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Research paper

Effect of Grid Size of the Digital Terrain Model on Hydrologic Simulation

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【 Summary 】

Digital Terrain Model (DTM) data are helpful for landscape representation, spatial analysis, and hydrologic modeling. In recent decades, DTM data have been widely applied in many fields, such as civil engineering, geography, and natural resources. Although DTM data are useful, their grid-based structures affect hydrologic simulation. Thus this paper attempts to understand the effects of grid sizes on the responses of the hydrologic model, TOPMODEL, including topographic indices, model parameter values, and streamflow simulation in Fushan watershed no. 2 (94 ha). The relationship between the topographic index and optimized parameter values of hydraulic conductivity in TOPMODEL was also examined. Five different grid size DTM data, at 10, 20, 30, 40, and 50 m, were applied to calculate topographic indices. The hydrologic data, including precipitation, streamflow, and air temperature from July to October 1995 in the study area, were selected. The Rosenbrock optimization algorithm was used to find optimal parameters within their reasonable ranges. Results show that the mean of topographic indices increases as grid size increases. When optimal parameters of TOPMODEL for 10-m DTM data are fixed and then applied to other grid sizes, model efficiencies slightly decrease with increase of grid size. However, model efficiencies can become virtually identical if parameters are properly optimized for different DTM data. The optimized parameter value of hydraulic conductivity increases as grid size increases. This is due to compensation for the effects of changing DTM grid size on topographic indices. In addition, there is a positive relationship between optimized parameter values of hydraulic conductivity and means of topographic indices. Based on the hydrologic simulation, landscape representation, and data handling requirements for these 5 different gird sizes, the 10-m grid size is recommended for DTM-based applications of geomorphologic and hydrologic modeling in the study area. However, we should check our results again if there are finer DTM grid sizes in Fushan watershed no. 2 in the future.

Key words: digital terrain model, hydrologic simulation, hydraulic conductivity.

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研究報告

數值地形模型網格大小對水文模擬之影響

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摘 要

數值地形模型有助於地景展現、空間分析及水文模擬等，近年來，它已廣泛應用於土木、地理及自然資源等領域。雖然數值地形模型甚爲有用，但它的網格結構常影響到水文模擬，故本研究旨在瞭解數值地形模型的網格大小對水文模式TOPMODEL反應之影響，包括地形指標、模式參數值及逕流模擬等，並探討地形指標與最佳水力傳導性參數之關係。研究區域爲福山二號集水區(94 ha)，水文資料取自1995年7月至10月間，含流量、雨量及氣溫等，透過五種不同網格邊長(10, 20, 30, 40, 50 m)的數值地形模型求取地形指標，供水文模式TOPMODEL模擬所需，並應用Rosenbrock最佳化演算法找出模式最佳參數值。結果顯示，地形指標平均值隨網格大小增加而增加，當網格邊長爲10 m的模式最佳參數組套用於其他不同網格大小上時，模式有效率將隨網格大小增加而略爲減少，不過當每一不同網格大小的模式參數值被最佳化後，其模式有效率則趨近相同，此時最佳水力傳導參數值卻隨網格大小增加而增加，此乃爲了補償網格大小的改變對地形指標之影響；此外，地形指標平均值則與最佳水力傳導參數值成正相關。考慮水文模擬、地景展現及資料處理需求等條件，此五種不同網格邊長之數值地形模型，以10 m邊長之數值地形模型較爲適宜，但爾後研究區域若有更精細之數值地形模型資料，則應作進一步之探討。

關鍵詞：數值地形模型、水文模擬、水力傳導性。

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INTRODUCTION

Jordan (1994) has pointed out that "the lack of consideration of the spatial variability of runoff generating mechanisms comes from the fact that most studies are done in small catchments or basins with relatively homogeneous characteristics". However, larger watersheds usually exhibit a wide range of heterogeneity and variability in space such as soil hydraulic characteristics, vegetation cover, soil moisture status, and flow pathways. Spatial variability often affects simulated results when hydrologic models are applied to predict hydrologic responses in natural watersheds (Bloschl and Sivapalan 1995). Using spatial point data to predict hydrologic responses of an entire watershed or expanding simulations in small experimental watersheds to large areas may cause significant errors. However, it is difficult to investigate the effects of spatial variability on watershed responses because of the lack of detailed information as well as computational limitations (Chairat 1993).

Fortunately, the development of the Geographic Information System (GIS) in recent years provides a tool to overcome this difficulty. Benefits for data management and mathematical operation, especially for the topographic representation incorporating Digital Terrain Model (DTM) data, have made GIS a useful tool to study the effects of spatial variability on hydrology. Although DTM data are helpful for spatial analysis, their discrete characteristics of grid-based structures, particularly for different grid sizes, have obvious influences on hydrologic modeling (Moore et al. 1993). DTM data are available at a variety of scales derived from a variety of original data sources. Different DTM grid sizes will cause different results in watershed delineation and streamflow simulation (Bruneau et al. 1995, Quinn et al. 1995). However, there have been few studies that have investigated the interactions between the simulated results of hydrologic modeling, appropriate parameter values, and DTM grid sizes. Therefore, this paper attempts to do so through the application of TOPMODEL in a humid forested watershed of the Fushan Experimental Forest, Taiwan.

The TOPMODEL (TOPography MODEL) is a physically based hydrologic model, which is suitable for hillslope watersheds, and reasonably simulates the effects of watershed topography on hydrologic responses (Beven and Kirkby 1979). It simulates the physical reality of the hydrologic system as closely as possible, and is widely used throughout the world. Each component of the hydrologic system is expressed in the form of known physical laws or relationships that have physical interpretation. Due to its ease of incorporating GIS and DTM data, TOPMODEL has become one of the more commonly used hydrologic models in recent years. Although TOPMODEL has been widely applied in many countries, so far there is little research testing its applicability in Taiwan (Liaw et al. 1999). It has also not been evaluated for use with extremely steep watersheds, such as those in Taiwan, with different DTM grid sizes.

Thus, the objectives of this research are: (1) to understand the effects of grid sizes on the responses of TOPMODEL including topographic index, parameter values, and streamflow simulation in an extremely steep watershed; and (2) to recognize the relationship between topographic indices and the optimized parameter values of hydraulic conductivity in TOPMODEL.

MATERIALS AND METHODS

Study area

Fushan watershed no. 2 (94 ha) is located in the Fushan Experimental Forest in northeastern Taiwan and is a site designated for international long-term ecological research (LTER). The elevation relief is from 675 m at the weir to 1230 m at the ridge, and the average slope is 55% (Fig. 1). The annual mean air temperature was 18.5°C, and average annual precipitation was 3315 mm from 1994 to 1996. Typhoon events are frequent, and sometimes bring large amounts of rainfall. Soils are strongly acidic (pH 3.8-5.0), with low CEC (cation exchangeable capacity), and low base saturation percentage (Lin et al. 1996). The main soil types are silt loam and silty clay loam. Vegetation cover is moist subtropical forest dominated by evergreen broadleaf trees.

DTM data, GIS software, and TOPMODEL

Raster DTM data in the study area were derived from the Fushan topographic map whose map scale is 1: 5000 and contour interval is 5 m. These DTM data contain 5 different grid sizes, of 10, 20, 30, 40, and 50 m. The hydrologic model, TOPMODEL, used in this paper was programmed by the United State

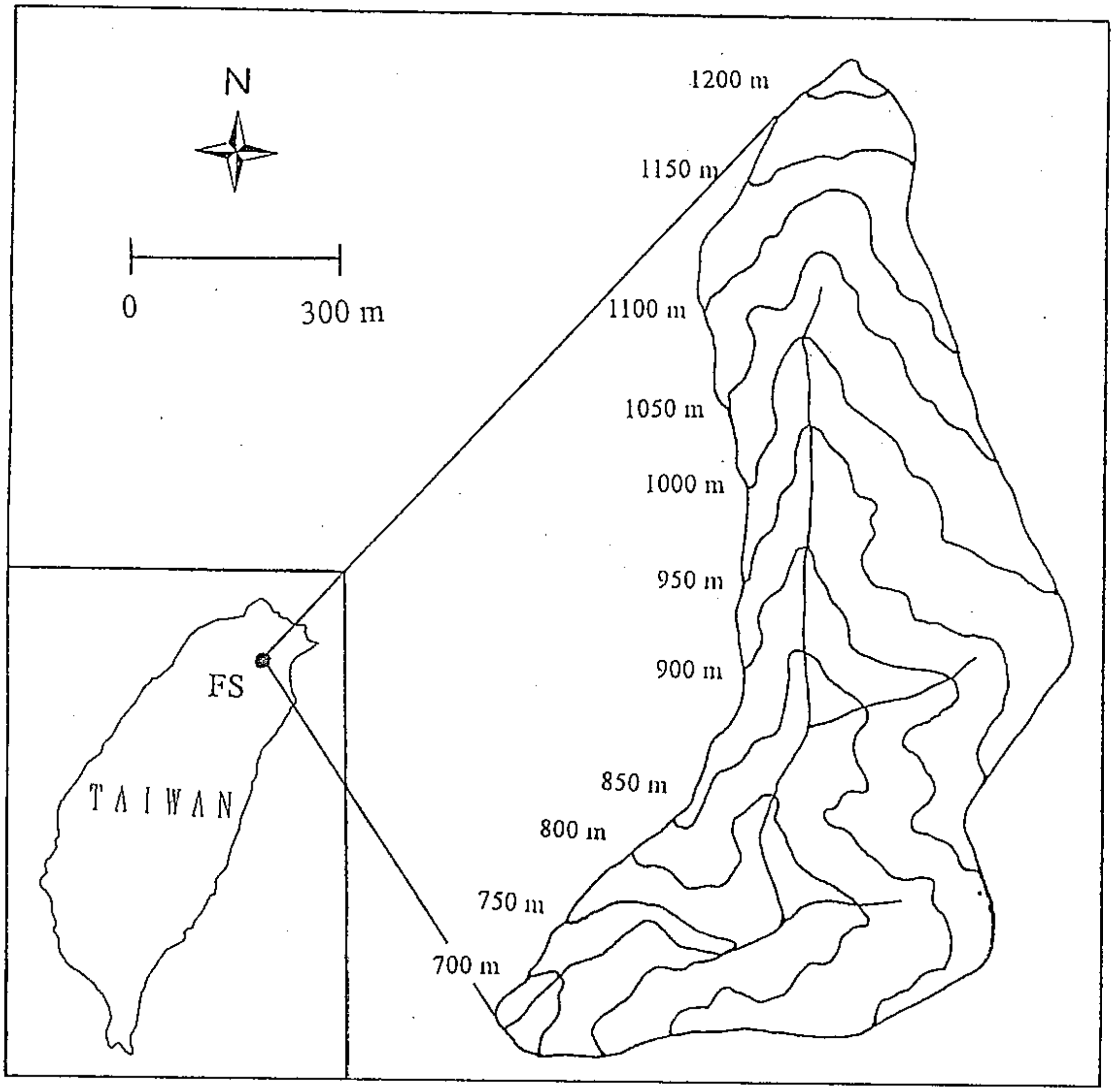

Fig. 1. Map of Fushan watershed no. 2

Geological Survey (USGS) (Wolock 1993). In this model the topography of a watershed is lumped into a parameter which is called the topographic index: $\ln(\alpha/\tan\beta)$, where a is the upslope area per unit contour length; and $\tan\beta$ is the local slope angle. The GIS software, ARC/INFO, was used with incorporation of DTM data to calculate the topographic index through the multiple-flow-direction algorithm (Wolock and McCabe 1995), including both cardinal and diagonal directions that water flows along these downslope directions.

Model calibration

Hydrologic data of Fushan watershed no. 2 from July to October 1995 were chosen for this research. These data include daily runoff, rainfall, and air temperature. An automatic optimization algorithm (Rosenbrock 1960) was incorporated into TOPMODEL to search for optimal parameters. The user can choose a parameter, more than 2 parameters, or all parameters to be optimized at 1 time. In this study we chose all parameters of TOPMODEL to be optimized together. The sum of squared errors (SSE) was selected as the objective function for minimizing the difference between observed and simulated streamflow. Following Rosenbrock's paper, this optimization algorithm's procedures are briefly described as follows.

The first step is to try an increment of arbitrary length, e. If the new value of the objective function is less than or equal to the old value, this is defined as success. If e is so small that it makes no change in the objective function, then it is increased on the next attempt.

Second, it must be decided when and how to change the directions, ξ, in which the steps e are taken. We decided to work throughout with n orthogonal directions ξ_1, ξ_2,...., ξ_n, rather than choosing a single direction in which to progress at each stage. It is necessary to examine neighboring points in each of n directions in order to determine the best direction of advance. If one of the points examined makes the objective function lower than the previous value, we accept it as a new starting point.

Last, a criterion is needed to determine when to stop the search. The optimization procedures continue until there is no further improvement in the objective function.

Model evaluation

The coefficient of efficiency (EFF), proposed by Nash and Sutcliffe (1970), was chosen as a criterion for evaluating TOPMODEL performance in this research. This equation is expressed as:

$$EFF = \frac{\Sigma\,(QOBS_i - QOBS_m)^2 - \Sigma\,(QOBS_i - QSIM_i)^2}{\Sigma\,(QOBS_i - QOBS_m)^2} \qquad (1)$$

where $QOBS_i$ is observed discharge, $QSIM_i$ is simulated discharge, and $QOBS_m$ is the mean of observed discharge.

RESULTS AND DISCUSSION

Effects of grid size on topographic indices

Values of topographic indices calculated through the multiple-flow-direction algorithm with 5 DTM grid sizes are shown in table 1. The mean value of topographic indices increases as grid size increases from 5.25 for a 10-m grid to 5.92 for a 50-m grid. This difference is due to a decrease of watershed slopes (tans) with an increase of grid size. The average slope in the Fushan watershed no. 2 changes from 55% for a 10-m grid to 42% for a 50-m grid (Liaw 1998). The variance of topographic index distribution increases as grid size increases from 5.32 for a 10-m grid to 5.85 for a 50-m grid. The range between maximum and minimum topographic indices becomes narrower when grid size increases. However, the skewness doesn't trend along with increases of grid size.

Effects of grid size on streamflow simulation

The optimal parameters of streamflow simulation with 10-m DTM data during July to October 1995 for the Fushan watershed no. 2 were m = 61.8 mm, K = 130 mm/d, P_m = 0.1, Z_{tot} = 1.10 m, Z_{ab} = 0.69 m, and θ = 0.2. The parameter m is a scaling parameter based on

Table 1. Values of the topographic index with different grid sizes in Fushan watershed no. 2

Grid size(m)	Mean	Variance	Skewness	Maximum	Minimum
10×10	5.25	5.32	29.77	17.09	0.75
20×20	5.45	5.60	33.10	17.08	1.16
30×30	5.58	5.65	32.38	17.04	1.86
40×40	5.77	5.79	29.75	16.87	1.94
50×50	5.92	5.85	27.00	16.98	2.30

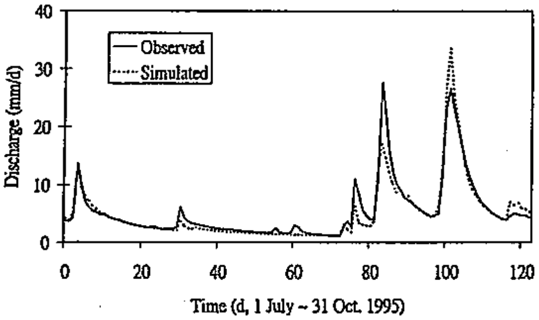

Fig. 2. Results of streamflow simulation from July to October 1995 in Fushan watershed no. 2

soil properties, and K is the hydraulic conductivity of C-horizon soil. The parameter P_m represents the fraction of precipitation bypassing the soil zone, while Z_{tot} and Z_{ab} are total and AB-horizon soil depth, respectively. The parameter, θ , is soil field capacity. After streamflow simulation, the model efficiency (EFF) was 0.894. The observed and simulated hydrographs are shown in figure 2. The percentage of simulated saturation overland flow, which includes direct precipitation and return flow (Dunne and Leopold 1978), over total simulated streamflow was 14.9%. A more detailed discussion about model concept, parameterization, calibration, and validation was reported by Liaw et al. (1999).

The above optimal parameters were fixed and then applied to other grid sizes, of 20, 30, 40, and 50 m, to determine the effects of spatial resolution on streamflow simulation.

Table 2. Results of streamflow simulation using fixed parameters in Fushan watershed no. 2

Grid sizes (m)	10	20	30	40	50
EFF[1]	0.894	0.890	0.883	0.869	0.856
SOF (%)[1]	14.9	15.8	16.7	19.3	20.9

[1] EFF: model efficiency, SOF: saturation overland flow.

The results of model efficiencies and percentages of saturation overland flow are showed in table 2. Based on the results, model efficiencies decrease slightly from 0.894 to 0.856 with an increase of grid size using fixed optimized parameters. In contrast, percentages of saturation overland flow obviously increase from 14.9% to 20.9% with an increase of grid size. The only difference among simulations is grid size, so this reveals that simulated streamflow generation mechanisms are affected by grid size. The reason is that increasing grid size increases the mean $\ln(\alpha/\tan\beta)$ value (Table 1), which means a flatter slope ($\tan\beta$) and causes a decrease in the subsurface flow. The mean $\ln(\alpha/\tan\beta)$ value enables the prediction of the initial storage deficits for all points in a watershed, and its high values indicate a greater likelihood for the occurrence of saturated contributing areas (Chairat and Delleur 1993). Thus, larger grid sizes are more likely to generate saturated areas because they produce higher

Table 3. Optimal parameters and results of simulation in Fushan watershed no. 2

Grid size (m)	m (mm)	K (mm/d)	P_m	Z_{tot} (m)	Z_{ab} (m)	θ	EFF[1]	SOF[1] (%)
10 × 10	61.8	130	0.1	1.10	0.69	0.2	0.894	14.9
20 × 20	62.2	158	0.1	0.76	0.68	0.2	0.892	14.7
30 × 30	63.2	210	0.1	0.89	0.69	0.2	0.890	13.6
40 × 40	63.3	267	0.1	0.86	0.68	0.2	0.895	15.0
50 × 50	61.5	434	0.1	1.50	0.71	0.2	0.894	14.6

[1] EFF: model efficiency, SOF: saturation overland flow.

values of mean ln(α/tanβ).

Next, the Rosenbrock optimization algorithm was used to find optimal parameter sets for each grid size. Results are shown in table 3. These optimal parameters m, Z_{tot}, and Z_{ab} vary with increase of grid size, but there are no systematic trends. The values of parameter m are concentrated in a range from 61.5 to 63.3. On the other hand, the optimal parameter K increases as grid size increases from 130 mm/d for a 10-m grid to 434 mm/d for a 50-m grid. These significant changes of parameter K are due to compensation for the effects of DTM grid size on the topographic index distribution (Wolock and McCabe 1995). Franchini et al. (1996) also pointed out that "the hydraulic conductivity parameter values increased with the increase of grid size because the topographic index distribution was greatly affected by the DTM grid size and this dependence was reflected in the hydraulic conductivity parameter". Therefore, it is obvious that grid size affects the optimal values of hydraulic conductivity in TOPMODEL.

As shown in table 3, model efficiencies vary in a narrow range from 0.890 to 0.895. In addition, percentages of saturated overland flow vary little with grid size: from 13.6% to 15.0%. This result demonstrates that different grid sizes can produce identical model efficiencies if parameters are properly optimized. Wolock and McCabe (1995) indicated that any difference in model efficiency essentially disappears when a model is calibrated by adjusting subsurface hydraulic parameters. A similar result was shown by Franchini et al. (1996) in which model efficiencies were identical when grid size varied from 60 to 480 m, and the hydraulic parameters were calibrated. However, Bruneau et al. (1995) obtained an opposite result where model efficiencies decreased and percentages of saturation overland flow increased with increase of grid size, even when the optimal parameter sets were applied.

Relationship between mean ln(α/tanβ) and parameter K

In order to determine the relationship between mean ln(α/tanβ) and parameter K, Franchini et al. (1996) assumed that 2 ln(α/tanβ) distributions had the same shape, but that they were distinct from each other. The first distribution had a mean ln(α/tanβ) value of λ_1, and the second distribution had a mean ln(α/tanβ)value of λ_2, ($\lambda_1 < \lambda_2$). Keeping the parameter m constant, it is possible to obtain the same runoff using the 2 distributions with appropriate K values. The relationship between mean ln(α/tanβ) and parameter K was expressed by Franchini et al. (1996) as:

$$\lambda_1 - \lambda_2 = \ln(K_1 / K_2) \qquad (2)$$

In our research, there are 2 steps which examine the relationship between the topographic index distribution and the parameter K, as proposed by Franchini et al. (1996), in Fushan watershed no. 2. First, the parameter m was fixed (m = 61.8 mm), and the Rosenbrock method was used to find optimal K values for different grid sizes. Second, Equation (2) was used to obtain the calculated K values, which were compared to the optimal K values in the first step. Results are shown in Table 4. Both

Table 4. Comparison of optimal and calculated K values in Fushan watershed no. 2

Grid size(m)	λ	m (mm)	Optimal K (mm/d)	Calculated K (mm/d)
10×10	5.25	61.8	130	130
20×20	5.45	61.8	158	159
30×30	5.58	61.8	219	181
40×40	5.77	61.8	279	219
50×50	5.92	61.8	438	254

the optimal K values using the Rosenbrock method and the calculated K values using Equation (2) increases as grid size increases. The optimal K values are obviously larger than the calculated K values for the same grid size except for the 10-m and 20-m grids. This result reveals that Equation (2) is insufficient to describe the relationship between the topographic index distribution and the parameter K in Fushan watershed no. 2. This could be because Fushan watershed no. 2 is too steep to fit this equation. In addition, Franchini et al. (1996) archived this equation through larger grid sizes from 60 to 480 m, but our research only focused on finer grid sizes from 10 to 50 m.

Appropriate grid size

Even though model efficiencies are virtually identical for different DTM grid sizes (Table 3) using optimal parameters for Fushan watershed no. 2, the landscape representation and data handling requirements must also be considered to determine an appropriate grid size. Large grid sizes are unrepresentative of the detailed watershed form, but finer grid sizes cause a huge increase in data and require more processing time (Quinn et al. 1995). Through their study on 2 small steep watersheds (0.3 km^2 in Oregon and 1.2 km^2 in California), Zhang and Montgomery (1994) pointed out that "a 10-m grid size presents a reasonable compromise between increasing spatial resolution and data handling requirements for modeling surface processes in many landscapes".

A 10-m grid size was chosen in order to accurately extract stream networks from DTM data and to model the steep topographic characteristics in Fushan watershed no. 2 (Chen et al. 1997, Liaw 1998). Although a grid size finer than 10 m can be created, greater interpolation errors may be produced. In addition, Fushan watershed no. 2 is small (94 ha), so data handling is not difficult with a 10-m grid size. Therefore, based on the hydrologic simulation, landscape representation, and data handling requirements for these 5 different grid sizes, the 10-m grid size is recommended for Fushan watershed no. 2. However, we should check our results again if there are finer DTM grid sizes in the future.

CONCLUSIONS

The effects of DTM grid sizes on the responses of TOPMODEL, including topographic indices, parameter values, and streamflow simulation, in Fushan watershed no. 2 are examined in this paper. The relationship between topographic indices and the optimized hydraulic conductivity of C-horizon soil in TOPMODEL is also recognized. Results show that the mean of topographic indices increases as grid size increases. When optimal parameters of TOPMODEL for 10-m DTM data are fixed and then applied to other grid sizes, model efficiencies slightly decrease with increase of grid size. However, model efficiencies become virtually identical if parameters are properly optimized for each grid size. The optimized parameter value of hydraulic conductivity of C-horizon soil increases as grid size increases. This is due to compensation for the effects of changing DTM grid size on topographic indices. In addition, there is a positive relationship between optimized values of hydraulic conductivity and the topographic index distribution in Fushan watershed no. 2, but this relationship doesn't fit the mathematical expression provided by Franchini et al. (1996). Considering hydrologic simulation, landscape representation, and data handling requirements for these 5 different grid sizes, the 10-m grid size is more appropriate in the study area. However, we should check our results again if there are finer DTM grid sizes in the future.

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LITURATURE CITED

Beven KJ, Kirkby MJ. 1979. A physically based, variable contributing area model of basin hydrology. Hydrol Sci Bull 24:43-69.

Bloschl G, Sivapalan M. 1995. Scale issues in hydrological modelling: a review. Hydrol Processes 9:251-90.

Bruneau P, Gascuel-Odoux C, Robin P, Merot P, Beven K. 1995. Sensitivity to space and time resolution of a hydrological model using digital elevation data. Hydrol Processes 9:69-81.

Chairat S. 1993. Adapting a physically based hydrological model with a geographic information system for runoff prediction in a small watershed [DPhil thesis]. Purdue Univ., West Lafayette, IN. 106 p.

Chairat S, Delleur JW. 1993. Effects of the topographic index distribution on predicted runoff using GRASS. Water Res Bull 29(6): 1029-34.

Chen HH, Liaw SH, Jan JF, Hwong JL. 1997. A study of the extraction of channel networks from digital terrain model in small steep watersheds. Quart J Exp For Nat Taiwan Univ 11(3):41-52. [in Chinese with English abstract].

Dunne T, Leopold LB. 1978. Water in environmental planning. New York: WH Freeman. 818 p.

Franchini M, Wensling J, Obled C, Todini E. 1996. Physical interpretation and sensitivity analysis of the TOPMODEL. J Hydrol 175: 293-338.

Jordan JP. 1994. Spatial and temporal variability of stormflow generation processes on a Swiss catchment. J Hydrol 153:357-82.

Liaw SC. 1998. Streamflow simulation using a physically based hydrologic model in humid forested watersheds [dissertation]. Colorado State Univ., CO. 163 p.

Liaw SC, Smith FM, Hsia YJ, King HP, Hwong JL. 1999. TOPMODEL simulation of Fushan watershed no.2 discharge. Taiwan J For Sci 14(3):323-30.

Lin KC, Horng FW, Cheng WE, Chiang HC, Chang UC. 1996. Soil survey and classification of the Fushan experimental forest. Taiwan J For Sci 11(2):159-74. [in Chinese with English abstract].

Moore ID, Turner AK, Wilson JP, Jenson SK, Band LE. 1993. GIS and land-surface subsurface process modeling. In: Goodchild MF, editor. Environmental modeling with GIS. Oxford University Press, UK. p 196-230.

Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models. Part I A discussion of principles. J Hydrol 10:282-90.

Quinn PF, Beven KJ, Lamb R. 1995. The ln ($\alpha/\tan\beta$) index: how to calculate it and how to use it within the TOPMODEL framework. Hydrol Processes 9:161-82.

Rosenbrock HH. 1960. An automatic method for finding the greatest or least value of a function. Computer J 3:175-84.

Wolock DM. 1993. Simulating the variable-source-area concept of streamflow generation with the watershed model TOPMODEL. USGS Report 93-4124. 33 p.

Wolock DM, McCabe Jr GJ. 1995. Comparison of single and multiple flow direction algorithms for computing topographic parameters in TOPMODEL. Water Res Res 31(5):1315-24.

Zhang W, Montgomery DR. 1994. Digital elevation model grid size, landscape representation, and hydrologic simulations. Water Res Res 30(4):1019-28.