Quantitative Evaluation of the Relationship between Grid Spacing of DEMs and Surface Depression Storage

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Abstract

Digital elevation models (DEMs) are commonly utilized for characterizing surface topography in watershed modeling. More often, DEMs can be the sole information that is used for watershed delineation, determination of flow directions and accumulations, and identification of subbasin boundaries. Thus, the resolution or grid size of the DEM data is critical. Surface depression storage is one of the primary topographic attributes and an essential hydrologic variable in watershed hydrologic modeling. Efforts have been made to evaluate the effects of grid spacing of DEMs on topographic attributes and hydrologic analyses. However, previous studies showed varied relationships between grid spacing and surface depression storage. The objective of this study is to quantitatively evaluate the effects of DEM resolutions on the computed maximum depression storage (MDS) and maximum ponding area (MPA). Six surfaces that possess varying spatial scales and microtopographic features are used in the discussion. In addition, six interpolation methods are selected and their influences on MDS also are evaluated. It is found from this in-depth study that grid pacing of DEMs affects MDS and MPA differently, depending on the characteristics of surfaces, delineation methods, and interpolation approaches used for generating the DEM data for various spatial scales.

Introduction

Spatially-distributed raster DEM data have been widely used for watershed-scale hydrologic and environmental modeling and management. DEMs vary in resolutions or grid sizes, which subsequently affect terrain attributes in the related analysis. Thus, DEM-based watershed delineation, a fundamental step of watershed modeling, can be sensitive to the grid spacing of DEMs. Studies have been conducted to evaluate the effects of grid spacing of DEMs on: estimation of surface depression storage (Huang and Bradford 1990; Kamphorst et al. 2000; Carvajal et al. 2006; Abedini et al. 2006), landscape process modeling (Schoorl et al. 2000), computation of topographical indices (Sorensen and Seibert 2007), characterization of terrain attributes (Erskine et al. 2007), surface runoff modeling (Kuo et al. 1999; Vazquez and Feyen 2007; Wu et al. 2007), hydrologic modeling parameters and peak discharge (Moglen and Hartman 2001), topography-based watershed modeling (Wolock and Price 1994), soil water content (Kuo et al. 1999), watershed soil erosion modeling (Rojas et al. 2008), and shallow landslide hazard and soil redistribution modeling (Claessens et al. 2005).

As one of the major hydrologic variables, surface depression storage plays an important role in overland flow, infiltration, soil erosion, and other hydrologic processes. Depressions start to retain rainfall before surface runoff begins (Mitchell and Jones 1976; Ontad 1984). Water ponded on a permeable surface may significantly strengthen the infiltration process (Fox et al. 1998). Importantly, surface depressions, and their storages and distribution dominate the initiation timing and duration of the puddle to puddle filling-spilling-merging process (referred to as P2P process, Chu 2010), which in turn affects the physical mechanisms of hydrologic processes. Due to the difficulty in direct measurement of depression storage on a permeable soil surface, surface depression storage is often estimated indirectly and then input as a constant in many hydrologic models. Methods have been developed to estimate MDS based on roughness indices (e.g., Onstad 1984; Mwendera and Feyen 1992; Hansen et al. 1999). However, roughness indices are scale dependent, implying that one roughness value alone cannot always properly quantify surface roughness (Huang and Bradford 1992). Alternatively, DEMs that represent detailed surface topography allow one to precisely calculate MDS. Some algorithms have been developed to calculate MDS from DEMs (e.g., Mitchell and Jones 1976; Moore and Larson 1979; Ullah and Dickinson 1979; Kamphorst and Duval 2001). A similar procedure is implemented in most of such DEM-based algorithms: local minima (center of a depression) are first indentified; the associated depressions are determined; and the depressions are then filled till the overflow points are reached. The MDS over the entire area is calculated by summing up the storages of all individual depressions.

Clearly, the DEM-based computation of MDS is affected by the grid spacing of the DEM. Efforts have been made to evaluate such influences and quantify the relationship of grid spacing and the surface depression storage computed from the DEM (e.g., Huang and Bradford 1990; Kamphorst et al. 2000; Carvajal et al. 2006; Abedini et al. 2006). However, their conclusions are varied. Huang and Bradford (1990) found that as the grid size increased, depressional storage decreased, which was primarily attributed to the loss of surface details. Kamphorst et al. (2000) studied the dependence of MDS on varying grid spacing for a series of plots and estimated their MDS values by using PCRaster (Van Deursen and Wesseling 1992). Contrary to the finding of Huang and Bradford (1990), they concluded that MDS did not structurally decrease with an increase in grid spacing. Instead, MDS stabilized after an initial increase. Carvajal et al. (2006) derived a relationship between DEM resolution and precision to estimate the MDS by introducing the standard deviation of unitary vectors (SDUV). Abedini et al. (2006) examined the relationships of grid spacing with the number of depressions, ponded area, and MDS; and quantified the effects of changing spatial resolution on geometric properties of depression storage and emphasized the scale dependence of geometric characteristics of depressions and the importance of fractal analysis.

The objective of this study is to quantitatively evaluate the effects of DEM resolutions on the computed MDS and MPA by examining a set of surfaces of varying spatial scales and microtopographic features. Six interpolation methods are employed to create new DEMs with different grid sizes. Their influences on MDS also are evaluated.

Puddle Delineation and Computation of MDS

A variety of watershed delineation methods have been developed (e.g., Marks et al. 1984; O'Callaghan and Mark 1984; Jenson and Domingue 1988; Jenson 1991; Martz and Garbrecht 1993; Garbrecht and Martz 1997; Martz and Garbrecht 1999; ASCE 1999). Based on these methods and techniques, software packages also have been developed to facilitate digital terrain analysis and automated watershed delineation. Examples of the commonly used software for DEM-based watershed modeling include ArcHydro (Maidment 2002), HEC-GeoHMS (USACE 2003, 2009), TOPAZ (Garbrecht and Martz 1995, 2000; Garbrecht et al. 2004), and PCRaster (Van Deursen and Wesseling 1992; Van Deursen 1995; Wesseling et al. 1996). Some special algorithms also have been developed for DEM-based delineation and computation of MDS (e.g., Ullah and Dickinson 1979; Planchon and Darboux 2001).

In this study, a new algorithm (Chu and Zhang 2009) and the associated Windows-based modeling system were used for puddle delineation and computation of MDS and MPA. The puddle delineation program involved implementation of a searching process, identification of puddles (including their centers, thresholds, and cells), determination of puddle relationships, and visualization of the delineation results. Filling, spilling, and merging of puddles were primarily controlled by their thresholds and relationships with others, as well as a set of "rules." Based on the puddle delineation results, MDS and MPA were respectively computed for the fully filled condition by summing up the depression storages and the ponding areas of all puddles across the entire surface. Schemes also were developed in the puddle delineation program to deal with some special topographic conditions, such as flats, common threshold(s) of multiple puddles, and multiple thresholds of one puddle.

Effects of DEM Resolution on MDS and MPA

To quantitatively evaluate the effects of DEM resolution on the computed MDS and MPA, six surfaces that possessed different spatial scales and microtopographic characteristics were selected in this study. They included one small mold surface, two lab-scale surfaces, and three large real surfaces. The original DEMs of the small mold surface and the two lab-scale surfaces were obtained by using a high-resolution (< 1 mm), instantaneous-profile laser scanner (Darboux and Huang 2003). The 10-m DEMs of the three real surfaces were downloaded from the USGS. The coarser DEMs with larger grid sizes (i.e., lower resolutions) were created using the kriging interpolation method. All surfaces were then delineated by using the Windows-based puddle delineation program. MDS and MPA of the six original surfaces and their interpolated surfaces with varying grid spacing were computed.

(1) A small mold surface – Surface I

Fig. 1 shows the small mold surface (Surface I) and the changes of MDS and MPA with grid spacing. The total area of Surface I is 400 cm^2. Detailed computation results are shown in Table 1. An overall decreasing trend can be observed for both MDS and MPA.

That is, MDS and MPA decrease with an increase in grid spacing, except for some points. The surface with the highest DEM resolution (1 mm) has the largest MDS (68.82 cm^3). MDS reaches the minimum value of 17.92 cm^3 at the largest grid spacing point (40 mm). MPA decreases from 125.46 cm^2 to 64.00 cm^2 for grid sizes ranging from 1 mm to 40 mm.

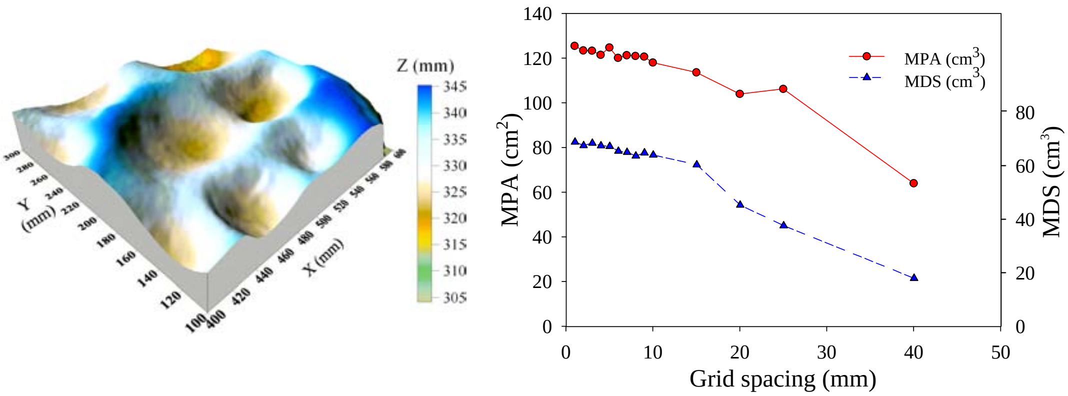

Fig. 1 Relationships between grid spacing and MDS and MPA for Surface I

Table 1 MDS and MPA computed by using the puddle delineation program for different grid sizes for Surface I (interpolation method: kriging; total area: 400 cm^2)

Grid spacing (mm)	MDS (cm^3)	MPA (cm^2)	Grid spacing (mm)	MDS (cm^3)	MPA (cm^2)
1	68.82	125.46	8	63.63	120.96
2	67.52	123.44	9	64.82	120.66
3	68.43	123.32	10	64.00	118.00
4	67.48	121.44	15	60.36	113.61
5	67.22	124.75	20	45.28	104.00
6	65.44	120.11	25	37.59	106.25
7	64.99	121.28	40	17.92	64.00

(2) Two lab-scale surfaces – Surface II-1 and Surface II-2

A soil box (100 cm × 120 cm) was used to create the two lab-scale surfaces (Fig. 2): Surface II-1 (a smooth surface) and Surface II-2 (a rough surface). The surfaces were scanned by using the laser scanner and delineated by using the puddle delineation program. The computed MDS values for Surfaces II-1 and II-2 are shown in Figs. 2a and 2b, respectively. Due to the higher roughness, the MDS values of Surface II-2 are much greater than those of the smooth surface II-1 for all grid sizes. Like Surface I (Fig. 1), MDS of the smooth surface II-1 decreases with an increase in grid spacing (Fig. 2a). However, Surface II-2 exhibits a significant variation in MDS as the grid spacing increases from 1 mm to 110 mm (Fig. 2b). Such a variation can be primarily attributed to the unique microtopographic characteristics of this rough surface, such as the number of puddles, their sizes and shapes, and their relationships.

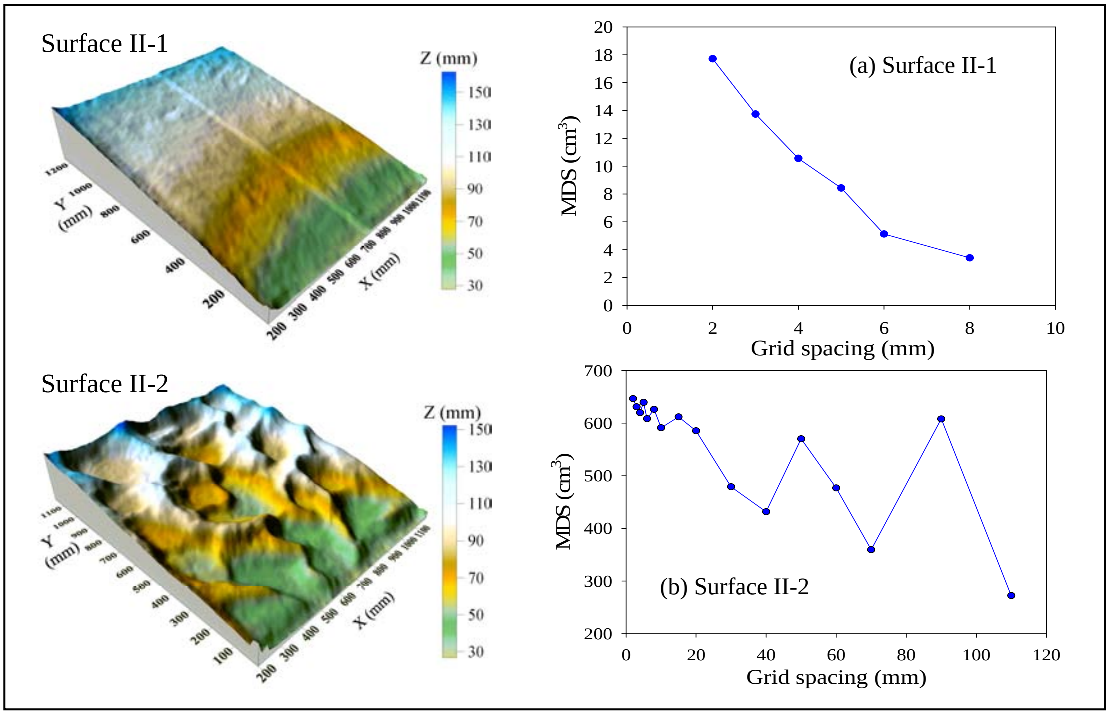

Fig. 2 Relationships between grid spacing and MDS for Surfaces II-1 and II-2

(3) Three real land surfaces – Surface III-1, III-2, and III-3

In addition to the three small scale surfaces, three real land surfaces: Surfaces III-1, III-2, and III-3 (Fig. 3), also were selected for DEM-based puddle delineation. The computed MDS values for these three surfaces are respectively shown in Figs. 3a, 3b, and 3c. Clearly, different MDS changing patterns can be observed. The MDS of Surface III-1 displays a decrease with an increase in grid spacing (Fig. 3a). However, Fig. 3b for Surface III-2 shows an opposite (i.e., increasing) trend; and Surface III-3 has a mixed relationship between MDS and grid spacing (Fig. 3c). These results again demonstrate that the relationship of MDS and grid spacing really depends on the characteristics of the surface microtopography.

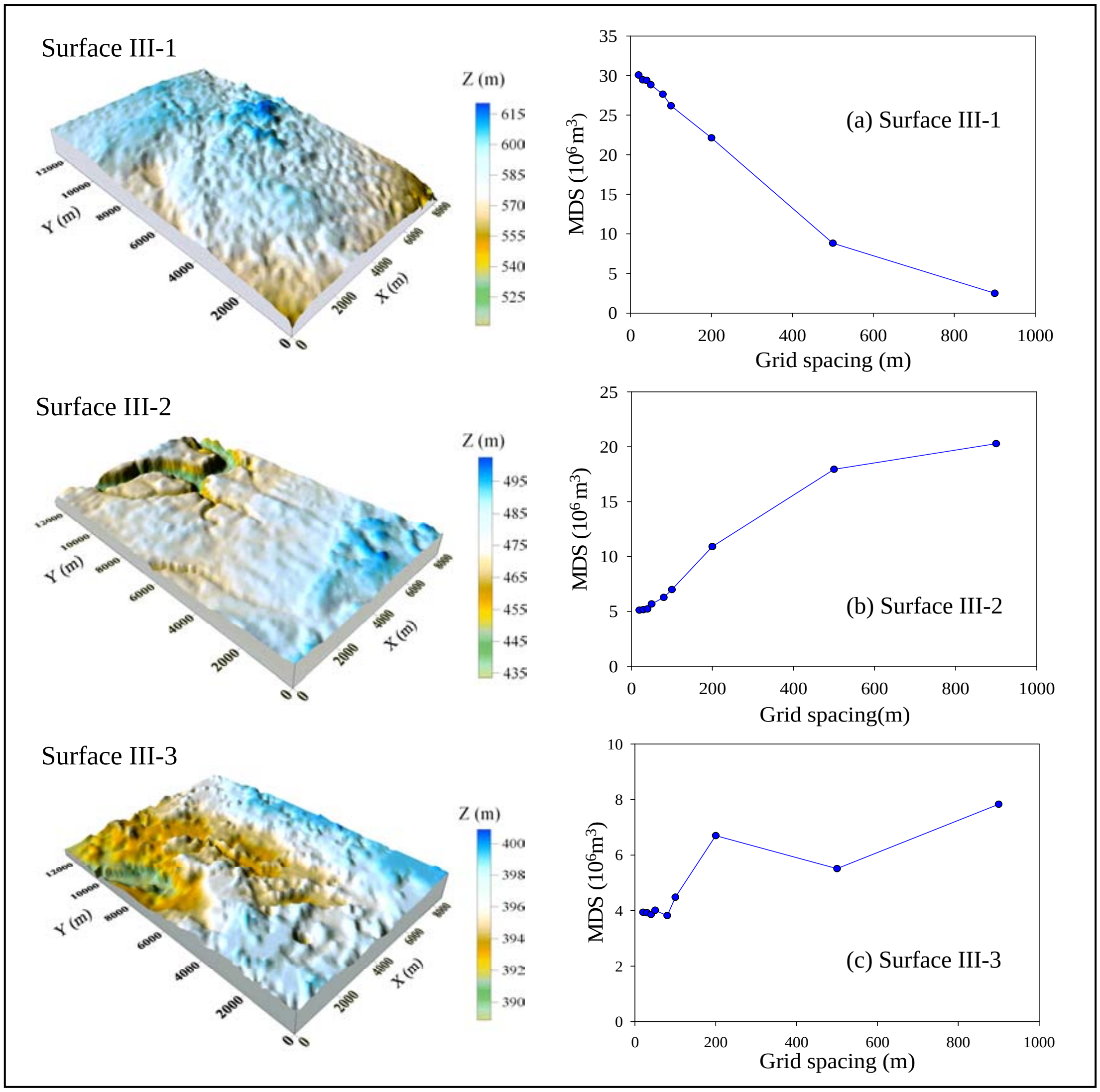

Fig. 3 Relationships between grid spacing and MDS for Surfaces III-1, III-2, and III-3

Effects of Different Interpolation Methods

Six different interpolation methods, including kriging (I1), inverse distance to a power (I2), minimum curvature (I3), modified Shepard's method (I4), nearest neighbor (I5), and radial basis function (I6), were used to generate new coarser DEMs. Surface I, Surface II-1, and Surface II-2 were utilized for evaluating the effects of these interpolation methods on the computed MDS.

For the small mold surface – Surface I

Based on the original DEM of Surface I (Fig. 1), the aforementioned six methods were applied to create new interpolated DEMs, which were further used for generating DEMs for all different grid sizes. Fig. 4 shows the changes in MDS with grid spacing for the six interpolation methods (I1 - I6). Similar to the kriging method (I1) (Figs. 1 and 4), all other methods result in the same decreasing pattern (Fig. 4). Except for the minimum curvature method (I3), the computed MDS values are very close for different interpolation methods. MDS was underestimated for the DEMs generated by the minimum curvature method (I3) for larger grid sizes (>15 mm) (Fig. 4).

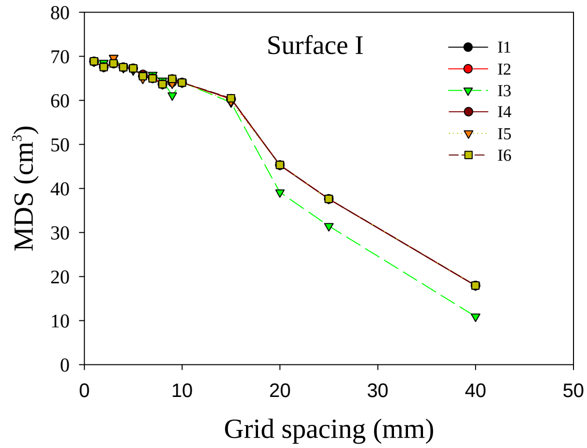

Fig. 4 Effects of the six interpolation methods on the computed MDS for various grid sizes for Surface I

For lab-scale surfaces – Surface II-1 and Surface II-2

Furthermore, Surfaces II-1 and II-2 also were selected to evaluate the effects of the six interpolation methods on the computed MDS for various grid sizes (Fig. 5). For Surface II-1, the highest MDS values were obtained for all grid sizes from the DEM generated by the kriging method (I1) (Fig. 5a). Substantial variations in the computed MDS can be observed for the method of inverse distance to a power (I2) for Surface II-1 (Fig. 5a). Except for the minimum curvature method (I3), similar MDS curves were obtained for all other interpolation methods for Surface II-2 (Fig. 5b). For both surfaces, the minimum curvature method (I3) tends to underestimate MDS for most grid sizes (Figs. 5a and 5b).

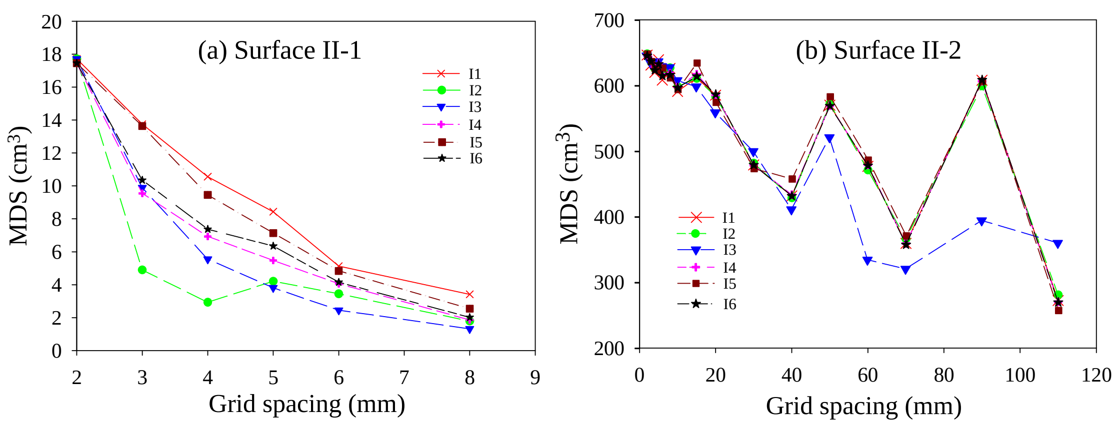

Fig. 5 Effects of the six interpolation methods on the computed MDS for various grid sizes for Surfaces II-1 and II-2

Conclusions

DEMs have been widely used for watershed hydrologic and water quality modeling and management. This study demonstrated that resolution or grid spacing of DEMs had significant effects on the digital representation of surface microtopography and watershed delineation, which in turn affected the computed MDS and MPA. It was concluded that the relationship between grid spacing and MDS or MPA varied, depending on the surfaces, their microtopographic characteristics, and delineation methods. In addition, the interpolation methods used to create low resolution DEMs also affected the computed MDS and MPA. According to this study, MDS tended to be underestimated for the DEMs generated by using the minimum curvature method.

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