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Digital elevation analysis for distributed hydrological modeling: Reducing scale dependence in effective hydraulic conductivity values

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Abstract. The recent widespread availability of digital terrain data has made automatic procedures for topographic analyses popular. Previous studies have shown that hydrological models and their effective parameter values are dependent on the resolution of the elevation grid. This paper examines the analysis of raster elevation data within the topography-based model, TOPMODEL, framework. It is demonstrated that the algorithm used in processing channel pixels in calculating the topographic index $\kappa = \ln(a/\tan\beta)$ can have a dramatic effect on the sensitivity of effective parameter values to the grid size. Suggestions are made for calculating the topographic index of channel pixels, consistent with the TOPMODEL assumptions, that strongly decrease the sensitivity of the calibrated effective hydraulic conductivity values to grid size.

Introduction

This study addresses the problem of grid scale dependence of the effective parameter values of distributed hydrological models. Such dependence has been recognized in the past but is not well understood. The rapid increase in both computer power and the availability of geographical information systems and digital terrain maps (DTMs) in many countries and catchments is encouraging the use of distributed models. This study makes use of the topography-based model, TOPMODEL [Beven and Kirkby, 1979; Beven *et al.*, 1995], which was one of the first attempts to model distributed hydrological responses based on variable contributing area concepts. It has become increasingly popular in recent years as it provides a relatively simple framework for the use of DTM data and entry to distributed prediction. TOPMODEL makes use of a topographic index of hydrological similarity based on an analysis of the topographic data, where the form of the index depends on assumptions about the profile of transmissivity [Ambroise *et al.*, 1996a, b].

In early studies [Beven and Kirkby, 1979] the topographic index was calculated from contour maps, where the expected downslope flow lines were drawn manually. This was an extremely tedious process but had the advantage that features affecting the accumulation of flow downslope, such as small channels and field boundary ditches, could easily be incorporated into the procedures. However, DTM data are now most

readily available in raster grid. Quinn *et al.* [1991, 1995] suggested an automatic procedure to calculate the topographic index of TOPMODEL based on the analysis of raster DTM data.

Some recent studies showed that the predictions of TOPMODEL are sensitive to the resolution of the DTM used to calculate the map of topographic index [e.g., Wolock and Price, 1994; Zhang and Montgomery, 1994], but that calibration of parameter values can often compensate for a lack of resolution of the DTM [e.g., Bruneau *et al.*, 1995; Quinn *et al.*, 1995; Wolock and McCabe, 1995; Franchini *et al.*, 1996; Saulnier *et al.*, 1997]. This scale dependence is probably true of all distributed models (see discussion of Beven [1989]) but has been investigated most fully for TOPMODEL where, probably as a result of the simplifications inherent in the index-based predictions, the effect is marked.

Within the TOPMODEL framework the form of the index distribution plays two roles [see Beven *et al.*, 1995]. The mean of the distribution λ enters into the calculation of subsurface drainage from the hillslope soils Q_b (for an exponential transmissivity profile) as

$$Q_b = T_0 \exp(-\lambda) \exp(-\bar{S}/m)$$

where T_0 is the transmissivity when the soil is just saturated, m is a parameter controlling the exponential decline of transmissivity with depth, and \bar{S} is a mean catchment storage deficit due to drainage. The magnitude of Q_b will directly affect the value of \bar{S} during a simulation. In the second role the upper tail of the distribution controls the expansion and contraction of the saturated contributing area as the catchment wets and dries

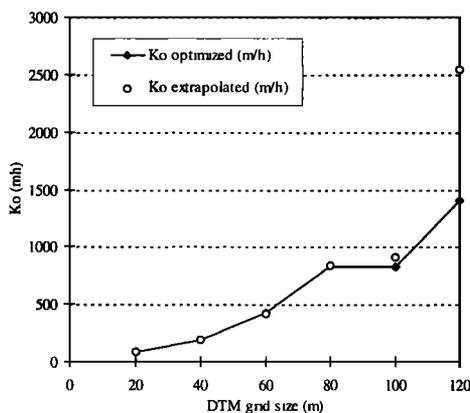


Figure 1. Extrapolated values of Ko for the 40, 60, 80, 100, and 120 m mesh size digital terrain map (DTM) versus independently optimized values of Ko for each DTM (Maurets catchment [Saulnier et al., 1997]).

through the relationship (also for an exponential transmissivity profile):

$$S_i - \bar{S} = m(\lambda - \kappa_i)$$

where S_i is the local value of storage deficit at a point with a topographic index value of κ_i . High values of κ_i will result in S_i values that are at or less than zero, indicating saturation. These roles are interlinked through the dynamic variation in \bar{S} . For the exponential profile, downslope transmissivity is related to a downslope effective saturated hydraulic conductivity at the soil surface approximately as $T_0 = mKo$.

It has been found that, in particular, calibrated downslope saturated conductivity value Ko increases with grid size, compensating for the change in the distribution of κ_i . Franchini et al. [1996] showed that an analytical link could be established between the calibrated value of Ko and the DTM grid size when the topographic index distribution of two DTMs of the same catchment but with different grid sizes are of identical form but shifted along the index axis (the "shift effect"). However, Saulnier et al. [1997] showed that when the DTM grid size increases, the topographic index distribution could also be deformed and that this shape effect could even be a first-order effect in controlling the way the effective conductivity Ko was increasing with the DTM grid size. They then suggested a generalized relation between the effective value of downslope saturated conductivity Ko and the characteristics of the topographic index distribution derived for a particular DTM grid size, taking into account both the shift effect and the shape effect. Figure 1 shows the change in the predicted values of effective conductivity Ko with DTM grid size, given a value for Ko at 20 m in comparison with the independently calibrated values of Ko for each DTM grid size.

Thus some understanding now exists of the sensitivity of the topographic index distribution to the DTM grid scale and the impact on effective parameter values. However, parameters that do not show such scale dependence would be a further improvement, and continued study has revealed that this sensitivity to grid size may, at least in part, result from the way in which channel pixels are handled in the digital terrain analysis.

The problem of calculating the topographic index values for pixels containing a channel has been examined by Quinn et al. [1995]. They proposed a solution to the conflicting require-

ments of a more realistic multidirectional method for hillslopes and a more realistic single-flow algorithm for valley bottoms by making different assumptions for hillslope pixels and channel pixels. For a pixel containing the river, the accumulated area is redistributed downslope to the steepest downslope pixel (single-flow direction algorithm), while accumulated area still continues to be propagated by a multiple-flow directions method as for pixels on hillslopes. Then pixels that contain a river are removed from the DTM and are not used for the calculation of the topographic index distribution [see also Iorgulescu and Jordan, 1995].

However, removing these channel pixels entirely could, in some circumstances, limit the predictive capability of the model as those pixels tend to be the most often saturated and thus the most important for the saturated area runoff generation. The remainder of this note explores the effect of the treatment of channel pixels on TOPMODEL simulations of the Maurets catchment in southern France.

The Maurets Catchment

The Maurets catchment (8.4 km²) used in this study is a subcatchment of the experimental research catchment of the Réal Collobrier (71 km²). It is located in the south of France in the Maures massif at nearly 15 km from the Mediterranean sea coast. The elevation ranges between 209 m at the outlet and 770 m, with an average altitude of about 440 m. A digital terrain map of the Maurets catchment at a resolution of 20 m was prepared by digitizing 10 m contour lines from a 1/25000 map [Weesakul, 1992]. Additional details are given by Saulnier et al. [1997].

Channel Network Identification on the DTM

To demonstrate the effect of channel pixels on the hydrological simulations, it is first necessary to determine the channel network within the DTM. This can be achieved by overlaying the channel network digitized from a map at an appropriate scale. Alternatively, an algorithm for the semiautomatic identification of the channel is required. Both approaches have their limitations; the second approach has been used here. The extraction of channel networks from DTM is a complex problem, as the prediction of the channel head can be difficult [see, e.g., Montgomery and Dietrich, 1989; Tarboton et al., 1991]. The algorithm used here searches first for the channel head and then assumes that the channel can be derived from those river endings using a steepest single-pathway descent method. This is similar to the algorithm suggested by Quinn et al. [1995], except that the channel heads are not identified in the same way. Quinn et al. [1995] assume that a river ending is a pixel with an upslope area that is greater than some threshold value. This threshold coarsely determines the length of the channel network. To this threshold another threshold on the topographic index value has been added. This new threshold gives greater control over the density of the network by allowing channels to start at less (low value of the threshold on the topographic index) or more (high value of the threshold) convergent or shallow hillslope pixels. The two values of the threshold are adjusted to best fit a map of the observed perennial network drawn on a map at the 1/25000 scale of the National Institute of Geography of France. Using this method, networks have been extracted for all grid sizes from 20 m to 100 m.

Structure of the Topographic Index Distribution

As noted above, the use of DTM data with increasing grid size affects the topographic index distribution by a shift effect and a shape effect. In the particular case of the Maurets catchment the shape effect is a first-order effect [Saulnier *et al.*, 1997]. This shape effect comes from the increase in the relative number of pixels with large topographic index values (the upper tail of the distribution). Where upslope areas are allowed to continue to accumulate along the valley bottom, this upper tail of the topographic index distribution is usually dominated by the topographic index value of the pixels in, or near, the channel network, as shown in Figure 2. Figure 2 shows also the values of the topographic index of the pixels near the river which, in the simplest multiple-flow direction method [Quinn *et al.*, 1991; Freeman, 1991], can receive area distributed from upslope from "channel" pixels, even if the pixel does not contain a channel. Thus pixels near the river are also influenced by the choice of the algorithm of calculation of the topographic index of the pixel crossed by a channel. Above a value of 10 on the topographic index, pixels on or near the river represent more than half of the total distribution. This problem gets worse as grid size increases, since it can be shown that the relative number of channel pixels will tend to grow linearly with increasing grid size.

This is an explanation of the linear sensitivity of the predicted saturated area to the DTM grid size, reported by Wolock and Price [1994] and Saulnier *et al.* [1997]. Thus it can be inferred that the sensitivity of the shape of the topographic index distribution to the DTM grid size is primarily due to the topographic index values of pixels that are crossed by a channel that are being overestimated by allowing area to accumulate down the valley axis. In many cases, river width will be small relative to DTM grid size. In such cases, it will be more appropriate to treat pixels crossed by a channel as hillslope pixels rather than channel pixels. There may be some contribution of subsurface from up valley but inclusion of all the up valley accumulated area will generate a bias in the calculated index. A similar argument applies to the slope values used. In the case of a hillslope drained by a channel, the slope of the hillslope toward the channel will control the subsurface drainage more than the down-valley slope [see, e.g., Merot *et al.*, 1995].

Techniques for Calculating the Topographic Index of a Pixel Crossed by a Channel

Two methods of calculation for the pixels crossed by a channel have been tested. In both cases all drainage from up valley is assumed to be transported in the channel, which also acts as a sink for the local hillslope runoff. Hillslope pixels have been treated by the multiple-flow direction algorithm of Quinn *et al.* [1991, 1995]. The first method does not differentiate between the hillslopes of the right and left river bank. The accumulated area is then the sum of the area of the right-hand and left-hand hillslope, spread over twice the channel length since each hillslope is independently drained by the channel. The slope that has been used is the average of the inflow slope from any upslope hillslope pixels (i.e., not crossed by a channel). The second method is similar, except that the right and left hillslope are now differentiated, using the actual upslope areas and inflow slopes separately. As two topographic index values are calculated here for a single pixel, these two values are given half the weight of a hillslope single topographic index value in

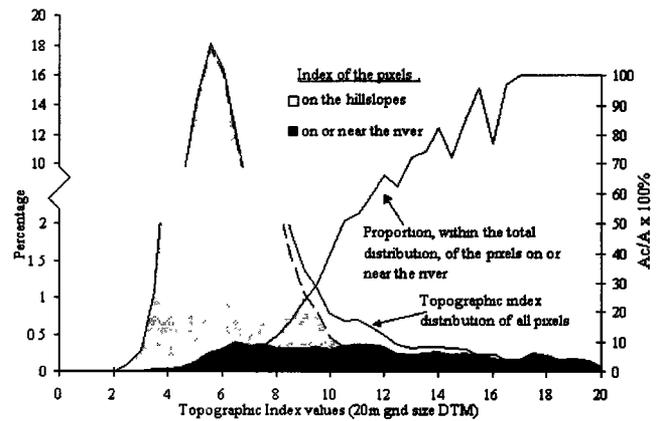


Figure 2. Position, within the total topographic index distribution, of the topographic index values of the pixel that are on or near the river.

the topographic index distribution. It was found that the results from both methods were very similar in the Maurets catchment, so that only the results of the first are examined in detail here. Other catchments may show a greater difference between the two methods.

Application to the Maurets Catchment

The two methods have been first tested on the 20 m grid size DTM of the Maurets catchment. The two new topographic index distributions look much more like the topographic index distribution of hillslope pixels. The upper tail of the distribution is now much reduced. The map of the topographic index is also sensitive to this change (Figure 3). It can be seen that the highest values of the topographic index in the valley bottom have been removed. Another point to observe, for example, within the square outline in Figure 3 is that areas of high values of topographic index can appear more disconnected. That was not the case in the initial map of the topographic index, where a large proportion of the predicted saturated area is in the continuous valley bottom, because of the propagating accumulated area. This phenomenon of saturated, but disconnected, contributing area could have an influence on the hydrological behavior, as suggested by Bazemore *et al.* [1994] and Cosandey [1994].

Figure 4 shows the results of applying the new technique to the range of DTM grid sizes from 20 to 100 m. It is clear that there is still a tendency for larger grid sizes to result in a shift of the topographic index distributions to larger values. However, the relative number of pixels with large index values no longer increases with grid size and even tends to decrease. This can be explained by the fact that the slopes that are now used are the average inflow slopes. When DTM grid size increases, these slopes are calculated using higher and higher points on the hillslope. Values of $\tan\beta$ will then tend to increase, resulting in a decrease in the topographic index values for pixels crossed by a channel.

Effects in Terms of Hydrological Simulations

TOPMODEL has been calibrated to rainfall-runoff data for the Maurets catchment using the different topographic index distributions for the different grid sizes and different methods of handling channel pixels. The version of TOPMODEL used

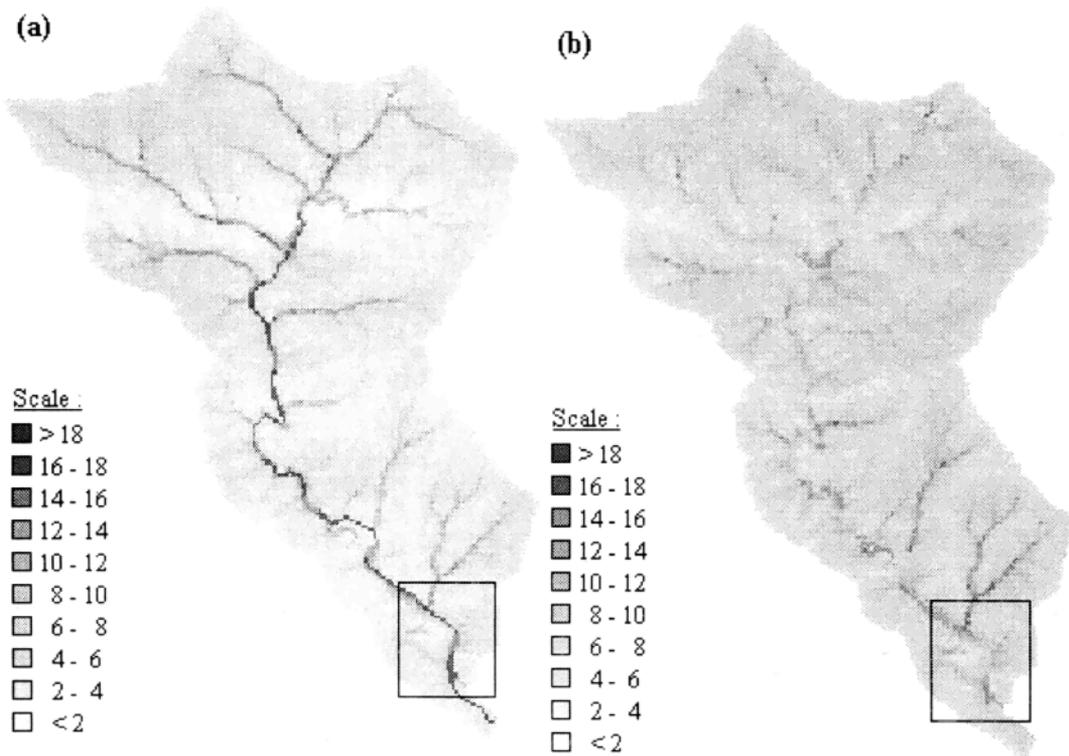


Figure 3. Comparison between (a) the initial map of the topographic index map and (b) the map calculated by taking into account the river network.

here is an event-based version, considering homogenous soils all over the catchment, with four parameters calibrated by a full exploration of a discretized parameter space. Additional details of the model structure, sample of storms, and calibration technique are given by *Saulnier et al.* [1997]. A sensitivity analysis of the calibrated values showed that the effective saturated conductivity K_o is still the parameter that compensates for increasing DTM grid size. However, a very important result is that saturated conductivity does not need to be increased nearly so much to achieve this compensation as shown in Table 1 and Figure 5, which compare the optimized saturated conductivity values for each DTM grid size for each method of handling channel pixels (values of the efficiency measure of *Nash and Sutcliffe* [1970] are given in parentheses).

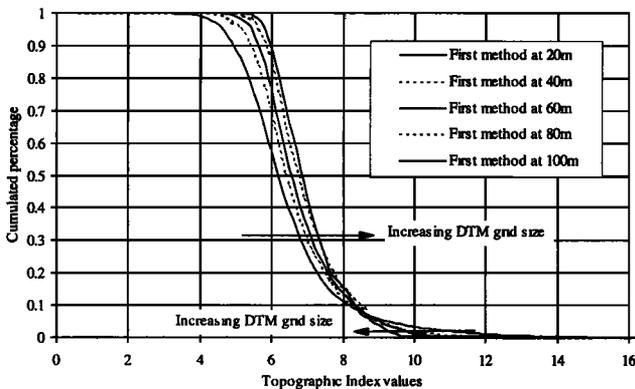


Figure 4. Sensitivity of the new topographic index distribution to the DTM grid size.

Discussion and Conclusions

Trying to be more consistent with the TOPMODEL assumptions and considering that for grid size of most available DTMs (≈ 20 m or greater) a pixel crossed by a channel is more a hillslope pixel than a pure river pixel, three modifications have been suggested to modify the calculation of the topographic index of the pixel crossed by a river. The first modification is the nonpropagation of the accumulated area once it has reached a pixel crossed by a channel. The second modification is the use of a weighted average inflow slope instead of the outflow slope for pixels crossed by a channel. Finally, right and

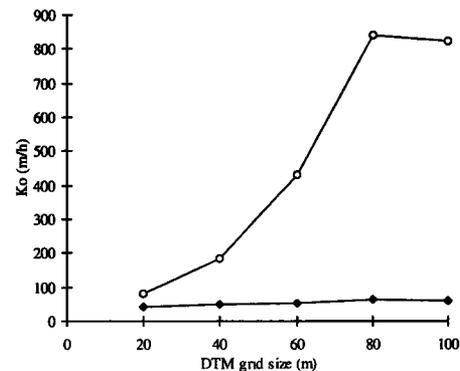


Figure 5. Optimized saturated conductivity for each DTM grid size, taking or not taking into account the river network pixels in the calculation of the topographic index. Circles indicate area allowed to accumulate down valley; diamonds indicate new treatment of river pixels.

Table 1. Optimized Saturated Conductivity for Each DTM Grid Size, Taking and Not Taking into Account the River Network in the Calculation of the Topographic Index

	DTM Grid Size, m				
	20	40	60	80	100
<i>K_o</i> , m/h optimized without taking account of the river	82 (0.83)	184 (0.83)	432 (0.83)	840 (0.83)	822 (0.83)
<i>K_o</i> , m/h optimized taking account of the river	42 (0.83)	48 (0.83)	54 (0.83)	62 (0.83)	60 (0.83)

Note that the values represent downslope hydraulic conductivities just at the soil surface, scaling a profile that is assumed to decline exponentially with depth. Values of the efficiency measure of *Nash and Sutcliffe* [1970] are given in parentheses.

left river banks may be differentiated by attributing a different topographic index value for each bank.

A comparison of the different analyses for the Maurets catchment suggests that the main effect is the nonpropagation of the accumulated area. The most significant result of this study is that the new index distribution calculation results in greatly reduced sensitivity of calibrated hydraulic conductivity values to the grid scale, resulting from a much more stable estimate of the upper tail of the index distribution with increasing grid size. This might allow the use of larger DTM grid size, keeping the same realistic simulation of saturated contributing areas as the DTM grid size changes.

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