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*Article*

# Effect of DEM Resolution on Runoff Yield, and Sensitivity of Parameters Contributing to Runoff in a Watershed

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**Abstract:** Digital Elevation Models (DEMs) are essential in watershed delineation, but the sensitivity of simulated runoff to DEM resolution is poorly understood. This study investigates the impact of DEM resolution on topological attributes and simulated runoff in the Mahabad Dam watershed, Iran. To delineate the watershed, DEMs with 12.5m, 30m, and 90m resolutions were acquired from the ALOS PALSAR, Space Shuttle Radar Topography Mission (SRTM), and ASTER global DEM data source, respectively. Watershed and streamlines were delineated in ArcGIS, with hydrologic analyses performed using the Soil and Water Assessment Tool (SWAT). Sensitivity analysis on parameters contributing to runoff was done using Sequential Uncertainties Fitting Ver-2 (SUFI-2) Algorithm, in SWAT Calibration and Uncertainty Procedures (SWAT-CUP) software. Results showed the watershed area, reach lengths, and elevations in the watershed varied due to DEM resolutions. Higher amounts of runoff were generated when DEMs with finer resolutions were implemented. The 12.5m DEM generated 3.48% and 0.42% more runoff compared with 90m and 30m DEMs, respectively. SWAT-CUP results showed the sensitivity of parameters contributing to runoff changes under different DEM resolutions. Regardless of DEM resolution, surface properties, available water capacity, and moisture levels in the soil are the most sensitive parameters. As the distribution of slope changes in different DEM resolutions, surface parameters are most affected. The findings indicate to reduce computation time and speed up computation procedures, researchers may use DEMs with coarser resolutions at the expense of minor decreases in accuracy.

**Keywords:** DEM Resolution; Runoff; Sensitivity Analysis; SWAT; SWAT-CUP; SUFI-2

## 1. Introduction

Application of practical models and appropriate data in hydrological studies is vital to understanding the processes occurring in the watershed scale. The ability of these models to represent the hydrological processes and estimate variables such as runoff, sediment, and nutrient yields within a watershed greatly depends on the quality of the input data. Model input data are the primary sources of errors in estimated hydrological variables [1—3].

The Digital Elevation Model (DEM) is one of the essential input files for hydrological models used in estimating a variety of variables in a watershed [4—7]. DEM is a digital (raster) dataset of elevations in x, y, and z coordinates, which represents the physical parameters of the watershed regarding the flow direction, drainage network, and drainage slopes [8]. DEM resolution can affect important watershed characteristics such as area, shape, length, and slope. The area of the watershed reflects the generated volume of water from rainfall. The shape of a watershed influences the shape of its characteristic hydrograph. The length affects the travel time of water through a watershed, and the slope affects the momentum of runoff.

The significant development in remote sensing technology has led to the development of high-quality DEMs with different resolutions, for commercial and research purposes. In ArcGIS, the spatial analysis computation speed is closely associated with the resolution of the input data. Therefore, in order to reduce the computation time and speed up the computation procedure, users may use DEMs with coarser resolutions.

The Soil and Water Assessment Tool (SWAT) is among software packages widely used for watershed-scale studies, that uses DEMs for watershed delineation. In 2003, Cotter et al. [4] used SWAT to evaluate the impact of different DEM resolutions on the uncertainties of predicted values of runoff, sediment, nitrate nitrogen ($NO_3$–N), and total phosphorus (TP) transport in Moores Creek watershed in Washington County, Arkansas, USA. In 2005, Chaubey et al. [6] found that the watershed delineation, stream network, and sub-basin classification in SWAT are affected by DEM resolution. They showed that a coarser DEM resolution results in decreased runoff, sediment, $NO_3$–N, and TP load predictions. Moreover, Dixon and Earls [9] used three DEMs with 30m, 90m, and 300m resolutions to compare the predicted streamflow in the Charlie Creek drainage basin, located in the Peace River drainage basin of central Florida, USA, using SWAT. Their study indicated a significant deviation in predicted streamflow.

In 2010, Lin et al. [10] studied the effect of DEMs with different resolutions (varying from 5m to 140m) on hydrological parameters in the Xiekengxi River watershed in Zhejiang Province of China. They showed that runoff values were more sensitive to coarser DEM resolutions but not so sensitive to finer resolutions. Peter et al. [11] studied the sediment delivery estimates in a coastal watershed in South Carolina, USA, using four DEMs with 3m, 10m, 30m, and 90m resolutions. The researchers noted that finer resolution DEM results in more accurate slope results and sediment output. Peipei et al. [12] studied the impact of different DEM resolutions on SWAT model outputs of sediment and nutrient yield in the agricultural watershed of Xiangxi River, Gorges Reservoir in China. The authors used 17 DEMs with resolutions varying from 30m to 1000m and analyzed the results of the model outputs of sediments and nutrients for each resolution. The researchers noticed that sediment yield was significantly affected by DEM resolution, and the prediction of dissolved oxygen load was significantly affected by DEM resolutions coarser than 500m. Moreover, the authors noticed that total nitrogen (TN), $NO_3$–N, and TP loads were slightly affected by DEM resolution, while ammonia nitrogen ($NH_4$–N) load was unaffected.

More recently, Liffner et al. [13] studied the sensitivity of hypsometric properties to DEM resolution, DEM type, and polynomial order through assessing differences in hypsometric properties derived from 417 catchments and sub-catchments in South Australia. The researchers found significant sensitivity of hypsometric properties across DEM types and polynomial orders.

Moreover, using four different DEMs, and the Universal Soil Loss Equation (USLE), Chen et al. [14] conducted a new analysis to compute the amounts of sheet and rill erosion of the Shihmen reservoir watershed in northern Taiwan. The authors concluded that the DEM created from airborne LiDAR, with the highest vertical resolution among the four DEMs, yields the highest amount of soil erosion. The lowest amounts of soil erosion were observed when using the two DEMs created from satellite images with the lowest vertical resolution, and an in-between soil erosion amount was observed when using the DEM created from aerial photographs.

## 2. Materials and Methods

According to the literature, studies have noted that DEM resolution has a direct impact on hydrologic model predictions. However, the use of finer resolution spatial data does not necessarily improve the performance of hydrological model predictions [15]. It was noted that no studies had investigated the relationship between DEM resolution and the sensitivity of parameters contributing to the variable of interest, such as runoff. Therefore, using DEMs with different resolutions, this study seeks to find the answer to the following questions:

1. What topological factors are affected in the delineated watershed (e.g., the minimum and maximum elevations, slopes)?
2. What is the impact on runoff yield in the watershed?
3. How are the sensitivity of parameters contributing to runoff (e.g., the runoff curve number, base flow alpha factor, Manning's "n" value for the main channel) affected?

In this regard, for the case study of the Mahabad Dam watershed in Iran during the period of 1991- 2012, three DEMs with resolutions of 12.5m, 30m, and 90m were implemented. In order to delineate the watershed and perform hydrologic analyses, the SWAT model, which runs in ArcGIS using the ArcSWAT extension was used. SWAT inputs for this study include the DEM, land use map, soil map, and climate data. Moreover, for sensitivity analysis on parameters contributing to runoff, the SUFI-2 module of the SWAT Calibration and Uncertainty Procedures (SWAT-CUP) software was used. The following flowchart given in Figure 1 summarizes the procedure of this study.

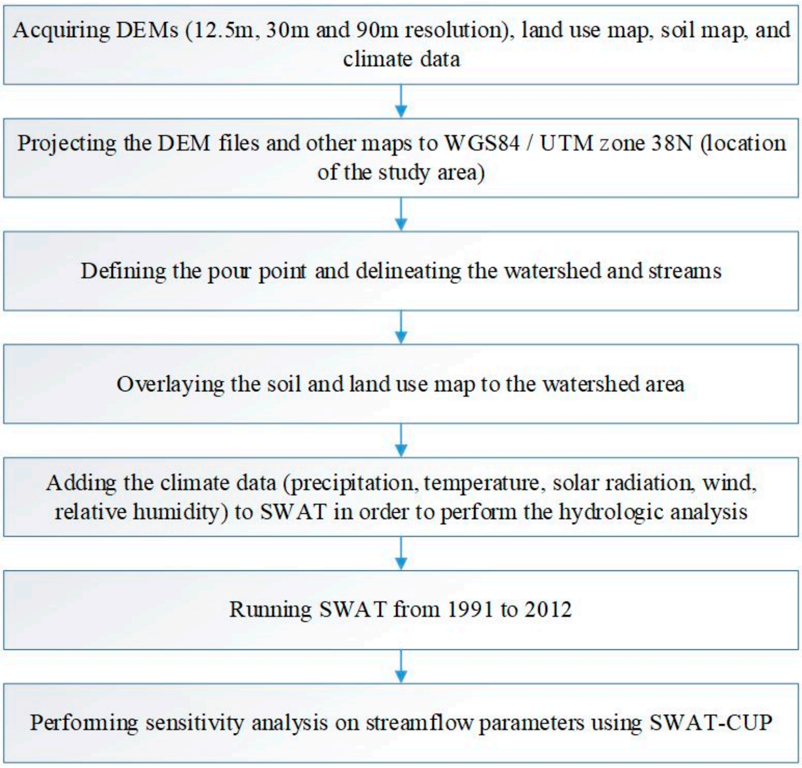

**Figure 1.** Flowchart of this study.

### *2.1. SWAT and SWAT-CUP*

Among the most commonly used continuous-time, semi-distributed, and physically-based models is the Soil and Water Assessment Tool (SWAT). To model processes within a watershed, SWAT integrates weather, surface and groundwater hydrology, soil properties, plant growth, nutrient cycles, and land management practices [16]. Based on interior outlet points along the stream network, SWAT divides the watershed area into several sub-basins. Watersheds, also known as basins or catchments, are physically delineated by the area upstream from a specific outlet point. Watershed delineation based on digital elevation models is the prerequisite to setting up a SWAT model. There are two methods for watershed delineation in a SWAT model: the DEM-based method; and the pre-defined method, in which users can define the reaches and sub-basins manually.

Sensitivity analysis is the process of determining the significance of the effect of a one or multi-parameter combination on the output of a model or target function. The SWAT-CUP program has been developed for the calibration, validation, and sensitivity analysis of SWAT model parameters. This software uses the p-value and t-stat factors to identify the more sensitive parameters in the model. A higher p-value (lower t-stat value) shows a higher sensitivity of the parameter [17].

### *2.2. Study Area and Data*

In this study, the Mahabad Dam watershed in Iran was selected as the case study, which topologically is located in a mountainous area. This watershed is located in the West-Azerbaijan province in the north-west of Iran (36°44′N, 45°39′E) and is one of the Urmia Lake basins. The area of the watershed is approximately 808 km$^2$ and is mostly covered by agricultural fields and grasslands, as shown in Figure 2.

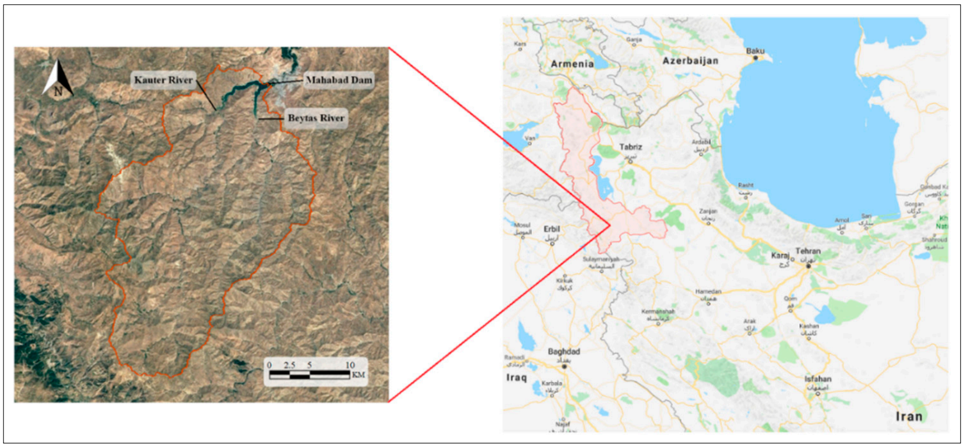

**Figure 2.** Location of the Mahabad Dam watershed.

Tables 1 and 2 represent the land use and soil classification of the watershed, respectively.

**Table 1.** Land use classification of Mahabad Dam watershed

| Land use type | Watershed area (%) |
|---|---|
| Grasslands | 66.37 |
| Agriculture (small grains) | 13.82 |
| Range shrublands | 11.09 |
| Agriculture (generic) | 4.49 |
| Mixed forest | 2.95 |
| Water | 1.03 |
| Urban (medium density) | 0.13 |
| Rock | 0.12 |
| Pasture | 0.01 |

**Table 2.** Soil types in Mahabad Dam watershed

| Soil type | Sand (%) | Silt (%) | Clay (%) | Watershed area (%) |
|---|---|---|---|---|
| Taconic | 43 | 35 | 23 | 72 |
| Benson | 35 | 37 | 30 | 28 |

In order to delineate the watershed, DEMs with 12.5m, 30m, and 90m resolution were acquired from the ALOS PALSAR, Space Shuttle Radar Topography Mission (SRTM), and ASTER global DEM data source, respectively [18—20]. The soil map was retrieved from the FAO soils portal using the Harmonized world soil database v1.2 [21]. The land use map was provided by Mahab Ghods consulting engineering company. Moreover, daily precipitation and temperature records were provided by I.R. of Iran Meteorological Organization for the weather station of Mahabad [22].

## 3. Results

Figure 3 shows the area delineation of the Mahabad Dam watershed in GIS under each DEM resolution. The stream networks were delineated based on the elevation and slope distribution characteristics of the land. The streams were laid out based on the SWAT model recommended minimum drainage areas of 1594.15 ha for the 12.5m DEM, 1589.78 ha for the 30m DEM, and 1571.78 ha for the 90m DEM. Moreover, a total number of 27 sub-basins were formed for all DEM resolutions.

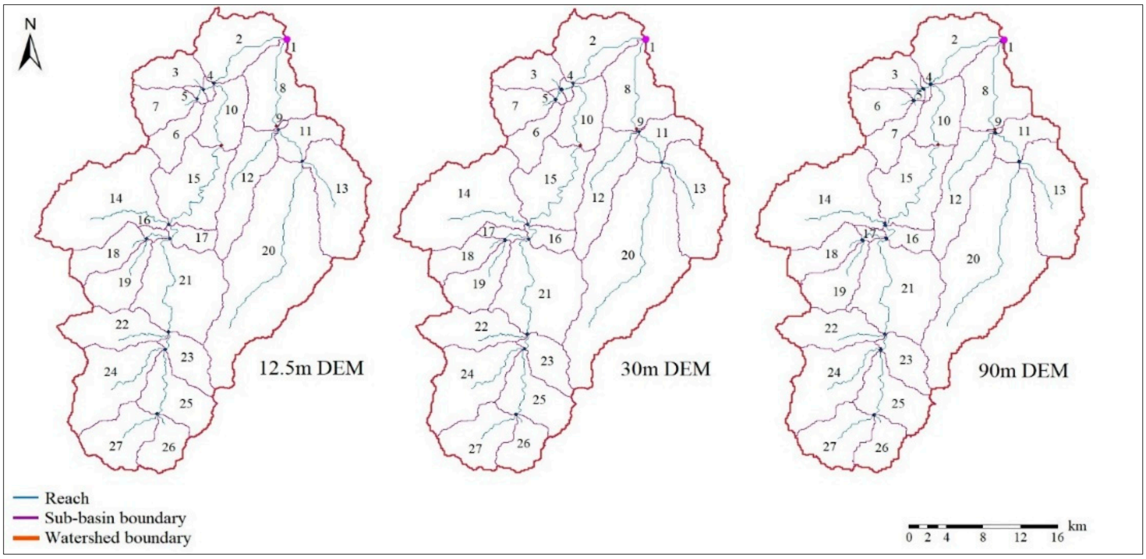

**Figure 3.** Delineated watershed using: 12.5m, 30m, and 90m DEMs.

After watershed delineation, features such as total area, elevations, average runoff (measured at the outlet of the watershed), cumulative stream length (Table 3), and slope distribution ranges (Table 4) were analyzed in order to determine how DEMs with different resolutions affect these features.

**Table 3.** Surface area and elevations, cumulative stream length, and average runoff within the watershed

| DEM Resolution (m) | Surface Area (ha) | Min. Elevation (m) | Max. Elevation (m) | Mean Elevation (m) | Cum. Stream Length (m) | Runoff ($m^3/s$) |
|---|---|---|---|---|---|---|
| 12.5 | 79708.97 | 1337 | 2824 | 1796.68 | 152458 | 4.286 |
| 30 | 79489.19 | 1320 | 2806 | 1778.38 | 154600 | 4.268 |
| 90 | 78591.08 | 1328 | 2799 | 1774.96 | 151040 | 4.142 |

According to Table 3, the DEM with the finest resolution shows the highest values of the surface area, and minimum, mean, and maximum elevations, along with highest average runoff value in the watershed. Moreover, as the DEM resolution gets coarser, the surface area and average runoff decrease. However, this pattern for minimum elevation is not regular, and the 30m DEM shows the lowest elevation. Similarly, the cumulative stream length in the 30m DEM is the highest, while in the 90m DEM it is the lowest.

Results show consistent trends of runoff and area variations. The runoffs based on 12.5m, 30m, and 90m all slightly decreased or increased with resolution correspondingly as the areas did, indicating that the changes in runoffs are mainly attributed to the changes in areas. The 12.5m DEM generated 3.48% more runoff compared with the 90m DEM, and 0.42% more runoff compared with the 30m DEM. Moreover, the 30m DEM generated 3.04% more runoff compared with the 90m DEM.

**Table 4.** Slope distribution within the watershed

| Slope (Degrees) | 12.5m | | 30m | | 90m | |
|---|---|---|---|---|---|---|
| | **Area (ha)** | **% Area** | **Area (ha)** | **% Area** | **Area (ha)** | **% Area** |
| 0-10 | 30.64 | 0.04 | 37.57 | 0.05 | 411.15 | 0.52 |
| 10-20 | 51255.88 | 64.30 | 51902.14 | 65.29 | 11514.77 | 14.65 |
| 20-40 | 23636.56 | 29.65 | 5059.92 | 6.37 | 59333.28 | 75.50 |
| 40-60 | 4785.89 | 6.00 | 22489.56 | 28.29 | 7331.88 | 9.33 |

As shown in Table 4, for the 12.5m and 30m DEMs, the slope range of 10-20 degrees is predominant, while for the 90m DEM, the predominant slope range in the watershed is 20-40 degrees. The results show that the mean slopes increased with coarser resolution.

Previous studies showed inconsistent results related to the effects of DEM resolutions on SWAT predicted runoffs. Some found that runoff decreased with coarser DEM resolutions [23—25,6], but some did not [26,9]. However, the above studies all found that mean slope decreased with coarser resolution, which is inconsistent with the findings of this study and illustrates that mean slope plays a minor role in the runoff output of SWAT.

### 3.1. Sensitivity Analysis

Ultimately, SWAT model parameters contributing to runoff in the watershed were analyzed. These parameters are listed in Table 5, and a short description of each parameter is provided.

**Table 5.** Parameters contributing to runoff in SWAT

| Parameter | Description |
|---|---|
| SHALLST.gw | Initial depth of water in the shallow aquifer (mm) |
| DEEPST.gw | Initial depth of water in the deep aquifer (mm) |
| GWHT.gw | Initial groundwater height (m) |
| ALPHA_BF.gw | Baseflow alpha factor (1/days) |
| GW_DELAY.gw | Groundwater delay time (days) |
| GWQMN.gw | Threshold depth of water in the shallow aquifer required for return flow to occur (mm) |
| GW_REVAP.gw | Groundwater “revap” coefficient |
| REVAPMN.gw | Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (mm) |
| RCHRG_DP.gw | Deep aquifer percolation fraction |
| GW_SPYLD.gw | Specific yield of the shallow aquifer ($m^3/m^3$) |
| SNO_SUB.sub | Initial snow water content (mm) |
| PLAPS.sub | Precipitation lapse rate (mm/km) |
| TLAPS.sub | Temperature lapse rate (°C/km) |
| CH_K1.sub | Effective hydraulic conductivity in tributary channel alluvium (mm/hr) |

| | |
|---|---|
| CH_N1.sub | Manning's "n" value for the tributary channels |
| CN2.mgt | Initial SCS runoff curve number for moisture condition II |
| SFTMP.bsn | Snowfall temperature (°C) |
| SMTMP.bsn | Snow melt base temperature (°C) |
| SURLAG.bsn | Surface runoff lag coefficient |
| SMFMX.bsn | Melt factor for snow on June 21 (mm/°C-day) |
| SMFMN.bsn | Melt factor for snow on December 21 (mm/°C-day) |
| TIMP.bsn | Snow pack temperature lag factor |
| CH_N2.rte | Manning's "n" value for the main channel |
| CH_K2.rte | Effective hydraulic conductivity in main channel alluvium (mm/hr) |
| ALPHA_BNK.rte | Baseflow alpha factor for bank storage (days) |
| ESCO.hru | Soil evaporation compensation factor |
| EPCO.hru | Plant uptake compensation factor |
| CANMX.hru | Maximum canopy storage (mm) |
| OV_N.hru | Manning's "n" value for the overland flow |
| SOL_ZMX.sol | Maximum rooting depth of soil profile (mm) |
| SOL_Z.sol | Depth from the soil surface to bottom of layer (mm) |
| SOL_AWC.sol | Available water capacity of the soil layer (mm $H_2O$/mm soil) |
| SOL_K.sol | Saturated hydraulic conductivity (mm/hr) |
| SOL_BD.sol | Moist bulk density (g/$cm^3$) |

The sensitivity analysis on parameters was done using the SUFI-2 module of the SWAT-CUP software. Figure 4 shows the results of the analysis for each DEM resolution. Parameters with higher p-value are more sensitive, and changing their value has a higher impact on runoff yield in the watershed.

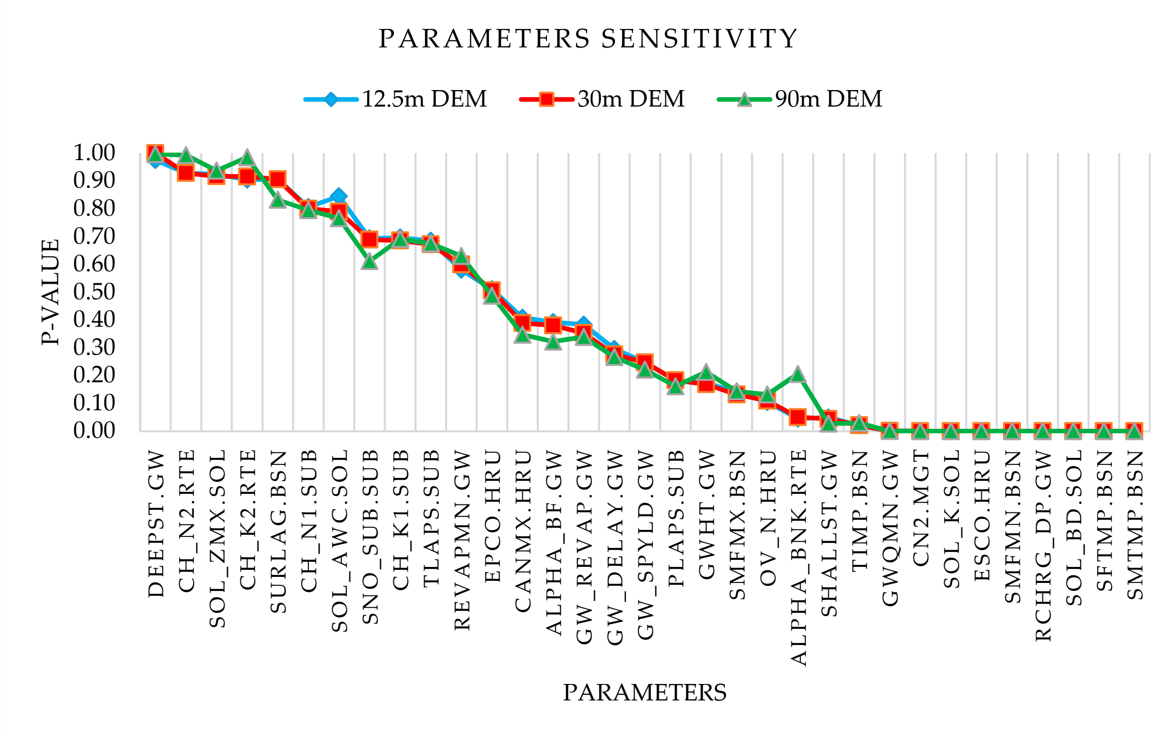

**Figure 4.** The sensitivity of runoff parameters in SWAT.

The first quartile of the sensitivity analysis results in Figure 4 shows that the initial depth of water in the deep aquifer (DEEPST.gw), Manning's "n" value for the main channel (CH_N2.rte), maximum rooting depth of soil profile (SOL_ZMX.sol), effective hydraulic conductivity in main channel alluvium (CH_K2.rte), surface runoff lag coefficient (SURLAG.bsn), Manning's "n" value for the tributary channels (CH_N1.sub), available water capacity of the soil layer (SOL_AWC.sol), and initial snow water content (SNO_SUB.sub) are the most sensitive parameters. On the other hand, the fourth quartile of the graph shows that the initial SCS runoff curve number for moisture condition II (CN2.mgt), saturated hydraulic conductivity (SOL_K(1).sol), soil evaporation compensation factor (ESCO.hru), melt factor for snow on December 21 (SMFMN.bsn), deep aquifer percolation fraction (RCHRG_DP.gw), moist bulk density (SOL_BD(1).sol), snowfall temperature (SFTMP.bsn), and snowmelt base temperature (SMTMP.bsn) are the parameters with the lowest sensitivity.

These findings indicate that the surface properties, along with available water capacity and moisture levels in the soil, are the most sensitive parameters in runoff yield in the watershed, regardless of the DEM resolution.

Moreover, Figure 4 shows that in different DEM resolutions, the highest fluctuations are more evident in the Manning's "n" value for the main channel (CH_N2.rte), effective hydraulic conductivity in main channel alluvium (CH_K2.rte), surface runoff lag coefficient (SURLAG.bsn), available water capacity of the soil layer (SOL_AWC.sol), initial snow water content (SNO_SUB.sub), maximum canopy storage (CANMX.hru), baseflow alpha factor (ALPHA_BF.gw), initial groundwater height (GWHT.gw), and baseflow alpha factor for bank storage (ALPHA_BNK.rte) parameters.

This can be justified by the fact that as the distribution of slope within the watershed changes in different DEM resolutions, surface parameters are affected more than other parameters.

## 4. Discussion

This study evaluated the effects of three DEM resolutions (ALOS PALSAR 12.5m, SRTM 30m, ASTER 90m) on the runoff yield and sensitivity of the parameters contributing to it, for the case study of the Mahabad Dam watershed in Iran.

The following are the main findings of this study:

- The total watershed area, reach lengths, and elevations in the watershed varied due to DEM resolutions.
- The 12.5m DEM (finest resolution) showed the highest values for the surface area, as well as the minimum, mean, and maximum elevations in the delineated watershed.
- Under the 12.5m DEM, higher amounts of runoff were generated in the watershed.
- The results showed consistent trends of runoff and area variations.
- Comparing the generated runoff for each case, a 3.48% increase was observed when using the 12.5 DEM instead of the 90m DEM. Furthermore, the 12.5 DEM generated 0.42% more runoff compared with the 30m DEM, and the 30m DEM generated 3.04% more runoff compared with the 90m DEM.
- The sensitivity of the parameters showed that for this case study, as the resolution of the DEM file gets coarser, the sensitivity of the model to parameters such as Manning's “n” value for the main channel, effective hydraulic conductivity in main channel alluvium, threshold depth of water in the shallow aquifer, initial groundwater height, increases, while for parameters such as surface runoff lag coefficient, available water capacity of the soil layer, initial snow water content, maximum canopy storage, baseflow alpha factor, and groundwater revap coefficient decrease.
- Regardless of the DEM resolution, the surface properties, along with available water capacity and moisture levels in the soil, are the most sensitive parameters in runoff yield in the watershed.
- As the distribution of slope within the watershed changes in different DEM resolutions, the surface parameters are affected more than other parameters.

Results of this study indicate that the choice of input DEM resolution depends on the watershed response of interest. As for this case study, the maximum increase in runoff yield was 3.48% when using the 12.5m DEM compared with the 90m DEM. For a future extension of this study, it is recommended for researchers to use more DEMs of different resolutions and repeat the same procedure in different topologies, in order to come to a general conclusion on the impact of DEM resolution on watershed yields.

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