Sensitivity of topographic slope and modeled watershed soil loss to DEM resolution

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Abstract A Digital Elevation Model (DEM) is a critical component for the parameterization of process-based watershed models. The influence of DEM resolution on runoff or water quality outputs is frequently ignored within watershed modeling studies. This research focuses on the effects of varying spatial DEM resolution on the determination of slope and how this can influence sediment yield estimates within a process-based watershed model. The 784 ha Thomas Brook watershed in Nova Scotia, Canada was used as a case study. The grid spacing of a LiDAR derived DEM was created at 1, 5, 10 and 20 meters and used to generate slope maps and predicted sediment loss with the Soil and Water Assessment Tool (SWAT). It was found that the occurrence of steep slopes increased in fine spatial resolution DEMs while predicted sediment loss decreased.

Keywords: LiDAR, DEM, Watershed Model, Sediment Yield, Spatial Resolution

INTRODUCTION

A Digital Elevation Model (DEM) is typically a required initial input for watershed modeling. The DEM provides a representation of the surface topography which is used to determine terrain properties such as slope and aspect. These terrain parameters will control watershed attributes such as extent, sub-basin locations, stream network topology, and ultimately hydrological outputs such as water yield, hydrograph timing and water quality. The DEM input is usually a regularly spaced horizontal grid of elevation values which are interpolated from irregularly spaced elevation observations. The appropriate horizontal grid spacing (spatial resolution) can be difficult to determine quantitatively. Ideally, a dense horizontal grid is desired which will accurately describe the true physical terrain. However, the appropriate spacing is often confined by the density and accuracy of the originally observed data, and limitations of computing resources. Typically, the DEM grid is not created at resolutions lower than the approximate spacing of the raw data, as the gridded values can contain large interpolation errors.

DEM resolution influences topographic parameters such as slope and aspect (Chang and Tsai, 1991, Kienzle, 2004) and has been shown to affect watershed model outputs (Cotter *et al*., 2003, Wechsler, 2006, Dixon and Earles, 2009). Hopkinson *et al*. (2010) demonstrated that at the grid node scale, DEM resolution altered surface area and energy balance calculations, while at the basin-scale it influenced runoff timing. Most studies on the effect of DEM resolution on watershed models have focused on large watersheds constructed with DEMs in which the finest spatial resolution was no less than 30 meters. Current remote sensing technology such as LiDAR (Light Detection and Ranging), IFSAR (Interferometric SAR), and photogrammetry are able to sample elevation at sub-meter spacing which can produce accurate DEMs with spatial resolution at the 1 meter level. To date, few studies have quantified the gain in watershed model accuracy that results from using fine resolution DEMs. Zhao, *et al*. (2009) used hydrologic parameters derived from a 1 m and 10 m LiDAR DEM to model only soil loss with the Revised Universal Soil Loss Equation (RUSLE). It was found that results were significantly improved using the higher resolution LiDAR DEM.

This study quantifies the influence of a fine scale DEM on topographic slope calculations and the prediction of sediment output produced by the Soil and Water Assessment Tool (SWAT). This will facilitate both improved understanding of DEM data capabilities and optimization of elevation acquisition operations to meet particular watershed modeling requirements. The test site for the analysis is the Thomas Brook Watershed located in the Annapolis Valley of Nova Scotia, Canada. The Thomas Brook Watershed is an agricultural watershed covering an area of 784 hectares. The watershed is well-studied and is a part of Agriculture and Agri-Food Canada's WEBS (Watershed Evaluation of Beneficial Management Practices) program. Consequently, several years of in situ monitoring data are available for the calibration and verification of the watershed model. In addition, the Applied Geomatics Research Group (AGRG) surveyed the site with LiDAR during the summer of 2006. The survey covered an area of 26 km^2 and the raw point spacing was less than one metre.

BACKGROUND

Soil and Water Assessment Tool

The Soil and Water Assessment Tool (SWAT) is a physically based watershed model designed for water resource and water quality simulations. The model requires several data inputs within a Geographic Information System (GIS), which at a minimum include a DEM, land use and soil coverage. The SWAT divides the watershed into several sub-basins which are based on the flow accumulation and stream network within the watershed. The model further characterizes several HRUs (Hydrologic Response Units) within each sub basin that share similar land use, soil and slope characteristics. The determination of slopes throughout the watershed from the DEM is a critical component to characterize the HRUs.

Light Detection and Ranging

Airborne Light Detection and Ranging (LiDAR) is an active remote sensing system that exploits the use of laser technology to measure ranges from a moving aircraft platform to the Earth's surface. Laser ranges are combined with Global Positioning System (GPS) technology to provide aircraft position, an Inertial Measurement Unit (IMU) to provide sensor orientation and a laser scanner to direct the laser pulse across a swath beneath the aircraft. Contemporary lasers are capable of producing individual pulses at rates exceeding 200 kHz, which allow LiDAR systems to observe and record a dense (sub-metre) sample of surface elevations, thus allowing for the creation of DEMs with spatial resolutions at the metre level. In addition to dense point spacing, LiDAR also has the capability of achieving sub-decimeter accuracy. The combination of point density and accuracy typically surpasses competing remote sensing technologies, such as traditional surveying, photogrammetry and Interferometric SAR (InSAR).

METHODOLOGY

A high resolution LiDAR dataset was used to generate the various DEMs at grid cell resolutions of 1, 5, 10 and 20 meters. Raw LiDAR observations initially include observations from objects upon the earth's surface such as trees and buildings. However, for terrain surface analyses all objects above the true ground surface need to be removed. Prior to generating the DEMs, the LiDAR observations were filtered to remove non-ground objects. This was performed in the TerraScan© software package. A description of the basic ground classification procedure for raw LiDAR point observations can be found in Axelsson (2000). Once non-ground returns were filtered out, each DEM grid node was interpolated from the remaining ground-level elevations using an inverse distance weighted (IDW) routine. The interpolation routine determines the value at a grid node through a linear weighted combination of surrounding elevations (Maune, 2007). The weights are inversely proportional to the distance an observation is from the grid node. For watershed stream network delineation, the DEM is typically pre-processed to eliminate depressions as described in Jensen and Dominigue (1988). Such DEM pre-processing was not performed here as it acted to modify the terrain slope attributes of interest in this study. Instead, the Thomas Brook stream network was manually verified to ensure accurate topology.

Each DEM was input to ARCSWAT, an extension of SWAT to the ARCGIS platform. To ensure results were only influenced by the variation in spatial resolution and not variations in simulated watershed area, the same watershed delineation was used throughout. The slope values within each DEM were calculated using Horn's algorithm (Horn, 1981) which is integrated into the ARCGIS platform. This produced raster representation of the slopes within the watershed. This was then used to determine the percentage of the watershed which was within five different slope classes, namely 0-2°, 2-4°, 4-8°, 8-15° and 15 – 90°. Publically available soils data, as well as land use information, were integrated with the slope information to produce the HRUs. Local precipitation and crop management and rotation information for agricultural land use areas were entered for a twenty year simulation period. The SWAT simulation was run for 15 years to initialize the model. Model outputs for the last five years of twenty year simulation period were exported and analyzed on a monthly time scale.

RESULTS

In Table 1, decreasing DEM resolution is accompanied by decreases in slope mean, maximum and standard deviation. Maximum slope in the 20 m DEM is less than half that of the 1 m DEM. This indicates that within areas of high relief, terrain slope is underestimated in the coarse DEM, which is consistent with previous studies such as Zhao et al. (2009).

Table 1. Summary statistics of the percentage of the Thomas Brook watershed which fell into the five slope classes.

Slope	1 m	2 m	5 m	10 m	20 m
Mean (°)	5.0	4.6	4.2	3.9	3.6
St. Dev (°)	6.0	5.7	5.2	4.8	4.3
Min (°)	0	0	0	0	0
Max (°)	73.8	61.4	45.8	42.1	35.6

Slope is a critical parameter in the Modified Universal Soil Loss Equation (Williams, 1995) used to model soil erosion in SWAT. The dependency of this formulation on slope combined with the demonstrated variability of slope with spatial resolution indicates that this simulated quantity is also sensitive to changes in spatial resolution. Figure 1 illustrates the difference in sediment loss at the watershed outlet simulated at each resolution.

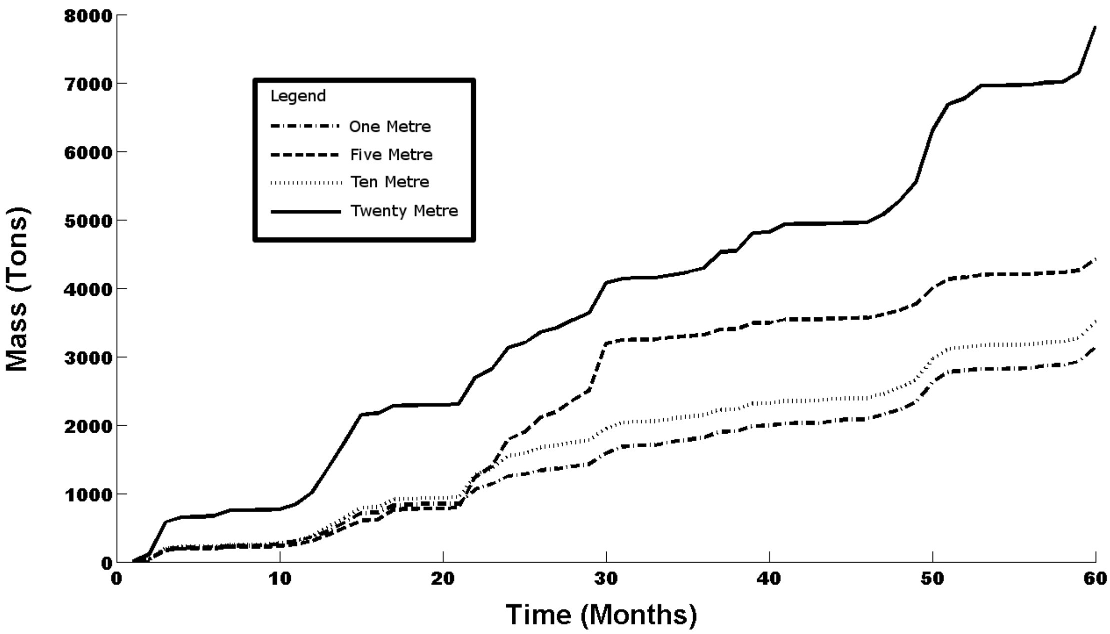

Figure 1. Five years of cumulative simulated soil loss as influenced by DEM spatial resolution.

Figure 1 demonstrates that as DEM grid cell spacing decreases the mass of sediment predicted at the watershed outlet tends to decrease. The 20 m DEM displayed cumulative sediment outputs which were generally more than double the values produced from the 10m DEM. The steeper slopes observed in the fine resolution DEM are generally expected to result in increased sediment loss but this is contrary to the outputs produced in Figure 1. This phenomenon is due to the increased slope lengths inherent to the coarse DEM. Although higher slope values exist within the fine spatial resolution DEM, they do not persist for lengthy horizontal distances and areas of level ground with minimal soil loss are also better characterized. The moderate slopes of the coarse DEM exist over prolonged horizontal distances which result in greater soil loss predictions. For most of the observed time period, the difference in soil loss between the fine spatial resolution DEMs (1, 5 and 10 m) showed minimal deviation. This indicates a 10 m DEM may be sufficient for this particular watershed.

At approximately the third year of the simulation period (months 22-30) an anomalous trend appears in which the highest rate of sediment output was associated with the 5 m DEM. Although there is a general trend of increased soil loss associated with the coarse resolution DEMs, the anomaly in this simulation period indicates that finer resolution DEMs can occasionally exhibit greater predicted soil loss. This is potentially caused by a particularly erosive portion of the crop management cycle in an area of the watershed in which the 5 m DEM accurately characterized the steep slopes, but did not characterize the level areas well, causing more extreme predictions of soil loss. However, several of the sub-basins experiencing increased soil loss possessed mostly non-agricultural land covers such as forest. This suggests that modeling steps other than land use parameterisation are also affecting the non-linear scaling behaviour between DEM resolution and sediment loss predictions. In order to identify the parameter or algorithm within SWAT that is affecting this particular soil loss anomaly, an in depth analysis of individual HRUs within each sub-basin is needed. This analysis is outside the scope of the present study but is part of ongoing investigations.

The variations in predicted sediment outputs will have significant impact on the calibration of the watershed model. Calibrating the model through statistical comparisons with in-situ data as described in Neitsch et al. (2000) will lead to unique calibration values for each spatial resolution DEM. This is potentially due to the inherent scale associated with utilizing the MUSLE, originally designed for a unit plot (22.1 meters in length and 9 percent slope). Applying it at a scale arbitrarily defined by the spatial resolution of the DEM requires an independent calibration. Therefore, caution should be exercised when applying calibration parameters determined with a DEM at one spatial resolution to a watershed model with a different spatial resolution DEM.

CONCLUSION

From this analysis it can be concluded that a DEM created with a coarse spatial resolution (20 m) will not characterize steep slopes which are represented in a fine spatial resolution DEM (1 m). When modelling watershed environments which contain steep slopes with SWAT, this will lead to discrepancies in the predicted outputs. The outputs associated with sediment transport will be particularly affected due to their strong dependence on the slope of the landscape. In general, a coarse spatial resolution DEM will produce larger predictions of soil loss than fine spatial resolution DEM. The increase is potentially caused by longer slope lengths of the coarse DEM cells which serve to enlarge soil loss predictions of the MUSLE. Due to the variation of predicted sediment output with DEM spatial resolution, calibrated model parameters determined from a DEM with a fine resolution cannot be transferred to DEMs with a different resolution. Future work will focus on quantifying the errors in agricultural watershed hydrological outputs due to DEM attribute representations by performing sensitivity analyses with the SWAT model.

REFERENCES

Axelsson, P. (1999). Processing of laser scanning data – algorithms and applications. *International Journal of Photogrammetry and Remote Sensing*. **54** (2-3), 138-147

Chang, K. and Tsai, B. (1991). The Effect of DEM Resolution on Slope and Aspect Mapping. *Cartography and Geographic Information Systems*. **18**, 69-77

Cotter, A.S., Chaubey, I., Costello, T.A., Soerens, T.S., Nelson, M.A. (2003) Water Quality Model Output Uncertainty as Affected by Spatial Resolution of Input Data. *Journal of the American Water Resources Association (JAWRA)*. **39** (4), 977-986

Dixon, B. and Earls, J. (2009) Resample or not?! Effects of Resolution of DEMs in Watershed Modeling. *Hydrol.Proc.* **23** (12), 1714- 1724.

Hopkinson, C., Chasmer, L., Munro, S. & Demuth, M. (2010) The influence of DEM resolution on simulated solar radiation-induced glacier melt. *Hydrol. Proc.* **24**, 775-788.

Horn, B.K.P. (1981) Hill Shading and the Reflectance Map. *Proceedings of the IEEE* **69** (1), 14-47.

Jensen S.K., Domingue, J.O. (1988). Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogrammetric Engineering & Remote Sensing*. **54** (11), 1593-600

Kienzle, S. (2004). The effect of DEM raster resolution on first order, second order and compound terrain derivatives, *Transactions in GIS*, **8** (1), 83-111.

Maune, D.F. (2007) *Digital Elevation Model Technologies and Applications: The DEM User's Manual*. American Society for Photogrammetry and Remote Sensing, Chapter 1, pg. 10.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R. (2000). *Soil and Water Assessment Tool User's Manual*. Blackland Research Centre, Temple, Texas.

Wechsler,S. (2007) Uncertainties associated with digital elevation models : a review. *Hydrology and Earth System Sciences*, **11** (4), 1481

Williams, J.R. (1995). Chapter 25: The EPIC model. p. 909-1000. In: V.P. Singh (ed.) *Computer Models of Watershed Hydrology*. Water Resources Publications, Highlands Ranch, CO.

Zhao, Z., Benoy, G., Chow, T.L., Rees, H.W., Daigle, J.L., Meng, F. (2009) Impacts of Accuracy and Resolution of Conventional and LiDAR Based DEMs on Parameters Used in Hydrological Modelling. *Water Resource Management*. **24**, 1363-1380.