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Research Article

Effects of DEM resolution and source on soil erosion modelling: a case study using the WEPP model

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Digital elevation models (DEMs) vary in resolution and accuracy by the production method. DEMs with different resolutions and accuracies can generate varied topographic and hydrological features, which can in turn affect predictions by soil erosion models, such as the WEPP (Water Erosion Prediction Project) model. This study investigates the effects of DEMs on deriving topographic and hydrological attributes, and on predicting watershed erosion using WEPP v2006.5. Six DEMs at three resolutions from three sources were prepared for two small forested watersheds located in northern Idaho, USA. These DEMs were used to calculate topographic and hydrological parameters that served as inputs to WEPP. The model results of sediment yields and runoffs were compared with field observations. For both watersheds, DEMs with different resolutions and sources generated varied watershed shapes and structures, which in turn led to different extracted hill slope and channel lengths and gradients, and produced substantially different erosion predictions by WEPP.

Keywords: DEM resolution; DEM accuracy; LIDAR; Forested watershed; Erosion modelling; WEPP

1. Introduction

Topography is an important control of processes on the Earth surface. It directly moderates water flow over and through the Earth's surface and in turn moderates the potential of soil erosion (Hutchinson 1996). A common format for representing topography in a geographic information system (GIS) is the digital elevation model (DEM). DEMs can vary in resolution and accuracy by the production method (Lo and Yeung 2002, Chang 2006). The interval between elevation points determines the resolution of a DEM; for instance, the USGS NED (US Geological Survey National Elevation Dataset) offers DEMs at 30-m and 10-m resolutions. The accuracy of a DEM depends on the quality and resolution of the input data (Garbrecht and Martz 2000, Van Remortel *et al.* 2001).

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How to automatically extract topographic and hydrological features from DEMs has been studied extensively over the last two decades (Mark 1983, O'Callaghan and Mark 1984, Band 1989a,b, Jenson 1991, Moore *et al.* 1991, 1993, Florinsky 1998, Walker and Willgoose 1999, Band *et al.* 2000, Flanagan *et al.* 2000). DEMs can be used in a GIS to derive a wealth of information about topography, hydrological flow, and hydrological connectivity. Recent developments have demonstrated significant movements towards automated terrain analysis, such as automatically delineating drainage networks and hill-slope profiles for soil-erosion modelling (Flanagan *et al.* 2000, MacMillan *et al.* 2003).

Using DEMs for terrain analysis, however, has been limited by the relatively coarse spatial resolution of most existing DEM data sets (MacMillan *et al.* 2003). There are two ways of obtaining high-resolution DEMs. The first method creates new DEMs by decreasing the interval between sampled elevation points. The cost of creating such DEMs, nevertheless, increases exponentially for finer resolutions (Cochrane 1999). The second method interpolates fine DEMs from coarse DEMs. Mitasova *et al.* (1996), for example, used the method of regularized spline with tension to interpolate a finer DEM from a 30-m DEM and reported accurate results of topographic analysis. However, the use of spatial interpolation for creating fine DEMs has been criticized by Zhang and Montgomery (1994), Desmet and Govers (1997), and Van Remortel *et al.* (2001).

Recent developments in light detection and ranging (LIDAR) technology suggest a new option for generating fine DEMs. LIDAR is a remote sensing technology that determines range by measuring the time it takes for a laser beam to reflect back from a target to a sensor (Turner 2000). LIDAR has become a new, cost-effective alternative to photogrammetry for creating high-quality, fine-resolution DEMs (Hill *et al.* 2000, Brovelli *et al.* 2004).

The main purpose of this study was to assess the effects of DEM resolutions on deriving topographic and hydrological attributes through a case application of runoff and erosion modelling for two small forested watersheds in northern Idaho, USA. Since there exist multiple sources of DEMs with the same resolution (e.g. 10-m USGS DEMs and 10-m LIDAR DEMs), the hydrological and erosion impact of DEMs from different sources was evaluated as well. In the application, different DEMs in terms of resolution and source were used in combination with WEPP (Water Erosion Prediction Project), a process-based watershed erosion model (Flanagan and Livingston 1995), for runoff and sediment yield predictions. The model results were subsequently compared with field observations, and statistical inferences were drawn. This paper reports our findings, which should be useful to researchers in selecting appropriate DEMs with proper accuracy and resolution for hydrological and environmental modelling.

2. DEM sources and resolution

2.1 *DEM sources*

Most GIS users in the United States use USGS DEMs, including NED DEMs. NED DEMs are updated with the latest, most accurate data available, such as high-resolution elevation data, 10-m DEMs, 30-m Level 2 DEMs, and 30-m Level 1 DEMs. The USGS used to create 30-m Level 1 DEMs by autocorrelation or manual profiling from aerial photographs but has been collecting DEM data by interpolation from vectors or digital line graph hypsographic and hydrographic data since the 1990s. Additionally, data corrections are made in the NED assembly process to minimize artefacts, perform edge matching, and fill sliver areas of missing data. Alternative DEMs include SRTM (Shuttle Radar Topography Mission) DEMs and LIDAR DEMs.

In 2000, the SRTM collected data over 80% of the Earth's land surface between 60°N and 57°S latitude. These data have been processed to generate global-scale digital topographic maps and seamless DEMs of homogeneous quality in 1-arc-second (approximately 30-m) and 3-arc-second (approximately 90-m) spatial resolutions (Rabus *et al.* 2003). SRTM elevations are canopy-based, whereas NED elevations are generally bare ground readings. Under normal circumstances, a ground-based DEM tends to be more appropriate for hydrological modelling than a canopy-based DEM.

In an airborne LIDAR system, laser pulses are emitted from an instrument mounted in an aircraft. The horizontal coordinates (x, y) and elevation (z) of the reflective objects scanned by the laser beneath the flight path are thus obtained. The resultant measurements create a three-dimensional cloud of points at irregular spacing (Lee and Younan 2003, Zhang *et al.* 2003). For typical commercial LIDAR systems, the vertical accuracy is 15 cm or higher, the planimetric accuracy is 10–100 cm, and the post spacing is 0.5–2 m (Flood 2001).

When a LIDAR sensor emits pulses to a forested area, the laser pulses pass through a forest canopy and reflect back to the sensor as layers of vegetation are hit. A single laser pulse can result in multiple returns as it passes through vegetation to the ground (Naesset 1997). To generate a DEM, raw LIDAR data must be processed, and measurements from non-ground features such as vegetation, buildings, and vehicles must be identified and removed (Wehr and Lohr 1999, Lefsky *et al.* 2002). A number of algorithms have been developed to remove non-ground points from LIDAR datasets, such as the linear least-squares interpolation algorithm (Kraus and Pfeifer 1998), the slope-based filter algorithm (Vosselman 2000), and, more recently, the progressive morphological filter algorithm (Zhang *et al.* 2003). After the removal of non-ground points, the irregularly spaced LIDAR points are converted to the regularly spaced DEM by spatial interpolation (e.g. kriging). The transformation from points onto a grid can introduce errors. In addition, if the grid spacing is too large, it may result in loss of data and higher errors at the boundaries of features (Smith *et al.* 2003).

2.2 *DEM resolution*

Numerous studies have shown that the accuracy of derived topographic and hydrological attributes depends on the quality and resolution of the input DEM (Jenson and Domingue 1988, Chang and Tsai 1991, Jenson 1991, Florinsky 1998, Gao 1998, Kienzle 2004, Usery *et al.* 2004). A coarse DEM resolution means a more generalized terrain, which preserves only major relief features. Different DEM resolutions can therefore produce different local slope and aspect results (Gerrard and Robinson 1971, Fahsi 1989). Generally, coarser DEMs result in less accurate slope results (Chang and Tsai 1991, Gao 1998, Kienzle 2004). The disappearance of short, steep slopes and microtopographic features tends to lengthen the flow paths, thus increasing the size of catchment areas (Wilson and Gallant 2000). In other words, a coarse DEM may not be able to fully capture a complete, integrated drainage network (MacMillan *et al.* 2003). A number of studies have also examined the influence of the computing algorithm on slope and aspect measures (Skidmore

1989, Hodgson 1998, Jones 1998, Kienzle 2004). However, there is no consensus as to which algorithm is superior, and at least one study (Kienzle 2004) has reported no significant statistical difference between two commonly used algorithms in GIS.

It is logical to conclude from previous studies that the choice of DEM resolution is important in minimizing representation errors of the terrain shape, which is measured by various primary terrain attributes computed from DEMs. However, determination of the appropriate resolution of a DEM is generally a compromise between fully honouring the true surface and the concern over practical limits of the density and accuracy of the source data. The spacing of the original data used to construct a DEM effectively limits the resolution of the DEM. Decreasing the grid size beyond the resolution of the original survey data does not increase the accuracy of the land surface representation by the DEM and can potentially introduce interpolation errors (Zhang and Montgomery 1994).

The research community is excited about the capability of extracting high-resolution DEM from LIDAR points. Yet researchers have found that the new technology presents its own problems for which solutions are still lacking or are insufficient. A fine-resolution DEM can sometimes pick out excessive topographic detail, and can deflect stream flows from their natural courses by assumed or artefact barriers (MacMillan *et al.* 2003). Hence, it seems inappropriate to claim that finer-resolution DEMs will invariably result in more accurate topographic and hydrological parameters. One of the objectives of this study was therefore to search for an appropriate resolution for hydrological and erosion modelling.

3. WEPP overview

Publicly released in 1995, WEPP is a physically based model for predicting water erosion and sediment delivery on hill slopes and watersheds (Flanagan and Livingston 1995). In the past decade, WEPP has been widely used to simulate soil erosion under various hydrological conditions (Laflen *et al.* 1991, 1997, Cochrane and Flanagan 1999, Renschler *et al.* 2000, Flanagan *et al.* 2002, Renschler and Harbor 2002). The WEPP v2006.5 was selected for use in this study.

As in using other soil-erosion models, one of the most demanding challenges in applying the WEPP model is to determine the effect of topography on erosion, especially in topographically complex areas such as mountain areas with large slope variations. Topography is a major factor influencing the amount of soils eroded by surface runoff from hill slopes because the physical characteristics of a slope, such as slope gradient, length, and shape, can determine the characteristics of flow across the surface (Foster 1982). A hill slope may be generally defined as a sub-catchment that drains from the top, left, or right side into a stream channel. In WEPP, a sub-catchment is conceptualized as a hill slope with a rectangular flow plane for hydrological and hydraulic computations. The length of the rectangular flow plane is the length of the longest hydraulic flow path, and the area equals that of the sub-catchment.

Runoff water on steep hill slopes is normally more erosive and can transport detached sediment downslope more easily. Long slope length allows a high volume of water to accumulate, resulting in greater potential to erode. Concave slopes are less erosive than convex slopes because the slopes at the foot of concave hills are less steep (Elliot and Ward 1995).

GIS has become an increasingly important and useful tool for preparing inputs for hydrological and soil erosion modelling (Jenson 1991, Moore *et al.* 1993, Hickey *et al.* 1994, Mitasova *et al.* 1996, Desmet and Govers 1996, 1997, Tarboton 1997, Cochrane and Flanagan 1999, Walker and Willgoose 1999). The geo-spatial interface for WEPP, GeoWEPP, was developed to link the WEPP model with a GIS and to utilize DEM data to generate the necessary topographic inputs for erosion model simulations (Renschler 2003). GeoWEPP uses TOPAZ (Garbrecht and Martz 1997) within the ArcView 3.x environment to derive topographic input parameters based on the D8 flow routing algorithm for WEPP applications. TOPAZ can rectify depressions and flat surfaces in a DEM, identify hydrographic segmentations, such as channel network and corresponding drainage divides, and calculate topographic input parameters, such as representative sub-catchment parameters required by WEPP.

WEPP uses a slope file to describe the hill slope topography, including slope gradient, slope length, and slope shape (convex, concave, and uniform). The slope inputs are extensively used in the hydrology and erosion components of the model for runoff and sediment transport calculations.

4. Study area and data sets

4.1 *Study area*

The study area covers a portion of the headwater part of the Paradise Creek watershed in northern Idaho (figure 1). The area consists of two small watersheds, located near the south-west boundary of Moscow Mountain. Forested steep slopes and moderately steep rolling hills characterize the area. The elevation varies from 880 to 1300 m, and the slope ranges from 3% to 47%. The two watersheds are named Watersheds 5 and 6 corresponding to their respective monitoring sites (figure 2). Monitoring site 5 is located upstream from monitoring site 6. Watershed 5 is therefore the upstream section of Watershed 6. Watershed 5 measures 106 ha, and Watershed 6 measures 177 ha.

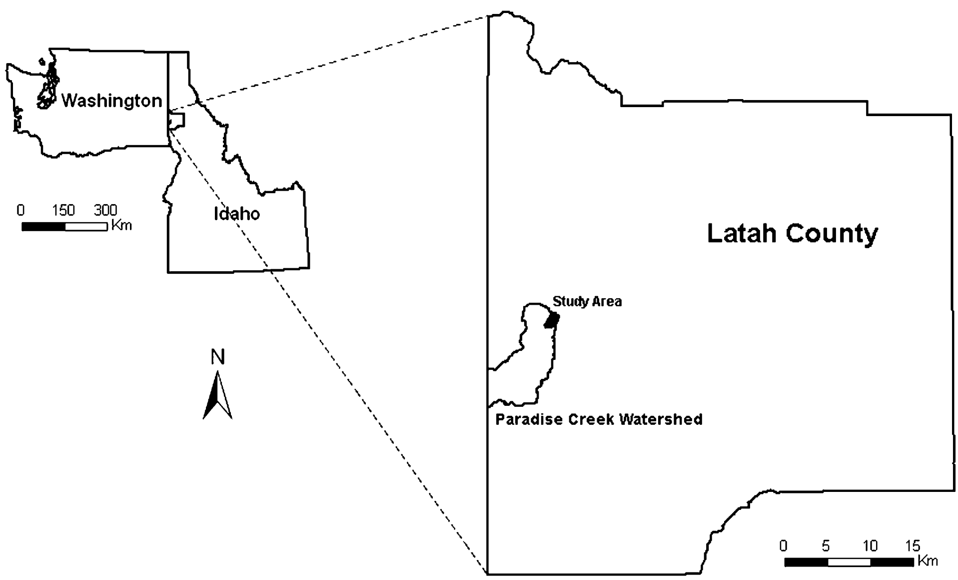

Figure 1. Location map of the study area.

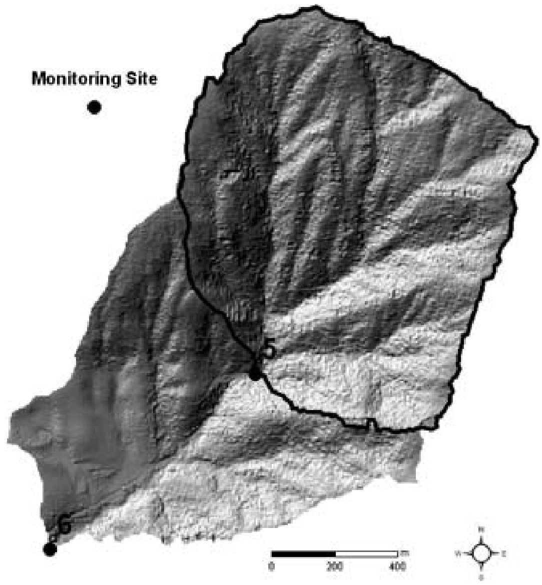

Figure 2. Hill-shade image of the study area from the LIDAR 4-m DEM. Watershed 5 is the upstream portion of Watershed 6.

4.2 *DEM data sets*

LIDAR data over the study area were acquired through Horizons, Inc., a LIDAR service company. The progressive morphological filter algorithm (Zhang *et al.* 2003) was applied to generate DEMs from LIDAR data. The algorithm separates ground from non-ground LIDAR measurements, such as vegetation, by gradually increasing the window size of the filter and by using an elevation difference threshold. After the removal of non-ground objects, three LIDAR DEMs at 4-m, 10-m, and 30-m resolutions were interpolated from ground points. Additionally, three publicly accessible DEMs were collected for the study area: the SRTM DEM at 30-m resolution and the USGS NED DEMs at 10-m and 30-m resolutions. The two NED DEMs were generated by the EROS Data Center; the 10-m DEM was created during 1999–2004 and the 30-m DEM during 1999–2000.

4.3 *DEM accuracy assessment*

The vertical accuracy of the six DEMs was assessed using in-field GPS points in and around the study area. Limited by the heavy canopy in the study area, a total of 18 GPS points were logged using Trimble TSC1 Asset Surveyor and differentially corrected by the GPS Pathfinder Office software. The accuracy of the GPS system was tested to be 0.826 m vertically and 0.704 m horizontally. Using the 18 GPS points as benchmarks, the RMSE (root mean square error) of each of the six DEMs for the vertical difference was calculated and listed in table 1.

The 4-m and 10-m LIDAR DEMs have the lowest RMSE, and the 30-m LIDAR and SRTM DEMs have the largest errors. The two NED DEMs, which do not differ considerably in accuracy, have the moderate level of RMSE.

Table 1. Root mean square errors (RMSEs) of six DEMs from three sources at three resolutions.

	LIDAR DEM			NED DEM		SRTM DEM
Resolution (m)	30	10	4	30	10	30
RMSE (m)	5.733	1.511	1.244	3.865	3.012	5.652

4.4 *Field observations*

Water discharge and total suspended solid for Watersheds 5 and 6 were measured at the monitoring sites on the Paradise Creek every 2 weeks starting March 1999. The observation lasted until December 1999 with 18 records for Watershed 5 and until June 2002 with 65 records for Watershed 6. Daily values of runoff and sediment yield were calculated from these records through linear interpolation. Annual values were determined by integration, and their averages were calculated. For Watershed 5, the average annual runoff was $1.39\times10^5\,m^3$, and the annual sediment yield was 1.38 t. For Watershed 6, the average annual runoff was $4.07\times10^5\,m^3$, and the annual sediment yield was 4.55 t.

5. WEPP simulation and results

A WEPP simulation requires climate, management, soil, and topographic inputs (Flanagan and Livingston 1995). To evaluate the effect of DEM resolution on soil-erosion modelling, we kept the climate, management, and soil inputs the same in each run but varied the DEM for generating the topographic inputs.

A 30-year climate input for 1973–2002, which covers the observation period of 1999–2002, was prepared. The climate data consisted of daily precipitation and temperature observed at the weather station closest to the study area (City of Moscow, University of Idaho station) as well as CLIGEN-generated climate parameters, including detailed storm characteristics (e.g. duration, peak intensity), wind velocity and direction, and solar radiation. CLIGEN is an auxiliary random climate generator (Nicks *et al.* 1995). Compared with the 30-year (1973–2002) average precipitation of 684 mm, annual precipitations for 1999–2002 were 695, 583, 588, and 590 mm, respectively, representing average to relatively dry conditions.

The management input was generated using the default file built in the WEPP model for a 20-year-old forest with 100% ground cover, which corresponds to the forest condition in the study area. The soil input was based on the default file in the WEPP model for a 20-year-old forest with silt loam texture. Several soil parameters were, however, adjusted after a preliminary assessment to attain adequate water-balance results for the study area. Modifications were also made in the soil input file to include the hydraulic conductivity ($3.6\times10^{-6}\,mm\,h^{-1}$) for the underlying granitic bedrock (Domenico and Schwartz 1998) and soil anisotropy ratio (50) for both hill slopes and channels as required by WEPP v2006.5. In addition, the surface soil hydraulic conductivity ($140\,mm\,h^{-1}$) and the rock content values for hill slopes (40%) and channels (50%) were increased from the default values to properly represent the conditions in the study area.

The topographic input, including both hill slope profiles and watershed channel files, were derived from each of the six DEMs through the TOPAZ application in GeoWEPP using a critical source area of 10 ha and a minimum source channel length of 100 m. These parameter values were chosen so that the derived channel networks and watershed structures would match well with the USGS DRGs (digital raster graphics). Figure 3 shows the derived Watershed 5 from each of the six DEMs and figure 4 the derived Watershed 6.

The 30-m DEMs resulted in blocky watershed boundaries as well as unsmooth hill slopes and stream networks for both watersheds. The shape of Watershed 5 derived from the 30-m SRTM DEM appeared the most unrealistic: almost all hill slopes in the watershed had straight-line boundaries, and one hill slope on the north-east, evidently incorrectly delineated, had a long 'tail' that stretched across nearly the entire watershed (figure 3). The watershed boundaries generated from the 10-m NED DEM showed only a few straight lines. The watersheds derived from the two LIDAR DEMs exhibited substantially improved representations of general topographic features. In addition to different shapes, the six watersheds had different delineated areas and different numbers of hill slopes and channels (tables 2 and 3).

WEPP-predicted average annual runoff and sediment yield for the 30-year period (1973–2002) were compared with the observed data for model performance assessment. Before comparison, the 9-month field observations for Watershed 5 were interpolated to 1-year values, and the 39 months of observed data for Watershed 6 were averaged to yearly values. Average annual values were preferred for the following two reasons. First, a 30-year simulation period is generally regarded adequate for estimating long-term average erosion potential (Elliot *et al.* 1999). Second, the climatic input for the WEPP runs was a combination of observed and CLIGEN-generated weather data, rendering detailed year-by-year comparisons inappropriate. Tables 2 and 3 list the model predictions and the observed data for Watersheds 5 and 6, respectively.

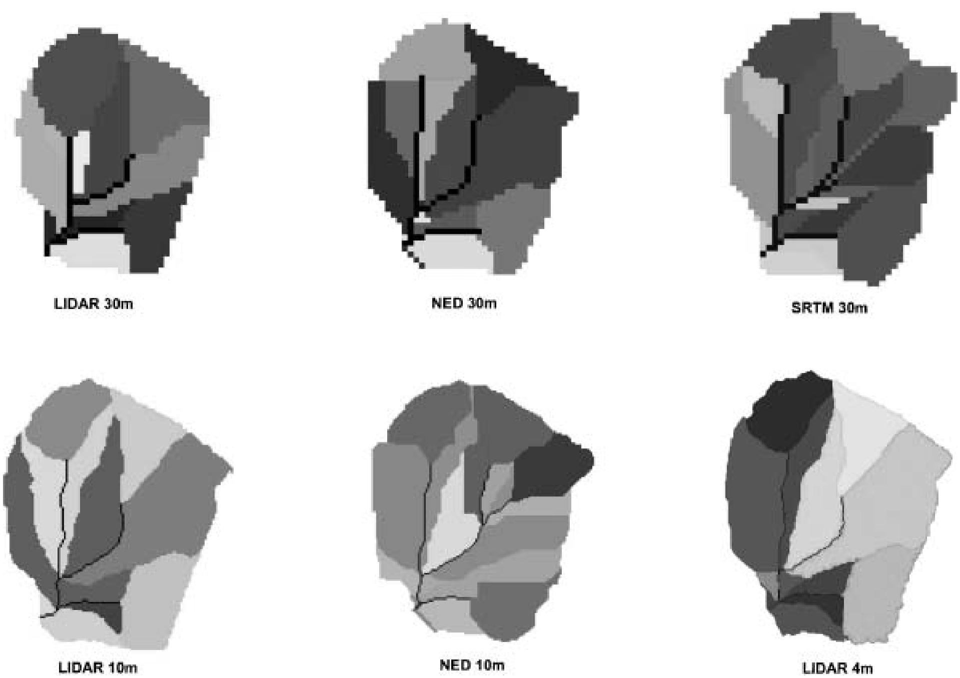

Figure 3. Hill slopes and stream channels (darker symbol) derived from the six DEMs for Watershed 5.

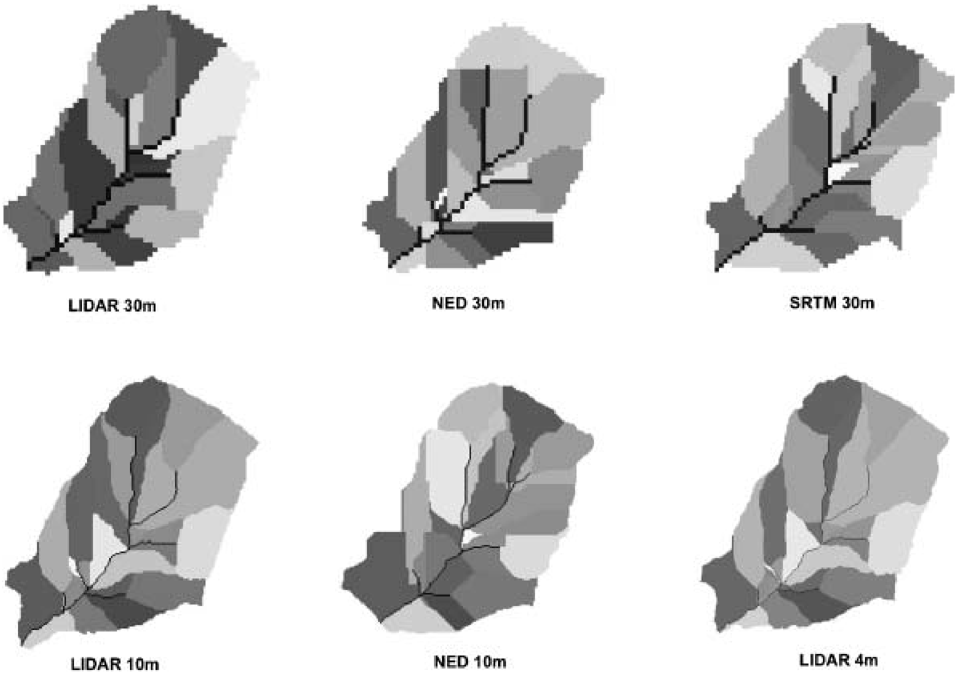

Figure 4. Hill slopes and stream channels (darker symbol) derived from the six DEMs for Watershed 6.

Compared with the observed data, all predictions of runoff and sediment yield were overestimates in Watershed 5 (table 2). The differences among the runoff predictions (63–74% greater than the observed value) were much less than the sediment yield predictions (52–922% higher than the observed value). All three 30-m DEMs led to overestimations of sediment yield by more than 100% of the observed value. Among them, the SRTM DEM had the greatest overestimate followed by the LIDAR DEM and the NED DEM. The finer-resolution DEMs improved the model performance substantially. The 10-m and 4-m LIDAR DEMs and the 10-m NED

Table 2. GeoWEPP-derived watershed areas, number of hill slopes, number of channels, and WEPP-predicted average annual runoff and sediment yield for each DEM for Watershed 5.[a]

DEM	Area (ha)	No. of hill slopes	No. of channels	Runoff ($m^3 yr^{-1}$)	Sediment yield ($t yr^{-1}$)
30-m LIDAR	112.9	13	5	2.41×10^5 (74)[b]	5.6 (306)[b]
30-m NED	110.7	13	5	2.39×10^5 (72)	4.0 (190)
30-m SRTM	112.3	18	7	2.35×10^5 (69)	14.1 (922)
10-m LIDAR	106.1	13	5	2.27×10^5 (63)	2.1 (52)
10-m NED	111.7	18	7	2.33×10^5 (68)	2.5 (81)
4-m LIDAR	107.3	13	5	2.29×10^5 (65)	2.2 (59)

[a]GeoWEPP uses TOPAZ to derive the topographic parameters. As a comparison, the same topographic parameters derived from ArcGIS 9® using LIDAR 4-m are: 106.4 ha for the watershed area, 11 for the number of hill slopes, and 6 for the number of channels.
[b]Shown in parentheses are deviations from the field-observed values in percentage.

Table 3. GeoWEPP-derived watershed areas, number of hill slopes, number of channels, and the WEPP-predicted average annual runoff and sediment yield for each DEM for Watershed 6.[a]

DEM	Area (ha)	No. of hill slopes	No. of channels	Runoff ($m^3\,yr^{-1}$)	Sediment yield ($t\,yr^{-1}$)
30-m LIDAR	178.3	22	9	3.76×10^5 (−8)[b]	6.2 (36)[b]
30-m NED	176.1	27	11	3.74×10^5 (−8)	6.2 (36)
30-m SRTM	176.0	27	11	3.63×10^5 (−11)	9.6 (111)
10-m LIDAR	176.6	28	11	3.79×10^5 (−7)	4.3 (−6)
10-m NED	179.6	28	11	3.72×10^5 (−9)	6.2 (36)
4-m LIDAR	176.8	28	11	3.83×10^5 (−6)	3.9 (−14)

[a]GeoWEPP uses TOPAZ to derive the topographic parameters. As a comparison, the same parameters derived from ArcGIS 9® using LIDAR 4-m are: 176.6 ha for the watershed area, 22 for the number of hill slopes, and 12 for the number of channels.
[b]Shown in parentheses are deviations from the field-observed values in percentage.

DEM generated smaller overestimations of sediment yield, all under 100% of the observed value. The 10-m LIDAR DEM provided the closest predictions of runoff and sediment yield, followed by the 4-m LIDAR and 10-m NED DEMs.

Results for Watershed 6 showed a different pattern of model predictions compared with those for Watershed 5 (table 3). All six DEMs resulted in underestimated runoff values, yet only four of them had overestimated sediment yields. The 30-m SRTM DEM had the poorest predictions among the six DEMs for both runoff and sediment yield. Predictions from the other five DEMs were all less than 10% from the observed runoff and less than 40% from the observed sediment yield. Overall, the predictions were much closer to the observed data than those for Watershed 5. The 30-m NED DEM and the 30-m LIDAR DEM provided similar predictions. The finer DEMs, 10-m LIDAR, 4-m LIDAR, and 10-m NED DEMs, did not improve the model performance as much as for Watershed 5. Still, they generated better predictions than the 30-m DEMs; the only exception was the 10-m NED DEM, which actually performed slightly worse than the 30-m NED DEM for the runoff prediction. The 10-m LIDAR DEM generated good runoff prediction and the closest sediment yield prediction. The 4-m LIDAR DEM had the closest runoff prediction and the second best sediment yield prediction. Clearly, the 10-m and 4-m LIDAR DEMs distinguished themselves from other DEMs by producing more agreeable predictions and consistent underestimation patterns for both runoff and sediment yield. Overall, the 10-m LIDAR DEM performed the best in predicting runoff and sediment yield values for both Watersheds 5 and 6.

An analysis of variance (ANOVA), at a significant level of 0.05, was carried out to compare the model predictions and field observations for the two watersheds. Model simulation results and field observation records for Watersheds 5 and 6 were combined for the single-replicate ANOVA test, with the three dependent variables being the watershed area, runoff, and sediment yield. The results showed that the differences among the watershed areas, as delineated by GeoWEPP (TOPAZ) and ArcGIS 9®, were not significant ($F=1.81$, $p=0.244$). The observed runoff value and the model-predicted runoff values from the different DEMs did not differ significantly either ($F=0.25$, $p=0.940$). However, the observed sediment yield and the model predictions from different DEMs were significantly different ($F=5.23$, $p=0.032$).

Table 4. Slope statistics for Watershed 5.[a]

DEM	30-m LIDAR	30-m NED	30-m SRTM	10-m LIDAR	10-m NED	4-m LIDAR
Average slope	18.17	18.93	16.85	20.79	20.37	21.46
Standard deviation	5.70	5.90	4.98	5.78	6.18	6.71
Minimum slope	0.26	1.38	1.38	0.28	1.04	0.00
Maximum slope	32.98	33.29	29.14	37.56	41.56	47.33

[a]ArcGIS 9® was used to compute slopes from DEMs.

6. Statistical analysis of slope

Descriptive statistics of slope was obtained for both Watershed 5 (table 4) and Watershed 6 (table 5). As the DEM resolution became finer, the average slope, standard deviation, and maximum slope values generally increased, and the minimum slope value generally decreased. This finding is consistent with the observation that an averaging of elevations and slopes occurs as the resolution is degraded (Gerrard and Robinson 1971, Fahsi 1989, Chang and Tsai 1991, Florinsky 1998, Gao 1998). The derived terrain tended to be smoother as the DEM resolution became coarser. Using the LIDAR DEMs as an example, the average slope in Watershed 5 increased from 18.2°, to 20.8°, and to 21.5° when the resolution was upgraded from 30 m, to 10 m, and to 4 m. Likewise, the average slope in Watershed 6 increased from 16.7°, to 19.5°, and to 20.2° when the resolution was upgraded from 30 m, to 10 m, and to 4 m. By holding the resolution constant, DEMs from different sources produced varied slope statistics. For the 30-m DEMs, the NED DEM had the highest average slope and the maximum slope, followed by the LIDAR DEM and the SRTM DEM. For the 10-m DEMs, the NED DEM had a smaller average slope but a larger maximum slope than the LIDAR DEM. The 4-m LIDAR DEM produced the highest average slope, standard deviation, and maximum slope, and the lowest minimum slope for both watersheds.

An ANOVA test was carried out to determine if the slope values derived from the six DEMs were significantly different. Slope readings at 30 randomly selected points were extracted from each of the slope grids derived from the six DEMs, resulting in a total of 180 slope readings for the ANOVA test. The results showed that the differences among the slopes derived from the six DEMs were significant (F=25.91, p<0.0001).

Table 5. Slope statistics for Watershed 6.[a]

DEM	30-m LIDAR	30-m NED	30-m SRTM	10-m LIDAR	10-m NED	4-m LIDAR
Average slope	16.71	17.63	15.85	19.53	18.86	20.15
Standard deviation	6.34	6.18	5.44	6.51	6.62	7.29
Minimum slope	0.26	1.10	1.02	0.44	0.49	0.00
Maximum slope	32.98	33.29	29.14	37.56	41.56	47.33

[a]ArcGIS 9® was used to compute slopes from DEMs.

Table 6. Major factors affecting the erosion simulations in Watershed 5.

DEM	Total erosion ($t\,yr^{-1}$)	Average hill slope length (m)	No. of erosion-generating hill slopes	Hill slope erosion ($t\,yr^{-1}$)	Average channel slope (°)	Total channel length (m)	Channel erosion ($t\,yr^{-1}$)
30-m LIDAR	5.6	228.1	1	2.7 (49)[a]	10.9	1933.7	2.9 (51)[b]
30-m NED	4.0	207.3	1	1.3 (33)	13.7	2341.2	2.7 (67)
30-m SRTM	14.1	238.1	2	10.9 (77)	14.6	2161.2	3.2 (23)
10-m LIDAR	2.1	211.3	0	0.0 (0)	12.6	1786.4	2.1 (100)
10-m NED	2.5	189.5	0	0.0 (0)	15.4	2150.2	2.5 (100)
4-m LIDAR	2.2	212.9	0	0.0 (0)	11.4	1833.5	2.2 (100)

[a]Shown in parentheses are ratios of hill-slope erosion to total erosion as a percentage.
[b]Shown in parentheses are ratios of channel erosion to total erosion as a percentage.

7. Discussion

7.1 *Erosion and topographic factors*

The analyses of erosion predictions and the slope statistics revealed that DEMs that generated steeper average slopes resulted in less erosion. This may appear counter-intuitive because it contradicts the general principle that steeper slopes have a greater potential to erode. However, average slope gradient is only one of many factors that can affect water erosion. Other important factors examined in this study included hill slope length, channel configuration, and channel slope. Further examination of the GeoWEPP and WEPP results revealed that different DEMs resulted in substantially different hill slope and channel systems, which in turn led to different erosion results (tables 6 and 7). A combination of these factors affected not only the gross sediment yield at the watershed outlet but also the distribution of erosion between the hill slopes and the channels.

As an example, the 30-m SRTM DEM simulated substantially more erosion than other DEMs. This result could be interpreted from several perspectives. First, the 30-m SRTM DEM resulted in the longest average hill slope length in Watershed 5 and the second longest in Watershed 6. Longer hill slopes tend to accumulate more runoff and increase the erosion potential. Second, the 30-m SRTM DEM yielded the highest number of erosion-generating hill slopes for both watersheds and predicted that hill slope erosion was the dominant form of erosion (77% of the total erosion

Table 7. Major factors affecting the erosion simulations in Watershed 6.

DEM	Total erosion ($t\,yr^{-1}$)	Average hill slope length (m)	No. of erosion-generating hill slopes	Hill slope erosion ($t\,yr^{-1}$)	Average channel slope (°)	Total channel length (m)	Channel erosion ($t\,yr^{-1}$)
30-m LIDAR	6.2	237.9	2	2.8 (45)[a]	8.6	2965.2	3.4 (55)[b]
30-m NED	6.2	204.7	3	1.6 (25)	11.1	3485.5	4.6 (75)
30-m SRTM	9.6	237.7	5	7.9 (83)	10.9	3247.6	1.7 (17)
10-m LIDAR	4.3	197.4	2	0.2 (5)	8.4	3390.8	4.1 (95)
10-m NED	6.2	209.4	2	2.7 (44)	12.2	3330.8	3.5 (57)
4-m LIDAR	3.9	187.7	1	0.1 (3)	7.9	3399.1	3.8 (97)

[a]Shown in parentheses are ratios of hill-slope erosion to total erosion as a percentage.
[b]Shown in parentheses are ratios of channel erosion to total erosion as a percentage.

for Watershed 5 and 83% for Watershed 6). Results using other DEMs, however, showed that channel erosion, instead of hill-slope erosion, was the predominant form. Third, the 30-m SRTM DEM produced relatively steep average channel slopes for both watersheds. Steep slopes greatly increase flow velocity, which then contributes to accelerated stream flow and channel erosion. The 30-m SRTM DEM had the second longest channel length in Watershed 5, but the second shortest in Watershed 6. Hence, the erosion overestimation was greater for Watershed 5 than Watershed 6.

In contrast to the 30-m SRTM DEM, the 4-m LIDAR DEM yielded substantially less erosion. It led to the shortest average hill slope length in Watershed 6, and fewest erosion-generating hill slopes for both watersheds. No hill slope erosion was predicted to occur in Watershed 5 and only 3% in Watershed 6, suggesting that the steepest hill slopes would not always produce the highest erosion. Channel erosion was predicted to be the dominant form of erosion, a finding consistent with field conditions in the study area (W. J. Elliot, USDA Forest Service, Rocky Mountain Research Station, Moscow, ID, USA, personal communication). The 4-m LIDAR DEM resulted in the second flattest average channel slope for Watershed 5 and the flattest for Watershed 6, likely contributing to the low erosion prediction.

Between the two extremes of the 30-m SRTM and the 4-m LIDAR DEMs, other DEMs produced intermediate hydraulic parameter values and erosion patterns. These results clearly showed that a single parameter (e.g. average slope gradient) cannot fully explain the erosion phenomena. Every physical terrain feature in this study can potentially contribute to the simulation outcome. The relationships between the terrain features, sediment yield, and the distribution of erosion (hill slope versus channel), as shown in tables 6 and 7, are therefore important to both the users and the developers of erosion models, including WEPP.

7.2 *Suitability of DEM for soil erosion modelling*

The study has found the 10-m LIDAR DEM to be a satisfactory topographic input source. The watersheds delineated from this DEM showed realistic boundaries, stream networks, and hill slopes. Both runoff and erosion predictions from the 10-m LIDAR DEM appeared most agreeable with the observed data. Overall, its performance was compatible with, if not better than, the 4-m LIDAR DEM, in this study, suggesting that a 10-m LIDAR DEM may be adequate for deriving topographic and hydrological parameters for runoff and water erosion modelling. The finding is consistent with Zhang and Montgomery's (1994) claim that 10 m is the proper resolution and the rational compromise between increasing resolution and data volume for simulating geomorphic and hydrological processes.

The 30-m LIDAR DEM in this study did not show any advantage over the 30-m NED DEM in terms of DEM accuracy, the quality of delineated watersheds, or hydrological and erosion predictions. This result supports the statement that large grid spacing in a LIDAR-extracted DEM may actually result in loss of data and high errors (Smith *et al.* 2003). Likewise, the 30-m SRTM DEM in this study appeared inadequate for generating topographic and hydrological attributes or for erosion prediction. In addition to its coarse resolution, its elevations are canopy-based and may not be appropriate for predicting erosion in small forested watersheds. Of the two NED DEMs for the study area, the 10-m DEM was slightly more accurate than the 30-m DEM. The 10-m DEM generated a relatively more realistic configuration of the watersheds than the 30-m DEM, but the two DEMs did not differ substantially in terms of runoff and sediment yield predictions.

7.3 *Comparison of hydrological and erosion predictions for Watersheds 5 and 6*

The runoff predictions showed different patterns for the two watersheds. For the smaller Watershed 5, all predictions were overestimates; for the larger Watershed 6, all were underestimates. One reason for such a runoff prediction pattern may be that WEPP does not model ground-water base flow. Deep percolation is not further routed to downstream watersheds as base flow. The overestimate of runoff for the upstream Watershed 5 is likely a result of an underestimation of the hydraulic conductivity for the bedrock beneath the soil profile. The under-prediction of runoff for the downstream Watershed 6, however, can be attributed to the lack of base-flow simulation.

For the erosion predictions, most were overestimates except those from using the 10-m and 4-m LIDAR for Watershed 6. Both runoff and erosion predictions appeared more agreeable with the field observations for Watershed 6 than for Watershed 5. The sediment yield predictions from the 30-m LIDAR, 30-m NED, and 10-m NED DEMs were identical for Watershed 6 but varied greatly for Watershed 5. Topographically, the smaller watershed has steeper slopes and more complex terrain, making it crucial to have accurate topographic inputs for runoff and erosion simulation. Selecting the appropriate DEM with proper accuracy and resolution is therefore critical in simulating hydrological and erosion processes in mountainous areas with large slope variations and complex terrain.

7.4 *Comparison with previous WEPP studies*

Previous WEPP applications have shown unsatisfactory results of hydrology and erosion simulations for forested watersheds. Elliot *et al.* (1996) found that WEPP predicted only 50% of the observed runoff and 10 times more sediment yield than was observed in a harvested forest watershed. Koopman (2002) claimed that using 30-m DEMs, GeoWEPP over-predicted the runoff by 10–50 times, and under-predicted the sediment yield by 50%, of the field-observed values in small forested watersheds. Compared with these findings, our study has shown that WEPP v2006.5 can generate satisfactory predictions of runoff and sediment yield for forested areas by using the proper DEMs. The predicted long-term average annual runoff from using the 10-m LIDAR DEM was 63% greater than the observed value ($1.39 \times 10^5\,m^3$) for Watershed 5, and was 7% smaller than the field observation ($4.07 \times 10^5\,m^3$) for Watershed 6. With respect to sediment yield, the predicted long-term average annual value from using the 10-m LIDAR DEM was 52% greater than field observation (1.38 t) for Watershed 5, and was 6% smaller than the observed value (4.55 t) for Watershed 6.

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