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Tile Drain의 영향과 GIS를 연계한 농경지 유역에 대한 수문학적 모의

Hydrologic Modeling of an Agricultural Watershed with Tile Drains and GIS

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Abstract

A physically based model for rainfall-runoff simulation in agricultural watersheds equipped with tile drains is developed from the TOPMODEL framework. The model is based on detailed topographical information provided by the Digital Elevation Model (DEM), which is available in the Geographic Information System GRASS. Nine possible flow generation scenarios are suggested and used in the development of the model. The storage and delaying effects in the soil matrix and in the tile system are simulated with a second order linear reservoir. The model can identify the portions of the hydrators resulting from tile flow, subsurface flow and surface runoff.

요 지

Tile drain의 특성을 갖는 농경지 유역에서의 강우-유출 모의를 위한 물리모형이 TOPMODEL 구조로부터 개발되었다. 본 모형은 GRASS 지리정보시스템에 의해서 DEM으로부터 제공되는 세부적인 지형정보를 기초자료로 하여 연구되었다. 9개의 가능한 흐름발생 시나리오가 제안되었고 모형개발 과정에 사용되었다. 토양 메트릭스와 tile 시스템에 있어서의 저류 및 지체효과가 2차 선형 저수지와 함께 모의되었다. 본 연구모형으로부터 tile 흐름, 지표하 흐름 및 지표면 흐름으로부터 야기되는 유출특성을 규명할 수 있었다.

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1. Introduction

During a storm event, different mechanisms can generate runoff from different parts of a catamount. Surface runoff can be generated by either infiltration excess (Horton, 1933) on low-permeability soils, or saturation excess (Dunne and Black, 1970) on relatively high-permeability soils when the water table rises to the ground surface. The subsurface runoff comes from groundwater or from the subsurface water which is displaced from the soil by the infiltrated rainfall.

Since many agricultural watersheds in the U. S. Midwest are equipped with tile drains, the hydrologic behavior can be more complex than that of a watershed without tile drains. Generally speaking, tile drainage is used in agricultural watersheds to lower the moisture content of the upper soil layer and improve the production of crops. The tile system accelerates the soil drainage, increases the average saturation deficit and permits more penetration of water into the soil layer. Therefore, the effects of tile drain systems need to be considered in the hydrologic modeling of the upland watershed equipped with a tile drain system.

With tile drains, the hydrologic behavior depends not only on the spatial distribution of surface elevation, saturation state and hydraulic conductivity, but also on the tile system including the drain size, depth to the tile, drainable porosity and maximum discharge capacity. This study of the effect of tile drainage on hillslope hydrology is cast in the framework of TOPMODEL (Beven, 1984; Beven et al., 1995; Sivapalan et al., 1990) because of its physical foundation based on a Digital Elevation Model (DEM). In this study a DEM with 10m resolution was available in the Geographic Information System GRASS (Geographical Resources Analysis Support System, USACERL, 1991).

The purposes of this paper are the following:

(1) To develop various flow generation scenarios for upland agricultural watersheds with tile drains in the framework of TOPMODEL.

(2) To extend the TOPMODEL formulation including tile drainage scenarios.

2. Basic Theory of TOPMODEL

A physically based runoff simulation model at hillslope hydrologic scale, TOPMODEL, was suggested by Beven and Kirkby (1979). The variable-source-area concept of streamflow generation is used in the simulation process. TOPMODEL simulates the movement of water through a watershed from the time that it enters the watershed as precipitation to the time that it exits the watershed as streamflow. The structure of TOPMODEL realizes several runoff generation paths such as the infiltration excess mechanism (Horton, 1933), the saturation excess mechanism (Dunne and Black, 1970) and subsurface flow through the soil matrix.

Overland flow for a given time step can be calculated from the areal extent of the saturated land-surface areas and the precipitation intensity. Subsurface flow rate is determined from a topographic index (Beven and Kirkby, 1979; Beven et al., 1995), and the watershed average depth to the water table. The watershed average depth to the water table is computed by a water balance which tracks input (precipitation) and output (overland flow, subsurface flow and evapotranspiration).

The flow delivered to the stream channel from the watershed is

$$q_{Total} = q_{Horton} + q_{Dunne} + q_{Subsurface} \tag{1}$$

where q_{Total} [L/T] is the total flow per unit area, q_{Horton} [L/T] is the infiltration excess overland flow per unit area, q_{Dunne} [L/T] is the saturation overland flow per unit area and $q_{Subsurface}$ [L/T] is subsurface flow per unit area.

Saturation overland flow is the sum of direct precipitation on saturated areas and return flow as

$$q_{Dunne}=q_{direct}+q_{return} \tag{2}$$

where q_{direct} [L/T] is direct precipitation on saturated areas and q_{return}[L/T] is return flow.

The starting points for deriving expressions to compute various flow components are the continuity equation at some location x in the watershed and Darcy's law. Assuming steady–state conditions with a spatially uniform recharge rate (R) to the water table,

$$A_x R=T_x tan\beta_x C_x \tag{3}$$

where A_x [L^2] is the area upslope from x that drains past the location, T_x [L/T] is the transmissivity of the saturated thickness at x, $\tan\beta_x$ is the hydraulic gradient of x, and C_x [L] is the contour length at x traversed by subsurface flow at the location.

Assuming that the saturated hydraulic conductivity, K_s, decreases exponentially along depth z, the transmissivity of the saturated thickness at x can be computed as

$$T_x=\frac{K_0}{f}\exp(-fZ) \tag{4}$$

where K_0 is the hydraulic conductivity at the soil surface and f is a parameter that controls the rate of decrease with depth. If K_0/f is referred to T_0, substitution of Eq. (4) to Eq. (3) and dividing by C_x provides the local ground water elevation Z_x as

$$Z_x=-\frac{1}{f}ln(\frac{aR}{T_0 tan\beta}) \tag{5}$$

Intergarting of this term about the total area of watershed and assuming that R is spatially constant, ln R can be eliminated and the relationship can be found between mean water table, local water depth, the topographic variables and saturated transmissivity.

$$Z_x=\bar{Z}+(\frac{1}{f})\ [\lambda-ln(\frac{a}{tan\beta})_x]+\frac{1}{f}(lnT_0-lnT_e) \tag{6}$$

where $a=A_x/C_x$ is the area drained per unit length of contour line

$$\lambda=\frac{1}{A}\int ln(\frac{a}{\tan\beta})_x dA \tag{6a}$$

$$lnT_e=\frac{1}{A}\int lnT_0\, dA \tag{6b}$$

$$\bar{Z}=\frac{1}{A}\int Z\, dA=-\frac{1}{f}ln\ R-\frac{1}{f}\Lambda \tag{6c}$$

$$\Lambda=\frac{1}{A}\int ln(\frac{a}{T_0\tan\beta})_x dA \tag{6d}$$

T_0 is the lateral transmissivity and R [L/T] is the recharge rate of the water table.

Eq. (6) is used to calculate q_{direct} and q_{return}. Any location x in the watershed where $Z_x < 0$ is saturated and has potential to produce saturation overland flow and any location where $Z_x > 0$ produces return flow. The subsurface flow can be computed by combining Darcy's Law for saturated subsurface flux with Eq. (4) as

$$q=(T_0\tan\beta)_x e^{-fz} \tag{7}$$

This equation is integrated along the lengths of all stream channels to compute the total subsurface flow delivered to the stream and is divided by the watershed area to get

$$q_{subsurface}=\frac{\int (T_0 \tan\beta)_x e^{-fz} dL}{A}=e^{-\Lambda} e^{-fZ} \qquad (8)$$

where Λ is the areal mean value of $ln\ (a/(T_0 \tan\beta))$

3. Moisture-Content Profiles and Tile Flow Generation

Above the level of the water table, there is first a zone with nearly, or at, 100% saturation called the capillary fringe, where the water pressure is less than atmospheric. This is equivalent to the capillary rise in small tubes. Above this zone, the capillary pressure or suction increases and the saturation decreases until it reaches an equilibrium saturation and the profile is static (Fig. 1).

Near the ground surface the roots of the crop can affect the saturation state of the soil. For the purpose of modeling, the layer from the ground surface to the bottom of the crop roots is referred to as the root zone, and the layer from the bottom of the root zone to the water table is referred to as the unsaturated zone. While the soil moisture varies nonlinearly along the depth, the equilibrium pressure exhibits a linear variation of the pressure with the elevation. The pressure is zero (i.e., equal to the atmospheric pressure) at the water table. Below it, the pressure increases linearly with the depth; above it, it decreases with elevation and becomes a suction.

In this approach, it is assumed that the capillary pressure gradient can be neglected and the tile system is uniformly distributed over the entire the subbasin. Since the tile system connects to the outlet which is open to the atmosphere, the pressure within the tile drainage system is atmospheric. The depth of the water table with respect to the tile system is important in the tile flow generation mechanism. If the water table elevation is lower than the elevation of the invert of the tile drain, then the water within the unsaturated soil layer does not contribute to the tile flow because of the negative pressure in the unsaturated soil matrix (Fig. 2).

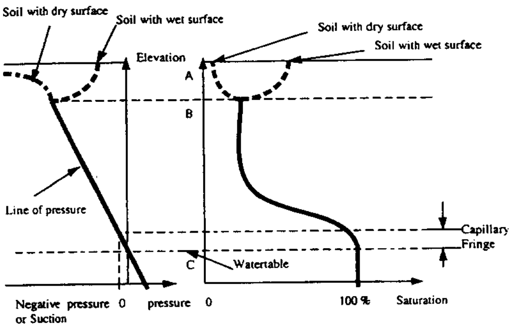


Fig. 1. Typical Profile of Saturation and Pressure in a Soil

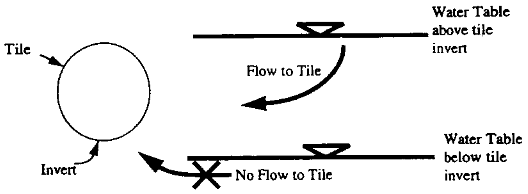


Fig. 2. Relationship between Water Table and Tile Flow

As raindrops reach the ground surface, infiltration into the soil layer propagates the saturation front from the upper soil layer towards the water table. The decrease of the hydraulic conductivity with depth (Beven, 1984) can lead to an accumulation of water on the ground. This results in surface runoff and in hypodermic flow which occurs in the upper part of soil and lags the concentration time and the peak of the storm hydrograph. The existence of macropores leads to faster and unpredictable fluxes in the unsaturated zone. The moisture distribution in the unsaturated zone depends on the hydraulic conductivity as well as the structure of macropores.

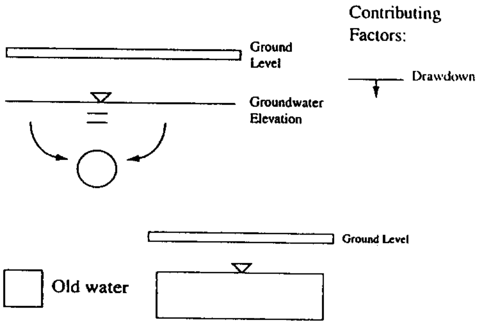
The response time of the tile flow hydrograph is seen to be closely related to the percolation time from the soil surface to the saturated zone. The travel time of water through the unsaturated zone depends not only on the hydraulic conductivity but also on the structure of macropores between the surface and the water table. The development of macropores in agricultural watersheds is mainly associated with the crop impact on the soil structure. The subwatersheds are selected so that the agricultural practice within each subwatershed is spatially uniform. Therefore, the effects of macropores on the spatial fluctuation of water table can be neglected.

The degree of saturation and the depth to the tile are needed to determine the rate of tile flow. The depth to the saturated zone and the saturation deficit both vary spatially and in time and are affected by the spatial variation of the topography and by the previous rainfall events. Although the TOPMODEL algorithm considers the influence of the hydraulic conductivity and topography on the hydrologic simulation at hillslope scale, the introduction of a tile drainage system makes it necessary to reconsider the hydrologic behavior in this new environment.

4. The Tile Flow Generation Scenarios

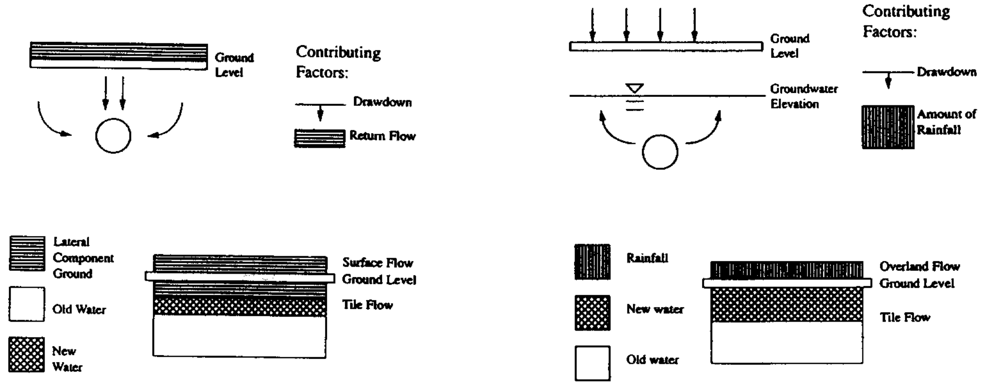
The local flow generation pattern (tile flow, overland flow and subsurface flow) mainly depends on the drawdown (DD) caused by the tile drain, the effects of topography expressed as the saturation deficit (SAT), the water content in the unsaturated zone (SUZ) and the precipitation depth (P). The combinations of these conditions determine the possible flow generation mechanisms. Each of these combinations can be described as one of nine possible flow generation scenarios. These nine scenarios are illustrated in Figs. 3 to 5.

Each figure shows on the top left side a schematic of the location of the drain pipe with respect to the ground surface and/or the water table. On the top right hand side the factors contributing to the runoff are listed. The lower part shows the composition of the hydrologic state as well as the tile flow and overland flow components.



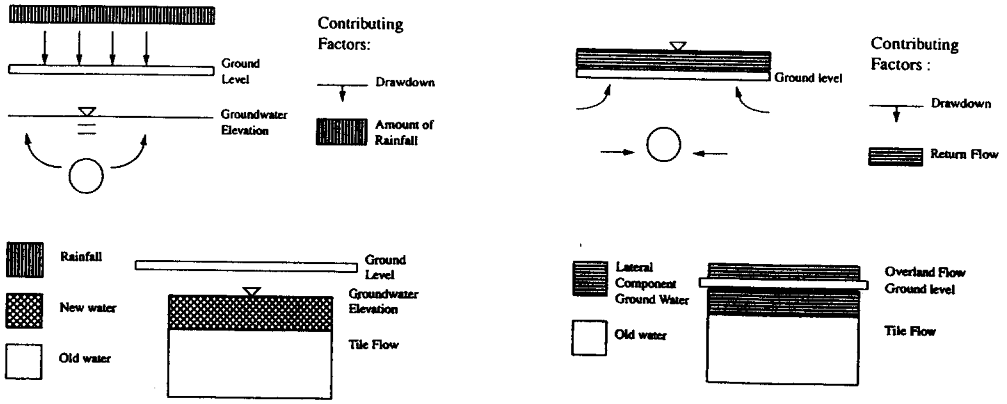
Case 1. Saturation Deficit > 0 & No Rainfall (SAT > SUZ)

Fig. 3. Flow Generation Scenario 1



(a) Case 2. Saturation Deficit > 0 & No Rainfall (STA < SUZ)

(b) Case 3. Saturation Deficit > 0 & Rainfall Event (Precipitation > SUZ+DD)



(c) Case 4. Saturation Deficit > 0 & Rainfall Event (Precipitation < SUZ+DD)

(d) Case 5. Saturation Deficit < 0 & No Rainfall (Return Flow > DD)

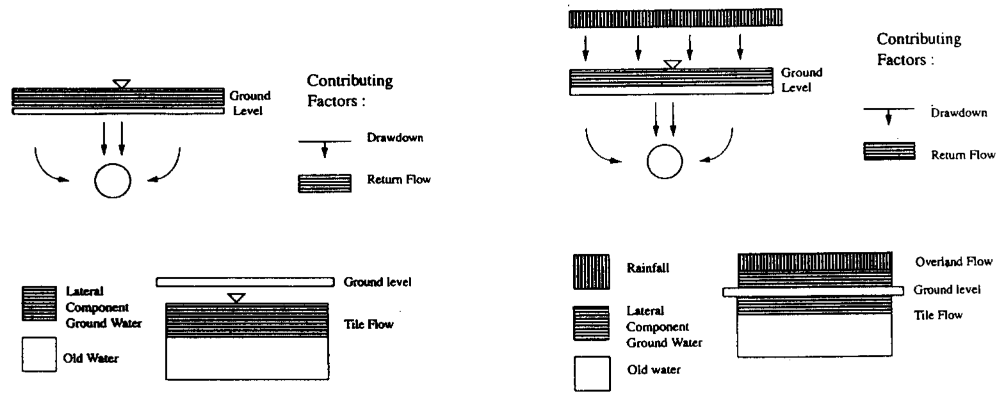
Fig. 4. Flow Generation Scenario 2 to 5

4.1 Scenario One, SAT > 0, P = 0, SAT > SUZ

In this scenario there is a positive saturation deficit and no rainfall during the time interval. If the water table is above the invert of the tile drain some portion of the water in the saturated zone will be drained and the saturation deficit will increase (Fig. 1). In this particular case, the principal factor determining the flow is the drawdown caused by the tile system. Since no new additional water enters vertically or horizontally, the water, which already exists in the saturated zone, i.e. old water, generates both tile flow and subsurface flow. Water with a relatively long residence time constitutes the storm hydrograph.

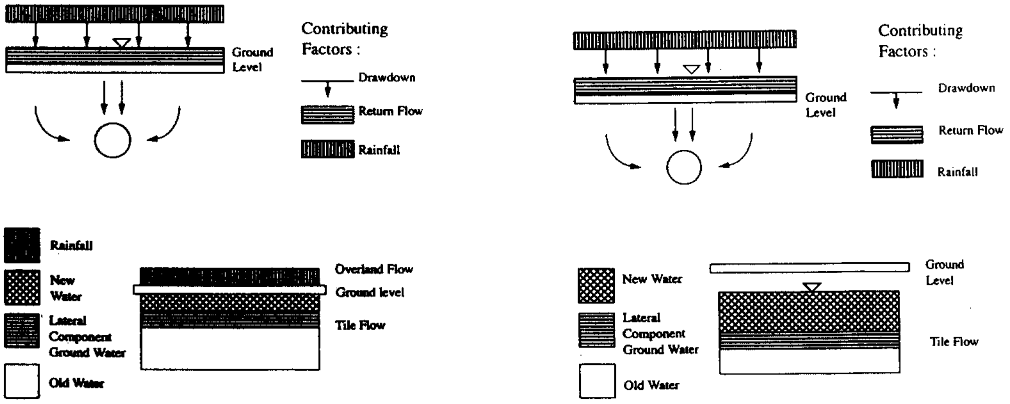
4.2 Scenario Two, SAT > 0, P=0, SAT< SUZ

After a rainfall event, the movement of water at a shallow depth in the horizontal direction can be greater than that in the vertical direction due to the decrease of the hydraulic con-



(a) Case 6. Saturation Deficit < 0 & No Rainfall (Return Flow $<$ DD)

(b) Case 7. Saturation Deficit < 0 & Rainfall Event (Return Flow $>$ DD)



(c) Case 8. Saturation Deficit < 0 & Rainfall Event RF $<$ DD, (Rainfall+Return Flow) $>$ DD

(d) Case 9. Saturation Deficit < 0 & RF > 0 Rainfall Event (Rainfall+Return Flow $<$ DD)

Fig. 5. Flow Generation Scenario 6 to 9

ductivity along the vertical direction. This results in a decrease in the local saturation deficit.

Since the antecedent rainfall event provided a high water content condition in the unsaturated zone (high SUZ), the decreasing tendency of the local saturation deficit can result in local saturation. In this case, the resulting overland flow comes from return flow (RF) (Dunne and Black, 1970) from the shallow groundwater. The tile flow is composed of the lateral component of ground water, new water from the previous rainfall event and old water. The drawdown by the tile system and the return flow determine the behavior of the hydrological system. Runoff is composed of overland flow, tile flow and subsurface flow.

4.3 Scenario three, SAT > 0, P $>$ (SUZ + DD)

When the saturation deficit is positive and there is rainfall during the time interval, the amount of precipitation must be compared to the initial volume of the unsaturated zone

(SUZ) plus the volume of drawdown by the tile (DD). This scenario considers the case where the amount of rainfall is greater than the available space in the unsaturated zone.

After the precipitation fills the available space in the subsurface zone, the rest of the water becomes saturation excess overland flow. Tile flow and subsurface flow also contribute to the runoff process. Some portion of tile flow can come from the water which already exists in the subsurface zone, some comes from the water which penetrates into the ground from rainfall.

A small positive saturation deficit and a large amount of rainfall at a given time interval can produce this flow generation mechanism. Both the drawdown by the tile system and the amount of rainfall mainly determine the hydrologic states.

4.4 Scenario Four, SAT $>$ 0, P $<$ (SUZ + DD)

This scenario occurs when the saturation deficit in a particular portion of the watershed is positive and the amount of rainfall is less than the sum of available space in the unsaturated zone plus the drawdown. In this case, the water is absorbed into the ground and becomes either tile flow or subsurface flow.

A relatively large saturation deficit and small rainfall intensity at this time step produces this kind of flow generation process. The tile flow is a combination of the old water (long residence time, soil water) and the new water (short residence time, rainfall). This kind of process could mainly happen in a relatively elevated portion of the watershed. The drawdown effect of the tile and the precipitation rate are the main factors in this particular hydrologic scenario.

4.5 Scenario Five, SAT $<$ 0, P $=$ 0, RF $>$ DD

A depressed topography usually results in an accumulation of horizontal subsurface flow which makes this depressed portion saturated. If the degree of saturation is high enough to fill the pore space up to the surface, the subsurface flow seeps at the surface producing overland flow, called return flow, even though there is no rainfall input during that time interval.

The volume of return flow should be compared to the volume drawn down by the tile system. When the return flow (RF) is greater than the drawdown (DD) and the saturation deficit is negative with no rainfall, then surface runoff occurs. The overland flow, which comes from the subsurface, can be characterized as an intermediate residence time response from the rainfall input because its travel path is relatively shallow and moves horizontally (generally speaking, horizontal hydraulic conductivity is greater than vertical hydraulic conductivity in a field).

The tile flow is composed of the horizontal component of groundwater and old water which has a long residence time in soil. Subsurface flow from a soil matrix also contributes to the storm hydrograph.

4.6 Scenario Six, SAT $<$ 0, P $=$ 0, RF $<$ DD.

If the saturation deficit is negative (i.e. the soil is saturated) with no rainfall during the time interval and the tile drawdown is greater than the return flow, then the tile system absorbs most of the horizontal component of the groundwater. In other words, the drawdown by the tile system makes space available and lets the return flow fill the empty space. Therefore, there is no surface runoff, both the water in the soil layer and the water from the rainfall of the previous time interval can be sources of tile flow. Subsurface flow from soil water also participates in building a storm hydrograph.

4.7 Scenario Seven, SAT < 0, P > 0, RF $>$ DD.

For scenario seven the conditions are the same as for scenario five except for the addition of the rainfall. In this case, there is overland flow which is a mixture of rainfall and return flow. Runoff is composed of tile flow (horizontal component of groundwater and old water in soil layer), subsurface flow (old water in soil layer) and overland flow (rainfall and return flow). This particular flow generation mechanism may occur when the degree of saturation (flow accumulation) is higher than in other saturated parts in the watershed. The tile drawdown and the amount of return flow must be compared to identify this flow generation process.

4.8 Scenario Eight, SAT < 0, P > 0, RF $<$ DD, (P + RF) $>$ DD

When the saturation deficit is less than zero in the presence of rainfall and with a return flow which is less than the tile drawdown effect, but the addition of the rainfall to the return flow exceeds the drawdown effect, then the flow generation pattern is more complex than in the previous case. The effects of tile drawdown, return flow and amount of rainfall in this time interval are the main factors in determining the hydrologic behavior. The overland flow is purely from rainfall. The combination of rainfall, horizontal groundwater flow and old water contribute to the tile flow, and the soil water of long residence time is the source of the subsurface flow. From another point of view, the effect of climate and topography dominates the effect of the tile system in the hydrologic behavior of the system.

4.9 Scenario Nine, SAT < 0, P > 0, RF > 0, P + RF $<$ DD

If all of the conditions are the same as in scenario eight except that the summation of rainfall and return flow is less than the amount of drawdown by the tile, the tile system strongly dominates the entire hydrologic system. In order to determine whether this process could occur or not, it is necessary to compare the amount of drawdown, return flow and rainfall. Runoff could appear to be tile flow, a combination of rainfall, horizontal movement of groundwater and old water, and subsurface flow.

With the Digital Elevation Model (DEM) in GRASS it is possible to calculate the spatial distribution of the saturation tendency by employing the multiple flow direction algorithm suggested by Quinn et al. (1991). For a specified tile system, given the raster representation of the saturation deficit in a watershed and the hyetograph of a rainfall event and with the tile system information, then one of the nine tile flow generation scenarios can be assigned to each raster. The hydrologic process of the watershed can be described as the successive and spatial variation of the raster representation of one of these flow generation scenarios. Each of these flow generation mechanisms is composed of different combinations of flow components which have different paths and residence times. Table 1 summarizes the combination of flow components of the nine possible cases of flow generation scenarios.

It is now necessary to extend TOPMODEL to include the tile effects on hillslope hydrologic processes based on the nine flow generation scenarios presented above. The procedures for the tile flow computation and the connection to the

Table 1. Flow Component in Tile Flow Mechanism

CASE (1)	Saturation Deficit (2)	Rainfall Event (3)	Condition (4)	Tile Flow (Old Water) (5)	Tile Flow (New water) (6)	Tile Flow (Lateral) (7)	Overland Flow (Rainfall) (8)	Overland Flow ReturnFlow (9)	Base Flow (10)
1	+	No	SAT > SUZ	Yes	No	No	No	No	Yes
2	+	No	SAT < SUZ	Yes	Yes	Yes	No	Yes	Yes
3	+	Yes	P > SUZ+DD	Yes	Yes	No	Yes	No	Yes
4	+	Yes	P < SUZ+DD	Yes	Yes	No	No	No	Yes
5	–	No	RF > DD	Yes	No	Yes	No	Yes	Yes
6	–	No	RF < DD	Yes	No	Yes	No	No	Yes
7	–	Yes	RF > DD	Yes	No	Yes	Yes	Yes	Yes
8	–	Yes	P+RF > DD	Yes	Yes	Yes	No	Yes	Yes
9	–	Yes	P+RF < DD	Yes	Yes	Yes	No	No	Yes

SAT : The local saturation deficit SUZ : The water content in the unsaturated zone
P : Precipitation to the unsaturated zone DD : Drawdown by tile system RF : Return Flow
+ : Unsaturated State – : Saturated State

traditional TOPMODEL components are also essential in the determination of the flow generation scenarios.

5. Extension of TOPMODEL Formulation Including Tile Drainage Scenarios

The tile drainage system increases the saturation deficit and the percolation of water into the ground. Therefore the initial saturation deficit in TOPMODEL, given by the first term in the right hand side of Eq. (9) (Beven, 1984), requires the addition of the average drawdown, caused by the tile drainage, thus,

$$S = -m\ln(\frac{q_{in}}{q_0}) + \Delta S \tag{9}$$

where, $\bar{S}$ is average saturation deficit, q_{in} is the observed base flow at the beginning of time period, q_0 is the base flow of the totally saturated watershed ($\bar{S} = 0$) and m is the scaling parameter related to the rate of decrease of the downslope transmissivity: (Beven et al., 1995) $T = T_0 e^{-s/m}$, where T_0 is the lateral transmissivity when the soil is just saturated and s is the local saturation deficit or, equivalently, m governs the exponential rate of decrease of hydraulic conductivity with depth (Beven, 1984) $K(z) = K_0 \exp[-\frac{n}{m} z]$ where K_0 is the hydraulic conductivity at the surface, z is the depth and n is the drainable porosity. According to Eq. (9), the tile network will quickly drain much of the water in most cases.

In TOPMODEL, the average saturation deficit must be updated at each time step by the mass balance Eq. (10) and the tile drainage effect must be considered in this equation.

$$S_t = S_{t-1} + q_{base} + q_{return} - q_v + q_{tile} \tag{10}$$

where, q_{base} is subsurface flow, q_{return} is return flow, q_v is the vertical component of subsurface flow, and q_{tile} is tile flow.

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 a combination of tile depth and tile diameter. The saturation deficit at a particular point is converted to the actual depth to the saturation zone by dividing the saturation deficit by the drainable porosity. This depth to the saturation zone, Z is compared to the depth of the tile system, deptil. The difference, *deptil–Z*, is treated as the potential volume of tile drainage which is the actual source of tile flow.

In order to separate the storage and the delaying effects in the soil matrix from those due to the drainage in the tile system, a second order linear reservoir model was chosen. A linear reservoir is one whose storage is linearly related to its output by a storage constant K, which has the dimension of time because S_{sto} is a volume while Q is a flow rate

$$S_{sto}=KQ \tag{11}$$

The second order linear reservoir model consists of two linear reservoirs in series with different storage coefficients. The rate of flow from the soil layer to the tile system is also related to the flow cross-sectional area within the tile drain. The tile discharge depends on the portion of the cross-sectional area of the tile drain which actually conveys the water. In other words, the local saturation deficit is related to the efficiency of the tile drain as well as to the storage amount in the local soil matrix.

The tile drain efficiency effect was considered by computing the ratio, R, of the tile flow cross-sectional area to the whole cross-sectional area of the tile drain. Therefore, if the watertable is lower than the invert of the tile drain,

$$R=0 \tag{12}$$

If the watertable is between the top and the invert of the tile drain,

$$R=\frac{A}{A_{full}} \tag{13}$$

Otherwise,

$$R=1 \tag{14}$$

where, R is the ratio, A is the flow cross-sectional area, and A_{full} is the whole cross-sectional area of the tile drain. The size of the tile drain also limits the capacity of flow conveyance. The maximum capacity of the tile drain can be estimated by assuming the flow velocity within the tile. In the application described below, a tile flow velocity of 1m/s was used. This value of 1 m/sec was obtained from measurements at the outlets in the Animal Science Farm Watershed (Fig. 6) and a similar value is quoted by Bouwer (1978).

The several flow paths in this extended version of TOPMODEL are shown in Fig. 5.

The upper portion of the figure shows the original TOPMODEL with its three stores: 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. The soil matrix storage for tile flow computation in the saturated zone (SAT) connects the original TOPMODEL to the tile flow mechanism which is shown in the lower part of Fig. 7. The tile flow mechanism principally consists of two linear reservoirs. The first, with 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 reservoir is

$$q_{sat}=\frac{(deptil-Z)n_{drain}}{K_{sto}}R \tag{15}$$

where $\{deptil-Z\}$ 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 Eqs.

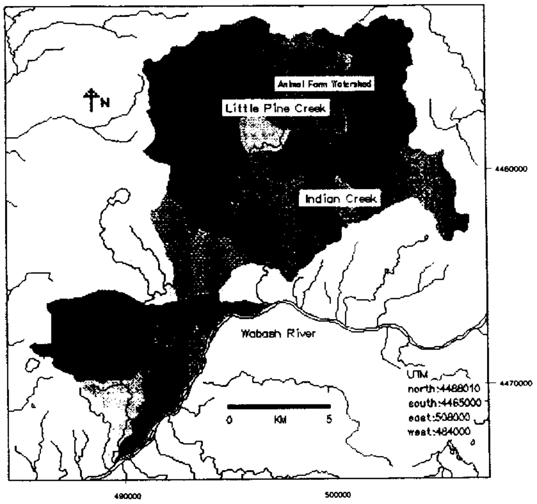


Fig. 6. Subwatershed in Little Pine Creek and Indian Creek Watershed forming the Indian Pine Natural Field Station

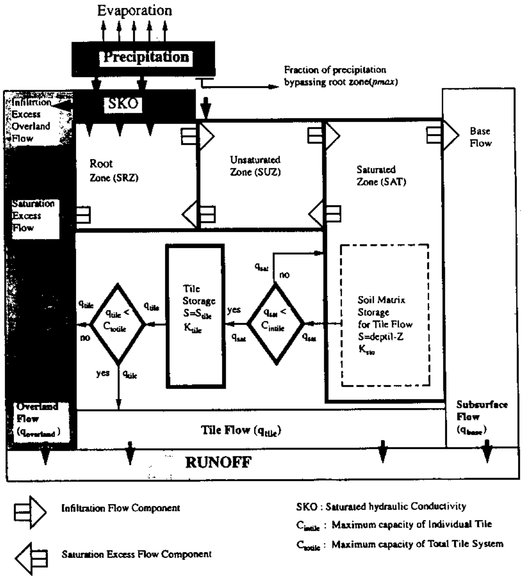


Fig. 7. The Tile Path Chart for TOPMODEL with Tile System

(12) to (14).

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, if $q_{sat} < C_{intile}$, then q_{sat} contributes to the tile storage:

$$S_{tile,t+1}=S_{tile,t}+q_{sat}+q_{tile} \qquad (16)$$

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},

$$q_{tile}=\frac{S_{tile}}{K_{tile}} \qquad (17)$$

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 qtile contributes directly to the tile flow.

It is thus seen that this approach accounts for the number and size of tiles in the watershed, and makes it possible to predict the hydrologic behavior of upland agricultural watershed under different conditions. In each time interval, the computation of the accumulated flow to the tile is performed from the highly saturated portion of the watershed to the unsaturated parts. Whenever the accumulated amount of flow to the tiles exceeds the maximum capacity of the tile drain, the tile drain no longer plays a role in transporting the water in excess of the maximum discharge.

6. Conclusions

A physically based hydrology model to simulate the runoff response from rainfall on an agricultural watershed with tile drainage is developed from the framework of TOPMODEL. It accounts for the effects of topography, soil property, land use and tile drainage. Spatial information of the topography can be obtained from a GRASS data base and involved the computation of the topographic index. Nine possible flow generation mechanisms in the tile drained basin are suggested depneding upon the relative position of the water table, the tile invert and the moisture content in unsaturated zone. The structure of model realizes every possible flow generation scenarios which are suggested in this work. The storage and the delaying effects in the tile system are simulated using a second order linear reservoir model. The flow can be generated as overland flow, tile flow and subsurface flow. Each flow component is designed to be calculated from the combination of possible flow generation scenarios. The model is designed to handle overland flow caused by infiltration excess as well as the saturation excess flow generation mechanism. It is expected that the structure of the model presenting the hydrograph with its several components associated with various possible flow generation scenarios (Table 1), can be useful in understanding the hillslope hydrology of agricultural watersheds with tile drainage.

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