Effect of grid size on runoff and soil moisture for a variable-source-area hydrology model

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Abstract. Soil chemical and biological dynamics in mixed use landscapes are dependent on the distribution and pattern of soil moisture and water transport. In this paper we examine the effect of different grid sizes on soil water content for a spatially explicit, variable-source-area hydrology model applied to a watershed in central New York. Data on topography, soil type, and land use were input at grid sizes from 10 to 600 m. Output data consisted of runoff and spatial pattern of soil moisture. To characterize the spatial variability at different grid sizes, information theory was used to calculate the information content of the input and output variables. Simulation results showed higher average soil water contents and higher evaporation rates for large grid sizes. During a wet year, runoff variability at different grid sizes, increasing grid sizes caused the information content of the input and output variables. Simulation results showed higher average soil water contents and higher evaporation rates for large grid sizes. During a wet year, runoff was not affected by grid size, whereas during a dry year runoff was greatest for the smallest grid size. While the information content (i.e., spatial variability) of soil type and land use maps was not affected by the different grid sizes, increasing grid sizes caused the information content of the slope gradient to decrease slightly and the Laplacian (or curvature of the landscape) to decrease greatly. In other words, increasing grid cell size misrepresented the curvature of the landscape. During wet periods the decrease in information content of the soil moisture data was the same as for the Laplacian as grid size increased. During dry periods, when local fluxes such as evaporation and runoff determine the moisture content, this relation did not exist. The Laplacian can be used to provide a priori estimates of the moisture content deviations by aggregation. These deviations will be much smaller for the slowly undulating landscapes than the landscape with steep valleys simulated in this study.

1. Introduction

Nonpoint source and habitat degradation problems must be addressed at the basin or watershed level for efficient management of water quality [U.S. Environmental Protection Agency, 1994, 1995, 1996]. This requires spatially explicit models to simulate ecosystem processes. Most models are lumped and are unable to describe the variation in water and nutrient fluxes in a watershed [Swaney et al., 1996; Fisher et al., 1997]. This is especially true for well-vegetated watersheds in the northeastern United States in which shallow and sloping soils predominate and for which the hydraulic conductivity of soils exceeds rainfall intensity by several fold. In these watersheds, runoff is generated from localized saturated areas, and evaporation and interflow (flow parallel with the impermeable layer) are important components in water balance calculations [Dunne, 1978; Petch, 1988; Steenhuis et al., 1995].

Simulating water dynamics in these watersheds requires fast computers and a vast amount of spatial information, including topography, soil type, and land use [Beven and Kirkby, 1979; Beven, 1986, 1995] and has been feasible only during the last decade [Mendicino and Sole, 1997]. To efficiently integrate these data with computational routines, grid-based distributed models have been developed employing geographic information systems (GIS) for spatial data management [Moore et al., 1991; Burrough, 1996]. The behavior of these highly nonlinear distributed models can be characterized by the information content or entropy of their input and output data [Vieux and Farajalla, 1994]. The information content is a measure of temporal or spatial variability. Vieux [1993] showed that by smoothing and aggregating digital elevation data, its information content decreased, resulting in greater errors in predicted runoff. It is obvious then that grid size in distributed models will have a direct effect on information content and the accuracy of simulation output. The most common grid sizes in GIS databases are those used by the geological surveys of the United States and the United Kingdom of 30 m and 50 m, respectively [Quinn et al., 1991; Moore et al., 1993], but little is known about the effect of grid size on simulation results or information content.

A few studies have examined the effect of grid size on watershed simulations. Using TOPMODEL, Quinn et al. [1991], Moore et al. [1993], Zhang and Montgomery [1994], Bruneau et al. [1995], and Wolock and Price [1994] looked at how grid size affected the computed topographic characteristics, wetness index, and outflow. In general, they found that the finer grid size gave more accurate results. TOPMODEL assumes that the downslope flows take place predominantly in a saturated zone...
with a transmissivity that decreases with depth [Ambroise et al., 1996]. In the northeastern United States and other areas of the world, where thin soils overlay slowly permeable subsoils or bedrock, the soils are only saturated for a short period after storm events and then the remainder of the interflow takes place as unsaturated flow [Steenhuis et al., 1988]. The assumption in TOPMODEL that flow takes place only through the saturated soil is not valid for these watersheds. With the exception of the few studies with TOPMODEL the effect of GIS grid size on watershed simulations has not been well investigated [Star and Estes, 1990; Star et al., 1997; Baveye and Boast, 1999]. Thus the goal of this study is to elucidate the role of grid size on information loss of water movement and soil moisture in the simulation of a watershed with impermeable sloping subsoils at shallow depths.

In this study we use a GIS-based model that includes unsaturated flow and that was specifically developed for undulating landscapes with a relatively thin conductive soil layer over glacial till [Zollweg et al., 1996; Kuo et al., 1996; Frankenberger et al., 1999]. Soil water movement and dynamics were simulated for three watersheds in upstate New York to evaluate the effect of scale on simulated soil water content and runoff. The sensitivity of the model to aggregation of specific types of input data was studied by increasing the grid size for one type of input data while keeping the other input parameters at the original scale. This constituted a factorial simulation experiment with the input parameters as treatments and the grid size as level within the treatment. Information loss due to aggregation was calculated.

2. Methods

2.1. Study Site

We chose three adjacent watersheds, typical of the northeastern United States, of 647, 2360, and 742 ha (Table 1 and Plate 1). The watersheds are part of the Fall Creek watershed and located upstream from Freeville, New York (N42°32', W76°17'). Terrain elevation ranges from 317 to 561 m, and slope gradient ranges from 0 to 60% (Table 1). Agriculture and forest are the main land uses. Annual precipitation averages 94 cm, and mean annual air temperature averages 8.3°C [Owensby and Enzell, 1992]. Precipitation is nearly evenly distributed throughout the year. Most soils have a shallow depth to a layer that restricts water movement [Cornell University Department of Geology, 1959; Neeley, 1965].

Three digital maps were made for elevation, soil type, and land use using 10-m-square grid cells. Elevation data were digitized from the contours of 1:24,000 U.S. Geological Survey maps. Soil maps were obtained from soil surveys at 1:20,000 scale of Tompkins, Cortland, and Cayuga Counties. Land use information was interpreted from 1991 aerial photographs at 1:24,000 scale [Poiani et al., 1996]. For the purpose of this study the 10 by 10 m grid maps were considered to be a true representation.

2.2. GIS-Based Hydrology Model

The analysis was performed with a GIS-based model originally developed by Zollweg et al. [1996] and further improved by Kuo et al. [1996]. The model was designed for simulation of soil water and nitrogen fates in mixed use landscapes with sloping and shallow soils. The model was coded in shell script commands within the Geographic Resources Analysis Support System [Construction Engineering Research Laboratory, 1993; Mitasova et al., 1995]. The simulations were performed using a daily time step.

Water balance equations were written to operate on a per grid cell basis and for each soil layer. The model divides the soil into two main layers: a potential root zone and the combination of several subsoil layers. The potential root zone is divided into the actual root zone (from which evaporation occurs) and the remaining part which the roots eventually penetrate during the growing season. The change of soil water in a layer in a cell is calculated by combining Darcy's law for the lateral flux and perpendicular flux to the surface $f$ with the conservation of mass equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial s} \left( K(\theta) \frac{\partial h}{\partial s} \right) - \frac{\partial f}{\partial n},$$

where $\theta$ is the volumetric water content, $h$ is the hydraulic head, $K(\theta)$ is the hydraulic conductivity as an exponential function of moisture content, $s$ is the coordinate along the slope, and $t$ is time. The first term on the right-hand side is the net lateral flux between cells, and the second term expresses the net upward and downward fluxes between layers in a cell. The coordinate normal to the surface is $n$.

The flux $f$ includes the daily precipitation, evaporation water loss to the atmosphere, and the water flux between the layers. Water flows downward at the rate of the saturated conductivity when the layer is above field capacity. If the layer below is filled up with water, downward movement stops. Local runoff occurs when the soil reaches saturation or when precipitation intensity is greater than local saturated conductivity. Evapotranspiration takes place out of the active evaporation zone and is based on the Thornthwaite-Mather procedure [Steenhuis and van der Molen, 1986]. For moisture contents from field capacity to saturation the evaporation is equal to the potential rate; and for moisture contents from field capacity to wilting point, evapotranspiration decreases linearly from a potential rate to zero. During the winter, snow accumulation and snowmelt are included.

Equation (1) can be rewritten as

$$\frac{\partial \theta}{\partial t} + \frac{\partial f}{\partial n} = \frac{\partial K(\theta) \frac{\partial h}{\partial s}}{\partial s} + K \frac{\partial^2 h}{\partial s^2},$$

which shows that the net lateral exchange of water between cells (right-hand side) depends on the hydraulic conductivity and is a function of the first derivative ($\partial h/\partial s$ or slope gradient) and the second derivative of the elevation ($\partial^2 h/\partial s^2$ or the
Plate 1. Location, soil type, and land use maps of the study area, a subcatchment of the Fall Creek watershed in central New York.
where the length of the cell boundary \( X \) is approximated by 

\[
\]

2.3. Spatial Aggregation

Increasing grid size results in a change in watershed area if the border cells are not adjusted for the area inside the "true" boundary [Bruneau et al., 1995]. When comparing total runoff and average moisture content for different grid sizes, the watershed area needs to be conserved. To do so, we calculated for each aggregated cell the proportion of 10 by 10 m cells \( (a_p) \) that was within the watershed. The fluxes of the aggregated border cells were then multiplied by this factor \( (a_p) \) ensuring that no water was gained through the scaling process. Figure 1 shows an example of spatial aggregation on a simple catchment from the small scale \( L = l \) to the larger scale \( L = 3l \). At the small scale, \( L = l \), the catchment area, shown as shaded, is equal to \( 13L^2 \). At the larger scale, \( L = 3l \), four coarse cells are within the catchment, and \( a_p \) for those cells is 2/9, 2/9, 3/9, and 6/9, giving a value of 13/9\( L^2 \). Because \( L^2 = 9L^2 \), the area is again equal to 13\( L^2 \).

On the basis of above discussion, (1) can then be written in finite difference form for a layer \( i \), with height \( D_i \), of a cell with length \( L \), using the appropriate volumes and cross-sectional areas:

\[
a_p D_i L^2 \frac{\Delta \theta_i}{\Delta t} = \Delta (\lambda D_i K(\theta) S) - \Delta (a_p L^2 \mathcal{L}),
\]

where the length of the cell boundary \( \lambda \) is approximated by

\[
\lambda = \sqrt{a_p L^2}
\]

and shows, as expected, that for internal cells \( \lambda = L \). The left-hand side of (3) expresses the change in volumetric moisture content in the part of the cell that is within the watershed. On the right-hand side of (3) the term \( \Delta (\lambda D_i K(\theta) S) \) is the net lateral flux of water over a cross-sectional area \( \lambda D_i \) and is computed as the product of the unsaturated conductivity \( K(\theta) \) and slope \( S \) in the flow direction. The last term is the net vertical flux between the layers.

Another issue in aggregation was the value of the cell parameters. A distinction was made between continuous data (e.g., elevation) and categorical data (e.g., soil type and land use). For continuous data the values of the component cells were averaged. For categorical data the most common value of the component cells was selected. In case of a tie one of the (equally) most common values was chosen at random. For border cells, only the portion inside the watershed was considered.

2.4. Simulation Experiment

The 10 \( \times \) 10 m maps of elevation, soil type, land use, and watershed boundaries for the study area were aggregated to produce 14 sets of data with grid sizes of 10, 20, 30, 50, 70, 100, 120, 150, 170, 200, 300, 400, 500, and 600 m. This procedure is different than those used by others [i.e., Zhang and Montgomery, 1994; Wolock and Price, 1994] where the digital elevation maps were resampled for each grid size. The aggregated base maps were used to obtain the input maps for the simulation model (e.g., slope gradient and Laplacian from the elevation map, saturated conductivity from the soil map, and potential rooting depth from the land use map). A 3-year simulation was performed using daily weather data from April 1, 1991, to March 31, 1993, obtained from the Northeast Regional Climate Center at Cornell University for the Game Farm Road Station located in the Fall Creek watershed. Year 0 (April 1, 1991, to March 31, 1992) was used to set the initial moisture content of the cells. Year 1 consisted of the climate data for the period April 1, 1992, to March 31, 1993 (108 cm of precipitation). Year 2 consisted of the period April 1, 1991, to March 31, 1992 (82 cm of precipitation) used a second time.

2.5. Determination of Dominant Parameters: Factorial Experiments

To determine the types of data for which grid size had the greatest effects on simulation output, we conducted two-factor simulation experiments [Neter et al., 1996]. Among input maps we varied the grid size of the topographic (topo) map as one factor and varied the grid size of both the land use and soil map (lu-s) as the other factor. Each factor had two spatial resolutions, 20 m and 200 m. Thus, we ran four different simulations: 20 m topo with 20 m lu-s; 20 m topo and 200 m lu-s; 200 m topo and 20 m lu-s; and 200 m topo and 200 m lu-s.

2.6. Information Content

The numerical values for each grid cell compose the information of a map. Typically, as map resolution decreases (i.e., larger grid size), information is lost. To describe the effect of aggregation on the simulation results, we used the information (or entropy) theory by Shannon and Weaver [1949] which was introduced to hydrology by Vieux [1993], Vieux and Farajalla [1994], Mendicino and Sole [1997], and Singh [1997].

For categorical data, such as land use, information content \( \Omega \), which represents a measure of variability of spatial information associated with a range of outcome values, is defined as

\[
\ln \Omega = - \sum_{i=1}^{N} P_i \ln (P_i),
\]

where \( N \) is the number of categories (or bins) in the range into which the categorical values have been divided and \( P_i \) is the
proportion of cells of category \( i \). Choices of range of outcome values and \( N \) are critical in comparing information indices over different scales.

Choice of bins for evaluating \( \Omega \) for continuous data is more problematic. As the number of bins increases, \( \Omega \) approaches \(-\ln (M)\), where \( M \) is the number of distinguishable values. This is clearly meaningless from the point of view of information content. So a proper value of \( N \) has to be chosen so that there is a clear distinction for different grid sizes. We want \( N \) large enough to reflect the fact that the data are continuous but not so large as to be approximately equal to \(-\ln (M)\). Figure 2 shows there is a middle range in which \( \ln (\Omega) \) is changing approximately linearly with \( \ln (N) \), and effective comparisons can be made between grid sizes. Hence we chose \( N = 80 \) for quantifying information loss for slope gradient and \( N = 600 \) for the Laplacian.

### 3. Results and Discussion

Simulated cumulative runoff, average monthly soil moisture, and cumulative effective precipitation over the three catchments are shown in Figure 3. Because of difference in saturated moisture content between cells, the soil moisture content is normalized: 0 is air dry soil and 1 is saturation. Effective precipitation is defined as the difference between rainfall and evapotranspiration. Soil moisture values (Figure 3b) increased as the grid sizes increased. Larger grid sizes resulted in higher average moisture contents (Table 2). As we will discuss later, the increase in moisture content is directly related to a decrease in the variation of slope gradient and curvature. The differences in moisture content established on April 1 of year 1 (resulting from the initialization of the simulation with the year 0 precipitation) were approximately maintained throughout the 2 years, although differences were greatest during the dry summer of the second year (Figures 3a and 3c). The cumulative effective precipitation became less over the 2-year period for increasing grid sizes. This was a direct consequence of the higher moisture content at the large grid sizes that gave higher actual evaporation amounts and thus lower effective precipitation amounts. Runoff was the same for all the grid sizes during the wet year 1 (Figure 3a) despite the difference in effective precipitation (Figure 3c). Thus the lower effective rainfall input for the larger grid sizes was offset by a smaller decrease in moisture content during the summer compared with the smaller grid sizes (which is confirmed by Figure 3b). A similar argument can be made for the lower total in cumulative runoff at large grid size (Figure 3c). Since for the 400-m grid the moisture content at the beginning and end of the simulation period was approximately the same (Figure 3b), water balance considerations dictate that decreases in effective precipitation are directly related to a decrease in outflow from the watershed. Because the watershed becomes drier over the 2-year period for the smaller grid sizes (Figure 3b), the differ-

![Figure 2](image.png)

**Figure 2.** Information content (\( \Omega \)) of slope gradient and Laplacian versus number of bins at cell sizes of 50, 200, and 600 m.

![Figure 3](image.png)

**Figure 3.** Monthly simulation results for the whole catchment of total area at cell sizes of 10, 30, 50, 100, and 400 m: (a) cumulative monthly runoff, (b) monthly average soil moisture, and (c) cumulated monthly effective precipitation. Legends are shown in Figure 3a.
Table 2. Results of a Two-Factor Experiment: Topography Versus Soil Type and Land Use With Two Levels of 20 and 200 m

<table>
<thead>
<tr>
<th></th>
<th>Year 1 Topography</th>
<th>Year 2 Topography</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 m</td>
<td>200 m</td>
</tr>
<tr>
<td>Runoff, mm</td>
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<td></td>
</tr>
<tr>
<td>Soil type, 20 m</td>
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<td>481</td>
</tr>
<tr>
<td>Land use, 200 m</td>
<td>481</td>
<td>491</td>
</tr>
<tr>
<td>Averaged Soil Moisture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil type, 20 m</td>
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<td>0.972</td>
</tr>
<tr>
<td>Land use, 200 m</td>
<td>0.803</td>
<td>0.968</td>
</tr>
<tr>
<td>Effective Precipitation, mm</td>
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<td></td>
</tr>
<tr>
<td>Soil type, 20 m</td>
<td>500</td>
<td>450</td>
</tr>
<tr>
<td>Land use, 200 m</td>
<td>498</td>
<td>457</td>
</tr>
</tbody>
</table>

ences in runoff are not as great as the differences in effective precipitation.

The spatial distribution of soil moisture for a selected sample date, March 31, 1993, at cell sizes of 10, 30, 50, 100, and 400 m is revealing (Figure 4). This was the second day after a rain event (0.83 cm precipitation), and there had been no rainfall or snowmelt for 5 days prior to the rain. In Figure 4, darker regions represent drier soil, and open areas indicate soil near or at saturation. In the 10 m-simulation most areas were at field capacity, except areas near valley bottoms. The spatial pattern of the saturated areas indicated potential locations of flow channels and wetlands (open areas in Figure 4). The pattern of wetness also changed with grid size: The areas at field capacity on the 10 by 10 m grid in the middle of Figure 4 became completely saturated ($\theta > 0.99 \theta_s$) in the 400-m grid.

Although Figure 4a is too small to see the many saturated individual 10 by 10 m grid cells, the overall pattern of wet areas shows a close correspondence with the poorly drained areas in Plate 1. Poorly drained areas are defined in the soil survey as mostly wet throughout the year, but otherwise they have the same hydraulic properties as similar soils in upland areas of the landscape. Thus input parameters were the same for the wet and dry areas, and the simulated degree of wetness was only dependent on terrain location.

The difference in annual runoff for the various grid sizes was much smaller between the three basins than between the 2 years of simulation (Figure 5a). Differences between the years in soil moisture averaged over all days and grid cells were relatively small (Figure 5b). The average soil water saturation changed rapidly with grid sizes up to 150 m but changed very little after that.

The relative deviation $E$ of the moisture content was plotted against the grid size (Figure 6). $E$ is defined as

$$E = \left| \frac{\theta_1 - \theta_0}{\theta_0} \right|,$$

Figure 4. Spatial simulation soil moisture for a selected sample date, March 31, 1993, at cell sizes of 10, 30, 50, 100, and 400 m.

Figure 5. Simulation results of three basins in year 1 and year 2: (a) annual runoff and (b) yearly average soil moisture. Legends are shown in Figure 5a.
where $\theta_i$ is the average yearly soil moisture content at scale $i$ and $\theta_0$ is the reference moisture content for an infinitesimally small cell obtained by an extrapolation to a grid size of 0 m using a linear regression of $\ln \theta$ versus the grid size (Figure 5b). The relative deviation in moisture content for a particular scale was almost the same between years, and variation in relative deviation between basins became obvious (Figure 6). The magnitude of the deviation for larger grid sizes was greater for basin 1 (Plate 1) which has a relatively high percentage of shallow, less well drained soils than basins 2 or 3. The slope of the lines was, initially, about 1.2 (Figure 6), indicating that the relative deviation increased by a factor of $10^{1.2}$ or 16 when grid size increased from 10 to 100 m.

The results of the two-factor factorial experiment are summarized in Table 2. One factor represents the map derived from elevation (topography), and the other factor represents the maps from soil type and land use. In Table 2 the effective precipitation is the difference of the precipitation and the actual evaporation. Both the annual effective precipitation and yearly averaged soil moisture for the whole watershed changed little when the soil type and land use maps were changed from 20 to 200 m, while the grid cell size of the topography remained the same (Table 2). For example, for the 20-m grid topography map the average moisture content for year 1 was 0.798 when the grid spacing for the soil type and land use maps was 20 m, while using a 200-m grid cell size for these two maps (and retaining the topography grid size at 20 m) resulted in an average moisture content of 0.803. In contrast, aggregation of topography from 20 to 200 m had a large effect on model outputs. The change in scale from 20 to 200 m for topography resulted in an increase in the watershed moisture content of nearly 20% in both years and at both the 20- and 200-m scales of the soil type and land use maps. Because aggregation of topography increased wetness, it increased evapotranspiration and thereby decreased the effective precipitation (Table 2).

The spatial moisture distributions on two dates (Figure 7a) and the average soil moisture contents for three monthly periods (Figure 7b) were analyzed to assess the grid size effect. These were either in dry or wet periods. The "wet" day, March 31, 1992, had 1.3 cm precipitation in the previous 3 days, while evaporation was small. The "dry" day, June 19, 1992, occurred during a drought period with no rain for the previous 12 days under high evaporative conditions. For monthly average data, August 1991 (dry) was compared with August 1992 and October 1992 which were both wet but with vegetation in different growth stages. In all cases, aggregation caused a dramatic loss in information of moisture content distribution of the soil. During wet periods the information content $\Omega$ decreased 1 to 2 orders of magnitude when the grid size changed from 10 to 600 m (Figures 7a and 7b). The decrease in $\Omega$ for increasing grid sizes was less during dry periods than during wet periods but was still substantial. Thus, using the typical American grid cell size of 30 m, rather than 10 m for the simulation, results in a loss of information on soil moisture distribution of 50% during the wet period. For the usual British grid size of 50 m, the information loss was 70%. Since soil moisture is a major factor that controls biological and chemical processes, we infer that simulation of those dynamics at larger grid sizes may overestimate the rate of anaerobic soil processes and the growth rate of the plants. Therefore we recommend for watershed simulations use of a grid cell size smaller than 30 m and preferably 10 m if the data are available.

As expected, the information content $\Omega$ for soil type and land use showed only a weak dependence on grid size (Figure 8a). Also, aggregation did not change the information content of the distribution of grid cell elevations and resulted in only moderate information loss for slope gradient (Figure 8b).
main factor in moisture loss and lateral transport is small, characterized by the Laplacian. During dry periods, evaporation is the dominant fluxes of percolation, rainfall, and evaporation at a particular location and thus is independent of the curvature of the landscape. For wet soils, moisture content is dominated by lateral fluxes which are a function of, primarily, the Laplacian.

Figure 8b shows that a large grid size results in a small range of the Laplacian spectrum. This, in turn, can be used to partially explain why soils become wetter for the larger grid sizes (Figure 4): For the 10-m grid, although the overall moisture content is lower, the wide variation in curvature (or Laplacian) causes different inflows and outflows for each cell. As a result, there are many small but saturated areas throughout the watershed after a heavy rainfall. Thus water in the 10-m grid has only a small distance to travel via interflow to the wet areas compared to the larger grid sizes. Once in a saturated area, water flows overland to the outlet. Overland flow is the most effective way (i.e., the path with the least resistance to water flow) to drain the watershed. Thus the 10-m-grid water drains relatively quickly because of the short travel distance, and there is thus less resistance to water flow than for the larger cell sizes. Since the amount of water which has to be transported out of the watershed remains approximately the same, the unsaturated conductivity must compensate for the decrease in driving force. Since conductivity depends on moisture content, the moisture content increases. In addition, for large grid sizes the variation in curvature is decreased. We obtain, in the limit, a uniform slope. For uniform slope without rain, inflows and outflows are equal, and the slope has a uniform water content. Thus, during a rainfall event, saturation occurs over the whole hillslope at the same time and stops at the same time too.

Our unsaturated flow model and its saturated flow counterpart, TOPMODEL, both showed the same sensitivity of scale with respect to the topographic input data. Even more remarkable is that Zhang and Montgomery [1994] found, similarly, for two watersheds with TOPMODEL that the 10-m grid size provided a substantial improvement over the 30- and 90-m data. In addition, we recently found that for a single hillslope with some simplifications the unsaturated Richards's formulation is the same as the Boussinesq's approximation for saturated flow [Steenhuis et al., 1999]. Thus, despite the conceptual differences between TOPMODEL and ours, the model structure might be more similar than originally anticipated.

4. Concluding Remarks

Errors introduced by aggregation of spatial input data have important ramifications for the use of GIS-based hydrology models. In this study, deviations from the simulations at the smallest grid size increased proportionally to grid size over the range of scales most commonly used in GIS simulation studies (Figure 6). This is in agreement with the argument used by Beven [1995] that the aggregation approach toward macroscale hydrological modeling, using averaged parameter values, is inadequate for representing hydrological processes at a large scale. Thus a disaggregation approach to developing scale-dependent models is advocated by Beven [1995]. However, the computation cost (CPU time) decreases in proportion to the square of the grid size. Our results, such as represented in Figure 6, can, at least in the northeastern United States, help guide the choice of a grid size in variable-source-area distributed models which is a compromise between accuracy and computation time in large-area simulations.

In this study we showed that among the several types of input information changes in the scale of topography had the greatest effects on the simulation results. This parallels the
results with TOPMODEL. [Braun et al., 1997; Zhang and Montgomery, 1994]. Aggregation had an especially large effect during wet periods. The scale of topography is critical because hydrological behavior is driven by the first derivative (slope gradient) and the second derivative (Laplacian or slope curvature) of the elevation data. The information of the Laplacian has the same response to grid size as the relative deviation in the simulation of the moisture content (Figures 6 and 7). Thus the Laplacian \( \Omega \) value can provide an a priori estimate of the magnitude of the deviation in soil moisture content values created by aggregation and can aid in deciding the optimum grid scale for simulating the hydrology of large areas. For example, for the slowly undulating landscapes in the midwestern corn belt where the Laplacian changes little with scale, a larger grid size than that used for the landscape with steep valleys simulated in this study can be used without adversely affecting the output.

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References


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