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What is the effect of LiDAR-derived DEM resolution on large-scale watershed model results?☆

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A R T I C L E I N F O

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A B S T R A C T

This paper examines the effect of raster cell size on hydrographic feature extraction and hydrological modeling using LiDAR derived DEMs. LiDAR datasets for three experimental watersheds were converted to DEMs at various cell sizes. Watershed boundaries and stream networks were delineated from each DEM and were compared to reference data. Hydrological simulations were conducted and the outputs were compared. Smaller cell size DEMs consistently resulted in less difference between DEM-delineated features and reference data. However, minor differences been found between streamflow simulations resulted for a lumped watershed model run at daily simulations aggregated at an annual average. These findings indicate that while higher resolution DEM grids may result in more accurate representation of terrain characteristics, such variations do not necessarily improve watershed scale simulation modeling. Hence the additional expense of generating high resolution DEM's for the purpose of watershed modeling at daily or longer time steps may not be warranted.

Software and data availability

Name BASINS 4.0 (Better Assessment Science Integrating point & Non-point Sources) with a non-proprietary, open source, free GIS system, MapWindow (www.MapWindow.org)
Developer U.S. EPA with AquaTerra Consultants and Idaho State University
Contact http://www.aquaterra.com/contact/index.php
Availability and cost The software is available for free download at USEPA (United States Environmental Protection Agency) website. Mapwindow is an open source programmable GIS (VB, C++, .NET, and Active × controls) that supports manipulation, analysis, and viewing of geospatial data and associated attribute data in several GIS data formats.

1. Introduction

Hydrologic simulation models and water resources planning tools often use hydrographic datasets (most importantly stream network polylines and watershed boundaries) which can be

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derived from gridded (raster) digital elevation models (DEMs) using well-established terrain analysis techniques (Jenson and Domingue, 1988; Tarboton et al., 1991; Tarboton and Ames, 2001; Teng et al., 2008; Tesfa et al., 2011). DEMs used in these processes are derived from various sources including: manually surveyed topographic maps, aerial photogrammetry, interpolated global positioning system (GPS) points, and the NASA Shuttle Radar Topography Mission (Farr and Kobrick, 2000; Kinsey-Henderson and Wilkinson, 2013; Han et al., 2012). In recent years, another source of data from which DEMs can be derived has emerged in the form of Light Detection and Ranging data (LiDAR).

LiDAR technology offers a relatively efficient way to produce DEMs for high accuracy mapping applications. LiDAR sensors are capable of receiving multiple laser pulse returns which, when combined with precision GPS location data, can provide highly accurate and dense point sample measurements of terrain height and ground features (e.g. vegetation, built structures). In this way, LiDAR can be used to define a detailed representation of the earth's surface horizontally as well as vertically, making the LiDAR data source increasingly important for surface structure derivation and its application in hydrographic feature extraction. Indeed, channels extracted from a LiDAR-derived DEM have been shown to have a more complex morphology and correspond better with field-mapped networks than those derived from a conventionally produced DEM (Charrier and Li, 2012).

Murphy et al. (2007) suggests that when considering hydrologic modeling, DEM cell size has a greater impact on results than does the method by which the DEM was produced. Chow and Hodgson (2009) demonstrated that DEM resolution progressively affects the mean and deviation of slope within the range of 2–10 m. Shore et al. (2013) used a 5 m resolution DEM was to study subcatchment connectivity and found that detailed ditch data did not contribute significantly to improving results. These observations contribute to the primary question motivating the work presented here: What is the relationship between hydrographic derivatives (specifically watershed boundaries and stream network centerlines) and the cell size of the LiDAR-derived DEM? Furthermore, is there an optimal resolution of LiDAR-derived DEMs for hydrologic modeling? These questions are important because of the extensive use of DEM derived vector data features in both mapping and hydrologic modeling applications.

To address these questions, we produced several DEMs at different resolutions (cell-sizes) from LiDAR datasets from three different watersheds and delineated stream network centerlines and watershed boundary polygons for each watershed at each DEM resolution. The resulting vector data were then compared to best available reference datasets for each watershed. An assessment of the "correctness" of each extracted stream network is made through the use of longitudinal root mean square error (LRMSE), sinuosity deviation, and selected hydrographic parameters. To assess the effect of LiDAR-derived DEM cell size variation on streamflow simulation, a hydrologic model for a watershed was calibrated using input watershed and stream networks from each DEM resolution and resulting streamflow simulations were compared to observed data.

2. Background

Historically, literature on the effect of spatial scale on topographic modeling largely focuses on DEMs created by means other than LiDAR (Jenson, 1991; Moore, 1991; Tarboton et al., 1991; DeVantier and Feldman, 1993; Olivera, 2001). However, more recent studies include research on the effect of DEM resolution on hydrology-related parameters from LiDAR data (Kienzle, 2004; Vaze et al., 2010; Sørensen and Seibert, 2007). Tarboton et al. (1991) explored the length scale or drainage density for network derivation from traditional digital elevation data, and suggested criteria for determining the appropriate drainage density at which to extract networks from DEMs. Zhang and Montgomery (1994) found that increasing the grid size resulted in an increased mean topographic index because of increased contributing area and decreased slopes. Wolock and Price (1994) found that increasing grid size resulted in higher minimum, mean, variance, and skew of the topographic index distribution. Techniques for generating DEM data from LiDAR have been greatly improved in the last decade (Kraus and Pfeifer, 2001; Agarwal et al., 2006; Xiaoye, 2008). With respect to the use of the LiDAR-derived DEMs for hydrologic modeling, Murphy et al. (2007) compared stream network modeling results using LiDAR and photogrammetric derived digital elevation which reveals that a flow network modeled from the LiDAR-derived DEM was most accurate.

Kienzle (2004) investigated the effect of DEM raster resolution on first order, second order and compound terrain derivatives and identified an optimum grid cell size between 5 and 20 m, related to terrain complexity. Sørensen and Seibert (2007) also showed that the resolution and information content of a DEM has great influence on the computed topographic indices.

Spatially distributed hydrological models have been shown to be sensitive to DEM resolution (Zhang and Montgomery, 1994; Wolock and Price, 1994) both in horizontal and vertical measurement (Kenward et al., 2000). Chauby et al. (2005) indicated that finer resolution DEM cell sizes may result in improved output from the Soil and Water Assessment Tool (SWAT). The effect of DEM resolution on water quality modeling and calibration – specifically due to changes in delineated watersheds – was reported by Teegavarapu et al. (2006) using a Hydrologic Simulation Program FORTRAN (HSPF) model.

3. Data

3.1. Study area

The three watersheds used for this study are located in Idaho, U.S.A., and include: Dry Creek Experimental Watershed (DCEW), Reynolds Creek Experimental Watershed (RCEW) and Slate Creek Watershed (SCW), as shown in Fig. 1. These watersheds were chosen because of: 1) the availability of extensive high point density airborne LiDAR datasets; 2) the availability of 1 m aerial images and existing stream feature data used for creating reference stream networks; and 3) areas with distinct topographical (and hence hydrographical) characteristics which represent different steep watersheds in this area. We recognize that our results will not necessarily apply in broader flatter watersheds due, in part, to the inherent difficulty in extracting drainage areas and networks from flat terrain. A brief description of each watershed follows.

3.1.1. Dry Creek Experimental Watershed (DCEW)

DCEW is located within the Boise Mountains in Southwestern Idaho (about 43° latitude, −116° longitude). DCEW includes the 28 km^2 northeastward trending Dry Creek drainage extending from 1000 to 2100 m in the granitic region of the Boise Front.

3.1.2. Reynolds Creek Experimental Watershed (RCEW)

RCEW, typical of much of the intermountain region of the western United States (Seyfried and Wilcox, 1995) is a rangeland located in the Owyhee Mountains of southwestern Idaho, approximately 80 km southwest of Boise, Idaho, USA. The watershed ranges in elevation from 1101 to 2241 m and has 239 km^2 drainage area.