유출경로 추적을 위한 GIS상에서의 유역 포화성향 고찰

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포화도의 공간적 변화인 지형지수를 계산하기 위한 다중흐름 알고리듬이 지형정보시스템인 GRASS와 연계되어 개발되었다. 본 연구는 소규모 농경지 배수구역에 대하여 적용하였다. 지하수위에 대한 타일 시스템의 영향이 DEM 모형과 Laplace식에 의해서 효과적으로 고려 될 수 있었다.

본 연구결과, 타일 시스템을 고려한 유역은 타일 시스템을 고려하지 않은 경우와 비교하여 높은 포화도를 가지고 있는 것으로 나타났으며, 예측된 riparian 유역은 실제의 유역조건과 잘 일치되고 있었다. 본 연구에서는 지형지수를 산정함에 있어 타일 시스템의 효과를 고려해야 함을 제안하였다.

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Saturation Tendency for Tracing of Runoff Path on GIS Platform

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Abstract

The spatial variation of saturation tendency can be calculated from the Digital Elevation Model (DEM) employing the multiple flow direction algorithm on the platform of Geographic Resources Support Analysis System (GRASS). It is expected that a better understanding of dynamical runoff processes in hillslope hydrological scale is obtained through tracing various runoff path such as infiltration excess overland flow component, saturation excess overland flow component and subsurface runoff component. A procedure is suggested to consider the effect of a tile system on calculating the topographic index. A small agricultural subwatershed (3.4 km2) is used for this study.

Introduction

Runoff generation are strongly affected by the local saturation state. The hydrological state of a watershed varies spatially because of the spatial variation of the rainfall event, topography and hydraulic conductivity. Troch et al. (1993) found a large discrepancy between the hydraulic conductivities at the catchment scale and in laboratory measurements on soil samples. Many researchers (Kirkby and Chorley, 1967; Dune et al., 1975; Beven and Wood, 1983) have found that the topography is the main factor governing the runoff from watersheds in humid, temperate climates.

The spatial information of saturation tendency (i.e. the topographic index) can be effectively obtained by considering only the DEM in the watershed (Quinn et. al., 1991). Since the highly saturated portion in a watershed generally is the riparian portion at the hillslope hydrologic scale, the topographic index (wetness index) (Beven and Kirkby, 1979) is a useful tool for predicting the riparian area in upland watersheds. 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. Since tile systems strongly affect the elevation of the water table, the runoff generation patterns are different from those of a watershed without tile drainage. The calculation of the topographic index in an agricultural watershed equipped with tile drains is essential for the runoff simulation at hillslope hydrological scale. The purposes of this paper are the following: 1) To integrate the multiple flow direction algorithm to calculate the topographic index in the GRASS environment. 2) To evaluate the effect of the tile system on the spatial and statistical distribution of the

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topographic index.

Geographic Information System

A new trend of hydrologic modeling has focused on the representation of spatial heterogeneity in watersheds. The appearance of the Geographic Information System (GIS) provides powerful data management facilities for handling spatial data bases. Furthermore, GIS supports various functions to maintain and analyze spatial and attribute data, integrate information, and display the results of analysis in both a tabular and map format. In this study, one of the most popular raster based GIS systems Geographical Resources Analysis Support System (GRASS) (USACERL, 1991), is used to manipulate the Digital Elevation Model (DEM).

Study Areas

The Animal Science Farm Subwatershed (3.6 km2) is located in a field station, called the "Indian Pine Natural Field Station" composed of two major watersheds, Little Pine Creek (139 km2) and Indian Resources Creek (67 km2), near the campus of Purdue University, West Lafayette, Indiana. The slope of the Animal Science Farm Watershed varies from 0 to 4 degrees. This watershed is primarily used for agricultural purposes and is strongly drained by a tile system.

Basic Theory of TOPMODEL

The hydrological processes at the hillslope scale vary both spatially and dynamically due to the heterogeneous features of the topography, of the soil hydraulic conductivity, of the vegetation and the unsteadiness of the rainfall inputs. This complexity of the hydrologic system results in several runoff processes such as overland flow generated by either the infiltration excess mechanism (Horton, 1933) or the saturation excess mechanism (Dunne and Black, 1970) and the subsurface flow through the soil matrix. In an attempt to schematize the complex hydrologic processes into a functional and mathematical structure in a manageable way, the following three basic assumptions were introduced in the development of TOPMODEL (Beven, 1995).

1. The temporal-spatial distribution of the saturation tendency can be approximated by a succession of steady state representations.
2. The local hydraulic gradient can be approximated by the local surface slope, .
3. The saturated hydraulic conductivity decreases exponentially with the depth from the surface.

Assumption 3 is validated by the abundant micropores near the soil surface (Beven, 1984). Based on assumptions 1 and 2, the topographic index, , where $a = A_x / C_x$ (see below) is the area drained per unit length of contour line, was proposed by Kirkby (1975) and used in developing the TOPMODEL by Beven and Kirkby (1976,1979). The area, Ax[L2], is upslope from the location that drains past x, is the hydraulic gradient at x and Cx [L/T] is the contour length at x traversed by surface flow. Considering the role of topography, integration of continuity equation with assumption 3 can be expressed as;

$$Z = Z + 1/f(\quad - \ln(a/\tan\beta)x) \qquad (1)$$

Equation (1) indicates that local hydra c behavior can be expressed in terms of the topographic index. In other words, locatior having the same topographic index show very similar hydrologic response patterns. Therc re, the spatial and statistical distribution of this parameter is very important for understanding the hydrologic processes at the hillslope scale.

Calculation of Topographic Index

In order to compute the spatial and statistical distribution of the topographic index from the DEM, either single flow direction or multiple flow direction algorithms can be used. A single flow direction algorithm, which is based on the methods suggested by Jenson and Dominque (1988), assumes that subsurface flow occurs only in the steepest downslope direction from any given point. The multiple flow direction algorithm (Quinn et al., 1991) assumes that subsurface flow occurs in all downslope directions from any given point and allows for flow convergence (several cells draining into one downslope neighboring cell) and flow divergence (one cell draining into multiple downslope neighboring cells). The single flow direction algorithm, in contrast, allows only flow convergence.

The total area draining into each grid cell(A) as well as the contour length(C) and slope(tanB) along which this area drains out of the cell are calculated in the GRASS environment. To perform the calculation for a given cell, the elevation of a cell was compared to that of its four diagonal and four cardinal neighboring points. The area that drained into the cell(A) was then partitioned into all its downslope neighbors in quantities proportional to tanB and C and added to the previous values of A for these downhill points (Quinn, 1991).

The values of ln(A/tanB) are directly related to the topographic likelihood of developing saturated surface runoff producing areas. This method is coded in C language employing library functions supported by GRASS. The topographic index in the Animal Science Farm Watershed was calculated using the digital elevation data in GRASS. Due to the flat topography of this watershed and the type of elevation data(integer) in GRASS, the calculation was not successful in representing the expected riparian area.

The frequency histogram of DEM (figure 1.a) shows that a few categories are dominant in the statistical distribution of DEM. This can be connected to the existence of the flat regions in DEM, which is extremely detrimental in the calculation of the topographic index. Based on the assumption of the topographic index that the groundwater table is the reflection of topography, Laplace's equation can be used to determine a new digital elevation model. The frequency analysis of the new DEM (figure 1.b) shows a statistically more continuous distribution which is more realistic in describing of the natural topography. The new topographic index map (figure 2.a), which was calculated based on the above elevation map layer, showed a good correspondence with the expected portion of the riparian area (grass waterway).

The spatial distribution of the water table in a tiled watershed usually is different from that in an untiled watershed. Because the original topography no longer plays a determinant role in the water table distribution, it is necessary to modify the original elevation to reflect the effect of tile on the groundwater level. For the purpose of this analysis the tile drain system is considered as a small ditch in the artificial DEM. This artificial DEM surface lowers the water table to the flow level within the tile. From a hydraulic point of view, the water level in the tile acts as a fixed boundary head.

Based on the assumption of the topographic index that the groundwater table is a reflection of topography, Laplace's equation can be used to determine a new digital elevation

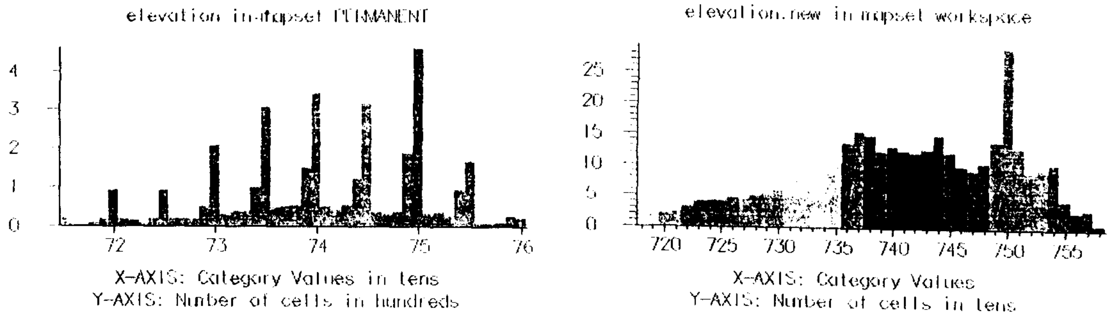

Figure. 1 (a) The Frequency Histogram(FH) (b) FH after Application of Laplace's Equation to Surface Level

model with the boundary condition at the tile drain location. The number of iterations necessary to build the artificial DEM can be related to the capacity of the tile. As the size of the tile gets bigger, the influence of the tile on the groundwater table is expected to expand and number of iterations to represent the tile's influence on the water table is increased. The calculation is propagated from the positions of the tile drainage to the extent of the tile influence. In this study, the extent of the tile influence was assumed to be 100m from the typical modelling scale (Dooge, 1982,1986) for the hillslope. Hence, the number of iterations to build the artificial DEM with 10m grid size can be determined as 10.

Figure 2 (a) The Topographic Index Map w/o tile. (b) The Topographic Index Map w tile

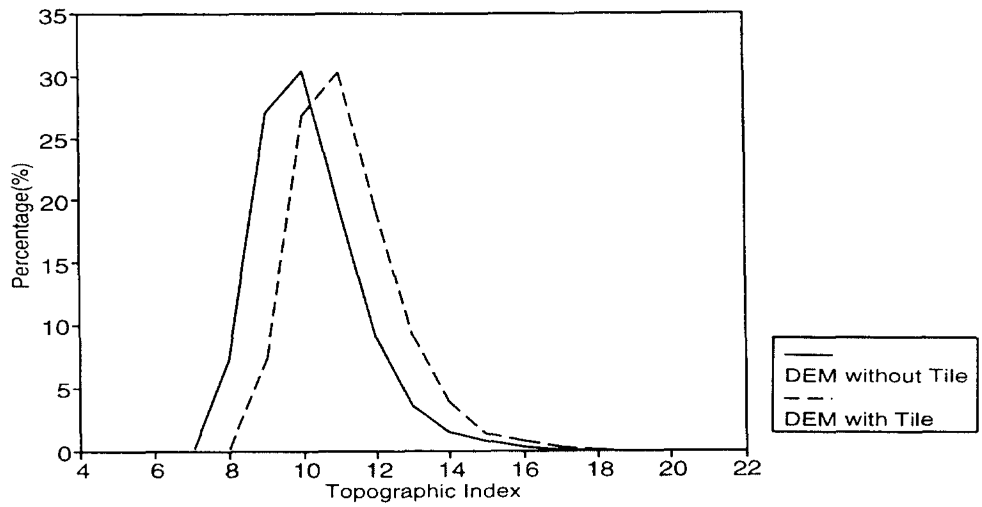

Figure 3. The Probability Distribution Function of the Topographic Index w and w/o tile

The topographic index of the artificial DEM considering the effects of the tile on the water table was calculated at the Animal Science Farm subwatershed. Figure 3 compares the probability density functions of the topographic index using the natural topography and the modified topography considering the tile system. This figure shows the PDF of DEM with tile is shifted to the right-hand side from the case without tiles. This means a subwatershed with a tile drainage system provides faster response about a given rainfall event than the case without a tile system. However, the impact of the tile system on the hillsope hydrology can be expressed not only statistically but also spatially. Figure 2.b shows the spatial distributions of the topographic index at the Animal Science Farm subwatershed with a tile system. Compared to the case without a tile system, the topographic index map layer with the tile system shows a higher degree of grass waterway development.

Conclusion

The topographic index map layer is calculated to predict the riparian area at an agricultural watershed equipped with tile drainage. The incorporation of GIS spatial data manipulation capability with the multiple flow direction algorithm makes this task successful. The impact of a tile system on the spatial variation of the ground water table can be efficiently considered by the application of Laplace's equation to the DEM with fixed boundary conditions at the tile location. The analysis also shows that the watershed with a tile system shows a higher degree of saturation than the case without tile drainage. The predicted riparian area is well fitted to the actual watershed condition.

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