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Journal of Hydrology 286 (2004) 113–134

Journal of Hydrology

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Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes

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Received 4 March 2003; revised 3 September 2003; accepted 19 September 2003

Abstract

The geostatistical properties of soil moisture patterns from five different sites in Australia (Tarrawarra and Point Nepean) and New Zealand (three sites from the Mahurangi River Basin—Carran's, Clayden's and Satellite Station) are analysed here. The soil moisture data were collected using time domain reflectometry and consistent methods for all sites, thereby allowing comparisons to be drawn between sites without the complication of methodological differences. The sites have contrasting climatic and soils characteristics. Soil moisture in the top 30 cm of the soil profile was measured using time domain reflectometry on 6–8 occasions at each site. The variance and correlation structure of the patterns was analysed. Typical correlation scales lie between 30 and 60 m. We found that there was a seasonal evolution in the spatial soil moisture variance that was related to changes in the spatial mean moisture content at all sites. At the Australian sites there was also a seasonal evolution in the correlation length related to changes in the spatial mean moisture, but not at the New Zealand sites. The seasonal evolution of the correlation length in the Australian catchments is likely to be associated with a seasonal change in the processes controlling the soil moisture pattern. The more humid climate at the New Zealand sites leads to more consistent spatial controls over the year. Similarities between the correlation structure of the moisture and topographic indices representing lateral flow and topographically modulated evaporative forcing were found at Tarrawarra, Carran's and Clayden's. At Point Nepean the correlation structure of the soil moisture pattern is controlled by a larger (than the topography) scale variation in soils, properties and at Satellite Station a smaller scale source of variability is apparent in the data (although there were also topographical effects apparent, associated with valley features). The results demonstrate that the processes controlling spatial patterns can change between places and over time with catchment moisture status; however, when similar general conditions reoccur in a catchment, similar spatial patterns result. Soil characteristics and climate do provide a general pointer to what we might expect but the results also show subtleties specific to place.

Keywords: Soil moisture; Variogram; Correlation structure; Time domain reflectometry; Topography

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doi:10.1016/j.jhydrol.2003.09.014

1. Introduction

Soil moisture has a major influence on a range of hydrological processes including flooding, erosion, solute transport and land–atmosphere interactions, as well as a range of geographic and pedogenic processes. Soil moisture is highly variable in both time and space. This variability has a significant impact on the above processes due to the nonlinearities involved. Therefore, knowledge of the characteristics of soil moisture variability is important for understanding and predicting the above processes.

The spatial distribution of soil moisture has been studied in the past using both ground-based and remote sensing measurements. Generally studies using ground measurements have focussed on relatively small scales while those using remote sensing have studied larger scales. Each source of data has its advantages and disadvantages. Ground measurements usually provide data that are more easily calibrated, but only cover small areas and the analysis of spatial correlation is often limited by the small number of measurements (Western et al., 1998). Remote sensing provides more complete data sets over large areas, but the interpretation of the remote sensed signal is more challenging, especially for vegetated surfaces, and the footprint often leads to significant smoothing of small-scale variability.

Geostatistical techniques are often used to characterise spatial soil moisture patterns (Entin et al., 2000; Mohanty et al., 2000; Liu, 2001; Western et al., 2002). A central concept in geostatistics is the variogram, which describes the variance between the points in a spatial field as a function of their separation. The main structural parameters of the variogram are the sill, the correlation length (or range) and the nugget. The sill is the level at which the variogram flattens out. If a sill exists, the spatial soil moisture distribution is stationary and the sill can be thought of as the spatial variance of two distantly separated points. The correlation length (or range) is a measure of the spatial continuity of the variable of interest. The range is the distance beyond which the correlation between points is minimal. The correlation length and range are directly related, with the relationship depending on the specific variogram type selected. The nugget relates to the variance between pairs of points separated by very small distances and is usually interpreted as a combination of measurement error and small-scale variability.

Western et al. (1998) summarise the measurements of six studies of the spatial variation and spatial correlation of soil moisture in small catchments (Charpentier and Groffman, 1992; Lehmann, 1995; Loague, 1992; Nyberg, 1996; Warrick et al., 1990; Whitaker, 1993). Similar recent studies include Fitzjohn et al. (1998), Mohanty et al. (2000), Huisman et al. (2002), Wang et al. (2001), Anctil et al. (2002) and Guo et al. (2002). Typical correlation lengths, λ vary between 1 and 600 m and there is a tendency for λ to increase with extent and spacing as would be expected given the effects of these scale characteristics on λ (Western and Blöschl, 1999). Most of these small catchment studies suggest that λ lies in the range 20–300 m. A number of studies in the literature have small sample sizes compared with those required for reliable estimates of the correlation length (Western et al., 1998).

Analyses of the spatial structure of soil moisture at other scales of up to 10 km have found fractal behaviour (Hu et al., 1997; Peters-Lidard et al., 2001; Rodríguez-Iturbe et al., 1995) in the remotely sensed ESTAR soil moisture data set collected during Washita92 (Jackson et al., 1995). At even larger scales data sets from ground-based point measurements at agricultural sites in the Former Soviet Union, Mongolia, China, and the USA suggest that soil moisture variation could be represented as a stationary field with a correlation length of about 400–800 km (Vinnikov et al., 1996; Entin et al., 2000). Vinnikov et al. (1996) and Entin et al. (2000) noted the existence of a smaller scale (<50 km) component to the spatial variability that was unresolved by their data.

Part of the differences in correlation lengths in small scale and large scale studies may be explained by sampling effects (Western and Blöschl, 1999) and sampling uncertainty (Western et al., 1998), but there are also important changes in process controls with scale causing such differences. Generally the spatial soil moisture field has been found to be stationary at small catchment scales (<1 km, where catchment processes dominate) (Western et al., 1998) and at large scales (100 s + km, where atmospheric processes dominate) (Vinnikov et al., 1996). It would be expected that soil characteristics (Seyfried, 1998) and vegetation may play a significant role over these intervening scales; however, this has not been fully analysed to date. It should be noted that the stationarity observed at both small and large scales is not inconsistent because there is a large difference (three orders of magnitude) in the correlation lengths so the large-scale variability component basically has no effect at the small catchment scale. In summary, when we compare across vastly different scales (extents), we see the scales of the dominant source of soil moisture variability reflected in the correlation length of the soil moisture pattern.

What is unclear is whether differences in the correlation lengths of soil moisture can be attributed to the relative importance of different processes operating at a single scale. This has been mainly due to different measurement techniques in different studies, which have made comparisons difficult. At the small (first order) catchment scale we expect topography (e.g. lateral flow), soils, vegetation and microclimate (e.g. spatially variable radiative exposure of hillslopes) to all contribute to the spatial variability of soil moisture. In different hydrological settings we might expect one or other of these to be most important in determining the spatial pattern of soil moisture. For example in wet situations topographically routed subsurface lateral flow may be important but the controls on vertical fluxes are likely to dominate under dry conditions (Grayson et al., 1997). It has become traditional in hydrology to assume that topography plays a dominant role at this scale (Grayson and Western, 2001), however, the generality of this hypothesis is poorly supported in the literature. Indeed there are clear examples where other controls are more important (Famiglietti et al., 1998; Grayson et al., 1997; Western et al., 1999)

In this paper we consider five different small catchments with contrasting topography, soils, climate and hydrologic processes. The catchments are Tarrawarra and Point Nepean in south-eastern Australia, and Satellite Station, Carran's and Clayden's in the Mahurangi River catchment, New Zealand. We use these catchments as a basis to analyse whether differences in the geostatistical structure of moisture patterns can be used to detect differences in spatial hydrologic processes. The main strength of this paper is that comprehensive soil moisture data from different topographies, soils, and climates, have been collected in a *consistent* way thus enabling direct comparisons of the differences in the spatial geostatistical structure. This paper extends the earlier work of Western et al. (1998) in that five rather than a single site are examined. The data are therefore ideally suited to assessing whether similarities and differences in the geostatistical characteristics can be explained by similarities and differences in the dominant process controls.

The paper is structured as follows. First the catchments, data and analysis methods are described. Then we analyse the geostatistical structure of the soil moisture fields in each catchment, based on the comprehensive data sets. The relationship between geostatistical structure and spatial soil moisture processes is then examined by considering the effects of climatic and seasonal differences and by comparing soil moisture variograms with variograms of indices representing topographically driven subsurface lateral flow and microclimatic (radiative exposure) processes. Finally we consider the role of soils in controlling spatial patterns of soil moisture.

2. Study sites and data descriptions

Soil moisture data are from three main locations: Tarrawarra, Point Nepean and the Mahurangi catchment. Both Tarrawarra and Point Nepean are isolated sites located close to Melbourne, Australia while the Mahurangi River catchment is located on the North Island in New Zealand. All data are of volumetric soil moisture (here always expressed as % m^3 water/m^3 soil) in the top 300 mm of soil, which in these sites represents the majority of the active root zone. The vegetation at all sites consists of grass pasture for grazing cattle and or sheep. Key climatic, topographic, and soils characteristics of each catchment are given in Table 1. All data analysed here were collected during 1998 and 1999 using consistent methods for each site.

Fig. 1 shows the topography of the two Australian catchments. The Tarrawarra catchment is located 50 km east of Melbourne, Australia at 37°40′S, 145°27′E. The climate is temperate and the average soil moisture levels are generally high during winter (April–September) and low during summer (October–March). Mean annual rainfall is 820 mm and

Table 1
Summary of climate, soil and topographic characteristics of the Tarrawarra 1, Tarrawarra 1 and 2, Point Nepean, Satellite Station, Carran's and Clayden's sites

Site	Physical dimensions		Soils characteristics		Annual climate		Topography Mean slope (%)
	Area (ha)	Grid size (m)	Sand:silt:clay	Profile type	Rainfall (mm)	PET (mm)	
Tarrawarra 1	10	20 × 40	5:70:25	Duplex	820	830	8
Tarrawarra 1 and 2	45	40	5:70:25	Duplex	820	830	8
Point Nepean	13	15	96:4:0	Uniform	750	830	8
Satellite Station	60	40	22:51:27 (Hills) 8:34:59 (flats)	Gradational	1200	920	16
Carran's	5	10	27:38:35	Gradational	1300	920	14
Clayden's	13	20	18:39:43	Gradational	1350	920	14

the areal potential evapotranspiration (PET) is 830 mm (Bureau of Meteorology, 2001). The areal PET is calculated using Morton's model with coefficients calibrated for Australia (Chiew et al., 2002). The topography at Tarrawarra is undulating with maximum slopes of 14%. The soils at Tarrawarra have a 20–35 cm deep loam to clay-loam A horizon, which is believed to be the hydrologically active zone from the perspective of lateral subsurface flow. Tarrawarra has pasture vegetation and is used for cattle grazing. Spatial patterns of soil moisture were collected in about 45–50 ha of the catchment area. The Tarrawarra research area has two neighbouring catchments: Tarrawarra 1 and Tarrawarra 2. Western et al. (1998) and Western and Grayson (1998) studied Tarrawarra 1 in detail over the period 1995–1997. More recently the study area has been expanded to incorporate Tarrawarra 2. Data used in this paper come from both catchments. Two sets of analyses have been conducted for these data. The first only uses data from Tarrawarra 1 to enable comparison with the results of Western et al. (1998). The second uses the data from both Tarrawarra 1 and Tarrawarra 2 combined to enable larger scale analysis. This analysis is referred to as being for Tarrawarra 1 and 2. The patterns used consist of approximately 250 point measurements on a grid of 40 × 20 m over the 10.5 ha Tarrawarra 1 catchment and 250 point measurements on a 40 × 40 m grid over Tarrawarra 2.

Point Nepean lies 60 km south of Melbourne on the Mornington Peninsula, Australia, at 38°25′S, 144°55′E. This site occupies approximately 13 ha of pasture on deep, very well drained sandy soil. The soils are the main difference between this and the Tarrawarra site (where surface soils have sand, silt and clay contents of 5, 70 and 25%, respectively). A spatial grid of 15 × 15 m comprises some 570 point measurements. The mean annual rainfall is 750 mm and mean annual areal potential evapotranspiration is 830 mm (Bureau of Meteorology, 2001). The seasonality of the climate is similar to Tarrawarra.

The Mahurangi River catchment is located approximately 70 km north of Auckland, New Zealand (36.4°S,174.7°E) and drains 50 km^2 of steep hills and gently rolling lowlands. Within this catchment, three soil moisture monitoring locations: Satellite Station, Carran's and Clayden's are used in this study, which form part of the Mahurangi River Variability Experiment (MARVEX) (Woods et al., 2001). Fig. 2 depicts the topography of the three New Zealand sites. The climate is warm and humid and the maximum rainfall is usually in July, the middle of the austral winter. Most soils in the catchment are clay loams (clay content ~30–60%), no more than a meter deep. The vegetation at all these locations is predominantly pasture with the same coverage of measurements as the Australian sites. These patterns consist of approximately 370 point measurements on a grid of 40 × 40 m for Satellite Station, 485 point measurements on a grid of 10 × 10 m for Carran's, and 280 point measurements on a grid of 20 × 20 m for Clayden's.

Given our later comparison of sites it is important to emphasise here the key differences between sites in terms of characteristics and processes. All sites have a seasonal variation in soil moisture controlled by

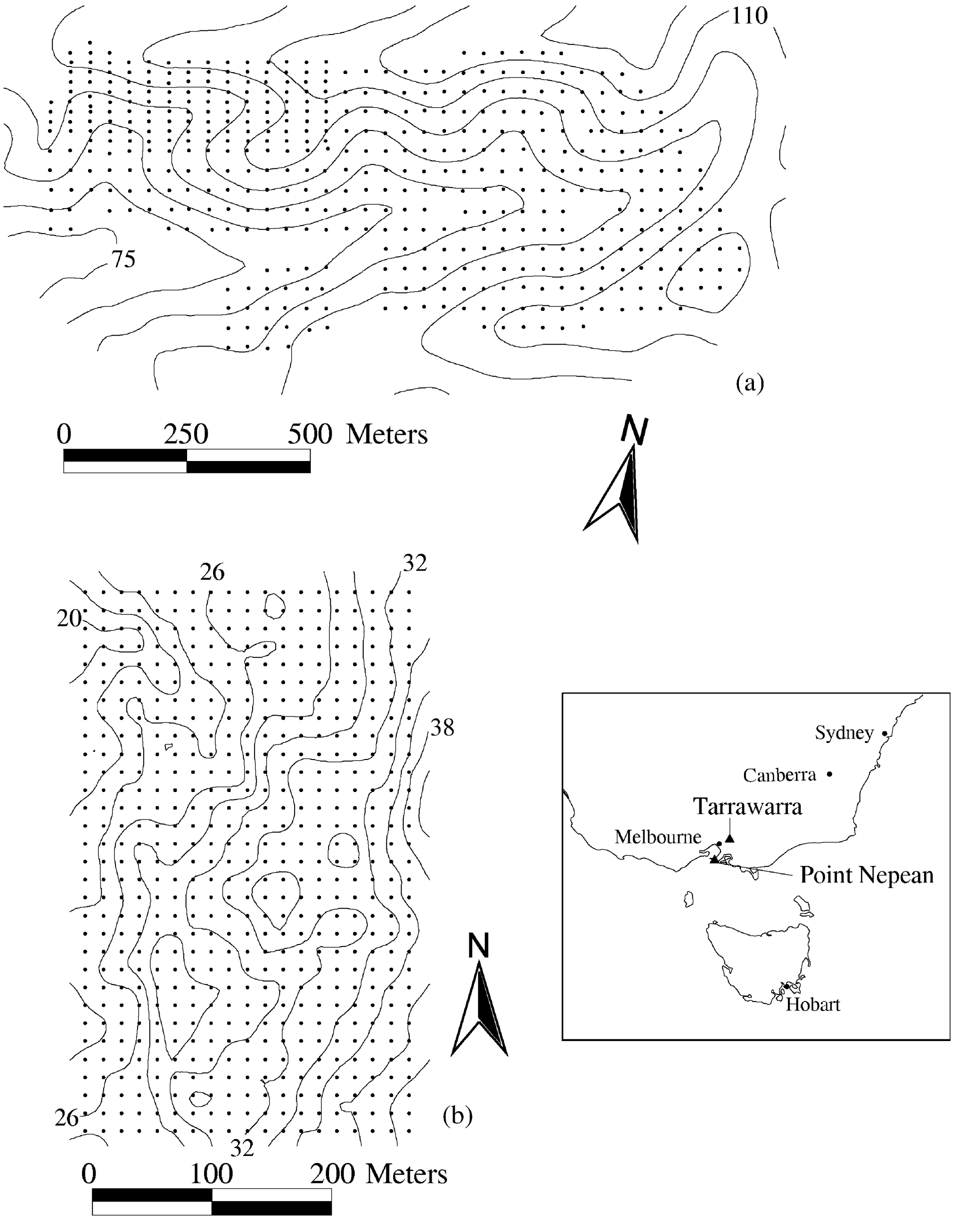


Fig. 1. The topography of (a) Tarrawarra and (b) Point Nepean catchments in Australia. Contour intervals are 5 and 2 m, respectively, and the sampling grid is shown.

the seasonal variation in potential evapotranspiration, however, the two Australian sites come from a significantly drier climate (Fig. 3). In Australia this leads to a marked deficit of rainfall compared with PET in summer and excess in winter whereas in New Zealand rainfall and PET are approximately in balance in summer while there is a substantial excess of rainfall over PET in winter. Differences in topography are also evident in Figs. 1 and 2. In particular topography is fluvial in New Zealand and at Tarrawarra, while at Point Nepean the topography results from wind blown sand overlying a limestone basement. Key differences in soils relate to clay content and drainage characteristics. Point Nepean

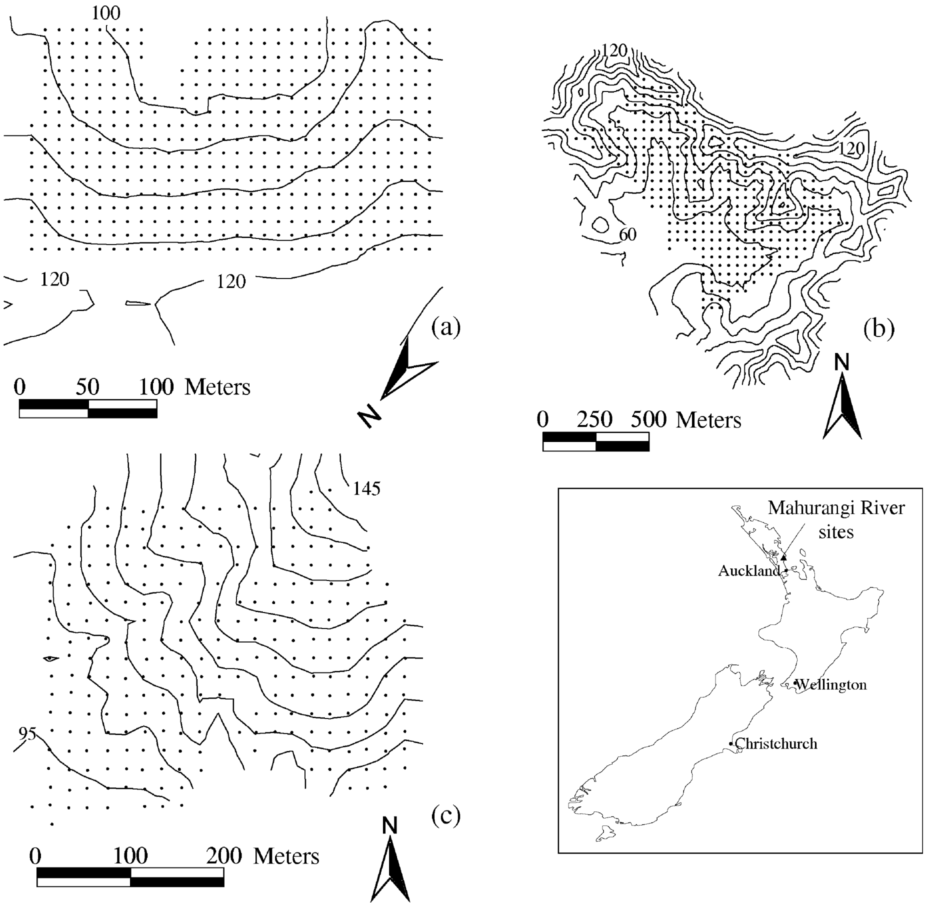


Fig. 2. The topography of (a) Carran's, (b) Satellite Station, and (c) Clayden's sites from the Mahurangi River Variability Experiment (MARVEX), New Zealand. Contour intervals are 5, 10 and 5 m, respectively, and the grid is shown.

has deeply drained sand with no evidence of topographically induced lateral flow. Tarrawarra commonly has a texture contrast (duplex (Northcote, 1979)) soil with loam-clay loam A horizon and clay B horizon, both of which are well structured. The New Zealand sites are dominated by gradational soils in general that vary in clay content between sites (Table 1). Satellite Station has two different soil units, a silty-loam on the hillslopes and a clay soil on the low lying flats. Lateral flow of water is evident at all sites except Point Nepean but the depth at which lateral flow occurs may vary between sites. There is evidence of soil piping in the New Zealand catchments, particularly Satellite Station.

The measurements at all sites were made over the top 30 cm of the soil profile using time domain reflectometry (TDR) sensors mounted on an all terrain vehicle with an integrated differential Global Positioning System (dGPS) (Tyndale-Biscoe et al., 1998; Western and Grayson, 1998). At Carran's, Clayden's and Point Nepean the measurements were made during a single day. At Tarrawarra and Satellite Station measurements typically took 2 days. The TDR was calibrated in the laboratory for each site and checked against field gravimetric samples (Western et al., 2001c). Comparison of closely spaced (<1 m) TDR measurements allowed an error variance to be estimated for each site. This varied from 1.9 to 2.5%^{2} between sites. However, under extremely wet

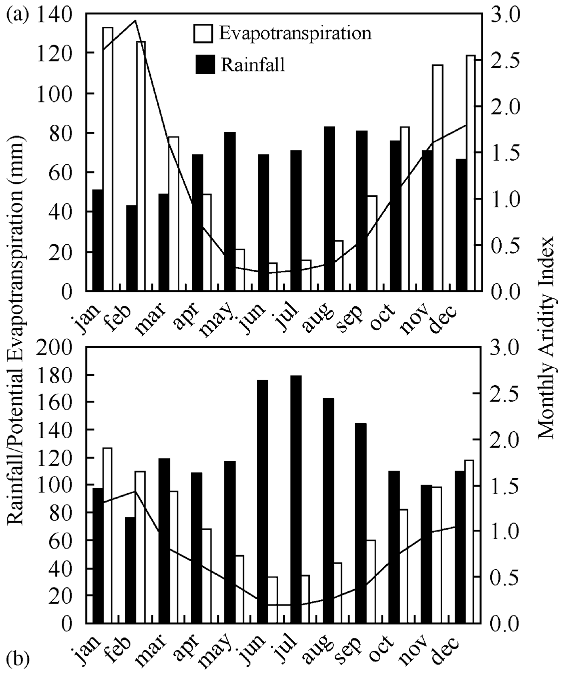


Fig. 3. The mean seasonal pattern of rainfall and potential evapotranspiration for (a) Tarrawarra and (b) the three New Zealand sites. Point Nepean has a very similar pattern to Tarrawarra. Seasonal changes in the climatic aridity index (defined as areal potential evapotranspiration/rainfall) are shown as lines.

conditions when there is surface ponding or overland flow, some unrealistically high TDR measurements were obtained. To limit the effect of these high estimates on variance estimates, moisture values were truncated at a maximum moisture selected on the basis of measured soil porosity at each site.

Forty spatial patterns of soil moisture from the five sites were used in this analysis. Fig. 4 presents an example of soil moisture pattern from each site. Table 2 provides the sites, dates, antecedent rainfall, number of sample points, mean, variance, coefficient of variation, and 5th and 95th percentiles for each of the data sets used in the analysis. It is important to note that the number of points available is very large compared to what is normally the case, and is of the order recommended by Western et al. (1998) for reasonably reliable estimation of variogram parameters.

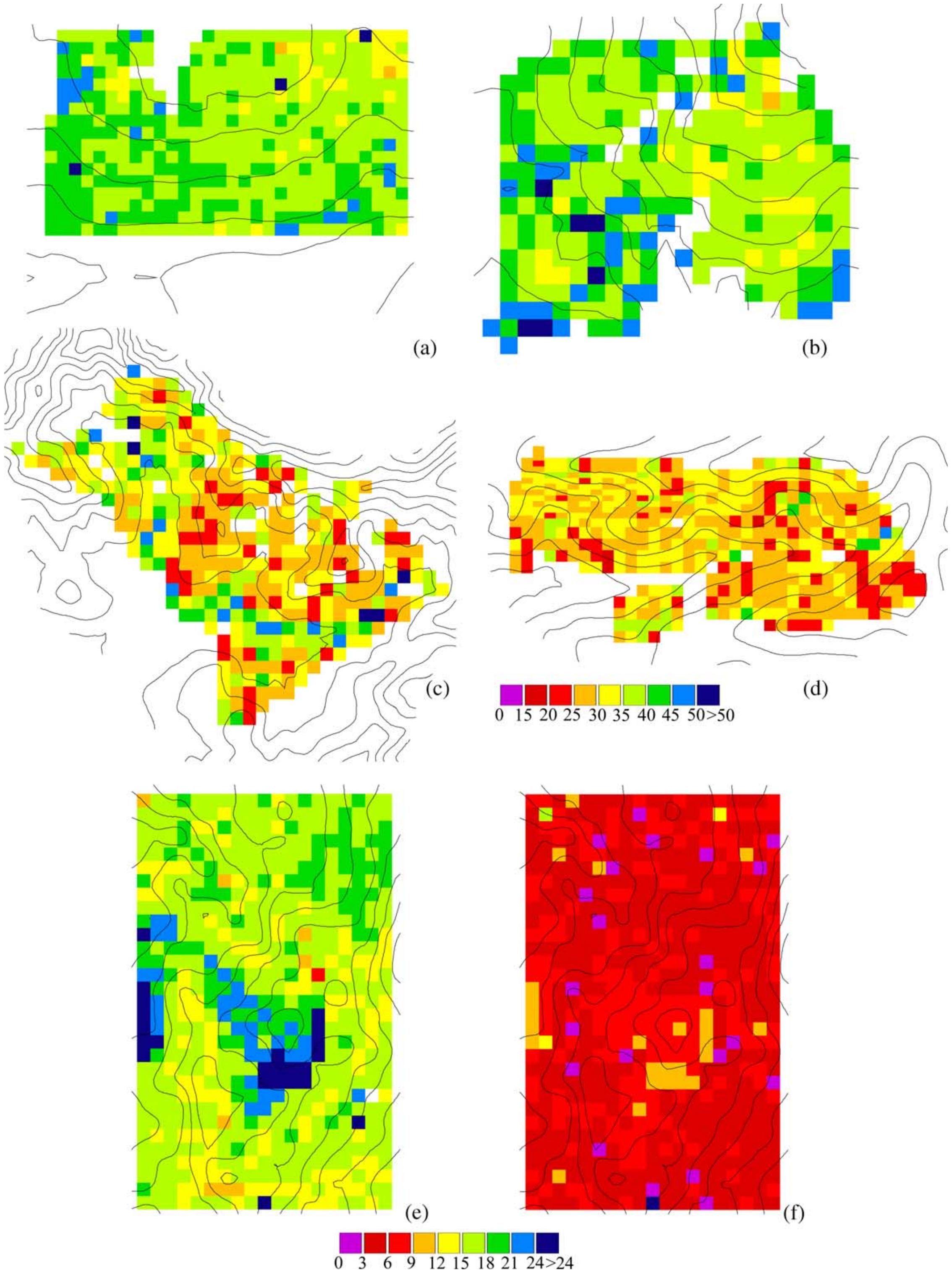
A geostatistical analysis of a variety of terrain parameters was also conducted at each site for comparison with the soil moisture geostatistics. The digital terrain models (DTM) used for all sites except Satellite Station were based on dGPS measurements of elevation at each soil moisture measurement site, plus additional dGPS data from the surrounding area. These data are accurate to ~0.1 m. At Satellite Station a DTM based on 1:10,000 scale aerial photography was used. This DTM has a vertical accuracy of 0.2 m and a horizontal resolution of 10 m. Standard terrain analysis algorithms were used to calculate slope, aspect, topographic wetness index (Quinn et al., 1995) and potential solar radiation index (Moore et al., 1991). The topographic wetness index is defined as $\ln(a/\tan(\beta))$, where a is the specific upslope area in meters and β is the local surface slope angle. The specific upslope area is the upslope catchment area per unit contour length or flow width (Wilson and Gallant, 2000). The topographic wetness index is a surrogate for lateral subsurface flow processes on hillslopes. The potential solar radiation index is defined as the ratio of radiation received on a slope to that received on a horizontal surface, in the absence of atmospheric effects, on a given day. It is a measure of the spatial variation in solar radiation due to the effect of slope and aspect.

3. Methods of analysis

The analysis involved first calculating the sample variogram for each soil moisture pattern and then fitting a variogram model to the sample variogram in order to estimate the variogram of the population represented by the sample. The traditional nonparametric estimator of the semivariogram (hereafter referred to as the sample variogram), $\gamma_s(h)$, is half the average squared difference between the values of data pairs (e.g. Isaaks and Srivastava, 1989; Journel and Huijbregts, 1978):

$$\gamma_s(h) = \frac{1}{2N(h)} \sum_{i,j} (\theta_i - \theta_j)^2 \quad (1)$$

where h is lag, $N(h)$ is the number of pairs of data located in a given lag bin; θ_i and θ_j are the soil moisture at points i and j, respectively, and the summation is conducted over all i, j pairs in the lag bin. The variogram is a function of both the distance


(a)
(b)
(c)
(d)
0 15 20 25 30 35 40 45 50 >50
(e)
(f)
0 3 6 9 12 15 18 21 24 >24

and direction, and so it can account for direction-dependent variability (anisotropic spatial pattern). In this analysis, the omnidirectional variogram was computed, and hence the spatial variability is assumed to be identical in all directions. Western et al. (1998) showed this to be a reasonable assumption at Tarrawarra 1. In this study, the sample variograms were calculated using all pairs separated by lags up to about 70% of the maximum extent in each catchment. Pairs were grouped into lag 'bins' and Eq. (1) was used to calculate the variogram value for that bin. The mean lag of all the pairs in a particular bin was used as the representative lag for that bin.

For the purpose of estimating the geostatistical properties of the population of possible soil moisture patterns, a variogram model can be fitted to the estimated sample variogram. In this process we are averaging out some of the sampling variance apparent in the sample variograms. This inference step involves the preliminary selection of a parametric model and the estimation of model parameters. The basic variogram models can be conveniently divided into two types; those that reach a plateau and those that do not. Variogram models of the first type are often referred to as transition models and they are applicable to stationary data. The plateau they reach is called the sill and the distance at which they reach this plateau is called the range. The numerical value of the sill is usually similar to the variance. Variogram models of the second type do not reach a plateau, but continue increasing as the magnitude of h increases. Such models are often necessary when there is a trend or drift in the data values, i.e. the data are nonstationary in the mean.

Several factors, such as sampling error and short scale variability, may cause sample values separated by extremely small distances to be quite dissimilar. This causes a discontinuity at the origin of the variogram. The vertical jump from the value of 0 at the origin to the value of the variogram at extremely small separation distances is called the nugget effect. In this study, an exponential model (a type of transition model) with a nugget was used for all sample variograms:

$$\gamma_e(h) = \sigma_0^2 + (\sigma_\infty^2 - \sigma_0^2)(1 - e^{-h/\lambda}) \tag{2}$$

where $\gamma_e(h)$ is the fitted variogram, σ_0^2 is the nugget, σ_∞^2 is the sill and λ is the correlation length. This model reaches its sill asymptotically, with the practical range 3λ defined as that distance at which the variogram value is 95% of the difference of sill and nugget. The quality of the variogram fits was characterised using the root mean square error (RMSE) calculated as:

$$\mathrm{RMSE} = \left[\frac{\sum(\gamma_e(h) - \gamma_s(h))^2}{n_h}\right]^{1/2} \tag{3}$$

where n_h is the number of lag bins in the sample variogram. The sill, nugget and correlation length were estimated by fitting the variogram model to the sample variogram visually.

4. Results

4.1. Sample variogram estimates

The first step of this analysis is to compute sample variograms, using standard geostatistical techniques, for each soil moisture pattern from the five catchments. A statistical summary of each soil moisture pattern is provided in Table 2. The sample variograms are shown in Fig. 5. The horizontal dashed lines indicate the random measurement error estimated from the closely spaced TDR measurements. The variogram values increase with the separation distance, reflecting our intuitive feeling that two soil moisture data close to each other are more alike, and thus their squared difference is smaller than those that are further apart. At Tarrawarra 1 and Point Nepean,

Fig. 4. An example volumetric soil moisture (% m^3/m^3) pattern from each experimental catchment. Topographic contours (contour interval) are also shown for each site. (a) Carran's 1 April 1998 (5 m), (b) Clayden's 30 March 1998 (5 m), (c) Satellite Station 26 March 1998 (10 m), (d) Tarrawarra 3 June 1998 (5 m), (e) wet conditions at Point Nepean 16 July 1998 (2 m), (f) dry conditions at Point Nepean 13 April 1999 (2 m). Each square represents one TDR soil moisture measurement for the top 30 cm of the soil profile. Measurement grid spacings are Carran's—10 m, Clayden's—20 m, Satellite Station—40 m, Tarrawarra—40 m and Point Nepean—15 m. The upper colour bar applies to panels a–d and the lower colour bar applies to panels e and f.

Table 2
Summary of the soil moisture patterns observed in the Tarrawarra 1, Tarrawarra 1 and 2, Point Nepean, Satellite Station, Carran's and Clayden's sites

Site	Date	Antecedent rainfall (10 days, mm)	Sample size	Mean (%)	Variance (%^{2})	Coefficient of variation	Percentiles (%)	
							5th	95th
Tarrawarra 1	3 Jun 98	5	145	31.9	13.0	0.113	25.1	37.5
	7 Oct 98	24	146	35.3	22.8	0.135	27.1	41.2
	29 Oct 98	26	146	30.0	18.7	0.144	23.2	36.1
	14 Jan 99	11	143	19.9	4.2	0.102	16.4	23.0
	7 Apr 99	32	145	30.1	12.9	0.119	23.8	35.2
	15 Jul 99	2	147	35.2	12.8	0.102	27.7	39.2
	18 Aug 99	34	142	40.1	16.3	0.101	32.0	44.2
	7 Oct 99	17	145	29.5	15.2	0.132	21.3	34.6
Tarrawarra 1 and 2	3 Jun 98	5	471	31.3	13.6	0.118	25.0	36.9
	7 Oct 98	24	465	33.5	33.6	0.173	20.5	41.0
	29 Oct 98	26	473	28.7	17.7	0.147	21.8	35.4
	14 Jan 99	11	469	19.1	5.9	0.127	15.7	23.6
	7 Apr 99	32	471	29.5	18.4	0.146	22.6	35.8
	15 Jul 99	2	470	34.4	14.4	0.110	27.7	39.6
	18 Aug 99	34	467	38.8	16.6	0.105	32.1	44.0
	7 Oct 99	17	468	28.7	13.8	0.129	22.4	34.4
Point Nepean	16 Jul 98	37	588	17.1	9.6	0.181	13.4	23.1
	4 Nov 98	11	589	8.0	7.4	0.339	5.1	13.0
	19 Jan 99	11	589	7.4	6.5	0.344	4.5	11.3
	13 Apr 99	6	589	5.8	4.3	0.358	3.2	9.0
	5 Aug 99	5	589	12.1	9.6	0.257	8.1	18.5
	11 Oct 99	37	589	11.6	13.4	0.316	6.4	18.1
Satellite Station	26 Mar 98	11	358	32.4	43.2	0.202	23.9	45.1
	13 Aug 98	112	366	46.3	25.3	0.109	40.2	55.0
	23 Nov 98	23	377	33.2	41.2	0.193	25.1	45.9
	20 Feb 99	5	378	25.3	38.7	0.246	19.9	38.2
	7 May 99	84	372	42.1	18.1	0.101	35.3	49.4
	1 Nov 99	11	377	40.4	28.4	0.132	32.2	48.8
Carran's	1 Apr 98	7	485	39.2	11.1	0.085	34.3	44.9
	20 Aug 98	165	481	48.1	4.5	0.044	45.0	51.7
	30 Nov 98	43	485	47.2	5.0	0.048	43.9	50.8
	16 Feb 99	5	484	27.3	6.2	0.091	23.6	31.3
	14 May 99	11	485	40.2	5.3	0.057	36.8	44.0
	8 Nov 99	158	485	43.0	4.5	0.049	39.6	46.7
Clayden's	30 Mar 98	7	280	39.8	19.9	0.112	33.9	47.4
	17 Aug 98	161	265	47.7	4.2	0.043	44.3	50.9
	26 Nov 98	40	279	43.7	7.7	0.064	39.5	47.8
	12 Feb 99	5	275	32.1	8.2	0.090	27.7	37.1
	10 May 99	95	267	42.8	7.0	0.062	38.8	47.6
	5 Nov 99	163	276	46.1	4.0	0.044	42.7	49.0

most sample variograms indicate that the soil moisture field is stationary since they reach a plateau. An exponential variogram model with a nugget provides a good match to the shape of the sample variograms and therefore can be used as a reliable estimator of the characteristics of the measured field. Satellite Station, Carran's and Clayden's are also approximately stationary although not as close to

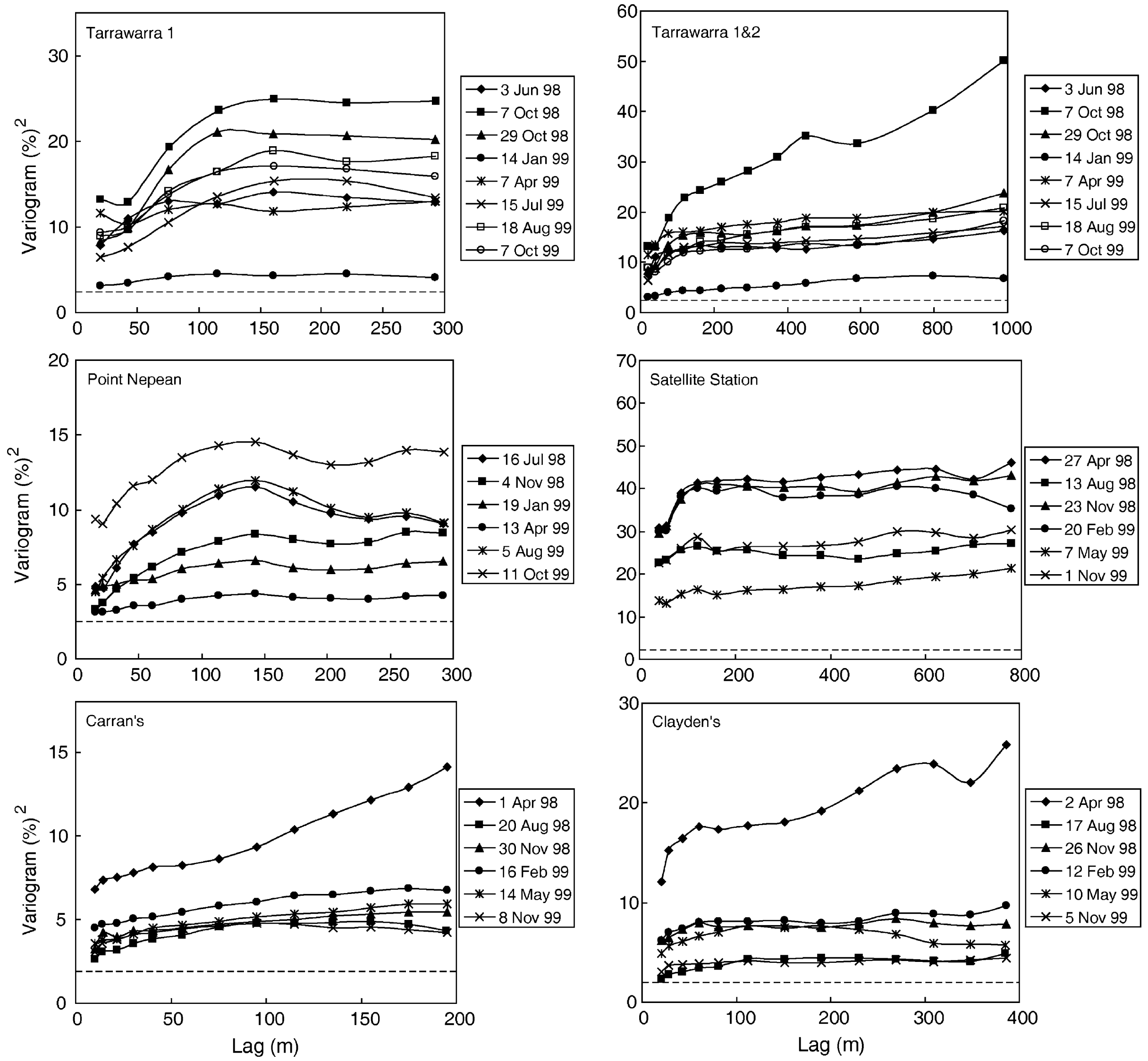


Fig. 5. Sample omnidirectional variograms for the soil moisture patterns from Tarrawarra 1, Tarrawarra 1 and 2, Point Nepean, Satellite Station, Carran's and Clayden's catchments. The dashed line indicates our estimate of measurement error variance.

exponential as the other sites. The sample variograms for the soil moisture patterns of 7 October 1998 for the Tarrawarra 1 and 2, and the April 1998 patterns at Carran's and Clayden's sites show a much greater variance than the other surveys at the respective sites, and they tend to be nonstationary. Some other sample variograms for Tarrawarra 1 and 2 also exhibit weakly nonstationary characteristics. However, for the purpose of comparison among the sites, an exponential variogram model with a nugget was adopted for all the soil moisture patterns.

4.2. Model fitting to the sample variograms

To quantify the geostatistical structure of the soil moisture patterns, the exponential model was fitted to

Table 3
Summary of the geostatistical structure of the soil moisture patterns from the Tarrawarra 1, Tarrawarra 1 and 2, Point Nepean, Satellite Station, Carran's and Clayden's catchments

Site	Date	Nugget (%^{2})	Sill (%^{2})	Correlation length (m)	RMSE (%^{2})
Tarrawarra 1	3 Jun 98	1.2	13.3	25	0.41
	7 Oct 98	2.0	25.0	50	1.72
	29 Oct 98	0.3	21.1	50	1.31
	14 Jan 99	1.9	4.4	35	0.17
	7 Apr 99	5.0	12.5	35	1.30
	15 Jul 99	2.3	15.1	63	0.94
	18 Aug 99	4.4	18.8	67	0.88
	7 Oct 99	5.0	17.0	55	0.81
Tarrawarra 1 and 2	3 Jun 98	4.2	13.6	38	0.98
	7 Oct 98	3.0	35.0	120	5.27
	29 Oct 98	3.0	17.0	60	2.25
	14 Jan 99	2.9	7.1	330	0.31
	7 Apr 99	7.0	18.0	50	1.10
	15 Jul 99	4.1	15.0	77	0.86
	18 Aug 99	5.0	18.0	140	1.23
	7 Oct 99	5.0	13.5	80	1.62
Point Nepean	16 Jul 98	0.4	10.1	32	0.74
	4 Nov 98	1.3	8.3	48	0.25
	19 Jan 99	3.9	6.3	48	0.22
	13 Apr 99	2.6	4.2	48	0.13
	5 Aug 99	0.5	10.4	31	0.81
	11 Oct 99	6.2	13.8	37	0.51
Satellite	26 Mar 98	5.0	43.6	45	1.49
	13 Aug 98	4.9	25.4	21	1.06
	23 Nov 98	7.5	41.3	41	1.15
	20 Feb 99	1.5	39.0	31	1.64
	7 May 99	8.0	17.0	60	1.76
	1 Nov 99	13.0	28.0	45	1.42
Carran's	1 Apr 98	5.1	12.4	65	0.99
	20 Aug 98	2.0	4.8	34	0.16
	30 Nov 98	3.4	5.4	62	0.19
	16 Feb 99	4.0	6.9	65	0.13
	14 May 99	3.1	5.9	65	0.11
	8 Nov 99	1.9	4.5	17	0.14
Clayden's	1 Apr 98	3.0	20.0	25	1.98
	17 Aug 98	1.3	4.4	49	0.12
	26 Nov 98	3.1	7.9	20	0.26
	12 Feb 99	4.2	8.4	29	0.29
	10 May 99	2.0	7.1	24	0.46
	5 Nov 99	0.1	4.1	14	0.10

the sample variograms. Table 3 provides a summary of the fitted model parameters for each soil moisture pattern of the five catchments. The sills are close to the estimated variance of the respective pattern. Fig. 6 depicts the model fit to the sample variograms for some representative soil moisture patterns. As noted above the exponential model may be inappropriate for Tarrawarra 1 and 2.

The seasonal evolution of the geostatistical structure is shown in Fig. 7. In Fig. 7a the spatial mean

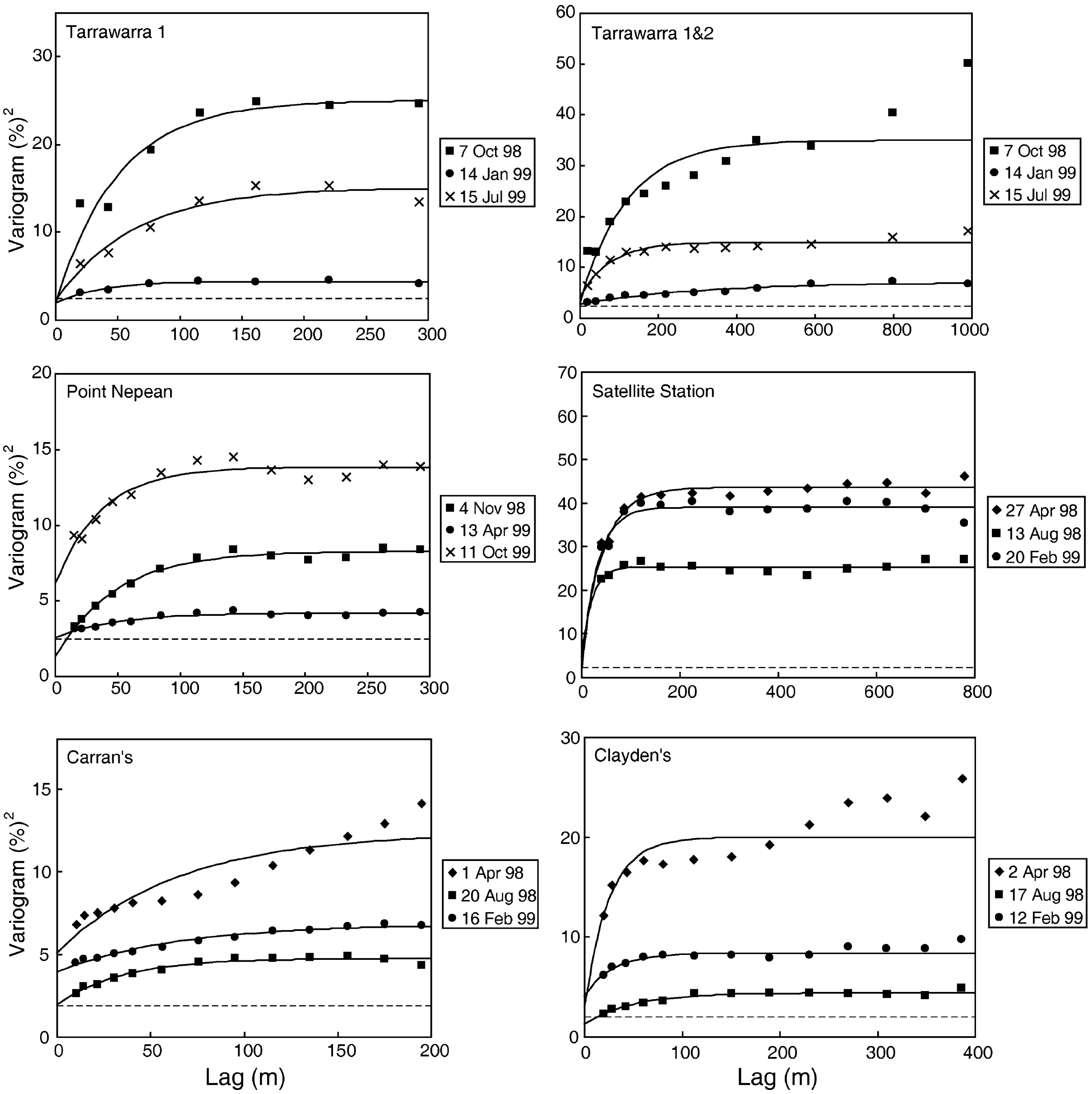


Fig. 6. Exponential variograms (solid lines) with a nugget fitted to the sample variograms (solid circles) for the representative soil moisture patterns from Tarrawarra 1, Tarrawarra 1 and 2, Point Nepean, Satellite Station, Carran's and Clayden's catchments. See Eq. (3) and Table 3 for the formula and parameters of these lines.

moisture content is shown for each sampling occasion. The means vary between 19 and 40% for Tarrawarra (both 1 and 1 and 2), 5 and 20% for Point Nepean, and between 25 and 50% for Satellite, Carran's and Clayden's. They all tend to be wet in winter and dry in summer, with this seasonal trend being strongest in the Australian catchments due to a seasonal switch between dominance of rainfall and potential evapotranspiration depths, whereas there is substantially more rainfall than potential

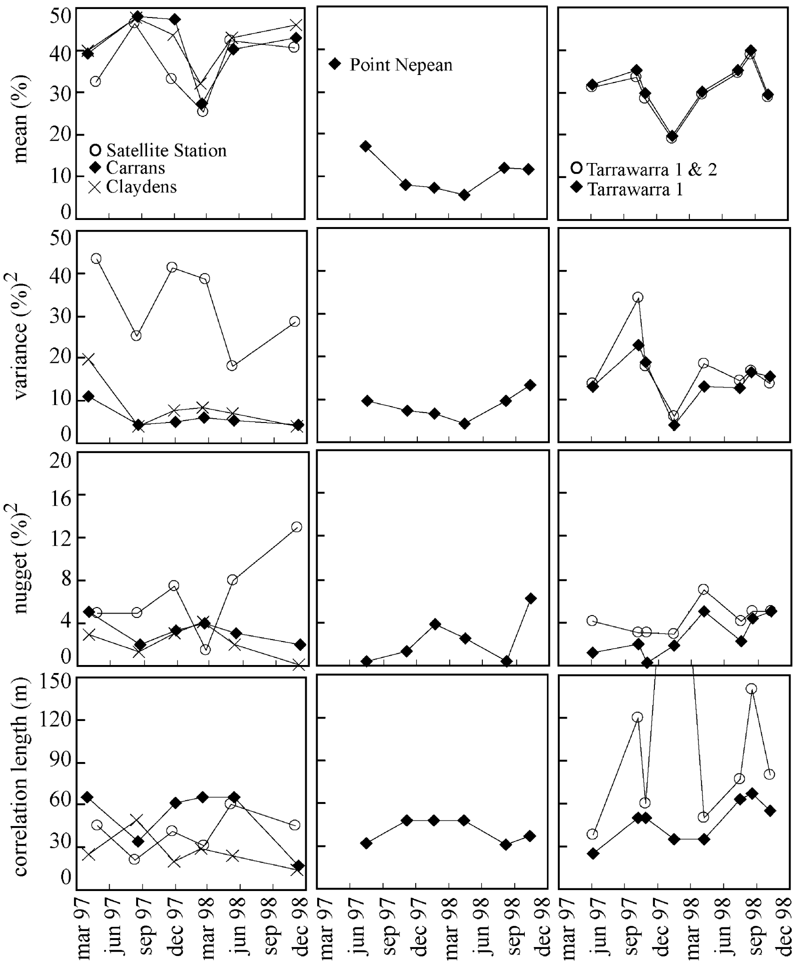


Fig. 7. Time series of (a) mean soil moisture, (b) spatial soil moisture variance, (c) correlation length and (d) nugget for the soil moisture patterns from Tarrawarra 1, Tarrawarra 1 and 2, Point Nepean, Satellite Station, Carran's and Clayden's catchments.

evapotranspiration at the New Zealand sites for all but 2 months of the year. The soil moisture in Point Nepean is substantially lower due to the well drained sandy soils at this site.

At the Tarrawarra catchment, the variance (and sill) varies between 4 and 34%^{2} and follows a clear seasonal trend in phase with the seasonal pattern of mean soil moisture (Grayson et al., 1997; Western et al., 1999). The variances at Satellite Station are persistently high and between 18 and 44%^{2}. Variance at Satellite Station increases as the catchment dries due to the presence of perennial source areas that are captured by the measurements. The variances range between 4 and 20%^{2} at Carran's and Clayden's, seasonal trends are not obvious but there is a weak tendency for the variance to reduce as the mean moisture increases. At Point Nepean variances tend to be low, they are positively related to mean moisture and they do exhibit a seasonal trend. The relationships between variance and mean moisture discussed above are illustrated in Fig. 8.

There is a seasonal trend of the correlation length at Tarrawarra 1 (Fig. 7). A similar seasonal trend is evident at Tarrawarra 1 and 2, although there is less seasonal consistency (due mainly to the very high correlation length on one occasion) and greater

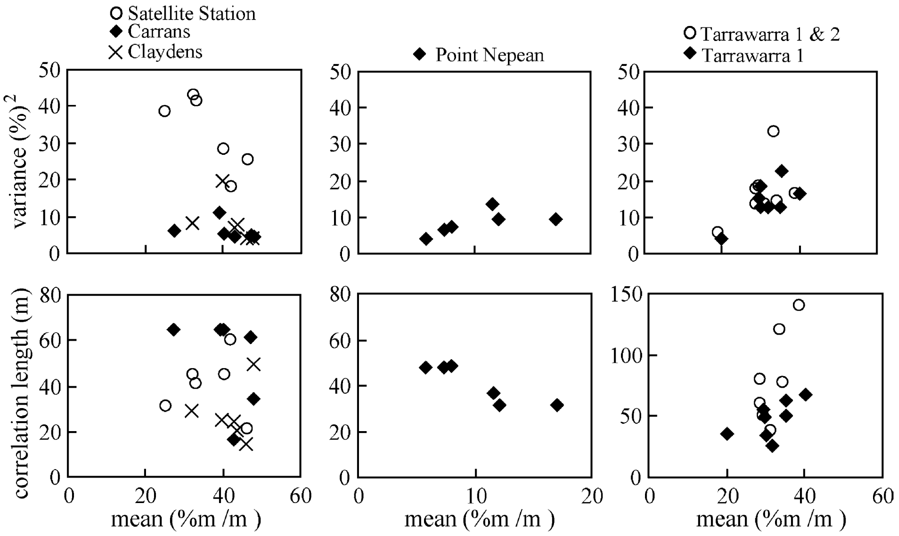


Fig. 8. Relationships of variance and correlation length to mean soil moisture for each study site.

variations in correlation length for the larger site. There is a tendency for correlation length to increase with increasing moisture content at Tarrawarra ($R^2 \approx 0.5$, Fig. 8). The variations in the correlation length do not follow a seasonal pattern at the three Mahurangi River sites and are not related to mean moisture content. Correlation lengths tend to be slightly longer under dry conditions at Point Nepean and there is a strong relationship between mean moisture and correlation length ($R^2 = 0.8$). In terms of temporal variability, correlation lengths are most consistent throughout the year at Point Nepean. Moderate temporal variability in correlation length is evident at Carran's and Clayden's, Satellite Station and Tarrawarra 1, whereas substantial deviations exist at Tarrawarra 1 and 2.

The variations in the nugget (Fig. 7) do not follow a seasonal pattern at any site and relationships to mean moisture are weak. There is a slight tendency for higher nuggets during wetter conditions in both the Tarrawarra catchment and at Satellite Station and for lower nuggets during wetter conditions at the other sites. The variation in the nugget is small compared to the variation in the sill at all sites. Large estimated nugget values at Satellite Station are related to grid size (40 m) compared to correlation length. Some soil moisture data for transects with a spacing of 4 m (Wilson, 2002) indicate that actual nuggets are close to those expected on the basis of measurement errors and that there is a rapid increase in moisture variability for ranges up to 10 m. This is not resolved by the grid data.

5. Geostatistical characteristics and process

In general we expect that soil moisture patterns at the small catchment scale would be influenced by spatial variations in topography, soils, vegetation and microclimate, as these affect the flow of water within the catchment and inputs and outputs of water. Topography is an obvious source of variability since it determines surface and to a lesser extent subsurface flow paths, as well as hydraulic gradients driving flow. Soils affect the flow of water through the hydraulic conductivity and water retention properties and they affect evapotranspiration via water retention properties. Vegetation, particularly rooting depth, surface cover, and the particular species water use characteristics affect evapotranspiration processes (including interception). Microclimate can affect both precipitation reaching the ground and evapotranspiration. To some extent these influences are interrelated. Soils, particularly soil depth, depend on topography as well as other factors such as the parent material. Vegetation grows better on more suitable soils and sometimes different species mixes occur on different soils or topographic aspects. Microclimate is affected by topography, which modulates radiation input, among other factors.

All of these influences will have an impact on the soil moisture pattern but some will be more important than others in a particular setting. For example, we would expect the spatial patterns of wilting point and possibly soil depth to be important during dry conditions. Under saturated conditions, the spatial pattern of soil porosity will be important. During relatively wet conditions we might expect that the pattern of topographic convergence combined with soil depth and hydraulic conductivity would be important. Which of these three is the most important depends on their relative spatial variability and how this variability affects processes. While we might expect some relationships between all these influences, those relationships are often weak and there is little reason to assume that they would have the same characteristic spatial scales. Thus we might expect differences in the geostatistical structure of the soil moisture patterns that are related to differences in the geostatistical structure of the dominant spatial controls on the soil pattern. These controls may change seasonally or with moisture condition (Grayson et al., 1997).

Here we explore this possibility. Initially we establish that the statistical structure of the soil moisture patterns is consistent for consistent catchment conditions by comparing variograms for Tarrawarra 1 from Western et al. (1998) and this study. Then we compare soil moisture variograms and the seasonal evolution of the variance and correlation length between sites. Finally we compare soil moisture variograms with variograms of two topographic indices. The topographic indices were chosen to represent topographic convergence that is likely to affect subsurface lateral flow, as well as slope-aspect effects on the radiation microclimate. The topography is chosen as a convenient reference here for pragmatic reasons of data availability. The effects of spatial patterns of soils are considered qualitatively below.

It is interesting to compare results at Tarrawarra 1 with the results of Western et al. (1998) at this site. The sample variograms for patterns collected during the recent study (1998 and 1999) are very similar to those collected earlier. For example the conditions (mean moisture, stage in seasonal moisture cycle) for the pattern variogram for 7 October 1998 closely match those on 27 September 1995 and the two dates have similar variograms (Fig. 9). Both the catchment conditions and variograms for 14 January 1999 and 23 February 1995 are also similar. There are greater differences between variograms for 15 July 1999 and 13 April 1995, which have similar mean moisture contents but are at different stages in the seasonal moisture cycle. The same comments apply for variograms for 18 August 1999 and 2 May 1996. Overall there is a high degree of similarity between variograms from these two studies, when catchment conditions are similar. This results from similarities in the underlying processes controlling the soil moisture patterns and demonstrates that a particular catchment operates in a similar way in every year. The implication of this is that calibrated hydrological models are likely to work for different periods on the same catchment because of the similarities (assuming consistent landuse and management). However, transposition to other catchments is difficult because catchment to catchment differences are much larger, as we show below.

The sample variograms are similar between sites in terms of overall shape, but there are differences in terms particularly of sill and correlation length. Sills (and variances) are lowest at Point Nepean, Carran's and Clayden's. Tarrawarra has intermediate sills and

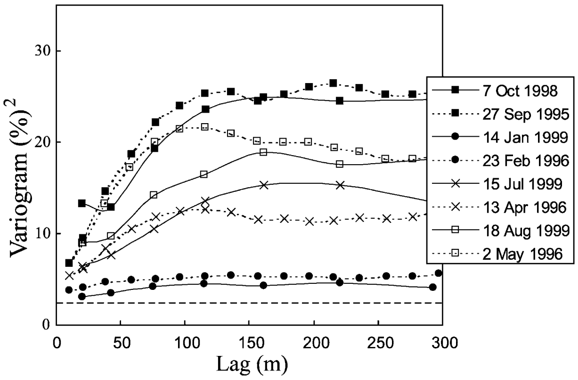


Fig. 9. Comparison of variograms from Western et al. (1998) (dotted lines) and this study (solid lines) for similar conditions at Tarrawarra 1.

Satellite Station has high sills. Correlation lengths are fairly consistent everywhere except Tarrawarra 1 and 2, although Carran's tends to be slightly longer and Clayden's slightly shorter. At Tarrawarra 1 and 2 correlation lengths are about twice the other sites. This is partly an influence of the weak nonstationarity at Tarrawarra 1 and 2 and its effect on the fitted correlation length, which is partly due to a large-scale variation in aspect and probably soils at this site. The estimated correlation lengths are not related to the size of the field sites.

The soil moisture variance (and variogram sill) tends to be related to mean soil moisture but variance increases with increasing soil moisture at the Australian sites and decreases at the New Zealand sites. This is partly related to differences in meteorological forcing between the sites and partly to differences in soil properties. The MARVEX catchments have high rainfall compared with potential evapotranspiration and a much less pronounced summer soil moisture drought. Thus the catchments tend to be quite wet all the time. The both Australian catchments experience pronounced drying during summer. This is more pronounced and extends through most of the two winter periods during this study due to the study period coinciding with an extended drought period in the Melbourne region. This means that the Australian catchments tended to be quite dry. A study of the relationships between spatial mean and variance of soil moisture based on a wide range of published data is underway and has found that as mean moisture increases from low to high, spatial variance tends to first increase before reaching a peak at moderate levels of mean soil moisture and then to decrease as conditions become wet (Western et al., 2001b, 2002). This is similar to the behaviour observed in this study.

The correlation length for the soil moisture fields is related to mean moisture for the Australian catchments but not the New Zealand catchments. This may also be related to differences in meteorological forcing which are likely to lead to greater contrasts in controlling processes (especially temporal changes in the influence of local and upslope processes (Grayson et al., 1997)) for the Australian catchments than for the New Zealand catchments. The differences in the seasonal patterns of relative importance of evaporative demand and rainfall are clear in Fig. 3 where a seasonal climatic aridity index is shown. The accumulated excess of evapotranspiration over precipitation in summer completely dries the soil store at Tarrawarra for a significant period of time, leading to ephemeral lateral flow systems, ephemeral discharge zones, and the observed changes in both moisture variability and correlation length seasonally.

In the Mahurangi catchments, the summer is much wetter and discharge areas at the bottoms of the hillslopes remain active, particularly at Satellite Station where our measurement area extended further down the drainage network. As a consequence the basic characteristics and correlation lengths of the soil moisture patterns do not change, although the soil moisture variability increases as the areas remote from the perennial discharge zones dry. While the climate can certainly explain these differences, it should be noted that the gradational soil profile in the Mahurangi may lead to deeper lateral flow paths than the duplex soils at Tarrawarra and this may also contribute to the perennial nature of the discharge zones in the Mahurangi.

Soil moisture processes at Tarrawarra are strongly influenced by terrain during certain parts of the year (Western et al., 1999, 2001a; Western and Grayson, 2000). Terrain is also important at some of the other sites. Fig. 10 shows variograms of various terrain attributes for the six sites. The variogram values have been normalised by dividing by the variance. Comparing Fig. 10 with the soil moisture variograms in Fig. 5 enables the link between terrain and soil moisture patterns to be explored. At Tarrawarra 1, 1 and 2 and Carran's, the ranges for the topographic wetness index and slope are about 150 m and the soil moisture variograms have similar ranges to this on most occasions. At Tarrawarra 1 and 2 the soil moisture variogram for 7 October 1998 exhibits some strong similarities with the variogram for the potential solar radiation index for this occasion. In particular both variograms have quite sharp reductions in slope that occur at lags of about 150 and 450 m. This occasion is during the spring drydown when the spatial pattern of radiation is expected to have the greatest influence. At Tarrawarra 1 the potential solar radiation index has a slightly longer range than the topographic wetness index and the soil moisture

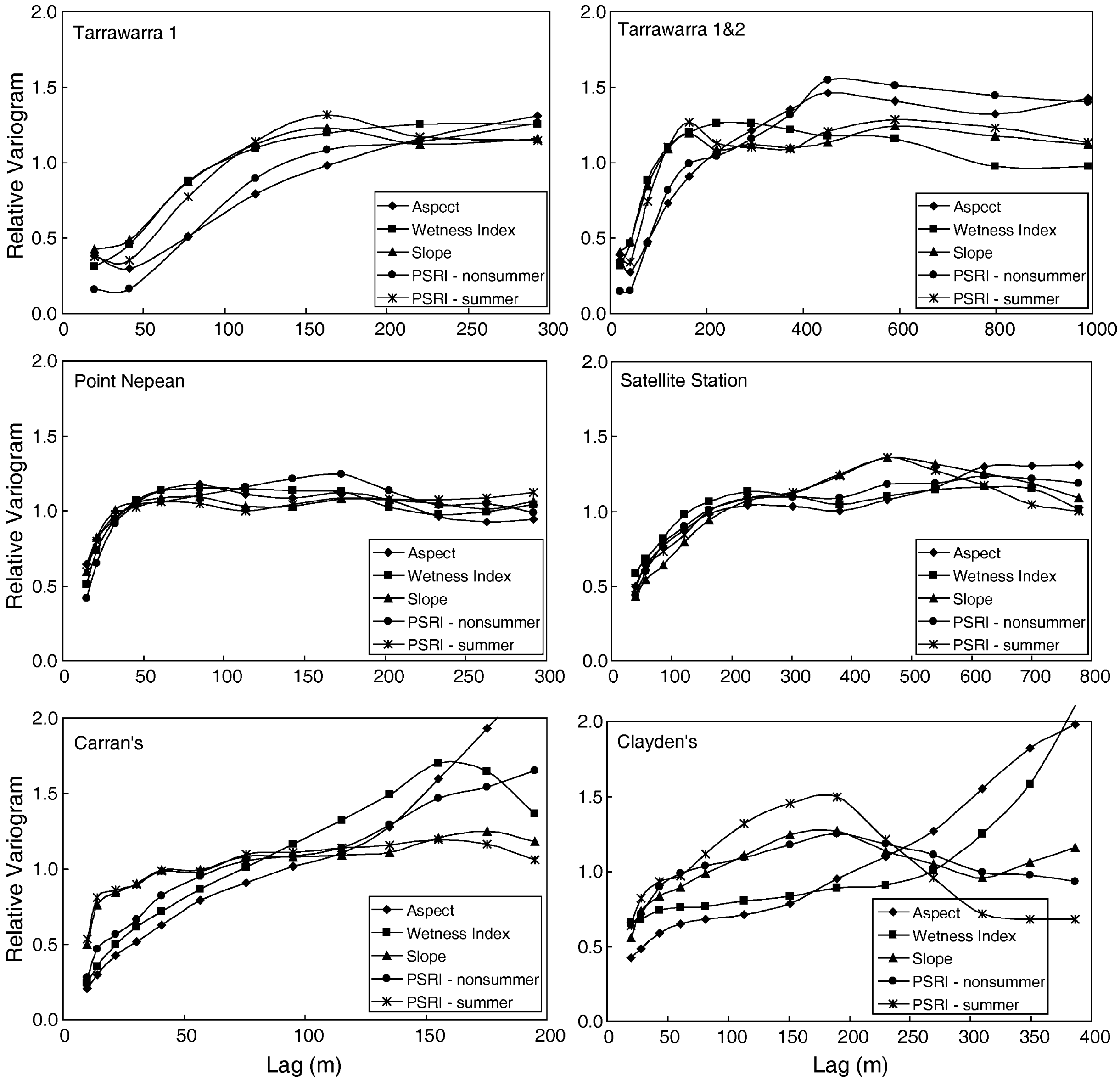


Fig. 10. Relative variograms for aspect, slope, topographic wetness index [ln(a/tan(β))], and potential solar radiation index (PSRI) for December–January (summer) and for the remainder of the year (nonsummer).

variogram for this time (7 October 1998) also has a slightly longer range than for other occasions. At Carran's and Clayden's the shape of the potential solar radiation index variograms and soil moisture variograms are quite similar for 7 April 1999, which is at the end of summer. Other differences in variograms at Tarrawarra 1 and Tarrawarra 1 and 2 appear to be linked to differences in the scales of variation of topography at these sites.

At Satellite Station, the terrain variograms have a range of about 200 m, which is about twice the range of the soil moisture variograms. Satellite Station is the most variable site (Fig. 5) and this variation occurs at quite small scales, as evidenced by the high variability at the grid (40 m) scale. These results indicate that there are processes operating at scales smaller than the topography that are leading to significant variability in the soil moisture field. Transect data with 4 m spacing indicate that much of this small-scale variability is occurring at sub 10 m scales. Visual inspection of the vegetation at Satellite Station indicated that it was quite uniform at the field scale so it is unlikely that vegetation is causing this small-scale variation. It is likely that this small-scale variability is associated with the soils. Significant pipe erosion at Satellite Station may be influencing the soil moisture pattern, or the existence of other preferred flow pathways may be leading to both the high overall variability and to the large small-scale variability. There is also some evidence of pipe erosion at Carran's and Clayden's; however, at these sites it tends to be more closely associated with surface drainage features in the terrain. There is also a marked difference in the soil textures (Table 1) for the soils at Satellite Station compared with those at Carran's and Clayden's. These differences will almost certainly lead to differences in soil matrix hydraulic properties and perhaps more importantly soil structure and macroporosity. These differences may help explain the difference between the behaviour of these three sites in the Mahurangi River catchment. The topographic variability at Point Nepean occurs over quite short spatial scales (range ≈ 50 m) (Fig. 10). In contrast, the soil moisture varies over longer distances (Fig. 4). One would expect very limited terrain influence at this site due to the deep, well drained sandy soils occurring there. However, there is a larger scale variation in soil texture and colour observable in the field. This is associated with two areas of shallower regolith where the underlying limestone comes close to outcropping and there is a greater percentage of fine material (15–25% silt and clay compared with 4% in the deeper soil areas) in the soil, which also has a much darker colour indicating that organic matter content is likely to be higher. Both finer texture and higher organic matter content would be expected to lead to greater water retention and would explain the temporal consistency in the observed patterns, their variograms (Fig. 5) and correlation lengths (Fig. 8). The wettest and driest patterns measured at Point Nepean are shown in Fig. 4, with two wetter areas being evident in both patterns. It is this influence of the spatial distribution of soils that leads to the longer correlation lengths for the soil moisture. Seyfried (1998) and Kim and Barros (2002) have found a similar dependence of moisture variation on soil type, albeit at larger scales.

Fig. 11 shows correlation lengths for the soil moisture patterns plotted against correlation lengths for the topographic wetness index and the potential solar radiation index for the day of the sampling. In general the scatter in the soil moisture correlation lengths spans the 1:1 line for both the topographic wetness index and potential solar radiation index, except for Point Nepean and Satellite Station. At

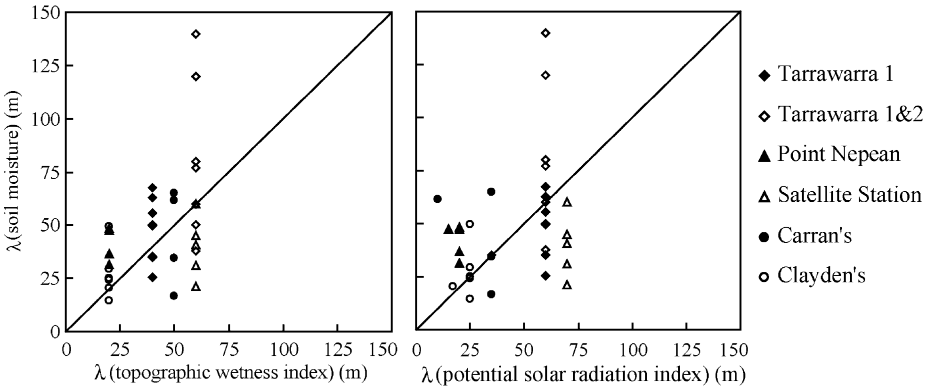


Fig. 11. Relationships between correlations lengths for (a) topographic wetness index and soil moisture and (b) potential solar radiation index and soil moisture.

Satellite Station the moisture correlation length is consistently shorter than the correlation lengths for both the terrain indices, while at Point Nepean it is consistently longer. This further illustrates the roles of small-scale processes (compared with terrain) at Satellite Station and the larger-scale soils, variability at Point Nepean.

6. Conclusions

In this paper we characterised the geostatistical behaviour of soil moisture at several small humid and subhumid catchments. This was done using data measured in a consistent way with TDR for scales up to 1 km. In nearly all cases the soil moisture patterns were stationary. Typical correlation scales lie between 30 and 60 m.

The spatial variance and, to a lesser extent, the correlation length were found to be related to mean soil moisture. We were able to identify differences in the spatial variability and correlation scales both between different sites and within sites at different times. Differences in variability were systematically related to spatial mean soil moisture but these relationships varied between sites. In particular, in the wetter New Zealand catchments variability decreased with increasing moisture content, whereas it increased in the drier Australian catchments. These differences in behaviour are related to differences in the seasonal patterns of controlling processes associated with seasonal changes in spatial mean soil moisture, particularly the lateral flow processes, which are related to climatic differences.

By comparing the soil moisture correlation lengths with the spatial correlation of terrain attributes, we were able to identify sites where the spatial scales of the soil moisture variation are similar to the topography. Here it is inferred that the topography plays an important role in controlling the soil moisture variation in space. At other sites (Satellite Station and Point Nepean) the spatial scales of the soil moisture variability were quite different to those of the topography and it is inferred that variations in soil properties play an important role in controlling the scales of the soil moisture variability there.

There are a number of implications for hydrological measurements and modelling in general. If we are interested in spatial patterns, we need to consider controlling processes and to recognise that these can change between places. Soil characteristics and climate do provide a general pointer to what we might expect but there are subtleties such as those illustrated by the behaviour of Satellite Station. The controlling processes can also change as catchment conditions change. However, our results do suggest that when similar conditions (e.g. spatial mean moisture and time of year) recur within a catchment, then similar patterns result.

Acknowledgements

Funding for this work was obtained from the Australian Research Council (Projects A39801842 and C39804872), the Cooperative Research Centre for Catchment Hydrology, the Austrian Academy of Sciences (Project HÖ18) and the New Zealand National Institute for Water and Atmospheric Research (NIWA). The cooperation of Ted Bradnam, Harvey Carran, Ross Clayden, The Cistercian Monks (Tarrawarra), and Gordon Storey in providing access to their land for the field studies is much appreciated. Rodger Young assisted with data collection and management.

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