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Research papers

Evaluating DEM conditioning techniques, elevation source data, and grid resolution for field-scale hydrological parameter extraction

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ABSTRACT

Although digital elevation models (DEMs) prove useful for a number of hydrological applications, they are often the end result of numerous processing steps that each contains uncertainty. These uncertainties have the potential to greatly influence DEM quality and to further propagate to DEM-derived attributes including derived surface and near-surface drainage patterns. This research examines the impacts of DEM grid resolution, elevation source data, and conditioning techniques on the spatial and statistical distribution of field-scale hydrological attributes for a 12,000 ha watershed of an agricultural area within southwestern Ontario, Canada. Three conditioning techniques, including depression filling (DF), depression breaching (DB), and stream burning (SB), were examined. The catchments draining to each boundary of 7933 agricultural fields were delineated using the surface drainage patterns modeled from LiDAR data, interpolated to a 1 m, 5 m, and 10 m resolution DEMs, and from a 10 m resolution photogrammetric DEM. The results showed that variation in DEM grid resolution resulted in significant differences in the spatial and statistical distributions of contributing areas and the distributions of downslope flowpath length. Degrading the grid resolution of the LiDAR data from 1 m to 10 m resulted in a disagreement in mapped contributing areas of between 29.4% and 37.3% of the study area, depending on the DEM conditioning technique. The disagreements among the field-scale contributing areas mapped from the 10 m LiDAR DEM and photogrammetric DEM were large, with nearly half of the study area draining to alternate field boundaries. Differences in derived contributing areas and flowpaths among various conditioning techniques increased substantially at finer grid resolutions, with the largest disagreement among mapped contributing areas occurring between the 1 m resolution DB DEM and the SB DEM (37% disagreement) and the DB-DF comparison (36.5% disagreement in mapped areas). These results demonstrate that the decision to use one DEM conditioning technique over another, and the constraints of available DEM data resolution and source, can greatly impact the modeled surface drainage patterns at the scale of individual fields. This work has significance for applications that attempt to optimize best-management practices (BMPs) for reducing soil erosion and runoff contamination within agricultural watersheds.

1. Introduction

Topography is a major control of earth surface processes (Jenson, 1991; Florinsky, 1998). In particular, hillslope morphology directly influences surface and subsurface water flow due to the gravitational potential involved in flow path determination (Dunne and Black, 1970; Quinn et al., 1991; Beven and Wood, 1983). Understanding watershed hydrology therefore involves significant knowledge of the land surface. Topography can be used to develop more physically realistic models of hydrological processes due to the inherent relationship between surface relief and downstream flow.

Digital elevation models (DEMs) have contributed substantially to progress in spatial hydrological modelling over the past several decades. DEMs are commonly used to portray earth surface topography and are useful for a number of common hydrological applications such as watershed delineation (Jenson and Domingue, 1988; Jenson, 1991), stream network extraction (O'Callaghan and Mark, 1984; Tarboton, 1997), and surface and near-surface flowpath mapping (Erskine et al., 2006; Costa-Cabral and Burges, 1994). Advanced techniques in elevation data acquisition, DEM interpolation, and hydrological DEM conditioning have revolutionized DEM accuracy and the extraction of topographic derivatives from the digital terrain surface.

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Advancements in automated DEM analysis techniques have allowed researchers to transfer derived DEM surface parameters into meaningful inputs for hydrological models (Jenson and Domingue, 1988; Martz and Garbrecht, 1998). Automated hydrological parameterization methods ultimately rely on two critical factors: (1) a method for overland flow routing to define contributing areas and channel networks (O'Callaghan and Mark, 1984), and (2) a method for managing topographic depressions and flat areas that inhibit overland flow routing (Martz and Garbrecht, 1998, 1999).

Flow paths in DEMs are created based on elevation differences among grid cells and their downslope neighboring cells. Flow routing algorithms use DEMs to estimate the direction of the downslope redistribution of topographically driven overland flow passing through each grid cell in the DEM (Tribe, 1992). The flow direction information derived from these routing algorithms can be used to derive hydrological attributes such as upslope catchment area and the location of drainage divides. Each flow routing method has a unique approach redistributing flow from a grid cell to its downslope neighbours. Algorithms such as the D8 (O'Callaghan and Mark, 1984) and D-infinity (Tarboton, 1997) have been incorporated into hydrological models as methods for overland flow routing prior to watershed parameterization.

Topographic depressions, often termed sinks or pits (Lindsay, 2016a), are characteristically prevalent in DEMs. Depressions can be defined as an individual DEM grid cell or groups of neighboring grid cells that do not have a downslope flow outlet (Jenson and Domingue, 1988). Surrounding grid cells possess higher elevation values resulting in a topographic hollow or bowl-like feature. DEM depressions are particularly problematic for overland flow routing because they accumulate water, creating discontinuity in flow paths and negatively influencing the modeled hydrological response of a catchment (Lindsay and Creed, 2005; Grimaldi et al., 2007). DEM conditioning techniques have been developed to resolve the negative effects associated with topographic depressions. Each conditioning technique is based on an assumption regarding the true nature of depressions. Topographic depressions are actually a combination of artifact and actual features (Lindsay and Creed, 2006; Grimaldi et al., 2007). Artifact depressions typically result from elevation data inaccuracy, interpolation error, and limited data resolution (Walker and Willgoose, 1999). Actual depressions, however, represent true topographic features on the landscape (Lindsay and Creed, 2005). Though less common than artifact depressions, real depressions exist in most non-fluvial landscape, including glacial and karst landscapes.

Hydrological DEM conditioning techniques are distinguished by their approach for accommodating depression features. Every technique is designed to enforce downstream flow by connecting flow path grid cells. DF (e.g. Jenson and Domingue, 1988; Planchon and Darboux, 2001; Wang and Liu, 2006), DB (e.g. Rieger, 1998; Lindsay and Dhun, 2015), and SB (e.g. Saunders, 1999) are the most common types of drainage enforcement or conditioning methods. DF techniques remove depression features by raising the elevation value of a depression cell. DB, however, works to lower the grid cells that are adjacent to depression cells (Rieger, 1998; Lindsay, 2016a). SB uses digital streamline data to reinforce mapped drainage networks in a DEM (Hutchinson, 1989; Saunders, 1999; Lindsay, 2016b). Elevation values in a DEM along a mapped stream network are lowered, or 'burned' into the elevation model (Saunders, 1999). While SB is effective at removing depressions situated along the mapped stream line, the technique cannot remove depressions in hillslope positions within the DEMs and must therefore be followed by a DF or DB operation to ensure continuous flowpaths.

Traditional flow enforcement methods can each resolve flowpath interruptions resulting from DEM depressions; however, the effectiveness of these techniques in human-modified landscapes has been limited. Lindsay and Dhun (2015) developed a novel DB technique to accommodate the linear flow paths associated with anthropogenic landscapes, such as agricultural drainage ditches. The construction of various landscape infrastructure has been shown to increase downstream water discharge and modify surface drainage networks (Duke et al., 2003). The sensitivity of DEM-derived drainage patterns to varying flow enforcement methods is particularly relevant in human-modified, agricultural basins, which are often the focus of intensive water quantity and quality modelling applications. Furthermore, the characteristic low-relief topography of many agricultural landscapes has the potential to demonstrate substantial sensitivity to the specific flow enforcement technique used to condition DEMs. Previous research has demonstrated that modeled surface hydrological attributes are sensitive to DEM grid resolution and elevation source data across a range of topographic settings and landscape types (Chang and Tsai, 1991; Wolock and Price, 1994; Gao, 1997; Wolock and McCabe, 2000; Deng et al., 2007; Sørensen and Seibert, 2007; Wu et al., 2008). However, there has been less focus on the hydrological implication of DEM conditioning techniques particularly over low relief agricultural areas.

The purpose of this study is to examine and evaluate the effects of various DEM grid resolutions, elevation source data, and conditioning techniques (i.e. depression removal and flow enforcement methods) on field-scale hydrological parameter extraction and distribution. This study aims to assess the uncertainty associated with various DEM characteristics. In this case, uncertainty refers to data precision, or the degree to which derived hydrological parameters vary when grid resolution, source data, and conditioning technique is changed. We therefore ask, how does DEM grid resolution, elevation source data, and DEM conditioning techniques influence the definition of field-scale drainage divides and their downslope flowpath length patterns? While many different DEM-derived topographic attributes are used in hydrological applications (e.g. the topographic wetness index), surface drainage patterns are characterized by the locations of divides and the timing of surface and near-surface flow is related to the distribution of flowpath lengths within individual catchments.

2. Data and methodology

2.1. Study area

The study was conducted using elevation data acquired from the Rondeau Basin (42°17′N 81°52′W), a Lake Erie coastal zone in Kent County, southwestern Ontario, Canada (Fig. 1). This site was chosen because of its size, the availability of data (particularly LiDAR data), and because it is representative of the regional topography. The topography of the study area is typical of agricultural landscapes within the larger Great Lakes region. The northeastern portion of the basin runs east to west along the Blenheim moraine, resulting in gently undulating topography toward the centre of the basin and gently sloping topography leading away from the moraine. Deep gullies drain the northern portion of the watershed, with flow reaching the thirteen main tributaries that drain south to Lake Erie (Gilbert and Locke, 2007). These features constitute a portion of the approximately 12,000 ha Rondeau watershed. The dominant land use in the region is agriculture. Intensive farming practices produce increased agricultural runoff, exacerbating high nutrient and sediment loading from local fields to adjacent draining tributaries (e.g. Molder et al., 2015).

2.2. Data

A publicly accessible DEM was collected for the study area: the 2006 Ontario Provincial Tiled DEM Dataset, produced by the