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The Impact of DEM Resolution on Runoff and Sediment Modelling Results

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ABSTRACT

Discrete landscape characterizations with raster-based Digital Elevation Models (DEM) are commonly used for representing elevation surface in watershed modeling. As different resolution of elevation models could be available, this study investigates the impact of DEM resolution on a set of important topographic attributes and simulated runoff and sediment of the Zanjanrood watershed in northwest of Iran. Fifteen DEM realizations of different mesh sizes ranging from 10 to 500 m were used for comparative examinations. Models with different DEM resolutions were created in the SWAT model. The model was calibrated for flow and sediment yield using 10 m DEM data. The predicted output at the calibrated scale was used to evaluate output accuracy for the remaining input resolutions. Results of this study showed that DEM resolution affects the watershed delineation and all the terrain variables tested vary with the grid size change. It is found that the mean reach depth, mean elevations, mean slopes and the cumulated lengths of sub-basins and stream network, decrease as DEMs are aggregated progressively to coarser resolutions. As shown in this study a decrease in DEM resolution resulted in decreased runoff and sediment. The RE (%) variations of the yearly runoff and sediment loads due to resampled resolutions from 10 to 500 m were 1 and 11%, respectively. The decrease of the predicted sediment presents a nonlinear relationship with the DEM resolutions. Decreasing the resolution above 50 m did not substantially affect the simulation of runoff but it did have an impact on simulation of sediment yield.

Key words: DEM resolution, topographic attributes, sediment yield, runoff, SWAT model

INTRODUCTION

Effective control of water and soil losses requires implementation of the best management practices in erosion-prone areas of the catchment. Based on research by Iikhchi *et al*. (2003), the mean annual erosion rate in Iran is estimated to be about 2500 ton km^{-2} which is 4.3 times more than the mean erosion rate in the world. Also, available information shows that 59% of 17 large basins studied in Iran have been severely degraded (Iikhchi *et al*., 2003). The use of physically based distributed hydrological models and geographic information systems can assist water authorities to identify the most vulnerable erosion-prone areas of a catchment and select appropriate management practices (Tripathi *et al*., 2005). Distributed hydrological modelling commonly requires investigation of landscape and hydrological features such as terrain slope, drainage networks, drainage divides and catchments boundaries. Digital Elevation Models (DEM) offer an efficient way to represent ground surface and allow automated direct extraction of hydrological features, thus bringing advantages in terms of processing efficiency, cost effectiveness and accuracy assessment, compared with traditional methods based on topographic maps, field surveys or photographic interpretations. For the last few decades, DEMs are widely used for resource management, urban planning, transportation planning, earth sciences, environmental assessments and Geographic Information System (GIS) applications. Digital Elevation Model data play an important role in SWAT and the topographic attributes of the sub-basin, including area, slope and field slope length are all derived from the DEM. Resolution of elevation data represents the horizontal accuracy of a DEM. Different resolution of DEMs could be available for one area of interest from various sources. An issue with the topography based hydrologic modelling has been that at what spatial resolution a model would perform optimally.

There are numerous studies which compare spatial indices derived from different resolution DEMs and researchers have also investigated the effect of using different resolution DEM on the results from hydrological and hydraulic modelling (Jenson and Domingue, 1988; Chang and Tsai, 1991; Zhang and Montgomery, 1994; Jenson, 1991; Florinsky, 1998; Gao, 1997; Schoorl *et al.*, 2000; Claessens *et al.*, 2005; Wechsler, 2007; Murphy *et al.*, 2008; Zhang *et al.*, 2010; Wu *et al.*, 2008; Lin *et al.*, 2010). For example Zhang and Montgomery (1994) examined the effect of grid cell resolution on landscape representation and hydrologic simulations using elevation data from two small watersheds. Their results showed that increasing the grid size resulted in an increased mean topographic index because of increased contributing area and decreased slopes. Another study on DEM resolution effect on surface runoff modeling by Vieux and Needham (1993) showed that outputs from the AGNPS model (Young *et al.*, 1987) also varied with changes in the cell size. Brown *et al.* (1993) showed that the prediction of sediment yield using the ANSWERS model began to change at DEM meshes greater than 120 m.

Mamillapalli *et al.* (1996) reported that modeled results from SWAT showed increased accuracy while predicting discharge with a finer resolution of data, however, they also found an interesting result that there was a level (threshold) beyond which higher resolution of data does not produce better results of predicted flow. FitzHugh and Mackay (2000) using the Soil and Water Assessment Tool (SWAT), indicated in a watershed of Wisconsin a 44% drop of sediment estimates from the coarsest to the finest watershed delineations. A decrease of sediment yield was observed with an increase of DEM mesh from 100 to 200 m due to decreasing channel erosion. Cotter *et al.* (2003), evaluated the impact of resampled the same input soil, Landuse (LU) and DEMs to new resolutions (30, 100, 150, 200, 300, 500 and 1000 m) on the uncertainties of SWAT predicted flow, sediment, NO_3-N and Total Phosphor (TP) transport in Moores Creek watershed. Their studies showed that For flow, sediment, NO_3-N and TP predictions, minimum DEM data resolution should range from 30 to 300 m, whereas minimum land use and soils data resolution should range from 300 to 500 m and depending on the output variable that a researcher was looking at; a minimum threshold could be used for resolution of input data to achieve less than 10% Relative Error (RE). Chaplot (2005) evaluated the impact of the mesh size of DEM (from 20 to 500 m) within SWAT to simulate runoff, sediment and NO_3-N loads at the outlet of an agricultural watershed. This study showed that an upper limit to DEM mesh size of 50 m was required to simulate sediment and NO_3-N loads.

The objective of this study is to evaluate the effect of input Digital Elevation Model (DEM) data resolution on the 13 watershed topographic attributes and the SWAT outputs for surface runoff and sediment yield, in Zanjanrood river basin. Different resolutions, from 10 to 500 m (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150, 200, 300, 400, 500 m) were compared in this study. It is hoped that this work will contribute some insight on to what extents of the DEM grid size SWAT can still achieve reasonable simulations.

MATERIALS AND METHODS

Model description: In study to assess the spatial distribution of water resources and sedimentation, one needs to use a physically-based distributed model. SWAT2005 (available on website http://swatmodel.tamu.edu, accessed on 29 January 2010) was used in this study because of its ability to characterize complex watershed representations to explicitly account for spatial variability of soils, rainfall distribution and vegetation heterogeneity; its ability to show the effects of resolution DEMs on surface runoff and sediment yield. Major hydrological processes that can be simulated by the model include Evapotranspiration (ET), surface runoff, infiltration, percolation, shallow aquifer, deep aquifer flow and channel routing (Neitsch *et al.*, 2002). The hydrological component of SWAT is based on the following water balance equation Eq. 1:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - ET_i - W_{seep\,i} - Q_{gw}) \tag{1}$$

where, SW_t is the final soil water content (mm), SW_0 is the initial soil water content on day i (mm), t is the time (days), R_{day} is the precipitation on day i(mm), Q_{surf} is the surface runoff on day i (mm), ET_i is the evapotranspiration on day i(mm), W_{seepi} is the amount of water entering the vadose zone from the soil profile on day (Soil interflow) i (mm) and Q_{gw} is the amount of return flow on day i (mm) (Arnold *et al.*, 1998).

SWAT uses Modified Universal Soil Loss Equation (MUSLE) (Williams, 1995) to estimate soil erosion and sediment Eq. 2:

$$Y = 11.8\ (Q \times Area \times qp)\ 0.56\ K \times C \times P \times LS \times R \tag{2}$$

where, Y is the sediment generation (metric tons); Q is volume of runoff (m^3); qp is the peak runoff rate (m^3s^{-1}); K is the USLE soil erodibility factor; C is the cover and management factor; P is the support practice factor; and LS is the topographic (slope gradient and slope length) factor; and R is the coarse fragment factor. For each day with rainfall and runoff, sediment generation is estimated by applying Eq. 2 for each HRU in the watershed.

The study area: The study area is located in Zanjanrood, in the North-West of Iran (Fig. 1). The catchment has an area of 4364 km^2. The mean elevation of the basin is 1796 m, with mountains up to 2915 min the south and eastern parts and plains down to 1100 m in the central and northern parts. The average mean slope extracted from the 30 m Digital Elevation Model (DEM) is 6.95%. The climate in the Zanjanrood Basin is semi-arid in the uplands to arid in lowlands (Koppen type C), with typical short, high-intensity rain storms. The average annual precipitation was 232 mm and the average annual temperature was 18°C. The oldest rocks exposed in the area are Precambrian dolomitic limestones in the uplands (mountains).The youngest rocks exposed are the Cenozoic upper red formations which mainly consist of shale and clay (Zadeh, 2002). The soils are predominately a heterogeneous mix of silt or clay, with some local deposits of sand in the lowlands. The lowland soils are clay to heavy clay and are poorly drained but in the uplands the soil texture is sand-loam and the soils are moderately drained. The upper Zanjanrood catchment has good vegetation cover, with grassland. The lowlands have patchy shrubland, with a mixed distribution of rain-fed agriculture and fallow. The major crops grown in the area are wheat and barley.

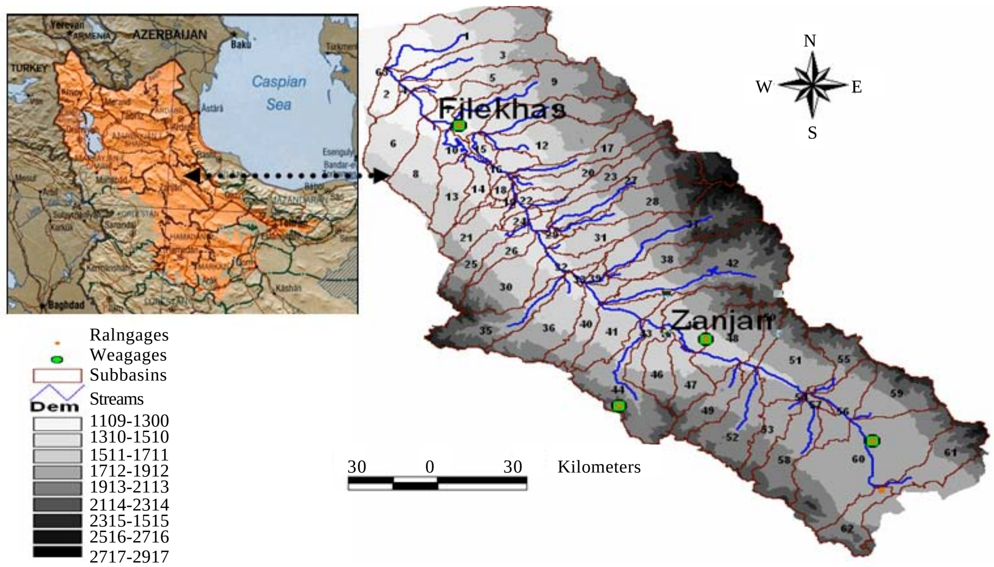

Fig. 1: Location of the zanjanrood river basin in the northwest of Iran, digital elevation model with 10 m resolution and the 63 subbasins

Input data and model implementation: Spatial datasets used in this study included, land use, soil, Digital Elevation Model (DEM), daily weather, monthly discharge and suspended sediment load. For generating the land-use map, Linear Imaging Self-scanning Sensor III (LISS-III) data of August 2009 from Indian Remote Sensing Satellite 1C (IRS-1C), were used. The images were geo-referenced and ortho-rectified, using topographic maps, aerial photographs and field observations. Six land-use classes were identified: rain-fed agriculture, irrigated agriculture, grassland, shrubland (savanna), bare ground (badland) and urban areas. The soil map was constructed from soil and geological data acquired from the Soil and Water Research Institute. In order to complete the soil input (sol) file, 1700 soil samples were obtained from depths of 0.5 and 1 m as well as from ground surface in Zanjanrood basin. The high resolution Digital Line Graph (10 m interval counter lines) of Iran Topography Organization based on ground survey was used as the standard data and model simulation.

The climatic and stream-flow data were derived from six hydro meteorological stations. For the simulation, the Zanjanrood was divided in to 602 HRUs, on the basis of their land use and soil type. Initially, the model was run for the period between 1995 and 2004. The simulation results from January 1998 to December 2002 were used for parameter calibration and the model was calibrated on monthly and yearly basis by comparing the calculated stream flow and sediment load with measured stream flow and suspended sediment load at the outlet of the Zanjanrood catchment. In this study SWAT-CUP (Calibration and Uncertainty Programs) was used for the sensitivity analysis, calibration and uncertainty analysis of the model runs. SWAT-CUP is a public domain program linking the SUFI-2 (Sequential Uncertainty Fitting, version. 2) procedure to SWAT (Abbaspour, 2007). Further goodness of fit was quantified by the R^2 and Nash-Sutcliff (NS) coefficient between the observations and the final best simulation. An ideal situation would lead to a P-factor approaching 100% and a d-factor approaching zero (Abbaspour *et al.*, 2007). Based on this information, the calibration was performed for a limited number of influential parameters. Finally, the model was validated from January 2003 to December 2004.

The topographic representations and model output sensitivity to the DEM resolution: To understand the effect of DEM resolution on model outputs, the DEM-based watershed terrain characteristics were studied. The 10 m grid size is selected as the best resolution and DEM was generated from the original contour lines (10 m interval) before resampling to 15 DEMs of 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150, 200, 300, 400 and 500 m resolutions (Fig. 2). The resampling method was the nearest neighbourhood. The nearest-neighbour method simply assigns the value of the single closest observation to each cell. Once the location of the cell's center on the output grid is located on the input DEM, the nearest neighbor assignment will determine the location of the closest cell center on the input grid, identify the value that is associated with the cell and assign that value to the cell that the output cell center is associated with (Mitchell and Netravali, 1988).

When evaluating the uncertainties of model results duo to DEM resolution, it is necessary to examine the uncertainties of watershed topographic properties as model inputs. Therefore, the 13 topographic properties were compared in this study: the sub-basin properties (minimum, maximum and mean of the elevation, the mean slope, the cumulated sub-basins length (longest path within the sub-basin), the cumulated drainage area and the mean elevation of the sub-basins centroid within the catchment) and the stream properties (the minimum, maximum and mean elevation of the stream reach, the mean slope, the cumulated length of reaches and the mean depth of reaches). The 63 sub-basin were used to estimate the mean or cumulated of sub-basin and stream reach parameters.

The SWAT running outputs and the topography parameter tables due to different DEM resolutions were saved for 15 runs, keeping other simulation conditions constant. Estimations for runoff and sediment using the 15 DEMs resolutions were compared to the finest DEM with 10 m resolution and was assumed to be the best value. Uncertainty in the model output due to different DEM resolutions was quantified as relative error (%). This was defined as Eq. 3:

$$RE\ (\%) = 100\times(Px-P10)/P10 \quad (3)$$

where, P10 was the finest DEM with 10 m resolution for comparison which was derived from the best DEM and Px was the model outputs based on different resolution DEMs.

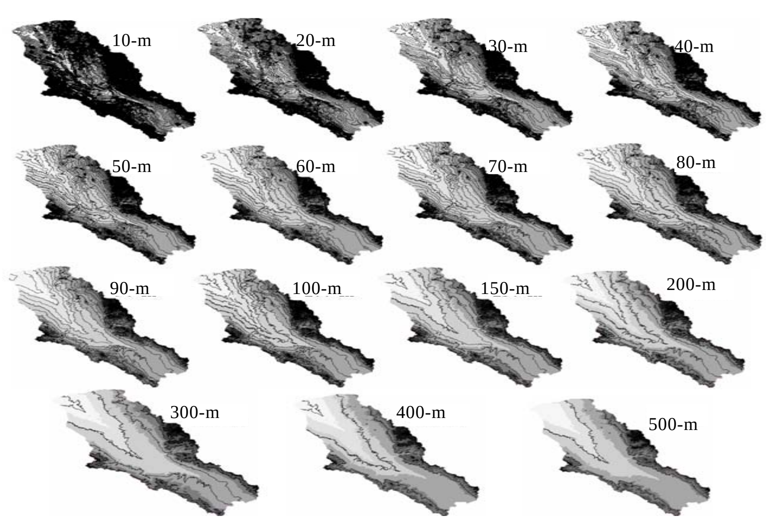

Fig. 2: DEMs and contour lines derived from different DEM resolutions ranging from 10 to 500 m

RESULTS AND DISCUSSION

Model calibration: The results show that the most sensitive parameters are those representing the surface runoff, groundwater, soil properties and snow process (Ghaffari *et al*., 2010). The results of the sensitivity analysis for the parameters deep aquifer percolation fraction, Available water capacity of the soil layer, SCS runoff curve number for moisture condition II (CN2), base flow alpha factor and the groundwater revap coefficient which describes the rate of groundwater transfer from the shallow aquifer to the overlying unsaturated zone through capillary fringe and deep roots are all consistent with the results of other researchers like Van Griensven *et al*. (2006), Jha *et al*. (2007) and Di Luzio and Arnold (2004) who found the same parameters to be sensitive.

Table 1 show the values of statistical test for measured and simulated monthly/yearly runoff and sediment yield during calibration and validation periods. The R^2 value of 0.86 and NS value of 0.79 for monthly runoff at the outlet of the Zanjanrood catchment indicated close relationships between simulated monthly runoff with measured values. In addition, p-factor increased to 0.48 and the d-factor decreased to 0.60, indicating improved model performance (Table 1). Comparisons of the modelled and observed runoff for validation period yielded R^2 = 0.80, NS = 0.79, p-factor = 0.52 and d-factor = 0.58 (Table 1). In other words, the simulated monthly runoff values matched the measured values satisfactorily.

The R^2 value of 0.83 and NS value of 0.78 indicates a good agreement between the observed and simulated monthly sediment yield. The P-factor value for monthly sediment yield was 0.46 while d-factor was 0.59. The validation yielded 0.80, 0.77, 0.52 and 0.55 values for R^2, NS, P-factor and d-factor, respectively. Overall, simulation of monthly sediment yield by the SWAT model during the validation period was found to be satisfactory and accepted for further analysis. Calibration for each run was not necessary in this study, because even with the best possible model calibration for each run at different resolutions, model errors solely due to DEM inputs could not have been isolated.

Effect of the DEM resolution on topographic characteristics: The results showed that, DEM resolution affected the subbasin delineation and stream network of the Zanjanrood watershed, in the SWAT model (Table 2, 3). The results indicated that, the coarser DEMs being unable to accurately estimate the mean elevation, mean slope and the cumulated length of longest path within the sub-basin. This is confirmed by the summary data of Table 2 showing a steady decrease of these parameters, from 10 to 500 m resolutions. For instance, the mean elevation decreased from 1799 at 10 to 1776 at 500 m, Also, the mean slope decreased from 6.99 at 10 m to 6.44% at 500 m. Finally, the cumulated length decreased from 1352 km at 10 to 1283 km at 500 m. The mean

Table 1: Criteria for examining the accuracy of SWAT outputs calibration (1998-2002) and validation (2003-2004)

	Runoff				Sediment yield			
	Calibration		Validation		Calibration		Validation	
Index	Monthly	Yearly	Monthly	Yearly	Monthly	Yearly	Monthly	Yearly
R^2	0.86	0.91	0.80	0.89	0.83	0.90	0.80	0.89
NS	0.79	0.80	0.79	0.81	0.78	0.79	0.77	0.80
P-factor	0.48	0.71	0.52	0.61	0.46	0.70	0.52	0.60
d-factor	0.60	0.67	0.58	0.62	0.59	0.65	0.55	0.60

Table 2: The subbasin parameters estimated for each of the DEM resolution

DEM resolution	Minimum elevation		Maximum elevation		Cumulated subbasin length		Mean elevation		Cumulated drainage area		Mean slope		Mean elevation of centroid	
m	m	RE (%)	m	RE (%)	Km	RE (%)	m	RE (%)	Km^2	RE (%)	(%)	RE (%)	(m)	RE (%)
10	1454	0	2917	0.00	1352	0.00	1799	0.00	4374	0.00	6.99	0.00	1674	0.00
20	1456	0.1	2916	-0.03	1347	-0.56	1798	-0.06	4368	-0.14	6.96	-0.35	1668	-0.36
30	1460	0.4	2916	-0.03	1344	-0.84	1796	-0.17	4364	-0.23	6.94	-0.57	1665	-0.54
40	1459	0.6	2917	0.00	1344	-0.84	1795	-0.22	4374	0.00	6.92	-0.60	1676	0.15
50	1454	0.8	2916	-0.05	1337	-1.75	1794	-0.28	4368	-0.14	6.88	-1.09	1667	-0.42
60	1457	0.7	2916	-0.03	1330	-2.24	1793	-0.33	4364	-0.23	6.83	-1.66	1671	-0.18
70	1461	0.5	2916	-0.03	1327	-2.72	1791	-0.44	4366	-0.18	6.82	-1.88	1667	-0.44
80	1454	0.9	2916	-0.03	1325	-3.14	1789	-0.56	4361	-0.30	6.77	-2.00	1663	-0.66
90	1461	0.5	2916	-0.04	1316	-4.12	1788	-0.61	4362	-0.27	6.73	-2.66	1672	-0.12
100	1460	0.9	2916	-0.04	1309	-4.47	1787	-0.67	4367	-0.16	6.71	-3.20	1666	-0.48
150	1458	1.1	2916	-0.05	1303	-5.38	1785	-0.78	4373	-0.02	6.69	-3.62	1672	-0.12
200	1461	1.2	2916	-0.03	1299	-5.66	1783	-0.89	4361	-0.30	6.61	-3.89	1676	0.14
300	1457	1	2915	-0.06	1296	-6.15	1781	-1.00	4364	-0.23	6.57	-4.15	1675	0.05
400	1454	1.2	2915	-0.06	1287	-7.55	1779	-1.11	4365	-0.21	6.53	-4.80	1674	0.01
500	1460	1.2	2915	-0.06	1283	-8.80	1776	-1.28	4367	-0.16	6.44	-5.07	1676	0.12

Table 3: The stream network characteristics estimated for each of the DEM resolution

DEM resolution	Mean reach depth		Maximum elevation		Minimum elevation		Mean reach slope		Mean elevation of main stream		Cumulated reach length	
m	m	RE (%)	m	RE (%)	m	RE (%)	%	RE (%)	M	RE (%)	Km	RE (%)
10	1.71	0.00	1571	0.00	1454	0.00	1.23	0.00	1541	0.00	475.0	0.00
20	1.70	-0.57	1564	-0.45	1456	0.14	1.22	-0.80	1540	-0.06	474.7	-0.07
30	1.69	-1.00	1560	-0.70	1460	0.41	1.21	-1.70	1538	-0.20	474.0	-0.21
40	1.68	-1.80	1575	0.25	1459	0.32	1.20	-2.10	1535	-0.39	472.1	-0.40
50	1.67	-2.50	1578	0.45	1454	-0.02	1.20	-2.60	1531	-0.63	471.5	-0.74
60	1.62	-4.40	1573	0.13	1457	0.19	1.17	-4.80	1527	-0.90	469.5	-1.16
70	1.60	-6.10	1569	-0.13	1461	0.48	1.16	-6.00	1522	-1.20	467.3	-1.64
80	1.59	-7.12	1571	0.00	1454	0.00	1.14	-7.70	1517	-1.56	464.7	-2.21
90	1.58	-7.76	1573	0.13	1461	0.48	1.11	-10.00	1511	-1.96	461.7	-2.87
100	1.56	-9.04	1571	0.00	1460	0.38	1.09	-11.30	1503	-2.43	458.4	-3.60
150	1.53	-10.40	1574	0.19	1458	0.25	1.07	-13.30	1495	-2.96	454.7	-4.43
200	1.52	-11.04	1573	0.13	1461	0.45	1.06	-13.90	1486	-3.55	450.4	-5.40
300	1.50	-12.24	1575	0.25	1457	0.19	1.05	-14.93	1477	-4.18	445.6	-6.54
400	1.49	-12.88	1571	0.00	1454	0.02	1.03	-16.40	1466	-4.86	440.4	-7.78
500	1.47	-13.98	1576	0.32	1460	0.40	1.02	-17.42	1455	-5.60	434.7	-9.16

elevation did not decrease as much as the mean slope and the cumulated length of subbasins in this study. The minimum and maximum elevation, cumulated drainage area and the mean elevation of centroid varied on resampled resolution but did not show any significant bias in this study. The RE(%) variations of mean slope and the cumulated length of longest path within the sub-basins were similar, whilst the estimated minimum and maximum elevation, cumulated drainage area and the mean elevation of centroid, were much lower (less than 1.2% of RE difference) and they were irregularly varied.

Similarly, the stream reach characteristics estimated for each of the DEM mesh presented in Table 3 and indicated that, the mean elevation, mean slope, mean depth and the cumulated length of reaches decreased by increasing the DEM meshes from 10 to 500 m. Table 3 shows how RE for each parameter was affected by data resolution. The RE(%) variations of the mean elevation, cumulated length of reaches, mean depth and mean slope variations due to resampled resolutions from 10 to 500 m, were -5.60, -9.16, -13.98 and -17.42%, respectively (Table 3). The minimum and maximum elevation varied substantially on resampled resolution but no trend could be found. On the other hand they were not sensitive to resampled resolutions. In general while comparing all 13 topographic properties estimated for this study, the highest resolution of DEMs (500 m) yielded the largest RE (%) variations in stream network characteristics.

Effect of the DEM resolution on SWAT predictions: Assuming realistic estimations of runoff and sediment yields over 1998-2002, SWAT is used here as a decision tool to test the effect of the DEM resolutions on the estimation of runoff and sediment. The model predictions for runoff and sediment load at coarser resolutions were compared to the predictions at the calibrated DEM resolution (10×10 m). The RE(%) variation and average annual of predicted runoff and sediment loads are shown in Table 4 as a function of resampled DEM resolutions. The results indicate that the resolution of the input DEM not only impacts the watershed delineation and stream network to be used throughout the rest of the model runs but also impacts model-predicted runoff and sediment. In general, as the DEM resolution became coarser, the predicted runoff and sediment decreased but runoff did not decrease as much as sediment with coarser DEM resolutions. The mean annual runoff over 1998-2002 ranged from 13.2 mm for the 10 m mesh to 13.06 mm at 500 m (Table 4). The variance in RE(%) in each model output as affected by DEM data resolution is illustrated and show that RE in runoff prediction was less than one percent at all DEM resolutions. DEMs studied did not show any significant threshold for the prediction accuracy in the estimation of surface runoff.

The results of RE values of sediment loads showed that increase in DEM mesh size from 10 to 500 m led to 11.3% decrease in amount of estimated sediment loads. Higher RE for sediment indicates that the predicted sediment was more sensitive to resampled resolutions than runoff. The decrease of the predicted sediment presents a nonlinear relationship with the DEM resolutions. As shown by RE(%), better accuracies occurred by using the 10-50 m DEMs (less than 1% RE difference). Prediction values of sediment loads remained close for meshes from 10 to 50 m with predicted loads from 6.02 to 5.96 t ha^{-1} (Table 4). Poorest estimations are obtained with the 500 m DEM (5.34 t ha^{-1}). The results of RE variations revealed an increase of model inaccuracy up to 50 m, above the threshold of 50 m the prediction accuracy greatly decreased.

Table 4: The Effect of input DEM resolution on estimated runoff and sediment loads (1998-2002)

DEM (m)	10	20	30	40	50	60	70	80	90	100	150	200	300	400	500
Runoff															
mm	13.26	13.26	13.25	13.25	13.24	13.23	13.21	13.20	13.18	13.17	13.15	13.13	13.11	13.08	13.06
RE (%)	0.00	-0.02	-0.05	-0.11	-0.18	-0.26	-0.34	-0.42	-0.47	-0.52	-0.57	-0.61	-0.68	-0.75	-0.85
Sediment															
t ha^{-1}	6.02	5.99	5.98	5.98	5.96	5.87	5.81	5.76	5.72	5.68	5.64	5.61	5.55	5.46	5.34
RE (%)	0.00	-0.48	-0.67	-0.70	-0.94	-2.51	-3.46	-4.27	-5.03	-5.68	-6.26	-6.73	-7.84	-9.31	-11.3

RE: The relative error variation due to resampled resolutions

DISCUSSION

Use of models in making watershed response predictions can be expected to increase in the future and this is especially true for the SWAT model. When a hydrologic model is used to evaluate hydrological response of a watershed, every effort must be taken to minimize model uncertainties associated with input data. The high R and NS in the calibration and validation suggest that the calibrated model can describe the runoff and sediment of the basin. Thus we can be confident that the calibrated model with the set of optimized parameters can be applied to examine the impact of DEM resolution on runoff and sediment modelling of the Zanjanroord basin. These results are similar to those found by Mamillapalli *et al.* (1996), Cotter *et al.* (2003) and Dixon and Earls (2009), who all used the SWAT model to evaluate the effect of the DEM resolution on SWAT predictions.

In this study, effects of elevation data resolution on the 13 topographic properties are analyzed across 15 different DEM resolutions. Impacts are found for all the 13 examined derivatives as functions of DEM resolution. The mean reach depth, mean elevations, mean slopes and the cumulated lengths of sub-basins and stream network estimates are seen constantly decreasing with the resolution growing coarser. These impacts were direct consequence of losing topographic details at the coarser DEM resolutions. Since the coarsest-input DEM poorly represented the true topology of the watershed, the model was not able to correctly predict the subbasin and stream network characteristics. Previous studies showed inconsistent results about the effects of DEM resolutions on some topographic properties. Some found that flow length decreased with coarser DEM resolutions (Vieux and Needham, 1993) some did not (Wu *et al.*, 2008). However, they all found that mean slopes decreased with coarser resolution (Bolstad and Stowe, 1994; Chang and Tsai, 1991; Kienzle, 2004; Thompson *et al.*, 2001; Lin *et al.*, 2010). These results do not support a part of assertion from the published work by Lin *et al.* (2010) which investigated effects of DEM resolution, from 5 to 140 m on watershed terrain characteristics and SWAT outputs. Their findings showed that the reach lengths and reach slopes varied substantially on resampled resolution but no trend could be found. On the other hand the mean altitudes, mean areas and reach depths were not sensitive to resampled resolutions. The differences in these results might be caused by the different accuracies of different study areas and the much larger watershed area in this study. The findings suggest that DEM resolution would depend much on terrain complexity of the study site and topographic attributes used in the particular model.

In this study, no definite trend of bias is observed for the calculations of the minimum and maximum elevation of sub-basins and stream network, cumulated drainage area and the mean elevation of centroid while all are sensitive to the DEM resolution change. DEM aggregation may have influence on these attributes but the direction and extent of the effect would vary upon its base grid size and edge pattern of the DEM. Vieux and Needham (1993) also examined the effect of grid size change on the cumulated drainage area obtained from DEM and no consistent tendency is observed. The study believed that the area is varying because grid cells of different sizes cannot consistently cover the irregular shape of the watershed. A study done by Zhang and Montgomery, 1994 using TOPMODEL found that watershed area decreased as DEM resolution decreased. The perception is inconsistent with the finding on watershed area from this study.

Results of this study, also show when resampling DEM to a coarser resolution, SWAT predicted lower runoff and sediment yields but the RE(%) variations indicated that DEM resolutions had a more effect on sediments. Surface runoff slightly decreased with coarser resampled resolution. Such a low impact of the DEM mesh size could be explained by the fact that in the NRSC method, topography is given a low weighting in the surface storage, interception, infiltration and retention.

Also SWAT2005 does not adjust the curve number for slope. These results generally agree with the findings of Wolock and Price (1994), Lin *et al.* (2010) and Di Luzio and Arnold (2004). They surmised that a finer data resolution resulted in higher simulated runoff volume. The small decrease of surface runoff is similar to Kalin *et al.* (2003) and Chaubey *et al.* (2005) found in a similar model but under different resolutions.

Increasing the DEM mesh beyond a threshold of 50 m significantly affected the sediment output that decreased with an increase in DEM mesh size. The reason for such a threshold may be explained by the nonlinearity of erosion processes. The impact of the DEM resolution on the watershed outputs confirmed the pre-study expectations since sediment is estimated from the MUSLE equation involving the mean slope gradient and length (Williams and Berndt, 1977). The smothering of the landscape shape induced by coarser DEMs resulted in an observed bias in the estimation of these factors and thus of sediment outputs. Below 50 m, the differences in DEM accuracy did not induce changes in the estimated outputs since the topographic attributes are computed at the subbasin level which may be of a relatively large area and thus buffering the shape of landscapes. The sediment loads in the watershed outlet are greatly balanced by the channel degradations and depositions and might be affected by the sediment yield of sub-basins nearby the outlet. Therefore sediments did not decrease as much as slopes with coarser DEM resolution and they were irregularly decreased.

CONCLUSIONS

These conclusions are similar to the results reported by Wolock and Price (1994), Chaplot (2005), Cotter *et al.* (2003) and Lin *et al.* (2010). Results of this study indicate that the choice of input DEM resolution depends on the watershed response of interest. If only the runoff response is to be modeled, a DEM resolution up to 500 m will result in less than 1% RE in model predictions. If sediment is the output of interest, then an input resolution of less than 50 m is needed to achieve a similar level of accuracy in SWAT predictions.

Increasing or decreasing the size of HRUs would probably have changed the conclusions of this study. In particular, when HRUs have the size of the sub-basins, in the case of watersheds that have only one primary channel and very little variation in topography, soils and land use, the DEM mesh would not have affected the computed loads. This knowledge on the impact of the DEM mesh size on runoff and sediment loads should help scientists to optimize field surveys, input data preparation requirements as well as the computational resources needed for effective utilization of the SWAT model. In particular, this study showed that the extra cost and labor to obtain the greatest precision of input topography is not justified to obtain more accurate prediction. But these results have to be extrapolated to other models or sites with caution.

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