A comparative appraisal of hydrological behavior of SRTM DEM at catchment level

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SUMMARY

The Shuttle Radar Topography Mission (SRTM) data has emerged as a global elevation data in the past one decade because of its free availability, homogeneity and consistent accuracy compared to other global elevation dataset. The present study explores the consistency in hydrological behavior of the SRTM digital elevation model (DEM) with reference to easily available regional 20 m contour interpolated DEM (TOPO DEM). Analysis ranging from simple vertical accuracy assessment to hydrological simulation of the studied Maithon catchment, using empirical USLE model and semidistributed, physical SWAT model, were carried out. Moreover, terrain analysis involving hydrological indices was performed for comparative assessment of the SRTM DEM with respect to TOPO DEM. Results reveal that the vertical accuracy of SRTM DEM (±27.58 m) in the region is less than the specified standard (±16 m). Statistical analysis of hydrological indices such as topographic wetness index (TWI), stream power index (SPI), slope length factor (SLF) and geometry number (GN) shows a significant differences in hydrological properties of the two studied DEMs. Estimation of soil erosion potentials of the catchment and conservation priorities of micro-watersheds of the catchment using SRTM DEM and TOPO DEM produce considerably different results. Prediction of soil erosion potential using SRTM DEM is far higher than that obtained using TOPO DEM. Similarly, conservation priorities determined using the two DEMs are found to be agreed for only 34% of microwatersheds of the catchment. ArcSWAT simulation reveals that runoff predictions are less sensitive to selection of the two DEMs as compared to sediment yield prediction. The results obtained in the present study are vital to hydrological analysis as it helps understanding the hydrological behavior of the DEM without being influenced by the model structural as well as parameter uncertainty. It also reemphasized that SRTM DEM can be a valuable dataset for hydrological analysis provided any error/uncertainty therein is being properly evaluated and characterized.

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1. Introduction

Topography represented in the form of digital elevation model (DEM) has profound application in hydrological modeling. DEM is a computer representation of the earth’s surface in raster form as a two-dimensional array of cells where each grid cell has an elevation value (Burrough and McDonnell, 1998). DEM can be generated from various sources such as contour interpolation (GTOPO 30), radar interferometry (SRTM), optical stereo images (ASTER DEM), and Lidar cloud. In either case the methods of collection of elevation points are different and/or the principles behind DEM generation thereof, are different. This may potentially introduce some uncertainties in DEM.

The Shuttle Radar Topography Mission (SRTM) provides for the first time a near-global high-resolution DEM with great advantages of being homogeneous in quality and free availability. In the past eight–ten years, scientific communities have seen a large number application of SRTM DEM for various application (Yang et al., 2011). Unfortunately, the original SRTM data is not error free and contain error from different sources (Falorni et al., 2005). The unfinished SRTM elevation data includes surface elevation such as trees, buildings and other objects on the earth surface (Rodriguez et al., 2006), generalization (averaging or thinning) of SRTM DEM outside the USA (Slater et al., 2006), systematic error (sometime appears as stripping), presence of missing data called voids (Kervyn, 2001). All these error sources reduce its reliability for practical applications.

Many researchers have evaluated the accuracy and usefulness of SRTM DEM (Becek, 2008; Miliareis, 2008). SRTM DEM has been
evaluated across the globe using different reference elevation data including global positioning system (GPS) based check points (Athmania and Achour, 2014; Sun et al., 2003; Suwandana et al., 2012); LiDAR elevation data (Bhang et al., 2007); high resolution photogrammetric DEM (Du et al., 2013; Fujita et al., 2008; Huggel et al., 2008; Mukherjee et al., 2013) and elevation data from existing topographic maps (Bildirici et al., 2009; Jing et al., 2013; Lin et al., 2013; Liu et al., 2014; Sharma et al., 2010b; Tsanis et al., 2014; Wang et al., 2012).

Although several studies confirmed the ±16 m vertical accuracy at 90% confidence level for SRTM DEM, but some other researchers have reported that SRTM has failed to achieve the expected accuracy of ±16 m (Bonnici and Eisner, 2007) or of low accuracy than contour DEM (Sefercik, 2007) or photogrammetric DEM (Bonnici et al., 2013; Li et al., 2013; Nikolakopoulos et al., 2006; Shafique and van der Meijde, 2014; Thomas et al., 2014).

Errors of such a magnitude in input DEM can have serious effect on the hydro-geomorphological modeling (Bhang and Schwartz, 2008; Sanders, 2007). It has been also reported that DEM accuracy highly specific to a particular region (topography, geomorphology of the area) and to its specific application as well (Sharma et al., 2010a).

Thus, it is imperative to reevaluate the usefulness of the SRTM DEM. However, the accuracy and applicability of a DEM highly depends upon the purpose and regional topography. A simple vertical accuracy assessment of the DEM will not be of much useful to the researchers. In this article attempts have been made for a complete evaluation of hydrological behavior of SRTM DEM with reference to contour interpolated DEM. The manuscript provides a complete approach; from a simple vertical accuracy assessment to implementation of a semidistributed physically based hydrological model to understand the hydrological behavior of two terrain dataset. The main objective of this study is to make a comparative assessment of discrepancy in the hydrological behavior of the SRTM DEM in terms of terrain representation, and simulation of erosion potential, runoff and sediment yield at catchment scale.

2. Methodology

2.1. Study area

The catchment of Maithon Reservoir has been selected as study area for this research work. The catchment spreads over the undulating terrain of the Chota Nagpur plateau and is seriously affected by soil erosion. It lies at downstream of Tilayia dam, across the Barakar River and is located in the Jharkhand state of India (Fig. 1). The geographical extent of the catchment lies between 85°25’ and 86°54’ E Longitude and 23°45’-24°34’ N Latitude with an area of about 5550 km². The catchment is characterized by a wide diversity of physical and hydrological features viz. geology, topography, climate, and land use. The elevation of the catchment ranges from 120 m to 1332 m (Parasnath Hill) above the mean sea level. The southern portion of catchment is characterized by steep grounds, the Parasnath Hills and the adjoining Tundi Hills which separate the catchment from the Damodar catchment.

2.2. Data collection and preparation

The various spatial data and attributes data used in this study were obtained as follows:

2.2.1. Topography

The topography of the catchment was represented in the form of DEM obtained from two different elevation sources (Fig. 2). The first DEM was void-free SRTM dataset, version 3.0, obtained from the Consortium for Spatial Information of the Consultant Group for International Agriculture Research (CGIAR-CSI). The finished product is slightly coarser than the finished SRTM DEM and is good for areas where the SRTM delivered reliable data (Jarvis et al., 2006). The second DEM (TOPO DEM) was prepared by interpolation of 20 m interval contour lines extracted from the Survey of India (SOI) topographic maps of 1:50,000 scale. TOPOGRID interpolation method, implemented in ArcInfo GRID module, was used to generate the TOPO DEM. It is because TOPOGRID interpolation was found to be superior for the studied catchment as compared to several other interpolation methods to generate a DEM (Sharma et al., 2010a). To avoid any discrepancy accounting for DEM cell size, the TOPO DEM was obtained at regular posting of 90 m to match the resolution of SRTM DEM. Although TOPOGRID can incorporate ancillary hydrologic data (streams and lakes) to remove sink and to represent hydrographic features more accurately, this option was not used at this stage. Besides these, independent spot heights at 1011 points (comprised of geodetic bench marks, tertiary bench marks and geodetic triangulation stations) were also collected from the same topographic maps for vertical accuracy assessment of the SRTM DEM.

2.2.2. Soil

The detail spatial information on soil of the study area was extracted from the soil map (1:250,000 scale) provided by National Bureau of Soil Survey and Land Use Planning, (NBSS & LUP) Kolkata, India. Soil samples were collected from 179 sampling sites and were analyzed for texture, soil organic carbon and bulk density at Soil Laboratory, Damodar Valley Corporation (DVC), Hazaribagh, Jharkhand, India.

The different soil textural classes and their distribution within the catchment are shown in Fig. 3(a). Hydraulic conductivity and soil hydrologic group (SHG) were determined based on the analyzed soil parameters along with topography, drainage pattern, vegetation, parent rock material as well as weathering of parent materials. The final soil hydrologic group map (Fig. 3(b)) shows the presence of only two SHGs i.e. A and C.

2.2.3. Land use and land cover (LULC)

The spatial distribution of the different land use land cover (LULC) classes required for hydrological studies were prepared using IRS P6 LISS III satellite image of the year 2005. The satellite image was classified for five major LULC (i.e. namely water bodies, forest land, cropland, wasteland and settlement) using maximum likelihood classifier algorithm available in Erdas Imagine software. The required ground truth data were collected from field visit in the same month in which the image was acquired and from Google Earth images as well. A 5 × 5 modal filter was also applied to the LULC map to remove noisy pixels or isolated pixels resulting from boundary errors. The overall classification accuracy of the LULC map was 89%.

2.2.4. Hydro-meteorological data

The study area is very poorly gauged catchment and is suffering from scarcity of hydro-meteorological data. The various hydro-meteorological data, available only at coarse resolution for very few stations, were collected from the Soil Conservation Office of Damodar Valley Corporation (DVC) located at Hazaribagh, India. The long term meteorological data such as rainfall, minimum and maximum temperature, humidity, wind speed, and solar radiation and duration, are available for only Usri station. Thus, Usri was used as only climatic station in the present study to generate missing meteorological data during hydrological modeling using ArcSWAT model.

The daily rainfall, runoff and sediment yield data were also collected from four rain gauge stations located at Giridih, Pokharia,
Fig. 1. Location map of the study area.

Fig. 2. DEMs of the study area (a) TOPO DEM and (b) SRTM DEM.

Fig. 3. Soil maps of study area (a) soil textural class, and (b) hydrologic soil group.
Santrabad and Rajdhawan for monsoon season (i.e. June to September) for the year 1998–2005. The daily temperature (minimum and maximum) data were obtained from only two stations at Rajdhawan and Santrabad for the same time period.

2.3. Methods

2.3.1. Vertical accuracy

The vertical accuracy of the SRTM DEM was evaluated with respect to 1011 check-points collected from SOI topographic maps. These check points are mostly composed of geodetic bench marks, tertiary bench marks and few geodetic triangulation stations. It is worthless to mention that the elevations (reduced level) of the points are determined though conventional field surveying method (leveling procedure) by Survey of India i.e. the national geodetic surveying agency of India. Hence, it is one of most accurate point data available in the region for accuracy assessment of other topographic data. The accuracy was reported in terms of root mean square (RMSE), mean error (ME), and mean absolute error (MAE) calculated through 500 bootstrap iterations.

2.3.2. Terrain analysis

The hydrological behavior of SRTM DEM was further evaluated by comparing it with TOPO DEM for following terrain based hydrological indices:

- **Topographic wetness index (TWI):** It has been used extensively to describe the effects of topography on the location and size of saturated source areas of runoff generation. The concept was first used in TOPMODEL and further developed in the 1990s (Wilson and Gallant, 2000). It can be expressed as follows:

  \[
  W = \ln \left( \frac{A}{\tan \beta} \right)
  \]

  where \( A \) is calculated from specific catchment area (\( m^2 \)) of a point and \( \tan \beta \) is the local slope gradient in degrees.

- **Length-Slope factor (LS factor):** Moore and Wilson (1992) implemented LS factor in the Universal Soil Loss Equation (USLE) to estimate the value for water erosion potential relative to a slope of 22.13 m length and a slope angle of 5°. It can be represented as following equation:

  \[
  LS = (m + 1) \left( \frac{A}{22.13} \right) \left( \frac{\sin \beta}{0.0896} \right)^n
  \]

  where \( m = 0.4 \) and \( n = 1.3 \) for a slope length <100 m and a slope angle <14°.

- **Stream power index (SPI):** It calculates a spatially distributed sediment transport capacity of flowing water. It may be more suited to erosion assessment than any other approaches because it accounts for flow convergence and divergence. It computes soil loss potential by assuming uniform rainfall excess runoff and the erosion rate is transport limited rather than detachment (Wilson and Lorang, 1999). Mathematically,

  \[
  SPI = A \tan \beta
  \]

  where \( A \) and \( \tan \beta \) are specific catchment area (assumed to be proportional to discharge, q) and local slope, respectively.

- **Geometry number (GN):** Strahler (1964) combined three topographic attributes such as drainage density (D), slope (S), and relief (H) that quantitatively distinguish a landscape using following relation to form what is called geometry number:

  \[
  GN = HD/S
  \]

where \( GN \) is geometry number and its value vary from about 0.4 and 1.0 (a perfect triangular-shaped ridge-and-valley topography would give \( G = 0.5 \)). Relief \( H \) is measured as the elevation difference between highest peak and outlet of a watershed. Drainage density \( D \) is the length of stream per unit area (\( km^2 \)) of the watershed while slope is dimensionless and is generally expressed in percentage.

2.3.3. Hydrological simulation

The comparative evaluation of hydrological behavior of SRTM DEM was further extended to simulation of real world hydrological processes i.e. soil erosion potential, sediment yield and runoff generation from the catchment using an empirical model (USLE) and a physical model (SWAT).

- **Universal Soil Loss Equation (USLE).** The SRTM DEM and TOPO DEM were used as basic topographic data for comparative assessment of soil erosion potential of the catchment using USLE. It is an empirical model (Wischmeier and Smith, 1978) which calculates long-term average soil erosion potential on grid basis as follows:

  \[
  A = R \times K \times LS \times C \times P
  \]

  where \( A \) is average annual soil loss rate (t ha\(^{-1}\) yr\(^{-1}\)), \( R \) is rainfall erosivity factor (MJ mm ha\(^{-1}\) h\(^{-1}\) yr\(^{-1}\)), \( K \) is soil erodibility factor (t ha h\(^{-1}\) MJ\(^{-1}\) mm\(^{-1}\)), \( LS \) is topographic factor, \( C \) is crop management factor, and \( P \) is conservation supporting practice factor.

  The \( R \)-factor was estimated using Wischmeier (1959) formula using daily rainfall data collected from three rain gauge stations namely Rajdhawan, Pokhariya and Giridih for the year 1989–2001. The average annual \( R \) factors of the three stations were then interpolated using Thiessen polygon. For the estimation of \( K \)-factor, 179 representative soil samples and 1:1 M scale soil map (Source: NBSS–National Bureau of Soil Survey) were analyzed for soil textual classes and organic carbon. Finally, formula suggested by Foster et al. (1991) was used to determine the \( K \) factor. \( LS \) factor is product of slope length factor and slope steepness factor. It was calculated using McCool et al. (1987) formula in local operation for the DEMs. \( C \)-factor was determined using land use land cover (LULC) map. The values of \( C \)-factor assigned to individual LULC class is based on the published literature i.e. water bodies (1.000), forest land (0.004), cropland (0.320), wasteland (0.100) and settlement (0.002). Since no major conservation practice was prevailing in the catchment, \( P \)-factor was invariably considered as unity (Shinde et al., 2011).

2.3.3.2. Soil and Water Assessment Tool (SWAT).** The comparative assessment of DEMs for runoff and sediment yield from the catchment was carried out using Soil and Water Assessment Tool (SWAT) version 1.0.7. It is a semi-distributed physical and continuous-time model that operates on a daily/monthly/yearly time step to predict the long-term impact of management on runoff and sediment in large complex watersheds. The simulation of the catchment’s hydrological cycle is divided into two categories: the land phase and the water or routing phase. The land phase describes the movement of water, nutrients, and sediments throughout the sub-watersheds (based on hydrologic response unit – HRU) to their main channel. The water, or routing, phase characterizes how water moves through the water channel system (Neitsch et al., 2005). A soil water content water balance equation provides the basis for the modeling processes in SWAT:

  \[
  SW_i = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{runoff} - E_a - w_{leak} - Q_{gw})
  \]

  SWAT computes surface runoff from each HRU through Soil Conservation Service (SCS) Curve Number (CN) approach and estimates sediment yield using the Modified Universal Soil Loss Equation (MUSLE) from all sources within a sub-watershed. It uses
Muskingum method which is based on travel time of the flow to route runoff and sediment from the subwatersheds to the watershed outlet.

The SWAT model was autocalibrated using input data such as LULC map of 2004, soil map, meteorological data, and TOPO DEM. The calibration was done using observed runoff and sediment yield data for Rajdhawan microwatershed station. The calibrated model parameters were subsequently applied to all the microwatersheds of the catchment through manual calibration. It is quite obvious that optimum physical parameters of SWAT model for the two DEM dataset would be different. In order to avoid the uncertainty due to the optimum model parameters, SWAT model was rerun using SRTM DEM by keeping all the boundary conditions and model parameters remain unchanged.

3. Results and discussion

3.1. Vertical accuracy

The vertical accuracy of SRTM DEM was determined with respect to reference (check) point data through 500 bootstrap iterations. The values of various accuracy statistics; root mean square (RMSE), mean error (ME) and absolute mean error (AME) were found to be 27.58 m, 6.77 m and 14.48 m, respectively. Since the check points are SOI collected geodetic Benchmark and triangulation stations, it elevation accuracy is one most accurate reference data available in the region. Since the accuracy statistics were calculated through 500 bootstrapped iterations, any error owing to the presence of outliers or subjective selection of check points was eliminated to great extent. The positive value of ME indicates that SRTM DEM is over predicting the elevation values in comparison to reference point elevation data obtained from topographic maps. The RMSE values SRTM DEM was also found relatively higher (27.58 m) as compared to it specified standard of ±16 m. It suggests that the SRTM DEM quality is not uniform or as per the specified standard for many regions. This observation is very much similar to some of the other research works (Bonnici et al., 2013; Li et al., 2013; Shafique and van der Meijde, 2014; Thomas et al., 2014) on SRTM DEM accuracy assessment. The descriptive statistics of elevation and slope values are presented in Table 1.

The elevation values predicted by SRTM are higher than the TOPO DEM as envisaged from the range (Max–Min) and mean values. The mean and standard deviation (SD) of elevation of SRTM DEM are higher than TOPO DEM. A similar observation is also reported by Su and Guo (2014). In order to explore if the higher standard deviation are really corresponding to information content, a simple technique was applied. It involves the calculation of local mean and SD for both the DEMs using 5 x 5 windows. If any pixel in the studied DEM has an elevation value either lower than (Mean–3SD) or higher than (Mean+3SD) was assigned as noisy pixel. It was found that SRTM DEM has 0.23% noisy pixels as compared to 0.01% for TOPO DEM.

Similarly, SRTM DEM provided slope significantly higher as compared to TOPO DEM. These observations are quite comparable to those reported by (Kinsey-Henderson and Wilkinson, 2013). TOPO DEM under-predicts slope severely and mostly in low altitude due to flattening of profiles near contours. TOPO DEM is shown to have always less accurate to represent slopes where contour data are sparse while SRTM DEM is noisy (as represented by higher SD value) to be used in region slope less than 5% (Falorni et al., 2005). In order to get the spatial distribution of elevation errors, an error surface was generated by subtracting the SRTM DEM from reference TOPO DEM.

Error surface (Fig. 4) is a promising option to explore the spatial distribution of elevation error as well as depiction of terrain shape distortion in SRTM DEM. The error surface generated here may not be able reveal which one is the superior DEM. The main purpose of elevation error surface is to make a visualization of the eleven discrepancies between the DEMs and discrepancy in terrain shape thereof if any. This also helps to explore the terrain dependency of elevation discrepancy. Fig. 4 shows that the magnitude of elevation error for the SRTM DEM ranges from –226.8 m to 149 m. Error surface allows the visualization of error distribution more apparent which cannot be revealed otherwise. The place of serious errors and their terrain dependency are also become evident. The high positive errors represented by red color (under estimation) are generally found in the hilly region (steep slope) and over the reservoir while high negative error represented by blue color (overestimation) are generally found in northern slope of hill, valley and along the river channel. This may be due to the data hole corresponding large water body and radar shadow effect in the area of steep slope (Rodriguez et al., 2006; Slater et al., 2006). The error values are spatially correlated which is evident from the number of big patches of both positive and negative elevation error. Interestingly, the error surface did not show any stripping indicating the rectification of systematic error and misregistration errors of individual tile of elevation data. Finally, the frequency distribution of elevation error is shown using histogram plot (Fig. 5).

The histogram plot indicates that the distribution of error is more or less normal and the magnitude of ±40 m error comprises around 95% of the error distribution. The high elevation discrepancy (±40 m) occurs at local high points (peaks) which are measured accurately by SOI topographic maps but the SRTM DEM fails to do, may be due to hydrological conditioning of the same. The result shows a good agreement with Dowling et al. (2011). It suggests that the spatial resolution of SRTM DEM is not sufficient to discern the local peaks.

3.2. Terrain analysis

The possible implications on SRTM DEM error on its hydrologic behavior was further explored by comparative assessment of terrain based hydrological indices such as TWI, SPI, SLF, and GN. The terrain analysis was carried out using the above compound indices due to the fact that they have hydrological significance and are being used extensively as an input in one or another hydrological model. The values of minimum, maximum, mean, and standard deviations (SD) for various indices are presented in Table 2.

It is quite evident from the values of range (max–min) for SPI and SLF (slope dependent) that the variations among the two DEMs are quite large as compared to other two indices i.e. TWI and GN. This observation reconfirms a significant difference in the slope calculation by the two DEMs. Although the range and SD of these two indices is large for TOPO DEM as compared to SRTM DEM,

| Table 1 | | | |
|---|---|---|---|---|---|---|---|
| | Min | Max | Mean | Median | Lower quartile | Upper quartile | SD |
| TOPO DEM | 115.93 | 1322.06 | 317.45 | 326.43 | 278.06 | 360.00 | 85.66 |
| SRTM DEM | 88.00 | 1358.00 | 323.48 | 334.00 | 278.00 | 367.00 | 87.34 |
| TOPO slope | 0.00 | 28.53 | 1.18 | 0.47 | 0.18 | 1.05 | 2.42 |
| SRTM Slope | 0.00 | 42.32 | 2.12 | 1.58 | 1.04 | 2.22 | 2.72 |
the mean values for the same are higher in SRTM DEM. These results are in good agreement with the results obtained by Thomas et al. (2014). The median, lower and upper quartile values suggest that not only the range and mean but their distributions are also different. The difference in the values of TWI derived by the two DEMs is relatively less and for GN, the difference is least among the four hydrological indices examined in this study. The distributions of the values of these four indices were further compared using cumulative distribution functions (CDF) and non-parametric Kolmogorov–Smirnov (K–S) test. K–S test being the non-parametric test it so not assume any statistical distribution of the data (distribution free) and it is considered to be more robust than t-test when the mean of the data groups do not vary significantly (Table 2).

TWI, used in TOPMODEL, is based on the assumption that topography controls the movement of water in sloped terrain. Hence, it has bearing on the spatial pattern of soil moisture, areas of runoff generation and potential soil erosion.

Fig. 6 illustrates a remarkable difference in the CDF of TWI derived from the two DEMs. The CDF for TOPO 90 is S-shaped with upper limb and lower limb almost symmetrical and the central portion shows a gentle uniform slope. In contrast, the CDF of SRTM DEM is asymmetrical (skewed toward higher TWI value) with short lower limb and larger flat upper limb. The central part of the CDF is highly steep and shifted to the left of CDF of TOPO 90. All these observations indicated that CDF of TOPO 90 is skewed toward higher value. It means using SRTM will be resulted in less saturated surface and hence it is likely to generate less runoff as compared TOPO 90 DEM. The $D_{\text{max}}$ values obtained from K–S test carried out for the two CDFs were found to be 0.624 ($p$-value < 0.001 at $\alpha = 0.05$). It indicates that the SRTM and TOPO 90 DEMs are significantly different in terms of surface wetness property.

Table 2
Descriptive statistics of various terrain indices.

<table>
<thead>
<tr>
<th>Indices</th>
<th>Mean</th>
<th>Median</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Lower quartile</th>
<th>Upper quartile</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOPO_TWII</td>
<td>9.61</td>
<td>9.48</td>
<td>5.22</td>
<td>19.95</td>
<td>8.67</td>
<td>10.45</td>
<td>1.56</td>
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<tr>
<td>SRTM_TWII</td>
<td>8.30</td>
<td>8.37</td>
<td>5.20</td>
<td>11.05</td>
<td>8.14</td>
<td>8.59</td>
<td>0.54</td>
</tr>
<tr>
<td>TOPO_SPI</td>
<td>0.12</td>
<td>0.02</td>
<td>0.00</td>
<td>8.04</td>
<td>0.00</td>
<td>0.10</td>
<td>0.32</td>
</tr>
<tr>
<td>SRTM_SPI</td>
<td>0.14</td>
<td>0.10</td>
<td>0.00</td>
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<td>0.05</td>
<td>0.19</td>
<td>0.14</td>
</tr>
<tr>
<td>TOPO_SLF</td>
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<td>0.02</td>
<td>0.00</td>
<td>54.12</td>
<td>0.00</td>
<td>0.08</td>
<td>0.54</td>
</tr>
<tr>
<td>SRTM_SLF</td>
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<td>0.09</td>
<td>0.00</td>
<td>11.11</td>
<td>0.06</td>
<td>0.13</td>
<td>0.32</td>
</tr>
<tr>
<td>TOPO_GN</td>
<td>2.33</td>
<td>1.93</td>
<td>0.00</td>
<td>300.00</td>
<td>0.68</td>
<td>3.25</td>
<td>3.37</td>
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<td>SRTM_GN</td>
<td>2.80</td>
<td>2.25</td>
<td>0.00</td>
<td>299.86</td>
<td>0.80</td>
<td>3.85</td>
<td>3.26</td>
</tr>
</tbody>
</table>
SPI is the time rate of energy expenditure and is used extensively as a measure of the erosive power of flowing water. Unlike TWI, the CDFs of the SPI (Fig. 7) were spherical/parabolic. There is no shifting of curve with respect to each other. The lower limb is almost absent in both CDFs. However, the upper limb is comparatively longer and flattened for SRTM DEM than TOPO 90. Moreover, the steeper CDF of SPI in case of SRTM DEM indicates that it is skewed toward higher value. This could lead to higher sediment transport or lower deposition. Hence, comparatively higher sediment yield can be expected on using the SRTM DEM than TOPO DEM for the same catchment under a similar set of environmental condition and model set up. The $D_{\text{max}}$ value of 0.472 for K–S test indicates that the distributions of TPI obtained from SRTM and TOPO DEM are significantly different from each other ($p < 0.001$, $\alpha = 0.05$).

SLF implemented in USLE model is directly proportion to the total soil erosion per unit area. The cumulative distributions of SLF (Fig. 8) follow more or less similar shape as observed in case of SPI. However, the central part is relatively less steep and the upper limb is also relatively less flat for SRTM DEM. Hence, the gap between the two CDF is widen up in upper limb region while the gap is reduced in the central region. It indicates that CDF of SLF is comparatively less skewed toward higher value as compared to CDF of SPI. However, CDF of SRTM DEM derived LSF remains above the CDF of SLF derived from TOPO DEM. Thus, it can be inferred that using SRTM DEM will lead to prediction of higher soil erosion as compared to TOPO DEM. The $D_{\text{max}}$ value of 0.544 for K–S test also indicates statistically significant difference ($p < 0.001$, $\alpha = 0.05$) between the two cumulative distribution curves. As stated earlier the variation in the distribution of SLF and SPI for the two DEMs can be attributed to contour flattening/terracing effect in TOPO DEM and some noisy behavior of SRTM DEM for terrain less than 5% slope.

Geometry number (GN) is a useful indicator of catchment micro-topography as it derives from three geomorphometric parameters namely relief, drainage density and mean slope. The value of GN for a smooth triangular ridge and valley topography would be 0.5. As the value GN increases the topography becomes increasingly more rough and complex in nature, the GN value is supposed to be more. Fig. 9 presents the cumulative distribution of geometry number (GN) of the catchment topography as depicted by the two DEMs. The figure shows a curve with no lower limb, gentle sloping central part and an upper limb for both CDFs. The two CDFs do not show any crossover between them. It is observed that the CDF of TOPO DEM was consistently above the CDF of SRTM DEM for all the quantile values and the vertical distance ($D$ value) gradually decreases toward upper quantiles. This indicates that referring SRTM DEM the terrain of the catchment will be appeared more complex than what it would be depicted by the TOPO DEM. The K–S test indicates that difference between two cumulative distribution curves is significantly different ($p < 0.001$, $\alpha = 0.05$). Despite of high drainage density of SRTM DEM as compared to TOPO DEM, the CDFs of GN is not much different for the two DEMs ($D_{\text{max}} = 0.186$). It is because of reduction of relief and increase of slope values for SRTM DEM. It indicates that the difference in the geometry of catchment micro topography is relatively less as compared to other hydrological indices on using the SRTM in place of TOPO DEM.

The discussions above indicate that difference in elevation values of the two DEMs are propagated into terrain analysis. It is evident that indices that are derived directly from a single DEM value (e.g. TWI, SPI, SLF) show a larger variability than index that is indirectly computed using more than one terrain parameters (e.g. GN). The results agree with the observations of (Frey and Paul, 2012). It is further revealed that statistically significant differences in the hydrological property of the two DEM surfaces exist. It reaffirms that a proper evaluation of the SRTM DEM is required for its subsequent use for hydrological application.

### 3.3 Hydrological simulation

The effect of variations in topographic properties, as revealed from vertical accuracy assessment and the terrain analysis, of the two DEMs on their hydrological behavior were subsequently explored by simulating the soil erosion potential of the catchment using an empirical model (i.e. USLE), and also runoff and sediment yield using a semi-distributed physical model (i.e. SWAT). The results are discussed in sections below.
3.3.1. Universal Soil Erosion Equation (USLE) simulation

The potential use of SRTM DEM for soil erosion mapping was comparatively evaluated with TOPO DEM using Universal Soil Loss Equation (USLE) model. The output soil map was compared using their cumulative distribution function (Fig. 10).

Fig. 10 shows that the distribution curves are spherical/parabollic in shape for both the DEMs derived soil erosion potential maps. It illustrates that for SRTM DEM the catchment area with soil erosion rate less than one ton/ha/year comprising of 32% while for TOPO DEM it is as high as 42%. The relatively large area with low erosion potential in case of TOPO DEM could be due the error in the calculated slope or large amount of flat area. This may in turn due to the stair-case type effect accounting for insufficient vertical resolution and horizontal sampling density of elevation value (Sharma et al., 2011).

The slope errors in the TOPO DEM translated into relatively lower and less consistent erosion estimates than SRTM DEM. Moreover, the upper limb of the curve for TOPO DEM levels off much earlier to that of SRTM DEM. This suggests that using SRTM DEM would be resulted in a net higher soil erosion potential than using TOPO DEM. These results are quite similar to that of Kinsey-Henderson and Wilkinson (2013) who also observed that the SRTM DEM provides estimates of slope and erosion more accurate, and more consistent as compared to interpolated DEM. Although the shape of the two CDF appeared more or less similar, the K-S test obtained a $D_{max}$ value of 0.423 and indicated that the two distributions are significantly different from each other ($p < 0.001$, $\alpha = 0.05$).

In order to explore the soil erosion behavior of the catchment at basic management unit, erosion potentials for 205 microwatersheds provided by DVC were determined. It was found that SRTM DEM predicted higher erosion potential for different microwatersheds of the catchment than those obtained using TOPO DEM. The paired t-test carried out for equal means of erosion potential of microwatershed as simulated using two DEMs indicated a significant difference ($p < 0.001$, $\alpha = 0.05$). Even though the mean erosion potential varied significantly for the two DEMs, the microwatershed priority may be similar. Hence, Spearman rank correlation coefficient test was performed. The obtained $r$-value of 19.95 (df = 137, $p < 0.001$, $\alpha = 0.05$) suggests that there is also a significant difference in the microwatershed priority obtained using the two DEMs.

The microwatersheds were further categorized into conservation priority categories (Table 3) as suggested by Singh et al. (1992). It was found that 176 microwatersheds were falling under high to very high conservation priority when SRTM DEM was used as against only 88 microwatersheds on using the TOPO DEM. Similarly, none of the microwatershed is found under low conservation priority category if the soil erosion potential was predicted using SRTM DEM in contrast to 36 microwatersheds as obtained using TOPO DEM.

Table 4 indicates a poor agreement between conservation priority categories as predicted by USLE model runs using SRTM DEM and TOPO DEM. The prediction accuracy is only 34% and is completely biased toward higher conservation priority of different microwatersheds.

The results of various analyses indicate that SRTM DEM and TOPO DEM predicted soil erosion potentials are poorly matching (not in agreement) both at catchment scale and individual microwatershed level. The reason for this mismatching could be attributed to large variation in mean slope values predicted by the two DEMs. In most of the cases the discrepancies are statistically significant indicating that the two DEMs are reasonably different in their hydrological properties.

3.3.2. Soil and Water Assessment Tool (SWAT) simulation

Finally, the hydrological behaviors of the two DEMs were studied for the catchment response in terms of runoff and sediment yields simulation using ArcSWAT model. The model predictions were carried out at monthly time step for monsoon season (June–September) for the year 2002–2005. Initially the model was calibrated using TOPO DEM as input terrain data along with other required spatial data. The same calibrated model was run for the same spatial data except SRTM DEM in place of TOPO DEM. It is because, single model parametization allow exploring the effect of data input uncertainty (output discrepancy) for a hydrological modeling. The predicted hydrological responses were analyzed at single microwatershed level (i.e. Rajdhawan) and at entire catchment level. Fig. 11 shows the predicted runoff at Rajdhawan by these two model runs.

The predicted runoff using both DEMs follows trends almost similar to that of observed runoff. However, at many peaks model run using SRTM DEM fails to predict accurately. The sediment yield predicted by the same model runs are presented in Fig. 12.

Fig. 12 shows that the trend line of sediment yield predicted using SRTM DEM have number of large peaks corresponding to unusually higher prediction. In general, model run utilizing the SRTM DEM have consistently higher prediction than both the observed value and prediction made by the model run that utilizes the TOPO DEM. It is worth mentioning here that the SWAT model was calibrated for TOPO DEM. However, such comparison is able to reveal the difference in hydrological behavior of the catchment without being influenced by the model parameter uncertainty. The calibration statistics for both the model runs for the observation station Rajdhawan is presented in Table 5.

The calibration statistics indicates that it is relatively more likely to predict the runoff more accurately as compared to sediment yield using both the DEMs. It is also apparent that runoff prediction is more accurate using SRTM DEM while for sediment yield prediction reverse is true. The reason behind this could be the facts that SRTM DEM facilitates delineation of the drainage network, basin boundary and microwatershed more accurately as compared to TOPO DEM. Nevertheless, SRTM DEM elevation has high slope.

![Fig. 10. Comparison of CDFs of soil erosion potential maps of SRTM DEM and TOPO DEM.](image-url)
gradient, may be due to presence of more noise, which ultimately resulted in higher prediction of sediment yield. This is quite obvious from the sediment yield prediction at calibrating station (Fig. 12), USLE prediction (Table 3) and slope length factor (Fig. 8).

The predicted monthly runoff yield at catchment outlet is presented in Fig. 13. It does not reveal much variation in the prediction made using both the DEMs. A similar result was obtained by the Li et al. (2013) who reported insensitivity of the SWAT model in predicting runoff using different source DEMs even at many different resolutions. However, the variation in the runoff prediction using two DEMs at microwatershed level (Fig. 11) is more pronounced as compared to variation at the catchment level (Fig. 13). This indicates the presence of localized errors/variations in the two DEMs. The little variation in the runoff prediction could be attributed to the fact that SWAT model uses Curve Number (CN) method (which consider runoff as an infiltration excess phenomena) to estimate surface runoff. Thus, no terrain parameters are directly involved in the volume of runoff generation. Due to the non-availability of land phase routing, SWAT model behave as lumped model at microwatershed level which might be another explanation for little variations in the surface runoff predicted using two DEMs.

The difference in the Manning roughness values, due to the use of two different DEMs, during channel routing phase could be another probable reason for the observed variation in the predicted runoff. Had it been simulated using fully distributed model such as TOPMODEL which considered runoff generation as a saturation (moisture content-TWI value) excess phenomenon, the predicted runoff values using the two DEMs would have been quite different.

It is again more likely that hydrological response to rainfall at catchment outlet in terms of shape of the runoff hydrograph, lag time, peak runoff and time to peak could be quite different and need further investigations. These responses are more related to catchment geomorphology which in turn depends on how well a catchment’s terrain is represented by the DEM (Forkuor and Maathuis, 2012). Although the SRTM DEM based simulation yielded slightly higher runoff than the simulation using TOPO DEM, both DEMs are suitable and can be used in conjunction or as a replacement of each other provided due care has been taken to eliminate and/or characterize the terrain discrepancy.

**Table 4**
Microwatersheds conservation priority matrix for two DEMs.

<table>
<thead>
<tr>
<th>DEM</th>
<th>Priority class</th>
<th>Reference TOPO DEM</th>
<th>SRTM DEM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>SRTM DEM</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>74</td>
<td>59</td>
</tr>
</tbody>
</table>

Bold letters are placed to highlight the microwatersheds priority predicted correctly by SRTM DEM with respect to reference DEM.

**Table 5**
SWAT calibration statistics at Rajdhanwar station using two DEMs.

<table>
<thead>
<tr>
<th>Statistics</th>
<th>TOPO DEM</th>
<th>SRTM DEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff</td>
<td>Sediment</td>
<td>Runoff</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.667</td>
<td>0.503</td>
</tr>
<tr>
<td>RMSE</td>
<td>45.263</td>
<td>0.325</td>
</tr>
<tr>
<td>RSR</td>
<td>0.716</td>
<td>0.800</td>
</tr>
<tr>
<td>NSE</td>
<td>0.487</td>
<td>0.359</td>
</tr>
<tr>
<td>PBIAS/C0</td>
<td>-0.257</td>
<td>10.234</td>
</tr>
</tbody>
</table>

Fig. 11. Monthly runoff yield predicted at Rajdhanwar station during calibration phase.

Fig. 12. Monthly sediment yield predicted at Rajdhanwar station during calibration phase.
On the other hand the sediment yield at the catchment level (Fig. 14) shows a wide variability in the prediction made using the two DEMs. As observed in earlier results, sediment yield predicted using SRTM DEM is significantly higher from that obtained using TOPO DEM. The results also indicate that soil erosion is quite sensitive to DEM source as compared to runoff which is in line with observation made by Chen and Wu (2012). The terrain sensitivity of sediment yield is attributed to the fact that the SWAT model uses Modified Universal Soil Loss Equation (MUSLE) for estimation of soil erosion potential of the running water and the simplified stream power equation of Bagnold (1977) for routing of sediment in the channel to the catchment outlet. Ironically, both the methods use terrain indices such as slope length factor (SLF) and stream power index (SPI) and are affected by the fact that how accurately the terrain is represented by the input DEM. The cumulative effect of these two terrain based indices lead to unusually high prediction in sediment yield simulation using SRTM DEM. From this observation, vulnerability of the terrain based hydrological parameters and hydrological modeling to the choice of elevation data source is reconfirmed.

Thus, the two DEMs cannot be used in conjunction with each other as input terrain parameter for hydrological study. The ArcSWAT simulation results for runoff and sediment yield can be served as valuable clues in understanding the actual variations in hydrological properties of the two DEMs without being influenced by model structural as well as model parameters uncertainty.

4. Conclusion

Topography represented in the form DEM is a critical spatial data required in any hydrological study. In this study, SRTM DEM was evaluated with reference to contour interpolated DEM. The comparison involves the assessment of vertical accuracy, error surface, terrain analysis and simulations of hydrological models such as USLE and ArcSWAT. It was found that the vertically accuracy of SRTM DEM (±27.58 m) is less than specified standard (±16 m). The use of terrain indices of hydrological significance also proved to be a useful tool for distinguishing the hydrological behavior of the two DEMs. Results of CDFs and K–S test of hydrological indices indicate that hydrological behaviors of SRTM DEM and TOPO DEM are significantly different from each other. SRTM DEM irrespective of the analysis used shows a comparatively higher erosion potential and sediment yield with lower prediction accuracy. It was further found that soil erosion potential, sediment yield are more sensitive to choice of the two DEMs in comparison to runoff estimation. For runoff, there is only a moderate variation between predictions involving the two DEMs. However, future investigation on runoff parameters such as shape of hydrograph, and peak runoff and time to peak is deemed necessary to fully explore the runoff behavior of the two DEMs. The results obtained in the present study are vital to hydrological analysis as it helps distinguishing the hydrological properties of the two DEMs and the magnitude of variation without being influenced by the model structural uncertainty (statistical analysis of hydrological indices) as well as parameter uncertainty (comparison of USLE and ArcSWAT simulations). Finally, it can be concluded that SRTM DEM can be a valuable data for hydrological application provided it has been evaluated properly and characterized for its error and/or uncertainty.

References


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