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Spatial variability of soil moisture content and its relation to environmental indices in a semi-arid gully catchment of the Loess Plateau, China

Yang Qiu*†, Bojie Fu*‡, Jun Wang§ & Liding Chen*

* *Department of Systems Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, P.O. Box 2871, Beijing 100085, China*
† *Department of Resources and Environmental Sciences, Beijing Normal University, Beijing 100875, China*
§ *Land Consolidation and Rehabilitation Center, Ministry of Land and Resources, Beijing 100035, China*

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The degree of spatial variability of soil moisture and the ability of environmental attributes to predict that variability were studied at the Da Nangou catchment (3·5 km^2) in the semi-arid loess area of China. Soil moisture measurements were performed biweekly at five depths in the soil profile (0–5 cm, 10–15 cm, 20–25 cm, 40–45 cm and 70–75 cm) from May to October 1998 and from May to September 1999 using Delta-T theta probe. Results indicated that with increasing soil depth, the mean soil moisture content increases significantly for five layers and the coefficients of variation (CV) also increases with depth from 10–15 cm. It was observed that heavier rains and higher mean moisture contents are often associated with lower spatial variability (CV). Environmental attributes such as land use and topography play controlling roles in the spatial distribution of soil moisture content. However, the relative roles of these environmental indices vary with soil depth. The dominant controls on spatial variability of the time-averaged soil moisture changes from land use, aspect, relative elevation and hillslope position in the surface soil (0–5 cm) to relative elevation, hillslope position and aspect in the subsurface soil (10–15 cm, 20–25 cm), and to land use, relative elevation and slope gradient at larger depths (40–45 cm, 70–75 cm). The dynamic behavior of influences of different environmental indices on the layer-averaged soil moisture depends on several factors. In general, the correlation of soil moisture with slope gradient shows a more significant increase following a greater amount of antecedent precipitation (except for the extremely heavy storms), and declines afterwards. The relation of soil moisture with relative elevation and hillslope position exhibits an opposite trend. It was observed that the influence of land use corresponds to the difference in vegetative characteristics, with a stronger influence in June and August with a greater difference in vegetation. A significant influence of cos(aspect) was found during early spring and autumn with a rapid transient in solar irradiation. Finally, it was found that the sample size is adequate to estimate the catchment mean soil

‡ Corresponding author. Fax: + 86-10-62943840. E-mail: bfu@mail.rcees.ac.cn

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moisture at all five depths and on all 10 observations in 1999 (81 sites), while it is only enough for the upper soil layers (0–5 cm and 10–15 cm) in 1998 (26 sites).

Keywords: Loess Plateau of China; soil moisture content; spatial variability; land use; topography; precipitation

Introduction

Spatial variation of soil moisture content is a necessary and preliminary part for parametric soil and land survey (McKenzie & Austin, 1993), spatial prediction of soil moisture (Ladson & Moore, 1992; Grayson & Western, 1998; Lark, 1999; McKenzie & Ryan, 1999), soil and land evaluation for sustainable use (Fu, 1991; Fu & Gulinck, 1994; Fu *et al.*, 2000), specific farm planning and management (Odeh *et al.*, 1994; Lark, 1999), hydrologic modelling and watershed management (Henninger *et al.*, 1976; Fu, 1989; Fu *et al.*, 1994; Jordan, 1994; Western & Grayson, 1998) and climate models (Robock *et al.*, 1998).

Soil moisture content can vary in deterministic or stochastic ways or in a combination of the two (Seyfried & Wilcox, 1995; Western *et al.*, 1999). Stochastic variability is random referring to variability that is not predictable in detail but that has predictable statistical properties. Deterministic variability has also been labeled systematic and organizational. It conveys that variability is known. This may be expressed in the form of a map or mathematical relationship with spatial data, such as topography or land use type.

Terrain indices aim to represent the key hydrological processes controlling the spatial distribution of soil moisture in a simplified but realistic way. The initial aim using terrain indices is to obtain a lumped estimate of the contributing area (Beven & Kirby, 1979). Terrain indices are increasingly used to provide antecedent moisture patterns for event models (Grayson *et al.*, 1992) and to generate soil moisture maps to aid in land evaluation and land use (Fu & Gulinck, 1994; Fu *et al.*, 2000).

Land use, an alternative attribute that is easily obtained, also plays an important role in controlling spatial patterns of soil moisture by influencing the infiltration, runoff and evapotransipiration, particularly during the growth season (Reynolds, 1970*c*; Ng & Miller, 1980; Hawley *et al.*, 1983; Francis *et al.*, 1986; Fu *et al.*, 1994; Fu & Gulinck, 1994; Fu & Chen, 2000; Fu *et al.*, 2000). The difference in transpiration of vegetation resulting from land use can eliminate the effects of topography (i.e. aspect) (Ng & Miller, 1980). Thus, knowledge of the land use can improve the extent of the prediction power of environmental indices.

Soil moisture can vary at catchment scale vegetation (Vinnikov *et al.*, 1996). The relationships between soil moisture and environmental attributes at this small catchment scale were found to be very variable by Famiglietti *et al.* (1998). In some cases there is a significant relation but in many other cases the relationship is insignificant (Krumbach, 1959; Hills & Reynolds, 1969; Reynolds, 1970*a*, *b*, *c*; Reid, 1973; Henninger *et al.*, 1976; Beven & Kirby, 1979; Bell *et al.*, 1980; Hawley *et al.*, 1983; Burt & Butcher 1985; Francis *et al.*, 1985; Moore *et al.*, 1988; Charpentier & Groffman, 1992; Ladson & Moore, 1992; Niemann & Edgell, 1993; Robinson & Dean, 1993; Jordan, 1994; Nyberg, 1996; Crave & Gascuel-Odoux, 1997; Famiglietti *et al.*, 1998; Western *et al.*, 1999). This may be due to differences in climate, topography, soil, vegetation, scale, time and depth of sampling methods (Famiglietti *et al.*, 1998). Thus relationships between soil moisture and environmental factors need to be studied in a variety of places and over a large range of scales.

It may be limited to estimate the catchment mean soil moisture using a small number of sampling sites (Owe *et al.*, 1982). One solution is high-resolution observation of soil moisture patterns based on a large number of site samples, but this is too expensive and is not possible in some circumstances. Thus, to test the sampling intensity required to represent the mean soil moisture across the watershed, the minimum sample size has to be determined (Owe *et al.*, 1982; Seyfried, 1998).

Therefore, the objectives of this paper are (1) to characterize the mean and coefficient of variation (CV) of the soil moisture content on catchment scale, the distribution in the soil profile and the dynamic behavior of these variables; (2) to test the minimum sample size; (3) to understand the relative roles of land use and topographic attributes in controlling the observed spatial variability of the soil moisture, the distribution in the soil profile and the dynamic behavior of the influences of these environmental indices.

Material and methods

Description of study area

The Da Nangou catchment (36°53′N; 109°17′E) is situated on the middle part of the Loess Plateau in northern Shaanxi province, China. The catchment has an area of 3·5 km^2 and altitude is between 1000 and 1350 m. There is significant topographic variability with typical loess hills and gully slope shapes within the study area. Due to long-term human activity, natural vegetation has been destroyed. Land use types are cropland, fallow land, wasteland, shrub land, orchard, intercropping land and woodland. Fallow land slowly came into being after cultivated plots were abandoned two and three years ago. Wasteland has never been used as cropland. The main types of plant and the typical profile distribution of plant root density on different types of land use are given in Tables 1 and 2 (Zhao *et al.*, 2000). The plant cover and leaf area index (LAI, %) of plant on different types of land use were investigated for 17 plots distributed across the catchment in 1999 as shown in Tables 3 and 4 (unpublished data obtained from Dr Wu Yongqiu, Beijing Normal University, China).

The region has a semiarid continental climate with an average annual temperature of 8·8°C, and monthly mean temperatures range from 22·5°C in July − 7°C in January. The average annual precipitation is 562 mm with great interannual variability and 60% of the rain falls between July and September. There are 159 frost-free days and an average of 2415 h of sunshine each year.

Table 1. *Main types of plant on different types of land use*

Land use types	Main types of plant
Shrubland	Littleleaf peashrub (*Caragana microphylla*)
Woodland	Locust tree (*Robinia pseudoacacia* L.)
Orchard	Apple tree (*Malus pumila mill*)
Intercroping land	Apple tree (*Malus pumila mill*), Potato (*Solanum tuberosum*)
Wasteland	Small shrubs and grasses, such as Sweet wormwood (*Artemisia annua* L.), Annual fleabane (*Erigeron annuus* Pers.), Sandy needle grass (*Stipa glareosa p.* Smirn)
Fallow land	Annual grass
Cropland	Potato (*Solanum tuberosum*), Bean (*Phaseolus valgaris*), Maize (*Zea mays* L.), Miller (*Panicum miliaceum*)

Table 2. *Typical profile distribution of plant root density (%) on different types of land use (Zhao et al., 2000)*

Land use types	Shrub land	Woodland	Orchard	Intercropping land	Wasteland	Fallow land	Cropland	Mean	Standard deviation
0–10 cm	15	13	4	6	13	8	4	9·0	4·6
10–20 cm	18	13	15	16	13	13	16	14·9	2·0
20–30 cm	29	21	25	28	25	24	26	25·4	2·6
30–40 cm	35	8	28	40	48	29	10	28·3	14·8
40–50 cm	63	28	48	50	28	5	3	32·1	22·9
50–60 cm	67	55	37	35	6	1	0·5	28·8	26·9
60–70 cm	70	81	37	38	4	2	0·5	33·2	33·1
70–80 cm	75	28	28	25	3	1	1	23·0	26·2
80–90 cm	20	11	5	3	1	1	1	6·0	7·1
90–100 cm	5	4	1	1	1	1	1	2·0	1·7
100–110 cm	2	3	1	0·1	0·1	0	0	0·9	1·2
110–120 cm	1	2	0	0	0	0	0	0·4	0·8
120–130 cm	1	0	0	0	0	0	0	0·1	0·4

Table 3. *Temporal dynamics of plant cover (%) on different types of land use in 1999 (from Dr Wu Yongqiu)*

Land use types	Shrub land	Woodland	Orchard	Intercropping land	Wasteland	Fallow land	Cropland	Mean	Standard deviation
2-May-99	20	55	5	5	12	5	0	14·51	18·96
13-May-99	20	55	5	5	12	5	0	14·54	18·94
23-May-99	20	55	5	5	12	5	0	14·54	18·94
10-Jun-99	40	70	14	15	19	5	0	23·30	24·15
23-Jun-99	45	70	18	20	19	20	7	28·30	21·70
12-Jul-99	50	75	20	20	24	23	11	31·82	22·55
18-Jul-99	55	80	25	25	29	30	14	36·85	22·73
2-Aug-99	55	100	30	45	34	35	26	46·30	25·65
10-Aug-99	55	108	30	50	34	35	29	48·58	27·85
9-Sep-99	50	88	28	50	30	35	28	44·02	21·46

Table 4. *Temporal dynamics of leaf area index (LAI, %) of plant on different types of land use in 1999 (from Dr Wu Yongqiu)*

Land use types	Shrub land	Woodland	Orchard	Intercropping land	Wasteland	Fallow land	Cropland	Mean	Standard deviation
2-May-99	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
13-May-99	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
23-May-99	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
10-Jun-99	1·50	1·85	0·15	0·20	0·18	0·00	0·00	0·55	0·78
23-Jun-99	1·60	1·86	0·40	0·50	0·58	0·40	0·04	0·77	0·68
12-Jul-99	1·75	2·09	0·60	0·70	0·88	0·60	0·14	0·97	0·70
18-Jul-99	2·00	2·30	0·85	1·00	1·08	1·00	0·32	1·22	0·69
2-Aug-99	3·00	3·25	1·25	1·50	1·35	1·30	0·58	1·75	0·99
10-Aug-99	3·10	3·75	1·90	2·50	1·55	1·50	0·61	2·13	1·06
9-Sep-99	1·50	2·70	1·41	2·00	1·25	1·30	0·56	1·53	0·67

The soils, developing on wind-accumulated loess parent material, are thick at an average of 50–80 m. No distinct B-horizon has developed. The most common soil in the catchment is loessial with silt content ranging from 64 to 73% and clay content varying from 17 to 20%. The soil is weakly resistant to erosion. The erosion rate is high at about 10,000–12,000 ton $km^{-2} yr^{-1}$ (Song *et al.*, 1989).

Sampling methods

In 1998, a total of 26 sample sites was selected for measuring soil water (Fig. 1). These sites were distributed throughout the catchment according to different topographic characteristics and land use (Qiu *et al.*, 2001).

In 1999, four adjacent hillslopes (67 sites) were selected to measure soil moisture content. This has logistic advantages (Qiu & Zhang, 1999), particularly in relation to survey time (Fig. 2). Most of the 67 sites in the four neighboring hillslopes are located in two adjacent sub-catchments (Fig. 2). Another group of sample sites (14 sites), like in 1998, spreads throughout the catchment (Fig. 2). As a consequence, a total of 81 sites were sampled (Fig. 2) in 1999.

Survey methods

Soil moisture measurement and calibration

Volumetric soil moisture was measured using a Delta-T theta probe (Eijkelkamp Agrisearch Equipment, Netherlands) based on time domain reflectometry (TDR). The

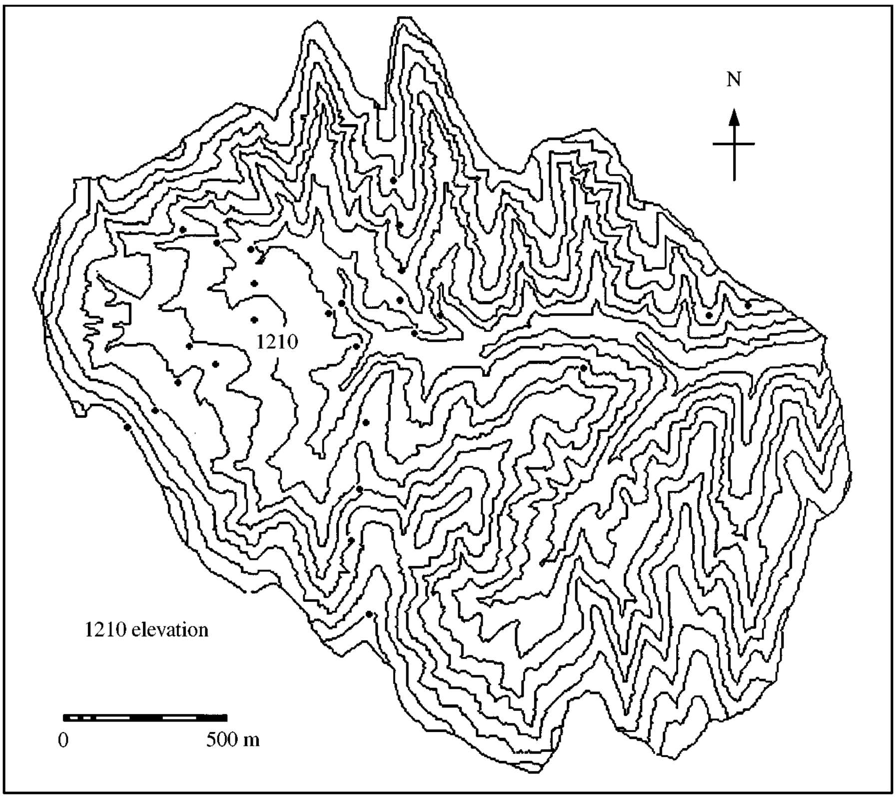

Figure 1. Spatial distribution of sampling sites (●) in 1998 at the Da Nangou catchment with the contour interval of 25 m.

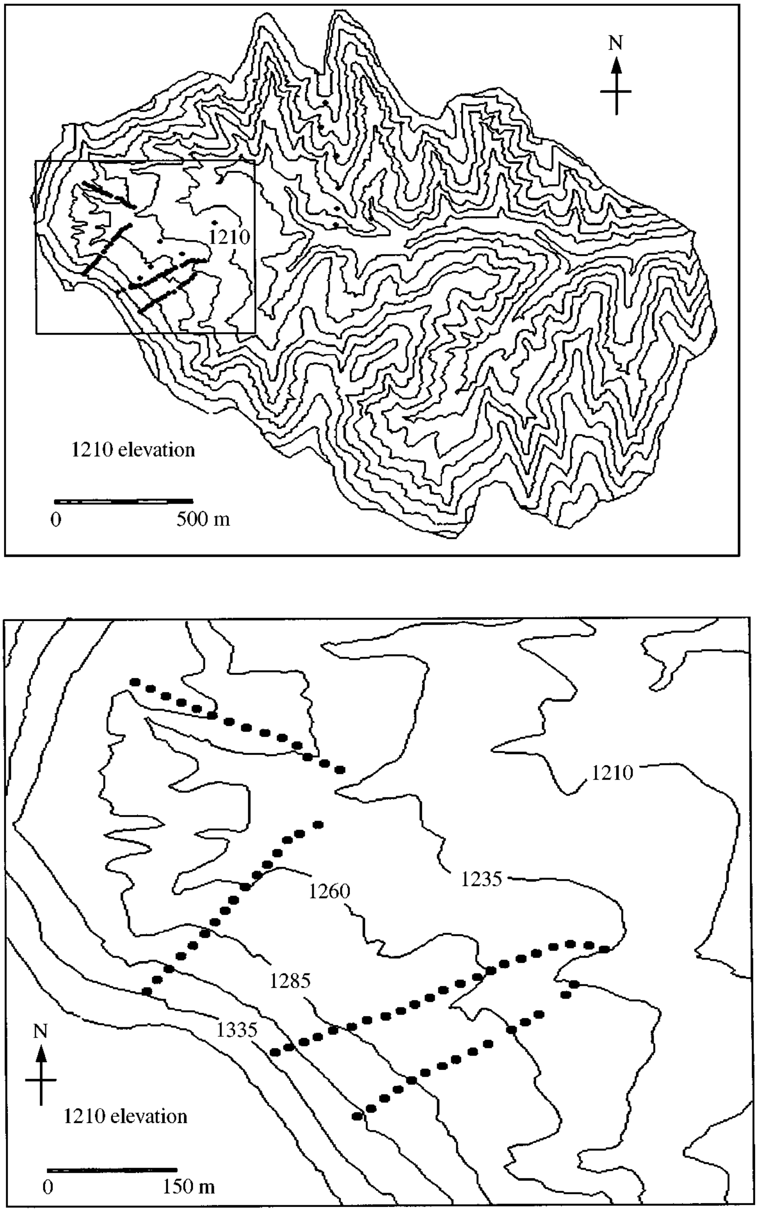

Figure 2. Spatial distribution of sampling sites (●) in 1999 at the Da Nangou catchment with the contour interval of 25 m.

measurements were performed at approximately biweekly intervals during the period May to October 1998 and May to September 1999, during the seasons of plant-growth and rainfall/runoff. At each sample site five measurements were performed to measure moisture content at five depths: 0–5, 10–15, 20–25, 40–45 and 70–75 cm. The mean of the five measurements is the soil moisture content at each depth on the sample site.

The Delta-T theta probe was calibrated by comparison with gravimetric water content measurements from saturated soil water content to permanent wilting point,

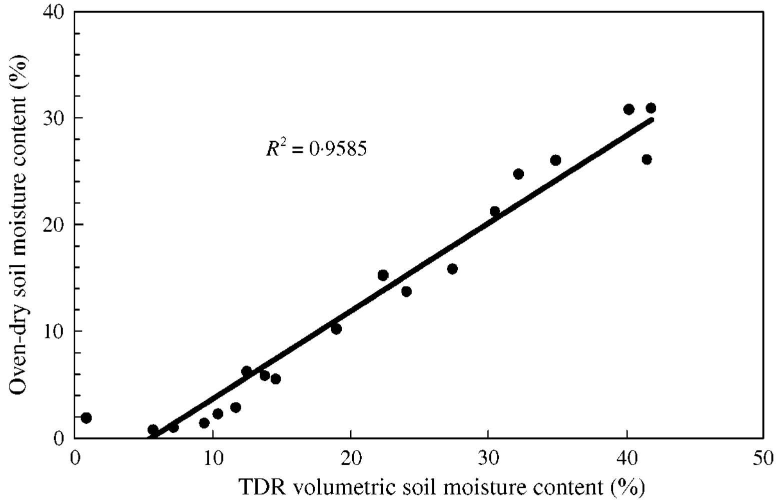

Figure 3. Calibration of the TDR using regression analysis (solid line = regression line).

obtained from conventional oven-dry weights and multiplied by bulk density data (Qiu *et al.*, 2001) (Fig. 3). Soil moisture data used below were based on this calibration.

Twenty repeat measurements of soil moisture were conducted in 1998 and 1999 combined. The total number of measurements is approximately 26,750.

Environmental attributes survey

Each sampling site was surveyed and its environmental characteristics were recorded. The environmental attributes assessed are: land use type, surface shape, plant species, hillslope position, aspect, elevation and slope degree on each site. Rainfall was measured in the catchment with five tipping-bucket raingauges equipped with dataloggers. Rainfall totals were 489 mm from 2 May to 10 October 1998 and 179 mm from 24 April to 9 September 1999.

Derivation of analysis variables

Soil moisture variables

Supposed that soil moisture content of plot (i), layer (j) and sampling occasion (k) is expressed as $M_{i,j,k}$. N_p is the number of sites and is equal to 26 for the 1998 data and 81 for the 1999 data; N_l represents the number of sampling soil layers or soil depths and is 5 for both years in this study; N_t is the number of sampling occasions and is 10 for both years in this study.

Mean soil moisture content at soil layer j (M_j):

$$M_j = \frac{1}{N_p \times N_t} \sum_{i=1}^{N_p} \sum_{k=1}^{N_t} M_{i,j,k} \qquad (1)$$

Mean soil moisture content on sampling occasion k (M_k):

$$M_k = \frac{1}{N_p \times N_l} \sum_{i=1}^{N_p} \sum_{j=1}^{N_l} M_{i,j,k} \qquad (2)$$

Layer-time-averaged soil moisture content on plot i (M_i):

$$M_i = \frac{1}{N_l \times N_t} \sum_{j=1}^{N_l} \sum_{k=1}^{N_t} M_{i,j,k} \tag{3}$$

Time-averaged soil moisture content on plot i and at layer j ($M_{i,j}$):

$$M_{i,j} = \frac{1}{N_t} \sum_{k=1}^{N_t} M_{i,j,k} \tag{4}$$

Layer-averaged soil moisture content on plot i and on sampling occasion k ($M_{i,k}$):

$$M_{i,k} = \frac{1}{N_l} \sum_{j=1}^{N_l} M_{i,j,k} \tag{5}$$

Spatial variability (coefficient of variation, CV) of time-averaged soil moisture at soil layer j (VS_j):

$$VS_j = \frac{100}{M_j} \sqrt{\frac{N_p \sum_{i=1}^{N_p} (M_{i,j})^2 - (\sum_{i=1}^{N_p} M_{i,j})^2}{N_p(N_p - 1)}} \tag{6}$$

Spatial variability (CV) of layer-averaged soil moisture on measurement occasion k (VS_k):

$$VS_k = \frac{100}{M_k} \sqrt{\frac{N_p \sum_{i=1}^{N_p} (M_{i,k})^2 - (\sum_{i=1}^{N_p} M_{i,k})^2}{N_p(N_p - 1)}} \tag{7}$$

Environmental variables

There are seven types of land use identified in the field: shrub land, woodland, orchard, intercropping land, wasteland (has never been used as cropland), follow land, and cropland. The surface shape was classified into four types: convex slope, straight slope, terrace and concave slope. Hillslope position was divided into five types, i.e. up, middle-up, middle, middle-down and down. Aspect (clockwise from north), which is a circular variable, was transformed into cos(aspect), as recommended by Bourennane *et al.* (1996) and King *et al.* (1999). Relative elevation was defined as the elevation deviation from that of the stream. Slope gradient was recorded as degrees.

Analysis methods

Correlation analysis

This analysis tool measures the relationship between two data sets that are scaled to be independent of the unit of measurement. The population correlation calculation returns the covariance of two data sets divided by the product of their standard deviations. The coefficients of correlation (r) were used to determine the relationship between soil moisture content and quantitative environmental variables.

Variance analysis and multiple comparison

Analysis of variance, or ANOVA, is a method of testing the null hypothesis that several group means are equal in the population, by comparing the sample variance estimated from the group means to that estimated within the groups. The *F*-ratio is used to determine the influence of qualitative attributes on soil moisture content.

Once we have determined that differences exist among the means of soil moisture, pairwise multiple comparisons can test the difference between each pair of means. The LSD (least significant difference), or *t*-test, was used in this paper.

Estimation of minimum sample size

To determine essential future sampling criteria and to test the sampling intensity required to predict the soil moisture across the watershed, the minimum sample size has to be determined. Since soil moisture data are normally distributed (Hills & Reynolds, 1969; Bell *et al.*, 1980) one may use the algorithm used by Owe *et al.* (1982) and Seyfried (1998). The minimum sample size required at given level of confidence is given as:

$$Nr = (t^2_{\alpha,n-1} \times s^2)/L^2. \quad (8)$$

Where Nr is the number of samples required, $t_{\alpha,n-1}$ is the value of the *t*-statistic at the $(1 - \alpha)$ confidence level with $n - 1$ degree of freedom, $\alpha = 0{\cdot}05$ in the study, n is the number of samples actually measured, s is the standard deviation calculated, and L is the allowable error and is 1% in this study.

Results

Mean and coefficient of variation of the catchment soil moisture content

Profile distribution

Figure 4 shows the catchment mean and spatial variability (coefficient of variation, CV) of the time-averaged soil moisture at different soil depths in 1998 and in 1999. It is shown that the mean soil moisture is lower in 1999 (dry year) than in 1998

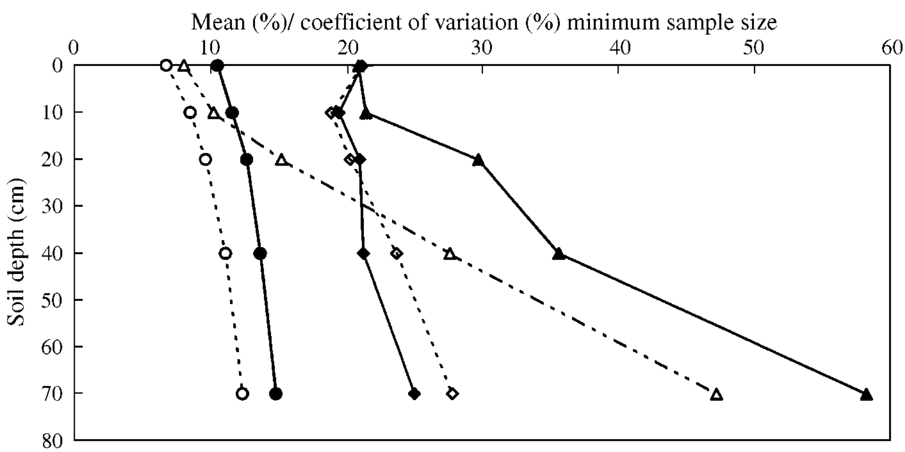

Figure 4. Profile distribution of the mean (%) and coefficient of variation (CV) of the time-averaged soil moisture in 1998 and 1999. Minimum sample size is also shown. Mean 1998 (—●—); mean 1999 (--○--); minimum sample 1998 (—▲—); minimum sample 1999 (–△–); coefficient of variation 1998 (—◆—); coefficient of variation 1999 (--◇--).

(wet year), which is consistent with previous findings on the Loess Plateau by Wang & Li, 1995; Wang *et al.*, 1996, 1998, but the CV is greater in 1999 than in 1998. The data of both years indicate that there are significant differences in the mean soil moisture at different soil depths as determined by ANOVA and *t*-test ($p = 95\%$). With increasing soil depth, the mean moisture increases significantly for all five layers, which is consistent with previous findings on the Loess Plateau (Wang & Li, 1995; Wang *et al.*, 1996; Li *et al.*, 1996, 1998; Zhang *et al.*, 1998). The CV also increases with soil depth but beginning at 10–15 cm, which is consistent with a previous study of Loague (1992) in Oklahoma, U.S.A.

Dynamic behavior

The catchment mean and coefficient of variation (CV) of the layer-averaged soil moisture versus date are shown in Fig. 5. As shown in Fig. 4, Fig. 5 also indicates an obvious difference in mean and CV of the soil moisture existing between the two years. In general the mean soil moisture is lower in 1999 than in 1998, but the CV is higher in 1999 than in 1998. This is because there is less precipitation in 1999 than in 1998. Therefore, an equal amount of rainfall in 1999 can results in a more significant change in both the mean and CV of the soil moisture than in 1998 (Fig. 5). The seasonal trends in mean and CV of soil moisture content are also different for 1998 and 1999. For example, in 1999 both the highest mean moisture and the lowest CV were observed in July, however in 1998, the highest mean moisture was observed in May through the lowest CV was observed in August.

As shown in detail by Vinnikov *et al.* (1996), there is a difference between the catchment or hydrological scale (fast acting and fast varying processes) and the meteorological scale (slower changing both in time and space) (Robock *et al.*, 1998). Obviously, the temporal dynamics of the mean and CV of the soil moisture at the catchment scale are more difficult to characterize. It is likely that a larger sample size and an increased temporal monitoring frequency would have resulted in better estimates of the soil moisture and its behavior through time. However, some general observations

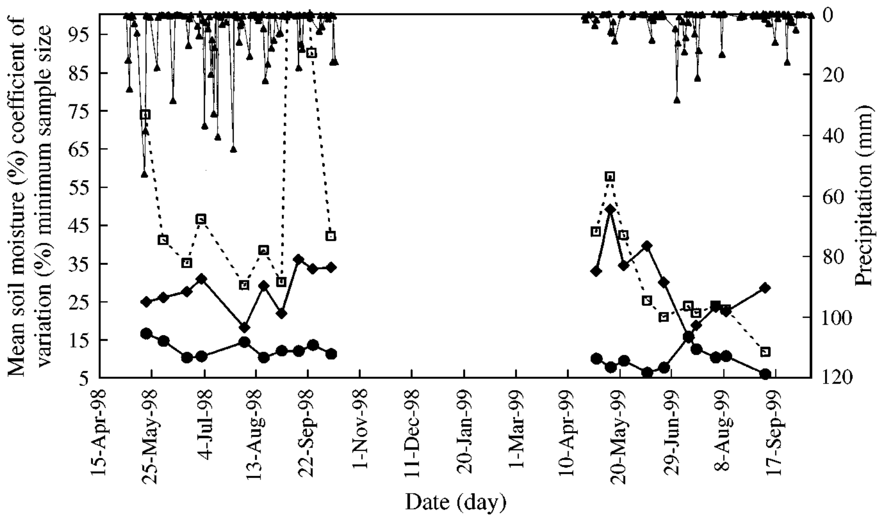

Figure 5. Temporal changes in the mean (%, —●—) and coefficient of variation (CV, —◆—) of the layer-averaged soil moisture content in 1998 and 1999. Daily precipitation depths (mm, —▲—) and the minimum sample size (--□--) are also shown.

can be made in a qualitative description. Figure 5 shows that the behavior of the mean soil moisture seems to be determined by the mutual effect of soil water loss through evapotranspiration and the gain of soil water from precipitation. In general, the magnitude of the mean moisture peaks corresponding to the amount of antecedent precipitation, with higher mean moisture occurring after greater antecedent precipitation. For example, the highest mean moisture (16·69%, on 21 May 1998) observed during the measurement periods in both years appears to be due to the heaviest storm (52·46 mm, on 20 May 1998) observed. However, there is a potential for decrease of soil moisture levels owing to the evapotranspiration, with several distinct 'dry down' sequences (e.g. beginning on 21 May 1998, 4 August 1998, 2 May 1999, 12 July 1999). While several rain events occurred between these dates (e.g. on 30 May 1998 and 10 July 1999), they served only to temporarily interrupt more pronounced drying trends. Another factor influencing the soil moisture level is the date of measurement relative to the date of precipitation. Similar findings have been made on the Loess Plateau (Yu *et al.*, 1992; Wang & Li, 1995; Wang *et al.*, 1996; Li *et al.*, 1996, 1998; Zhang *et al.*, 1998; Zhao *et al.*, 1999) and in other environments (Famiglietii *et al.*, 1998; Gong *et al.*, 1998).

Figure 5 indicates that the dynamic behavior of CV is nearly identical to the mean soil moisture, though opposite in sign. The CV is lowest following rain events and increases as the soil dries. This is shown most clearly in the two dry down sequences that follow the two heavy storm events of 20 May 1998 and 4–10 July 1999. The minimum value of CV is directly related to the amount of antecedent precipitation. For example, the lowest CV (15·47%, on 12 July 1999) observed during the whole measurement period is related to the great amount of antecedent precipitation including a heavy storm even on 4 July 1999. This can partly be explained as the uniform wet-condition across the catchment following heavy rain events. An alternative explanation may be the spatial homogeneity of soil properties (e.g. porosity) which would be at a maximum influences on soil moisture following a rainfall event (Reynolds, 1970*c*; Hawley *et al.*, 1983; Famiglietii *et al.*, 1998; Western *et al.*, 1999). Thus, heavier rains and higher mean moisture content are often associated with lower spatial variability (CV), and vice versa. However, Famiglietii *et al.* (1998) concluded that heavier rains and higher mean moisture content are often associated with higher variability (variance) in Texas, U.S.A. This inconsistency may be caused by the fact that the index used for description of spatial variability is different; CV (coefficient of variation) is used in this paper while variance was used by Famiglietti *et al.* (1998). In general, the variance is dependent on the mean while the CV is independent on the mean.

Minimum sample size

The estimation of sample size (Nr) to achieve the prediction of the catchment-mean at five depths and on 20 measurement occasions are shown in Figs 4 and 5 for both years. The minimum sample number are different for 1998 and 1999, ranging between 8 and 58 in 1999 and between 21 and 195 in 1998. This is because the value of $t_{\alpha, n-1}$ in Eqn (8) is considerably greater due to the smaller value of n (actual sample size) in 1998 than in 1999. The minimum sample size is therefore also larger. It is obvious that our sample size is adequate to predict the catchment-mean soil moisture at all five depths and on all 10 observations in 1999 ($n = 81$). However, the sample size ($n = 26$) in 1998 in only large enough for estimation of the catchment-mean soil moisture in near surface soils (0–5 cm and 10–15 cm). To estimate the mean soil moisture at 0–75 cm across the watershed at least 17 sites are required in 1999. This was tested by randomly selecting 17 sites from the total of 81 sites in 1999. The mean soil moisture for these 17 sites was calculated. The procedure was repeated 30 times. It was found that six of these 30 repeats gave estimates of catchment mean soil moisture at 0–75 cm across the catchment with an error of greater than 1% whilst 24 of 30 repeats provide estimates with less than

1% error. This implies that a few 'bad' sites do exist, influencing the predicting ability of the samples in 1999. Nevertheless, the overall results shown the relevance of the math used for calculating the minimum sample size.

It is shown in Fig. 4 that the minimum sample size exhibits a similar profile distribution as the CV, increasing with increasing soil depth in both years. This is because the minimum sample size is proportional to the square of standard deviation (s^2) in addition to the $t^2_{\alpha, n-1}$ (Equation (8)), and again the standard deviation is the result of 'CV' by 'mean'. For example, in 1999, to estimate the mean time-averaged soil moisture during the whole measurement periods at 0–5 cm (with CV of 21·07%) at least eight sites are required, whereas at least 47 plots are required at 70–75 cm (with CV of 27·83%) (Fig. 4). The dynamic behavior of the minimum sample size also loosely mimics that of the CV, with minimum values after rain events and increases during the ensuring measurements (Fig. 5).

Spatial variability of soil moisture in relation to environmental attributes

In this section, the spatial variation in soil moisture content observed was characterized by analysis of the relationships between soil moisture content and environmental attributes. The correlation coefficients were used to analyze the relationships between quantitative indices (such as slope gradient) and soil moisture content. One way analysis of variance (ANOVA) and multiple comparison (*t*-test) were performed to characterize the relationships between qualitative indices and soil moisture content, such as the difference in soil moisture content among different types of land use.

This section is further divided into two parts: the soil profile pattern of relationships of the time-averaged soil moisture with environmental indices and the temporal change of relationships of the layer-averaged soil moisture with environmental attributes. The data from 1999 will be mainly used since these data are more extensive than the data for 1998 and since they cover a wide variety of land use (Fig. 2) and topography. Furthermore, it was shown earlier in this paper that the 1999 data are adequate to estimate the mean soil moisture across the catchment.

Relationships between time-averaged soil moisture and environmental attributes

Performance of quantitative attributes The coefficients of correlation between the time-averaged soil moisture and quantitative indices are presented in Fig. 6(a) & (c) for 1998 and 1999, respectively. It is shown that the influences of these quantitative attributes on soil moisture distribution are different for the 1998 data and 1999 data. This may be due to the difference in the amount of precipitation (Fig. 7). An alternative explanation may be that a wider variety of environmental conditions was sampled in 1999 than in 1998 (Figs 1 and 2).

Aspect, or slope orientation, influences the redistribution of precipitation and evapotranspiration, and thus soil moisture. A negative correlation of time-averaged soil moisture with cos(aspect) is statistically significant at shallower soil depths (0–5, 10–15, and 20–25 cm) sampled in 1998 (Fig. 6(a) & (d)). This is consistent with the previous findings by Reid (1973) in Caydell, U.K.; Famiglietti *et al.* (1998) in Texas, U.S.A; and Western *et al.* (1999) in Melbourne, Australia, all of whom noted a positive correlation. However, a negative correlation between soil moisture and cos(aspect) was found in 1999 though the correlation is statistically insignificant. One explanation is that much more precipitation falls on the south-facing slope than on the north-facing slope resulting from the influence of wind and the Loess Plateau (data from Ansai County Meteorological Station). This difference is more evident in 1998 with more precipitation than in 1999. An alternative explanation is that all the sampled shrub lands (which have dry soil conditions due to large transpiration rate) are on the north-facing slopes

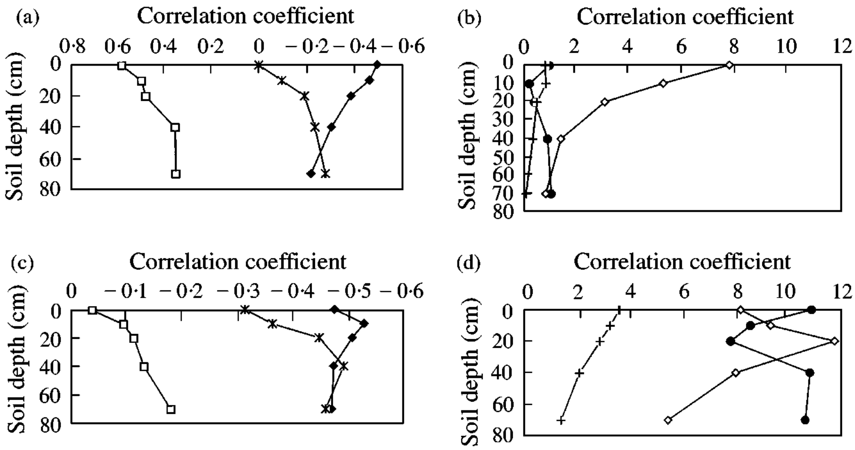

Figure 6. Profile pattern of relationships between the time-averaged soil moisture and the environmental attributes at Da Nangou catchment in 1998 and 1999; (a) correlation coefficients between soil moisture and quantitative attributes in 1998; (b) *F*-ratio reflecting the associations between soil moisture and qualitative attributes in 1998; (c) correlation coefficients between soil moisture and quantitative attributes in 1999; (b) *F*-ratio reflecting the associations between soil moisture and qualitative attributes in 1999. (a, c) Cos(aspect) (—□—); relative elevation (—◆—); slope gradient (—✳—); (b, d) land use (—●—); surface shape (—+—), hillslope, position (—◇—).

(Table 5). Ng & Miller (1980) also reported a wetter soil condition on the south-facing slopes than on the north-facing slopes because of the difference in transpiration of vegetation in the southern California chaparral, U.S.A.

With increasing soil depth, the correlation coefficient between cos(aspect) and the time-averaged soil moisture increases in 1999 (Fig. 6(c)), while it declines in 1998 (Fig. 6(a)).

Sites at greater relative elevation can have more soil water draining down and will receive less water from upslope. They might be more exposed and thus have higher evaporation rates. A negative correlation between relative elevation and soil moisture was observed in this study (Figs 6(a) & (c) & 7(a)). This is consistent with previous findings on the Loess Plateau (Huang *et al.*, 1999; Zhao *et al.*, 1999) and also in other regions [Krumbach (1959) in Mississippi, U.S.A.; Henninger *et al.* (1976) in Pennsylvania, U.S.A; Hawley *et al.* (1983) in Oklahoma, U.S.A; Robinson & Dean (1993) in Oxford, U.K.; Nyberg (1996) in Gardsjon, Sweden; Crave & Gascuel-Odoux, (1997) in Brittany, France; Famiglietti *et al.* (1998); and Western *et al.* (1999)].

The influence of relative elevation shows a decreasing trend with increasing soil depth, beginning at 0–5 cm in 1998 (Fig. 6(a)) but beginning at 10–15 cm in 1999 (Fig. 6(c)). This likely resulted from a more significant evaporation and a more significant lateral redistribution of soil water in the shallower soil layers. However, in 1999, owing to the very dry condition of surface soil (6·75%, Fig. 4), the lateral redistribution is weak, and the difference in surface soil moisture is therefore small.

Slope angle influences infiltration, drainage and runoff. Steeper slopes are likely to be drier than flat areas owing to lower infiltration rates, rapid subsurface drainage, and higher surface runoff. It is shown in Figs 6(a) & (c) & 7(a) that a negative correlation between slope gradient and soil moisture is statistically significant, and the influence of slope angle is more significant in 1999 than in 1998. This is consistent with previous findings on the Loess Plateau by Zhao *et al.* (1999) and in other regions by Hills & Reynolds (1969) in Chew Stoke, U.K.; Moore *et al.* (1988) in New South Wales, Australia; Nyberg (1996); Famiglietti *et al.* (1998); and Western *et al.* (1999).

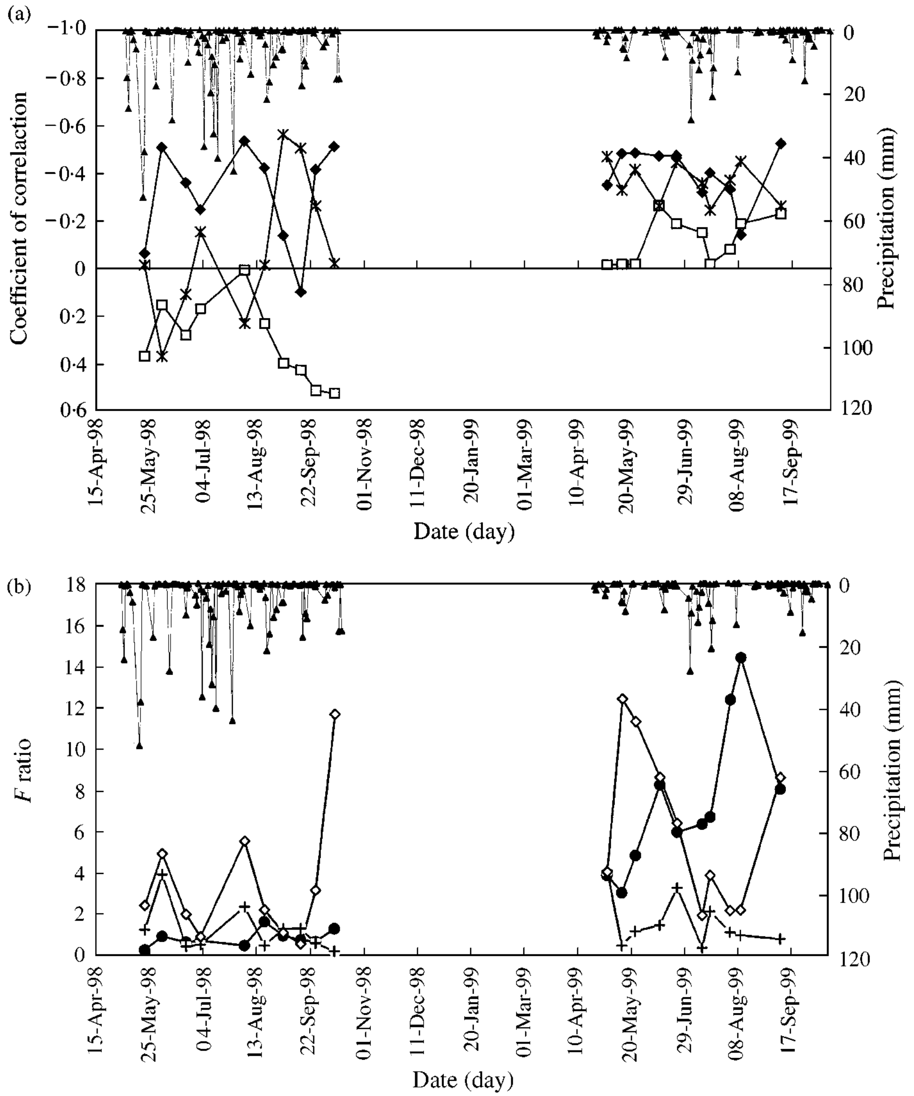

Figure 7. Temporal changes in the relationships between the layer-averaged soil moisture and the environmental attributes at Da Nangou catchment in 1998 and 1999; (a) correlation coefficients between soil moisture and quantitative attributes; Cos(aspect) (—□—); relative elevation (—◆—); slope gradient (—✳—); precipitation (—▲—) (b) *F*-ratio reflecting the associations between soil moisture and qualitative attributes. Daily precipitation depths (mm) are also shown. Land use (—●—); surface shape (—+—); hillslope position (—◇—); precipitation (—▲—).

The profile pattern of correlation between slope angle and soil moisture is similar for 1998 and 1999, increasing with increasing soil depth (Fig. 6(a) & (c)).

Performance of qualitative attributes The profile pattern of relationships (*F*-ratio) between the time-averaged soil moisture and qualitative attributes are shown in Fig. 6(b) & (d). It is shown that the influences of these three qualitative attributes (land use, surface shape and hillslope position) are more important in 1999 than in 1998.

Land use with different vegetation types influences soil moisture variability by the pattern of throughfall imposed by the canopy; by shading the land surface, thus

Table 5. *Mean soil moisture content on different types of land use together with ANOVA and* t*– test in 1999*

Land use types	Shrub land	Woodland	Orchard	Intercropping land	Wasteland	Fallow land	Cropland	Total	*F*–ratio
Total	5·47 A#	11·62 B	8·75 C	9·19 C	9·67 BC	10·42 BC	10·07 C	9·70	9·068**
Time-averaged soil moisture									
0–5 cm	5·37 A	9·98 B	6·29 AC	6·76 CD	6·56 AD	6·55 AD	6·58 CD	6·75	10·945***
10–15 cm	5·98 A	11·15 B	8·70 C	8·40 C	9·29 BC	9·31 C	8·46 C	8·53	8·547**
20–25 cm	5·88 A	11·65 B	9·14 B	9·34 C	9·86 BC	10·64 BC	9·90 C	9·67	7·756**
40–45 cm	5·20 A	12·18 BC	9·75 BC	10·38 C	11·19 BC	12·24 BC	11·87 B	11·15	10·867**
70–75 cm	4·93 A	13·16 BC	9·86 C	11·08 C	11·45 BC	13·35 BC	13·54 C	12·39	10·687**
Layer-averaged soil moisture									
2 May 1999	6·11 A	13·50 B	7·76 AC	9·95 C	7·94 AC	12·60 BC	10·06 C	10·02	3·908**
13 May 1999	3·72 A	10·87 B	6·90 AB	5·53 AC	8·11 AB	8·45 BC	8·34 B	7·77	3·056**
23 May 1999	5·20 A	12·91 B	8·52 ABC	7·76 A	9·09 AB	11·71 BC	9·86C	9·50	4·886**
10 Jun 1999	3·07 A	9·60 B	4·73 AC	4·78 A	9·76 B	8·58 BD	6·48 CD	6·37	8·325**
23 Jun 1999	4·05 A	10·01 B	6·23 ACD	6·80 C	7·25 BC	9·32 BD	7·93 CD	7·65	6·020**
12 Jul 1999	11·49 A	15·91 BC	15·56 BC	15·47 BC	13·81 ABC	14·30 C	16·63 B	15·83	6·407**
18 Jul 1999	8·03 A	13·83 B	14·91 B	11·95 B	13·65 B	12·32 B	12·92 B	12·53	6·761**
2 Aug 1999	4·51 A	10·79 BC	9·83 BC	11·55 C	11·63 BC	9·41 B	10·87 BC	10·41	12·449**
10 Aug 1999	5·82 A	10·90 B	6·42 A	12·18 B	7·02 A	10·76 B	11·30 B	10·73	14·469**
9 Sep 1999	2·70 A	7·91 B	6·62 BC	5·93 C	7·20 BC	6·72 BC	6·11 C	6·03	8·110**

Numbers in a row followed by the same letter are not significantly different at the 95% level of probability by *t*-test.
** Denotes the significance at the level of 99% of probability that differences exists within a row as determined by analysis of variance.

affecting the rate of evaporative drying and by extracting moisture for transpiration from the soil profile. The degree to which these factors affect the soil moisture distribution varies with vegetation type, density and season. It is shown that land use is one of the major factors influencing the soil moisture variability (Table 5, Figs 6(d) & 7(b)) in 1999. This is consistent with the previous findings on the Loess Plateau (Wang & Li, 1995; Wang *et al.*, 1996; Li *et al.*, 1996, 1998; Huang *et al.*, 1999). Similar findings were made in other regions by Reynolds (1970*b, c*) in Somerset, UK; Ng & Miller (1980); Hawley *et al.* (1983); and Francis *et al.* (1986) in Murcia, Spain.

The profile pattern of relationship between land use and the time-averaged soil moisture is similar for 1998 and 1999 with lower associations at 10–15 cm and 20–25 cm (Fig. 6(b) & (d)) though it is insignificant at all soil depths sampled in 1998. This may be because the difference in density of plant roots between land use types is less significant at 10–15 cm and 20–25 cm than at other depths (Table 2) (Zhao *et al.*, 2000). Table 5 gives the mean soil moisture content on different types of land use together with ANOVA and *t*-test in 1999. The shrub land is significantly drier than other type of land use at all soil depths (Wang & Li, 1995). This is because the density of plant roots is greater on the shrub land than on the other types of land use in these five soil layers (Table 2) and thus a greater loss of soil water through transpiration. In shallower soil layers (0–5 cm, 10–15 cm), the woodland is significantly wetter than other types of land use. This is partly due to a weaker direct evaporation under a higher coverage of plants (Table 3) and thus a wetter condition at 0–5 cm. Another explanation is that the root density of woodland is lower at 10–15 cm (Table 2), thus there would be less loss of water through transpiration at 10–15 cm (Li *et al.*, 1996). At greater depths (40–45 cm, 70–75 cm), the cropland and fallow land also become wet (Li *et al.*, 1998) due to small removal of water by small roots of plants at these depths (Table 2).

Figure 6(b) & (d) indicates that the relation between surface shape and the time-averaged soil moisture is weak in both years, which is in agreement with the previous findings by Moore *et al.* (1988) and Famiglietti *et al.* (1998). Obviously, the influence of surface shape on soil moisture contents decreases sharply with increasing soil depth in both years. Since soil surface curvature influences the convergence of lateral flow (Western *et al.*, 1999), the time-averaged soil moistures at all depths in 1999 show a larger value on plots with higher concavity (terrace and concave slope) than on plots with higher convexity (convex slope and straight slope) (Table 6).

It is obvious that the relationship of hillslope position with soil moisture is similar to that of relative elevation since there is a significant association between relative elevation and hillslope position (Famiglietti *et al.*, 1998; Qiu *et al.*, 2001). In addition to draining more slowly than the upper parts of a hillslope, lower parts receive more lateral moisture inputs (at least while lateral redistribution is active), and thus remain wetter than their uphill neighbors. Figure 6(b) & (d) shows that the soil moisture is significantly influenced by hillslope position. In general, the soil moisture at the same soil depth increases with changing of hillslope position from up to down (Table 7). This is consistent with previous findings in the Loess Plateau (Huang *et al.*, 1999; Zhao *et al.*, 1999) and also in other regions [Krumbach (1959); Henninger *et al.* (1976); Hawley *et al.* (1983); Robinson & Dean (1993); Nyberg (1996); Crave & Gascuel-Odoux, (1997); Famiglietti *et al.* (1998); and Western *et al.* (1999)].

The profile distribution of the relationship between hillslope position and soil moisture loosely mimics that of the relative elevation. The relation is stronger in the upper soil layer and decreases with increasing soil depth for five soil layers in 1998 but begins at 20–25 cm in 1999 (Fig. 6(b) & (d)).

Relationships between layer-averaged soil moisture content and environmental attributes

Performance of quantitative attributes The dynamic behavior of the correlation coefficients between the layer-averaged soil moisture and quantitative indices are shown in Fig. 7(a).

Table 6. *Mean soil moisture content on different types of surface shape together with ANOVA and* t*-test in 1999*

Surface shape type	Convex slope	Straight slope	Terrace	Concave slope	Total	*F*-ratio
Total	8·79	9·36	10·71	10·44	9·70	2·028
Time-averaged soil moisture						
0–5 cm	6·60	6·50 A #	7·04 AB	7·55 B	6·75	3·428*
10–15 cm	8·64	8·19 A	9·20 AB	9·40 B	8·53	3·072*
20–25 cm	9·52	9·29	10·74	10·50	9·67	2·674
40–45 cm	9·65	10·75	12·57	11·88	11·15	1·860
70–75 cm	9·53	12·06	13·99	12·85	12·39	1·140
Layer-averaged soil moisture						
2 May 1999	10·62	9·21 A	12·09 B	11·76 B	10·02	4·136**
13 May 1999	7·47	7·47	9·02	8·15	7·77	0·480
23 May 1999	7·93	9·09	10·84	10·30	9·50	1·185
10 Jun 1999	4·49	6·02	7·25	7·22	6·37	1·484
23 Jun 1999	5·43	7·21 A	9·12 B	8·58 B	7·65	3·314*
12 Jul 1999	14·36	15·78	16·52	15·68	15·83	0·377
18 Jul 1999	10·05	12·19	13·07	13·66	12·53	2·158
2 Aug 1999	10·40	10·08	10·94	11·30	10·41	1·143
10 Aug 1999	11·27	10·45	11·77	11·15	10·73	0·993
9 Sep 1999	5·84	5·84	6·37	6·56	6·03	0·809

Numbers in a row followed by the same letter are not significantly different at the 95% level of probability by *t*-test.
* and ** denote the significance at the level of 95% and 99% of probability that differences exist within a row respectively, as determined by analysis of variance.

Table 7. *Mean soil moisture content on different classes of hillslope position together with ANOVA and* t*-test in 1999*

Hillslope position classes	Up	Middle-up	Middle	Middle-down	Down	Total	*F*-ratio
Total	8·37 A#	9·11 AB	9·64 B	9·97 B	11·58 C	9·70	8·150**
Time-averaged soil moisture							
0–5 cm	5·97 A	6·43 A	6·53 A	6·68 A	8·25 B	6·75	9·329**
10–15 cm	7·66 A	7·95 A	8·33 A	8·29 A	10·38 B	8·53	11·823**
20–25 cm	8·49 A	9·01 AB	9·65 B	9·78 B	11·49 C	9·67	7·955**
40–45 cm	9·53 A	10·63 AB	11·20 B	11·70 BC	13·03 C	11·15	5·302**
70–75 cm	10·22 A	11·53 AB	12·49 B	13·44 BC	14·75 C	12·39	5·485**
Layer-averaged soil moisture							
2 May 1999	8·52 A	9·00 A	10·06 A	10·08 AB	12·40 B	10·02	4·072**
13 May 1999	5·72 A	6·32 A	6·86 A	7·94 A	12·20 B	7·77	12·492**
23 May 1999	7·77 A	8·10 A	8·82 A	9·74 A	13·16 B	9·50	11·409**
10 Jun 1999	5·19 A	5·24 A	5·94 A	6·36 A	8·97 B	6·37	8·685**
23 Jun 1999	6·37 A	6·96 A	7·36 A	8·48 AB	9·50 B	7·65	6·447**
12 Jul 1999	14·67 AC	16·17 AB	15·81 AC	16·60 BC	16·57 BC	15·83	1·958
18 Jul 1999	11·29 A	12·49 AB	12·98 BC	11·88 AC	13·95 B	12·53	3·919**
2 Aug 1999	9·12 A	10·54 AB	11·08 C	10·62 AB	10·90 B	10·41	2·189
10 Aug 1999	9·75 A	10·71 AB	11·33 C	12·00 B	10·38 AB	10·73	2·219
9 Sep 1999	4·81 A	5·56 AB	6·15 C	6·04 B	7·60 C	6·03	8·673**

Numbers in a row followed by same letters are not significantly different at the 95% level of probability by *t*-test.
** and *** denote the significance at the level of 95% and 99% of probability that differences exist within as row as determined by analysis of variance respectively.

A significant correlation between cos(aspect) and soil moisture was observed in early summer (e.g. 21 May 1998 and 10 June 1999) and fall (after 2 September 1998 and 9 September 1999) (Fig. 7(a) & 5). Aspect influences solar irradiation, evapotranspiration and redistribution of precipitation, and thus soil moisture (Reid, 1973; Famiglietti *et al.*, 1998). This influence is more obvious in early spring when the solar irradiation increases dramatically and during autumn when the solar irradiation declines rapidly.

In general, the negative correlation of relative elevation with soil moisture content decreases with the occurrence of heavy precipitation, and is followed by an increase in correlation (Fig. 7(a)). This can be explained because heavy precipitation events lead to a uniform wet-condition of soil moisture content across various elevations (Famiglietti *et al.*, 1998). The size of the decrease in the correlation is generally dependent on the amount of antecedent precipitation. For example the heaviest storm (52·464 mm, on 20 May 1998) observed during the measurement periods results in the lowest degree of correlation (− 0·06) on 21 May 1998. However, the smaller rain events (e.g. 16 August 1998 and 15 June 1999) yield slight decreases in correlation on the ensuing measurements (e.g. 19 August 1998 and 23 June 1999). In addition, the size of the decrease in correlation is related directly to the time lag between precipitation and measurement. This lag-effect is especially significant during the summer, when temperatures are high. For example, heavy storm event on 4 July 1999 results in a small decrease on 12 July 1999, and the heavy storm event on 27 July 1998 yields an increase rather than a decrease. However, it is limited to characterize the temporal evolution in the correlation in a more quantitative ways because of the limitation of data with 14 days apart. A similar finding was also made by Famiglietti *et al.* (1998).

In contrast to the relative elevation, the absolute value of the correlation of slope gradient with the soil moisture content increases with the occurrence of precipitation events, and decreases afterwards (Fig. 7(a)). This is indicative of an important influence of slope gradient on soil moisture that operates during and following storms. It is noted here that the significant correlation between slope gradient and soil moisture was observed for negative values only. One possible explanation is that during precipitation events, locations with higher slope angles yield more infiltration excess runoff, thus less water infiltrates water and the moisture content are lower than in the case of more gentle slopes. An alternative explanation is that drainage is faster for steeper slopes, so that lower moisture contents remain after rainfall events. Famiglietti *et al.* (1998) noted a similar trend in the correlation between slope gradient and soil moisture following precipitation events. However, the very heavy storms such as occurred on 20 May 1998 and 4 July 1999 did not result in an increase but in a decrease in correlation. This may be attributed to the uniform very wet conditions across various ranges in slope gradient after an extremely heavy storm event.

Performance of qualitative attributes As in the case of time-averaged soil moisture (Fig. 6(a) & (d)), Fig. 7(b) indicates that the influences of three qualitative indices (land use, surface shape and hillslope position) on the spatial distribution of the layer-averaged soil moisture are more significant in 1999 than in 1998.

It is shown that the relationship between land use and the layer-averaged soil moisture content is statistically significant at level of 99% on all the ten measurement dates in 1999, while it is statistically insignificant in 1998 (Fig. 7(b)). The *t*-test shows that shrub lands are significantly drier than other types of land use especially after May 1999 (Table 5). This may be due to the stronger transpiration of littleleaf peashrub (Wang & Li, 1995) with more leaves after May 1999 (Table 4). Though there are not significant differences in the mean of soil moisture among additional types of land use by *t*-test on most of the measurement occasions in 1999, the following results are obvious as shown in Table 5. Woodlands are relatively wetter than other types of land use on most of the measurement occasions (Li *et al.*, 1998). This may be accounted for by the higher canopy cover and thus the weaker evaporation of a surface protected by canopy, as shown in Table 3. However it is not so wet in August (Table 5) because of the increased transpiration in the rapid-growing season with increased leaf area index (LAI) as shown in Table 4. Orchard is relatively drier compared to other types of land use (except for shrub land) (Table 5) due to stronger evaporation from the ground with less coverage (Table 3), but it becomes relatively wet in July resulting from weak transpiration of plants with low LAI (Table 4). The intercropping lands are relatively drier than other land uses (except for shrub land) during most of measurement periods (Table 5) resulting from the larger transpiration of multiple layers of plants with higher LAI (Table 4). However, they become relatively wetter in August because of weaker evaporation of surface soil tilled by farmers and because the soil is protected by multiple leaf layers of both fruit trees and crops with high coverage (Table 3). Wastelands are dryer than woodland, fallow land and cropland, but wetter than shrub land, orchard and intercropping land (Table 5) because of the moderate degree of transpiration of plants with moderate LAI (Table 4), while they get wetter than other land uses under dry conditions (e.g. 10 June, 2 August and 9 September 1999) (Table 5) resulting from the weaker evaporation of ground covered by more plants (Table 3). Fallow lands are relatively wetter than other types of land use (except for woodland) (Table 5) owing to weaker evaporation of soil surface with high coverage (Table 3) and weaker transpiration of plants with lower LAI (Table 4), whilst it is not so wet in July and August because there is little infiltration due to a crust that developed on surface during the rainfall season. Croplands show a wetter condition compared to other land uses just after significant rainfall events (e.g. 12 July and 10 August 1999) (Table 5) because the tilled soil has large infiltration rates and looses only a small amount of soil water through evaporation even though the plant coverage is low, and because only little soil water was lost from transpiration of plants with lower LAI (Table 4).

The temporal changes in relationship between land use and soil moisture are similar for 1998 and 1999, with maximum associations during June and August (Fig. 7(b)), though the relationship is statistically insignificant in 1998. This trend seems to be consistent with the temporal evolution in differences of vegetative characteristics. The first maximum of *F*-ratio in June (Fig. 7(b)) corresponds to the first increases of differences (standard deviation) in both coverage (Table 3) and leaf area index (Table 4) between different types of land use (Table 4). In early June, some land uses (e.g. woodland) had high leaf cover while others (e.g. cropland) had little leaf cover. This can result in the larger differences in infiltration rate, drainage and evapotranspiration between different types of land use. These differences become largest in August (also rapid growing months). Thus emerges the second peak of *F*-ratio (also the greatest) in August.

Table 6 indicates that as in the case of the time-averaged soil moisture content the layer-averaged soil moisture contents are generally larger on plots of high concavity (terrace and concave slope) than on plots of high convexity (convex slope and straight slope). However, ANOVA indicates that the influence of surface shape types on spatial distribution of layer-averaged soil moistures is not statistically significant on most of the measurement dates in both years (Fig. 7(b)). It is difficult to characterize the seasonal dynamics of the association between surface shape and soil moisture.

Figure 7(b) indicates that the hillslope position provides a significant influence on spatial variation in the layer-averaged soil moisture content as determined by ANOVA. It was observed that soil moisture increases systematically with decreasing hillslope position, because of redistribution of soil water along the hillslope (Table 7). As shown in Fig. 7(a) & (b), the temporal change in relation of hillslope position with soil moisture is nearly identical to that between relative elevation and soil moisture content. In fact, the hillslope position and relative elevation are highly related (Famiglietti *et al.*, 1998; Qiu *et al.*, 2001). Consequently, the behavior of the temporal change in relationships between hillslope position and moisture mimic that of the correlation coefficient between relative elevation and moisture content, but with much more temporal variability. In general, the association strength decreases because of precipitation events, and increases afterwards. The size of the decrease in F ratio is dependent on both the amount of antecedent precipitation and the time lag between rain event and measurement. A similar finding was made by Famiglietti *et al.* (1998).

Discussion

Dominant control on the spatial variation in soil moisture and the predictive ability of environmental indices

The spatial variation in soil moisture content can be understood in the context of a combination of several hydrological processes (i.e. infiltration, vertical and lateral redistribution, and evapotranspiration) that are related to precipitation, topography and land use. Environmental attributes including land use and terrain indices provide controlling roles in the spatial distribution of both the time-averaged soil moisture (Fig. 6) and the layer-averaged soil moisture (Fig. 7).

The relative roles of these environmental indices in controlling the spatial variation in the time-averaged soil moisture observed at the Da Nangou catchment are different for different soil depths (Fig. 6). In the surface soil (0–5 cm), the spatial variability of the time-averaged soil moisture (Fig. 4) is determined by several topographic attributes including aspect, relative elevation and hillslope position. However, the presence of land use tends to diminish the spatial variations of soil moisture explained by these three terrain indices. In the subsurface soil (10–15 cm, 20–25 cm), the difference in the moisture content between different types of land use is small, but relative elevation, hillslope and aspect remain important in the redistribution of soil water. Therefore, the spatial variation in subsurface soil moisture is mainly attributed to the spatial distribution of the relative elevation, hillslope position and aspect. In 'deeper' soil layers (40–45 cm, 70–75 cm) the redistribution driven by relative elevation remains significant and the influence of slope angle becomes obvious. Land use also plays an important role since the difference in root density of plants between different land use types becomes greater at these depths. Consequently, the spatial variation in soil moisture is controlled by land use, relative elevation and slope gradient.

Then, the dynamic behavior in the dominant control of different environmental indices on the layer-averaged soil moisture is discussed (Fig. 7). It seems that the influence of different environmental indices depends on several factors. The relation of soil moisture with slope gradient, relative elevation and hillslope position are determined by the antecedent amount of precipitation. In general, the correlation of soil moisture with slope gradient shows a more significant increase with the occurrence of greater antecedent precipitation (with the exception of the extremely heavy storm) and is followed by a decline.

The relations of the soil moisture with both relative elevation and hillslope position exhibit an opposite trend. The influence of land use corresponds to the difference in vegetative characteristics, with a stronger influence in June and August with a greater difference in vegetation. A significant influence of cos(aspect) was found. A significant influence of cos(aspect) was found during early spring and autumn with a rapid change in solar irradiation.

Implications for prediction of soil moisture

Areal prediction of soil moisture content over large areas is needed for a variety of applications in hydrology, soil survey and land management etc. (Seyfried, 1998).

However, representation of the variability of soil moisture should be a necessary and preliminary part prior to the soil moisture prediction model.

In general, there are two distinct types of prediction: areal average estimates and spatial prediction. To estimate mean soil moisture across the watershed, the minimum sample size needed for this has to be determined (Seyfried, 1998). It was concluded that our sample size is adequate to estimate the catchment mean soil moisture at all five depths and on all 10 measurements in 1999 and that it is enough at shallower soil depths in 1998. For example, the catchment mean soil moisture at 0–75 cm on 12 July 1998 can be simply calculated based on the layer-averaged soil moisture of the 81 sites sampled using Eqn (2).

There are several ways in which spatial prediction of soil moisture content can be performed. The first builds on local soil moisture classifications; the second uses direct interpolation of data from field sites; and the third is performed using environmental correlation. Combinations of approaches are also possible. Significant relationships of soil moisture with easy-to-measure attributes such as land use and hillslope position were found in 1999. Therefore, we can map the classification of soil moisture based on the map of land use and hillslope position in 1999.

Although powerful geostatistical techniques exist for optimum interpolation of soil moisture from sample grids (Webster & Burgess, 1980; Yates & Warrick, 1987; Western *et al.*, 1998), recent studies have incorporated environmental variables as predictors (Ahmed & DeMarsily, 1987; Stein *et al.*, 1988, 1991; Odeh *et al.*, 1994; Bourennane *et al.*, 1996). The significant relationships between soil moisture and environmental indices (e.g. hillslope position and slope gradient) observed in this paper may then form a trend model for use in combination with various forms of kriging and co-kriging (e.g. Odeh *et al.* 1994; Knotters *et al.*, 1995; Bourennane *et al.*, 1996).

The third is that soil distribution is predicted on the basis of environmental correlation, in which surrogates or easy-to-measure environmental factors are used as explanatory variables (McKenzie & Ryan, 1999). Such environmental correlation can be expressed explicitly and conveniently via a class of regression model known as generalized linear models (GLMs) (McKenzie & MacLeod, 1989; McKenzie *et al.*, 1991; Moore *et al.*, 1993). Generalized linear models provide a framework that brings separate statistical models and methods of analysis into a single system with a common notation and unified estimation procedure. Both the correlation of soil moisture with quantitative attributes such as relative elevation and slope gradient and the association between soil moisture and qualitative indices such as hillslope position were found to be significant in Da Nangou catchment in 1999. Therefore, all these relationships can be integrated into the generalized multiple-linear regression models to develop the spatial prediction models of soil moisture. For example, the spatial prediction model of soil moisture can be developed using the generalized multiple linear regression with land use, hillslope position, cos(aspect), relative elevation slope gradient, and will be reported in a forthcoming paper.

Summary

The degree of spatial variation in soil moisture content and its relation to environmental attributes were studied at the Da Nangou catchment (3·5 km^2) in the semiarid Loess Plateau of China. Soil moisture measurements were performed biweekly at five depths in the soil profile (0–5 cm, 10–15 cm, 20–25 cm, 40–45 cm and 70–75 cm) from May to October 1998 and from May to September 1999 using Delta-T theta probe.

It was found that the mean and the coefficient of variation (CV) of the soil moisture content exhibit a similar pattern of profile distribution in 1998 and 1999 at the Da Nangou catchment. With increasing soil depth, the mean soil moisture content increases for all five layers and the CV also increases but beginning at 10–15 cm.

However, the dynamics behavior is different for the mean and CV in both years. It was observed that the CV is greater in 1999 with lower mean moisture than in 1998, and is lower following heavier rains and increases as the soil dries. However, it was found that in both years, heavier rains and higher mean moisture contents are often associated with lower variability (CV), and vice versa.

It was found that the environmental attributes such as land use and topography play controlling roles in the spatial distribution of both the time-averaged soil moisture and the layer-averaged soil moisture.

However, the relative roles of these environmental indices are different at different depths. In the surface soil (0–5 cm), the spatial variability of the time-averaged soil moisture (Fig. 4) is mainly attributed to the multiple environmental factors including land use, aspect, relative elevation and hillslope position. In the subsurface soil (10–15 cm, 20–25 cm) the relative elevation, hillslope position and aspect are the dominant factors. In 'deeper' soil layers (40–45 cm, 70–75 cm), the spatial variation in soil moisture is mainly due to land use, relative elevation and slope gradient.

The dynamic behavior in influence of different environmental indices on the layer-averaged soil moisture is different under different conditions of precipitation, moisture and vegetation. The relation of soil moisture with slope gradient, relative elevation and hillslope position is determined by the antecedent amount of precipitation. In general, the correlation of soil moisture with slope gradient shows a more significant increase following a greater amount of antecedent precipitation (with the exception of extremely heavy storms), and is followed by a decline. The relation of the soil moisture with both relative elevation and hillslope position exhibits an opposite trend. The influence of land use corresponds to the difference in vegetative characteristics, with a stronger influence in June and August with a greater difference in vegetation. A significant influence of cos(aspect) was found during early spring and autumn with a rapid change in solar irradiation.

The minimum sample size to characterize the spatial pattern of the soil moisture are different for 1998 and 1999, with a range between 21 and 195 in 1998 and a range between 8 and 58 in 1999. The sample size in this study is adequate to characterize the spatial variation in moisture at all five depths and on all 10 observations in 1999 (81 sites), but it is adequate only in the upper soil layers (0–5 cm and 10–15 cm) in 1998 (26 sites).

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