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Study of Time Dependency of Factors Affecting the Spatial Distribution of Soil Water Content in a Field-Plot

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Abstract. Temporal and spatial variability of water content in soil results from a complex interaction of different factors such as duration and frequency of rainfall, soil layering, vegetation, and topography. The objectives of this study were (i) to use a resistant median-polishing scheme to quantify the temporal variability of a depth and a horizontal location factor in an additive model, and (ii) to investigate the time stability of those two factors at a detailed temporal scale during different infiltration and redistributions cycles. Time series of water content were measured at 5 depths and 12 locations along a transect of 6 m using Time Domain Reflectometry (TDR). Measurements were repeated every 2-hours for 168 days under natural boundary conditions. At each time step, the mean water content of the soil profile, 5 depth factors and 12 location factors were estimated. The time series of these factors were qualitatively interpreted and related to the atmospheric and prevailing soil conditions. It was found that micro-heterogeneity plays an important role, even at this small plot-scale. The relative contributions of the factors were dependent on the antecedent soil moisture conditions. Also, the ratio of the deterministic variance, i.e., variance explained by the deterministic factors, of water content to the observed variance is variable in time. © 2001 Elsevier Science Ltd. All rights reserved

1 Introduction

Near-surface water content plays a key-role in many hydrological processes such as surface runoff, subsurface hydrology and describing interaction between different components of the hydrological cycle, e.g., across the land-atmosphere boundary. The response of the near-surface water content to rainfall is the resultant of many controlling factors such as topography, vegetation, soil properties and conditions (see Famiglietti et al. (1998) and references therein). An important research issue is to find a relation between the measured local-scale water content and the estimated water content at larger scales (e.g. Grayson and Western, 1998). Therefore, attention was paid to temporal stability of the spatial structure of water content and scale issues (e.g. Vachaud et al., 1985, Kachanoski and de Jong, 1988; van Weesenbeeck and Kachanoski, 1988; van Weesenbeeck et al., 1988; Mohanty et al., 2000b).

As pointed out by Famiglietti et al. (1998) and Mohanty et al. (2000b), different studies revealed some contradictions of the effects of the different factors on the mean and variance of water content. The site-specific combination of climate, soil, vegetation, topography, time and space of sampling of a specific study has an unique interaction affecting the spatial structure of the near-surface water content. However, to be useful in large-scale environmental studies, the basic processes controlling this interaction should be identified and quantified. In addition, most of the studies were conducted with low spatial and / or temporal sampling frequency as was stated by Famiglietti et al. (1998). To identify the processes driving the interaction between the different factors, a more detailed sampling both in time and space is needed.

In their detailed study, Famiglietti et al. (1998) identified a relationship between the mean soil water condition and the factors affecting the variability of the near-surface water content: for initial wet conditions, soil water content variability is mainly influenced by soil heterogeneity after rain events, whereas the combined effect of heterogeneity and topography influences the effect of a rain event on the water content variability of an initial drying soil. In an attempt to explain the controversy of the relation between the mean water content and the water content variance, Mohanty et al. (2000b) measured surface water contents at four hundred locations on a gentle slope on two successive days. They observed that although the overall mean of water content remained approximately constant between the two sampling dates, the field variances changed significantly due to water redistribution across the landscape. This implies that subsurface hydrological processes are important to understand the variability and spatial distribution of near-surface water content. Therefore, spatial and temporal variability of the

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near-surface water content should be investigated in relation with the dynamics of the water content at the deeper soil layers. In a parallel study, Mohanty et al. (2000a) showed the dominance of microheterogeneity in soil moisture variation.

To quantify the impact of land use changes on the variability of the near-surface water content, a quantification of the dynamic nature of the different factors (e.g. topography, vegetation, soil, ...) is needed. In other words, since, generally, the spatial variability is influenced by both deterministic and stochastic sources (e.g. Philip, 1980), a simple but robust method is required to determine the fraction of the observed variability that can be explained by nonrandom and deterministic sources. When a detailed picture of the magnitude of this fraction at different times is obtained, one can assess what the impact of changes in land use, topography, climate on water content (and, consequently, on hydrological processes) might be. The scale of observation (both in space and time) has an impact on the fraction of the variability explained by deterministic factors (e.g., Seyfried and Wilcox, 1995). In this paper, we will use a robust algorithm to explore the dynamic relations between the observed variability of water content and different deterministic factors.

Given the importance of the subsurface and microheterogeneity on the temporal variability of the near-surface water content, detailed (both in time and space) studies on water content variability at the plot-scale are needed to identify interactions between the different factors influencing near-surface water content. A primary objective of this study was to quantify the contribution of two factors (depth and location) to the observed variance of field-measured water content at a small spatial scale. A resistant median-polishing technique was used to estimate the coefficients of an additive model. This approach is similar to that of Mohanty et al. (2000a). Mohanty et al. (2000a) used this method to investigate the spatial structure of the residuals of an additive model. In this study, the factors itself are of interest, and the variance explained by a given factor or combination of factors as a function of time is defined. The second objective was to apply the approach to investigate the time stability of these contributions at a detailed, small temporal scale during different infiltration and redistribution cycles. Note that time stability within this study is associated with factors affecting the water content rather than the time stability of (geo)statistical parameters of the water contents itself (as introduced by Vachaud et al., 1985). Furthermore, given the temporal and spatial scale effects, the results obtained from this study are location-specific. However, we believe that the proposed algorithm has a generic applicability at different temporal and spatial scales.

2 Materials and methods

2.1 Experimental design

The experimental field is located in at Bekkevoort, Belgium. The soil is characterized as an Eutric Regosol in the FAO-classification system. In the upper 100 cm of the soil profile, three horizons were identified: Ap (0-25 cm), C1 (25-55 cm), and C2 (55-100 cm). Soil structure is weak (in Ap and C1) to moderate (in C2) and subangular blocky. Macropores are present throughout the entire soil profile. Soil physical properties were measured at different scales and using different methods and results are compiled in Jacques et al. (1999b).

Water content, solute concentration, pressure head, soil temperature, water fluxes and solute fluxes were measured during one year at several locations under natural boundary conditions in a 8 meter long and 1 meter deep soil profile. The experimental site has little microtopography and situated on a gentle slope. A complete description of the experimental set up, the measurement systems, and calibration procedures are found in Jacques et al. (1999b) and Jacques et al. (2000). In this paper, we selected a part of the water content data between 11 March 1998 and 28 August 1998 measured in the first 6 meters of the transect where Time Domain Reflectometry (TDR)-probes were installed (see below). For the benefit of the reader, a short description of the experimental design is repeated here.

Water content in the soil was measured using Time Domain Reflectometry (TDR). A trench was dug and TDR-probes (2 rods, 25 cm long, 0.5 cm rod diameter, 2.5 cm rod spacing) were horizontally installed at 12 locations with 50 cm spacings at 5 depths (15, 35, 55, 75, and 95 cm below the soil surface). Next to the trench, the vegetation (grass) was removed from the soil surface over an area of 8x2 m^2, since the focus of the research was on the physics of water flow in the soil medium. The soil surface was leveled and covered with a thin layer of gravel to minimize the erosive impact of rain and evaporation. The reflectogram for each TDR-probe was measured with a Tektronix 1502B cable tester and automatically recorded every 2 hours using the TDR-system developed by Heimovaara and de Water (1991). The travel time was derived using the algorithm of Heimovaara and de Water (1991) and related to the apparent dielectric constant of the soil. A site-specific calibration curve between the apparent dielectric constant and the water content was used (Jacques et al., 1999b).

2.2 Spatial-temporal data analysis

Two factors (location and depth) were quantified in a space-time analysis using a multiple random space function approach with the water content as the random variable. Although such an approach is generally used when the space domain is more densely informed than the temporal domain (Kyriakidis and Journal, 1999), it is appropriate in this exploratory study since time series of the effect of location in the spatial domain are the main subject of this study. At each time step, the spatial distribution of the measured water contents is considered as a random function. In this exploratory stage, an additive model is considered to describe the spatial structure of the regionalized random variable (similar to analysis of different soil properties by Mohanty and Kanwar, 1994; Jacques et al., 1999a; Mohanty et al., 2000a) in which it is intrinsically assumed that all terms in the additive model are dynamic and thus time dependent:

$$\theta_t(x,z) = \mu_t + \delta_t(z) + \eta_t(x) + \varepsilon_t(x,z) \qquad (1)$$

where x and z are the horizontal and vertical coordinates, subscript t is the time, $\theta_t(x,z)$ is the water content at time t and location (x,z), μ_t is the mean water content for the total spatial domain at time t, $\delta_t(z)$ is the depth effect at time t, $\eta_t(x)$ is the location effect in the horizontal plane at time t and $\varepsilon_t(x,z)$ the small scale variability at time t and location (x,z) due to experimental error and microheterogeneity. No interaction between the vertical and horizontal factors is assumed.

To estimate the different terms in Eq. (1), an iterative resistant median-polishing approach is used (Cressie, 1993; Mohanty and Kanwar, 1994; Jacques et al., 1999a). For the random function at time step t, we obtain one estimate of μ_t, one estimate of δ_t for each depth, one estimate of η_t for each location on the horizontal plane and one estimation of ε_t for each measurement site (x,z). Estimates of the overall mean, the ith depth factor, the jth location factor at a given time t are represented by $M(t)$, $D(i|t)$, and $H(j|t)$, respectively. Given the specific two-dimensional sampling layout used in the experiment and the nature of the median-polishing estimation technique (see Cressie, 1993, for details about the algorithm), the water content at a specific location j, depth i and time t is expressed as:

$$\theta(i,j,t) = M(t) + D(i|t) + H(j|t) + r(i,j|t) \qquad (2)$$

where $r(i,j|t)$ is the residual term and may be interpreted as an estimate of $\varepsilon_t(x,z)$. In some studies, $r(i,j|t)$ is used for further geostatistical analysis. In this study, it is considered as an error term and only the estimate of the mean and the two factors are investigated. $M(t)$, $D(i|t)$, and $H(j|t)$ are estimated for each time step ($t = 0,\ldots,160$ days) and their time series are plotted to identify if they are stable in time and to investigate their interdependence with the specific sequence of flow conditions (infiltration and redistribution) in the field. In the remainder of the paper, the depth factor of the ith depth is denoted as D_i.

Next, the effect of a given factor is quantified by calculating the variance of the water content after removing the factor. We first defined the total variance of the water content at a given time t as:

$$s^2(t) = \frac{1}{N-1}\sum_i \sum_j \left(\theta(i,j|t) - M(t)\right)^2 \qquad (3)$$

The fraction of the variance of the measurements due to the two factors is (Russo and Jury, 1986; Jacques et al., 1999a):

$$s^2_{DH}(t) = \frac{1}{N-1}\sum_i \sum_j \left(D(i|t) + H(j|t)\right)^2 \qquad (4)$$

which is called the deterministic variance. We also defined two additional variables to filter out the estimated depth or horizontal location factor:

$$\begin{aligned} \theta_{-D}(i,j,t) &= \theta(i,j,t) - D(i|t) \\ \theta_{-H}(i,j,t) &= \theta(i,j,t) - H(j|t) \end{aligned} \qquad (5)$$

The variance of these two median-polished variables are then defined as:

$$\begin{aligned} s^2_{-D}(t) &= \frac{1}{N-1}\sum_i \sum_j \left(\theta_{-D}(i,j,t) - Med[\theta_{-D}(i,j,t)]\right)^2 \\ s^2_{-H}(t) &= \frac{1}{N-1}\sum_i \sum_j \left(\theta_{-H}(i,j,t) - Med[\theta_{-H}(i,j,t)]\right)^2 \end{aligned} \qquad (6)$$

with Med[.] an operator for the median of a given series of data.

3 Results and discussion

Figure 1a shows the rainfall conditions during the study period with a total amount of precipitation equal to 39.05 cm. Seven characteristic periods were identified: (1) Dry I, between March 11 and April 1, (2) Wet I, between April 1 and May 6, (3) Dry II, between May 6 and May 25, (4) Wet II, between May 25 and June 17, (5) Interwet I, between June 17 and July 29, (6) Dry III, between July 29 and August 19, and (6) Wet III, after August 19. Using the median-polishing technique, the different components of Eq. (1) at each time t (days) were calculated. Fig. 1b shows that the estimates of μ_t, $M(t)$, reflected a strong correlation with the different characteristic periods. During the first and second dry periods M gradually decreased. During the wet periods, M increased gradually when rainfall is small (e.g., the seven days of rain after 1 April). A sharp increase followed by a rapid decrease in mean soil moisture was noticed during heavy rainstorms. When several heavy rain storms occurred in short intervals, M became quite erratic (end of Wet II). In general, a net increase in M during the wet periods was observed. During the Interwet I, a decrease in M was observed followed by a sharp (and sometimes erractic) increase. During the first week of Wet I, we observed a gradual increase during moderate rainfall, whereas during the Interwet I, a decrease or erratic behavior was observed during moderate rainfall (roughly between 7 and 21 July). This difference may be due to the history of the soil water content. In the first case, the soil was relatively dry and absorbed the water. In the second case, the soil was very wet (due to Wet II), so water was still draining and any additional amount of water (due to Interwet I) was also rapidly removed from the profile. The time series of s^2 (Eq. 3) is shown in Fig. 1c. Variances (s^2) showed a strong negative correlation with the general pattern of $M(t)$. Heavy precipitation events showed pronounced effects on M but limited effects on s^2 (e.g., the two peaks in M between April

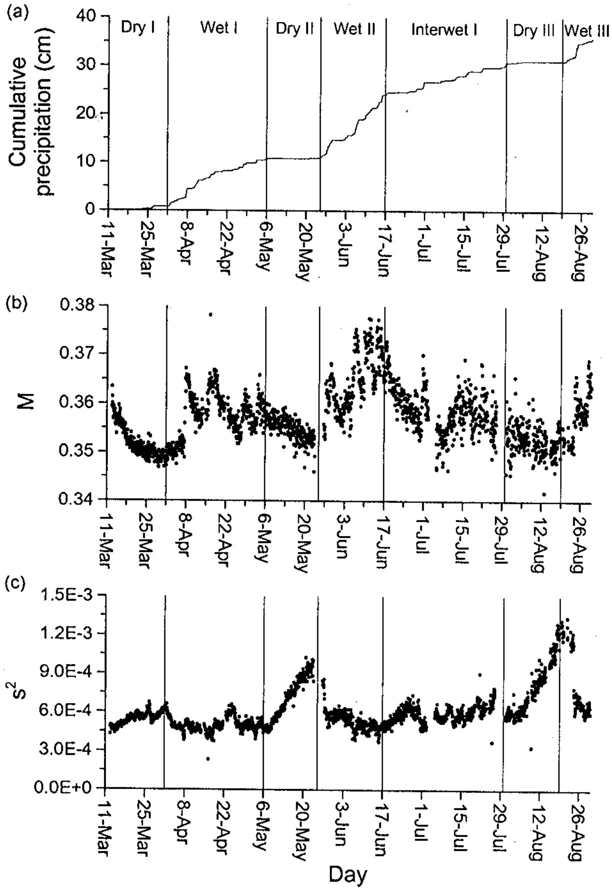

Fig. 1. (a) Cumulative precipitation during the experimental period, (b) time series of estimated overall mean $M(t)$, and (3) time variance of total variance of the water contents $s^2(t)$. The vertical lines indicate the seven different periods.

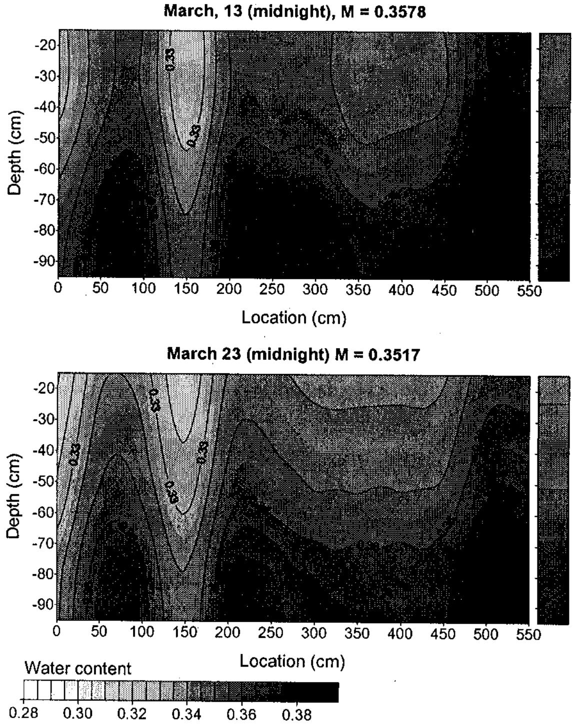

Fig. 2. Contour plots of water contents estimated from $M + D_i + H_j$ at two moments during Dry I. Vertical bars at the right hand side give the water contents estimated from $M + D_i$.

8 and April 22 do not result in distinctive decreases in s^2). However, rain after a long dry period (Dry II) gave a steep decrease in s^2. Interestingly, above a threshold value of M (somewhere above 0.36) the field variance s^2 decreases gradually. Below this threshold M-value, s^2 increased or decreased with rain events. During the interwet I period, s^2 changed gradually.

Depth factors at the 15 and 35 cm depths, D_{15} and D_{35}, were in general smaller than those at the 75 and 95 cm depths, D_{75} and D_{95} (results not shown) indicating wetter zones were located deeper in the profile. The time dependency of the depth factors was most pronounced for the upper layer following the general pattern of M. At the second depth, variation in D was less pronounced compared to the first depth. A small delay in the Dry II and Dry III was observed for D_{35} compared with D_{15}. No decreasing effect in D_{35} is observed during the first dry period whereas this was the case for D_{15}. One possible explanation may be the absence or presence of limited evaporation during the early spring and summer months, respectively. D_{75} and D_{95} showed an opposite behavior with M as a function of time. For example, during Dry I, D_{75} and D_{95} increased whereas M decreased, whereas the opposite was observed in the Wet I, implying that the water content at those depths changed less with time compared to the upper parts of the soil profile.

A total of 12 time series of H-factors were calculated (not shown). In general, H_j were rather close to zero and relatively stable in time. In some cases, large-scale temporal variation was observed. In the second half of the experiment, the estimated H-factors showed more error due to the malfunctioning of some of the TDR-probes. There was some spatial variability in H along the transect indicating alternating wet and dry zones at the plot scale. To illustrate the H-factors, water content profiles estimated as M+D_i+H_i at the beginning and the end of Dry I are shown in Fig. 2 (obtained by an inverse squared distance interpolation method). The effect of the different H-factors was very clear: some drier spots on the left side, some wetter spots on the right side and average values in the center. At the beginning of Dry I, the location factor determined the variation in the water content distribution between 250 and 450 cm. At the end of Dry I, however, much of this variation of H between 250 and 450 cm was leveled out.

Fig. 3a shows that the variance attributed to the depth and location factors during time, s^2_{DH} (Eq. 4) had a similar pattern to the time series of s^2 (Fig. 1c) although less pronounced for individual rain events. Interestingly, in Dry II, there was a small time delay effect between the total variance of the water observed variance are plotted. Interestingly, this ratio reached sometimes almost 100 % for factor D (Fig. 4b)during the rain events indicating that, for these events, D did not explain water content variability. The depth to total variance ratio reacted also directly on dry or rain events (in contrast to s^2_{DH}). Moreover, this ratio reached lower values at the end when the three drying periods are compared with each other. This indicated a more pronounced depth effect in the latter dry events, probably due to evaporation. The ratio of s^2_{-H} over s^2 was more constant in time, except during the second half of the experiment. During the second half we experienced some malfunctioning for few TDR-probes. However, accounting for the location factor on the small spatial scale of the field experiment (6 meter) decreased the variance already by 20%.

4 Conclusions

The spatial and temporal variability of the soil water content was investigated using an additive model. Given the specific and small-scale experimental set-up, only two main factors were defined: depth and horizontal location. A median-polishing algorithm was used to estimate the different components (i.e., a mean factor, five depth factors, and twelve location factors) of the model as a function of time. This approach allowed to investigate the time dynamics of the main factors and the contribution of these factors to the overall observed variability of water contents. Since an additive model was used, the relative effect of one specific factor (here depth and location) on the water content dynamics could be quantified. When a larger area is investigated, the location factor can be divided in different subcomponents such as climate, vegetation, topography, and soil type. The dynamics of the near-surface water content in a plot-scale depends, in a complex manner, on the antecedent soil moisture conditions, and the history, the amount and frequency of rain. In addition, the detailed plot-scale study showed that, even at the small spatial scale, micro-heterogeneity is an important component contributing to the spatial distribution of soil water content (e.g. up to 20% in the horizontal direction for a 6 m long transect).

Given the small spatial sale of this study, the obtained conclusions are site-specific. We believe, however, that the adapted algorithm is applicable at larger spatial and temporal scales. This algorithm allows to quantify the temporal dynamics of factors influencing water content variability both near the surface and at the deeper depths. Detailed analysis of the time series of the median-polished estimated factors might reveal how the spatial water content variabilitity is organized and structured. As shown by Merz and Plate (1997), this structure has a tremendous effect on the runoff process, and, therefore, on other hydrological processes, as well as on migration of nutrients and on plant growth.

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