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Evaluation of the U.S. Geological Survey standard elevation products in a two-dimensional hydraulic modeling application for a low relief coastal floodplain

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SUMMARY

Growing use of two-dimensional (2-D) hydraulic models has created a need for high resolution data to support flood volume estimates, floodplain specific engineering data, and accurate flood inundation scenarios. Elevation data are a critical input to these models that guide the flood-wave across the landscape allowing the computation of valuable engineering specific data that provides a better understanding of flooding impacts on structures, debris movement, bed scour, and direction. High resolution elevation data are becoming publicly available that can benefit the 2-D flood modeling community. Comparison of these newly available data with legacy data suggests that better modeling outcomes are achieved by using 3D Elevation Program (3DEP) lidar point data and the derived 1 m Digital Elevation Model (DEM) product relative to the legacy 3 m, 10 m, or 30 m products currently available in the U.S. Geological Survey (USGS) National Elevation Dataset. Within the low topographic relief of a coastal floodplain, the newer 3DEP data better resolved elevations within the forested and swampy areas achieving simulations that compared well with a historic flooding event. Results show that the 1 m DEM derived from 3DEP lidar source provides a more conservative estimate of specific energy, static pressure, and impact pressure for grid elements at maximum flow relative to the legacy DEM data. Better flood simulations are critically important in coastal floodplains where climate change driven storm frequency and sea level rise will contribute to more frequent flooding events.

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1. Introduction

Hydraulic modeling is an important tool for resource management in populated areas subject to potential flooding. The algorithms used to simulate a flood-wave have been coded into a number of software packages that are available as public domain and 'for purchase' products. A growing list of model choices can be found at the Federal Emergency Management Agency (FEMA) website (FEMA, 2015). While each model is coded for a different simulated outcome to help resource managers make informed decisions regarding their jurisdictions, all require the best possible input data to achieve a simulation that reflects the potential flood scenario. Elevation data are critical input and the resolution and accuracy of the available products can influence modeling outcomes.

The evaluation of various resolutions of elevation data on the outcome of hydraulic modeling simulations overwhelmingly suggests that better resolution produces better simulations. However, many of these studies have focused on a variety of non-standard elevation products and one-time collections of high-resolution source data. For example, Charrier and Li (2012) used light detection and ranging (lidar) derived Digital Elevation Models (DEM) to improve the morphology of stream channels for modeling applications. Casas et al. (2006) compared seven customized terrain models in a one-dimensional hydraulic model to investigate differences in output demonstrating that lidar data provide far greater accuracy than a contour-based DEM. Zazo et al. (2015) determine that high precision photogrammetry rendered into a DEM provided a more accurate calibration product for two-dimensional (2-D) hydraulic models. Zhao et al. (2010) used lidar source 1 and 10 m DEMs and a photogrammetrically-derived 10 m DEM to demonstrate improved soil loss predictions using the Revised Universal Soil Loss Equation. Zhenghong et al. (2014) investigated the use of lidar to provide more accurate slope resolution, detailed ditch

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morphology, and greater drainage density as possible improvements to the hydrologic modeling process. Goulden et al. (2010) showed that improving DEM resolution increased the accuracy of slope determination and simulated soil loss output from the Soil and Water Assessment Tool (SWAT). Chaubey et al. (2005) also looked at DEM resolution effect on the SWAT model output. Their minimum grid size was 30 m but the study showed significantly better simulation results than six other custom grid size comparisons. A critical investigation on uncertainties associated with DEMs for hydrologic applications point to problem areas that include DEM error, DEM scale, DEM interpolation into model grid elements, and terrain surface modifications in DEM products to achieve flattened water surfaces for cartographic interpretations (Wechsler, 2007). Wu et al. (2008) investigated the uncertainties in 10 m and coarser resolution DEM data to derive topographic attributes used in hydrologic modeling. While these investigations demonstrate the value of using high resolution elevation data for hydrologic and hydraulic modeling investigations, they do not focus on standard products that are transferable and widely available to the modeling community.

Investigations focusing on lidar as a high resolution input for improving to model accuracy typically use one-off collections of data at relatively dense point spacing. Yang et al. (2014) determined that the expense of acquiring higher resolution elevation data for watershed modeling at daily or longer time steps was not worth the investment because the higher resolution data were costly and required substantially more time to process for modeling applications. While lidar data can be collected in such a manner to achieve point spacing as dense as 70 points/m^2, these collection efficiencies are not realistic for supporting a national publically-available database of elevation data where collection cost and dataset size can influence annual coverage rates. Furthermore, the collection, processing, and data management of these extremely high-resolution data can increase hydraulic modeling costs to unsupportable levels hence validating Yang et al. (2014) concerns.

To provide new higher resolution publicly-available elevation data for use in science and engineering, the U.S. Government has designed and implemented a program to collect high-resolution lidar data at resolutions beneficial to many applications at a cost that supports national coverage. The program is the 3-Dimensional Elevation Program (3DEP). The 3DEP is currently (2015) built on six collection categories based on resolution quality related to points per square meter and vertical accuracy (Sugarbaker et al., 2014; Heidemann, 2014). The 3DEP provides a nationally consistent elevation data collection procedures with costs shared among Federal agencies. An important benefit will be the improvement of the FEMA flood-risk map program by enhancing the model input data used to predict flood elevations (Snyder, 2012).

Improving the reliability of flood simulations is important for resource managers that have the responsibility to manage land development and mitigate the effects of natural disaster. To ensure that hydrologists, hydraulic engineers, and resource managers are aware of new datasets that can potentially improve modeled outcomes, this investigation demonstrates the value of using 3DEP data for supporting modeling efforts.

Through comparative analysis, 3DEP and legacy USGS elevation data have been tested within a commonly available 2-D hydraulic model. Analysis is focused on interpolation of the various resolutions of data within the finite difference grid of the model; the influence these resolutions have on volume conservation, velocity, specific energy, static pressure, and impact pressure output; and flood inundation response relative to a significant historic flooding event. It is expected these comparisons will provide the hydraulic/hydrologic modeling community with needed information regarding model calibrations using publicly-available standard elevation products.

2. Methods

2.1. Study area

The location selected for applying a 2-D model using multiple resolutions of 3DEP data is Greenville, North Carolina. Greenville is located within the North Carolina coastal plain and is characterized by low relief topography with hardwood swamp floodplains. The incorporated city is located to the south and on the right bank of the Tar River which flows west to east draining to the Pamlico River (Fig. 1). Greenville was selected for this investigation because it was the site of extensive flooding during the 1999 hurricane season which led to rainfall rates driving peak flow to more than the 500-year recurrence interval, severely displacing the population of 134,000 and causing damages in excess of $91.5 M (Department of Planning & Community Development, 2004). Hurricane Dennis was the first storm to impact the North Carolina coastal plain in early September 1999 contributing about 7.03 in of rain in Greenville, creating high flows exceeding 11,000 ft^3/s in the Tar River basin by September 10th, and completely saturating local soils. Just one month prior to Hurricane Dennis, the Tar River had reached its lowest flow of 851 ft^3/s for the period of record (USGS, 2015). Ten days after Hurricane Dennis weakened, Hurricane Floyd contributed 12.63 in of rain to the Greenville area. The combined impact of the two storms caused the Tar River at Greenville to crest at 29.7 ft with an estimated peak flow of 73,000 ft^3/s on September 21, 1999 (Bales et al., 2000). Aerial imagery showing flood inundation at Greenville was acquired by the FEMA on September 23, 1999. Therefore, polygons derived from this imagery for comparative purposes with flood inundation models represent post-crest conditions.

The Greenville area has been extensively studied with respect to the 1999 hurricane season, which provided an enormous amount of insight into the modeling environment for this analysis. For example, Colby et al. (2000) modeled the flood extent from the combined hurricanes demonstrating the difference in flood extent patterns between the output of the one-dimensional (1-D) HEC-RAS model and a more simplified Geographic Information System (GIS) DEM inundation method. Bales et al. (2007) demonstrated the value of using lidar data for creating flood inundation models for the Tar River basin. This effort provided extensive detail on the Tar River basin stream gage network as well as boundary conditions for model constraint. Wagner (2007) used both 1- and 2-D models to simulate water-surface elevations in Greenville, and Abshire (2012) investigated the impacts of hydrologic and hydraulic modeling on flood inundation mapping for the Tar River basin.

2.2. 3D Elevation program products

Elevation data products used for this comparative modeling output analysis are publicly available through The National Map from the 3D Elevation Program database (formerly known as the National Elevation Dataset). The 3DEP is an ambitious multi-agency data collection program led by the USGS to collect high-resolution elevation source data for the nation using both lidar and IFSAR technology (Sugarbaker et al., 2014). Lidar is the primary data collection technique for the conterminous United States, Hawaii, and the U.S. territories, and IFSAR is the primarily technique for Alaska where cloud cover and sensor deployment conditions are more challenging.

Elevation products used for this analysis include the standard products available to the public. Data include the 1/9, 1/3 and 1 arc-second DEM hereinafter referred to as the 3, 10, and 30 m data, respectively, and the new 1 m DEM and original project resolution lidar point cloud. The USGS legacy 3, 10, and 30 m data were down-