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Modeling the effects of elevation data resolution on the performance of topography-based watershed runoff simulation

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Abstract

The spatial uncertainty of a topography based rainfall runoff model (TOPMODEL) is addressed in this study to assess its variability in simulating watershed hydrologic response with regards to the change of digital elevation model (DEM) resolution. Twelve DEM realizations of different grid sizes ranging from 30 m to 3000 m for each of two case watersheds are used for comparative examinations. The study shows that DEM grid size has significant influence on the topographic index distribution which represents the effect of topography on watershed hydrology in TOPMODEL. The smoothing effect of grid size increase may result in deteriorated topographic index distributions at coarse resolutions as the ratio of grid cell area to watershed area gets larger. The simulated discharges and model efficiencies using a same set of TOPMODEL parameters are sensitive to DEM grid size especially at coarse resolutions. This sensitivity, however, can be moderated by parameter calibrations as the optimization runs show that fairly equal efficiencies can be preserved by the compensation effect of transmissivity parameter T_0 within a large extent of DEM resolution for each watershed. The interaction between T_0 and the topographic index distribution with respect to TOPMDOEL model performance is also examined. It is found that both study watersheds demonstrate a similar pattern of change in model performance along with the increase of the grid-to-watershed ratio. The analysis reveals that the ratio poses an important factor in controlling the effect of DEM grid size on TOPMODEL performance. A ratio of less than 5% is suggested in DEM resolution selection for TOPMODEL applications based on the results of this study.

Keywords: Digital elevation model; Grid size; TOPMODEL; Topographic index; Hydrologic modeling

1. Introduction

Topography plays an important role in distributed hydrologic modeling. Discretized landscape characterizations with raster-based digital elevation models (DEMs) are commonly used for representing elevation surface in rainfall-runoff simulations supported by geographic information systems (GIS). We have seen greatly increased availability of digital elevation models for the past decade. Resolution of elevation data represents the horizontal accuracy of a DEM. Different resolutions of DEMs could be available for one area of interest from various sources. An issue with the topography based runoff modeling has been that at what spatial resolution a model would perform optimally. Effects of DEM grid sizes on hydrologic simulations have been examined in a number of studies with applications of TOPMODEL (Beven, 1997), a semi-distributed model based on the contributing area concept. The concept states that overland flow will occur only over a certain portion of the total watershed area where there is no soil moisture deficit. The dynamics of the saturated source areas is controlled by watershed topographic and subsurface hydraulic characteristics and the state of the watershed wetness. The spatial distribution pattern of soil moisture throughout a watershed depends partly on its landscape topography. In runoff

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estimations by TOPMODEL, the topographic influence is considered by using a prescribed topographic index, which represents the extension of saturated areas and the spatial variation of groundwater levels and soil moisture. TOPMODEL has a relatively simple and versatile application framework with very limited number of parameters. The raster-based modeling allows calculated output to be mapped back to spatial context and easily to be visualized. Its applicability in runoff simulations has been tested and proved by numerous studies, and the model has gained much popularity in recent years (Beven, 1997; Peters et al., 2003; Silberstein, 2006).

The simplicity of the TOPMODEL structure has allowed the issue of resolution dependency to be studied in some detail. Zhang and Montgomery (1994) examined the effect of grid cell resolution on landscape representation and hydrologic simulations using elevation data from two small watersheds (0.3 km^2 and 1.2 km^2). The DEMs at the resolutions of 2, 4, 10, 30 and 90 m were used in the modeling for the two watersheds. Their results showed that increasing the grid size resulted in an increased mean topographic index because of increased contributing area and decreased slopes. A same set of TOPMODEL parameters for each watershed was used in the runoff computations for all the five grid sizes without calibration. Hydrographs were generated for a 4-h rainfall event with different intensity and base-flow conditions. They reported that the DEM resolution also affected hydrologic response significantly, and with the increasing DEM grid size, the simulated peak discharge decreased and the simulated depth to the water table increased. In another study by Wolock and Price (1994), effects of both DEM map resolution and scale on TOPMODEL predictions of hydrologic characteristics were evaluated with topographic data for 71 areas, each of which corresponds to a USGS DEM quadrangle. They found that increasing the grid size resulted in higher minimum, mean, variance, and skewness of the topographic index distribution. The study also showed that increasing the coarseness of the data resolution appeared to decrease the simulated mean depth to the water table, and to increase the ratio of predicted overland flow to total flow. Some subsequent studies found that a link could be established between DEM grid size and other calibrated parameters values (Beven, 1997).

A sensitivity analysis on the space and time resolutions was performed by Bruneau et al. (1995) using TOPMODEL on a 12-km^2 experimental watershed in France. The analysis showed that the modeling efficiency is fairly high inside a relevant domain of space and time resolutions and that working outside this domain induces a strong decrease of modeling efficiency. Franchini et al. (1996) obtained similar results from their tests with 3-month hourly data in Real Collobrier Basin, France. They indicated that a close interaction exists between the hydraulic conductivity parameter and the DEM grid size in the calibrations for optimal performance of TOPMODEL. Saulnier et al. (1997), generalizing the results of Franchini (1996), used TOPMODEL to simulate 11 storms for a subwatershed (8.4 km^2) of Real Collobrier Basin on event basis. The study suggested that the effective hydraulic conductivity parameter should be estimated on the basis of keeping a realistic simulation of saturated contributing areas as the DEM resolution changes.

This work examines the effects of DEM grid size on the performance of TOPMODEL in its applications to two experimental watersheds (21.3 km^2 and 64.0 km^2) with their daily hydrologic data for one year. Twelve levels of DEM grid sizes between 30 m and 3000 m are used, and parameter calibrations are conducted at each level. As the basis of this study, the influence of resolution changes on the spatial distributions of the topographic index is first evaluated as compared to the results of previous studies. The simulations are also performed with a same set of uncalibrated parameters at all the grid sizes to check on the variations of model prediction and efficiency. The interactions between model parameters and DEM grid size are explored by the calibrated runs for optimized efficiency. It is hoped that this work will contribute some insight on to what extents of the DEM grid size TOPMODEL can still achieve reasonable simulations.

2. TOPMODEL

The initiation of TOPMODEL was intended to propose a collection of concepts rather than to make it a modeling package. Thus there have been many revisions to the original version to adapt to specific circumstances. The model used in this work is based on the TOPMODEL 95.02 version, which has been most frequently tested and applied (Beven et al., 1995; Beven, 2001). Based on the variable source area concept of runoff generation, TOPMODEL has three basic assumptions: (1) the dynamics of the saturated zone can be approximated by successive steady-state representations; (2) the hydraulic gradient of the saturated zone can be approximated by the local surface topographic slope, $\tan\beta$; groundwater table and saturated flow are parallel to the local surface slope; (3) the distribution of downslope transmissivity with depth is an exponential function of storage deficit or depth to the water table.

The assumptions lead to simple relationships between watershed storage and local water table level where the topographic index poses the determining factor. The topographic index is given as $\ln(\alpha/\tan\beta)$ where α (m) is upslope contributing area per contour length. Based on the assumptions, the downslope subsurface flow rate per unit contour length at any location i in the watershed q_i (m^2/h) is approximated as:

$$q_i = T_0 e^{-S_i/m}(\tan\beta_i) \tag{1}$$

where T_0 (m^2/h) is the lateral downslope transmissivity when the saturated zones reaches the ground surface, S_i (m) is the local soil moisture deficit, and m (m) is a scaling parameter controlling the rate of decrease in soil hydraulic conductivity with depth.

As the water table recharge and the soil transmissivity are assumed to be spatially constant, S_i (m) can be expressed as:

$$S_i = \bar{S} + m(\bar{\lambda} - \ln(\alpha_i/\tan\beta_i)) \tag{2}$$

where: $\bar{S}$ (m) is mean soil moisture deficit of the watershed, $\bar{\lambda}$ is the watershed average of the topographic index $\ln(\alpha/\tan\beta)$.

Unsaturated and saturated zone fluxes q_v (m/h) are simulated as follows:

$$q_v = \frac{S_{\mathrm{uz}}}{SD_i t_{\mathrm{d}}} \tag{3}$$

where S_{uz} (m) is the storage in the unsaturated zone, SD_i (m) is the local saturated zone deficit due to gravity drainage which is dependent on the depth of the local water table, and t_{d} (h/m) is a time delay constant expressed as the mean residence time for vertical flow per unit of deficit.

Following the widely adopted practice, TOPMODEL calculates the actual evapotranspiration E_{a} (m/h) as a function of potential evapotranspiration E_{p} (m/h) and maximum root zone moisture storage deficit, S_{rmax} (m) in case E_{a} is not available directly.

$$E_{\mathrm{a}} = E_{\mathrm{p}}\left(1 - \frac{S_{\mathrm{rz}}}{S_{\mathrm{rmax}}}\right) \tag{4}$$

where S_{rz} is the root zone moisture deficit.

In a typical TOPMODEL application, basic input includes precipitation, potential evapotranspiration, and digital elevation data for channel routing and topographic index calculation. As described above, the four important parameters present in the model, m, T_0, t_{d} and S_{rmax}, need to be calibrated with observed discharge data. A GIS is normally used to produce topographic index distributions and channel routing components from the DEM. There have been a few published TOPMODEL implementations with coupling DEM processing in GIS. A typical program is AVTOP which integrates the model into ESRI ArcView GIS (Huang and Jiang, 2002).

3. Study watersheds

Two watersheds in the United States are selected as study areas. In addition to adequate data available for hydrologic simulations, their appropriate sizes and typical terrain conditions are favored for the study purpose.

3.1. Goodwin Creek Watershed (GCW)

The Goodwin Creek watershed is a 21.3-km^2 experimental watershed located in northwestern Mississippi (Fig. 1). The terrain of the watershed mainly consists of broad ridges and narrow valleys. Its elevation ranges between 70 and 128 m above the mean sea level (Fig. 2). This watershed is largely free of land management activities with 13% of its total area being under cultivation and the rest in idle, pasture and forest land. Silt loams soils mostly cover poorly to moderately well drained areas including much of the cultivated area. The watershed climate is humid, hot in summer and mild in winter. The area exhibits an average annual temperature of approximately 17 °C and an average annual rainfall of approximately 1460 mm during 1982–1992 (Blackmarr, 1995). The watershed has been closely monitored by the U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS).

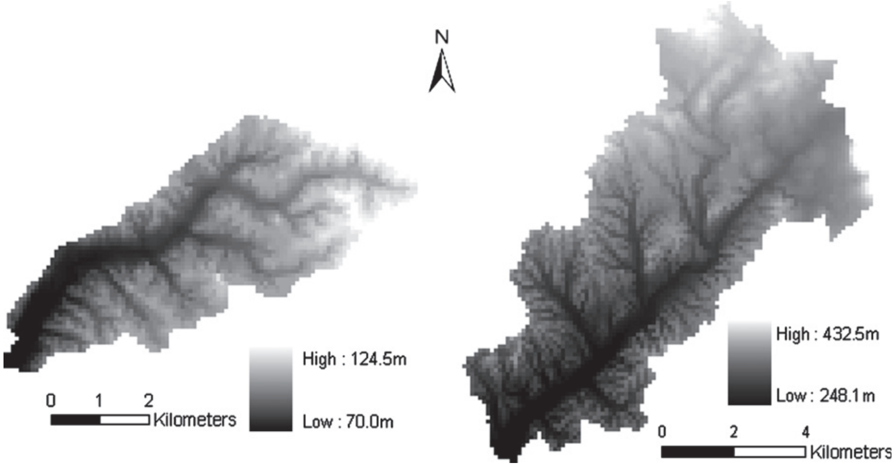
Fig. 1. Locations of the study watersheds in the United States.

3.2. Peacheater Creek Watershed (PCW)

Peacheater Creek is a tributary to the Barren Fork River in the Illinois River watershed. The Peacheater Creek watershed is located in the northeastern corner of Oklahoma with an area of 64.0 km^2 (Fig. 1). The surface elevation of the watershed varies from 248.1 to 432.5 m above the mean sea level (Fig. 2). Its terrain presents extensive valleys with distinct variability in the southern part as revealed by the DEM while the northern (upstream) part lies in a low-relief landscape. The predominant surface soil type is silt loam in the area. The watershed is primarily characterized by agricultural and forest land uses with minimal urban coverage (Smith et al., 2004).

4. Data and study approach

The digital elevation quadrangles at 30 m resolution containing each study watershed are downloaded from the data center website of the United States Geological Survey (USGS). The watersheds are delineated and extracted with the Hydrology Tools of ESRI ArcGIS Spatial Analyst (Fig. 2). The 30 m grid size is selected as the base resolution, and resampled to 11 DEMs of 60 m, 100 m, 150 m, 200 m, 250 m, 500 m, 1000 m, 1500 m, 2000 m, 2500 m, and 3000 m resolutions, respectively, using the nearest neighborhood method. In a preceding study conducted by the authors with the three commonly used methods (nearest neighbor, bilinear interpolation, and cubic convolution), applications of different methods have shown little effect on topographic index distribution and TOPMODEL output. The nearest neighborhood method is thus chosen for its simplicity. Each of all the 12 DEMs of different resolutions is used to generate the topographic index distribution required by TOPMOEL for the comparative study. A multiple flow direction algorithm to calculate the upslope contributing area is used as opposed to the single flow direction algorithm (Quinn et al., 1995). The multiple flow direction algorithm is believed to be more reasonable



Goodwin Creek Watershed

Peacheater Creek Watershed

Fig. 2. Elevation maps of the study watersheds at 30 m resolution.

as it partitions the runoff between all contiguous downslope cells proportional to their relative slope gradients.

We divide the 12 applied DEM resolutions into two categories, "fair resolution" category and "coarse resolution" category, to better present our study results. The gird sizes less than 500 m belong to the former, while 500 m and above to the latter. The DEM grid sizes used in the previous studies on resolution effect on TOPMODEL performance have been virtually limited to the fair resolution category (Bruneau et al., 1995; Franchini et al., 1996; Saulnier et al., 1997). The model efficiency remained almost the same or no significant difference was found within the DEM resolution extents examined in their studies. In this work, the maximum examined grid size is extended to 3000 m with a purpose to explore the model sensitivity to coarser DEM resolutions.

The DEM derived watershed area fluctuates as the grid size changes. The variation would result in inconsistencies between model simulations and observed data. While the variations are relatively small over the examined DEM resolution extent for the two watersheds used in this study, all relevant calculation results are adjusted according to the watershed reference areas of 21.3 km^2 and 64.0 km^2 for Goodwin Creek Watershed and Peacheater Creek Watershed, respectively. For example, a simulated unit discharge at an aggregated DEM grid size is corrected proportionally to that corresponding to its reference area.

Continuous precipitation data have been collected at 30 recording rain gauges located uniformly at sites both inside and surrounding the Goodwin Creek watershed. Both the rainfall data and watershed outlet runoff measurements for 1983 are obtained from the ARS Water Database of USDA, ARS. Daily rainfall values from the rain gauges are averaged for model input. Precipitation data for Peacheater Creek Watershed in 1998 is obtained using the hourly Stage III NEXRAD grids from the Arkansas-Red River Forecast Center (ABRFC) of the National Weather Service (NWS). The projection conversion and local extraction (by mask with the 30 m DEM) are performed in ArcGIS. The values in the extracted grids are averaged to get the rainfall input for TOPMODEL. The daily runoff data for Peacheater Creek Watershed (Site No. 07196973) in 1998 is downloaded from the USGS National Water Information System Web (NWISWeb). Daily potential evapotranspiration in each watershed is estimated using a simple method proposed by Linacre (1977). The method computes potential evapotranspiration only with temperature data, elevation and latitude of the study site.

TOPMODEL is applied to simulate rainfall runoff at each resolution in the two study watersheds with parameter optimization for optimal performance. Hydrologic data records for a period of one full year are used for continuous simulation for each watershed. We select the daily data in the calendar years of 1983 and 1998 for Goodwin Creek Watershed and Peacheater Creek Watershed, respectively (Table 1).

The performance of a TOPMODEL simulation is represented by the Nash and Sutcliffe efficiency coefficient (E_{ns}) in this study (Nash and Sutcliffe, 1970) as it remains the most commonly used criterion in assessing hydrologic modeling performance. The coefficient stands for the goodness of fit between observed and simulated hydrographs as defined as follows:

$$E_{\mathrm{ns}} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{\mathrm{sim}_i} - Q_{\mathrm{obs}_i}\right)^2}{\sum_{i=1}^{n}\left(Q_{\mathrm{obs}_i} - Q_{\mathrm{avg}}\right)^2} \tag{5}$$

Table 1
Basic information for simulation and calibration

Study area	Goodwin Creek Watershed	Peacheater Creek Watershed
Starting date	1983-01-01	1998-01-01
Number of time steps	365	365
Hours of each time step	24	24
Total rainfall (mm)	1709	1156
Total measured runoff (mm)	864	281
Runoff coefficient (%)	50.6	24.3

where n is the number of time steps, Q_{sim_i} and Q_{obs_i} are the simulated and observed discharges at the time step i, respectively, and Q_{avg} is the average observed discharge over the simulation period.

The E_{ns} coefficient is used as the objective function being maximized in calibration to obtain optimal model parameters. There are four TOPMODEL parameters considered for the calibrations in the study. The four most important parameters are m, T_0, t_{d}, and S_{rmax} as defined in eqs. (1)–(4). Both the Monte Carlo method and automatic optimization are employed for model calibrations. Each of the parameters is initially assigned a relatively large sampling range that is believed to be physically reasonable. A significant number (>10,000) of simulations are run for each DEM grid size with the four parameter values randomly drawn from the given intervals in uniform distributions. A scattergram for each parameter against the Nash and Sutcliffe efficiency is recorded from the Monte Carlo simulations. Therefore the most probable range of each parameter can be significantly narrowed down through the sensitivity analysis. The Simplex automatic optimization method (Nelder and Mead, 1965) is used subsequently with the reduced intervals.

5. Results and discussion

5.1. Topographic index distributions

The topographic index is the natural logarithm of the ratio of the upslope contributing area α to the ground surface slope $\tan\beta$. All locations in a watershed with the same topographic index value are assumed to have similar hydrologic responses. The topographic index values in frequency distribution intervals are used in TOPMODEL calculations to estimate hydrologic states across the watershed. The spatial distributions of the topographic index under different DEM grid sizes for the two study watersheds are obtained from ArcGIS, and its mean values are shown in Fig. 3. The mean index values for both watersheds keep increasing when the DEM grid size increases throughout the entire study extent (30–3000 m). This is consistent with the results of previous studies (Wolock and Price, 1994; Quinn et al., 1995; Saulnier et al., 1997). The effects of varying DEM resolution on calculated slope and upslope contributing area have been studied independently. Their findings adequately justify our observations on the topographic index. Chang and Tsai (1991), and Gao (1997) showed that lower resolution DEMs under-represent slope classes. Obviously, coarser grid cell resolutions filter the roughness of the terrain. This smoothing effect leads to similar elevations among neighboring grid cells, thus reducing the calculated slope presented as $\tan\beta$. Grid cell resolution determines minimum unit area for upslope contributing area and how its boundaries are defined. Zhang and Montgomery (1994) stated that changing grid size has significant effects on both the mean and local upslope contributing area as larger grid sizes bias in favor of large contributing areas. The joint contributions from the slope and the contributing area are attributable to the increase of the topographic index with increasing grid size. The dual effects on the mean topographic index for Goodwin Creek Watershed are depicted in Fig. 4. The illustration shows that the topographic index is affected due to the DEM resolution influence on both $\ln(\alpha)$ and $\ln(1/\tan\beta)$. The majority of the contribution to the mean $\ln(\alpha/\tan\beta)$ value comes from the $\ln(\alpha)$ portion. However, the slope share $\ln(1/\tan\beta)$ exhibits more sensitivity to the DEM resolution. The mean value of $\ln(1/\tan\beta)$ increases from 0.31 for 30 m DEM to 1.89 for the 3000 m DEM while the mean value of $\ln(\alpha)$ gets up to 12.98 from 7.48 accordingly.

Cumulative frequency distributions of the topographic index at each DEM resolution for the two watersheds are given in Figs. 5 and 6. The distributions can well reveal the variations of local index values with the grid size change. Both figures show that DEM resolution significantly affects the frequency distributions of $\ln(\alpha/\tan\beta)$ which serve as the topographic input to TOPMODEL. The cumulative distribution is driven towards higher values of $\ln(\alpha/\tan\beta)$ by the DEM grid size increase. The minimum $\ln(\alpha/\tan\beta)$ is influenced most evidently due to the smoothing effect on hillslopes and enlarged minimum contributing areas. Fig. 5a shows the distributions under the fair resolution category for Goodwin Creek Watershed. With the increase of DEM coarseness, the distribution curves start to show some rough variations at the 300 m resolution. The curves under the fair resolution category for Peacheater Creek Watershed (Fig. 5b) are all smooth. Under the coarse resolution category, the distribution curves for both watersheds become jagged with increasing DEM coarseness while the curve smoothness for the Goodwin Creek Watershed

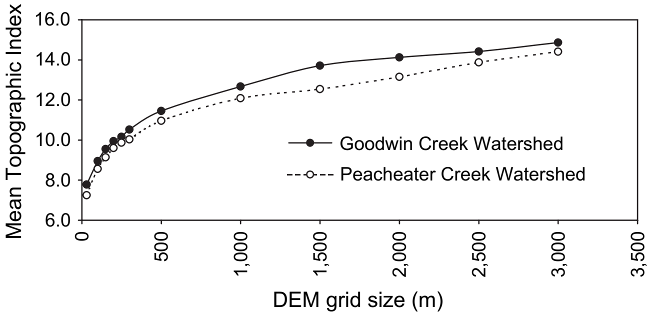


Fig. 3. Mean values of the topographic index.

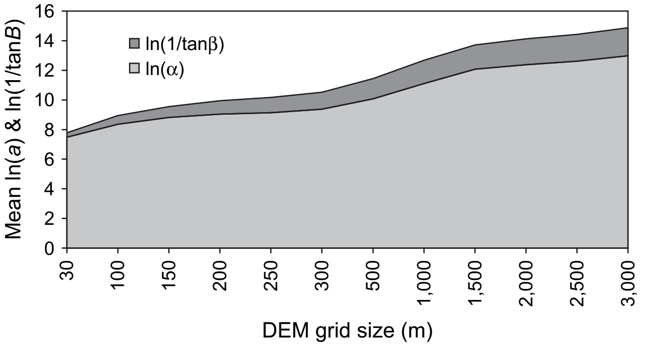


Fig. 4. Contributions of upslope contributing area and slope to the topographic index.

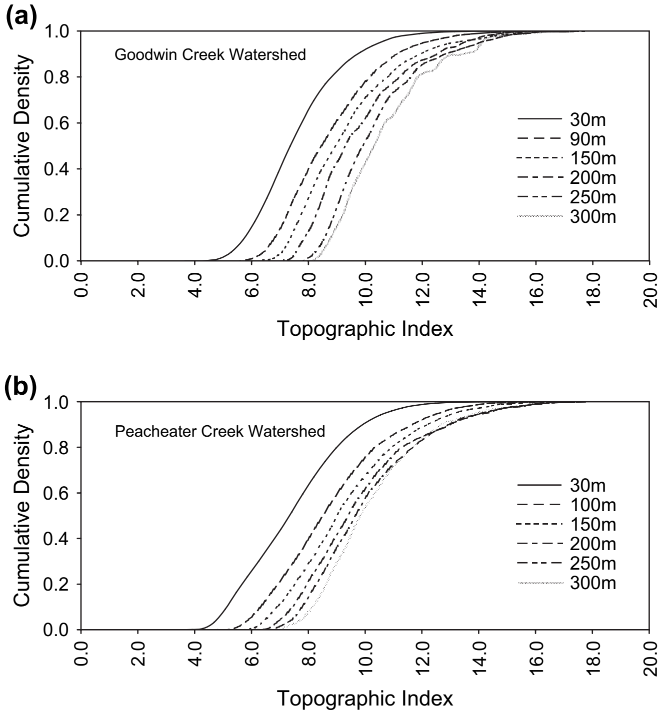


Fig. 5. Topographic index distributions under fair DEM resolution category.

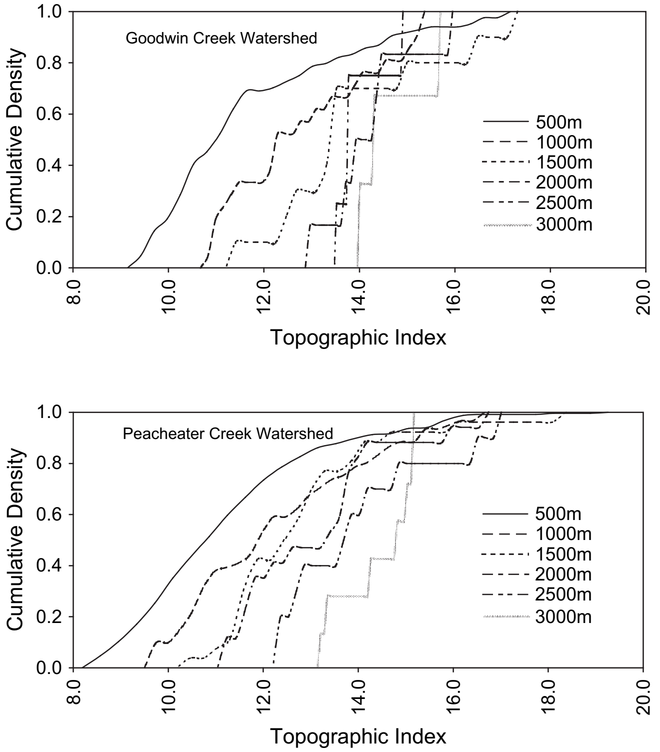


Fig. 6. Topographic index distributions under coarse DEM resolution category.

seems deteriorating faster than that for Peacheater Creek Watershed (Fig. 6). Apparently, a major factor attributable to the observations is the number of grid cells in the DEM. The continuity of the index distribution would become broken up due to the lack of $\ln(\alpha/\tan\beta)$ supply and variations when the number of grid cells is getting smaller with the grid size increase. From this perspective, watershed size could be significantly influencing in regards to the DEM resolution effect on topographic index distribution. Garbrecht and Martz (1994) investigated the impact of DEM resolution on extracted drainage properties such as mean channel link slope and drainage area for a study watershed. They applied the grid coefficient, defined as the ratio of the grid cell area to the network reference area, to compare the capabilities of reproducing drainage features for different resolutions of DEMs. It was found that all extracted drainage properties are within 10% of the baseline reference values for grid coefficients less than 0.01. Most of the drainage properties are within 10% of the reference values for coefficients between 0.01 and 0.04. For grid coefficients greater than 0.08, the properties increasingly diverge from the baseline values. The study suggested that a DEM should have a grid area less than 5% of the network reference area to reproduce drainage features with a 10% accuracy.

Similar to the approach of Garbrecht and Martz (1994), we introduced and applied to this study the ratio of grid cell area to total watershed area (grid-to-watershed ratio), as an indicator of grid cell quantity in a DEM. Table 2 shows the grid-to-watershed ratios corresponding to all the applied grid sizes for both watersheds. The higher the ratio, the fewer the number of cells in the DEM. Now when looking at the cumulative distributions of $\ln(\alpha/\tan\beta)$ on Figs. 5 and 6 with the obtained ratios instead of the grid sizes, it can be found that the smoothness of the curves is more reasonably correlated to the grid-to-watershed ratio. For the distributions for Goodwin Creek Watershed, obvious roughness begins to appear around the 300 m grid size which corresponds to a grid-to-watershed ratio of 0.42%. A similar finding is observed on the distributions for Peacheater Creek Watershed around the 500 m grid size or the ratio of 0.39%. Fig. 6 shows that the distributions become totally stepped at 1000 m and 2000 m grid sizes (equivalent to the ratios of 4.69% and 6.25%, respectively) for Goodwin Creek Watershed and Peacheater Creek Watershed, respectively.

Table 2
Grid-to-watershed ratios for different resolutions of DEMs

Grid size (m)	Goodwin Creek Watershed	Peacheater Creek Watershed
30	0.004%	0.001%
100	0.047%	0.016%
150	0.106%	0.035%
200	0.19%	0.063%
250	0.29%	0.098%
300	0.42%	0.14%
500	1.17%	0.39%
1000	4.69%	1.56%
1500	10.6%	3.52%
2000	18.8%	6.25%
2500	29.3%	9.77%
3000	42.3%	14.1%

Although this correlation seems in a large part independent of the particular study watershed, the ln(α/tanβ) distribution must also be influenced by specific topographic conditions of the watershed in addition to its size. The topographic effect can be reflected by some statistics of ln(α/tanβ), especially its variance (Table 3). A topographic index distribution with a larger degree of variation may better offset the aggregation effect of the grid size increase. As we can see from Table 3, the ln(α/tanβ) distribution at the base resolution of 30 m for Peacheater Creek Watershed has a variance of 4.89 and a range of 18.36, as opposed to 4.18 and 14.51 respectively for Goodwin Creek Watershed. The higher values for Peacheater Creek Watershed are believed to be to some extent contributable to the different behaviors of the index distributions with the resampled DEMs of coarser resolutions.

5.2. TOPMODEL simulations without calibration

The sensitivity of TOPMODEL simulations to DEM grid size is first examined using uncalibrated parameters. The model is applied to produce hydrograph with a same set of parameters under different DEM resolutions for each watershed. The estimations of the parameters need to be made based on the knowledge of watershed properties and behaviors. In this study the preliminary parameter values are largely derived from the results of some previous publications on the two study watersheds such as Blackmarr (1995) and Smith et al. (2004). The estimations also provide initial values and ranges for the model calibrations to be described in the next section. Table 4 shows the estimated values of the four parameters m, T_0, t_d and S_{rmax} used for the uncalibrated runs and their ranges used in calibrations.

The TOPMODEL simulation runs are performed to generate runoff hydrographs at different DEM resolutions for the two annual periods (1983 and 1998) for Goodwin Creek Watershed and Peacheater Creek Watershed, respectively. With the initial parameter values, the TOPMODEL runs with the base DEMs of 30 m resolution obtain the Nash and Sutcliffe efficiencies (E_{ns}) of 47.7% and 42.8% for Goodwin Creek Watershed and Peacheater Creek Watershed, respectively (Fig. 7). Variations of the model efficiencies for the two study watersheds present somewhat different profiles while their performances are generally going down with the increase of DEM grid size. The model efficiency for Goodwin Creek Watershed declines only slightly from the base 30 m to 500 m grid size, but then suffers some noticeable losses till 2500 m ($E_{ns} = -11.1\%$), and plunges to -38.0% at 3000 m. For Peacheater Creek Watershed, the efficiency even gains some increase when the grid size is resampled from 30 m to 100 m ($E_{ns} = 45.2\%$) and then to 150 m ($E_{ns} = 50.7\%$). Thereafter the performance keeps getting worse gradually all the way to the 3000 m resolution where it has an efficiency of 3.5%. Obviously, the effects of DEM grid size on the topographic index distributions are passed onto the TOMODEL simulations as the distributions are fed into the model as input. The variations of model performances can hardly be interpreted by the steady increase of mean value of the topographic index with the DEM aggregation. It can be found, however, that some consistency exists between the results of simulations and topographic index distributions. The observation can be further associated with the grid-to-watershed ratio. The quick performance decline in the coarse resolution category with substantial efficiency drop at 3000 m (equivalent to the grid-to-watershed ratio of 42.3%) for Goodwin Creek Watershed are believed to be attributable to the deteriorated index distributions at the large grid sizes as a result of high grid-to-watershed ratios. For Peacheater Creek Watershed, the efficiency undergoes nearly 40% of decrease caused by the grid cell increase from 30 m to 3000 m. The grid-to-watershed ratio at 3000 m resolution for Peacheater Creek Watershed is only 14.1% which is, for Goodwin Creek Watershed, equivalent to a grid size of about 1730 m. Therefore the reduction in the TOPMDOEL performance for Peacheater Creek Watershed brought about by the same increase of DEM grid size is much smaller than that for Goodwin Creek Watershed.

Table 3
Statistics of topographic index distributions for 30 m DEM

Watershed	Mean	Range	Variance
Goodwin Creek Watershed	7.78	14.51	4.18
Peacheater Creek Watershed	7.25	18.36	4.89

Table 4
TOPMODEL parameter settings for the two study watersheds

Parameter	Goodwin Creek Watershed		Peacheater Creek Watershed	
	Initial value	Range	Initial value	Range
m [m]	0.05	0.001–1.0	0.02	0.001–1.0
ln(T_0) [ln(m^2/h)]	1.0	−10–10	0	−15–10
t_d [m/h]	10	0.1–100	15	0.1–100
S_{rmax} [m]	0.1	0.01–0.5	0.45	0.05–1.0

As indicated by eq. (2), an increase of the topographic index would lead to a larger contributing area for a given set of TOPMODEL parameters. Also it can be induced from the basic TOPMODEL equations that the average soil moisture deficit of the watershed decreases with a grid size increase. The combined effect results in a greater simulated runoff.

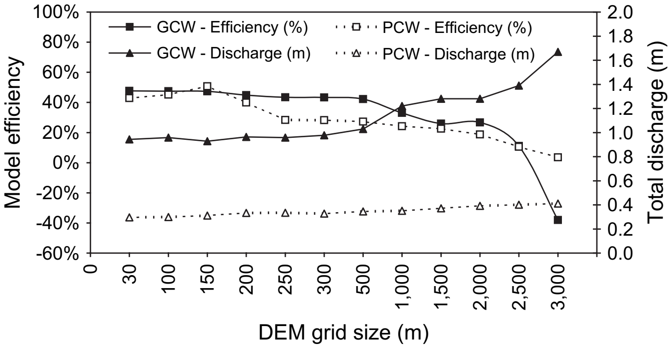


Fig. 7. TOPMODEL efficiencies and simulated discharges of uncalibrated runs.

Thus the total watershed discharge is supposed to increase with every DEM resampling to a coarser resolution. This is mostly true with the observations in this study as we look at the overall change of calculated discharge over the whole DEM resolution extent. There are, however, some minor deviations in the fine resolution category for both watersheds (Fig. 7). The total discharge calculated for Goodwin Creek Watershed becomes a little smaller when the grid size is increased to 100 m and 250 m. The same deviation happens to Peacheater Creek Watershed for the 300 m DEM. It is also interesting to observe that the variations of the simulated total discharge with the grid size increase generally present an opposite trend to that of model efficiencies, especially for Goodwin Creek Watershed, as demonstrated in Fig. 7.

5.3. TOPMODEL performances with parameter optimization

Simulations with model calibration are performed for each watershed at different DEM resolutions with an adequately wide range assigned to each parameter as shown in Table 4. For the base DEM of 30 m, 80.1% and 71.0% of model efficiency are obtained with optimized parameters for Goodwin Creek Watershed and Peacheater Creek Watershed, respectively. The lower efficiency for Peacheater Creek Watershed can be well explained by its smaller runoff coefficient (24.3%) in the study period as compared to 50.6% for Goodwin Creek Watershed. It is widely accepted that TOPMODEL is more suitable for modeling humid watersheds where the saturation excess overland flow process can be expected to dominate surface runoff, and soil transmissivity decreases most exponentially with soil depth (Franchini and Pacciani, 1991).

The model efficiency throughout the fair resolution category maintains within two percentage points of the base value at 30 m for each of the two watersheds. This is consistent with previously published studies (Franchini et al., 1996, Saulnier et al., 1997) in which the model performance with calibration kept the same or experienced little reduction over their study extents of DEM resolution. In the coarse resolution category, a significant drop in the performance for Goodwin Creek Watershed occurs at 1500 m where the efficiency falls down to 70.3% from 78.2% at 1000 m. Its subsequent efficiency till 3000 m stays above 67.0%, which can still be regarded as satisfactory for continuous modeling with daily data. For Peacheater Creek Watershed, it is to our surprise that the topographic index distribution has little influence on the optimized model performance in the coarse category except a ∼6% efficiency decrease at 3000 m, the maximum grid size in this study. It is believed that the sound performance of TOPMODEL at coarse DEM resolutions is due to the compensation effect of the saturated hydraulic conductivity parameter, T_0. Franchini et al. (1996) and Saulnier et al. (1997) have reported that, by adjusting T_0 (lateral transmissivity when the soil is just saturated) to higher values according to the shifts of topographic index distribution caused by the grid size increase, one can obtain almost identical model efficiencies. The results in this study with the two watersheds prove the connection between $\ln(\alpha/\tan\beta)$ and T_0. Fig. 8 demonstrates that the values of $\ln(T_0)$ for both watersheds keep increasing constantly with DEM grid size, which is offsetting the effect of topographic index change shown in Figs. 5 and 6.

Interactions exist among the parameters according to the basic equations of TOPMODEL. There is, however, no consistent pattern of change found on any of the three other parameters (m, t_d, or S_rmax) in this study. The scattergrams of the four parameters versus the efficiency created from the calibration runs for Goodwin Creek Watershed are depicted in Fig. 9. Note that the plots for Peacheater Creek Watershed show almost the same profiles for the parameters, thus are not necessarily shown here. It is found that the model efficiency is very sensitive to T_0. An observable degree of sensitivity to the parameter S_rmax is shown, but certainly it has no significant influence within the given range. There is no sensitivity for the efficiency to m and t_d as demonstrated by the plots. The results from this parameter sensitivity analysis strongly corroborate our observations on the relationships among model efficiency, grid size and T_0.

There is a further numerical experiment on the T_0 compensation worth mentioning. All model parameters except T_0 are kept constant for all the grid sizes. Their values for each watershed can be taken from the optimized parameter set for the 30 m DEM, or for a larger grid size at which the model obtains equal efficiency (100–1000 m for Goodwin Creek Watershed, and 100–2500 m for Peacheater Creek Watershed). Strikingly, model calibrations by only optimizing T_0 produce nearly the same efficiencies for all the DEM grid sizes as those obtained from the normal optimization runs given in Fig. 8. However, the T_0 value obtained from this experiment for each grid size is larger than that from previous optimization. It is supposed that a stronger compensation is required in this case. The result further verifies the model insensitivity to other parameters than T_0 which can compensate the effect of the topographic index variation on its own.

The explanation of the T_0 compensation can be derived from the basic equations of TOPMODEL. With simplifications, Franchini et al. (1996) proposed an equation for determining optimal T_0 value according to the mean value of the topographic index.

$$T_{0_{\Delta 2}} = T_{0_{\Delta 1}} \exp(\bar{\lambda}_{\Delta 2} - \bar{\lambda}_{\Delta 1}) \tag{6}$$

where Δ1 and Δ2 represent two different DEM grid sizes, and Δ2 > Δ1.

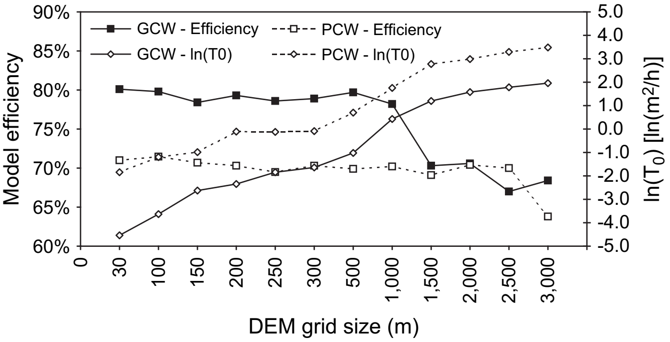


Fig. 8. Optimized TOPMODEL efficiencies and watershed mean $\ln(T_0)$.

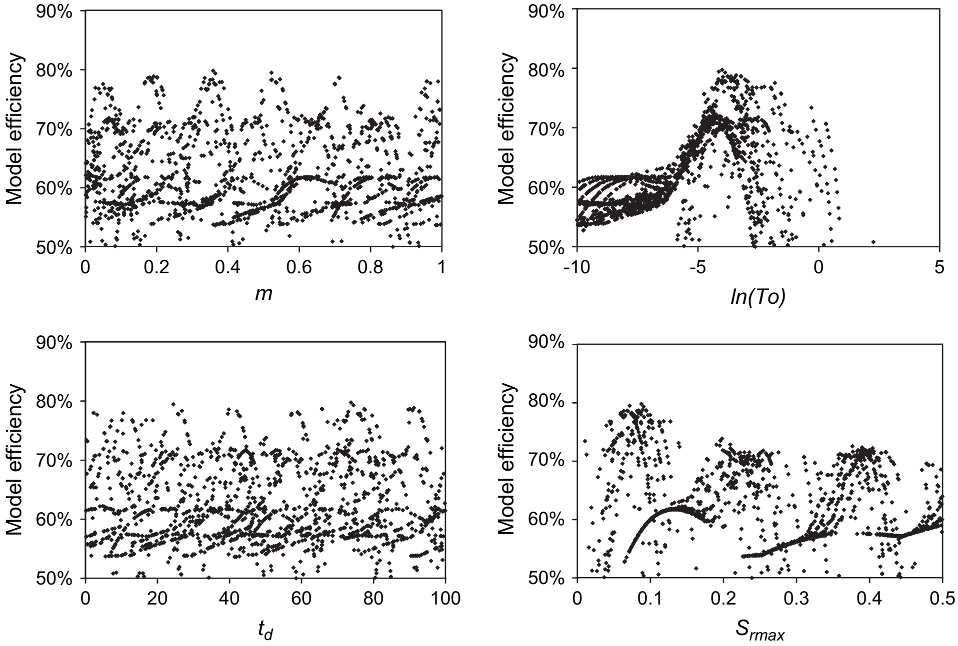


Fig. 9. TOPMODEL parameters versus efficiency for the Monte Carlo simulations.

The relationship is based on the concept that subsurface flow contribution must be the same for different simulations (with different DEM grid sizes). Also the parameter m is assumed to be constant. Their application to Real Collobrier Basin produced good results which are close to those obtained from parameter optimizations (Franchini et al., 1996). Obviously this method, by using the mean value, ignores the effect of actual distribution of the topographic index over the study area.

Saulnier et al. (1997) applied the method of Franchini et al. (1996) to their Mauret Catchment study, and found that using the mean index value is not sufficient to account for the change in optimized T_0 values. Indicating that the change in the shape is also important, they introduced a scaling factor k which generalizes the change of topographic index distribution. Thus we have:

$$T_{0_{\Delta 2}} = kT_{0_{\Delta 1}} \tag{7}$$

The natural logarithm value of k, $\ln(k)$ can be obtained by plotting the topographic index values of the base grid size against the values of the larger grid size at the identical proportion of saturated contributing area (Saulnier et al., 1997).

Both methods are applied to the two watersheds in this study using 30 m as the base grid, and the T_0 estimates are given in Fig. 10 with comparisons to the values obtained from optimizations. For Goodwin Creek Watershed, both estimations are very close to the optimizations for all the resampled grid sizes. The "optimal" T_0 value for Peacheater Creek Watershed gets overestimated at all higher grid sizes. The method of Saulnier et al. (1997) performs better throughout than that of Franchini et al. (1996), especially at finer grid sizes. As can be seen from Fig. 10, the estimates from eq. (7) for the grid sizes of 100–250 m are merely a little above the optimized values. However, the gap tends to be much larger at coarser grid sizes, and the estimate for 3000 m is nearly the same as that from eq. (6), which works poorly for Peacheater Creek Watershed. The results indicate that neither method can be effectively applied ubiquitously, while that of Saulnier et al. (1997) appears to be relatively more dependable.

As previously noted, a certain degree of connection could be established between grid-to-watershed ratio and topographic index distributions, and further between the ratio and the efficiencies of TOPMODEL simulations using a single set of parameters. Now we look at whether the model performances with calibrations have any correlations with the ratio. For this purpose, Fig. 11 is produced by replacing grid size with grid-to-watershed ratio as X-values in Fig. 8 in order to directly examine the variations of the model efficiency against the ratio. The figure shows that the model performance for each watershed starts to fall significantly at a certain grid-to-watershed ratio. The threshold ratio for Goodwin Creek Watershed is in between 5% and 10%, and for Peacheater Creek Watershed it is about right above 10%. It appears that the model behaves somewhat better on Peacheater Creek Watershed than on Goodwin Creek Watershed in this regard. We have to, however, admit that both watersheds have similar thresholds in terms of the grid-to-watershed ratio, above which a significantly lower model efficiency is expected. There are too few DEM cells to generate the least required topographic index distribution for a reasonable TOPMODEL simulation when the ratio is beyond the threshold. In this case, the compensation from the transmissivity parameter T_0 will not be effective in retaining model efficiency. Our results generally agree with the findings of Garbrecht and Martz (1994), which stated that the grid area should be less than 5% of the watershed area to reproduce accurate drainage features.

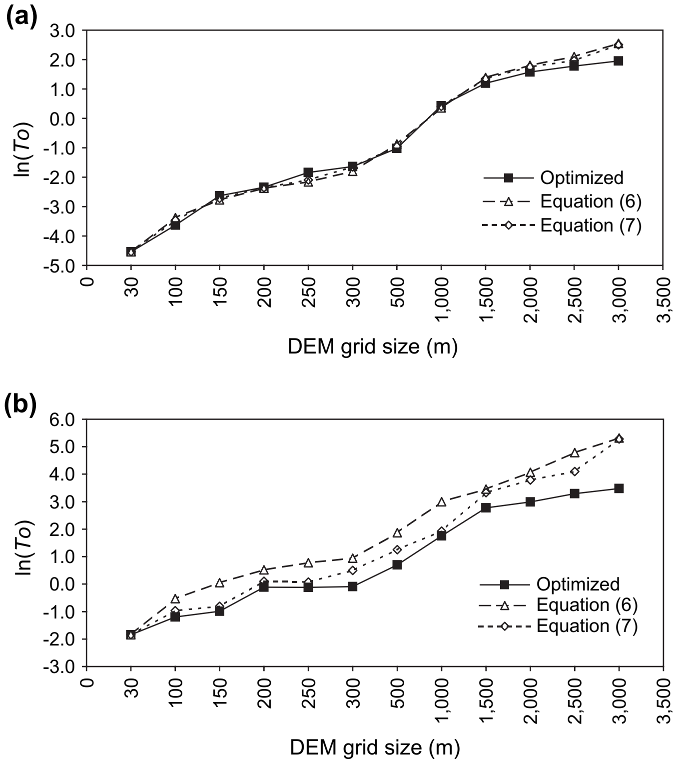


Fig. 10. Parameter T_0 values obtained from optimization and estimations.

6. Conclusions

The effect of DEM grid size on modeling performance is analyzed for TOPMODEL, a topography based hydrologic model with physical parameters. A wide range of DEM resolutions up to 3000 m are applied to one-year continuous simulations with daily time-step data for two study watersheds using TOPMODEL. It shows clearly that an increase of DEM gird size shifts the topographic index towards higher values due to greater upslope contributing area and smaller slope. The smoothing effect could greatly alter index distribution over the study area, especially at coarse resolutions. The shape of index distribution may be severely stepped due to insufficient grid cells in a DEM with large grid size relative to its total area. Thus an indicator, namely grid-to-watershed ratio, is utilized here to correlate with topographic index distributions and TOPMODEL simulations. The results have shown that the watershed size does play an important role in the grid size dependency of TOPMODEL.

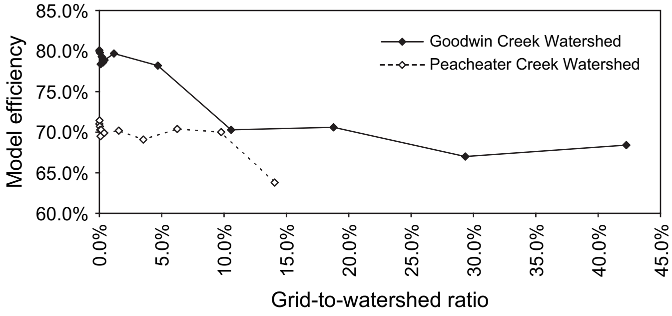


Fig. 11. Optimized TOPMODEL efficiency vs. grid-to-watershed ratio.

The simulations without calibration exhibit a fair effect of the grid size on model efficiency as an identical set of parameters is used. The TOPMODEL performances present a general trend of proportional degradation with the deterioration of topographic index distribution. On the other hand, the simulations with parameter optimization reveal that TOPMODEL can be highly insensitive to grid size change as a result of the compensation effect of transmissivity parameter T_0. Equal efficiency can be maintained under a threshold gird-to-watershed ratio of about 5–10%.

This study intends to be a valuable addition to the discussions on determination of optimal DEM resolution for watershed hydrologic modeling. When suggesting a DEM should have a grid area less than 5% of the network reference area, Garbrecht and Martz (1994) explained the importance of the capability of reproducing actual drainage features. Coarser grid size results in shorter channel lengths for sinuous channels. Also, channel and drainage area capturing could occur when the DEM resolution is unable to resolve the separation between channels or drainage boundaries. Consequently, hydrologic features derived from the DEM could depart significantly from those obtained by high-resolution data. Thus a general conclusion can be drawn is that the selection of DEM resolution must be conducted with taking into account landscape conditions including the size of the study area. In this study with two case watersheds, a grid size equivalent to 5% grid-to-watershed ratio or less is found to be able to provide consistent performances for continuous TOPMODEL simulation on a daily basis. This is definitely not a coincidental agreement with the result of Garbrecht and Martz (1994). It is believed, however, that extensive studies with various landscape characteristics are needed to validate a particular conclusion on the selection of DEM resolution for hydrologic applications.

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