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Characterization and Evaluation of Elevation Data Uncertainty in Water Resources Modeling with GIS

Simon Wu · Jonathan Li · G. H. Huang

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Abstract Grid based digital elevation models (DEM) are commonly used in water resources modeling. The quality of readily available DEM, however, varies from source to source in terms of horizontal resolution and vertical accuracy which are the two important aspects of elevation uncertainty in the modeling with raster GIS. This paper addresses the issue of elevation data uncertainty in GIS supported hydrologic simulations. The essential role of elevation data in the modeling is revealed by presenting DEM processing processes in distributed and semi-distributed hydrologic analyses. It is very difficult to examine the elevation uncertainties analytically due to complexities of the hydrologic models. An ideal approach is to assess the effect of the DEM uncertainty by applying varying resolutions or accuracies of elevation data in the modeling. Different grid sizes of DEM are used in observing DEM resolution dependence and resulting model outputs are compared to obtain a profile of its effect. Impact of DEM vertical accuracy is explored by Monte Carlo simulation with a large number of DEM realizations generated based on different levels of specified error. The approach is implemented in a case study with a topography based hydrologic model on an experimental watershed to analyze both aspects of the uncertainty. The results show that both DEM grid size and vertical accuracy could have profound effect on hydrologic modeling performance. The impact can be compensated by model calibrations due to interactions between model parameters and spatial factors. The study indicates that the DEM uncertainty can be effectively evaluated using the applied method. The work is to provide some insight into the characterization of elevation data quality and the association between topography and water resources models.

S. Wu (✉)
Environmental Systems Engineering, University of Regina, Box 413, 4246 Albert Street, Regina, Saskatchewan S4S 3R9, Canada
e-mail: wusimon@env.uregina.ca

J. Li
Department of Geography, University of Waterloo, Waterloo, ON N2L 3G1, Canada

G. H. Huang
Faculty of Engineering, University of Regina, Regina, Saskatchewan S4S 0A2, Canada

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1 Introduction

Characterization of the land surface is essential for many modeling applications in water resources management. Digital elevation data are commonly used nowadays to acquire watershed topographic properties for spatial analysis supported by geographic information systems (GIS). These digital elevation data are usually organized into one of three data structures: (1) square-grid network, (2) triangulated irregular network (TIN), and (3) contour-based network, depending on the source and/or preferred method of analysis. Square-grid digital elevation models (DEM) have emerged as the most widely used data structure during the past decade because of their simplicity (i.e., simple elevation matrics that record topological relations between data points implicitly) and ease of computer implementation (Moore et al. 1991; Wilson and Gallant 2000). Many topographic attributes commonly used in hydrologic, geomorphological, and ecological applications such as slope, specific catchment area, aspect, and profile curvature can be derived from all the three types of elevation data. The popularity of the grid-based DEM in water resources applications stems from both its applicability to landscape-based runoff modeling and its practicability of utilization together with other data layers such as land use and soil type (Bhattarai and Dutta 2006; Bahremand and De Smedt 2007). The availability of DEMs has been greatly increased with the development of effective spatial data acquisition tools. The progress has led rainfall-runoff modeling to evolve towards spatially distributed simulations of watershed conditions. Distributed watershed models use the grid DEMs to define watershed boundary, configure channel network, locate drainage divides, calculate channel length and slope, and acquire subwatershed geometric properties.

The quality of production DEMs varies from country to country and from source to source. There are basically two extents for the elevation data quality, horizontal resolution and vertical accuracy, which have been handled separately. The quality issues bring about uncertainty to any application dependent on spatial variability derived from the DEM. The uncertainty with elevation data has been an important topic in environmental applications of GIS. In watershed resources modeling applications, any uncertainty with the DEM is propagated to derived watershed physiographic properties, and further to hydrologic model output. This paper identifies techniques to characterize the DEM uncertainties with regards to their effects on hydrologic features. An overview of the quality issues is first provided, followed by DEM processing concepts for hydrologic applications. Approaches to modeling the effects of the uncertainties on watershed runoff simulations and their applications are discussed with case studies.

2 Quality of Production DEMs

The quality of a derived DEM can vary greatly depending on the source data and the interpolation technique. The desired quality depends on the application for which the DEM is to be used, but a DEM created for one application is often used for other purposes. Any DEM should therefore be created with care, using the best available data sources and processing techniques (Hutchinson and Gallant 2000). While there are still viable alternative sources, most of hydrologic applications use readily available DEMs typically produced and/or distributed by governmental agencies such as the United States Geological Survey (USGS), the Natural Resources Canada (NRC), and the UK Ordnance Survey. These production DEMs are created in regular grids at various resolutions and with various accuracy levels.

2.1 DEM Resolution

The USGS distributes several terrain data products at different resolutions and coverage ranges, and continuously reorganizes and updates its DEM data as part of the National Elevation Dataset (NED) by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. Complete US nationwide coverage is available with a 1 arc second (30 meter) resolution. There is also a large collection of 1/3 arc second (10 meter) resolution elevation data covering most of the US. NED is designed to provide national elevation data in a seamless form with a consistent projection (geographic), elevation unit (meters), horizontal datum (NAD83) and vertical datum (NAVD88). Sources for the NED are all the available USGS DEMs, other "non-standard" sources and also LiDAR data for the production of 1/9 arc second (about 3 m resolution).

The Canadian Digital Elevation Data (CDED) comprise raster data stemmed from the National Topographic Data Base (NTDB) contours at scales of 1:50,000 and 1:250,000. Depending on the latitude of the CDED section, the grid spacing, based on geographic coordinates, varies in resolution from a minimum of 0.75 arc seconds to a maximum 3 arc seconds for the 1:50,000 National Topographic System (NTS) tiles and from a minimum of 3 arc seconds to a maximum 12 arc seconds for the 1:250,000 NTS tiles, respectively. The CDED's elevations are recorded in metres relative to Mean Sea Level (MSL), based on the NAD83 horizontal reference datum (NRC 2000). The United Kingdom's Ordnance Survey offers DEMs created from contour maps at 1: 50,000 and 1: 10,000 (10 m spacing) scales (Ordnance Survey 1999). The Australian Surveying and Land Information Group (AUSLIG) provides a DEM of 9 s longitude and latitude (approximately 250 m resolution) for all of Australia. A DEM with grid spacing of 3 s (about 80 m spacing) is also available for part of the country.

2.2 DEM Accuracy

The quantification of DEM accuracy is commonly provided with a statistic value of the Root Mean Square Error (RMSE). The USGS describes the accuracy of its 7.5 min DEMs with one RMSE value for each quadrangle. This RMSE value is based on the difference between DEM elevation and the elevation of 28 test points measured by field survey or aerotriangulation, or from a spot height or point on a contour line from an existing source map. The USGS DEM data are organized in three classification levels in terms of their accuracy. Level 1 DEMs are elevation data sets in a standardized format. A vertical RMSE of 7 m is the desired accuracy standard, and a RMSE of 15 m is the maximum permitted. Level-2 DEMs are elevation data sets that have been processed or smoothed for consistency and edited to remove identifiable systematic errors. DEM data derived from hypsographic and hydrographic data digitizing, either photogrammetrically or from existing maps, are entered into the Level-2 category. A RMSE of one-half contour interval is the maximum permitted. Level-3 DEMs are derived from digital line graph (DLG) data by incorporating selected elements from both hypsography (contours, spot elevations) and hydrography (lakes, shorelines, drainage). A RMSE of one-third of the contour interval is the maximum permitted.

The resultant RMSE statistic summarizes the standard error in the DEM:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (y_i - yt_i)^2}{N}}$$

where: y_i refers to the ith interpolated elevation, yt_i refers to the ith known or measured elevation of a sample point and N is the number of sample points (N=28). The "true" values (yt_i) are 28 points that are well distributed throughout the specified area and presumed to be representative of the terrain. The RMSE expresses the degree to which interpolated values differ from these true values. The "true" elevations are the most probable elevation, and do not always reflect actual elevations.

3 Elevation Data Processing for Hydrologic Analysis

Distributed watershed modeling is based on some essential topographic features derived from the elevation data such as surface drainage and stream network. The methods used to produce watershed properties are closely related to DEM resolution and accuracy.

3.1 Flow Path and Accumulation

Flow path algorithm serves as the basis for the derivation of topographic drainage information from elevation data in hydrologic modeling. It functions to determine the outflow distribution pattern from a DEM cell to lower adjacent areas. Various flow routing algorithms have been applied to GIS supported water resources modeling by simulating surface water hydrology. The difference among those algorithms lies in how flow direction is determined. D8 algorithm, namely the nearest-neighbour steepest descent model, (O'Callaghan and Mark 1984) is most widely used due to its simplicity and practicability. Many hydrologic modeling studies have selected D8 for calculating contributing area and other hydrologic parameters (Martz and Garbrecht 1992). The steepest descent slope from a cell to its steepest downslope neighbour is basically determined with a simple formula taking the elevation of the adjacent cells and the distance between the centers of cells into consideration. D8 has been widely used to partition a study watershed into sub-watersheds in semi-distributed modeling (Tarboton et al. 1991).

Another popular model is Fractional flow algorithm (F8) which may achieve more accurate representation of surface hydrology. It divides flow from a cell to all its eight neighbours by weighting flow according to relative slope (Quinn et al. 1991). There have been several other algorithms proposed to overcome uncertainties associated with F8 weighting schemes, including DEMON (Costa-Cabral and Burgess 1994), D-Infinity (Tarboton 1997) and Continuous Flow Direction (Lea 1992) that all consider both aspect and gradient of surface plane. Flow directions of all the cells on a study landscape are obtained by a selected flow path algorithm. The flow accumulations of the cells can be calculated by summing the corresponding flow values of all neighbouring cells.

3.2 Channel Network Identification

Extraction of channel networks from DEM is critical for watershed delineation. Channel initiation is an essential step in defining drainage characteristics. Two common methods have presented themselves for channel definition, the constant area-threshold method (Jenson and Dominique 1988) and the slope-dependent critical support area method (Dietrich et al. 1993). A minimum drainage area required initiating a channel is defined in both methods.

The constant threshold area method assumes that channel sources represent the transition between the convex profile of the hillslope (sheet flow dominated) and the concave profiles of the channel slope (channel discharge dominated). The constant threshold area method has found widespread applications (Tarboton et al. 1991). Garbrecht and Martz (1995) broadened the use of the constant threshold area method by allowing the threshold area to vary within the DEM. This is particularly useful in large watersheds in which geology and drainage network characteristics display distinct spatial patterns. The slope-dependent critical support area method is based on the assumption that the channel network extends up to the point where unstable fluvial sediment transport processes change to stable diffusive hill-slope processes. This implies that the channel source represents an erosional threshold. The major difference between extracted networks using the constant and slope-dependent thresholds support area methods lies in the spatial variability of the slope which is dependent on available elevation data.

3.3 Watershed Segmentation

DEMs have also been commonly used for watershed segmentation in semi-distributed modeling. Subwatersheds basically represent the direct contributing areas of each channel link, and of the upstream end of each exterior link. Subwatershed boundaries are determined by defining a threshold that regulates the smallest amount of upstream area to ensure enough amount of excess rainfall to generate surface runoff. Each subwatershed then becomes the element of modeling calculation in stead of using all the cells in the entire watershed. However it has been a challenge to reflect the spatial variation in modeling with a minimum number of subwatersheds.

There are other approaches to segmenting watershed in semi-distributed modeling. They basically involve defining hydrologic similarity of different points in a watershed based on topographic, soil, and/or land use information (Beven 2001). For example, the watershed segmentation for TOPMODEL is based on the assumption that all points in the watershed with the same value of the topographic index would respond in a hydrologically similar way. The topographic index (α/tan β) is defined as the natural logarithm of the ratio of the upslope contributing area per unit contour length (α) to the ground surface slope at the location (tan β). The index is solely dependent on elevation data, and thus DEM choice was critical for models like TOPMODEL in determining topographic input and consequently simulated outputs.

4 DEM Resolution Dependence

Wilson and Gallant (2000) summarized primary topographic attributes that can be calculated from raster digital elevation data. The primary attributes computed from directional derivatives of a topographic surface include slope, aspect, plan and profile curvature, and upslope contributing area. The impact of DEM grid size on the primary attributes have long been recognized and examined in much literature on terrain modeling. Among those attributes, slope is of the most interest to hydrologists as the very basic property deciding flow path. 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 β. 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.

A number of studies have been conducted to extend the evaluation to the DEM resolution impact on watershed rainfall-runoff modeling, covering both spatial distributions of hydrologic parameters and overall estimates for the entire watershed. The comparative approach with multiple resolutions of DEM for the same area has been used in almost all the studies. Different grid sizes of DEM used for comparative examination were obtained normally by cell aggregation from a base DEM to coarser resolutions. Majority of the studies involves the application of TOPMODEL which assumes that the local hydraulic gradient is equal to the local surface slope and implies that all points with the same value of the topographic index. The topographic index has become an important component in many physically based geomorphic and hydrologic models as it reflects the spatial distribution of soil moisture, surface saturation, and runoff generation processes (Zhang and Montgomery 1994).

Zhang and Montgomery (1994) examined the effect of grid cell resolution on landscape representation and hydrologic simulations using DEMs at resolutions of 2 m through 90 m from two small watersheds. Their results showed that increasing the grid size resulted in an increased mean topographic index because of increased contributing area and decreased slopes. 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. Another study by Wolock and Price (1994) found that increasing the grid size resulted in higher minimum, mean, variance, and skewness of the topographic index distribution. Some subsequent studies applied parameter calibration in their examinations on the DEM resolution impact on the TOPMODEL efficiency. They found that a link could be established between DEM grid size and some calibrated parameters values (Beven 1997). A sensitivity analysis on the space and time resolutions was performed by Bruneau et al. (1995) using TOPMODEL. The analysis showed that the modeling efficiency keeps fairly consistent over a wide range of DEM resolution. Similar results were obtained by Franchini et al. (1996) and Saulnier et al. (1997), and 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.

Several studies on this topic using other hydrologic models have also been seen in literature. Vieux (1993) investigated the DEM aggregation effect on surface runoff modeling using the GRASS program. It was found that errors due to cell-size aggregation from 30 to 90, 150, and 210 m could be propagated to the simulation as the apparent slope is flattened or the flow path is shortened. Molnar and Julien (2000) evaluated the effects of grid cell size from 17 to 914 m on surface runoff modeling using a raster-based CASC2D hydrologic model for event-based simulation. Their findings indicate that coarser cell resolutions can be used for runoff simulations with appropriately parameter calibration, and the primary effect of increasing grid cell size on simulation parameters is to require an increase in overland and channel roughness parameters. Chaubey et al. (2005) evaluated the effect of input data resolution on predictions from the SWAT model by running seven scenarios at increasing DEM grid sizes from 30 m to 1000 m. Results of the study showed that DEM resolution affects the watershed delineation, stream network and sub-basin classification in the SWAT model. A decrease in DEM resolution resulted in decreased stream flow prediction. They indicated that minimum DEM data resolution ranged from 100 to 200 m to achieve less than 10% error in SWAT model predictions.

5 Effect of Vertical Accuracy

A conceptually ideal approach to assessing the effect of DEM vertical accuracy is to derive the uncertainty measure analytically. Analytical solutions for uncertainty in complex DEM applications like hydrologic modeling, however, have not been found in literature. In watershed modeling applications, errors with DEM are propagated to derived physiographic properties, and further to hydrologic model output. Due to the complication of natural processes, mechanisms of the error propagation are poorly understood. It is therefore very difficult to perform analytical examination of the uncertainties.

A straightforward method has been to compare DEM estimates with accurate field elevation measurements. A work by Walker and Willgoose (1999) compared Australia-published DEMs of various grid spacings with a ground truth data set, obtained by ground survey, and studied the implications of these differences on key hydrologic statistics. Inferred watershed sizes and stream networks from published DEMs were found to be significantly different from those derived based on the ground truth in most instances. Their results also suggested that some hydrologic properties such as cumulative area are poorly estimated from published DEMs. Kenward et al. (2000) studied the effect of vertical accuracy of elevation data on hydrologic prediction by comparing stream-flow simulations associated with three DEMs for a small watershed from different sources. A DEM derived from low altitude aerial photography was used as the base reference. The second one was a standard USGS DEM, and the third was produced from Spaceborne Imaging Radar-C (SIR-C). Comparisons showed that apparent inaccuracies with drainage network and contributing area exist in both the USGS and SIR-C DEMs. Obvious differences in simulated hydrographs and runoff volumes were also found in the two DEMs as compared to the reference. Survey-quality terrain measurements as demonstrated in the above two studies are, however, not usually available for an area of interest to be used as the ground truth. The comparative approach is thus believed not a general option in studying elevation uncertainty in runoff modeling.

For environmental applications, a viable approach to assessing the DEM vertical uncertainty is to apply stochastic analysis to the propagation of DEM uncertainty. This is implemented by generating a set of plausible realizations of a DEM through Monte Carlo simulation. The watershed runoff modeling is run upon all the realizations, producing a distribution of results for the statistical analysis. The only work found in published literature closely related to hydrologic modeling was conducted by Veregin (1997) who examined the effects of vertical error in DEMs on the determination of flow path direction.

There have been a few other published applications of similar simulation modeling to studies in geography and earth sciences. Fisher (1991) evaluated the impact of DEM error for viewshed analyses using Monte Carlo simulation. Lee et al. (1992) and Lee (1996) applied similar methods to simulate errors in grid DEMs and found that small errors introduced into the database significantly affected the quality of extracted hydrologic features. Hunter and Goodchild (1997) investigated the effect of simulated changes in elevation on slope and aspect calculations. This study showed that errors in the calculated slope and aspect were dependent on the spatial structure of DEM errors.

The stochastic modeling framework adopted for simulating DEM uncertainty in watershed runoff modeling is depicted in Fig. 1. The original DEM is used as the base estimate of watershed elevation data. The elevation of each cell on the DEM is perturbed randomly to create a new realization of the DEM. The perturbation is restricted within a limit which is normally determined based on the vertical accuracy of the DEM, for example, published RMSE. A large number of DEM realizations are needed for the Monte Carlo simulation to generate a range of model outcomes. Each realization, characterized as a possible true elevation surface, is used as the elevation input to perform watershed runoff modeling. A distribution of obtained model outputs can be produced with all the realizations, and would be analyzed statistically to reveal the effect of vertical accuracy of elevation data.

It is difficult to predetermine the number of realizations adequate for generating a reliable distribution of modeling outcomes. An appropriate approach is to run the simulations until the aggregative statistics become stable. For example, the standard deviation for perturbed simulations can be used as the stabilization measure to determine how many Monte Carlo runs are sufficient. Another important issue is that an uncertainty surface generated from the stochastic approach may not be properly specified with respect to real-world landscape. A natural characteristic of spatial objects is that value at any one point in space is dependent on values at the surrounding points. This characteristic is referred to as spatial autocorrelation, and it needs to be applied to every randomly perturbed DEM to obtain a reasonable surface before the use in hydrologic modeling.

6 Case Study: A Topography Based Rainfall-Runoff Model

This case study demonstrates applications of the suggested approaches to examining the elevation data uncertainties in rainfall runoff modeling at the watershed scale. The effects of both horizontal resolution and vertical accuracy are modeled separately using TOPMODEL, a topography based hydrologic model. The application assessments are based on 1-year continuous simulations with daily hydrologic data for a study watershed.

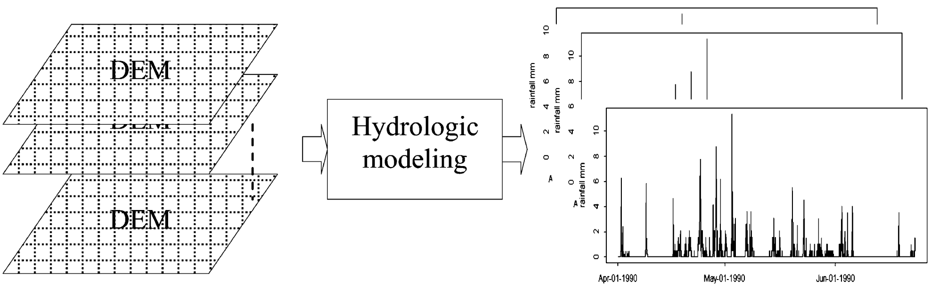

Fig. 1 Stochastic modeling approach to DEM uncertainty

6.1 TOPMODEL

The TOPMODEL is a semi-distributed hydrologic model, based on the contributing area concept, to characterize the spatial distribution and extent of zones of saturation and variable source areas for runoff generation (Beven 1997). 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 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 calculation 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).

6.2 Case Watershed and Data

The Goodwin Creek watershed is a 21.3 km^2 experimental watershed located in northwestern Mississippi (Fig. 2). 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). The area exhibits an average annual temperature of approximately 17°C and an average annual rainfall of approximately 1,460 mm during 1982–1992 (Blackmarr 1995).

The 7.5-min digital elevation quadrangles at 30m resolution containing the study watershed are downloaded from the data centre website of the United States Geological Survey (USGS). The resultant DEM of the watershed has a maximum RMSE of 2 m according to the published vertical accuracy information. Both the rainfall data and watershed outlet runoff measurements for 1983 are obtained from the ARS Water Database of US Department of Agriculture (USDA), Agricultural Research Service (ARS). Daily rainfall values from the raingages are averaged for TOPMODEL input.

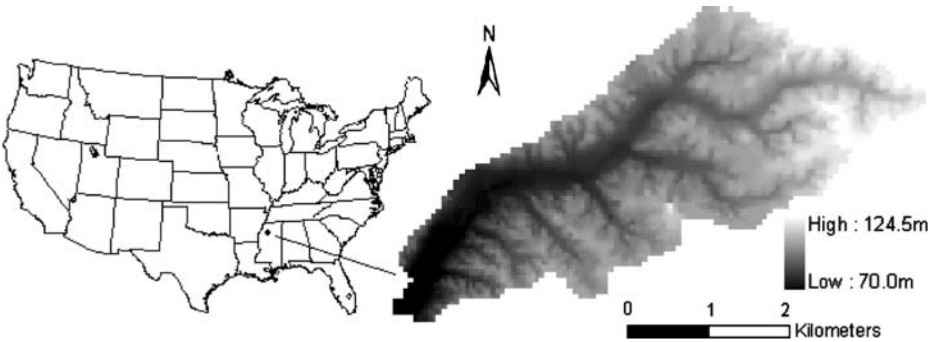

Fig. 2 Location and elevation map of Goodwin Creek Watershed

6.3 Grid Size Uncertainty

This subject is explored using the DEMs of different resolutions for the study watershed. The original 30 m grid size is selected as the base resolution, and resampled to six DEMs of 60, 100, 150, 200, 250, and 500 m resolutions using the nearest neighborhood method. Each of all the seven DEMs of different resolutions is used to generate the topographic index distributions for the comparative study. The effect of grid size upon the spatial and probability distributions of the topographic index required by TOPMODEL is evaluated. The performance of a TOPMODEL simulation is represented by the Nash and Sutcliffe efficiency coefficient (E_{ns}) (Nash and Sutcliffe 1970) as it remains the most commonly used criterion in assessing hydrologic modeling performance. 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. Interactions between model parameters and DEM scale is subsequently examined with calibrating the model parameters at each resolution.

As shown in Fig. 3, the mean index value for the watershed keeps increasing when the DEM grid size increases throughout the entire study extent (30–500 m). The effects of varying DEM resolution on calculated slope and upslope contributing area have been studied independently. Their findings adequately justify the observations on the topographic index. As aforementioned, Chang and Tsai (1991), and Gao (1997) showed that greater grid size leads to smaller calculated slope due to the smoothing effect of reduction in DEM resolution. Grid cell size 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 simulations without calibration exhibits a fair effect of the grid size on model efficiency as an identical set of parameters is used. The model performance keeps getting worse gradually from the base 30 m resolution all the way to 500 m where it has an efficiency of 23.5%. Obviously, the influence of DEM grid size on the topographic index distributions is passed onto the TOPMODEL simulations. Simulations with model calibration are performed at different DEM resolutions with an adequately wide range assigned to each parameter. The model efficiency maintains within two percentage points of the base value at 30 m. It is believed that the sound performance of TOPMODEL at coarse DEM resolutions is due to the compensation effect of the saturated hydraulic conductivity

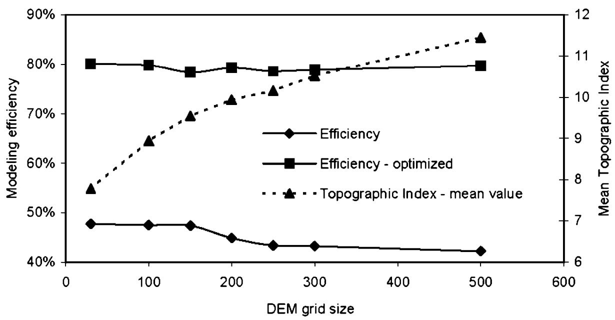

Fig. 3 Topographic index and TOPMODEL efficiency vs DEM resolution

parameter (lateral transmissivity when the soil is just saturated), T_0. Franchini et al. (1996) and Saulnier et al. (1997) have reported that, by adjusting T_0 to higher values according to the shifts of topographic index distribution caused by the grid size increase, one can obtain almost identical model efficiencies.

6.4 Uncertainty from Vertical Inaccuracy

This case study presents the Monte Carlo simulation approach to the vertical accuracy uncertainty in rainfall runoff modeling. The 7.5 min 30 m USGS DEM for the Goodwin Creek watershed is assumed to be the ground truth. Four levels of accuracy, 2.0, 5.0, 10 and 15 m of RMSE, are applied to produce uncertainty elevation surfaces. Each cell on the base DEM is randomly assigned to a new elevation based on a specified RMSE until all the cells are perturbed to form an uncertainty surface. The degree of autocorrelation of the watershed DEM is measured by Moran's I coefficient. The original DEM obtained from USGS has a coefficient value of 0.002. Each perturbed surface is autocorrelated to possess the same coefficient value. The autocorrelated DEM is supplied to spatial processing to calculate the topographic index distribution and the routing component. The TOPMODEL runoff computation is then run with the two spatial inputs to obtain simulated hydrograph for this surface realization. This process is repeated until the number of DEM realizations is deemed appropriate for capturing the distribution of modeling output. The stabilization measure used in the case study is the standard deviation of the Nash and Sutcliffe modeling efficiency within all the Monte Carlo simulations. Figure 4 shows the stabilization of the deviation with increasing number of realizations under each the four RMSE settings. Obviously a case with a higher RMSE requires a larger number of realizations to reach a steady level of modeling efficiency variance. It takes over 2,000 runs under 15 m of RMSE as compared to about 400 runs for 2 m.

Each DEM realization generated at each vertical error level is first used to obtain a topographic index grid through the calculation of each cell's slope and upslope contributing area. The standard deviation for each cell is calculated with all the realizations. The values are averaged for all the cells to obtain mean standard deviation of the topographic index under the RMSE. As shown in Table 1, the values of mean standard deviation increase with the RMSE as expected. The rate of increase, however, declines slightly as the error gets greater. This is believed to be attributable to the effect of adequate spatial autocorrelation. Nevertheless, significant difference can be found in the topographic index distribution over the entire watershed among the realizations of the different RMSE levels.

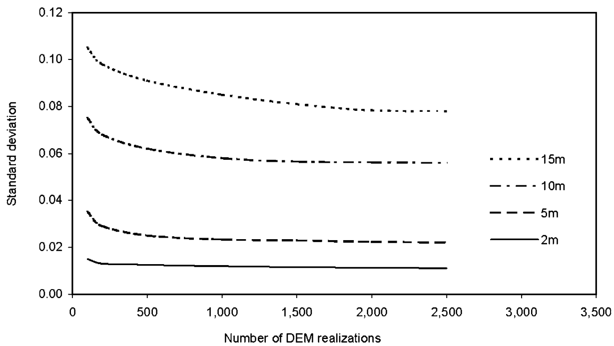

Fig. 4 Determination of appropriate number of DEM realizations

Table 1 Mean values of the standard deviation of the topographic index

RMSE (m)	2	5	10	15
Mean standard deviation	0.263	0.927	1.36	1.60

The magnitude of the effect of vertical accuracy on TOPMODEL simulation performance is examined both without and with parameter calibration. For the non-calibration scenario, simulations are run for all DEM realizations using the parameters optimized with the base DEM. As presented in Table 2, the vertical accuracy does present a fair impact on the model efficiency for the Monte Carlo simulations without calibration. The average Nash and Sutcliffe efficiency for all the realizations at 2 m of RMSE is 76.2% as compared to the optimum efficiency of 80.2% with the based DEM. It drops to 55.1% for the error level of 15 m RMSE. The mean standard deviation of the efficiencies increases from 0.029 to 0.165 accordingly. Apparently, the much greater variation of the topographic index distribution contributes to the significant reduction of model performance.

The modeling results for simulations with calibrations present a different profile of vertical accuracy impact. Values of both the efficiency and its standard deviation remain almost the same at all the four levels of RMSE as shown in Table 2. This indicates that TOPMODEL efficiency is insensitive to vertical accuracy of watershed elevation data for calibrated simulations. The effect of change in the topographic index distribution must be offset by adjustment of TOPMODEL parameters in the calibration process. The principal compensation also comes from the saturated hydraulic conductivity parameter T_0 similar to the fact shown in the examination of the DEM resolution effect.

7 Concluding Remarks

Topography plays an important role in many water resources processes as described in this paper on spatial processing for hydrologic modeling. Elevation is recognized as a critical factor affecting land based hydrologic features. Raster based digital elevation data are commonly used to represent the topography in GIS supported regional water resources studies. Inaccuracies with DEMs constitute uncertainty which is propagated with manipulation of elevation data into hydrologic analysis results. Horizontal resolution and vertical accuracy are the two principal issues of DEM quality. Considering the complexity of distributed or semi-distributed hydrologic models, an ideal approach to examining their effects in hydrologic modeling is to propagate the uncertainties through application analyses to identify how modeling results are influenced.

Table 2 Mean values and standard deviations of modeling efficiency

RMSE (m)	Uncalibrated		Calibrated	
	Mean	Standard deviation	Mean	Standard deviation
2	0.762	0.029	0.802	0.007
5	0.716	0.055	0.797	0.007
10	0.635	0.096	0.801	0.008
15	0.551	0.165	0.798	0.009

To examine the ramifications of varying DEM grid size for the use of a hydrologic model, the uncertainty propagation approach is accomplished using the comparative method with multiple resolutions of elevation data. DEM cell aggregation based on a fine grid is normally used in obtaining the spatial input to for comparison. The results of a case study exhibit grid size effects on the performance of TOPMODEL, a topography based hydrologic model. The simulations without calibration exhibits 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 suggest that TOPMODEL can be highly insensitive to grid size changes of grid size as a result of the compensation effect of model parameter adjustment. This is consistent with results commonly obtained from other published studies that the model performance for larger grid sizes can be improved by parameter calibration.

The examination of spatial uncertainty in TOPMODEL simulation caused by vertical accuracy is undertaken by generating a series of DEM realizations. Autocorrelation is dispensable on the randomly perturbed elevation data. A stochastic distribution of model performance is obtained by running the model upon reasonably autocorrelated realizations. The procedure has also been demonstrated with the case of Goodwin Creek Watershed. The results show that the Monte Carlo simulations with a same set of TOPMODEL parameters lead to significant variations of the model performance in regards to the error levels applied. The standard variation of the modeling efficiency increases steadily with applied RMSE of the DEM. Similar to the situation with the grid size uncertainty, model calibration can compensate the effect of the spatial uncertainty caused by DEM vertical inaccuracy. The TOPMODEL efficiency can be kept almost no change with a RMSE of 15 m.

A general portrayal on effect of elevation data input quality can be acquired by propagating the uncertainties through application modeling. The magnitude of model performance loss due to the inaccuracies has been well illustrated using the topography based TOPMODEL. Results of the analyses in this study have indicated that hydrologic models can be very sensitive to elevation data uncertainties. The sensitivities may, however, be offset by model parameter optimization. The works have implied that the applied analysis technique can be a logical and effective approach to evaluating elevation uncertainty in water resources modeling.

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