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지표면 조건의 변화에 따른 토양수분의 변화 평가

Evaluation of the Impact of Land Surface Condition Changes on Soil Moisture Field Evolution

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Abstract

Soil moisture is affected by regional climate, soil characteristics and land surface condition, etc.. Especially, the changes in land surface condition is more than other factors, which is mainly due to rapid urbanization and industrialization. This study is to evaluate how the change of land surface condition impacts on soil moisture field evolution using a simple model of soil moisture dynamics. For the quantification of soil moisture field, the first half of the paper is spared for the statistical characterization based on the first- and second-order statistics of Washita '92 and Monsoon '90 data. The second half is for evaluating the impact of land cover changes through simulation study using a model for soil moisture dynamics. The model used is based on the linear reservoir concept along with the diffusion considering through the top soil layer. The model parameters, the loss rate and the diffusion coefficient, have been estimated using the observed data statistics, where the changes of surface conditions are considered into the model by applying various parameter sets with different second-order statistics. This study is concentrated on evaluating the impact due to the changes of land surface condition variability. It is because we could easily quantify the impact of the changes of its areal mean based on the linear reservoir concept. As a result of the study, we found; (1) as the variability of land surface conditions increases, the soil moisture field dries up more easily, (2) the variability of the soil moisture field is the highest at the beginning of rainfall and decreases as time goes on to show the variability of land surface condition, (3) the diffusion effect due to surface runoff or water flow through the top soil layer is limited to a period of surface runoff and its overall impact is small compared to that of the loss rate field.

Keywords: Soil Moisture, Soil Moisture Dynamics, Temporal-Spatial Variability, Land Surface Condition

요 지

토양수분은 기후, 토양 및 지표면의 조건 등에 의해 영향을 받는다. 특히, 급격한 도시화 및 산업화의 영향으로 다른 영향인자들 보다 지표면 조건의 변화가 크게 바뀌고 있다고 할 수 있으며 본 연구에서는 이러한 지표면 조건의 변화가 토양수분에 어떻게 영향을 미칠 수 있는지를 간단한 토양수분 동역학 모형을 이용하여 평가해 보았다. 먼저, 본 논문에서는 토양수분의 시간적 공간적 통계특성을 정량화 해보기 위해 논문의 전반부를 Washita '92 자료 및 Monsoon '90 자료의 1차원 및 2차원의 통계적 특성을 정리하는데 할애하였으며, 논문의 후반부에서 지표면 조건의 변화를 모형 매개변수의 통계적인 특성을 변화시킴으로서 고려하고 각각의 경우 토양수분이 어떻게 반응하는가를 살펴보았다. 사용된 모형은 선형저수지의 개념에 토양상층에서의 공간적 거동을 고려하기 위하여 확산의 개념을 도입하여 구성된 모형이다. 모형의 주요 매개변수는 손실률과 확산계수로 나타나고, 이들은 관측자료의 통계특성을 이용하여 추정될 수 있다. 지표면 조건의 변화는 모형의 매개변수에 다양한 통계특성을 적용하여 고려하게 된다. 특히, 본 연구에서는 지표면 조건의 평균적인 변화보다 이의 공간적인 분산도의 변화에 초점을 맞추어 분석하였다. 이는 평균적인 지표면 조건의 변화는 선형저수지의 이론에 근거하여 그 영향을 쉽게 판단할 수 있기 때문이다. 본 연구의 결과를 정리하면 다음과 같다. (1) 지표면 상태의 분산도가 커질 경우 토양수분은 더 쉽게 손실된다, (2) 토양수분의 분산도는 모의 초기에 강우의 영향으로 크게 나타나나 시간이 경과함에 따라 감소하고 점차 지표면 상태의 분산특성을 나타내게 된다, (3) 지표면 유출이나 토양상층에서의 토양수분 이동에 따른 확산의 영향은 지표면 유출이 존재하는 강우기간으로 제한되며 전체적으로 토양수분의 변화에 미미한 영향을 미친다.

핵심용어 : 토양수분, 토양수분동역학, 시공간 분산도, 지표면 조건

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1. Introduction

Soil moisture is a fundamental process connecting the atmosphere and the geosphere through precipitation and evapotranspiration. Soil moisture is also the dominant factor in shaping the ecosystem response to the physical environment, and in turn affected by climate changes or anthropogenic activities. The rapid urbanization during last decades has driven the changes in land use pattern to result in land cover changes, which has altered the characteristics of land surface processes like infiltration, surface runoff, evaporation, etc.. For example, urbanization results in the increase of impervious area, hence induces rapid drainage of water and evaporation. Also the conversion of forest to farm could increase the infiltration rate as well as accelerate the evaporation of soil water. With the possible mean temperature increase due to the global warming, the soil water could be evaporated more easily.

From the macroscale point of view, we may assume the top soil layer as a simple reservoir, where the input is the precipitation and the output is losses from surface runoff, evaporation and deep percolation. As the land cover controls the infiltration and evapotranspiration, the changes of it implies the changes of reservoir characteristics including the loss system.

The change of land cover may be divided into two cases; the changes of areal average and its spatial variability. For the case of changes in mean land surface conditions, the response from the reservoir (here, the top soil layer) is rather straightforward. That is, if we could quantify the land cover changes in a way such as an increase or decrease of the loss rate, the soil moisture content will be decreased or increased to make the system stabilized. However, the case of changes in its spatial variability with the same areal mean value is rather confusing. To approach the answer of this question, we will, first, review the basic statistical characteristics of the soil moisture field by summarizing the Washita '92 and the Monsoon '90 data analysis (Yoo and Shin, 1998; Kim et al., 1998). This will help us to understand the basic characteristics of soil moisture field in time and space, and could also be used for the parameter estimation of a soil moisture dynamics model to be used. The impact of land cover change on the soil moisture field, which will cover the second half of the paper, will then be evaluated numerically by investigating how the soil moisture field evolves depending on the land cover change. In this study the land cover change will be considered by applying different statistics for model parameters such as mean and variance.

2. Statistical Characteristics of Soil Moisture Field

The statistical characterization of the soil moisture field are summarized using the two soil moisture fields; the Washita '92 and the Monsoon '90 data. Basically, two data are different in their structures. The Washita '92 soil moisture data is a remotely sensed one which provides 8 sets of data collected once a day. It is composed of 200 m×200 m areal average soil moisture contents over the site of approximately 20 km×40 km in the Little Washita watershed, Oklahoma. On the other hand, the Monsoon '90 data provides several point measurements for a relatively long time period. Point gauges are located randomly over Walnut Gulch area in Arizona. That is, the Monsoon '90 data can be said to be good for temporal analysis and the Washita '92 data for spatial analysis. The reader could find detailed information on the Washita '92 data from Jackson et al. (1993) and Allen and Naney (1991), and the Monsoon '90 data from Kustas and Goodrich (1994).

2.1 Temporal Statistics of Soil Moisture

The one-dimensional temporal characteristics of the soil moisture field could be summarized using the correlogram of temporally sampled data and the cross correlogram between the rainfall and the soil moisture. The decay pattern depending on the soil, land use and cover could also be used supplementary for the one-dimensional characterization of soil moisture.

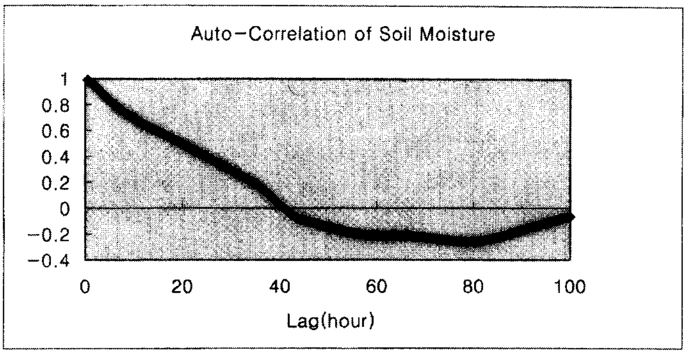
From the analysis of the Washita '92 (Yoo and Shin, 1998) and Monsoon '90 data (Kim et al., 1998) we can find that the soil moisture is basically affected by land surface conditions like soil texture, land use and land cover. The correlogram of soil moisture data collected in time has a highly correlated structure with a relatively long tail (e.g., Monsoon '90 data analysis by Kim et al. (1998)), and in some cases the lag-1 correlation coefficient is higher than 0.9 such as the Kendall South 1 data (one of Monsoon '90 data), Walnut Gulch watershed (see Figure 1(top)). The highly correlated structure seems to be due to the detention effect of soil as a big reservoir considering the amount of water it bears and the flow rate across it. Yoo and Shin (1998) also found that the autocorrelation function of soil moisture, vegetal cover and soil texture fields are very similar in shape, and concluded that the statistical characteristics of soil moisture field is strongly affected by the very highly correlated soil texture field, but disturbed a little by the less correlated vegetation field.

The impact of rainfall on soil moisture in time could be conjectured through the bivariate time series analysis between rainfall and soil moisture. The rainfall seems to play a role as a major source of water to the soil moisture. However, it was difficult to detect the phase shift between them as the soil moisture had sampled in a relatively long interval (e.g., 30 minutes for Kendall South-1 data). The impact of rainfall on soil moisture seems instantaneous, so more frequent sampling requires for the detection of it. It is also noticeable that the cross-correlation function (also see Figure 1 (bottom)) shows little connection between the soil moisture and the rainfall for any time lag, which might be due to the discrepancy between intermittent rainfall and continuous soil moisture. As each process is totally different (continuous /discontinuous), it my be farfetched to attempt to link them statistically under the assumption of stationarity (Kim et al., 1998).

The soil moisture decay rate in time varies widely depending on the soil type. Yoo and Shin (1998) estimated the decay rate of soil moisture in time using the Washita '92 data assuming that the soil moisture follows the linear exponential decay in time such as in the linear reservoir model (Entekhabi and Rodriguez Iturbe, 1994). The coefficients estimated for each soil type are significantly different from each other (see Table 1) ranging from 0.057 to 0.092/day. These values were verified by estimating the time after last rainfall for different soil type with the average soil moisture content at June 10 for each soil type. Excluding the soil type VI, the values are approximately 20 days, which coincides the reported rainfall events at the site. For the case of Monsoon '90 data, the decay rate was estimated to have 0.11 to 0.17/day with the mean of 0.14/day, which is higher than those for the Washita '92 data. The higher value of decay rate seems to be due to the higher evaporation rate rather than the soil characteristics of Walnut Gulch area (that is, the arid region for Monsoon '90 and temperate region for Washita '92). Example soil moisture decay curves for various soil types are shown in Figure 2.

2.2 Spatial Statistics of Soil Moisture Field

The spatial characteristics of the soil moisture



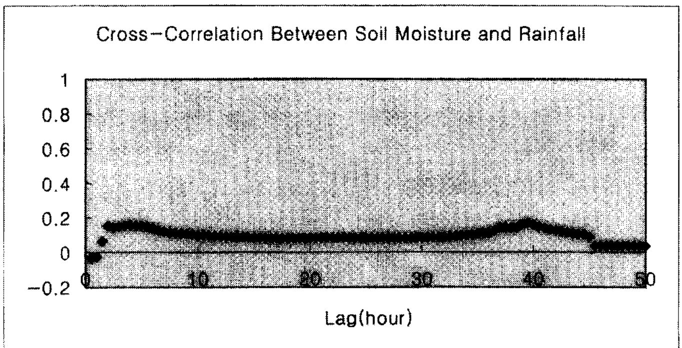


Figure 1. One-Dimensional Auto-Correlation Function of KS-1 Data (top) and Cross-Correlation Function Between KS-1 Soil Moisture Data and Surrounding Rainfall (bottom), Walnut Gulch Experiment.

Table 1. Decay Coefficients of Soil Moisture (SM) for Different Soil Texture (from Yoo and Shin, 1998)

Soil Texture Type (classification, porosity)	Soil Moisture Decay Coefficient, α(STDV)	Time after Rain (day)
I(sand, 0.417)	0.092 (0.035)	19.57
II(loamy fine sand, 0.401)	0.072 (0.027)	22.22
III(fine sandy loam, 0.412)	0.076 (0.033)	20.3
IV(loam, 0.434)	0.057 (0.027)	22.24
V(silt loam, 0.486)	0.062 (0.036)	19.7
VI(silty clay loam/clay loam, 0.437)	0.081 (0.033)	15
VII(pits, quarries and urban, ---)	---	---
VIII(gypsum, ---)	---	---
IX(water, ---)	---	---

field could be summarized using the two-dimensional correlogram and spectrum. These second-order statistics enable us to partially characterize the spatial structure of soil moisture, and can also be used to compare with the other related fields like land cover and soil texture. Impact of rainfall to soil moisture field variability could also be evaluated based on the observed data and/or simulation study (Yoo et al., 1998).

The two-dimensional correlogram of the soil moisture field is smoothly decayed to zero as the distance increases, and has a very high lag -1 correlation coefficient as in the Monsoon '90

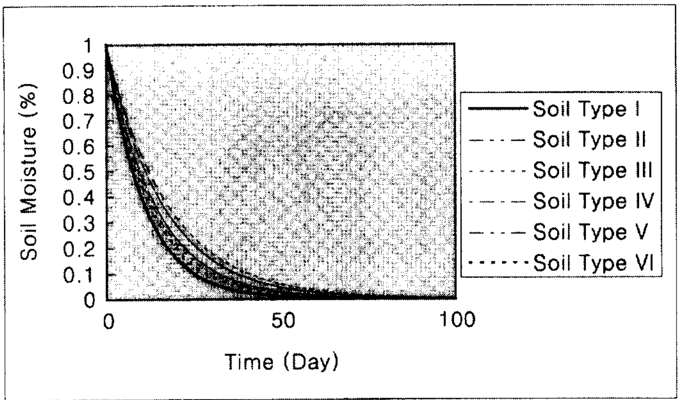


Figure 2. Example Soil Moisture Decay Curves for Soil Types in Table 1.

temporal data (Figure 3(top)). Yoo and Shin (1998) found that the soil texture field (i.e., porosity, conductivity, etc.) and the NDVI (Normalized Difference Vegetation Index) field has similar shape of correlogram, but different lag-1 correlation coefficients; highest for the soil texture field and lowest for the NDVI field. All these correlograms are not isotropic.

The spectrum (Figures 3(bottom)) of the soil moisture field is centered at 0 and smoothly decay to zero as the frequency increases, which is the typical shape of a highly correlated field. Spectra of the soil texture field and the NDVI field also show similar shape (Yoo and Shin, 1998). The normalized spectra derived by dividing each spectrum by the peak value to make the peak 1.0 show that the spectrum of the NDVI field decays most fast to zero among three and most slowly for the spectrum of soil texture field. The soil moisture field is in between the two, the same result as in the correlograms. This result directly indicates that the variability of the soil moisture field is a little higher than that of the soil texture field, but less than that of the vegetation. This observation could be explained as follows. For any site, the soil texture may be assumed as a non-varying field, but the soil moisture within the top soil layer is affected by several factors like rainfall, topography, vegetation, etc. Therefore, the variability could be increased. On the other hand, the vegetation is very dependent on the soil moisture content, hence it could have more variability than the soil moisture field. It is interesting to remind the result by Yoo et al. (1998) that the rainfall might be simplified as a source of water without any consideration of its spatial variability or organization. This means that the surface condition such as soil texture, land use and land cover plays the major role rather than the spatial structure or organization of rainfall.

The one-dimensional spatial correlograms derived in both longitudinal and latitudinal directions by Yoo et al. (1998) using the Washita '92 data also show similar results. With the assumption of stationarity, the correlation lengths were estimated in both the longitudinal and the latitudinal directions for the soil moisture and the soil porosity field of the Washita '92 data (see also Table 2). As explained by them, the rough estimation of the correlation length shows no considerable patterns in time. Rather a noticeable result could be found in the comparison of the correlation functions of the relative soil moisture field and the soil porosity field. These correlation functions are almost identical in both directions,

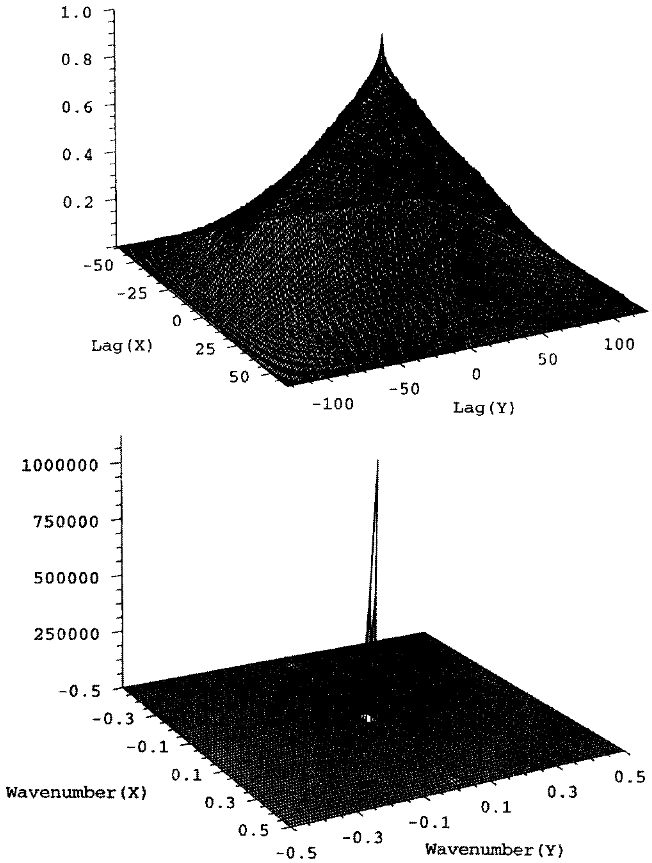


Figure 3. Two-Dimensional Correlogram (top) and Spectrum (bottom) of Washita '92 Soil Moisture Data

Table 2. Mean, Standard Deviation(STDV), and Correlation Length(CL) of the Washita '92 Soil Moisture Field and Soil Porosity Field Data (from Yoo et al., 1998)

Data	Mean(%)	STDV(%)	CL(Long.,m)	CL(Latt., m)
June 10	53.48	13.58	2556	1800
June 11	48.47	12.36	2440	1672
June 12	47.45	11.69	2612	1958
June 13	43.26	10.99	2330	2190
June 14	46.94	11.21	2490	1996
June 15	-		-	-
June 16	40.35	10.61	2648	1862
June 17	35.49	13.33	2492	1696
June 18	28.37	10.15	2024	1552
Porosity	0.4425	0.033	2418	1550

which shows the strong link of the soil moisture field variability to that of soil texture. As the last rain was reported about 20 days before, the impact of rainfall could be excluded in this case. The correlation lengths of the Washita '92 soil moisture, the soil texture, and the NDVI were estimated more or less the same about 2.4 km for longitudinal direction and 1.6 km for latitudinal direction. Recently, the Washita '92 soil moisture fields have been analyzed by Rodriguez-Iturbe et al. (1995) to show that it follows the power law. In the paper, an interesting part noticeable is that the spatial scaling structure of the soil moisture field may arise from the existing scaling in the soil properties.

3. Evaluation of the Impact of Land Surface Conditions on Soil Moisture Evolution

3.1 A Model for Soil Moisture Dynamics

The model for soil moisture dynamics used in the study is originally proposed by Entekhabi and Rodriguez-Iturbe(1994). This model has been used for evaluating the impact of rainfall on soil moisture variability by Yoo(1998) and Yoo et al. (1998) using different rainfall models. The model was derived based on the linear reservoir concept, where the input is the rainfall and the output is defined as loss due to surface run-off, evapotranspiration, and deep percolation. This model also considers the water propagation on surface or through the top soil layer by diffusion. These two components constitute the intrinsic dynamics of soil moisture driven by the stochastic rainfall process, which can be written as the following the linear stochastic partial differential equation form:

$$\frac{ds}{dt} = -\frac{\eta}{nZ_r}s + k\nabla^2 s + \frac{P}{nZ_r} \tag{1}$$

where; s is the relative soil moisture defined as the ratio of soil moisture in the total volume of void [dimensionless]; n is the soil porosity [dimensionless]; Z_r is the depth of the soil top layer [L]; η is defined as the loss rate with dimension of $[\mathrm{LT}^{-1}]$; k is the diffusion coefficient $[\mathrm{L}^2\mathrm{T}^{-1}]$; and P is the rain rate $[\mathrm{LT}^{-1}]$. nZ_r is also called as the effective soil depth.

This equation represents the dynamics of the soil moisture field and the relationship between the soil moisture spectrum, the noise forcing spectrum, and the rainfall spectrum can be derived easily using the Fourier analysis (Box et al., 1994).

$$\Phi_{ss}(\nu, \omega) = G(\nu, \omega)\Phi_{pp}(\nu, \omega) \tag{2}$$

where Φ_{ss} is the soil moisture spectrum, Φ_{pp} is the rainfall spectrum and the so-called gain function, $G(\nu, \omega)$, is

$$G(\nu, \omega) = \frac{(1/nZ_r)^2}{(4\pi^2 k\nu^2 + \eta/nZ_r)^2 + 4\pi^2\omega^2} \tag{3}$$

The model parameter estimation can be easily done for drying period. The loss coefficient can be estimated using the decay coefficient derived from the soil moisture data. For the Washita '92 data, η is estimated to be about 0.0105 m/day with nZ_r of 0.15 m. The diffusion coefficient can also be estimated using the spatial second-order statistics. For the stationary case, the model becomes

$$nZ_r(k\nabla^2 s) - \eta s + P = 0 \tag{4}$$

With the assumption of white noise for the noise forcing P, the solution of this equation is an isotropic random field, and the correlation $\rho(r)$ between two points of this field at distance r apart is represented such as:

$$\rho(r) = r\sqrt{\frac{\eta}{nZ_r \cdot k}}\, K_1\left[r\sqrt{\frac{\eta}{nZ_r \cdot k}}\right] \tag{5}$$

where K_1 is the modified Bessel function of the second kind, order 1. Provided the correlation function, the diffusion coefficient k can be easily estimated by the trial and error method. For the Washita '92 data, the diffusion coefficient is estimated to be about 487 m^2/day. The diffusion coefficient estimated here is relatively high comparing the lower bound of tens of square meters per day by Entekhabi and Rodriguez-Iturbe(1994), who estimated the lower bound considering the water velocity through the unsaturated porous media. A possible explanation for the difference is that the parameters by Entekhabi and Rodriguez-Iturbe are for the continuous space, however, the Washita '92 data is discrete and averaged over 200×200 m^2. Figure 4 shows the possible range of decay rate depending on the averaging size.

During the storm when soil is fully saturated, the role of diffusion mechanism increases to propagate the excess of water to the neighbor by surface water flow. Thus, the diffusion coefficient during storm period should be estimated by considering the surface water propagation velocity, which is up to hundreds of meters per hour. Resulting diffusion coefficient can be hundreds of km^2 per day. The loss rate also increases almost linearly as the diffusion coefficient increases as shown in Equation 5 (also see Figure 5).

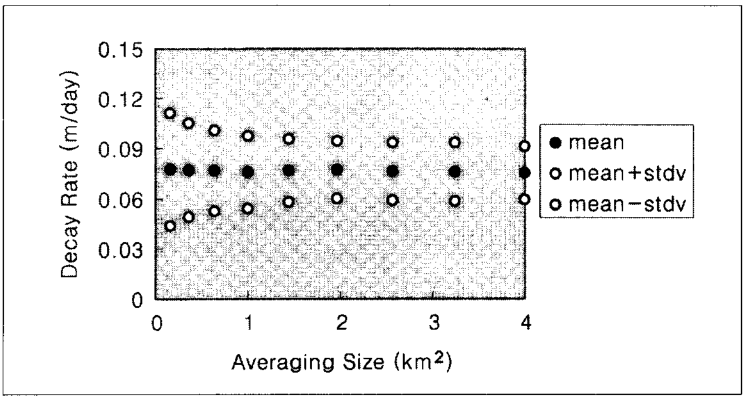


Figure 4. Spatial Variability of Decay Rate with Different Averaging Size (Washita '92 Data)

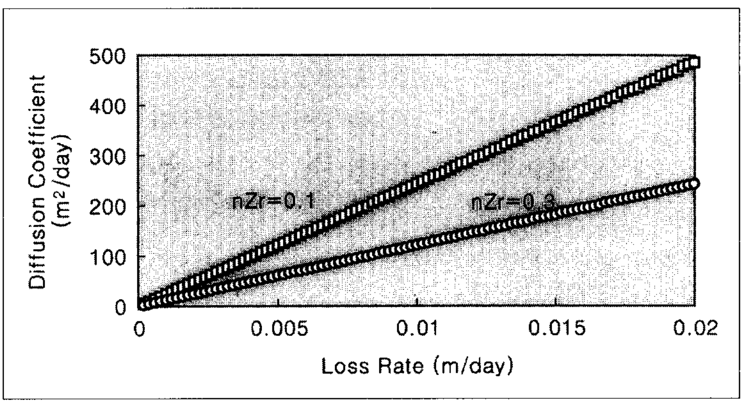


Figure 5. Relationship Between Loss Rate and Diffusion Coefficient With Different Top Soil Depth

3.2 Evaluation of the Impact of Soil and Land Surface Condition on Soil Moisture Field Evolution

The model mentioned at the previous section has two parameters, the loss rate and the diffusion coefficient. These two parameters count for the different soil texture, land use and land cover. In this part of the study, the impact of land surface condition to the soil moisture field evolution was evaluated by simulating the soil moisture evolution depending on different parameter variability with the mean value fixed.

The simulation study was performed over the domain of 64 km×64 km with the grid size of 1 km×1 km and for 60 days with the time interval of 1 day. The rainfall forcing was given randomly over the domain at the beginning of the simulation. The model parameters used were those estimated using the Washita '92 data. As you see in Equation 5, the model parameters are dependent with each other, and the relationship is almost linear (see Figure 5). Also, these parameters vary depending on the effective soil depth, nZ_r. For the case of Washita '92 data we could estimate these parameters using the first- and the second-order statistics, but is only for dry period. For the storm period when the surface flow occurs, these parameters become much higher, but unfortunately the direct estimation of them from the observed data is very difficult due to the deficiency of proper data such as the mean velocity of surface flow during rain. Hence, we adopt a rather simple method by comparing the typical values of flow velocities on land surface and through the porous media. That is, the diffusion coefficient during the storm period was multiplied by one million times when and where more that 100 % of soil moisture exists, and one thousand times for the loss rate. These multiplication factors have been derived by considering the typical water flow velocities through the soil medium during the dry period and on land surface during the storm period, which are tens of centimeters per day and tens of kilometers per day, respectively (Entekabhi and Rodriguez-Iturbe, 1994). Two different values of multiplication factor are from dimensional consideration. Also for easier simulation the temporal variation of these parameters, that is, the gradual shift from the highest to the lowest values depending on the existence of overland flow has not considered, but applied two extreme values. In the simulation we could see more than 100 % of soil moisture content, that is, the surface runoff, for the first four or five days.

The simulation study covers three different cases to see the impact of the spatial variability of the loss rate and diffusion coefficient on soil moisture field evolution and its spatial variability. These are 1) considering the variability of the loss rate field only, 2) considering the variability of diffusion coefficient field only, and 3) considering the variability of both loss rate and diffusion coefficient fields based on the relationship depicted in Figure 5. The results of the simulation study are summarized;

1) As the variability of the loss rate field increases, the soil moisture dries up faster and its spatial variability also increases (see Figure 6-(top)). As simulation goes on, the spatial variability of each soil moisture field becomes distinct counting the loss rate field (that is, the higher the variability of loss rate field, the higher the variability of soil moisture field), but the areal average of soil moisture converges to a certain value regardless of its loss rate variability.

2) As the variability of the diffusion coefficient field increase, no obvious impact of it could be found in the mean soil moisture content and its spatial variability. However, higher spatial variability of diffusion coefficient

field seems to smooth more the soil moisture field and also decrease the areal average of soil moisture content as time goes on (Figure 6-(middle)).

3) As we increases the variability of both loss rate and diffusion coefficient fields, the soil moisture field shows mixed impact of two model parameter fields applied separately

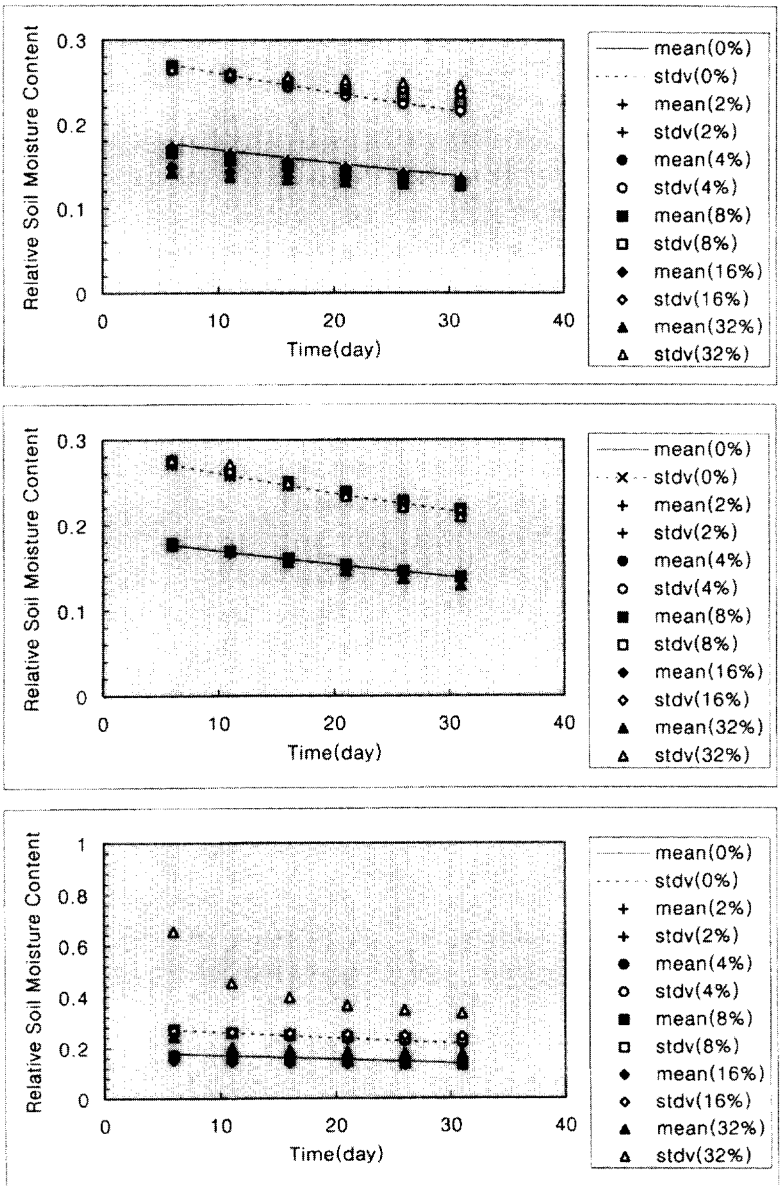


Figure 6. Temporal Changes in Areal Average Values and the Standard Deviations of Soil Moisture Field Due to the Different Loss Rate Field (top), the Different Diffusion Coefficient Field (middle) and both the Different Loss Rate and Diffusion Coefficient Fields Variability (bottom)

(Figure 6 (bottom)). The initial high variability of soil moisture field applying the 32 % of loss rate and diffusion coefficient fields decreases fast as simulation goes on.

The soil moisture field looks more sensitive to the loss rate field, which might be due to small values of diffusion coefficient applied during the dry period. Also the grid size we adopt in the simulation, 1 km×1 km, seems too big to extract the impact of the diffusion coefficient during dry period. Theoretically the spatial scale less than one half of the square root of the diffusion coefficient, i.e., about 20 m×20 m for Washita area, is necessary for the detection of it, but that may be too small for large scale simulation. During the existence of overland flow, however, the diffusion mechanism plays an important role to decrease the spatial variability of soil moisture field.

4. Concluding Remarks

In this study, the impact of land surface condition changes on soil moisture field evolution was evaluated. The model for the soil moisture dynamics used for the study is based on the linear reservoir concept along with the diffusion process through the soil media or by surface flow. The land surface condition changes are considered by applying various parameter sets with different second order statistics. The basic model parameters were estimated based on the first- and second order statistics of the observed soil moisture fields of Washita '92 and Monsoon '90 data.

As a result of the study, we could find that the high variability of land surface conditions accelerate the dry up of soil moisture field. The soil moisture field looks more sensitive to the loss rate field, which is due to small values of diffusion coefficient applied during the dry period considering relatively large grid size. The role of diffusion seems also to be limited during the existence of overland flow.

Although this study is limited for the case without considering the spatial organization of land cover, land use or soil, it is obvious that high variability of land surface condition increases the dry up of soil moisture. Further study on hydrological impact of land cover changes should consider its spatial organization such as clustered pattern of land use, then we could evaluate its impact on soil moisture field or any other hydrological processes more precisely.

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