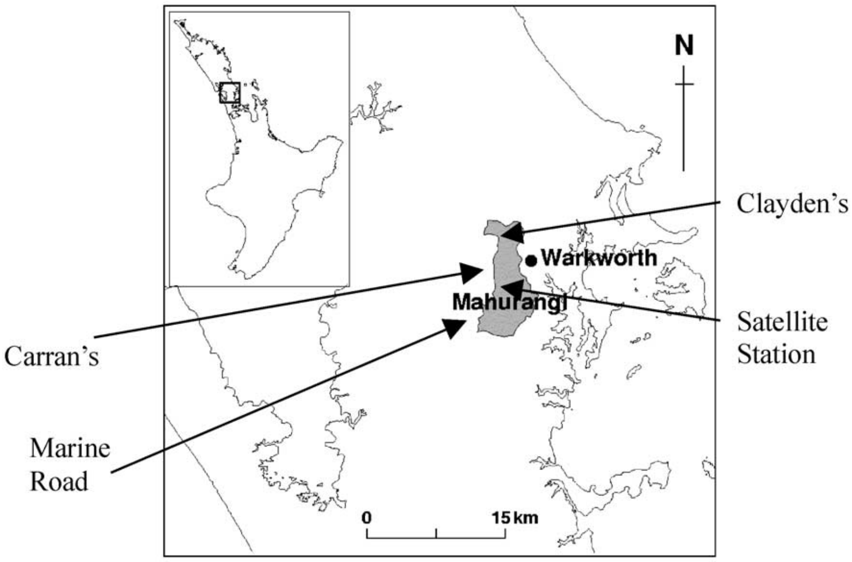

Fig. 1. Location of Mahurangi River catchment, New Zealand.

soil types are highly structured and crack during dry periods.

A weather station operated at Satellite Station by the NZ Meteorological Service recorded data representative of the surrounding Mahurangi River catchment.

2.2. Clayden's

Clayden's (Fig. 5) comprises one largely divergent hillslope covering an area of approximately 13 ha. The hillslope has a predominantly south–west aspect, although the undulating nature of the local landscape results in almost all aspects being represented. Elevation ranges from around 95 to 140 m ASL. Hillslopes are generally gentle with gradients of around 1:8, although several steeper slopes exist. The south–west corner of the field site is flat and becomes boggy in wet weather. Small-scale undulations occur around the mid-slope of Clayden's on the western side. Soils in the catchment are predominantly silty clay (43% clay, 39% silt, 0–30 cm depth). Sheep, horses and cattle all grazed on the well-grassed pasture at Clayden's during 1998–99.

2.3. Carran's

Carran's (Fig. 6) is a convergent hillslope site that drains to the south, with bowl-like edges flanking the field site on the northern, western and eastern sides. The dominant aspect of the field site is therefore southerly. The field site comprises an area of approximately 5 ha. Elevation ranges from 95 to 120 m ASL, with gentle hillslope gradients of typically 1:8. Small-scale undulations occur throughout Carran's, though their scale is not suited to representation on a field-scale digital elevation model (DEM). Soils at Carran's are silty clay (56% clay, 28% silt, 0–30 cm depth). No permanent watercourse exists at Carran's, though an eroded and incised gully exists off the southern edge of the sampling area. Exposed walls of this gully reveal a light coloured clay soil and evidence of pipe erosion. On one occasion (August 1998), water was seen to be freely

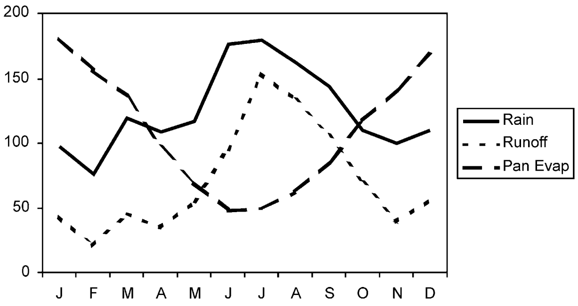

Fig. 2. Average climatic conditions in the Mahurangi River catchment, New Zealand.

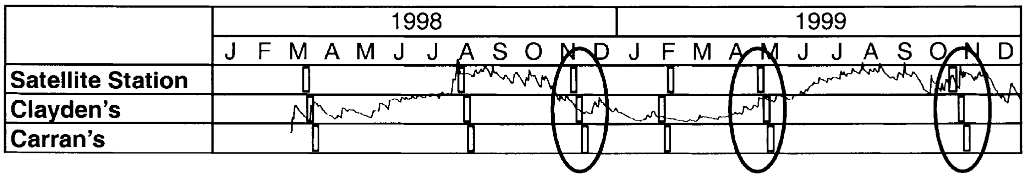

Fig. 3. Timing of spatial sampling of soil moisture during 1998–99 (vertical bars). Periods in which measurements were collected at both 0–30 cm and 0–6 cm are circled. Also shown is a time series of soil moisture from a point at Satellite Station (0–30 cm) varying from 25–55%V/V.

discharging from a pipe hole in the wall of this eroded gully. Sheep, horses and cattle grazed on the well-grassed pasture at Carran's during 1998–99.

3. Methodology

The soil moisture component of MARVEX used several sampling strategies including a network of continuously recording sensors, fixed neutron moisture meter access tubes, and seasonal mapping campaigns of saturated areas and patterns of root zone soil moisture (Woods et al., 2001). This paper utilises some of the spatial patterns data. Root zone soil moisture (0–30 cm) was mapped at the three pasture sites on six occasions within a two year period. On three of those occasions, surface soil moisture (0–6 cm) was also measured and we concentrate on those three occasions in this paper. Spatial mapping of 0–30 cm moisture was undertaken using TDR equipment mounted on a specially designed all-terrain vehicle known as the Green Machine (Tyndale-Biscoe et al., 1998). Spatial location was measured with a differential global positioning system (DGPS) system to better than 1m accuracy. Moisture measurements were made using 30 cm probes, which measure the average moisture content of a cylindrical volume of approximately 500 cm^3 at a depth coincident with pasture roots. The operating principle of TDR is described elsewhere (Roth et al., 1992). Volumetric soil moisture in 0–6 cm was sampled using a hand-held impedance device known as a Theta Probe. The probe consists of a 100 MHz sinusoidal oscillator, a coaxial transmission line, and a stainless steel sensing rod. The sensing rod behaves as an extension of the transmission line with an impedance dependant upon the dielectric constant of approximately 20 cm^3 of surrounding soil. Further information regarding this technique is found elsewhere (Gaskin and Miller 1996; Miller et al., 1997). Both the TDR and Theta probe were calibrated against gravimetric samples for local soil conditions (Western et al., 2001b). Both the TDR and Theta probe measure the dielectric properties of the soil matrix, which may then be related to soil moisture. The hand-held Theta probe is small in diameter and more accurate for surface measurements, but was not practical for deeper measurements. The large robust TDR device was better suited to measurements over 0–30 cm. Calibration relationships for both devices were checked in the field.

At each of the three pasture sites, sampling was based on a square grid overlaying a sub-catchment area; 40 m × 40 m at Satellite Station, 20 m × 20 m at Clayden's, 10 m × 10 m at Carran's. Sampling time per measurement was approximately two minutes (including travel time between points), so that the duration of mapping each site was 1–2 days. Points were sampled in the same order on each occasion. Each 0–30 cm and 0–6 cm pairing was

Table 1
Characteristics of pasture sites of the Mahurangi river catchment

Site	Area (ha)	Ave. Precip. (mm/y)	Ave. PET (mm/y)	% Clay	Grid Resolution	# Grid Points
Satellite Stn.	60	1200	1300	58-flats 27-hills	40 m × 40 m	370
Clayden's	13	1350	1300	43	20 m × 20 m	275
Carran's	5	1300	1300	35	10 m × 10 m	480

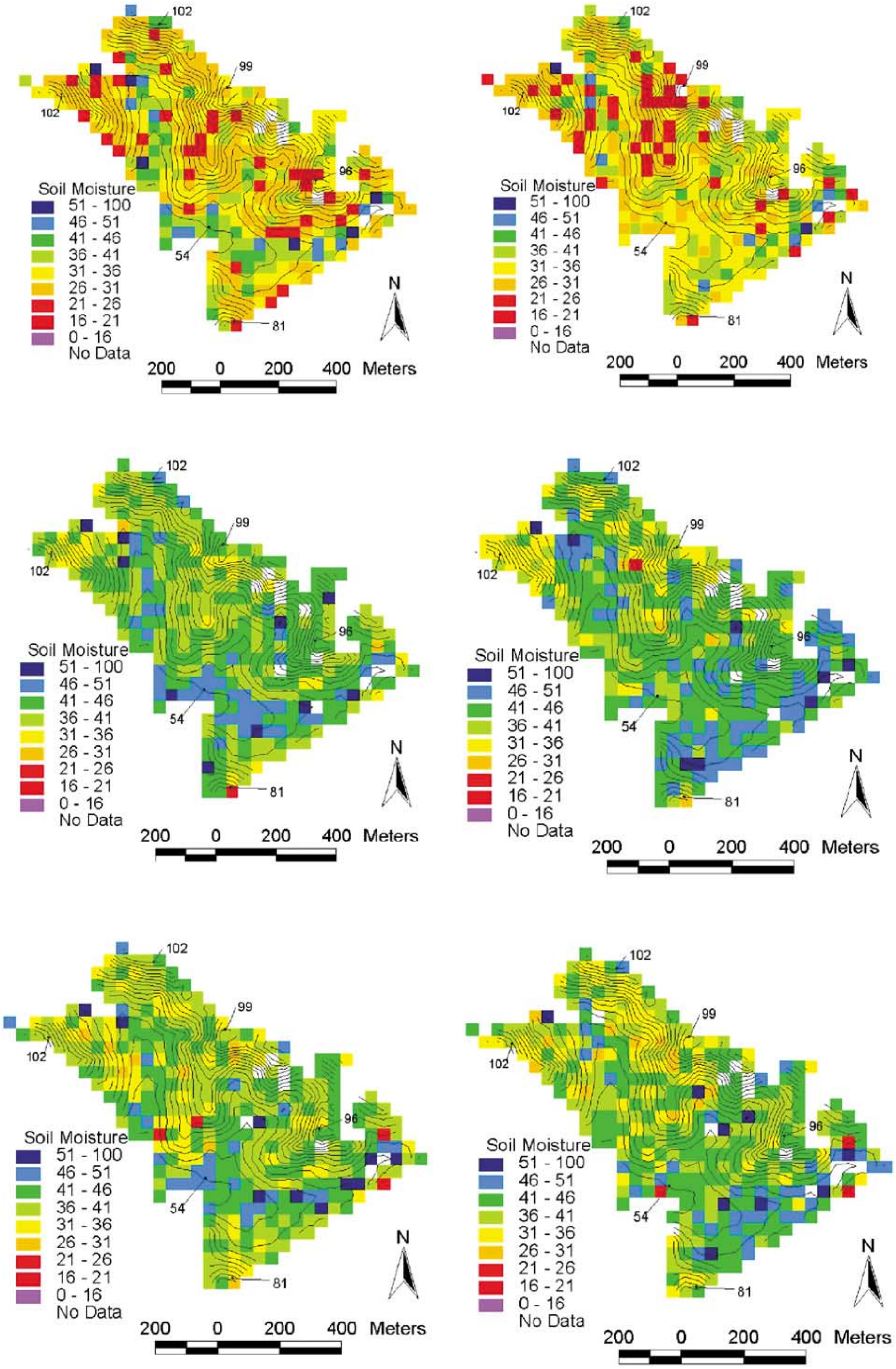

Fig. 4. Spatial distribution of soil moisture at satellite station over two depths on three occasions; 40 m × 40 m grid, 3 m elevation contours. Left to right: (a) 0–30 cm, November 1998. (b) 0–6 cm, November 1998. (c) 0–30 cm, May 1999. (d) 0–6 cm, May 1999. (e) 0–30 cm, November 1999. (f) 0–6 cm, November 1999.

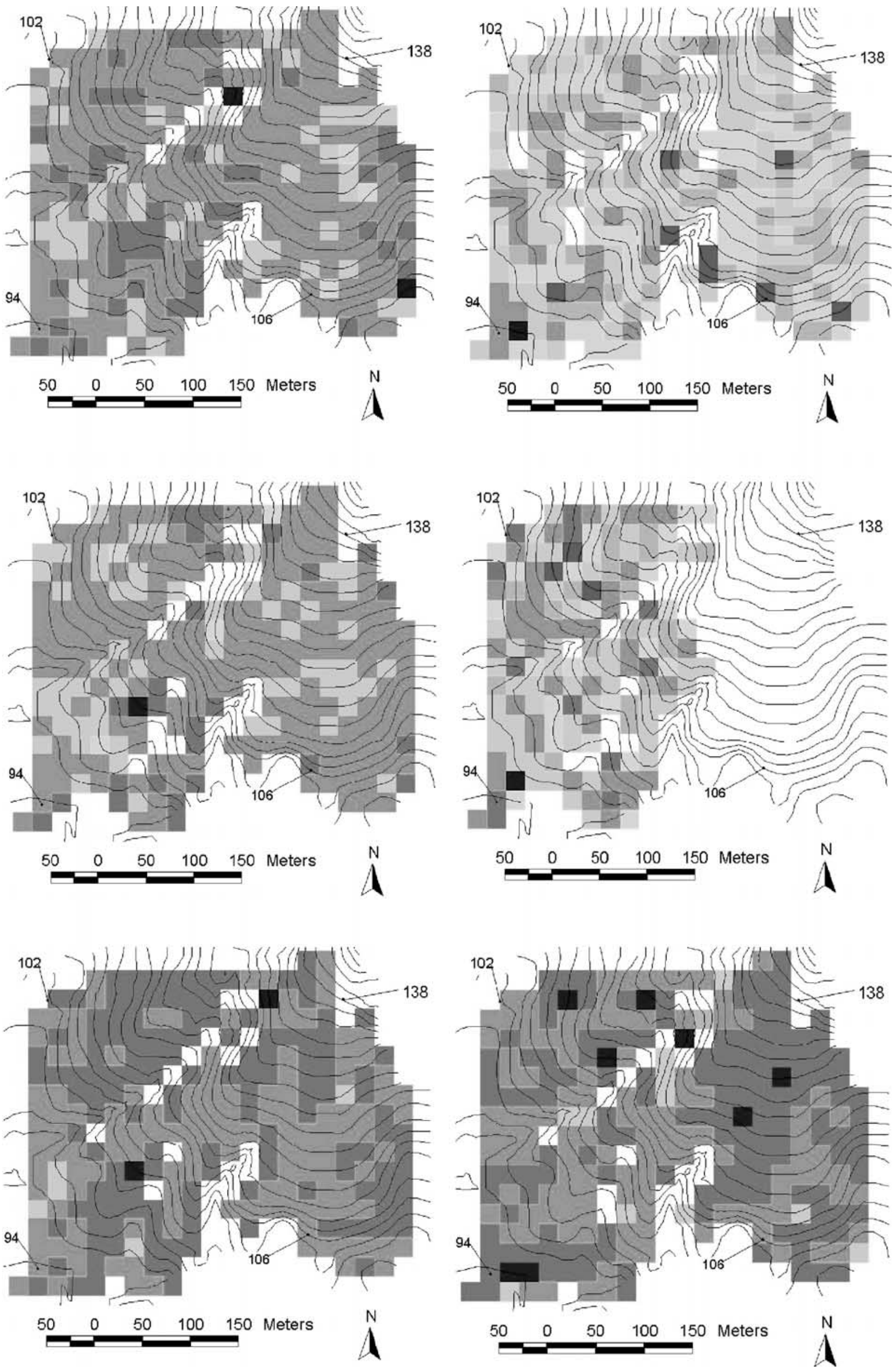

Fig. 5. Spatial distribution of soil moisture at Clayden's over two depths on three occasions; 20 m × 20 m grid. Colour scale as for Fig. 4, 2 m elevation contours. Left to right: (a) 0–30 cm, November 1998. (b) 0–6 cm, November 1998. (c) 0–30 cm, May 1999. (d) 0–6 cm, May 1999. (e) 0–30 cm, November 1999. (f) 0–6 cm, November 1999.

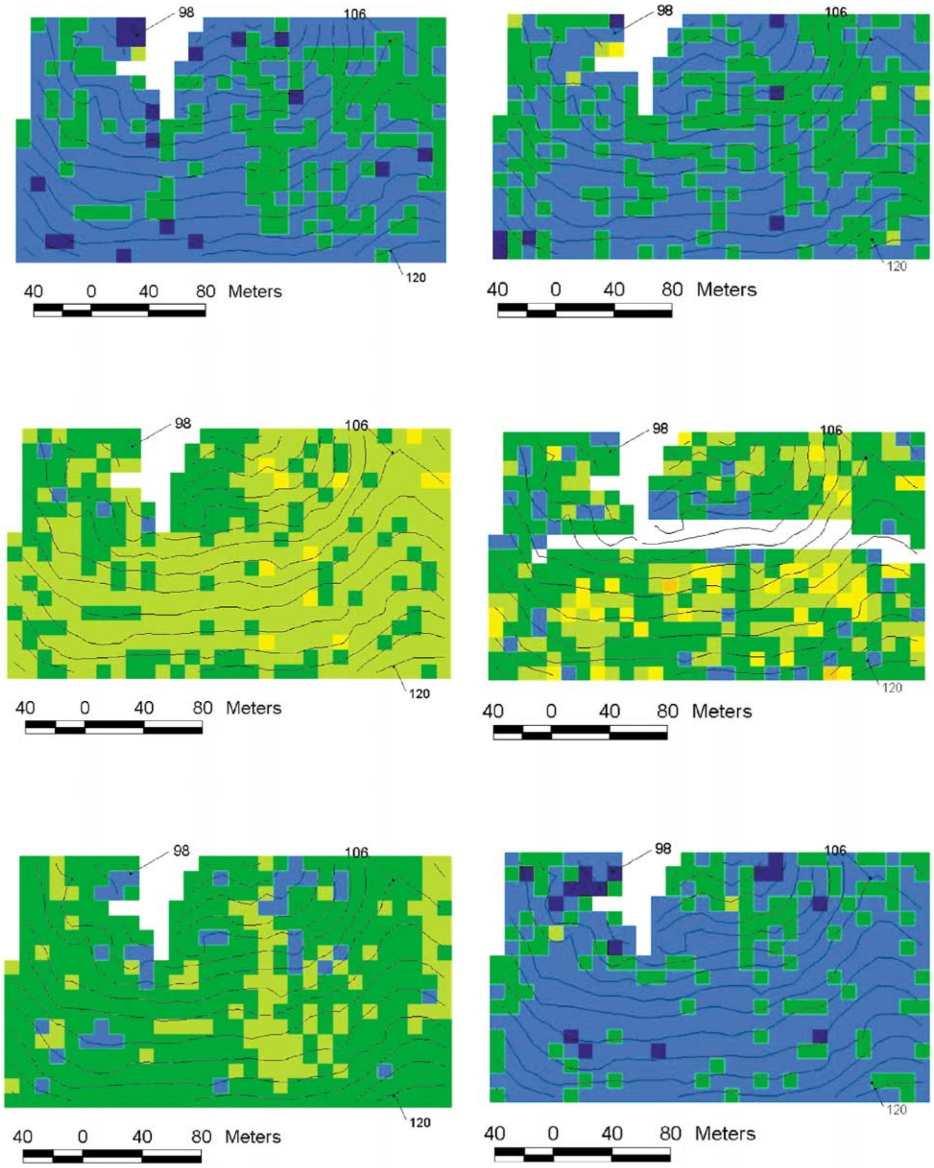

Fig. 6. Spatial distribution of soil moisture at Carran's over two depths on three occasions; 10 m × 10 m grid. Colour scale as for Fig. 4, 2 m elevation contours. Left to right: (a) 0–30 cm, November 1998. (b) 0–6 cm, November 1998. (c) 0–30 cm, May 1999. (d) 0–6 cm, May 1999. (e) 0–30 cm, November 1999. (f) 0–6 cm, November 1999.

taken concurrently to reduce the effect of temporal variability on the comparison of results. At each measurement point, one measure of 0–30 cm soil moisture content was made via TDR, while up to three measures of that in 0–6 cm were made with the Theta probe. Up to three 0–6 cm measurements were made to ascertain the repeatability of results and instrument error associated with the Theta probe. At some locations in the field, multiple TDR measurements (usually 4 or 25) were made. Collecting these data enabled sub-metre-scale variation of moisture content to be studied. In this study we considered only the first 0–6 cm reading obtained via the Theta probe at each measurement point. Variance statistics for 0–30 cm and 0–6 cm data sets were therefore comparable, and field methods consistent throughout. We compared Theta probe variance to TDR variance at the point scale via multiple measurements, and we also compared variance of point scale measurements across each field site.

We analysed the effect of smoothing spatial soil moisture comparisons by using a 3×3 moving average filter. This was done to make the data more representative of the pixel scale average measured by high spatial resolution remote sensing.

Comparison of the two spatial data sets, raw and smoothed, was carried out. Only those point locations at which soil moisture at both 0–30 cm and 0–6 cm depths were measured were included in the analysis. Where some point data were removed from a data set to accommodate this constraint, the data set was termed 'adjusted' (e.g. 30 cm_adj). Specifically, we examined: (i) spatial distribution of soil moisture via maps; (ii) summary statistical properties of the data sets including mean, median, variance, inter-quartile range, and 10th and 90th percentile moisture content, skewness and kurtosis; (iii) frequency plots; (iv) point-by-point correlation of moisture content measured over 0–30 cm versus that measured over 0–6 cm; and (v) geostatistical properties of the data sets.

3.1. Analysis methods

We compared 0–6 cm and 0–30 cm soil moisture using various approaches. Patterns were compared visually and scatter plots of soil moisture in the 0–6 cm and 0–30 cm layer were drawn for each pair of patterns. Standard summary statistics were also calculated and are tabulated in Section 4. Two sets of hypothesis tests were performed for each pair of patterns. First, a difference between the soil moisture means was tested for using a two-tailed t-test assuming unequal variances. The results are presented in terms of p-values.

Second, a chi-square test was used to test the hypothesis that the 0–6 cm and 0–30 cm soil moisture have the same distribution shape. Before performing the chi-square test, the mean soil moisture was subtracted from each sample. Thus, in effect, we tested for difference in distribution shape, including spread or variance, independently of differences in mean moisture. Calculated chi-square statistics were compared with relevant critical values calculated for a 5% level of significance.

To compare the spatial characteristics of the patterns, normalised variograms were calculated for both the 0–6 cm and 0–30 cm data for each occasion using standard methods (Issaks and Srivastava 1989). The variograms for each pair of patterns were then compared visually, with most emphasis placed on the correlation scale.

4. Results

Measurements of the spatial distribution of soil moisture are presented for Satellite Station (Fig. 4), Clayden's (Fig. 5) and Carran's (Fig. 6).

4.1. Satellite Station

Patterns of soil moisture over the spatial grid at Satellite Station indicated variable moisture within 0–30 cm, although low-lying flats were consistently wetter than hillslopes (Fig. 4). Corresponding patterns for soil moisture within 0–6 cm showed less topographic influence on wetness. Also the southeast portion of the field site was wetter than the northwest on all occasions; more noticeable in 0–6 cm than in 0–30 cm. In November 1998, soil of 0–30 cm was wetter than 0–6 cm soil in the flat land and on the west-facing slopes, while 0–6 cm was wetter elsewhere (Fig. 4a, b). A similar pattern was observed for May 1999 data although, in the headwaters of some drains on the flat land, 0–6 cm soil was wetter (Fig. 4c, d). Moisture values throughout the field site were similar for the 0–6 cm and 0–30 cm soil in November 1999 (Fig. 4e, f).

Table 2 shows that mean moisture content within 0–30 cm over the whole field site was very similar to that of 0–6 cm on all sampling occasions. Spatial maps indicate that moisture content of the flat land was slightly higher in 0–30 cm. Of the three sampling occasions, average wetness of both 0–6 cm and 0–30 cm soil was highest in May 1999, followed by November 1999 and lowest in November 1998. Variance of the 0–6 cm soil moisture grid was consistently similar to that of 0–30 cm soil. Inter-quartile ranges of the measurements were also very similar.

Table 2
Statistics of moisture content at Satellite Station

Satellite Station	November 1998		May 1999		November 1999	
	30 cm_adj	6 cm(1)	30 cm_adj	6 cm(1)	30 cm_adj	6 cm(1)
Number	376	376	372	372	372	372
Mean (%)	33.2	33.3	42.1	42.4	40.3	40.6
Median (%)	31.9	33.3	41.9	42.9	40.3	41.1
Standard Deviation (%)	6.42	5.99	4.25	4.76	5.09	5.54
Coefficient of Variation (%)	0.19	0.18	0.10	0.11	0.13	0.14
Skewness	0.89	0.47	0.13	−0.45	0.23	−0.08
Kurtosis	0.39	0.72	1.10	0.50	1.68	0.99
Inter-quartile Range (%)	8.5	7.9	5.5	5.7	6.1	7.2
10th Percentile (%)	26.1	25.9	37.4	35.8	34.2	33.9
90th Percentile (%)	42.4	40.1	47.6	47.7	45.9	46.9
R^2 (%)	20.5		13.4		26.8	
R^2–filtered (%)	21.3		23.6		38.4	
t-Test (p-value) probability same	0.848		0.441		0.349	
χ^2 (22 degrees of freedom) distribution-test	49.3 (>33.924) different		89.0 (>33.924) different		18.44(<33.924) same	

Scatter plots suggested that a positive correlation existed between moisture contents over the two depths (e.g. Fig. 7a), although the relationship was relatively weak with R^2 ranging from 13.4 to 26.9%.

Frequency plots of the soil moisture values showed the distribution of moisture over the field site to approximate the Normal distribution (e.g. Fig. 7b); this was reflected in skewness and kurtosis figures (Table 2). In all cases, the distribution of moisture values measured over 0–6 cm was slightly more negatively skewed than that of 0–30 cm, however the discrepancy was small. Comparisons of point measurements via t-tests indicated close agreement between the 0–30 cm and 0–6 cm moisture series. Results from Chi-square tests indicated that the two series were similar in distribution for November 1999 but different on the other two occasions (Table 2).

Smoothing of the measured data reduced the effect of point heterogeneities and measurement error (e.g. Fig. 8a). Correlation between 0–6 cm and 0–30 cm smoothed data indicated that a stronger relationship existed between the two depths for this larger measurement scale with R^2 increasing to 21.3–38.4%.

4.2. Clayden's

In November 1998, the soil moisture in 0–6 cm was relatively dry and had a higher variance compared with 0–30 cm (Fig. 5a, b). Unfortunately the 0–6 cm spatial grid was not completed in May 1999 due to rainfall during sampling (Fig. 5d). Of the 150 points measured, little spatial organisation was visible in soil moisture at either depth (Fig. 5c, d). In November 1999, 0–6 cm soil moisture values were less variable than at other times by a factor of 3 or 4 (Table 3) and also wetter. These trends were also evident in the 0–30 cm data but to a lesser degree (Fig. 5e, f). Overall, many wet points lay in gullies, and a zone existed at the foot of the slope that was consistently wetter than average. These areas were found to be wet in both 0–6 cm and 0–30 cm measurements.

Table 3 indicates that the statistical characterisation of moisture in 0–6 cm was not representative of that in 0–30 cm for two of the three sampling occasions. A difference in mean moisture content of 8.9%V/V was measured in November 1998. Mean moisture contents over two depths are equivalent only for the case of November 1999 (Table 3).

Correlation between point measurements of 0–6 cm and 0–30 cm moisture content revealed little or no relationship, although the overall range in moisture content was low, limiting the ability to detect any relationship (Table 3, e.g. Fig. 7c). Smoothing did not improve these correlations. Frequency plots of the point measurements over two depths showed the 0–30 cm moisture values were more constrained in range than 0–6 cm measurements (e.g. Fig. 7d). Both were approximately Normally distributed. No general

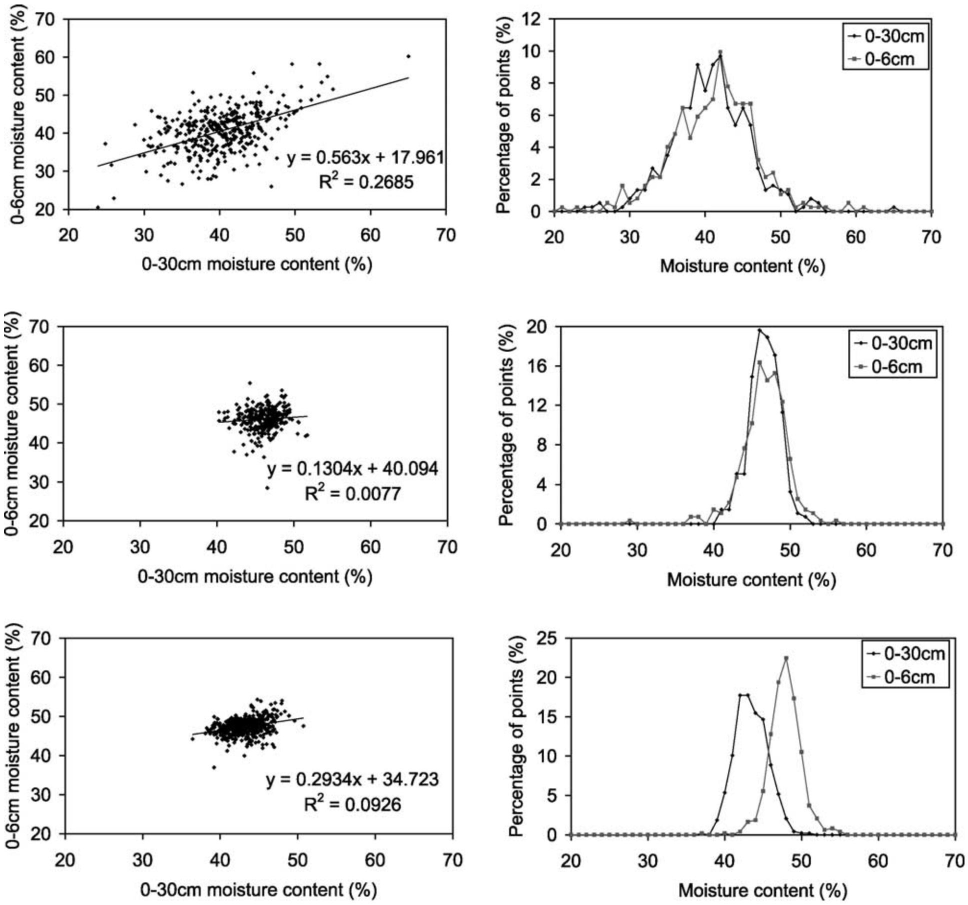

Fig. 7. Scatter plots of soil moisture in 0–30 cm versus that in 0–6 cm, and frequency plots of soil moisture at different depths; November 1999. Left to right: (a, b) Satellite Station. (c, d) Clayden's. (e, f) Carran's.

trend could be seen in the kurtosis or skewness statistics. Testing the similarity of the 0–30 cm and the 0–6 cm measurements via t-tests indicated that the means of the two series were statistically different in November 1998 and May 1999, but not in November 1999. Results from Chi-square tests indicated that the shapes of the distributions of the two series were similar for November 1999, but at no time could we conclude the distributions were statistically equivalent, after the effect of different mean values was removed (Table 3).

4.3. Carran's

Spatial distribution of soil moisture in 0–30 cm at Carran's was patchy. In November 1998, 0–30 cm soil was wettest in the northeast and driest in the southwest (Fig. 6a). A roughly similar trend existed for May 1999, with another dry area apparent in the concave centre of the site (Fig. 6c). November 1999 showed two relatively dry strips across the field site; one in the centre and one on the western fringe (Fig. 6e).

Moisture distribution at Carran's was more uniform than at the other sites. On two of the three measurement occasions at Carran's, virtually uniform moisture content existed throughout the 0–6 cm range of soil; November 1998 and 1999 (Fig. 6b, f). In comparison, moisture content in 0–30 cm displayed some variability, along with a seasonal indication of spatially variable evapotranspiration.

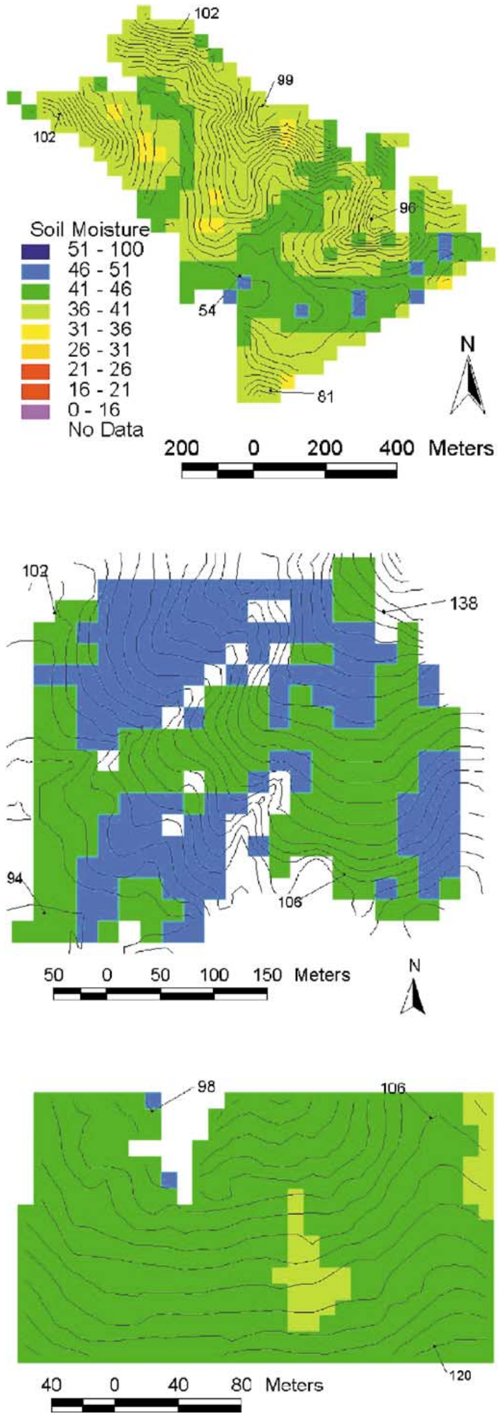

Fig. 8. Spatial distribution of soil moisture in the root zone November 1999, filtered over 3 × 3 window of neighbouring cells. (a) Satellite Station; (b) Clayden's; (c) Carran's.

No consistent relationship was seen between mean moisture content of the field site over the two depths. 0–30 cm soil was slightly wetter in November 1998, while slightly drier in both May and November 1999 (Table 4). In November 1999 the mean moisture content of 0–6 cm was much wetter than that of 0–30 cm. Variance of the 0–6 cm soil moisture was similar to that of the corresponding 0–30 cm for November 1998 and November 1999, but higher for May 1999 (Table 4). The low observed variability in moisture values was reflected in inter-quartile range summary statistics (Table 4).

Only a very weak linear relationship was suggested from correlation of 0–6 cm moisture content with that of 0–30 cm (e.g. Fig. 7e). Smoothing improved this correlation on the first two sampling occasions. Frequency distributions of the soil moisture data sets showed wetness in 0–6 cm soil to be similarly distributed in November 1998 and November 1999 with a very narrow range (Table 4, e.g. Fig. 7f). This narrow spread lead to a high statistical significance of the difference between the means, even though the absolute difference was only about 2% on the first two occasions. However, once the effect of different means was removed, results from chi-square tests suggested that at no time could we conclude the distributions to be equivalent (Table 4).

4.4. Spatial correlation

Normalised variograms of the data are presented (Fig. 9a–i). These were calculated following the procedures described in Western et al. (1998) and in various geostatistical texts (e.g. Issaks and Srivastava 1989). It should be noted that changes in 0–6 cm soil moisture at Satellite Station where sampling took up to three days, may have affected the spatial variance. This will have increased the variogram slightly at long lags, but at short lags, where points close in space are also sampled closely in time, there should be no increase. The sampling effect should not have significantly affected estimation of the correlation length. Variograms reached a stable sill, indicating that temporal changes in soil moisture did not substantially increase the variance and thus must have been small. Our interest was in whether the two data sets were similar, so the fact that the grids were measured simultaneously and in the same order on

Table 3
Statistics of moisture content at Clayden's

Clayden's	November 1998		May 1999		November 1999	
	30 cm_adj	6 cm(1)	30 cm_adj	6 cm(1)	30 cm_adj	6 cm(1)
Number	271	271	150	150	275	275
Mean (%)	43.7	34.8	43.1	38.3	46.1	46.1
Median (%)	43.9	34.8	42.9	38.8	46.2	46.3
Standard Deviation (%)	2.76	5.00	2.98	5.83	2.01	2.98
Coefficient of Variation (%)	0.06	0.14	0.07	0.15	0.04	0.06
Skewness	−0.35	0.13	−0.06	−0.27	−0.24	−1.04
Kurtosis	1.08	−0.08	0.24	−0.27	0.23	4.71
Inter-quartile Range (%)	3.5	7.4	3.9	8.4	2.6	3.4
10th Percentile (%)	40.4	28.5	39.8	30.6	43.5	42.5
90th Percentile (%)	46.9	41.2	46.9	45.0	48.6	49.4
R^2 (%)	2.1		15.4		0.7	
R^2 – filtered (%)	5.4		9.5		0.1	
t-Test (*P*-value) probability same	<0.001		<0.001		0.877	
χ^2 (22 degrees of freedom) distribution test	477.6 (>33.924) different		166.8 (>33.924) different		66.8 (>33.924) different	

each occasion meant that the variograms were directly comparable. Some spatial correlation was apparent in each data set, however it was never particularly strong. Normalised variograms for the 0–6 cm and 0–30 cm data at each site were consistent in shape for each measurement occasion, although the nugget effect varied between sites and depths due to differences in measurement error characteristics and between-site variances. Where they could be defined, the correlation lengths of both the 0–6 cm and 0–30 cm data were similar.

5. Discussion

Spatial distributions of moisture content in 0–6 cm did not correlate strongly with those in 0–30 cm (Tables 2–4). Their statistical distributions and means

Table 4
Statistics of moisture content at Carran's

Carran's	November 1998		May 1999		November 1999	
	30 cm_adj	6 cm(1)	30 cm_adj	6 cm(1)	30 cm_adj	6 cm(1)
Number (%)	485	485	442	442	485	485
Mean (%)	47.2	46.3	40.1	41.9	43.0	47.3
Median (%)	47.2	46.4	39.9	42.3	42.8	47.3
Standard Deviation (%)	2.24	2.23	2.33	3.71	2.11	2.04
Coefficient of Variation (%)	0.05	0.05	0.06	0.09	0.05	0.04
Skewness	0.18	−0.94	0.30	−0.58	0.24	−0.14
Kurtosis	0.44	3.70	0.61	−0.17	0.10	2.23
Inter-quartile Range (%)	3.1	2.6	2.8	5.1	2.8	2.4
10th Percentile (%)	44.5	43.7	37.4	36.4	40.3	45.0
90th Percentile (%)	50.2	48.9	43.2	46.2	45.7	49.5
R^2 (%)	5.6		8.1		9.3	
R^2 – filtered (%)	18.6		26.8		9.9	
t-Test (*P*-value) probability same	<0.001		<0.001		<0.001	
χ^2 (22 degrees of freedom) distribution test	65.9 (>33.924) different		551.3 (>33.924) different		62.5 (>33.924) different	

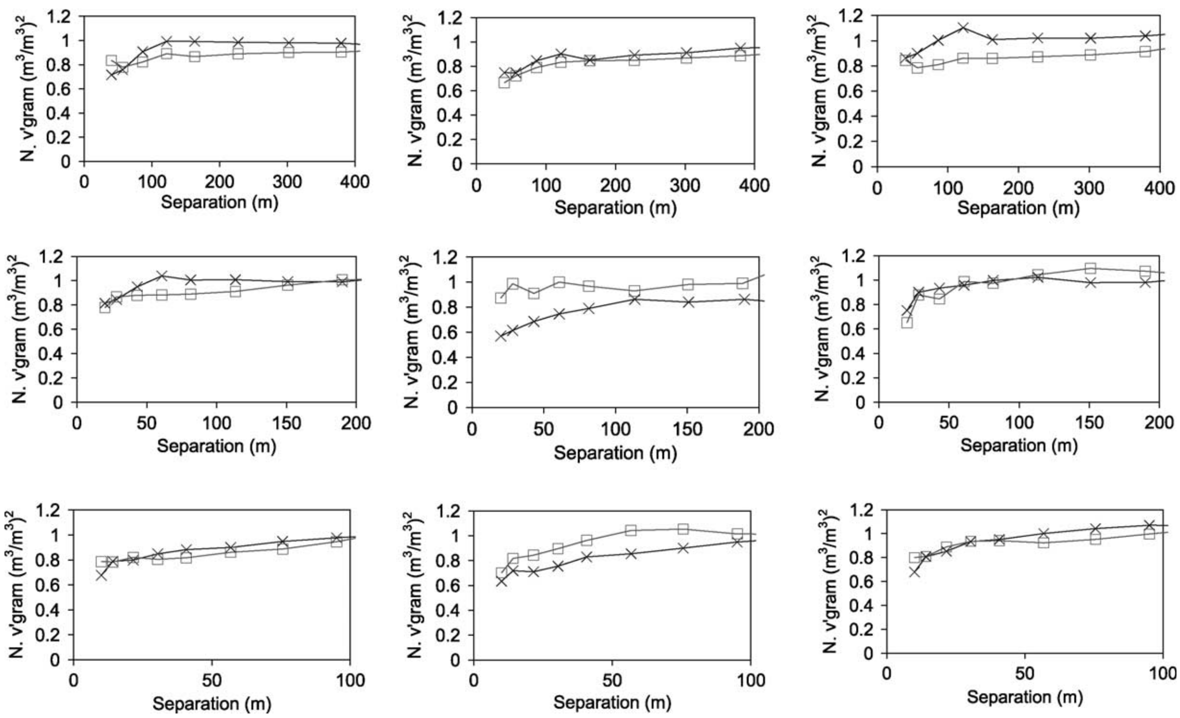

Fig. 9. Normalised variograms of 0–30 cm and 0–6 cm soil moisture data. Crosses 0–30 cm moisture content, squares 0–6 cm moisture content. Left to right: (a) Satellite Station, November 1998. (b) Satellite Station, May 1999. (c) Satellite Station, November 1999. (d) Clayden's, November 1998. (e) Clayden's, May 1999. (f) Clayden's, November 1999. (g) Carran's, November 1998. (g) Carran's, May 1999. (g) Carran's, November 1999.

could not be considered statistically similar (t and chi-square statistics, Tables 2–4), though the differences were often not hydrologically significant. Some broad trends in spatial distribution were common between the two data sets, yet the relationship between moisture at the two depths varied with site and time. Smoothed spatial patterns of soil moisture in 0–30 cm and 0–6 cm compared more favourably, though R^2 was still less than 40% (Table 2).

Errors inherently present in each measurement technique affected the R^2 statistic. We estimated the degree to which R^2 is affected by these errors by assuming that the total variance in each measurement was reduced by the random measurement error, and that the covariance was unaffected. The effect of random measurement errors on the calculated R^2 values was thought to have typically reduced calculated R^2 by about half of the real (in the absence of measurement error) value. R^2 values for Clayden's and Carran's may have been affected more than those for Satellite Station due to lower overall variance at these sites. Allowing for the effect of errors suggested that correlation between the soil moisture at 0–6 cm and 0–30 cm was weak at Carran's and Clayden's and moderate at Satellite Station. It should is noted that R^2 was often affected by the spread (spatial variance in this case) in the measurements. The variances observed at the Mahurangi sites were typical of other small catchments that have been studied around the world (Western et al., 1998; Western et al., 2001a). As one moves to larger scales, some increase in variance would be expected although increases in this case do not appear to be particularly large. Entin et al. (2000) estimated that the standard deviation of large scale (hundreds to thousands of kilometres) soil moisture was roughly twice that of small scale for their study regions of China, Iowa, Mongolia and Russia. This suggested that correlations we estimate should not have been greatly affected by changing scale or by unrepresentative sites in terms of spatial variability, although they may have changed for different types of landscapes.

Statistical properties of moisture content of the spatial grids changed with time (Fig. 10a, b), as did the relationship between the two sampling depths. Timing of the three spatial comparison field campaigns was designed to capture a range of soil moisture conditions, both in terms of mean moisture, and wetting and drying. In the context of temporal changes in moisture content in the Mahurangi River catchment during 1998–99, the field campaigns were conducted during periods of drying (November 1998), wetting (May 1999) and wet (November 1999) conditions (Fig. 3). The actual moisture contents covered the range from medium, or half way between wettest and driest moistures recorded over two years of continuous recording, to wet. It would have been ideal to capture a drier condition, however results are representative of typical conditions in these field sites. Records from permanently installed soil moisture loggers indicated that moisture conditions were drier that 25%V/V only 5% of the time, and drier than 30%V/V approximately 20% of the time. Antecedent conditions and rainfall patterns varied for each field campaign in the Mahurangi both seasonally and within each campaign itself (Fig. 10a, b). In the following discussion, we first look at each sampling occasion separately and then discuss conclusions from the data set as a whole.

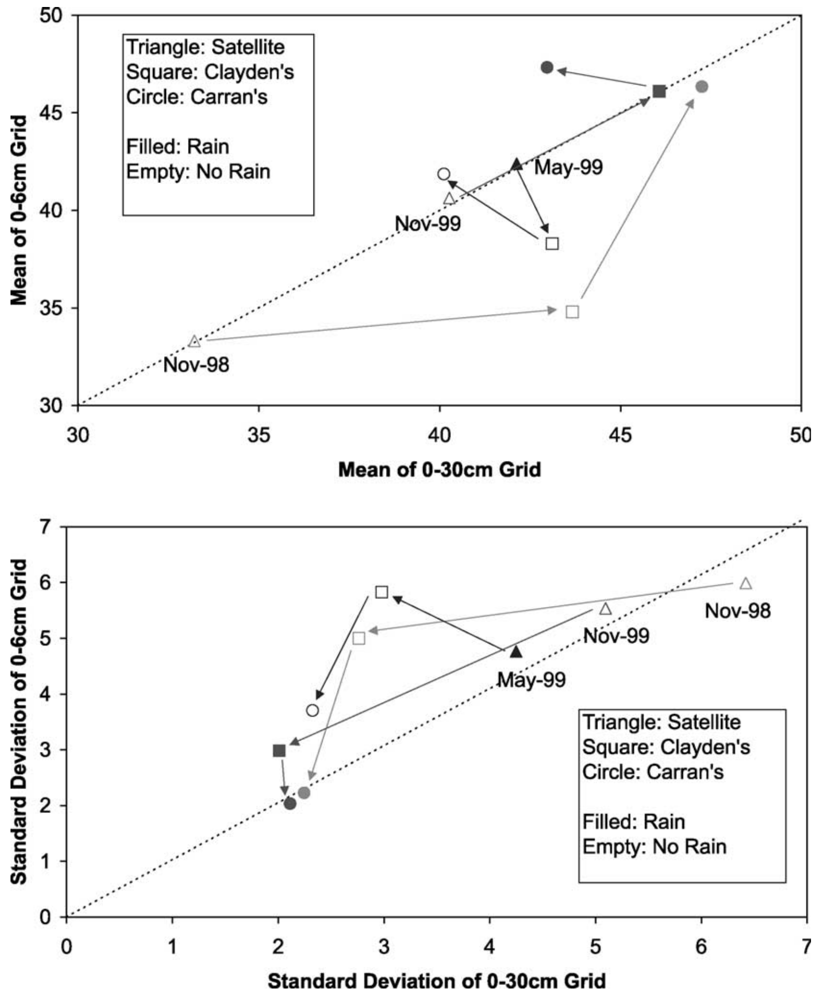

Fig. 10. Summary statistics of spatial grids. Arrows depict order of sampling. In all cases Satellite Station sampled first, then Clayden's, then Carran's. (a) Mean moisture content of spatial grids. (b) Standard deviation of moisture content of spatial grids.

5.1. November 1998

By late-November 1998, soil profiles were drying down when a storm event struck the Mahurangi River catchment (Fig. 11a). Fig. 11 shows a water balance estimated by subtracting potential evaporation from rainfall on a daily basis. Soil moisture increased markedly due to this storm; by 14%V/V in 24 h over 0–30 cm according to automatic loggers (Fig. 10a). Spatial distribution of soil moisture at Satellite Station was sampled prior to the storm, and had similar mean and standard deviation in moisture at 0–6 cm and 0–30 cm (Fig. 10a, b).

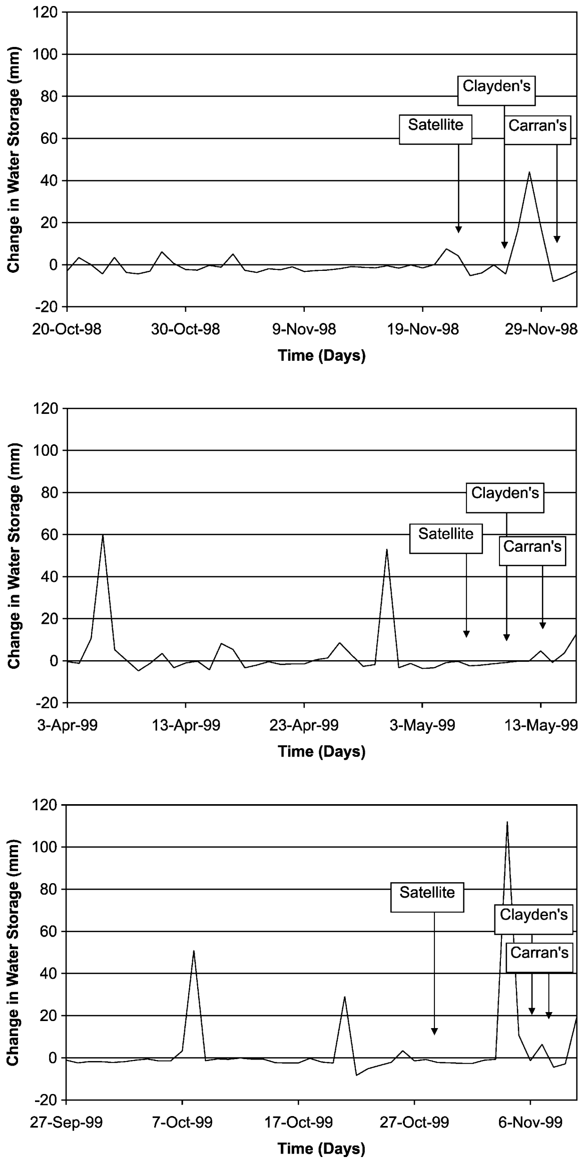

Fig. 11. Precipitation and potential ET water balance over Mahurangi river catchment. Time of spatial soil moisture sampling indicated. (a) October–November 1998. (b) April–May 1999. (c) October–November 1999.

At Clayden's, also sampled prior to the storm, soil moisture was both slightly wetter and less variable than at Satellite Station over both depths (Fig. 10a, b). 0–6 cm soil was consistently drier than 0–30 cm soil, and much more variable (Table 3). This behaviour differed from that at Satellite Station, where both moisture content and standard deviation were similar over the two depths (Fig. 10a, b). Such a marked difference was unexpected and has consequences for modelling since it was not predictable from the information we had regarding soils and vegetation. While there were some differences in the soils at these sites, one might have expected the higher clay content soils at Clayden's to show a more consistent profile than the siltier soils at Satellite Station. A possible explanation is that roots are concentrated more in the surface few centimetres at Clayden's compared to Satellite Station, although this was not obvious from field observations. Detailed sampling of root density needs to be undertaken at Satellite Station and Clayden's to test this hypothesis.

Intense rainfall at Carran's approximately 30 h prior to sampling had rapidly wet both the ground surface and the underlying soil. The spatial distribution of moisture was uniformly wet at both the 0–6 cm and 0–30 cm depths though wetter in 0–30 cm, and was less variable than at the other sites (Fig. 10a, b). Given that the storm occurred 30 h prior to sampling, a model assuming a saturated hydraulic conductivity (K_{sat}) of 10 mm/h would predict wet soil over 30 cm; the depth over which measurements of root zone moisture content were made. This is a realistic K_{sat} for structured soil.

5.2. May 1999

In May 1999, relatively dry weather leading up to and including field sampling dates, meant that of all the field sites, Satellite Station was sampled in closest temporal proximity to substantial rain (Fig. 11b). When sampling began at each site, total rainfall in

Table 5
Rainfall (mm) prior to spatial sampling at each site

	Satellite	Clayden's	Carran's
November 1998			
40 days before sampling (mm)	69.0	110.3	166.6
10 days before sampling (mm)	22.5	39.5	113.8
96 h before sampling (mm)	20.5	4.5	88.4
48 h before sampling (mm)	19.0	4.1	60.0
24 h before sampling (mm)	15.0	4.1	20.6
during sampling (mm)	2.0	9.7	2.8
Time since last storm > 1 mm/h	2 h	16 h	6 h
May 1999			
40 days before sampling (mm)	228.5	274.0	218.8
10 days before sampling (mm)	96.0	94.6	3.2
96 h before sampling (mm)	3.0	0.2	0.8
48 h before sampling (mm)	2.5	0	0
24 h before sampling (mm)	2.5	0	0
during sampling (mm)	0.5	0.2	12.6
Time since last storm > 1 mm/h	15 h	9days	12 days
November 1999			
40 days before sampling (mm)	90.5	240.8	250.0
10 days before sampling (mm)	33.5	162.8	145.2
96 h before sampling (mm)	10.5	148.4	144.8
48 h before sampling (mm)	0.5	148.4	8.2
24 h before sampling (mm)	0	90.8	8.0
during sampling (mm)	0	3.0	13.4
Time since last storm > 1 mm/h	3.5 days	1 h	1 h

the preceding 96 h was only 2.5 mm at Satellite Station, and 0 mm at Clayden's and Carran's, where storms had not affected either site for at least 9 days (Table 5). At Satellite Station, overall wetness and its standard deviation, were very similar at both 0–6 cm and 0–30 cm (Fig. 10a, b). Spatial distribution of moisture at 0–30 cm seemed to be strongly influenced by topography (i.e. gully areas were noticeably wetter), while at 0–6 cm by elapsed time since rainfall. For example, points sampled on Day 1 at Satellite Station, in the south east, were wetter than those in the north–west more clearly in 0–6 cm than in 0–30 cm (Fig. 4c, d). Given that daily evaporation may have been of the order of 1.5 mm in winter, some measurable drying of the surface soil would have been expected, though not enough to account for observed variation in moisture content across the field site.

Virtually no rain had fallen at Clayden's for over 9 days when sampling began there. Soil moisture content at 0–6 cm was low and spatially variable compared with that at 0–30 cm (Fig. 10a, b). This decoupling of the 0–6 cm and 0–30 cm moisture response was also seen in the November 1998 data. The results again suggested a shallower root zone at Clayden's, from which transpiration processes preferentially withdraw water rather than from the relatively wet 0–30 cm soil.

Carran's was sampled when no rain had fallen for in excess of fourteen days. In the absence of significant rainfall, moisture extraction processes such as evapotranspiration dominate spatial patterns of soil moisture. In May 1999 at Carran's, 0–6 cm and 0–30 cm soil moisture were similar but more variability existed in the 0–6 cm measurements (Fig. 10a).

5.3. November 1999

A significant rainfall event occurred after sampling Satellite Station but before sampling at Clayden's and Carran's in November 1999 (Fig. 11c).

Spatial patterns at Satellite Station were similar over the two depths, with no significant rainfall occurring for 3.5 days prior to sampling (Table 5). Evapotranspiration processes dominated the spatial distribution of soil moisture, affecting 0–6 cm soil moisture to a greater degree than 0–30 cm soil moisture (see below).

In the 24 h prior to sampling at Clayden's, the site received 90.8 mm of rainfall (Table 5). The decoupling of the 0–30 cm and 0–6 cm moisture response due to transpiration acting over a shallow root zone apparent in the earlier data was therefore not seen. Instead, the effect of evapotranspiration processes were overwhelmed by those of precipitation, and the soil at Clayden's was uniformly wet over both depths.

Sampling began at Carran's following a period of 8.2 mm rainfall in the previous 48 h (Table 5). Significantly, the site experienced a further 13.4 mm of rainfall between 7am and 11am on the day of sampling (Table 5). With redistribution processes having insufficient time to act, soil at 0–6 cm was found to be wetter than that at 0–30 cm (Table 4). As expected, moisture content throughout the soil was high, and standard deviation low (Fig. 10a, b). Moisture content was expected to be high in 0–30 cm given that sampling took place only days after a large storm event, and moisture content in 0–6 cm was also expected to be high given that 13.4 mm of rain fell during sampling. In the case of Carran's November 1999, the distributions of moisture values were almost identical; both depths were virtually saturated (chi-square, Table 4). Point-by-point correlation, however, was low. This was both because the two depths were saturated in slightly different areas following the action of different processes, and because the overall variance was low (Table 4).

5.4. Spatial effects

The spatial distribution of soil moisture was partly affected by static properties such as those of terrain and soil. This was perhaps most evident in the spatial maps of soil moisture over 0–30 cm depth at Satellite Station, where alluvial flats at 0–30 cm were shown to be consistently wetter than surrounding hillslopes.

For Satellite Station, on all occasions we began sampling in the southeast of the catchment and worked towards the northwest, and for all occasions the 0–6 cm moisture map indicated wetter soil in the southeast: the area measured in closest temporal proximity to recent rainfall. By the time the northwest was sampled, almost three extra days of fine weather had acted to transpire water from the soil profile, and reduce the moisture content in comparison to the southeast. This may have affected moisture in 0–6 cm to a greater extent than that in 0–30 cm, however differences in soil moisture between south–east and north–west were significantly greater than expected considering evapotranspiration alone. For the three sampling occasions at Satellite Station, records for six permanently installed soil moisture sensors showed reductions of 0.5, 0.0, and 0.2%V/V for November 1998, May 1999 and November 1999, respectively, in the 0–30 cm layer. This corresponds to 2.5, 0.0 and 1.0% maximum changes in moisture if all the water was withdrawn from the 0–6 cm layer, which is highly unlikely. Some differences in terrain exist between areas sampled over the three days; soil properties such as K_{sat} and soil depth are likely to be different in the south–east, which includes more alluvial flats, compared with the hillslope-dominated north–west. Drainage may also occur more readily from the north-western hill soils than from the south-eastern alluvial fill soils. We also note that the 0–6 cm and 0–30 cm soil moistures had similar means and variances on each sampling occasion, which suggested that the 0–6 cm and 0–30 cm layers dry at similar rates. The available evidence suggested that physiographic differences were likely to account for most of the spatial/temporal differences observed.

Some consistency was seen in the spatial patterns of moisture on different occasions, indicating soils or topographic effects on moisture content. Consistently wet in both depth ranges were the 'flats' of Satellite Station, often shallow groundwater discharge sites known to contain soil different to that of the hillslopes. No zones of consistent behaviour were observed at Clayden's, reflecting little organisation in the distribution of soils. Some consistency in moisture content was seen in the convergent downslope areas of Carran's. Overall, some consistency existed between wettest point locations at the two depths (e.g. Fig. 7a, c, e).

Normalised variograms indicated similar correlation scales for the two sampling depths on each occasion (Fig. 9), suggesting that processes controlling the spatial patterns of soil moisture in both 0–6 cm and 0–30 cm have similar spatial scales. This implied an underlying similarity in controlling process for the two depths. The similarity in mean moisture contents and in the shape of the moisture probability distribution functions at Satellite Station and Carran's lent further support to this conclusion.

5.5. Effect of spatial smoothing

Smoothing removed some of the point-to-point variance and measurement error in measured soil moisture values by taking into account the moisture of neighbouring cells, thereby increasing the effective spatial scale of the measurements so that the scale is more similar to high-resolution remote sensing measurements. As such it was used to help determine if any signal or trend was apparent in the data, notwithstanding random fluctuations and measurement errors at individual points (Fig. 8a–c). In almost all cases smoothing improved correlation between 0–6 cm and 0–30 cm soil moisture (Table 2–4). This implied that an underlying relationship existed between moisture levels within the soil depths.

Broad similarities were seen between aggregated soil moisture over the two depths, especially at Satellite Station and Carran's. Evidence existed at Satellite Station that terrain control of soil moisture was occurring, either topographically or due to soils effects, with a sharp transition between wet gullies and dry hillslopes obvious in filtered data. Moisture patterns at Clayden's, however, did not show an increase in similarity between moisture contents of the two soil depths after filtering. This was consistent with the decoupling noted above.

Aside from point-to-point comparison, the general spatial distribution of soil moisture content indicated the presence of zones of relative wet and dry. These zones, mapped independently for 0–6 cm and 0–30 cm soil depths, showed some commonality in their placement in the landscape.

5.6. Usefulness of surface moisture content for interpreting root zone moisture content

Usually one of two approaches is used in the retrieval of the soil moisture profile by assimilation of near-surface moisture observations: direct insertion or Kalman filtering. As summarised by Walker et al. (2001b), the 'Kalman filter is a statistical assimilation scheme that updates the model state values based on the relative magnitudes of the covariances of both the model state and the observation.' Direct insertion on the other hand 'replaces the model state values with the observed values directly' (Walker et al., 2001b). Each method requires a working model of soil hydrologic processes.

In this study, spatial distributions of soil moisture over two soil depths and the way these distributions change through time, indicated that site-specific characteristics may determine which processes dominate patterns of soil moisture. We observed topographically expected patterns at Satellite Station, where gullies were commonly wetter than hillslopes. Moisture content in the 0–6 cm and 0–30 cm layers appeared to be very similar at both Satellite Station and Carran's, suggesting they were controlled by the same dynamics.

Decoupling of the 0–6 cm and 0–30 cm soil moisture behaviour was seen at Clayden's, the reasons for which were not apparent from field observations of soils or vegetation, although root density may have been higher in the surface soil. Detailed knowledge of the soil profile and vegetation characteristics would therefore be needed for successful modelling of the relationships between surface moisture and the root zone soil. This knowledge would be required regardless of soil conditions, so that we knew over what depth range the soil moisture was active.

Intense storm activity dominated the observed response at Carran's where the soil profile was wet, but moisture at 0–6 cm and 0–30 cm may have been influenced by different storm events. For the case of November 1999, in which the 0–30 cm soil layer was wet by prolonged, intense rainfall four days prior to sampling, and the 0–6 cm layer was wet during sampling, moisture at the two depths was statistically similar on average, but the spatial distributions of wetness did not match. This reflected the action of different process controls.

Modelling of the vertical water redistribution was found to capture the dynamics of the relationship between 0–6 cm and 0–30 cm at Carran's (Wilson et al., 2001). Initially recommended values for the K_{sat} of matrix soil of the type found at Carran's were around 0.5 mm/h (Rijkse 1996). This was unrealistically low and would not correctly describe observed soil moisture behaviour. Improved K_{sat} for a 1D vertical distribution model of Carran's was around 5 mm/h (Wilson et al., 2001); soil moisture observations over two depths following storm activity were consistent with this, a reasonable value for structured clay soils like those at Carran's. Realistic soil property values were critical to temporal success of such a model.

Spatially, improvements in correlation were seen after smoothing. After allowing for measurement errors, we inferred that localised soil properties such as pore size and soil structure influenced the distribution of moisture, and a point-averaging factor would need to be introduced to minimise the effect of local heterogeneities.

Implications for predicting soil moisture distribution in the root zone based on surface measurements were therefore dependent on local meteorology and soil properties. If intense rainfall occurred, spatial distribution of 0–6 cm soil moisture became relatively uniform for a short time, before 0–30 cm moisture content was affected. Similarly, in times without rainfall, various processes acting with different degrees of relative dominance redistributed water within the profile such that direct comparison between soil depths was confounded; dynamic modelling of the profile should be able to accommodate such behaviour, though soil and vegetation properties identified must be detailed and accurate. For the case of shallow root distributions at Clayden's, this critical knowledge was not available from observations.

6. Conclusions

Intensive field measurements have allowed us to compare spatial distribution of soil moisture over two depths, 0–30 cm and 0–6 cm, for three snapshot occasions at field sites in the Mahurangi River catchment, New Zealand.

Specifically, we examined how representative the spatial distribution of soil moisture in 0–6 cm was in relation to that in 0–30 cm. Generally, soil moisture at 0–6 cm was found to have a similar mean, variance and frequency distribution to that in 0–30 cm when measured on a spatial grid, though exceptions were found. The degree of correlation between point 0–30 cm and 0–6 cm moisture values, however, was not high for individual spatial patterns.

In general, the relationships observed between 0–6 cm and 0–30 cm soil moisture were as would be expected from a dynamic model of vertical water flow, however decoupling occurred between 0–6 cm and 0–30 cm at Clayden's. The importance of realistic K_{sat} values on modelling the temporal behaviour of soil moisture following storms was also seen, optimum values differed from published K_{sat} values for these soils.

The results cover a range of dynamic conditions typical of the mid-latitude humid zone and augur well for the assimilation of remote sensing measurements into vertical flow models as a means of establishing soil profile moisture contents. Some exceptions, however, indicate that detailed and accurate knowledge of soil and vegetation properties, including rooting depths and their spatial distribution, are required if assimilation models are to be used with confidence. Some of these crucial properties were difficult to ascertain from field observations. The success or otherwise of data assimilation approaches will be very sensitive to the availability of good soil property data, particularly for locations like the Mahurangi where the range in soil moisture conditions is not great.

Acknowledgements

Land owners and managers provided free access to their land and willing cooperation throughout the project. Within the Mahurangi catchment, Ted Bradnam, Ross Clayden and Harvey Carran were generous in their attitude. Funding for this work was provided by: *the Australian Research Council* (grants C39813076, A39801842, C39804872) and the New Zealand Public Good Science Fund (contracts CO1635, CO1817). Assistance was forthcoming from the CRC for Catchment Hydrology. Field assistance was provided by Maurice Duncan, Harm Matthijs van der Worp and Rodger Young. Following on from earlier work at Tarrawarra, Günter Blöschl provided useful suggestions on the field data collection. Soils data were supplied by Breck Bowden and LandCare Research of New Zealand. Senlin Zhou contributed to the geostatistical calculations.

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