



Evaluation of TanDEMx and SRTM DEM on watershed simulated runoff estimation

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In hydrological models, digital elevation models (DEMs) are being used to extract stream network and delineation of the watershed. DEMs represent elevation surfaces of earth landscape. Spatial resolution refers to the dimension of the cell size representing the area covered on the ground. Spatial resolution is the main parameter of a DEM. The grid cell size of raster DEM has significant effects on derived terrain variables such as slope, aspect, curvature, the wetness index, etc. Selection of appropriate spatial resolution DEM depends on other input data being used in the model, type of application and analysis that needs to be performed, the size of the database and response time. Each DEM contains inherent errors due to the method of acquisition and processing. The accuracy of each DEM varies with spatial resolution. The present paper deals with Shuttle Radar Topography Mission (SRTM), TerraSAR-X add-on for Digital Elevation Measurements (TanDEM DEMs) and compares their watershed delineation, slope, stream network and height with ground control points. It was found that the coarse resolution DEM-derived attributes and terrain morphological characteristics were strongly influenced by DEM accuracy. The objective of the present study is to investigate the impact of DEM resolution on topographic parameters and runoff estimation using TanDEM-12, TanDEM-30 and SRTM-90 m with the Soil and Water Assessment Tool. The analysis of the results using different DEM resolutions gave a varied number of sub-basins, Hydrological Response Units (HRUs) and watershed areas. The results were optimum at a specific threshold value as extraction of drainage network has a significant influence on simulated results. The accuracy of DEM is important, as the source of construction of DEM is the main factor causing uncertainty in the output. The results showed variable amounts of runoff at the watershed level, which may be attributed to varied stream lengths, minimum and maximum elevations and sub-basin areas.

Keywords. Watershed hydrology; DEM; SWAT; runoff; TanDEMx; SRTM.

1. Introduction

Hydrological models are effective tools for understanding various hydrological processes occurring within a watershed. Hydrological models

and rainfall-runoff models need digital elevation model (DEM) as input to extract watershed geomorphologic parameters. Model ability to produce hydrological responses such as runoff mainly depends on the spatial resolution of the input

data. Watershed morphological characteristics (Paul *et al.* 2015), estimation of runoff, infiltration, drainage and soil erosion properties are dependent on the accuracy of DEM (Rawat *et al.* 2013). Knowledge regarding the accuracy of DEM (Jain *et al.* 2009) and extraction algorithm (Wu *et al.* 2017) are important factors when DEM is being used in hydrological modelling (Sánchez and Villarín 2012). When the coarse resolution data is used in hydrological models, the time required to compute the response and database requirement are comparatively low. Increasing the DEM resolution improves the accuracy of data with more terrain details and higher feature spatial accuracy. Few studies have investigated the impact of DEM on watershed delineation such as the formation of a number of sub-basins, reach length, reach slope and HRUs (Reddy and Reddy 2015; Zhang and Chu 2015). The mean slope is sensitive to grid size as it varies with a resolution of DEM (Zhang and Montgomery 1994). As the slope of a grid cell is represented by average slope of the area covered by the grid cell, the ability to represent the steeper and undulating landscape becomes less accurate with coarser resolution DEM. Wolock and Price (1994) demonstrated that the TOPMODEL results were sensitive to mean slope distribution, thus affecting land surface slope and shape with different DEM map scales and data resolution. Zhang and Montgomery (1994) tested 2-, 4-, 10-, 30-, and 90-m DEMs to analyse the effect on land surface and hydrologic simulations. Their research suggested that for many landscapes, a 10-m DEM presents a rational compromise between increasing resolution and data volume for simulating geomorphic and hydrological processes. Mamillapalli *et al.* (1996) have identified that Soil and Water Assessment Tool (SWAT) with higher resolution DEM data could be able to yield higher accuracy data at a particular threshold. Chaubey *et al.* (2005) have concluded that the modelling results are sensitive to the nature and quality of input variables at a given scale and that the interpretation of model output is limited to the resolution and quality of environmental data. Chaplot (2005) investigated the influence of DEMs with a varying resolution from 20 to 500 m on 21.8 km² watershed area in Lower Walnut Creek on runoff and sediment yield. Cotter *et al.* (2003) studied the impact of 30, 100, 150, 200, 300, 500 and 1000 m DEMs, land use and soil data on flow, sediment and nutrients such as nitrates. Findings of this study indicate the significant influence of DEM resolution on the watershed area and

slope and suggest that in order to achieve less than 10% error in output, the optimum resolution should be 30–300 m.

It was observed that with high-resolution DEM, the number of sub-basins formed was less when compared to coarser resolution DEM because of fine details about slope especially in the case of flat terrains (Bolch and Kamp 2006). In the SWAT model, total runoff is calculated as the sum of total runoff predicted at the HRU level within each sub-basin (Neitsch *et al.* 2005). Uncertainty in model input data is the primary source of error in evaluating hydrological variables. Azizian and Shokoohi (2014) have worked on the ungauged watershed to estimate flood peaks using the geomorphological instantaneous unit hydrograph (GIUH) and KW-GIUH models. Results showed sensitivity to input DEM resolution and stream delineation threshold to 15, 25, 50, 100, 200 and 300 m with 0.25, 1, 2 and 3% threshold. Tan *et al.* (2015) identified in their study that SWAT is sensitive to DEM resolution than DEM source and resampling techniques. Wu *et al.* (2017) experimented the impact of DEM resolution and threshold value on sub-basin count and stream length. It was observed that the suitable DEM resolution and threshold value depend on the geomorphology of the area to delineate drainage area and stream network. Different DEM resolutions result in different watershed delineations and watershed areas. The level of watershed topography and stream network representation accuracy decreases with coarse resolution DEM. A number of sub-basins and HRUs formed also differed due to watershed delineation and stream network. Spatial heterogeneity of soil, land use/land cover parameters and slope exert influence at HRUs and sub-basin levels. Varying DEM resolution results in a different number of HRUs and causes loss of information related to soil, land use/land cover parameters and slope gradient, resulting in basins that may show increased output uncertainty.

The objective of this study is to analyse the impact of different DEMs data on the same study area to evaluate watershed delineation and surface runoff using the SWAT model. Different resolutions of DEM from 12 to 90 m (TanDEM-12, TanDEM-30 and SRTM-90 m) were compared.

2. Methodology

Hydrological model SWAT is widely being used to study the hydrological process (Neitsch *et al.*

2011). SWAT is basically developed to predict the impact of different management practices on water, sediment and agricultural chemical yields from catchments or watersheds. SWAT is a physically based, continuous, semi-distributed watershed scale model developed by USDA-ARS (Arnold *et al.* 1998). SWAT uses D8 algorithms to delineate watershed into sub-basins and flow direction based on elevation (O'Callaghan and Mark 1984). The D8 algorithm has been proven to be the most popular due to specific features such as managing the scale effects of horizontal and vertical resolution (Chong and Dawen 2004) and the relation between topography and horizontal resolution of DEM (Wu *et al.* 2017). It is important to identify the spatial resolution of DEM at which watershed morphological characteristics are clearly delineated depending on topographic parameters in hydrological modelling such as SWAT. Accuracy and precision of soil and land use map are important as the land phase of the hydrological cycle is estimated in SWAT using the land use and soil data. HRUs are homogeneous units of land use and soil characteristics (Gassman *et al.* 2007). Surface runoff is estimated using the modified SCS (Soil Conservation Services) curve number (SCS 1972) or the Green–Ampt infiltration equation based on the temporal resolution of the rainfall data and different land use types, soil types and antecedent soil moisture conditions (Neitsch *et al.* 2005). Then the simulated SWAT model results with varying DEM resolutions were compared with the observed data to evaluate the model performance.

3. Study area

Pogilla watershed covers an area of 254 km² and is located in the Krishna basin, India (figure 1). The present study area Pogilla is located between latitude 16°15'–16°30'N and longitude 79°–79° 20'E. Major portion of this area falls under reserved forest. The soil group of the area belongs to hydrological soil groups C and D with highest runoff potential. Major land uses are agriculture 8%, deciduous forest 26%, degraded forest 2%, wasteland 22% and scrub forest 42%. The climatic condition in this area is semi-arid with maximum and minimum temperatures ranging from 34 to 38°C and 18 to 28°C. Annual rainfall varies between 800 and 1200 mm with the highest rainfall in monsoon season from June to September.

4. Data used

The SWAT model requires datasets of DEM, soil map, land use/land cover map and weather data. Details of datasets used in the present study are as follows.

4.1 Digital elevation models

TanDEM-12, TanDEM-30 and SRTM-90 m DEMs were used. Table 1 gives the details regarding different DEMs used in this study.

4.2 Soil map and database

The soil map of 1:50,000 scale was obtained from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur, India. The SWAT soil database requires soil parameters such as EPCO (soil evaporation compensation factor), ALPHA_BF (base flow alpha factor), GW_DELAY (groundwater delay), SOL_AWC (available water capacity of the soil layer), SOL_BD (moist bulk density), SOL_Z (depth from soil surface to bottom of layer), SOL_K (saturated hydraulic conductivity), SOL_CBN (organic carbon content), SOL_ALB (moist soil albedo), USLE_K (USLE equation soil erodibility (*K*) factor). Data of few parameters was calculated using SPAW (Soil Plant Air Water) such as available water content, organic matter, saturated hydraulic conductivity, bulk density (Saxton and Rawls 2006).

4.3 Land use/land cover map

Land use/land cover map was collected from the National Remote Sensing Centre (NRSC), Balanagar, Hyderabad, at 1:50,000 scale with different land use classes.

4.4 Meteorological data

The daily weather data was obtained from the India Meteorological Department (IMD), Hyderabad, from 2011 to 2016.

4.5 Runoff data

The observed data of surface runoff was collected from the Telangana State Irrigation Department and Central Water Commission (CWC).

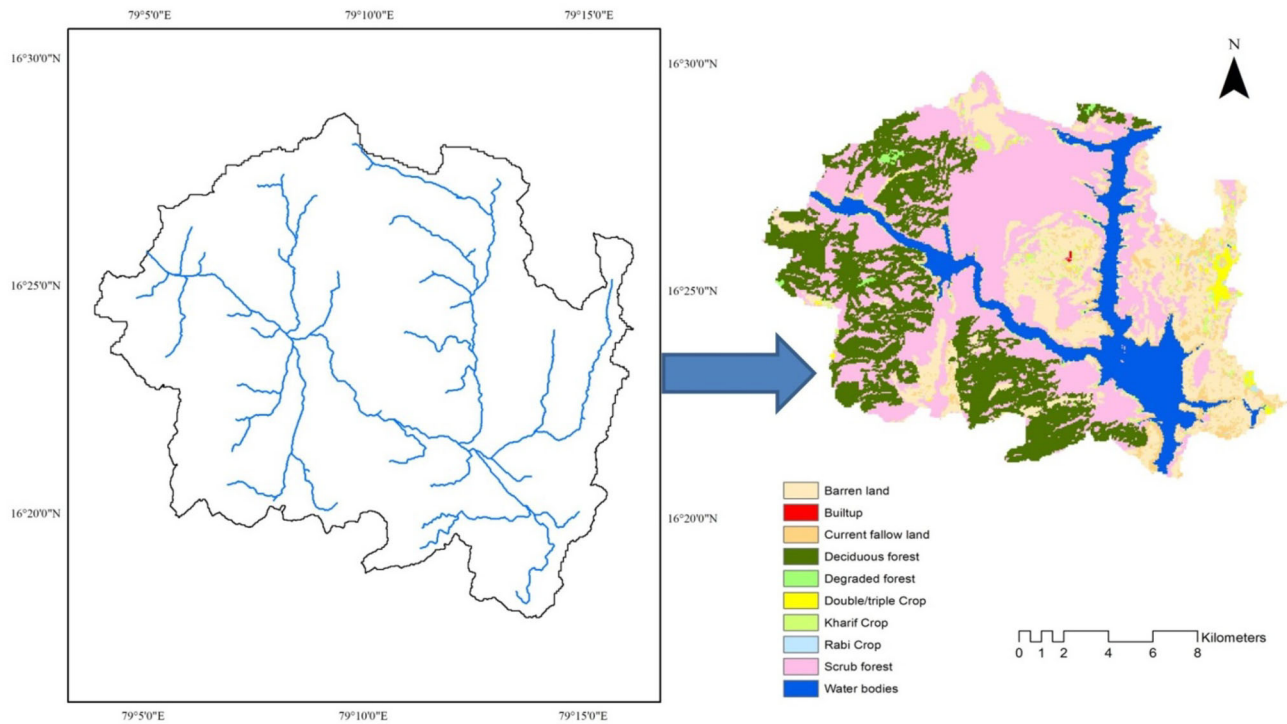


Figure 1. Location map of the study area with land use/land cover classes.

Table 1. Details of different sources of DEM.

| Name of the DEM | Resolution | Release year | Name of developer |
|-----------------|----------------|--------------|-------------------------------|
| TanDEM-12 m | 12×12 | 2015 | German Aerospace Center (DLR) |
| TanDEM-30 m | 30×30 | 2015 | German Aerospace Center (DLR) |
| SRTM | 90×90 | 2003 | NASA/USGS |

5. Results and discussion

Current paper deals with watershed delineation and runoff change estimations using different spatial resolution DEMs (figure 2). The important parameters obtained from DEMs are drainage network and slope. SRTM and TanDEM DEMs are evaluated for slope and drainage network accuracy. Slope gives the degree of the terrain inclination. The model was simulated separately for each DEM, while soil map, land use/land cover map, meteorological parameters were maintained to remain the same. Stream network was generated at 500 ha as threshold drainage area which is approximately 2% of the watershed area. The HRU generation thresholds were land use (20%), soil (20%) and slope (10%). Soil database and land use/land cover database parameters were maintained same for all simulations after model calibration. When different DEMs are being used for

model simulation the hydrological responses within the watershed are sensitive to physical properties such as watershed area, shape, slope and length which influence volume, travel time and momentum of runoff.

5.1 Validation

Accuracy is the capability to identify the presence of two objects. Higher resolution increases the details of terrain. Accuracy assessment was performed using 10 GCPs (ground control points) with elevation from mean sea level. The accuracy of SRTM and TanDEM DEMs was estimated by comparing with GCPs height. The validation was done using root mean square error (RMSE). RMSE value is based on the difference between DEM elevation and the elevation of ground control points measured by a field survey.

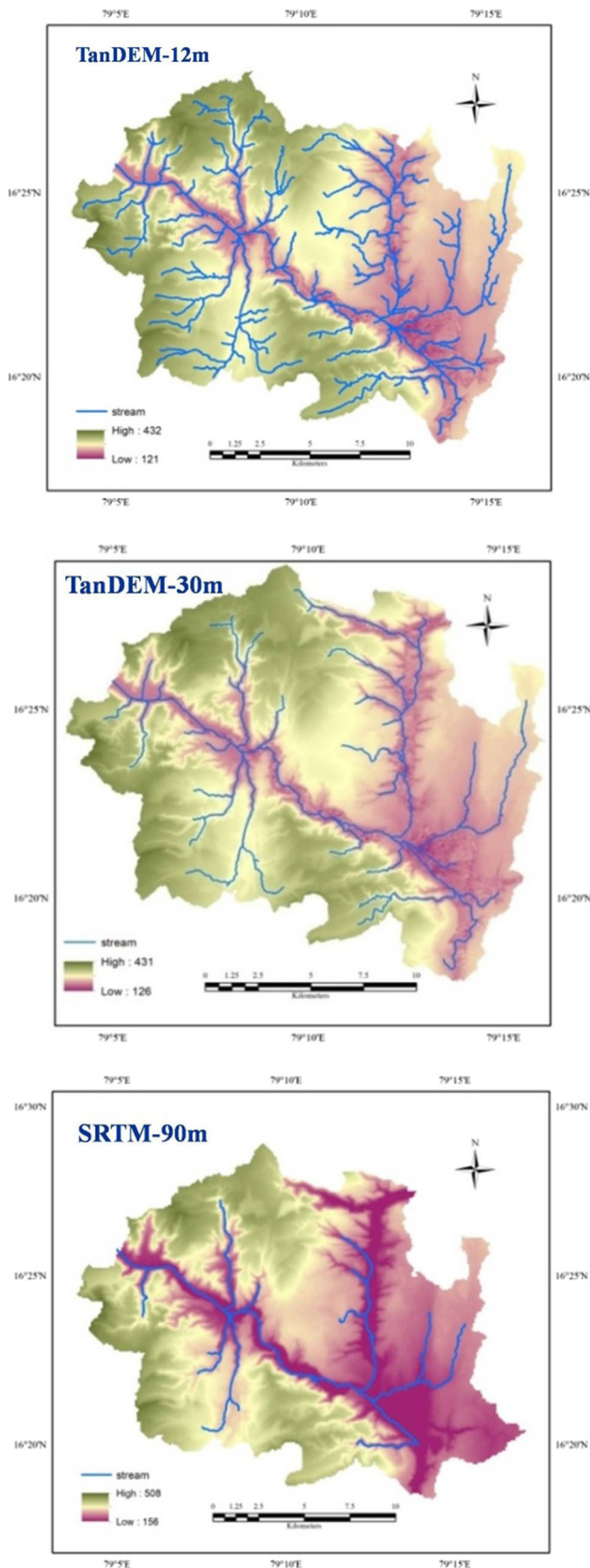


Figure 2. Different DEMs used in the study area with 12, 30 and 90 m resolution.

The elevation range of TanDEM-12 m is 121–431 m with mean 286 m. Elevation range of TanDEM-30 m is 126–431 m with mean 288 m. The SRTM elevation ranges from 156 to 508 with mean 292 m. The terrain surface representation mainly depends on the spatial resolution of DEM (Ravibabu *et al.* 2010). As resolution increases, surface representation becomes more detailed and finer characteristics of the land surface can be better identified. With decreasing resolution, surface heights become smoother because of averaged values within each cell. This can be better explained as area and elevation values of 90×90 m of SRTM have 1 single cell, 9 TanDEM-30 m cells and 56 TanDEM-12 m cells. It means the fine terrain details are well detailed in higher resolution DEM.

5.2 Comparison of SRTM-90, TanDEM-12 and TanDEM-30 m

The overall accuracy of three DEMs was calculated by comparing the DEM height and GCP location height. Table 2 shows the absolute difference between heights and error associated with reference location height.

It has been found that RMSE of TanDEM-12, TanDEM-30 and SRTM-90 m is 3.79, 5.76 and 10.36, respectively (Ravibabu and Jain 2008). The level of agreement between GCP location height and TanDEM and SRTM are 0.997, 0.994 and 0.981 (figure 3). Correlation (R^2) between TanDEM-12 m, -30 m and reference location height is higher than SRTM which indicated the better accuracy.

SRTM and TanDEM-30 m height were compared with TanDEM-12 m height on the same location points. The level of agreement (R^2) between TanDEM-12 m height with SRTM and TanDEM-30 m is 0.972 and 0.981 (figure 4).

5.3 Impact on watershed delineation

Watershed area, shape, slope and stream network were extracted in the present study using different resolution DEMs. The details of number of sub-basins, number of HRUs, stream length and slope that have formed with TanDEM-12, TanDEM-30 and SRTM-90 m DEMs are shown in table 3. From the results, it is observed that the number of sub-basins and HRUs are decreasing with increasing (coarse) DEM and the area of

Table 2. Error in SRTM-90 m, TanDEM-30 and -12 m with respect to GCPs.

| GCP name | Longitude | Latitude | GCP height (m) | SRTM-90 | Error in SRTM-90 m | TanDEM-30 | Error in TanDEM-30 m | TanDEM-12 | Error in TanDEM-12 m |
|-----------|-------------|-------------|-------------------|---------|-----------------------|-----------|-------------------------|-----------|-------------------------|
| Point 1 | 16° 47' 25" | 79° 20' 19" | 127 | 138 | 11 | 130 | 3 | 129 | 2 |
| Point 2 | 15° 44' 24" | 77° 59' 35" | 286 | 299 | 13 | 292 | 6 | 281 | -5 |
| Point 3 | 15° 52' 57" | 77° 57' 26" | 271 | 263 | -8 | 272 | 1 | 272 | 1 |
| Point 4 | 15° 56' 43" | 77° 25' 58" | 308 | 297 | -11 | 300 | -8 | 302 | -6 |
| Point 5 | 15° 39' 40" | 76° 57' 56" | 349 | 337 | -12 | 354 | 5 | 352 | 3 |
| Point 6 | 16° 26' 49" | 79° 06' 50" | 256 | 268 | 12 | 250 | -6 | 253 | -3 |
| Point 7 | 16° 26' 44" | 79° 08' 09" | 404 | 397 | -7 | 396 | -8 | 406 | 2 |
| Point 8 | 16° 24' 22" | 79° 09' 05" | 262 | 253 | -9 | 256 | -6 | 266 | 4 |
| Point 9 | 16° 21' 56" | 79° 10' 39" | 387 | 396 | 9 | 392 | 5 | 381 | -6 |
| Point 10 | 16° 20' 56" | 79° 11' 26" | 296 | 306 | 10 | 290 | -6 | 298 | 2 |
| RMS Error | | | | | 10.36 | | 5.76 | | 3.79 |

sub-basins is increasing with coarser resolution. Runoff is calculated at HRU level with soil and land use/land cover homogeneity within each sub-basin. The shape, area and slope of watersheds delineated from different DEMs were different.

5.4 Impact on stream network

In a watershed, the drainage system is evaluated based on total stream length and number of tributaries. When different grid sizes of DEM are being used for delineation, it has a significant impact on topographic representation and hierarchy of stream network (Paul *et al.* 2017). Table 4 gives the different watershed parameters for TanDEM-12, TanDEM-30 and SRTM-90 m DEMs. The stream lengths extracted show differences such as total stream length given by SRTM DEM is shorter than TanDEM-30 and -12 m resolution. Threshold value identifies number of cells contributing to the flow of water. Within the watershed, the size of the sub-basins is influenced by threshold value as lower threshold values result in smaller sub-basins with a high number of streams and higher values give larger sub-basins with a smaller number of streams. Generally, the stream delineation threshold is 1% of the catchment area. Average slope, minimum and maximum elevations were sensitive to DEM resolution. These parameters were inherently connected to stream length and stream slope. Such changes resulted in substantial variations in topographic features and stream network at sub-basin level. Landscape representation becomes smoother with coarse resolution DEM because of changes in slope.

The stream network delineated from TanDEM-12, TanDEM-30 and SRTM-90 m is shown in figure 5. Terrain morphology is one of the watershed parameters which influences the drainage network and slope. Results show the difference in stream orders and stream network with DEM resolution. Higher resolution DEM gives detailed topographic representation at HRU level which has shown significant impact on runoff simulation. Slope and aspect at HRU level along with soil map and land use/land cover has a significant influence on runoff. In the SWAT model, runoff simulation is carried out at HRU level considering soil characteristics, land use/land cover and slope. At sub-basin level, the details of representation of stream network order and segmentation are higher in high-resolution DEM (figure 6). A higher DEM resolution results in a more total number of streams

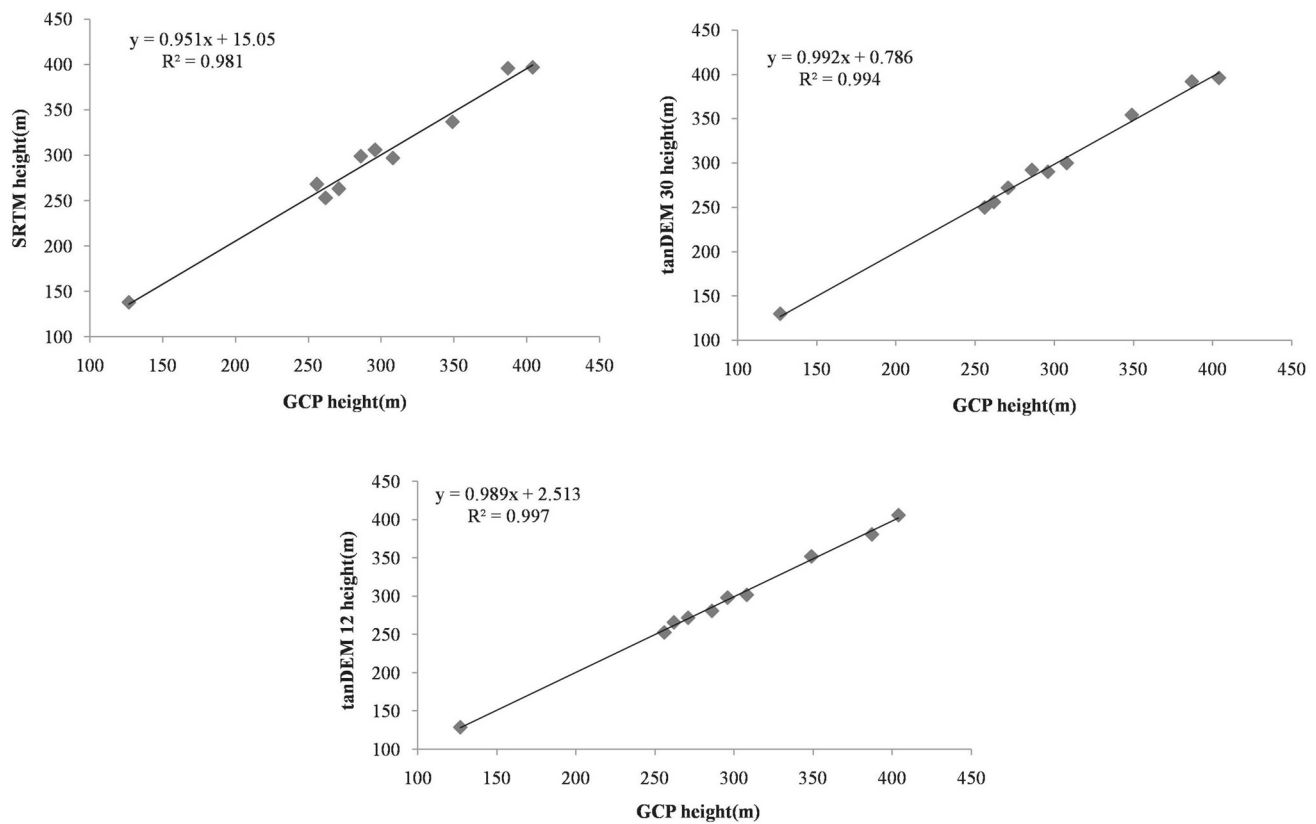


Figure 3. Level of agreement among GCP height and TanDEM-12 and -30 m and SRTM-90 m.

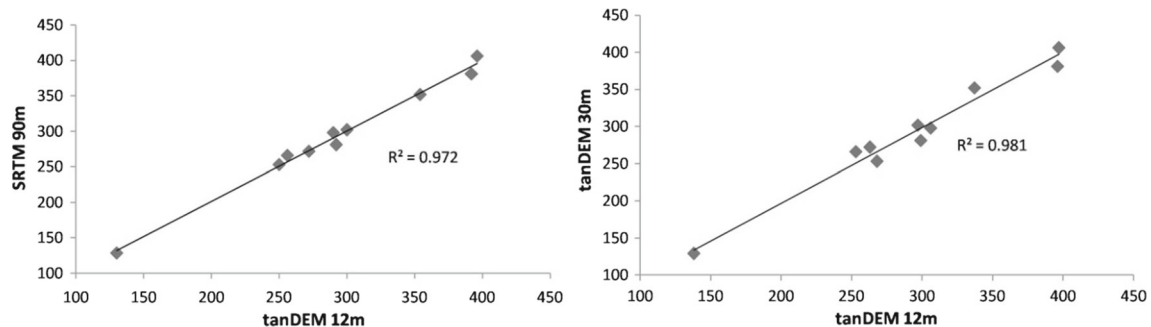


Figure 4. Level of agreement between SRTM-90 m and TanDEM-30 m with TanDEM-12 m.

with more first- and second-order streams than third- and fourth-order streams. The higher order streams delineated from TanDEM-12 m show more similarity with real stream network at 1:50,000 scale compared to SRTM. It is also observed that in coarse resolution (90 m) DEM the number of streams decreases with lower drainage density. Total stream length is greater in higher resolution DEM than in coarse resolution DEM because of the increased number of streams.

5.5 Impact on runoff

The SWAT model was simulated with different resolution TanDEM-12, TanDEM-30 and

Table 3. Details of the watershed area and mean elevation with different DEMs.

| DEM (m) | Area (km ²) | Mean elevation |
|-----------|-------------------------|----------------|
| TanDEM-12 | 275 | 286 |
| TanDEM-30 | 274 | 288 |
| SRTM-90 | 273 | 292 |

SRTM-90 m DEMs to estimate the runoff on a monthly scale. The model was run for 5 years from 2011 to 2016. The model was calibrated as sensitive parameters are specific to the resolution of DEM. The uncertainty associated with model parameters and input data propagates into the SWAT model

Table 4. Watershed parameters for different DEM resolutions.

| Name of the parameter | TanDEM-12 m | TanDEM-30 m | SRTM-90 m |
|-----------------------|-------------|-------------|-----------|
| Number of sub-basins | 31 | 28 | 24 |
| Number of HRUs | 281 | 265 | 243 |
| Stream length (m) | 1572 | 1542 | 1426 |
| Minimum elevation | 156 | 126 | 121 |
| Maximum elevation | 508 | 431 | 431 |

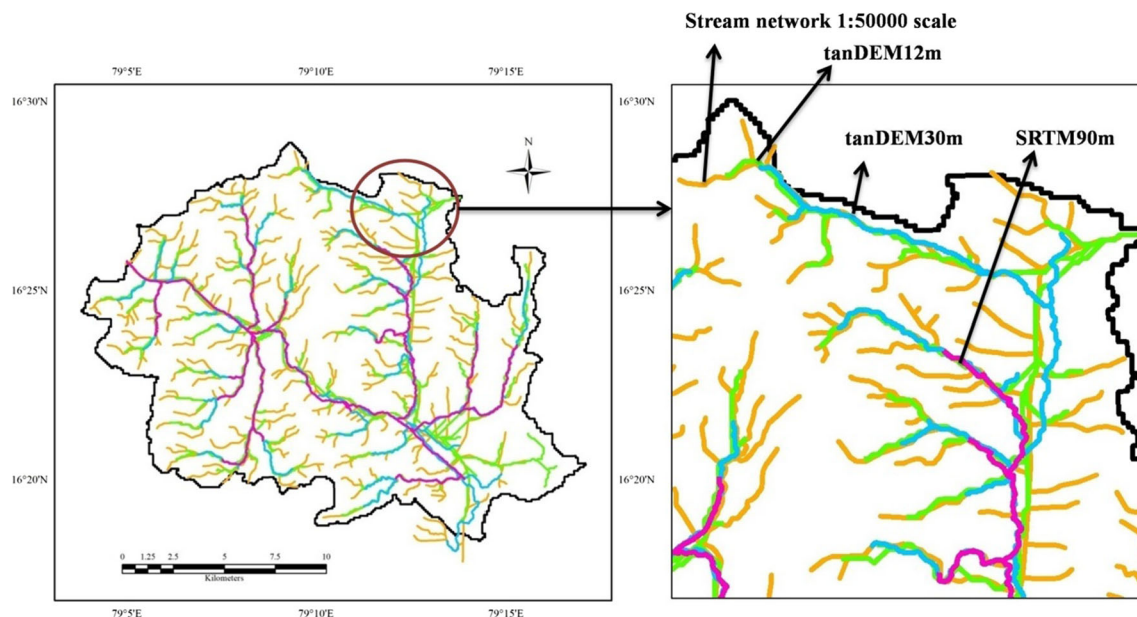


Figure 5. Comparison of stream network delineation with TanDEM-12 m, TanDEM-30 m and SRTM-90 m and 1:50,000 stream network map.

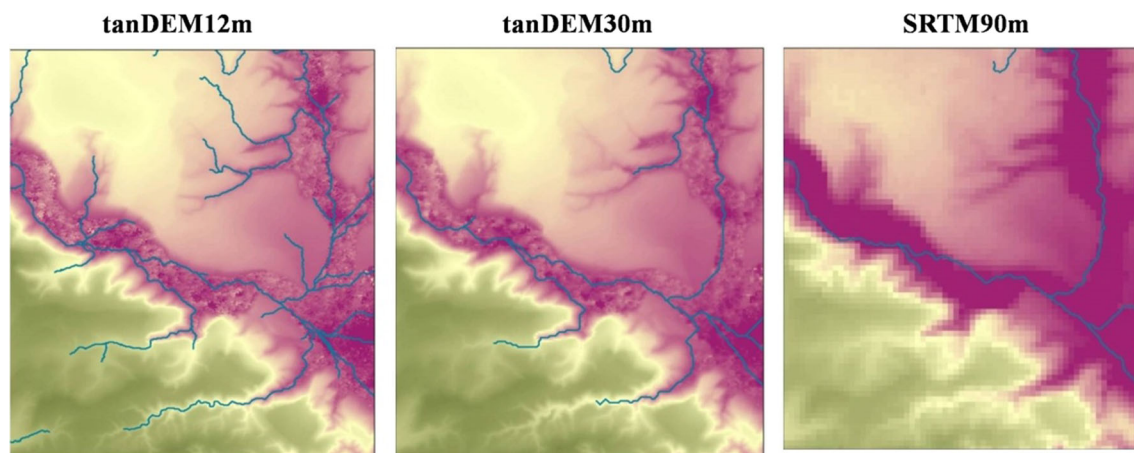


Figure 6. Comparison of stream network with TanDEM-12 m, TanDEM-30 m and SRTM-90 m at 1% threshold.

which influences the final estimation of surface runoff. Figure 7 shows the simulated runoff values with TanDEM-12, -30 and SRTM-90 m and observed values. Simulated values were compared with observed values of surface runoff to estimate the efficiency of the model performance. According

to Moriasi *et al.* (2007, 2012) model results were found to be satisfactory if $NSE > 0.5$ and $R^2 > 0.7$ for surface runoff. NSE and R^2 values for different DEMs are shown in table 5.

The runoff values showed mild variation with changing DEM resolution. TanDEM-30 m was able

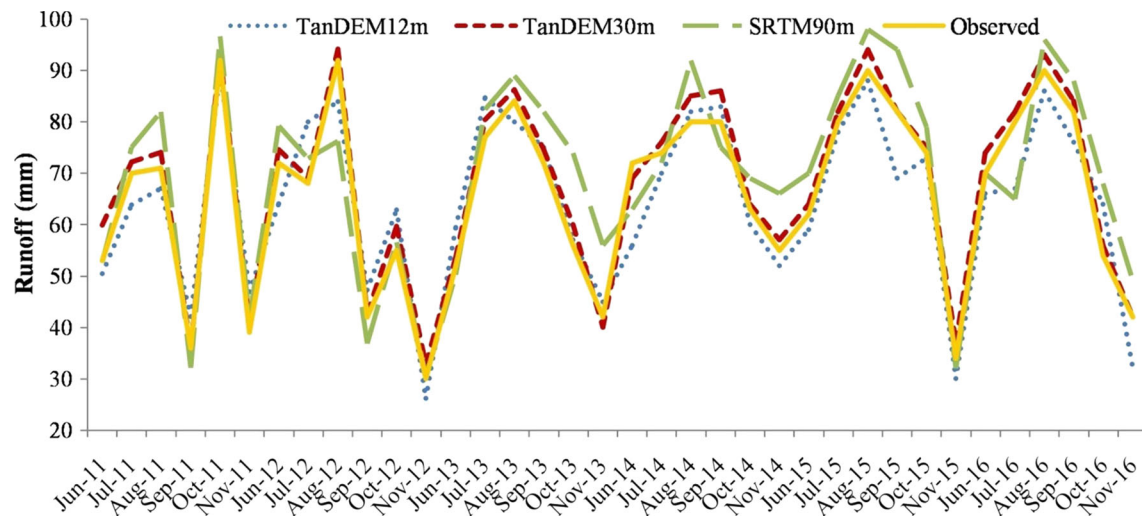


Figure 7. Runoff simulated from 2011 to 2016 for three different DEM resolutions.

Table 5. Efficiency of the SWAT model performance for different DEM resolutions for the period of 2011–2016.

| DEM (m) | Runoff | |
|-----------|--------|-------|
| | NSE | R^2 |
| TanDEM-12 | 0.64 | 0.78 |
| TanDEM-30 | 0.62 | 0.76 |
| SRTM-90 | 0.61 | 0.71 |

to predict much closer results with observed values. These changes can be attributed to change in watershed delineation process with respect to DEM resolution. Hence, care must be taken while calculating different land use/land cover and soil database parameters. Runoff is calculated using the SCS curve number method which changes with land use/land cover. The present analyses infer that runoff calculations in SWAT are dependent on antecedent moisture condition which changes with land use/land cover.

Overall, it can be concluded that runoff values are sensitive to DEM resolution in the SWAT model. The results of this study were able to predict runoff values but the accuracy of runoff estimation varies with DEM resolution. TanDEM-30 m results show a linear relationship with observed values. But with coarser DEM resolution slight decrease is identified. The study also explored the influence of DEM resolution on runoff estimation as the SWAT model is sensitive to uncertainties in data input. To estimate runoff and sediment, a higher resolution DEM

could yield a good agreement between the observed and simulated values when the study area is small (Ghaffari 2011). Different soil and land use/land cover parameters are common for watershed but are dependent on the size and resolution of DEM. In many studies, a higher resolution DEM is most suitable to estimate the hydrological responses up to 90 m. But coarser resolution DEM could decrease the model running time because of the size of DEM (grid area). A higher resolution DEM contains more grid cells which will incur longer processing time and higher computer resources. The accuracy of DEM depends on the quality of DEM and the source it has been created from. The size of the DEM grid cell influences the landscape representation, topography and hydrological simulations. With a higher resolution DEM, the land surface features become more accurately predictable but results depend on the accuracy of the data. Model results primarily related directly to the quality of data used to simulate surface processes. The slope is the main parameter which can affect the amount of runoff and sediment at sub-basin and HRU level. The results indicate that TanDEM-12 m DEM could yield more accurate estimates of runoff as compared to TanDEM-30 and SRTM-90 m in the current study area.

6. Conclusions

This study analyses the influence of DEM resolution (TanDEM-12, TanDEM-30 and SRTM-90 m) on a hydrological response from watershed

using the SWAT model. The validation of DEMs was carried out using the reference points and level of correlation (R^2). RMS error was calculated for each DEM against reference location heights. Major observations were found such as different drainage networks and slope at sub-basin levels. The total length of stream network, watershed area and shape and slope were different with each DEM. It was also observed that the average slope varies with DEM resolution. A higher resolution DEM resulted in a longer stream length than coarser resolution DEM. Stream delineation has given clear stream network at the threshold of 1% when compared to 0.25, 5 and 2% of the total area. It is also observed that the stream length, slope and mean elevation decreased due to smoothening impact of SRTM.

The runoff volumes estimated using TanDEM-12, TanDEM-30 and SRTM-90 m DEM showed variation in results. The soils of this area show impermeable rock layer below the topsoils which influence the rate of runoff and base flow. Moderate variations in slope and soil characteristics influence rate of runoff when different resolution DEMs were used. With higher resolution DEM, the number of sub-basins was more with clear slope variations within each sub-basin whereas coarser resolution DEM resulted in the smoother landscape which generated large area sub-basins. From the results, it can be concluded that for hydrological modelling such as runoff estimation DEM resolution plays an active role as slope and aspect are the main parameters to influence the runoff volume. When large watersheds are being modelled, it is important to select DEM with coarser resolution and threshold value lesser than 100 (Gitau and Chaubey 2010). The results estimate that the model simulations are sensitive to DEM resolution depending on the watershed area, landscape and topography. The runoff values from different DEMs have shown variations in runoff volumes up to 5%. Simulated runoff with TanDEM-12 m resulted in reliable output, in combination with 1:50,000 scale soil map, land use/land cover map and 1% threshold in the present study area. Findings of this study are important to understand the accuracy associated with freely available SRTM and recently released TanDEM. This study also analyses the spatial characteristics of DEM error associated with watershed delineation, stream network, slope and runoff at small-scale regional study area with a semi-arid climate and flat to hilly terrain morphology.

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