XVIII International Conference on Water Resources
CMWR 2010
J. Carrera (Ed)

INFLUENCE OF SPATIAL RESOLUTION ON THE DISTRIBUTED SURFACE ROUTING RESPONSE OF THE DES ANGLAIS RIVER BASIN (CANADA)

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Key words: DEM analysis, grid resolution, surface–subsurface hydrology, discharge

Summary. Digital elevation models (DEMs) at different resolutions (180, 360, and 720 m) are used to examine the impact of different levels of landscape representation on the hydrological response of the des Anglais river basin (Canada). Frequency distributions of local slope, plan curvature, and drainage area are calculated for each grid size resolution. This landscape analysis reveals that DEM grid size significantly affects computed topographic attributes which in turn explain some of the differences in the hydrological simulations. The investigation is carried out by analyzing the main hydrograph features (peak flow, time to peak, and total volume) at the main outlet of the catchment over-3-year simulation period. The simulation results, generated with the surface routing module of a coupled surface–subsurface model, indicate that time to peak decreases as grid resolution is coarsened due to a decrease in flow path lengths, that peak flows increase as grid resolution is refined due to an increase in local slopes, and that the simulated runoff volumes increase at coarser grid resolution due to the aggregation of cells at the border of the catchment.

1 INTRODUCTION

Distributed-parameter models using physically realistic, process-based equations are useful tools for simulating the spatial variability of surface–subsurface catchment processes [1,2]. The results of such models are useful in studies of hydrogeomorphology and solute transport processes and in the assessment of the event and pre-event hydrograph components and baseflow residence times.

The use of process-based distributed-parameter models, however, raises issues related to gridding options and the appropriate representation of physical parameters[3]. For instance,[4] showed that while adding complexity in model parameterization is beneficial and justified to accurately simulate distributed state variables such as soil moisture, the added complexity does not result in significantly improved predictions of runoff. [5] demonstrated that parameterization approaches having differing abilities to incorporate small-scale variability do not only influence the hydrograph at the main outlet, but also the simulated production of overland flow within the catchment. [6] addressed the issue of uniqueness (i.e., the set of parameter values estimated from a given set of observations must also represent the observed behavior for other hydrologic conditions) for both integrated (e.g., discharge) and distributed (e.g., piezometric) predictions and also underlined how the skill of a physically-based model in predicting outlet discharge does not necessarily imply accuracy in capturing physical processes within the catchment.

Although the increasing availability of digital elevation models (DEMs) allows rapid analysis of topographic attributes over even large drainage basins, the effects of DEM grid size on land surface representation and hydrological simulation results have not been examined systematically. In this study, we analyze the impact of DEM resolution on the predictions of a distributed process–based hydrological model for the des Anglais river basin located in southwestern Quebec. First, we present a terrain analysis based on frequency distributions of local slope, plan curvature, and drainage area for DEMs of resolution of 180, 360, and 720 m. We then examine the hydrological impacts of grid size on the surface routing component of the model, focusing in particular on the main hydrograph features (peak flow, time to peak, and total volume) at the main outlet of the catchment.

2 Study area

The des Anglais river basin has a drainage area of 690 km^2 and an average discharge of 300 $\times 10^6$ m^3 per year at its outlet. It is the largest sub-catchment of the transboundary Chateauguay River watershed, and has an elevation range from 30 m to 400 m (Figure 1. The Chateauguay basin constitutes the northern part of the Adirondack mountain range and initiates the physiographical region of the St. Lawrence Platform. The soils are characterized as mainly weathered Quaternary sediments[7], with the exception of bogs and swamps that overlie Champlain sea sediments in the northeastern part of the catchment. These wetlands correspond to closed depressions with a thick accumulation of organic material.

The study area belongs to the Great Lakes and St. Lawrence climate region, characterized by a semi-humid climate with cold winters and humid summers. The annual mean temperature is 6.3 °C, with monthly variations from -10 °C in Jan to 20 °C in Jul[8]. These temperatures result in frost conditions from mid-Nov to the end of Mar. The average annual precipitation is 958 mm, relatively uniformly distributed within the watershed, with snowfall prevalent from Dec to Mar when temperatures are below 0 °C.

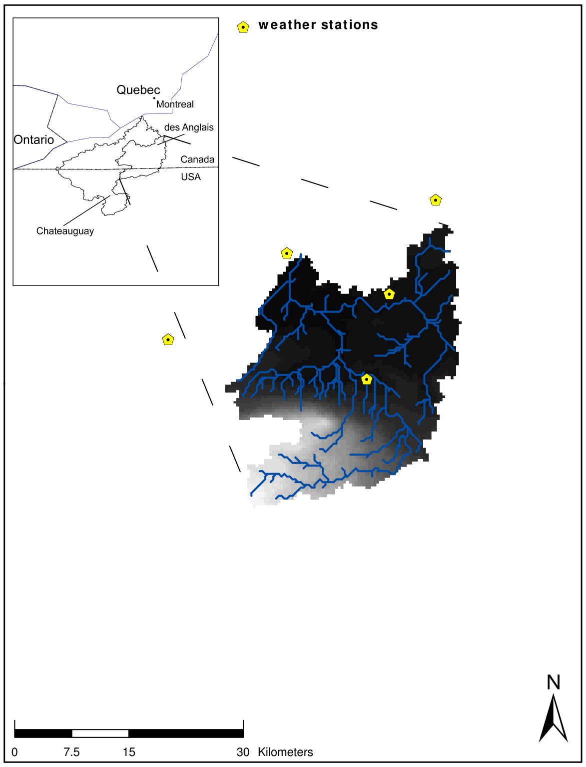

Figure 1: Topographic map of the des Anglais catchment at 360 m resolution (highest elevations in light grey) showing the network of weather stations.

3 Hydrological model

CATHY (CATchment Hydrology) is a coupled physically-based spatially-distributed model for surface–subsurface simulations[9]. The model is based on resolution of a one-dimensional diffusion wave approximation of the Saint-Venant equation for overland and channel routing nested within a solver for the three-dimensional equation for subsurface flow in variably saturated porous media (i.e., Richards equation). The routing scheme derives from a discretization of the kinematic wave equation based on the Muskingum-Cunge or matched artificial dispersivity method. Surface runoff is propagated through a 1D drainage network of rivulets and channels automatically extracted by a DEM–based pre-processor and characterized using hydraulic geometry scaling relationships. The distinction between overland and channel flow regimes is made using threshold-type relationships based on, for instance, upstream drainage area criteria. Lakes and other topographic depressions are identified and specially treated as part of the DEM pre-processing procedure. The subsurface solver is based on Galerkin finite elements in space, a weighted finite difference scheme in time, and linearization via Newton or Picard iteration.

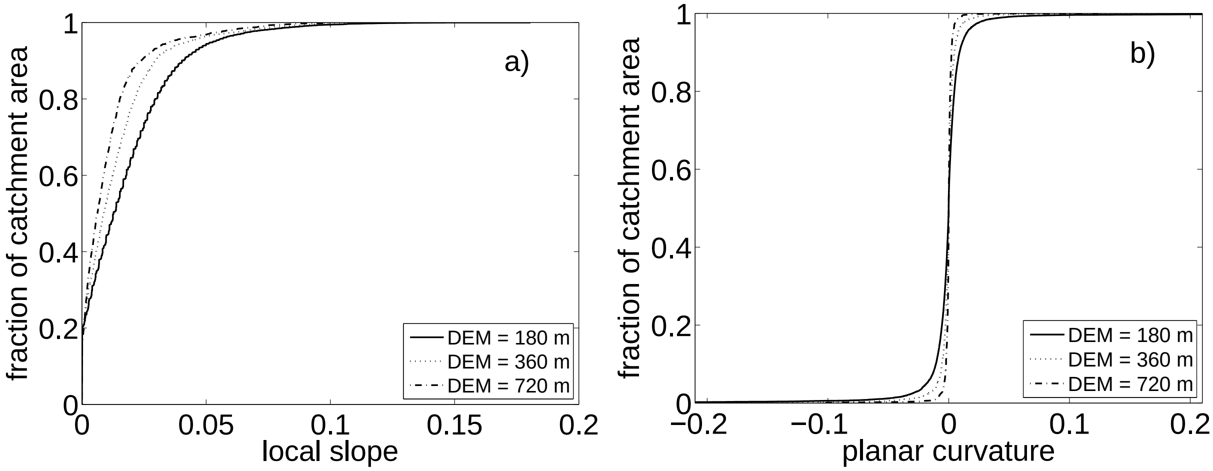

Figure 2: Cumulative frequency distributions of slope (a) and plan curvature (b).

4 Landscape representation

Cumulative frequency distributions of local slope, plan curvature, and drainage area determined for each grid size DEM reflect changes in both mean and local values. A comparison of the distributions of these topographic attributes allows direct assessment of the influence of grid size on landscape representation, and will inform the analysis of these impacts that will be conducted through model simulations.

4.1 Slope, plan curvature, and drainage area

As illustrated in Figure 2a, cumulative slope distributions are sensitive to DEM grid size. Indeed, the percent of the catchment steeper than a given slope systematically decreases as the DEM grid size increases, and the mean slope declines from 0.18×10^{-1} for the 180 m grid size to 0.10×10^{-1} for the 720 m case. Moreover, since the slope of a grid cell represents an average slope for the area covered by the cell, increasing the DEM grid size should particularly result in a decreasing ability to resolve the slope characteristics for those portions of the catchment with steeper and more dissected topography.

Figure 2b shows that a larger grid size results in a smaller spectrum of plan curvature. Plan curvature measures topographic convergence and divergence and hence the property of water to converge as it flows across the land. Thus, the aggregation process for this topographic attribute will likely produce higher values and less variability in spatially distributed hydrologic predictions such as moisture content.

The cumulative frequency distributions for drainage area are evaluated separately for hillsope and channel cells in Figure 3. As can be seen, grid size effects are smaller for larger drainage areas, in other words where runoff hydrographs are dominated by channel routing. More significant effects are encountered at the small hillslope scale, where Fig-

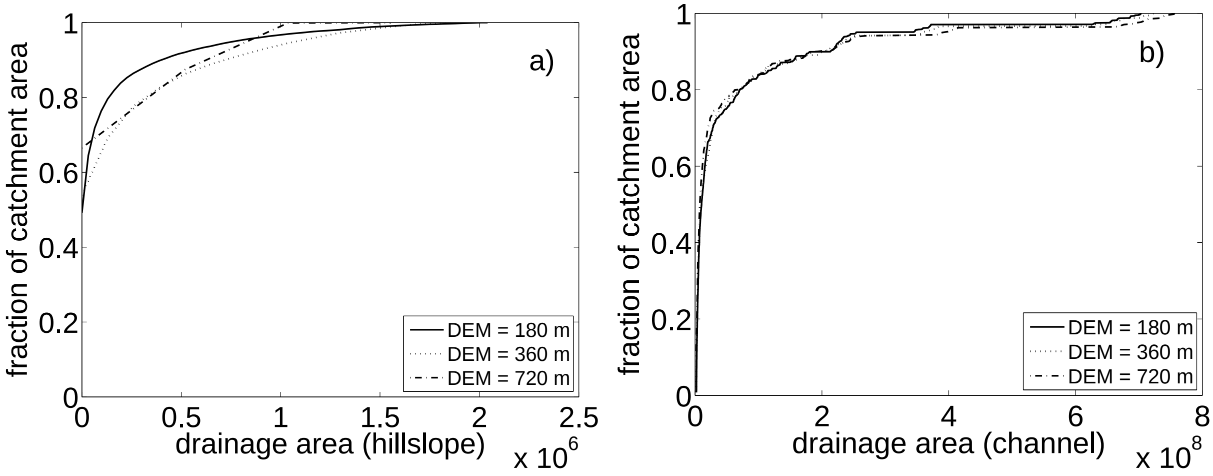

Figure 3: Cumulative frequency distributions of the drainage area for hillslope (a) and channel cells (b).

ure 3a shows that larger grid sizes lead to bias in favor of larger contributing areas. It is important to note that when the distinction between overland and channel cells is made using threshold-type relationships based on upstream drainage area, DEM resolution will also influence the partitioning between overland and channel cells, with a proportionately larger fraction of overland cells as the grid is refined.

5 Hydrologic simulations

To evaluate grid size effects on storm runoff, the surface routing scheme of the CATHY model was applied to the drainage networks extracted at each grid resolution. For each of the three DEMs, the channel cells were identified from each DEM of the catchment using an upstream drainage area threshold of 2.0 km^2, based on visual similarity between the extracted network and the river network depicted on topographic maps. Structural parameters for the channel and overland flow networks were calibrated using, for channel dynamics, the bankfull discharge measured at the main streamflow station as a reference value for the flow rate, and for overland (rivulet flow) dynamics, values reported in literature studies as a basis[10]. Model calibration was carried out for a single resolution (360 m, base configuration) and the calibrated set of parameters were then transferred to the other model resolutions.

5.1 Analysis of the catchment hydrographs

CATHY was applied at each DEM resolution for a 3-year simulation period from October 2002 to October 2005, where daily precipitation series were provided by five weather gauges located within or near the catchment (Figure 1). These time series were spatially distributed over the CATHY computational grid nodes through the inverse distance weighting method. This simulation period included a wide range of storm intensities and

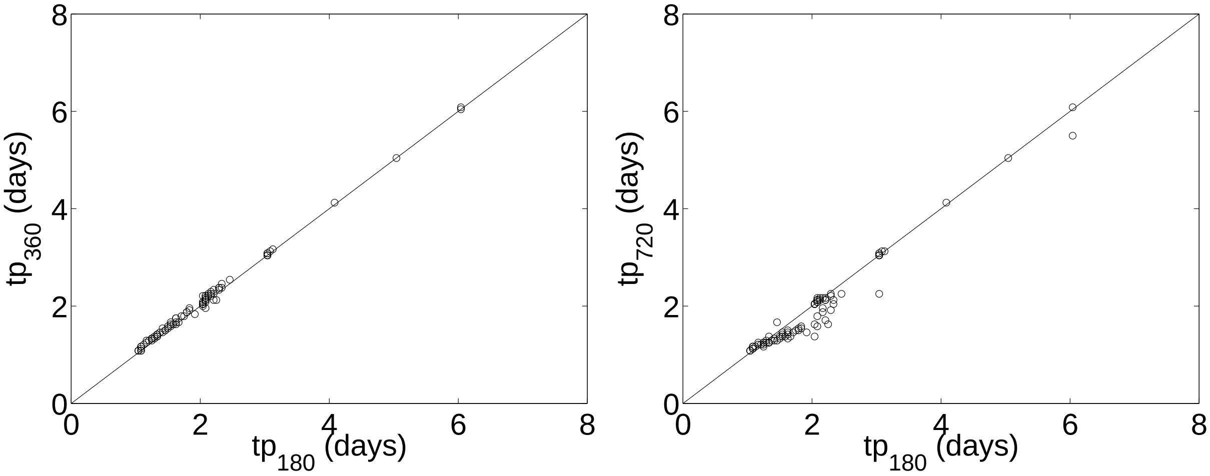

Figure 4: Scatter plots between time to peak at 180 m and 360 m (left) and at 180 m and 720 m (right) resolution.

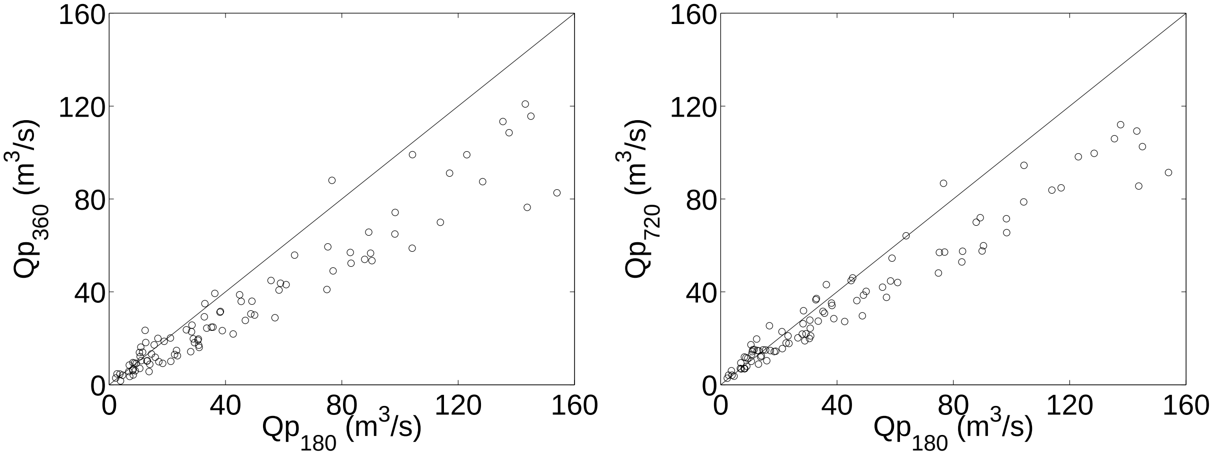

Figure 5: Scatter plots between peak flows at 180 m and 360 m (left) and at 180 m and 720 m (right) resolution.

some extended wet and dry periods. For each rainfall event we recorded the peak discharge (Q_p), the time to peak (t_p), and the total runoff volume (V) from the simulated hydrographs.

As illustrated in Figure 4, the times to peak decrease as the grid resolution is coarsened. This is probably due to the shortening of overland and channel flow paths as the number of model elements decreases. Indeed, the maximum upstream path length from the outlet of the catchment experiences a decrease of 13% from coarse to fine DEM resolution.

In Figures 5 and 6 we compare the peak discharge and the total runoff volume between

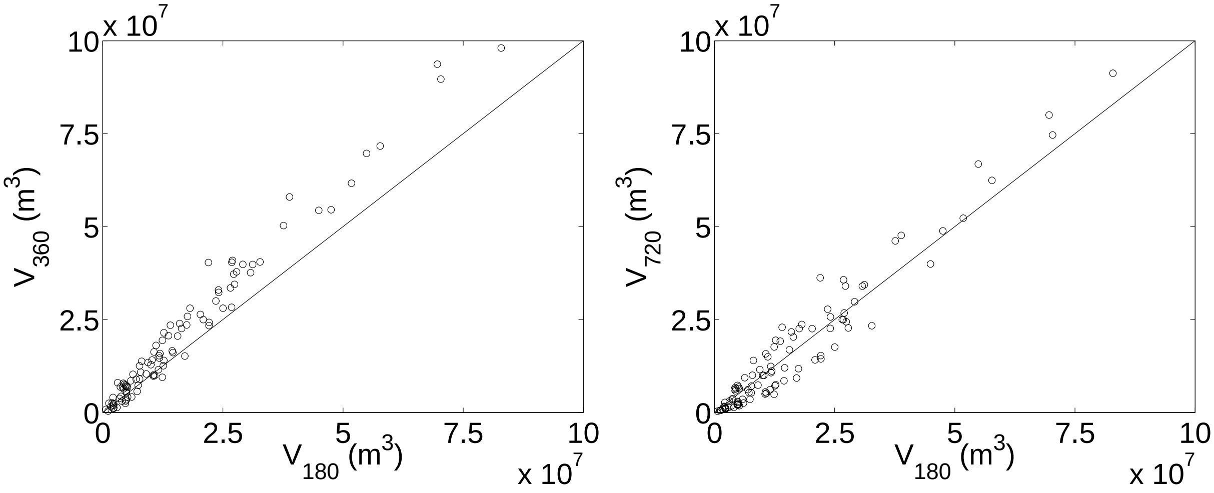

Figure 6: Scatter plots between total runoff volume at 180 m and 360 m (left) and at 180 m and 720 m (right) resolution.

the fine (180 m) and coarser resolutions (360 m and 720 m). For the hydrograph peaks, observable differences can be detected for those storm events characterized by higher flow rates, with the finest DEM resolution producing higher values. This is can be attributed to the higher local slopes obtained at the finest resolution. The comparison in Figure 6 shows that at larger DEM resolutions the model systematically simulates larger runoff volumes. This is mainly related to the increase of the total drainage area of the catchment through the aggregation process at the border cells of the DEM.

6 Conclusions

This paper presents an investigation of the influence of spatial resolution (i.e., DEM grid size) on hydrological catchment response. The analysis was carried out by running the surface routing module of the CATHY model to the case of the des Anglais river basin located in southwestern Quebec. An analysis of landscape representation at different DEM grid sizes showed a significant variation of topographic attributes at different level of resolution. In particular, a coarsening of grid resolution causes a decrease both in local slopes and in the range of plan curvature values, and larger contributing areas at the hillslope scale. As the DEM is coarsened, the hydrological model simulations produce a decrease in the times to peak due to the shortening of flow paths and a decrease in peak flows caused by milder local slopes. A further step of this analysis will consist in running the CATHY model in coupled mode to investigate the effects of grid size on the surface–subsurface interactions and spatially distributed state variables.

REFERENCES

[1] J. E. VanderKwaak and K. Loague. Hydrologic-response simulation for the R-5 catchment with a comprehensive physics-based model. *Water Resour. Res.*, **37(4)**, 999–1013, (2001).

[2] J. P. Jones, E. A. Sudicky, and R. G. McLaren. Application of a fully-integrated surface–subsurface flow model at the watershed-scale: A case study. *Water Resour. Res.*, **44**, doi:10.1029/2006WR005603, (2008).

[3] R. B. Grayson, I. D. Moore, and T. A. McMahon. Physically based hydrologic modeling 2. Is the concept realistic? *Water Resour. Res.*, **26(10)**, 2659–2666, (1992).

[4] C. W. Downer and F. L. Ogden. Appropriate vertical discretization of Richards' equation for two-dimensional watershed-scale modelling. *Hydrol. Process.*, **18**, 1–22, (2004).

[5] E. N. Mueller, J. Wainwright, and A. J. Parsons. Impact of connectivity on the modeling of overland flow within semiarid shrubland environments. *Water Resour. Res.*, **43**, W09412, doi:10.1029/2006WR005006, (2007).

[6] B. A. Ebel, K. Loague, D. Montgomery, and W. E. Dietrich. Physics-based continuous simulation of long-term near-surface hydrologic response for the Coos Bay experimental catchment. *Water Resour. Res.*, **44**, W07417, doi:10.1029/2007WR006442, (2008).

[7] L. Lamontagne. Base de données sur les propriétés physiques des sols du bassin versant de la rivière Châteauguay. Pedology and Precision Agriculture Laboratories, Agriculture and Agri-Food Canada, QC, CD-Rom., (2005).

[8] Environment Canada. Canadian Daily Climate Data (CDCD). http://climate.weatheroffice.ec.gc.ca, (2004).

[9] M. Camporese, C. Paniconi, M. Putti, and S. Orlandini. Surface–subsurface flow modeling with path-based routing, boundary condition-based coupling, and assimilation of multisource observation data. *Water Resour. Res.*, **46**, W02512, doi:10.1029/2008WR007536, (2010).

[10] A. D. Abrahams, G. Li, and A. J. Parsons. Rill hydraulics on semiarid hillslopes, southern Arizona. *Earth Surf. Proc. Land.*, **21(1)**, 35–47, (1994).