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확장 TOPMODEL의 영역화 민감도 분석

Regionalized Sensitivity Analysis of Extended TOPMODEL

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Abstract

An extension of TOPMODEL was developed for rainfall-runoff simulation in agricultural watersheds equipped with tile drains. Tile drain functions are incorporated into the framework of TOPMODEL. Nine possible flow generation scenarios are suggested for tile drained watershed and applied in the modeling procedure. In the model development process, the traditional physically based storage approach and a new approach using a transfer function for the simulation of the flow in the unsaturated zone were compared. In order to provide better insight into the simulation process, a regionalized sensitivity analysis was performed to test the performance of the model and to compare the behavior of the transfer function to that of the simple storage related formulation. The results of analysis show good performance of the transfer function approach. Since the rainfall-runoff response pattern tends to vary seasonally, seven events distributed throughout a year were used in the sensitivity analysis to investigate the seasonal variation of the hydrologic characteristics. It is found that the sensitivity of each parameter described by the model are varied seasonally.

Keywords: TOPMODEL, regionalized sensitivity analysis, transfer function, Monte-Carlo method

요 지

인공배수 되고 있는 농업유역을 위한 확장된 TOPMODEL은 강우유출 모의를 위해 개발되어졌다. 불포화흐름의 해석을 위해 기존 모형의 저류함수법과 본 연구에서 새로이 제시하는 전달함수법을 비교하였다. 매개변수의 민감도 결정과 저류함수법과 전달함수법간의 거동의 비교를 위하여 영역화 민감도 분석기법이 쓰였다. Monte-Carlo 방법을 활용한 변수 추정시, 전달함수를 활용한 모의가 보다 많은 성공적인 모의결과의 변수조합이 관찰되었다. 강우유출 양상의 계절적 변동을 고려하기 의해 일곱개의 강우사상이 민감도 분석에 활용되었다.

핵심용어 : 영역화 민감도 분석, 전달함수법, 강우유출모형, 난수발생기법

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1. INTRODUCTION

The hydrologic behavior of upland agricultural watersheds with tile drains is different from that of watersheds without artificial drainage. In addition to the influence of the topography and of the soil hydraulic conductivity on the hillslope hydrology, the human impacts such as fertilizer application, cropping practice, tillage practice and the installation of tile drains make the mechanisms of the runoff generation more complicated. Especially, the influence of the tile system on the hydrologic system is critical due to the close functional relationship between the tile and the watertable elevation. Several researches (Skaggs, 1980; Johnsen and Ahuja, 1994) had been performed to simulate the effect of tile drainage by Hooghoudt equation (van Schilfgaarde, 1957). The form of Hooghoudt equation used in the popular drainage model DRAINMOD (Skaggs, 1980) as well as in RZWQM (USDA-ARS, 1992). The steady state rainfall assumption for Hooghoudt equation is less appropriate in the midwest regions of the U.S. Midwest.

Based upon the TOPMODEL (Beven and Kirkby, 1979) framework, a new version of physically based model was developed for the watersheds equipped with tile drainage systems (Kim, 1996). It includes two alternative formulations of the simulation of fluxes through the unsaturated zone. The performance of each formulation can be assessed using the Monte-Carlo method in rainfall-runoff simulation.

The procedures used in TOPMODEL are generalizations of the physical flow process at the hillslope hydrologic scale. These rainfall-runoff patterns and amounts are not constant along the whole year due to the variations of meterological features (i.e. temperature, wind speed and solar radiation etc.) and the seasonal variation of the crop growth stage or tillage practice. A sensitivity analysis is used to assess the properties of the hydrologic system as described by the new model and its performance of the model is investigated with several events to cover the seasonal variations during a whole year.

The purposes of this paper are firstly to incorporate the tile drain functions on the base of TOPMODEL, secondly to suggest a new approach in the calculation of the flux in the unsaturated zone and to compare the performance of this formulation with the traditional approach (Beven and Wood, 1983), and finally to perform a sensitivity analysis using events along the whole year and to investigate the seasonal variation of the sensitivity of the included model parameters.

2. DESCRIPTION OF EXTENDED MODEL

The spatial distribution of the topographic index is calculated using the multiple flow direction algorithm (Quinn et al., 1991) on the platform of the Geographic Resources Analysis Support System (GRASS) (USCERL, 1991).

The framework of TOPMODEL (Beven and Kirkby, 1979) is extended to include the existence of tiles and their relationship to the hydrologic response. The tile flow generation process in the extended model considers the relationship between the saturation profiles and the pressure (suction) in a soil as well as the interaction between the tile drainage system and the elevation of the watertable (Kim, 1996). The tile system is assumed to be uniformly distributed over the entire subbasin. The initial average drawdown due to the tile system, ds, needs to be considered in addition to the effects of topography as

$$\overline{S} = -m \log\left(\frac{q_{in}}{q_0}\right) + ds \qquad (1)$$

where $\overline{S}$ is average saturation deficit, q_0 is the observed base flow at the beginning of the time period, q_{in} is the base flow of the totally saturated watershed ($\overline{S}=0$) and m is the scaling parameter related to the rate of decrease of the downslope transmissivity (Beven et al., 1995).

The mass balance equation of the average saturation deficit also includes the tile drain effect at each time step t as

$$\overline{S_t} = \overline{S_{t-1}} + q_{base} + q_{return} - q_v + q_{tile} \qquad (2)$$

where q_{base} is subsurface flow, q_{return} is the return flow, q_v is the vertical flux to the saturated zone and q_{tile} is the tile flow. In order to account for the storage in the soil matrix and the delaying effects on the flux from the soil matrix to the tile system, a second order linear reservoir model (Chow et al., 1988) was employed. Since the rate of flow from the soil layer to the tile system is closely related to the portion of the cross-sectional area of the tile drain which actually conveys the water, the computational algorithm is designed to involve the tile depth and tile diameter in calculating q_{tile}. The several flow paths in this extended version of TOPMODEL are shown in figure 1. The upper portion of the figure shows the original TOPMODEL with its three storages: the root zone (SRZ), the unsaturated zone (SUZ) and the saturated zone (SAT). The infiltration excess and the saturation excess overland flow as well as the base flow, all of which contribute to the runoff, are part of the original TOPMODEL. There are two types of arrows in the figure; thick arrows are referred to the flux in the soil matrix and thin arrows are associated with the flux through either tile or surface.

To account for watersheds which have two or more different types of tile drainage systems, the computational algorithm is designed to deal with several tile systems (up to 10). Each tile system covers some part of the watershed and is assigned to a combination of tile depth and diameter. The storage of soil matrix for tile flow computation in the saturated zone (SAT) is connected to the original TOPMODEL with the tile flow mechanism which is shown in the lower part of figure 1. The tile flow mechanism principally consists of two storages and time delay effects. The storage constant K_{sto} simulates the storage and the time delay of the water in the soil matrix. The rate of outflow, q_{sat}, from the local soil layer represented by the first storage is

$$q_{sat} = \frac{(deptil - Z) \cdot R \cdot n_{drain}}{K_{sto}} \qquad (3)$$

where $(deptil\text{-}Z)$ is the potential volume of tile drainage, K_{sto} is the storage coefficient of the soil matrix, n_{drain} is drainable porosity and R is the tile drain efficiency computed from depth to the tile, watertable and tile diameter. The outflow, q_{sat}, from the soil matrix reservoir is compared to the capacity, C_{intile}, of the individual tile underlying the local soil matrix. If $q_{sat} > C_{intile}$, the outflow q_{sat} is fed back into the saturated zone store SAT. Otherwise, q_{sat} is contributed to the tile storage:

$$S_{tile,t} = S_{tile,t-1} + q_{sat} - q_{tile} \qquad (4)$$

where $S_{tile,t}$ is the storage for the tile drain at time t.

The outflow from the tile storage is the tile flow, q_{tile},

$$q_{tile} = \frac{S_{tile}}{K_{tile}} \qquad (5)$$

where K_{tile} is the storage coefficient within the tile storage. Finally q_{tile} is compared to the maximum capacity of the total tile system, C_{totile}. If $q_{tile} > C_{totile}$, then q_{tile} contributes the saturation excess, otherwise q_{tile} contributes

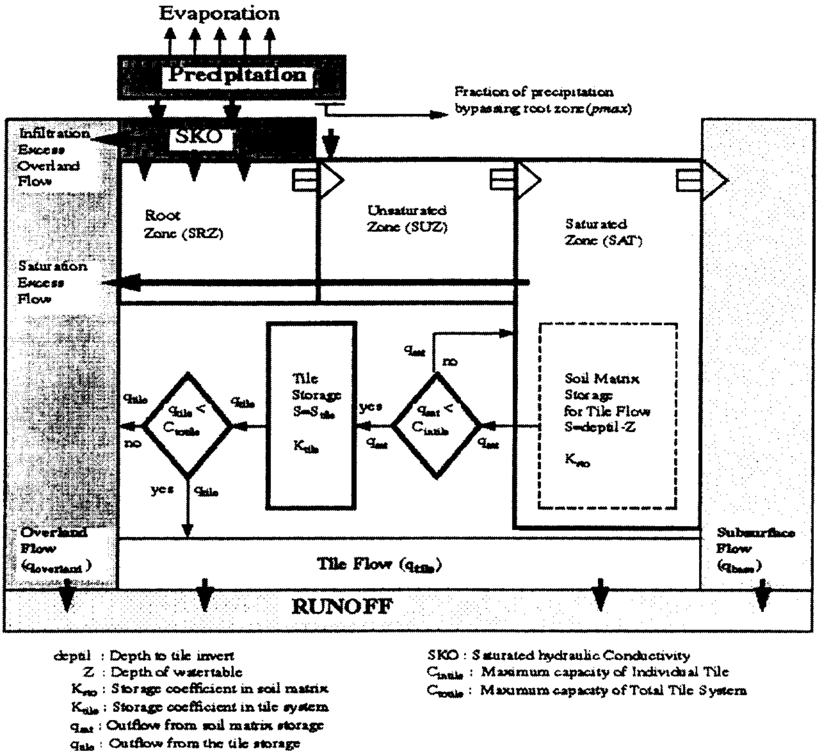

Figure 1. The flow Path Chart for TOPMODEL with Tile System

directly to the tile flow. Finally, the runoff can be produced as overland flow, tile flow or subsurface flow.

2.1 The Flow Computation in Unsaturated zone

One of the critical parts in the physically based hydrological simulation is the description of the fluxes in the unsaturated zone. In most field cases, topographical heterogeneity in micro and macroscales, variations in the vegetation and root distribution, the high variability in soil water hydraulic properties due to textural or density differences and large flux values caused by channeling through holes, cracks or by instabilities in flux fronts cause difficulties in the modeling of the unsaturated zone fluxes.

Troch et al.(1993) found that for a typical value of the drainable porosity, the hydraulic conductivity in Zwalm basin, situated in East-Flanders, Belgium, is about 25 to 100 times larger than the values derived from laboratory measurement on soil samples. This large discrepancy can be attributed to the fact that, at the field and catchment scale, the hydraulic conductivity involves not only flow paths in the soil matrix, but also paths through macropores and larger channels, which are not considered in the small-scale laboratory measurements.

Beven(1991) also found that it is very difficult to predict the fluxes in the unsaturated zone. The macropores may lead to spatial concentration of water flow through unsaturated soil that could not be simulated by the Darcy approach in the porous media. (Beven and Germann, 1982). No standard mathematical description of unsaturated porous media, with parameters that can be estimated at a practical prediction scale, is currently available (Beven, 1989, 1993).

Two formulations have been adopted in TOPMODEL for the simulation of flows in the unsaturated zone, which are essentially vertical, based on the goal of minimum parameterization. The first approach is a simple storage deficit-time delay formulation and the second is a conductivity-based flow equation. The first formulation suggested by Beven and Wood (1983) simulates the vertical flux q_v at any point as

$$q_v = \frac{S_{uz}}{S_i t_d} \tag{6}$$

where S_{uz} is storage in the unsaturated zone, S_i is the local saturated zone deficit due to gravity drainage, and t_d is a time constant. This simple linear storage relationship between storage and flux may not sufficiently represent the flux pattern by the following reason.

de Marsily(1986) determined experimentally the relationship between unsaturated hydraulic conductivity and the moisture content, found it to be non-linear function. Liakopoulos(1965) and de Marsily(1986) described the hysteresis effect between hydraulic head, h and the soil moisture content, θ. This non-linear hydraulic behavior makes it difficult to simulate the unsaturated zone's flux with a simple linear reservoir approach. The relationships for the relative hydraulic conductivity versus pressure and soil water content (van Genuchten et al., 1991) indicate that very small measurement errors in the water content near saturation can lead unacceptable large errors in the estimated saturated hydraulic conductivity.

The second formulation of the flow in the unsaturated zone was suggested by Beven (1986) on the basis of the Darcian flux in the base of the unsaturated zone, which for an exponential conductivity function, can be expressed as

$$q_v = \alpha \cdot K_0 \cdot e^{-fz} \tag{7}$$

where α is the effective vertical hydraulic gradient, K_0 is the saturated conductivity at the surface, f is the scaling parameter for decreasing hydraulic conductivity along depth and z is the local water table depth.

This approach also has a limitation in describing the uncertainty of the hydraulic conductivity within the unsaturated zone due to the existence of empty space (air bubbles) in macropores (Beven and Germann, 1982) as well as the hysteresis effects near the capillary fringe. Since the scaling parameter used in equation 7 is commonly used in the governing equation for the determination of the local saturation deficit, the uncertainty in the assumption of this formulation could affect the overall simulation result.

The most recent version TOPMODEL based on minimum parameterization, depends on the simple storage deficit-time delay formulation, equation 6, in the calculation of the fluxes in the unsaturated zone. However, the many causes of spatial variability of water flux(i.e. flow through cracks or root channels, unstable flow, presence of subsurface barriers) means that using the hydraulic and retention parameters in the simulation of the unsaturated zone flux may be unreasonable. As a consequence, an alternative to the deterministic approach to modeling water flux in the unsaturated zone, that is, the impulse response function or the kernel function approach (Chow et al., 1988) was introduced. The system, in this case, is characterized in terms of its method of transforming an input function (flux added to the unsaturated soil zone) into an output function (flux draining from the unsaturated soil zone).

The model developed by Jury (1982) and Jury and White (1986), which used the solute travel time as a random variable, was shown to be a special case of a kernel function model derived from an identity involving the joint probability density function (PDF) of the random input time of solute into a soil volume and the random solute travel time in soil unit.

If $Q_{in}(t)$ is the input function and dt' is an infinitesimal time interval, the $Q_{in}(t')dt'$ is the amount of the input to the system during the time interval. If the unit response of the system can be described by the kernel function $g(t-t' \mid t')$, the conditional probability density of $t-t'$ given t', (Benjamin and Cornell, 1970), then the resulting output function $Q_{out}(t)$ can be expressed as

$$Q_{out}(t) = \int_t^0 g(t-t' \mid t') Q_{in}(t') dt' \qquad (8)$$

This equation is known as the convolution integral which is the fundamental formulation for the solution of a linear system. In the approaches made by Jury(1982) $Q_{out}(t)$ is the fractional rate of solute mass loss from a soil unit of arbitrary size; Q_{in} is the fractional rate of initial solute mass input into the soil volume and $g(t-t' \mid t')$ is the PDF of solute lifetimes, $t-t'$, in the soil unit, conditioned on the solute input at time t'.

If it is assumed that the flux through the ground surface is maintained constant after start, the above equation can be applied in the form,

$$Q_{out}(t) = Q_{in} \int_t^0 g_{eff}(t') dt' \qquad (9)$$

where Q_{in} is the fixed rate input through the surface and is $g_{eff}(t')$ an effective travel time density function for the flux. In this approach $g_{eff}(t')$ is approximated by the following exponential function

$$g_{eff}(t') = b \cdot \exp(-bt') \qquad (10)$$

where b is a recession parameter.

The equation 10 is similar to the model suggested by Jury, et al. (1986) in fitting Chloride data

$$P(t) = a[1-\exp(-bt)] \qquad (11)$$

If the parameter a in equation 11 can be eliminated in case of water flux $(a=1)$, the equation (10) and (11) can be identical as

$$P(t) = [1-\exp(-bt)] \qquad (12)$$

Therefore, the vertical flux in the unsaturated zone can be expressed as

$$q_{vi} = \sum_{t=i}^{i'} q_{in}(t) \cdot (\exp(t-i') - \exp(t-i'-1)) \qquad (13)$$

where i is the starting point of rainfall event, i' is the present time. In TOPMODEL, equation 13 can be used instead of equation 6 or 8 to calculate the vertical flux through the saturated zone.

2.2 Comparison Between the Storage Deficit Formulation and the Kernel Function

The behavior of this formulation (kernel function) is now compared to that of the simple storage deficit-dependent time delay formulation in this computation of the fluxes in the unsaturated zone. Using a uniform input over three time steps, figures 2 and 3 show the results of this comparison. The initial soil moisture 33 % of soil moisture, the time delay in the storage deficit formulation is varied from 2 to 6 (hr) and the recession constant b in the kernel function formation is varied from 0.1 to 0.4 (1/hr). The general response patterns (i.e. peak time, the shape of recession curve) of the two formulations were similar. From figure 2, it

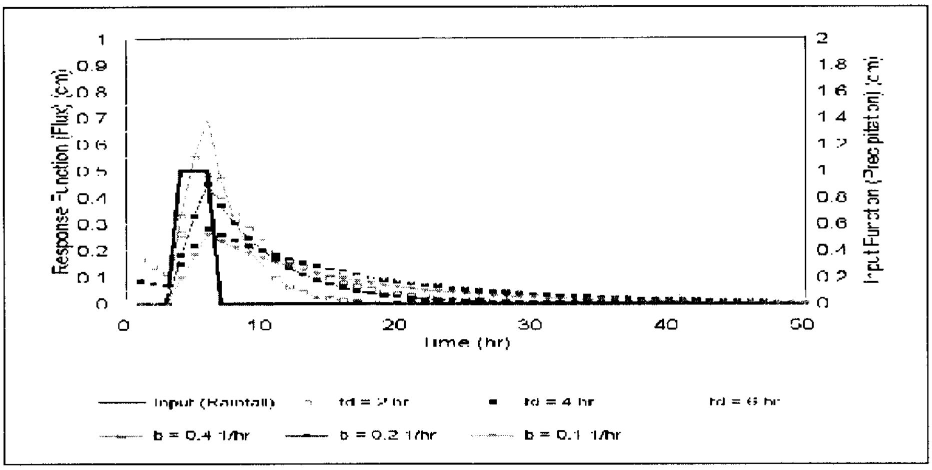

Figure 2. The Response Functions of the Storage Deficit Formulation and Kernel Function

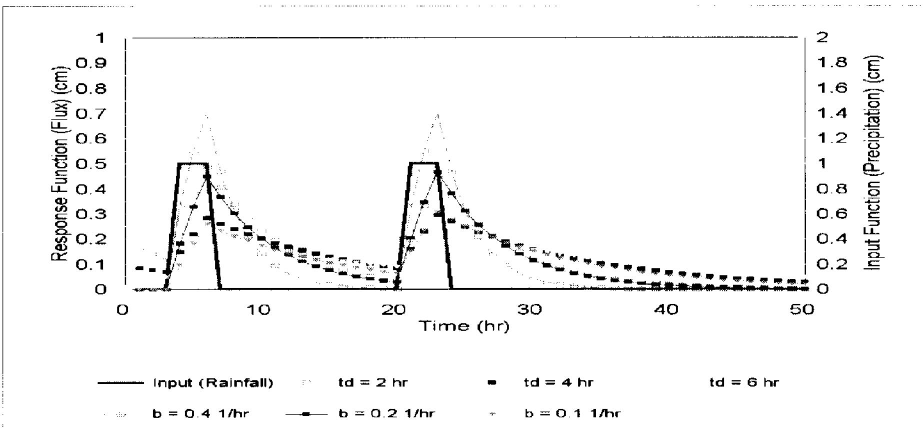

Figure 3. The Response Functions of the Storage Deficit Formulation and Kernel Function

is can be seen that the response is affected by the initial moisture content only in the storage deficit formulation.

Figure 3 shows the results of adding a second input at the time of 20 with the same condition as figure 2. The responses of the kernel function model show its capability to consider the effect of the previous rainfall event. The kernel function approach can thus be an alternative method for the calculation of the flux in the unsaturated zone. Especially, it is expected that the kernel function approach can show even better performance in case of uncertain initial moisture.

3. A REGIONALIZED SENSITIVITY ANALYSIS

A sensitivity test of the model using several rainfall and runoff observations can provide an insight into the hydrologic system. Because of the structural inaccuracies in the model formulation, one set of optimum parameters providing a clear physical interpretation is probably impossible (Beven, 1993). This means that the model could allow multiple sets of optimal parameters. Therefore, the Monte-Carlo method is used in the sensitivity analysis of the model instead of a deterministic approach. The regionalized sensitivity analysis (RSA) developed by Hornberger and Spear (1981) is adopted to determine the relative importance of the parameters in the simulation model. Chang and Delleur (1992) used the RSA to identify the important parameters in the watershed acidification model ILWAS (April and Newton, 1985).

The procedure of the RSA is given as follows;

1. Select the parameters for sensitivity analysis.

2. Determine the ranges of the parameters from the related literature or from experience.

3. Compute the trial values of each parameter as

$$PAR_{ij} = PARLB_j + PAND_{ij} \cdot (PARUB_j - PARLB_j) \tag{14}$$

where I varies from 1 to the trial number, j varies from 1 to the number of parameters, $PARUB$ and $PARLB$ are upper and lower boundaries of each parameter and $RAND$ is a random number generated from a uniform distribution between 0 and 1. The subroutine RNUN in the IMSL STAT/LIBRARY(IMSL, 1987) is used to generate the random numbers for the analysis.

4. In each simulation, the coefficient of efficiency, which was proposed by Nash and Sutcliffe (1970), is calculated to evaluate the model performance. This coefficient is expressed as;

$$EFF = \frac{\sum_{i=1}^{n} (\bar{y} - y_i)^2 - \sum_{i=1}^{n} (y - y_i)^2}{\sum_{i=1}^{n} (\bar{y} - y_i)^2} \tag{15}$$

where n is the number of time steps in the simulation; y and y_i are the computed and observed values, respectively, $\bar{y}$ is the average of the observed values.

5. The criterion of acceptance (RINT) is compared to the coefficient of efficiency and the ranges of acceptable and unacceptable values are determined for each parameter. In this study, a value of RINT of 0.3 was used and simulations resulting in EFF > RINT are acceptable.

6. For each parameter, the cumulative distribution (CD) of the parameter values associated with the acceptable cases, A(x), is compared to the CD of the unacceptable cases, U(x). The Kolmogorov-Smirnov (K-S) test, at a specified significance level α, 0.05, is used to test if the two continuous cumulative distribution functions (CDF's) are identical. The IMSL subroutine KSTWO is used to perform the test. The hypotheses tested by KSTWO are

$$H_0 \parallel A(x) = U(x)$$
$$H_1 \parallel A(x) \neq U(x)$$

The largest absolute value, D, of the positive and negative maximum differences between the CDF of $A(x)$ and of $U(x)$ is compared to a critical value at the selected significance level α, 0.05, under the null hypothesis that the distributions of the parameter values corresponding to the satisfactory and unsatisfactory cases are not significantly different, i.e. theparameter is insensitive.

4. ANALYSIS

4.1 Study Areas

The study area located in the “Indian Pine Natural Field Station,” composed of two major watersheds, Little Pine Creek (139 km^2) and Indian Pine Creek (67 km^2), near the campus of Purdue University, West Lafayette, Indiana.

The performance of the model was tested on the Animal Science Farm Subwatershed (3.6 km^2) which is located at the head of the Little Pine Creek. The slope of topography is varied from 1 to 4 degree. This area is mainly used for agricultural purposes such as corn or soy bean. The typical growing season of corn or soybean begin at mid of April and ends early of September. The entire watershed is artificially drained by two main tiles which are connected to many sub-tile systems.

The temperature varies from -15 C to 35 C over the year. The top portion of soil is remained as frozen status from December to February. The average annual rainfall amount is approximately 960 mm. During the growing season of crop, artificial irrigation has been applied to the entire watershed.

4.2 Comparison of Formulations

The sensitivity of the individual parameters of the transfer function and storage deficit time delay formulation for the unsaturated flux in the rainfall-runoff simulation were compared using the Monte-Carlo method. In order to avoid the period of artificial irrigation and snowfall form of precipitation, seven events throughout a year were carefully selected to perform the comparison(Table 1). The rainfall data with 1 hour time step were used to perform the simulation. Parameters about tile drainage such as depth to the tile, tile diameter, number of tile were obtained from field measurement. Since the size of watershed is small, the parameter related to the storage within the tile system, K_{tile} was assumed to 1. Parameters m, K_{sto}, srmax, ds, am, pmax (Table 2) and b were used to perform the Monte-Carlo simulation.

A few preliminary trials were performed to obtain reasonable ranges of the parameters for the test of the transfer function formulation. Each simulation was performed with 500 iterations. In each simulation, each parameter was randomly selected using a uniform distribution of the reasonable range of that parameter.

Table 1. Rainfall Events at ASF Sub watershed and Results of The Monte-Carlo Simulation for the two Formulation

Event	Date	Rainfall (mm)	Accepted (SDTD)	Accepted (TRANS)
1	06/13/1994	17.0	118	43
2	08/10/1994	26.9	0	83
3	11/09/1994	13.7	4	97
4	11/21/1994	25.7	192	109
5	12/06/1994	23.6	20	108
6	04/19/1995	9.9	0	64
7	06/25/1995	41.9	21	48

Table 1 also shows the performance of the models in both cases. The transfer function formulation is seen to provide a better performance overall and particularly for events 2, 3, 5, 6 and 7. The storage deficit dependent time delay formulation could not produce any acceptance case in events 2 and 6. In events 1 and 4 the formulation of the storage deficit dependent time delay shows a higher acceptance rate than the transfer function. This may be associated with the fact that the conditions, the moisture content in unsaturated zone, of the watershed at events 1 and 4 better fit the assumptions of the storage deficit dependent time delay formulation. While the performance of the storage related formulation appears to depend on the event and watershed condition, the transfer functional approach provides more stable results of simulation regardless of its saturation status. One explanation is that the uncertainty in the description of the storage and saturation deficit in the unsaturated zone and the uncertainty connected to the structure of the linear storage formulation can be reduced in the transfer function approach. Another advantage of the transfer function is the minimization of the number of parameters. The sensitivity analysis was performed and the results indicate that the recession parameter b in equation 9 is not sensitive from event 1 to event 7, thus this parameter can be replaced by a default value (0.4). Hence, the number of parameters can be reduced by one for actual simulation.

4.3 Sensitivity Analysis of Model

The adequacy of the structure of the model representing the hydrologic system in agricultural watersheds with tile drains can be assessed through a sensitivity analysis of the important parameters. Since the algorithm of the model is closely related to the physical phenomena, some of the simulation parameters are the reflection of the physical watershed properties which can be measured experimentally such as tile depth, tile size and the maximum capacity of tile drains or obtained from the literature such as the drainable porosity and the surface hydraulic conductivity (Troch et al., 1993). Some other parameters originate from assumptions or approximations in the modified TOPMODEL for the agricultural watershed with tile. The transfer function formulation (equation 13) is used to calculate the flux in the unsaturated zone. The parameters for the sensitivity analysis that were selected to provide an insight into the simulation of the physical process are listed and defined in Table 2.

Each parameter listed above represents a functional aspect in the model. The parameter m, describing the rate of change in the hydraulic conductivity with depth, is connected to the basic assumptions of the original TOPMODEL structure. The relationship between the tile system and the soil matrix of the watershed is considered by the parameter K_{sto}, which is the storage coefficient of the saturated soil contributing to the tile drainage. The land condition and the type and growth stage of crops in an agricultural watershed affect srmax, the maximum storage of the root zone and pmax, the fraction of precipitation bypassing the root zone. The antecedent moisture content (*am*) in the root zone is also very important in estimating the rainfall-runoff response and is considered in the sensitivity analysis. The effect of the tile on the hydrologic system also needs to be considered. The drawdown of the watertable, expressed as an additional average saturation deficit, ds, is used to reflect the additional drop of the watertable due to the tile system.

The runoff response characteristics of the watershed varies between the seasons. A sensitivity analysis using the Monte-Carlo Method was performed for each parameters. The seasonal variation of the ranges of the parameters in each event can be obtained through a comparison of the cumulative frequency distributions (CDF) of the accepted and rejected cases. It is necessary to have significant number of accepted event for good comparison of the CDF about both cases. Few

Table 2. Parameters used in the Sensitivity Analysis

Parameter Symbol	Definition	Unit
m	scaling parameter for hydraulic conductivity	m
K_{sto}	storage coefficient of the soil unit	hr
srmax	maximum root zone storage	m
ds	average initial tile drainage drawdown	m
am	antecedent moisture content of field capacity in root zone	.
pmax	fraction of precipitation by passing root soil zone	.

Table 3. The ranges of parameters for Monte-Carlo Simulation

Event\Range	m (10^{-3})	K_{sto} (hr)	srmax (cm)	dz (m)	am (%)	pmax
1 (06/13/94)	1 .. 4	1 .. 4	2 .. 5	0.5 .. 1	20 .. 90	0 .. 0.25
2 (08/10/94)	1 .. 4	1 .. 4	2 .. 5	0.5 .. 1	20 .. 90	0 .. 0.25
3 (11/09/94)	1 .. 5	1 .. 4	0.5 .. 2.5	0.5 .. 1	20 .. 90	0 .. 0.25
4 (11/21/94)	1 .. 5	1 .. 4	0.5 .. 2.5	0.5 .. 1	20 .. 90	0 .. 0.25
5 (12/06/94)	1 .. 5	1 .. 4	0.5 .. 2.5	0.5 .. 1	20 .. 90	0 .. 0.25
6 (04/19/95)	1 .. 4	1 .. 4	1.5 .. 3.5	0.75 .. 1	20 .. 90	0 .. 0.25
7 (06/25/95)	1 .. 4	1 .. 4	2 .. 5	0.75 .. 1	20 .. 90	0 .. 0.25

trials suggested that adjustment of some parameters can significantly increase the number of accepted cases. The adjusted ranges of parameter values are listed in Table 3. The parameter srmax, which is highly dependent on the state of the crop, shows different maximum and minimum values of the srmax parameter between growing crop and non active crop seasons. The value of ds can be expressed as the actual drawdown, dz, in field by dividing ds to drainable porosity. The long dry period in 1995 is reflected by higher minimum value of ds in event 6 and 7.

The RA was performed using the maximum and the minimum values in Table 3. The results of the Kolmogorov-Smirnov two-sample test about the accepted and rejected cases are summarized in Table 4. The p value listed in Table 4 is defined as the minimum level of significance that would lead to the rejection of the null hypothesis (Hines and Montgomery, 1990). The null hypothesis is that the distributions of the parameter values corresponding to the satisfactory and unsatisfactory cases are not significantly different, i.e. the parameter is insensitive. A small value of p indicates a sensitive parameter.

The parameters m, ds and am can be classified as the sensitive. The sensitivity of parameter m reflects seasonal variation of watershed hydrologic characteristics. It is considered that the status of top soil surface was frozen in event 4 and 5 so that the parameter m was not sensitive to the simulation. In most events, the parameter *ds* was found to be sensitive except event 6 which was the event in winter season. The parameter pmax was recognized as a sensitive parameter only in the growing season of crops (Events 1 and 7). The analysis results of parameter am indicated characteristics of sensitivity at two extreme cases. It is found to be non-sensitive in Event 6 when there was a long dry period before the rainfall event and in Event 3 when

Table 4. Sensitive Analysis Results

E #, Rain\Parameter	m	K_{sto}	srmax	ds	am	pmax
1 (06/13/94)	Y (0.000)	N (0.063)	N (0.436)	Y (0.000)	Y (0.007)	Y (0.000)
2 (08/10/94)	Y (0.027)	N (0.547)	N (0.105)	Y (0.000)	Y (0.000)	N (0.646)
3 (11/09/94)	Y (0.000)	N (0.607)	Y (0.015)	Y (0.000)	N (0.574)	N (0.395)
4 (11/21/94)	N (0.525)	N (0.864)	Y (0.000)	Y (0.000)	Y (0.000)	N (0.054)
5 (12/06/94)	N (0.396)	N (0.116)	N (0.062)	N (0.349)	Y (0.000)	N (0.251)
6 (04/19/95)	Y (0.000)	N (0.056)	N (0.185)	Y (0.003)	N (0.648)	Y (0.005)
7 (06/25/95)	Y (0.001)	Y (0.000)	N (0.127)	Y (0.000)	Y (0.000)	Y (0.000)

Note: Y means the parameter is sensitive and N means the parameter is not sensitive. the p value inside of ( ) is the level of significance for the rejection of the null hypothesis

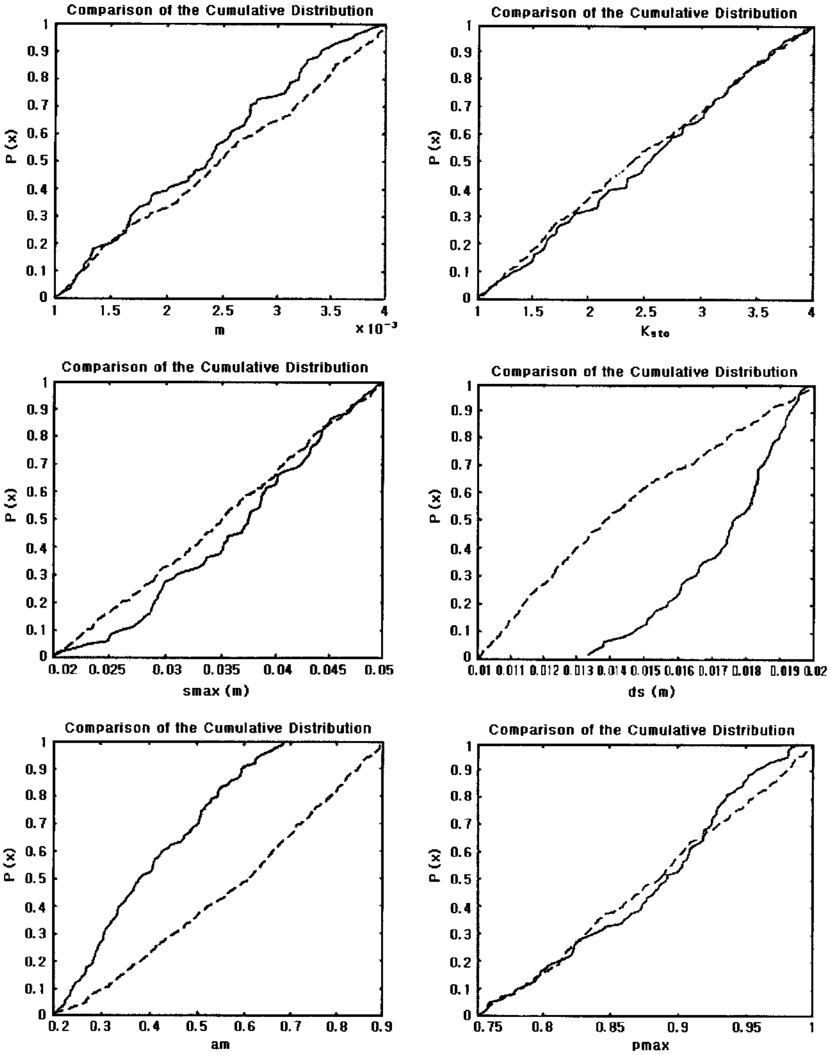

Figure 4. Comparison of the Cumulative Distributions for Event 2. The Solid Lines Represent Accepted Cases and Dotted Lines Represented Rejected Cases.

the status of watershed was almost saturated. It can be said that the entire pattern of parameter sensitivity in each case partially reflects the seasonal rainfall runoff characteristics of the watershed. In order to illustrate the difference between the acceptable and the unacceptable cumulative distribution of each parameter, figure. 4 presents the results of the analysis of the event 2. Figure 4 shows that parameters K_{sto}, srmax, pmax are not sensitive, which the parameters ds and am are most sensitive and the parameter m is moderately sensitive.

5. DISCUSSION

The application of the RSA to the modified TOPMODEL with seven rainfall-runoff events distributed through the year with different amounts of rainfall and different characteristics of watershed such as the crop stage and the previous rainfall history provide an insight into the relative importance of the components of hydrologic system in agricultural watershed equipped with tile drains.

The previous history of rainfall events is closely related to the antecedent moisture content. In most events parameter am was sensitive. The two exceptional cases are event 6 a long antecedent dry period followed a small amount of rainfall and event 3 saturated soil surface with small rainfall event. Generally, the sensitivity test of am implies that the saturation degree of the watershed can be a dominant factor for the simulation.

The tile system and the time interval since the previous rainfall event influence the average watertable drawdown ds. In order to consider the long dry period in the spring of 1995, the ranges of this parameter in the events 6 and 7 (April and June) were adjusted to higher values than those of the other events. The parameter *ds* was also found to be very sensitive.

The sensitivity test of the parameter m, which describes the decrease of hydraulic conductivity with depth, indicates that the importance of this parameter tends to vary seasonally. Even though the range of this parameter in events 4 and 5 (November and December) is a little bit wider than in the other cases, this parameter is found to be insensitive in these two events in the early winter season. The average air temperature in event 3 was 10 C degree and those of events 4 and 5 is close to 0 C degree. This implies that the role of this parameter to the hydrologic system tends to decrease in the winter season. The role of the tile to drain the water from the soil is expressed as the parameter K_{sto}. This parameter was proved to be insensitive except for one event in June, 1995, which had a very high intensity of rainfall. The impact of land/crop condition on the hydrologic system can be effectively investigated through the sensitivity of the parameters, srmax and pmax, the maximum root zone storage and the fraction of precipitation bypassing the root zone, respectively. Since the growth stage of crop can be connected to the maximum storage volume in the root zone, the seasonal adjustment of the srmax ranges is essential to obtain a reasonable number of successful simulations. The K-S test in table 4 indicate that this parameter is insensitive during the growing season of crop and it can be classified as a sensitive parameter in non-crop season. The parameter pmax proved to sensitive in three events in April and June, which is the active growing season. These results can be explained that the activity of root making holes and crack in root zone soil, which provide the preferential flow component, is one of the important component in runoff generation process during crop growing season.

6. CONCLUSIONS

The tile drainage function and various flow generation scenarios in the tile drained watershed were suggested and incorporated to the TOPMODEL framework. The regionalized sensitivity analysis (RSA) for the parameters in this modified TOPMODEL (Kim, 1996) for agricultural watershed equipped with tile drains provides the following conclusions:

(1) The RSA for two formulations for the fluxes in the unsaturated zone shows that the transfer functional approach provides stable simulation results than the storage deficit-time delay formulations.

(2) The RSA results of the transfer functional formulation indicate that the recession parameter for this formulation is not sensitive. Consequently, this parameter can be replaced to a default value, minimizing the number of parameters.

(3) The application of RSA for the six parameters using seven rainfall-runoff events yields the following conclusions;

1) The parameters related to the tile system

(ds, K_{sto}) and the history of previous rainfall events (am) show similar results of sensitivity throughout the year.

2) The sensitivity of parameters related to the land and crop condition (srmax, pmax) and to the variation of hydraulic conductivity with depth (m) show seasonal variation.

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