Assessment of land cover resolution impact on flood modeling uncertainty

Jihui Fan, Majid Galoie, Artemis Motamedi and Jing Huang

ABSTRACT

The main objective of this paper is to evaluate the impact of land cover resolution, in comparison with the digital elevation model (DEM) resolution, on hydrological modeling outputs. Three different basins in the various resolutions of DEM (12.5, 25, 50, 100, 500 and 1,000 m) and land-use maps (250, 1,000 and 2,500 m) were collected in this study, and the hydrological modeling process was performed using the Soil and Water Assessment Tool (SWAT) model. The soil type resolution was 1,000 m for all basins, and the runoff modeling was done based on the Soil Conservation Service Curve Number (SCS-CN) method. The final model outputs showed that the DEM cell size variations affect significantly the topographical characteristics of a catchment such as area, mean slope, river network and time to concentration which alter the flood modeling outputs especially in hilly watersheds (mean slope more than 15%) up to 15% for a DEM cell size of 1,000 m in comparison to 12.5 m. Also, the resolution and spatial distribution of land cover maps which directly specify SCS-CN values, can change the output simulated runoff results up to 49% for a land cover cell size of 2,500 m in comparison to 250 m. These results indicated that the quality of the land cover map is more important than the quality of DEM in hydrological modeling. Also, the results showed that for an identical land-use cell size, the differences between model outputs using DEM cell sizes less than 100 m were not very significant. Furthermore, in all models by increasing the DEM cell size, the simulated runoff depth was decreased.

Key words | DEM cell size, land-use resolution, SCS-CN method, sensitivity analysis, SWAT model

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HIGHLIGHTS

- The study attempts to show the impact of land-use resolution on hydrological model outputs.
- The effect of the resolution of land-use data, CN estimating and uncertainties of SWAT outputs are discussed in this paper.
- This paper shows that land-use land cover resolution is more important than DEM resolution in hydrological modeling.
- This paper would be useful to improve hydrological model outputs.
- This paper suggests the best DEM resolution for hydrological modeling.

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INTRODUCTION

Hydrological models are useful to identify present and future water resources, and they help researchers and water managers to estimate the spatial variability in resource over watersheds. Simulation models can be classified into two different types; physical-based models and empirical models. There are various physical-based models designed to simulate hydrological processes, such as Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) (Beasley *et al.* 1980), Simulator for Water Resources in Rural Basins (SWRRB) (Williams *et al.* 1985), Soil and Water Assessment Tool (SWAT) (Arnold *et al.* 2013), Better Assessment Science Integrating point and Nonpoint Sources (BASINS) (Whittemore 1998) and Hydrological Simulation Program – FORTRAN (HSPF) (Bicknell *et al.* 2001). The SWAT model, which was developed in the 1990s, has broad application in hydrologic studies. It can simulate the quality and quantity of surface and groundwater including pesticide loading. The most advantages of the SWAT model are its ability to perform on multiple geographic information system platforms, and four major input data of this model include digital elevation model (DEM), land-use land cover (LULC), soil types and meteorology data. As drainage networks are the key characteristics of watershed systems and universally derived from the DEM (Shen *et al.* 2013; Galoie *et al.* 2017), DEM is mainly used for the extraction of physical properties (Bourdin *et al.* 2012).

A decade ago, the lack of DEM availability was a big problem; however, it has been solved recently by using global remotely sensing DEM products (Lin *et al.* 2013). There are numerous studies available covering the impact of DEM resolution on physical characteristics of different watersheds. Almost all have shown significant influences on parameters such as the watershed area, slope, total reach length and longest flow path which are the key factors in the calculation of concentration time (Hutchinson & Dowling 1991; Jenson 1991; Wolock & McCabe 2000; Chaubey *et al.* 2005). However, by decreasing the DEM cell size, the total execution time of the modeling process is increased (Munoth & Goyal 2019). High-resolution DEM generates more accurate topographic estimations (Szczes ́niak & Piniewski 2015), but such information usually costs more, especially in the hilly and gully regions in comparison to some of the flat areas (Quinn *et al.* 1991; Qiu *et al.* 2012). Researchers have found that DEM quality and resolution significantly affect the accuracy of any extracted hydrological features (Kenward *et al.* 2000).

Many scholars have studied DEM resolution, and most or almost all of the reported studies indicate that the influence of the watershed subdivision method is related to the DEM resolution. López-Vicente & Álvarez (2018) by using different DEM resolutions for hydrological modeling in agricultural land with woody corps found good agreement between outputs for a fine DEM (1 m) when high-intensity rainfall and runoff events activate the whole sub-catchments. Wu *et al.* (2017) investigated the impact of DEM resolution on the drainage network using SWAT and showed that the suitable flow accumulation threshold value increases, as the DEM resolution increases. In a similar study, Nazari-Sharabian *et al.* (2019) showed that the main physical characteristics such as watershed area, reach lengths and elevations in a watershed can be varied due to DEM resolutions.

In some studies, the impact of DEM resolution on other aspects of hydrological modeling was investigated. Chaplot (2005) obtained better results in runoff and sediment modeling by using DEM with 50 m resolution in comparison to 500 m, and finally, DEM with (100–300 m) resolution was suggested in large watersheds. Similar results were also achieved by Reddy & Reddy (2015). Yang *et al.* (2014) found that higher DEM resolution could provide a more accurate representation of topographic features. Yang & Chu (2013a, 2013b) showed that the simulation results were influenced by DEM interpolation methods which could change the accuracy of the model. Moreover, studies in Northern ID, USA indicated that DEM source in different three spatial resolutions (4, 10 and 30 m) using the Water Erosion Prediction Project (WEPP) model gained different erosion outputs (Zhang *et al.* 2009). Chow & Hodgson (2009) showed that DEM resolution (2–10 m) had a direct effect on the accuracy of the slope calculation which was in agreement with other similar studies (Xu *et al.* 2004; Lin *et al.* 2010). Also, Tan *et al.* (2015) concluded that low

DEM resolution in SWAT changed the accuracy of slope, which directly impact sub-basin delineation and stream network formation which can alter the estimation of suspended sediment load along a channel.

There are few studies in China covering the selection of appropriate DEM resolution in the SWAT model. However, Liu *et al.* (2013) implemented research in an agricultural watershed of Xiangxi River, Three Gorges Reservoir in China, with various DEM resolutions (30–1,000 m) and showed that different sediment yield and also different dissolved oxygen load could be achieved especially for DEM larger than 500 m. In another river watershed in China named Xiekengxi River, Lin *et al.* (2013) investigated the impact of DEM resolution (5–140 m) and DEM source on SWAT model outputs, and the results showed that DEM source was more important and might produce better outputs in comparison to DEM resolution. Zhang *et al.* (2016) investigated the impact of DEM resolution on the topographic index (TI) and performed a sensitivity analysis. The research area was located in the Yi River Source region which was a tributary of the Yellow River in Henan Province in China. The results indicated that as DEM cell size increased from 250 to 1,000 m, TI was increased from 9.08 to 11.16.

The Soil Conservation Service Curve Number (SCS-CN) method is the main hydrological model in SWAT. CN values can be estimated from LULC and soil type maps and based on Technical Release 55 (TR-55) tables. According to TR-55, soil types are categorized into four major hydrologic soil groups (HSGs). When the diversity of soil types in a watershed is high, CN estimation depends on soil type rather than LULC (Li *et al.* 2019). On the contrary, when a watershed is covered by almost uniform soil types, the variation of CN values are more dependent on LULC (Galoie *et al.* 2017).

Although in the literature review there are a number of studies which focused on the selection of appropriate DEM resolution in the SWAT model, it should be noticed that there are few studies on the effect of the resolution of land-use data, CN estimating and uncertainties of SWAT outputs. Most studies related to LULC have investigated the impact of LULC change on hydrological modeling outputs (Jin *et al.* 2019; Li *et al.* 2019; Shrestha 2019), and only a few of them particularly considered the effect of LULC resolution. For example, Al-Khafaji & Saeed (2018) studied the effect of DEM resolution and LULC maps on runoff estimation and found that the watershed boundary and the total area are highly affected by the DEM resolution and the number of hydrologic response units (HRUs) depends on LULC resolution.

According to the above literature review, this study attempts to show the impact of land-use resolution (in comparison with DEM resolution) on hydrological model outputs.

MATERIALS AND METHODS

The impact of input DEM and LULC map quality on hydrological modeling have been investigated using three schematic watersheds which have similar areas but different properties (mean slope, topography and LULC) in Hubei province in China. In order to investigate the impact of DEM resolution on topographical properties of watersheds especially in hilly regions, in this study, the watersheds were selected with different mean slope angles as watershed WSA (strong slope) with a mean slope of 21.43° (Figure 1), watershed WSB (moderate slope) with a mean slope of 11.20° (Figure 2) and watershed WSC (gentle slope) with a mean slope of 4.92° (Figure 3). For each of these watersheds, DEM and LULC maps with various resolutions have been used for hydrological modeling using SWAT. Since these watersheds are covered with soils in which the majority of their HSGs are assigned as B and C; hence, the CN values are mostly estimated based on the LULC maps. Due to this, the main objective of this paper is to evaluate that which kind of DEM and LULC resolution have the maximum influence on the output of the hydrological model.

For each watershed, DEM maps in six different grid cell sizes as 12.5, 25, 50, 100, 500 and 1,000 m were collected. These maps were resampled from the original one (12.5 m) with the bilinear method using ArcGIS. The original DEM map (12.5 m) is the ALOS PALSAR and can be downloaded free of charge from the NASA website.

Also, three land-use maps with different grid cell sizes as 250, 1,000 and 2,500 m have been used for CN estimation in each watershed (Figures 1–3). These maps were downloaded

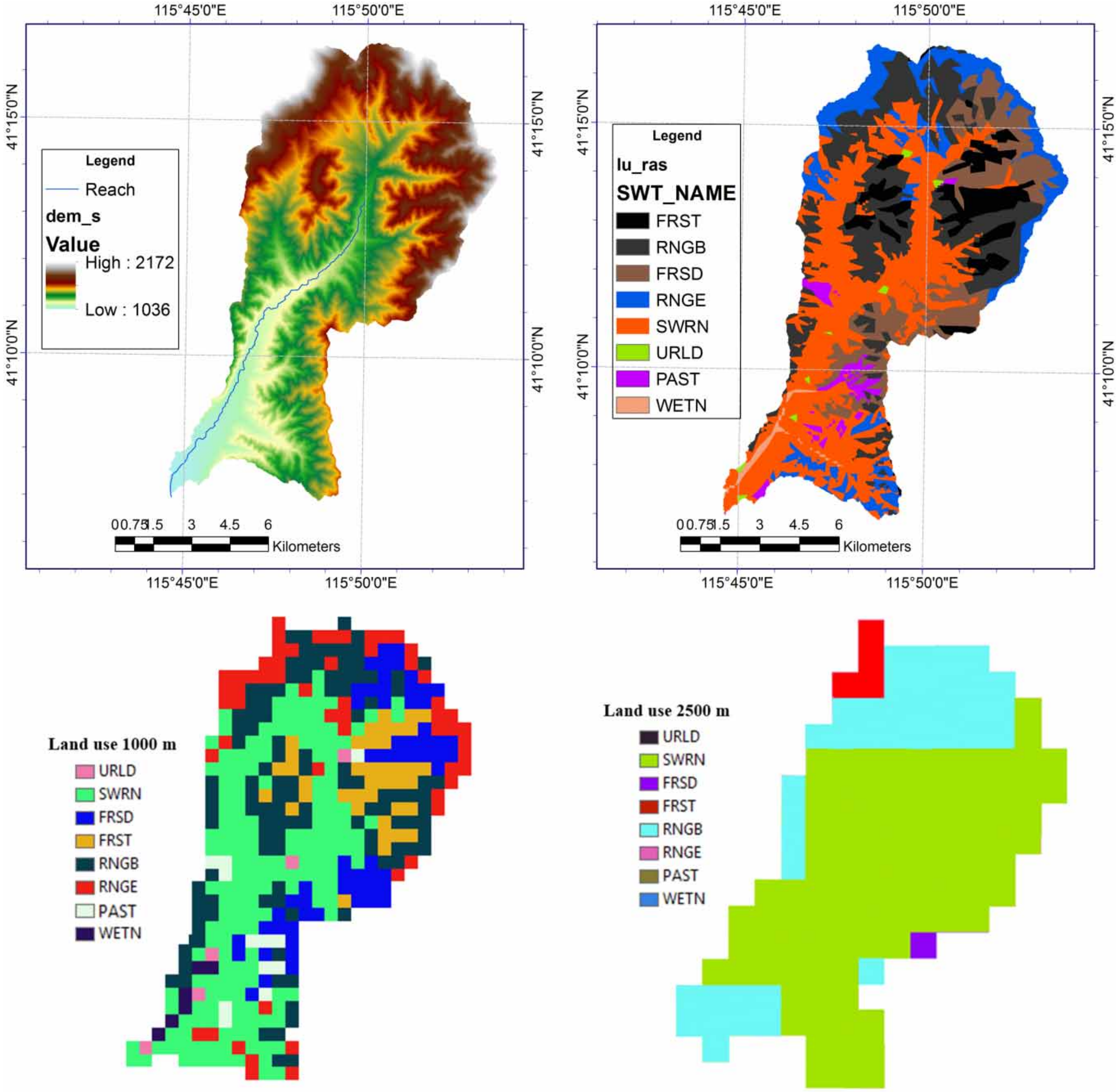

Figure 1 | DEM and LULC maps for watershed WSA with strong mean slope: (Top, left) ALOS PALSAR DEM with 12.5 m resolution, (Top, right) LULC map with 250 m resolution, (Bottom, left) LULC map with 1,000 m resolution and (Bottom, right) LULC map with 2,500 m resolution.

from various digital map websites (www.FAO.org, www.Globallandcover.com and www.Mapcruzin.com).

The climate data (precipitation, relative humidity, solar radiation, temperature and wind speed) which are needed for every SWAT model, were collected as daily data for all 22 stations in the vicinity of the watersheds for more than 30 years (1985–2017). The climate data as raster files were calculated using 22 stations and based on the inverse distance weight technique in ArcGIS. The mean annual rainfall maps (30 years) are represented in Figure 4 for each watershed.

Study area

The study areas are located in a semi-arid region in north-eastern China (Figures 1–3). Table 1 summarizes the topographical properties of the three selected study areas. In addition to the slope, the main difference between

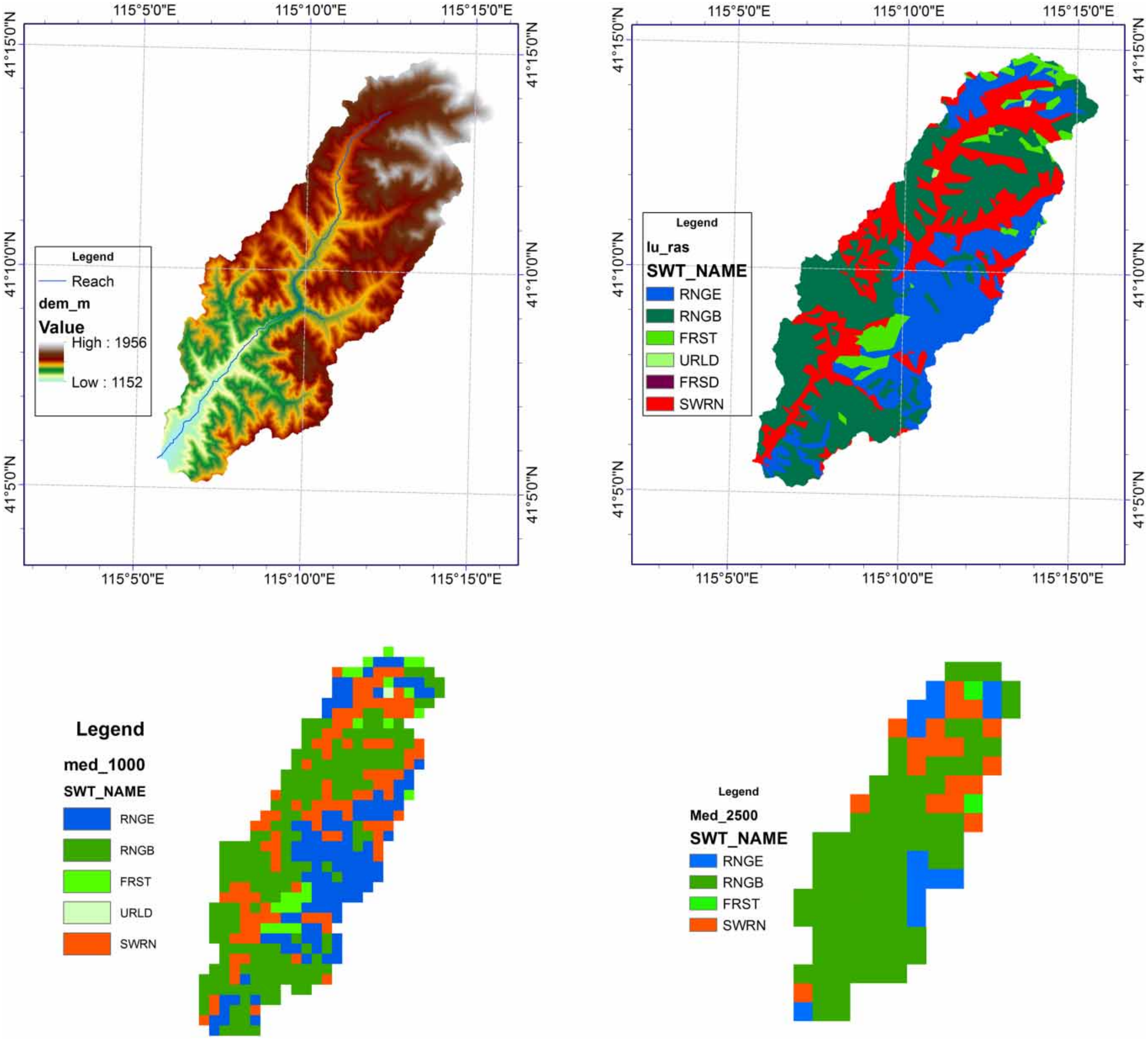

Figure 2 | DEM and LULC maps for watershed WSB with moderate mean slope: (Top, left) ALOS PALSAR DEM with 12.5 m resolution, (Top, right) LULC map with 250 m resolution, (Bottom, left) LULC map with 1,000 m resolution and (Bottom, right) LULC map with 2,500 m resolution.

watersheds WSA and WSB is their dominant land-use type in various grid resolutions (Figures 1–3) which affect the mean curve numbers (CN_{ave}) within the watershed (Galoie *et al.* 2017). Figure 4 shows the variation of land cover components in various grid resolutions in the study areas.

Hydrological modeling

The hydrological modeling of these watersheds has been implemented using the SWAT model. SWAT is a conceptual, fully distributed, physically based, continuous model which evaluates all components of the water cycle (runoff, evapotranspiration and percolation) within a watershed. The capability of the SWAT model in analyzing various detailed input data is an advantage in hydrological modeling.

Using input maps (DEM, LULC and soil type), SWAT dissects the watershed into multiple HRUs so that each contains almost uniform land cover and soil type; then, assigns a mean CN to HRU based on input LULC and soil type maps. In fact, a CN grid was made first in which, each pixel value was calculated based on corresponding

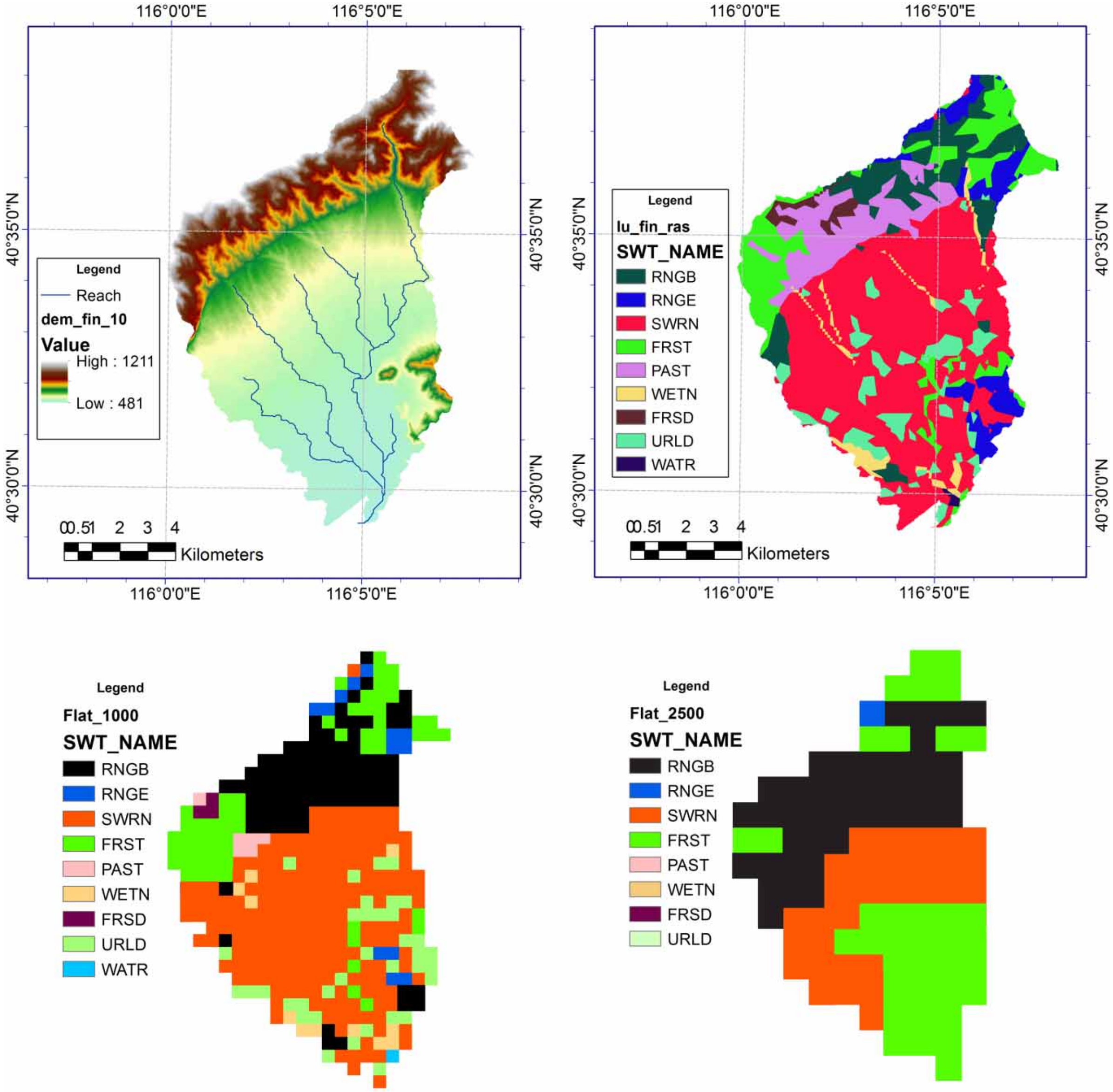

Figure 3 | DEM and LULC maps for watershed WSC with gentle mean slope: (Top, left) ALOS PALSAR DEM with 12.5 m resolution, (Top, right) LULC map with 250 m resolution, (Bottom, left) LULC map with 1,000 m resolution and (Bottom, right) LULC map with 2,500 m resolution.

pixels in the same coordinate (latitude and longitude) in LULC and soil type maps (regardless of pixel size), and then, a mean value was assigned to each HRU and subbasin (Arnold *et al.* 2013). The surface water in each subbasin for each time step was calculated based on the SCS-CN method which is the primary method for runoff modeling in SWAT, and then, the calculated runoff was routed (Muskingum or variable storage method) through the river network.

The SCS-CN method is expressed as follows (Mishra & Singh 2003):

$$Q = \frac{(P - I_a)^2}{P + (1 - I_a)} \qquad (1)$$

$$I_a = \lambda S, \quad S = \frac{25400}{\text{CN}} - 254$$

where Q is the discharge depth (mm), P is the daily rainfall depth (mm), CN is the curve number (dimensionless), S is

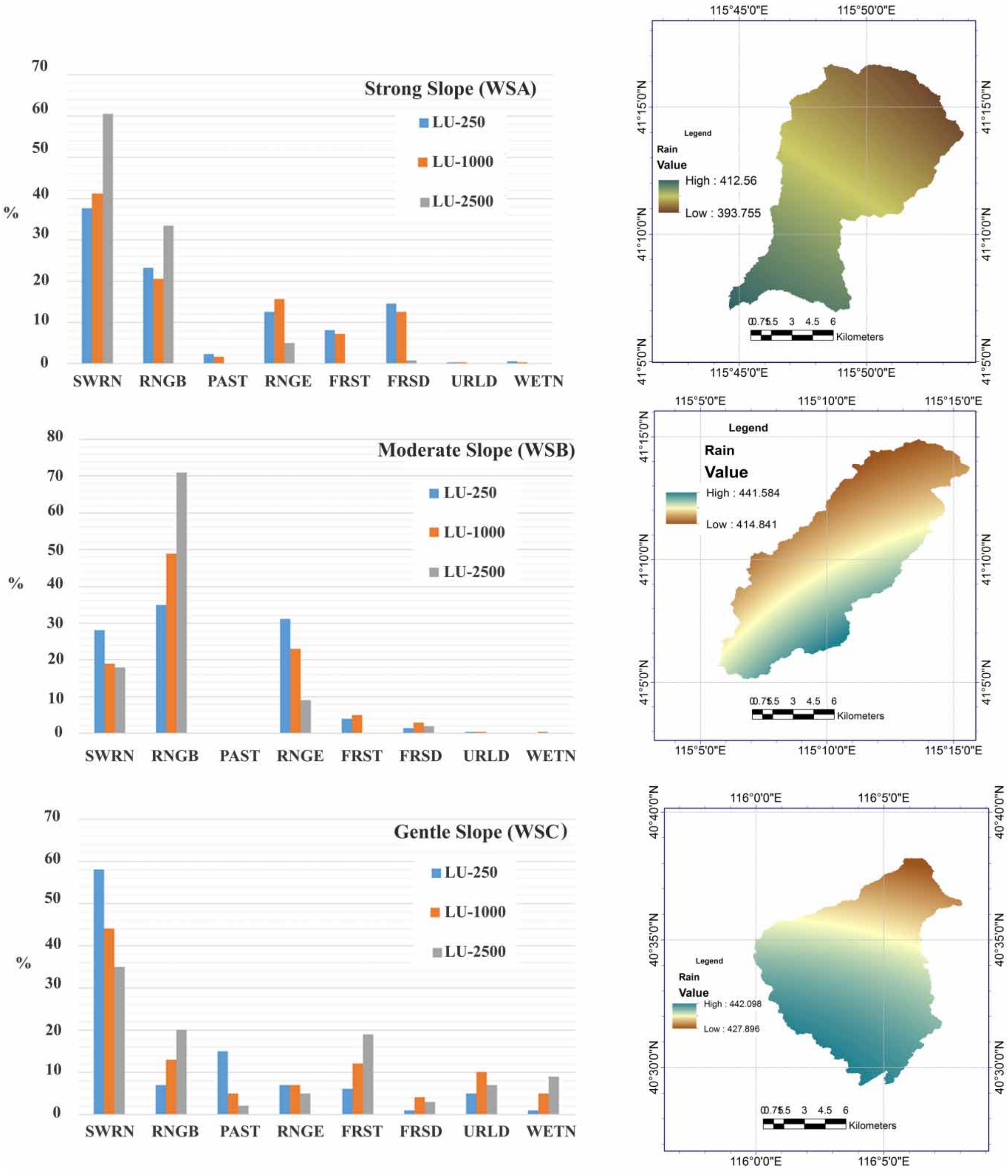

Figure 4 | Variation of land cover types in various LULC grid resolutions (left) and mean annual rainfall (right) for WSA, WSB and WSC.

the potential maximum retention (mm), and I_a is an initial abstraction (λ is generally considered as 0.2). Although the SCS-CN method relies on only one parameter (CN), this parameter depends on many other factors such as soil type, land use and terrain slope, which are spatially distributed in watersheds. SWAT estimates evapotranspiration by empirical relations (Hargreaves, Priestley–Taylor or Penman–Monteith). In fact, SWAT by using a

Table 1 | Topographical properties of the base (12.5 m) DEM maps based on SWAT model output

		Basin surface				Basin slope			
DEM	**Cell size (m)**	**Area – Ao (km^2)**	**Min El. (m)**	**Max El. (m)**	**Std.**	**Mean – So (°)**	**Min (°)**	**Max (°)**	**Std.**
Strong slope (watershed name: WSA)	12.5	114.70	1,036	2,172	229.98	21.43	0.00	67.38	8.96
Moderate slope (watershed name: WSB)	12.5	111.47	1,152	1,956	165.21	11.20	0.00	48.45	6.41
Gentle slope (watershed name: WSC)	12.5	109.94	481	1,211	128.66	4.92	0.00	29.59	10.38

water balance equation can model the water cycle across a watershed.

For each watershed, a complete SWAT model was implemented and calibrated using SWAT-CUP software (total 18 models for each watershed).

RESULTS AND DISCUSSION

Determining hydrological responses of a watershed is a very complicated procedure and depends on many factors especially physical and meteorological data. The distribution of physical properties of a watershed directly affects the hydrological model output such as runoff (rate and volume), time to peak and losses (percolation and evapotranspiration). For this reason, the impact of the grid resolution of input maps on the physical properties of each watershed is discussed here.

It should be noted that although all three zones have similar areas, in order to avoid any scale effect, all results in tables and graphs are shown dimensionless and based on the ratio of the output of any model to the model output of the base map (12.5 m).

Area and slope

Figure 5 shows the variation of the ratio of delineated area and mean slope (as two key parameters in hydrological modeling) in various DEM grid resolutions, to the delineated area and mean slope of the base (12.5 m) map as (A/Ao) and (S/So), respectively. All the parameters were derived from SWAT model outputs.

As can be seen from Figure 5, in all watersheds, by increasing the DEM cell size, the mean slope of the watershed was decreased. Mean slope plays a key role in calculating the time of concentration in watersheds and consequently, corresponding model outputs (runoff and percolation). This result is in agreement with previous studies (Xu *et al.* 2004; Chow & Hodgson 2009; Lin *et al.* 2010; Tan *et al.* 2015).

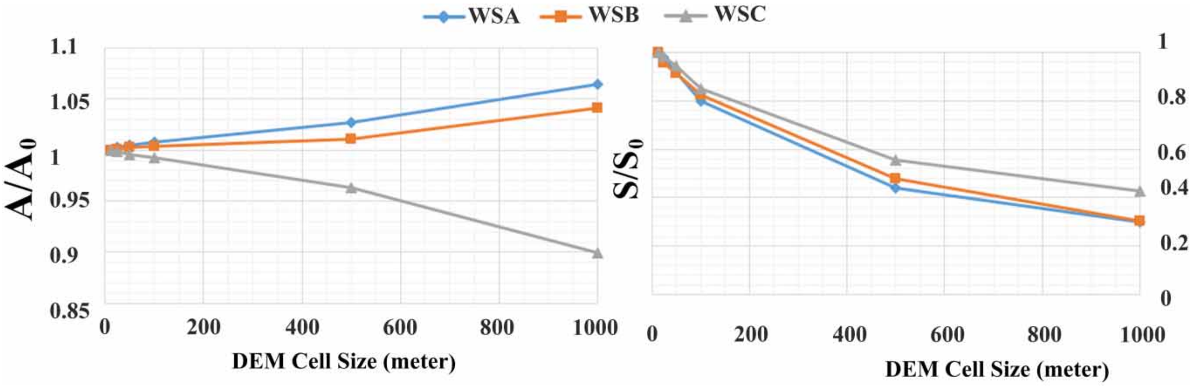

Figure 5 | Variation of the ratio of the area of the delineated models in various DEM cell sizes to the area of the model in 12.5 m DEM (A/Ao) (left) and the variation of the ratio of the mean slope of the delineated models in various DEM cell sizes to the mean slope of the model in 12.5 m DEM (S/So) (right).

Unlike the slope variation, the delineated area may increase (in steep mountainous basins) or decrease (in plain basins) when the cell size of the map is increased. The delineated area in hilly regions is increased because of the fact that when the cell size of the DEM is increased, the mean slope of the map is decreased and consequently, the bigger area should be delineated for a given outlet elevation. This result is in agreement with previous studies (Zhang *et al.* 2016; Nazari-Sharabian *et al.* 2019).

Also, by increasing the DEM cell size, the distribution of slope in a watershed was changed. This distribution in hilly regions is very important because this factor directly affects the amount and shape of the runoff hydrograph. For comparison, Figure 6 shows the slope distribution within each watershed for two DEM cell sizes of 12.5 and 1,000 m. As can be seen, almost all areas with slopes of more than 30% in the high-resolution DEMs (12.5 m), are shifted to the slopes of less than 30% in the low-resolution DEMs (1,000 m).

River network and sub-basins

In addition to the area and slope of the watersheds, changes in DEM cell sizes also affect the river network and consequently, delineation of sub-basins. Because the slope and pixel elevation were changed when the cell size of DEM was changed, the formation and even direction of reaches were completely deformed. This deformation might change river network properties such as the length of the longest flow path, which affects the time of concentration and model output significantly, especially in large watersheds. For comparison, Figure 7 shows this deformation in the derived river network and also sub-basins within the watershed WSA in different cell sizes (SWAT outputs). This result

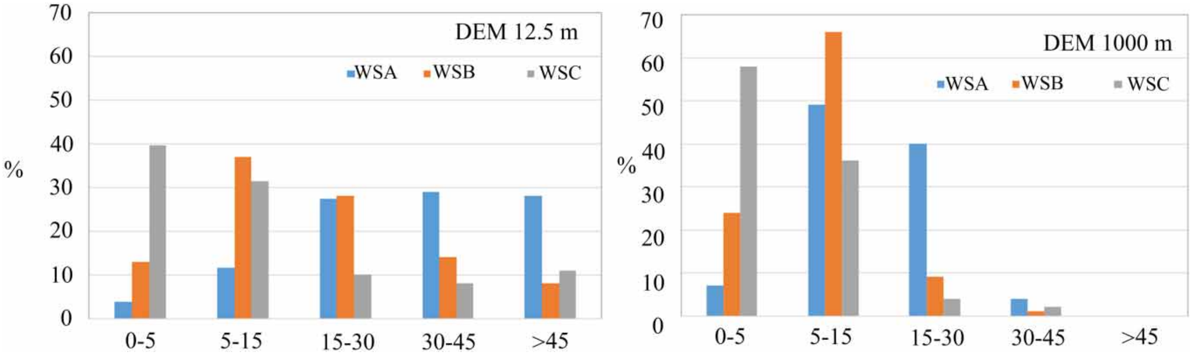

Figure 6 | Slope classification within each watershed in SWAT model output for DEM cell sizes as 12.5 m (left) and 1,000 m (right).

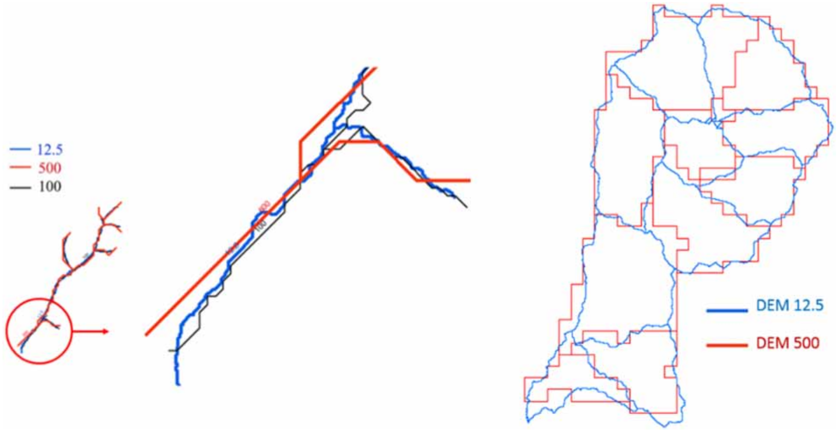

Figure 7 | Deformation of the derived main river (left) and delineated sub-basins (right) from SWAT outputs and for watershed WSA in various DEM cell sizes.

is in agreement with other studies (Vaze *et al.* 2010; Wu *et al.* 2017).

Time of preprocessing

Prior to starting the hydrological modeling in SWAT, a terrain preprocessing should be implemented on DEM in order to derive all physical properties of the watershed (i.e. fill sinks, flow accumulation, flow direction, catchment delineation, longest flow path, slope and river length). The time, which needs to complete these processes depends on the number of DEM pixels. As the DEM cell size decreases, the time of terrain preprocessing is nonlinearly increased. Figure 8 shows the ratio of the preprocessing time of various DEM cell sizes of WSA to the preprocessing time of the base DEM (12.5 m). As can be seen in Figure 8, the ratio of preprocessing time for DEMs with cell sizes from 12.5 to 100 m is decreased faster than cell sizes from 100 to 1,000 m. It is because of this fact that when the number of pixels is decreased, the overall time of analysis for some of the terrain preprocessing components (i.e. fill sinks) is decreased faster. However, the ratio numbers which are indicated in Figure 8 may be altered in large watersheds. This result is in agreement with other studies (Munoth & Goyal 2019).

Runoff modeling

The SWAT outputs showed that the resolution of the input maps can intensively affect the amount of basin runoff. Figure 9 shows how the variations of DEM cell size and land-use map resolution alter the modeled runoff. In Figure 9, all percentage changes are calculated based on the runoff value of DEM 12.5 m to show the changes clearly. Although hydrological modeling was implemented for 30 years, the results showed that maximum variation has occurred when the maximum rainfall has occurred which was in agreement with other studies (Mishra & Singh 2003; Galoie *et al.* 2017). Due to this, the maximum variation is shown in Figure 9.

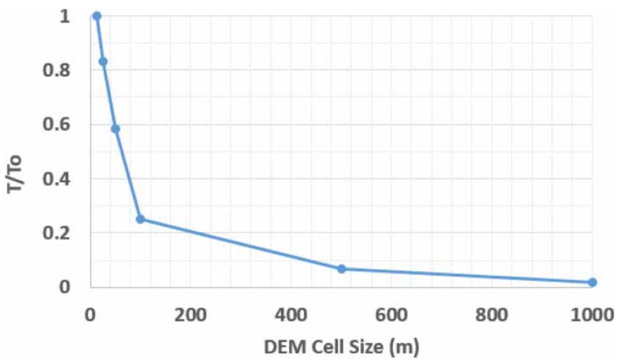

Figure 8 | The ratio of the terrain preprocessing time for various DEM cell sizes of WSA to the preprocessing time of the base DEM (12.5 m).

As can be seen in Figure 9, the following results can be obtained:

1. In all model outputs, when the DEM cell size increased, the runoff depth was decreased which is in agreement with Nazari-Sharabian *et al.* (2019), Al-Khafaji & Saeed (2018) and Sharma & Tiwari (2014). This is because when DEM cell size is increased, the mean slope of the area is decreased as shown in Figure 5. Therefore, by decreasing the mean slope, the runoff is decreased. Since the maximum mean slope reduction was occurred in strong slope watershed (WSA), the maximum reduction of runoff depth has also occurred in this watershed (Figure 9, top, left).
2. Regardless of LULC resolution, the amount of runoff reduction for DEM cell sizes smaller than 100 m was less than 10%. This shows that for hydrological modeling and deriving physical characteristics of DEM using SWAT, pixel size less than 100 m is sufficient.
3. By comparing the strong slope DEM (WSA) graphs with the others, it can be seen that the hydrological model output of WSA is very sensitive to the DEM cell size which is between −30 and −49%. This is because the variation of physical properties in high slope DEM such as mean slope and river length are more than the other DEMs. So, for mountainous areas, the DEM cell size should be selected carefully.
4. For a given DEM cell size, when the land-use cell size was increased, the runoff was increased or decreased based on the dominant land-use types within the basin and corresponding CN values, but this increment or reduction of runoff was more than when only DEM cell size was changed especially for strong slope watersheds. For example, in strong and moderate slope DEM (WSA and WSB), when the LULC cell size is increased, the dominant LULC is changed so that the mean CN value

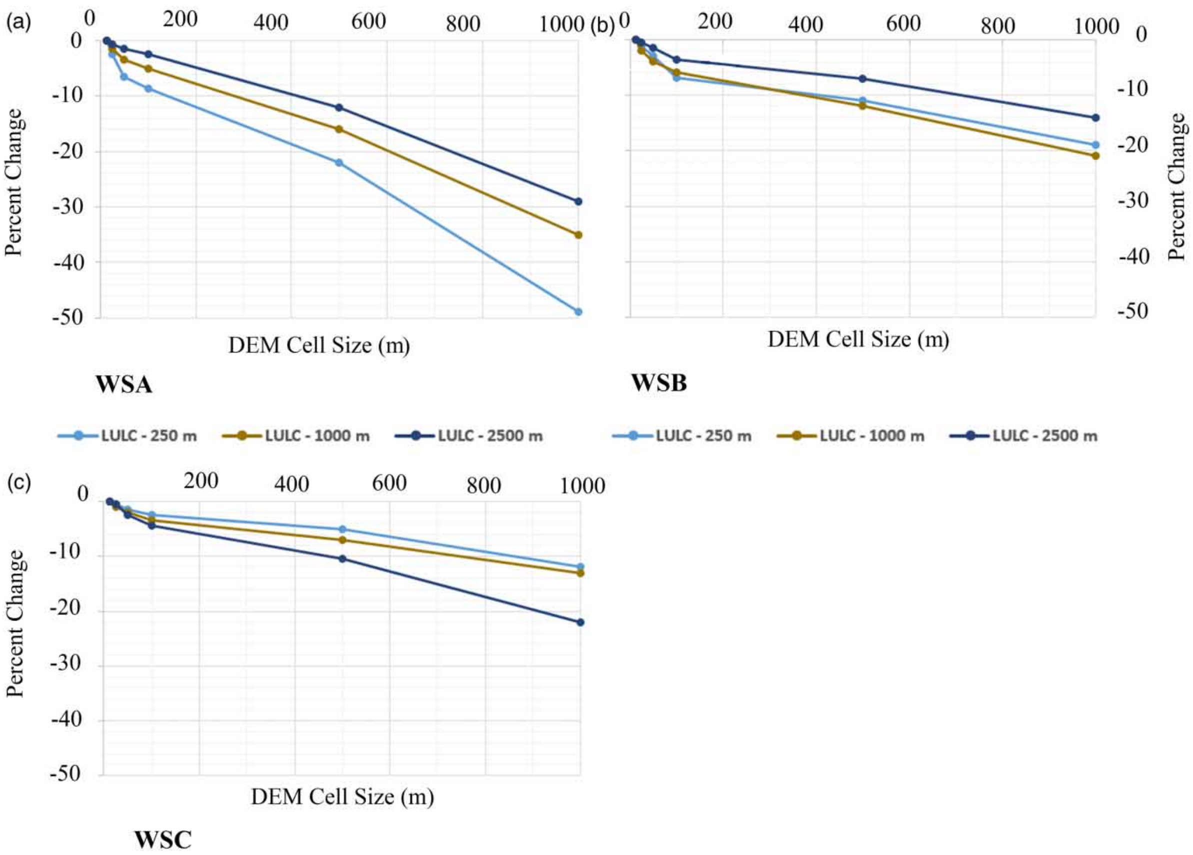

Figure 9 | The variations of DEM cell size and land-use map resolution alter the amount of modeled runoff. All percent changes are calculated based on the runoff value of DEM 12.5 m to show the changes clearly: (a) WSA, (b) WSB and (c) WSC.

is increased; therefore, the runoff is also increased. However, when the LULC cell size for gentle slope DEM (WSC) is increased, the dominant LULC is changed so that the mean CN value is decreased, and therefore, the runoff is decreased.

According to the above results, it can be said that in comparison to DEM cell size changes, runoff values are more sensitive to the land-use resolution. This is because the most sensitive parameter in the SCS-CN relationship is CN which is directly evaluated based on land use, soil types and mean slope within a basin. Therefore, for successive hydrological modeling, although a finer DEM cell size is better, the resolution of land use is more important. As it can be seen in Figure 9, for a land-use cell size of 2,500 m, the runoff change rate for WSA was between −30 and −50%.

Also, it seems that for any hydrological modeling, a DEM with a cell size of up to 100 m is enough for most cases. As can be seen in Figure 9, for a given land-use map, the differences between percentage changes of runoff using DEM cell sizes as 12.5, 25, 50 and 100 are not significant.

CONCLUSIONS

In this paper, the impact of the quality of input DEM and LULC maps on hydrological modeling output using SWAT is investigated. To do this, DEM maps in three kinds of strong, moderate and gentle slope DEM were collected as 12.5, 25, 50, 100, 500 and 1,000 m and land-use maps as 250, 1,000 and 2,500 m. The output results showed that runoff values were changed when DEM cell size or land-use resolution was changed, but the sensitivity of runoff to land-use resolution was more than DEM cell size. In addition to the LULC resolution, the analysis showed that the distribution pattern of the land use across a watershed can change the amount of modeled runoff. Also, in all models, when the DEM cell size was increased, the runoff depth was decreased, but this reduction for the strong slope watershed was more than moderate and gentle slope watersheds. Also, the results showed that, for a given land-use map in a watershed, the differences between runoff values for various DEM cell sizes less than 100 m are not significant, so for hydrological modeling, a DEM with cell size up to 100 m seems to be sufficient.

For future works, it is suggested that the impact of DEM and LULC resolution on groundwater level and evapotranspiration are evaluated. Also, the effect of soil type map resolution on hydrological modeling is investigated.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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