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Assessing the Impact of Spatial Accuracy of Digital Elevation Models on Simulating Discharge in Arid Regions Using SWAT Model: A Case Study of the Lar Watershed

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ABSTRACT

Aims: The Digital Elevation Model (DEM) plays a crucial role in the SWAT model and significantly impacts its output results. This study evaluated the effect of different spatial accuracy of DEM in runoff simulation using the SWAT and SWAT-CUP models for the Lar Watershed in Sistan and Baluchestan Province.

Materials & Methods: This study examines the impact of different accuracies of Digital Elevation Models (DEMs) with resolutions of 12.5, 30, 50, 90, 450, and 1000-meters on discharge simulation using the SWAT model for the Lar Watershed, located in an arid region. The model was selected for 30 years (1988-2017), with 18 years for the calibration period and 12 years for validation. The SWAT-CUP software and the SUFI-2 method were used. The model's accuracy was also evaluated using the Nash-Sutcliffe efficiency (NS), coefficient of determination (R^2), r, and p coefficients.

Findings: The discharge simulation results reveal that variables such as area, sub-basin, Hydrologic Response Unit (HRU), watershed slope, and mean channel slope are particularly affected by DEM accuracy. With increasing DEM accuracy, the length of the main channels decreases, and lower-order channels are eliminated, reducing the calculated discharge depth. Our sensitivity analysis identified seven key parameters influencing discharge simulation in the Lar Watershed. The most critical parameters were r__CN2.mgt, v__ALpha_BF.gw, and r__SOL_AWC.sol, consistently recognized as highly sensitive in similar studies.

Conclusion: During validation and calibration, DEM resolutions of 12.5 and 1000 meters exhibited lower accuracy than those of 30, 50, 90, and 450 meters, suggesting that extremely high or low spatial data accuracy does not enhance simulation accuracy. Additionally, minimal differences were observed among the results for DEM resolutions of 30, 50, 90, and 450 meters. This can be attributed to adjustments in calibrated variable values and the application of the SUFI-2 method across different DEM accuracies. Finally, based on the results of this research, the DEMs with spatial resolutions of 30, 12.5, 50, 90, 450, and 1000 meters demonstrated the best performance for simulating monthly discharge in the Lar Watershed. Additionally, based on the value of the objective function (NS) during the calibration and validation stages, it can be concluded that the SWAT model can simulate the monthly discharge of the Lar Watershed with acceptable accuracy. Therefore, it can be said that the SWAT hydrological model can be used in arid regions to implement management scenarios quickly and at a low cost for decision-making.

Keywords: SWAT-CUP; DEM; SUFI-2 Method; Nash-Sutcliffe Efficiency; SWAT Hydrological Model.

CITATION LINKS

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Introduction

Numerous models have been developed to simulate the watershed's hydrological response to precipitation in the context of simulating hydrological processes. Today, with enhanced access to a broad array of satellite information and ground data, the process of simulating the hydrological response of watersheds to rainfall events with specific spatial characteristics has significantly improved [1]. By establishing precise statistical relationships between model parameters and the physical characteristics of the watershed, hydrological models serve as the primary foundation for predicting flow in watersheds. However, it is notable that finding a model that perfectly matches the conditions of a watershed remains a challenge [2]. The effectiveness of hydrological models in presenting and estimating hydrological processes and variables, such as discharge, heavily relies on the spatial accuracy of the model's input data [3]. Discharge generation is influenced by precipitation and the hydrological, soil, and vegetative conditions of the watershed area. Thus, the spatial variability of these factors plays a critical role in hydrological simulation, emphasizing the significance of spatial accuracy and appropriate cell size selection in digital maps [4,5]. Spatial data also play a crucial role in extracting the hydrographic characteristics of the watershed and estimating the spatial distribution of discharge and sediment load [6]. The Digital Elevation Model (DEM) effectively displays the earth's surface characteristics, allowing for the automated extraction of hydrological features in a region [7]. Particularly in situations requiring discharge and sediment control measures at the watershed level, selecting the DEM accuracy becomes even more critical [8]. Given the unique characteristics of the country's watersheds, such as statistical deficiencies, high hydrological ecosystem complexities due to climate change, and human interventions, there is an increasing need for approaches enabling discharge estimation in watersheds lacking or having incomplete statistics [9]. To achieve hydrological changes in this watershed, generalization methods are used to transfer information from data-rich watersheds to data-scarce locations [10,11].

In recent years, the Soil and Water Assessment Tool (SWAT) hydrological model has gained significant popularity and is widely used globally in watershed management research. SWAT, a Physically-based Semi-distributed continuous-time model, is designed to simulate hydrological processes at the watershed scale and predict the impacts of land management activities on discharge, sediment yield, and water quality from nonpoint sources [12]. One of the model's advantages is its ability to efficiently analyze data across various time frames and simulate large and complex watersheds, offering diverse management solutions [13,14,15,16]. One of the crucial steps in SWAT is calibrating the model built for the study area. To expedite the calibration process and assess the uncertainty of the model's results, the SWAT CUP software package, developed by Abbaspour [17], is used in this software; various methods are available for calibration operations, including the SUFI-2 algorithm. The SUFI-2 algorithm can perform sensitivity analysis on parameters and analyze their uncertainty [17]. The SUFI-2 algorithm has been used in most studies that have utilized the SWAT model Khosravi & Mir Yagoub Zadeh (2019) [7], Mokhtari et al. (2019) [8], Rezaei Moghadam et al. (2018) [8], Sanjay & Vinayb (2021) [10], Aslam & Andrew (2017) [12], Fatehi and Shahoei (2020) [18], Ghezelsofloo et al. (2020) [18], Lucas et al. (2016) [21], Liu et al. (2016) [22], Rostamian et al. (2008) [23], and Safavi et al. (2021)

[24]. Globally, few reports have assessed the impact of the accuracy of the Digital Elevation Model (DEM) using the SWAT model. A few examples are provided below.

Numerous studies using the SWAT model have examined the impact of Digital Elevation Model (DEM) resolutions on discharge simulation and hydrological processes. Fard et al. [25] conducted a study in the Gorganrud watershed, which showed that increasing DEM resolution from 200 meters to 10 meters led to a decrease in simulated discharge. Similarly, Kavian and Mohammadi [26] examined the effects of three DEMs with 30, 90, and 1000-meter resolutions on hydrological simulations in the TaLar Watershed. Their results indicated that increasing the spatial resolution from 30 to 90 meters generally provided the best flow simulation for most months, while the 1000-meter resolution demonstrated the lowest accuracy. In another study, Chaplot et al. [27] investigated the effects of DEM resolutions ranging from 20 to 50 meters on sediment and discharge simulation using the SWAT model. They found that DEM resolutions higher than 50 meters had little impact on discharge simulation accuracy but were associated with significant changes in sediment simulation. Additionally, Lin at el [45] evaluated the effect of DEM cell size on simulated discharge in the Jiang watershed and found that increasing the DEM cell size did not significantly impact simulated discharge. On the other hand, Raesi et al. [16], in a study on factors influencing discharge generation and hydrological sensitivity in the upstream watersheds of the Karun River using the SWAT model, found that the threshold depth of water in shallow aquifers for evapotranspiration (REVAPMN) had a minor sensitivity. In contrast, soil evaporation compensation (ESCO), the delay time for water transfer from the lowest soil profile to the groundwater table (GW_DELAY), and the curve number under normal conditions (CN2) were the most sensitive factors, respectively. For simulation evaluation, the coefficients of R^2 (coefficient of determination), bR^2 (weighted correlation coefficient), and NS (Nash-Sutcliffe efficiency) during the calibration phase were 0.63, 0.33, and 0.57, respectively. Meanwhile, during the validation phase, these coefficients were found to be 0.69, 0.68, and 0.52, respectively. Studies examining the effect of Digital Elevation Models (DEMs) have established that the accuracy of DEM-based analyses largely depends on the resolution of the initial model. However, smaller cell sizes do not always yield more satisfactory results. The characteristics of a watershed, including physiography, topography, and dimensions, significantly impact the results derived from DEMs.

Although more accurate, high-resolution DEMs are not always available and often need to be modified or replaced with lower-resolution models that provide better spatial coverage. In developing countries, obtaining suitable DEMs from topographic maps derived from ground surveys is particularly challenging due to resource constraints [28,44]. As a result, remote sensing-based DEMs are widely used in hydrology and other sciences, providing a suitable accuracy and speed for calculating watershed parameters. These DEMs provide resolutions ranging from several hundred meters to less than two meters [25]. It is important to note that watersheds in arid regions have unique complexities due to prevailing conditions, which continually present challenges for study. The prolonged dry periods and the presence of dry, fragile, and vulnerable ecosystems result in high discharge rates in such watersheds due to observed rainfall events. This is attributed to the lack of vegetation cover, high soil

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erodibility, and minimal infiltration capacity [30]. On the other hand, the absence of baseflow in these areas, due to the lack of recharge from groundwater or snowmelt sources, causes the rivers in these regions to be non-perennial and exhibit a seasonal structure [31]. Additionally, the distribution of precipitation and observed rainfall patterns in these areas must be considered. Precipitation distribution in arid regions is highly variable and concentrated over a short period, often scattered and convective. These conditions collectively increase the complexities of modeling discharge [30].

The Lar Watershed, located in a dry region with a mean annual rainfall of 72 millimeters (significantly lower than the 250-millimeter mean for Iran), faces a severe water scarcity crisis. Therefore, understanding the amount of discharge generated from precipitation and its fluctuations throughout the year should be a priority in planning for arid regions worldwide, which are heavily affected by various types of drought. Modeling and evaluating monthly discharge in such areas is crucial for effective infrastructure management, planning, and enhancing resilience against water crises. The focus on humid climates in most hydrological models has limited our understanding of arid watersheds.

Therefore, given the severe water scarcity in arid regions and the lack of information on discharge generation mechanisms, this study aims to assess the performance and capability of the SWAT model in estimating discharge in dry watersheds using DEMs of varying resolutions. Monthly discharge for the Lar Watershed will be simulated using the SWAT model and six DEMs with different spatial resolutions (12.5, 30, 50, 90, 450, and 1000 meters). Based on the watershed's specific climatic conditions, sensitive parameters will be optimized, calibrated, and analyzed for uncertainty using the SUFI-2 algorithm. The model's performance will be assessed using four statistical indices (Nash-Sutcliffe, R-squared, p-factor, and r-factor) to determine the optimal DEM accuracy for simulating discharge in the Lar Watershed.

Materials & Methods

Study Area

The Lar Watershed is in southeastern Iran, within the Sistan and Baluchestan Province. It spans an area of 1,768.36 km^2, ranging from latitudes 30°29' to 30°37' N and longitudes 45°60' to 52°60' E (Figure 1). Due to its geographical position in low latitudes and its distance from the influence of Mediterranean fronts, the Lar Watershed experiences less humidity than other parts of Iran. Consequently, it frequently faces risks and complications associated with drought [31].

The mean long-term rainfall at the synoptic station of the Lar Watershed ranges between 72 and 75 mm, with most precipitation occurring in spring and winter [33]. Specifically, on mean, %18 of the rainfall occurs in autumn, %60 in winter, %20 in spring, and %2 in summer [31]. Table 1 presents the climatic characteristics of the Lar Watershed.

The primary river flowing through the studied watershed is the non-permanent and seasonal Lar River. This river experiences flooding over short periods following continuous rainfall in the region. Torrential rains significantly increase the likelihood of severe and destructive floods within the watershed [32].

Statistics and Data Used

In the current research, a comprehensive set of hydro-climatic data from existing monitoring stations in the Lar Watershed was collected from the Sistan and Baluchestan Meteorological Organization and the Regional Water Company of Sistan and Baluchestan Province. Specifically, daily

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discharge values from the Lar hydrometric station and daily precipitation data from four rainfall gauge stations (Tassfeah Khaneh, Fabi, Ghatar Khanjak, and Podeh Chah), as well as one synoptic station (Zahedan) were compiled for the statistical period from 1991 to 2017.

Tables (2) and (3) present the characteristics of the rainfall gauge, synoptic, and hydrometric stations used in this research. Data from the Zahedan synoptic station and the Lar hydrometric station were utilized to investigate annual changes in rainfall and discharge in the Lar Watershed during the selected period (1991-2017). The results indicated that the lowest recorded rainfall was 32.7 mm in 2006, while the highest was 92.6 mm in 2012 (Figure 2). By calculating the coefficient of variation for the period 1991-2017, it was found that the lowest value was 0.9 and the highest was 2.25, revealing that the Lar Watershed experiences irregular and highly variable rainfall. This variability indicates the potential for extreme events in the region.

Additionally, analysis of the annual streamflow rate changes in the Lar Watershed during the study period showed that rainfall intensity significantly impacts discharge volume (Figure 2). A surface discharge peak forms

Table 1) Climatic characteristics of the Lar Watershed in Sistan and Baluchestan Province during the statistical period of study (1991-2017).

Climatic Characteristics	The Amount of
Mean Annual Rainfall (mm)	72
Mean Annual Minimum Temperature (°c)	-1.6
Mean Annual Maximum Temperature (°c)	42
Mean Relative Humidity (%)	31
The Type of Climate Based on Emberger and De Martonne Methods	Moderate and Dry

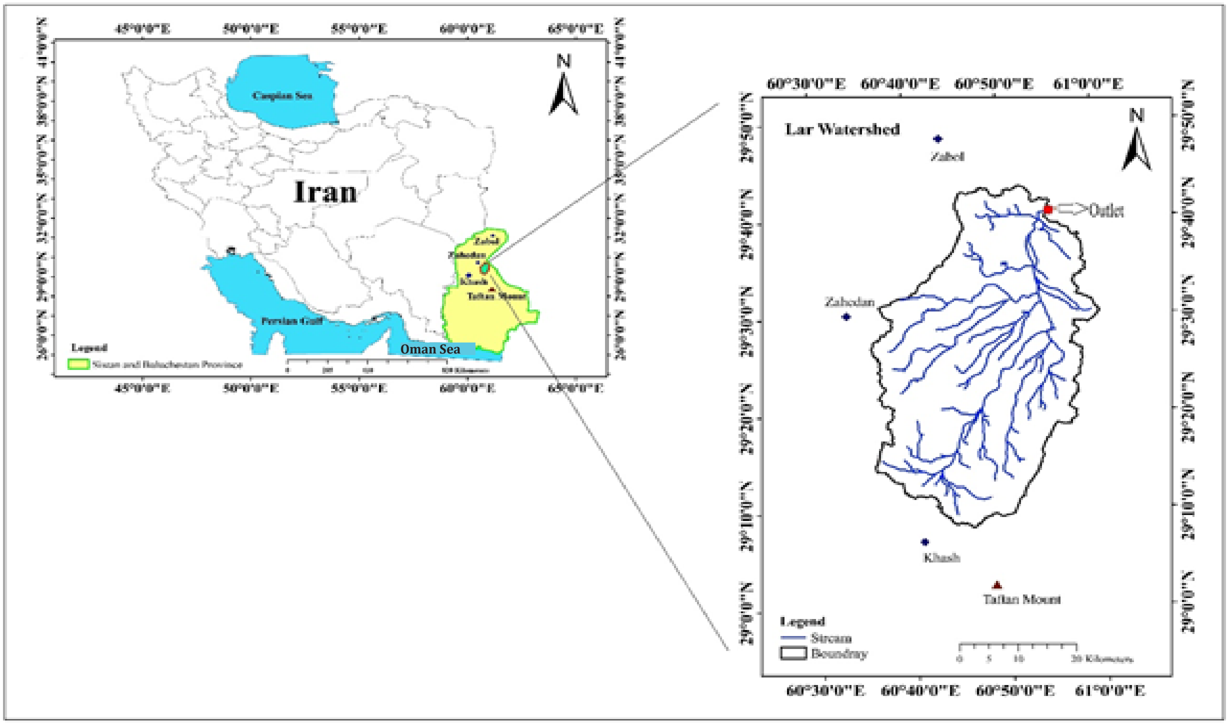

Figure 1) Rivers network and location of the Lar Watershed in Sistan and Baluchestan Province and Iran.

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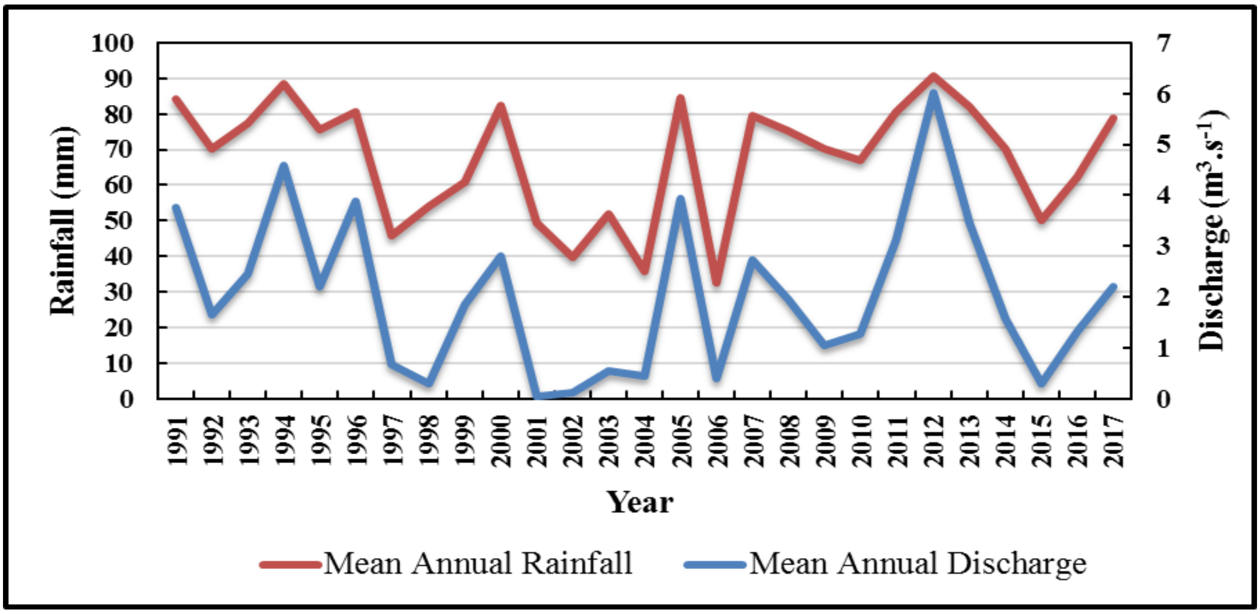

Figure 2) Chart of the mean annual rainfall and discharge changes in the Lar Watershed of Sistan and Baluchestan Province in the studied period (1991-2017).

Table 2) Characteristics of selected rain gauge and synoptic stations in the Lar Watershed of Sistan and Baluchestan Province.

Station Name	Type of Station	Height (m)	Longitude	Latitude	Station Code	Annual Rainfall during Period (1988-2017)
Fabi	Rain Gauge	2096	60° 37‹ 49“	29° 35‹ 20“	53059	118.7
Poudeh Chah	Rain Gauge	1937	60° 40‹ 34“	29° 19‹ 41“	53055	108.9
Ghatar Khanjak	Rain Gauge	1695	60° 43‹ 42“	29° 14‹ 07“	53061	97.5
Tassfeah Khaneh	Rain Gauge	1396	60‹51° 11“	29‹29° 02“	53002	69.8
Meteorology of Zahedan	Synoptic	1385	60‹53° 00“	29‹28° 00“	40856	73.7

when rainfall exceeds the soil's infiltration capacity or when discharge flows along slopes after filling surface depressions (Figure 2). However, in some years (e.g., 2001 and 2002), no discharge peak was observed due to insufficient rainfall intensity and losses from evaporation, infiltration, and surface retention (Figure 2). Moreover, the gentle slope of the rivers and their relatively long length to the watershed outlet allow for substantial infiltration before reaching the outlet, resulting in minimal irrigation and no formation of a discharge peak in the study area.

SWAT model

SWAT is a semi-distributed conceptual model developed by the United States Department of Agriculture's Agricultural Research Service [3].

This model is a valuable tool for simulating various hydrological processes, such as water quality, soil erosion, agricultural production, rangeland management, and the impacts of climate change within complex and large watershed areas encompassing different

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soil types and Land-Uses [4]. Notably, SWAT is recognized for its high computational efficiency.

The model operates on the principle of water balance, primarily influenced by meteorological inputs like daily precipitation, maximum air temperature, and minimum air temperature. The water balance equation, as shown in Eq. (1) [34], describes the dynamics of water movement within the system.

The equation is as follows:

$$SW_t = SW_0 + \sum (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad \text{Eq. (1)}$$

where SW_t is the final water content in the soil every day (mm), t time (d), SW_0 is the amount of primary water in the soil daily (mm), R_{day} amount of precipitation per day (mm), Q_{surf} amount of surface discharge per day (mm), E_a amount of daily evaporation and transpiration (mm), W_{seep} is the amount of water percolating into the subcortical area every day (mm) and Q_{gw} is the amount of permeation to the underground aquifer every day (mm).

Land-Use Map and Soil Texture

Land-Use map of the studied area based on different uses, including agricultural lands (%0.37), residential areas (%3.6), garden areas (%0.87), barren lands (%22.09), water bodies (%1.02), man-planted forests (%2.2) and pastures (%70.79) are separated.

Land-uses affect the amounts of discharge, evaporation, transpiration, and surface erosion in the watershed, which is why these maps are among the most important input factors in hydrological models [32].

This study used Google Earth Engine (GEE) to

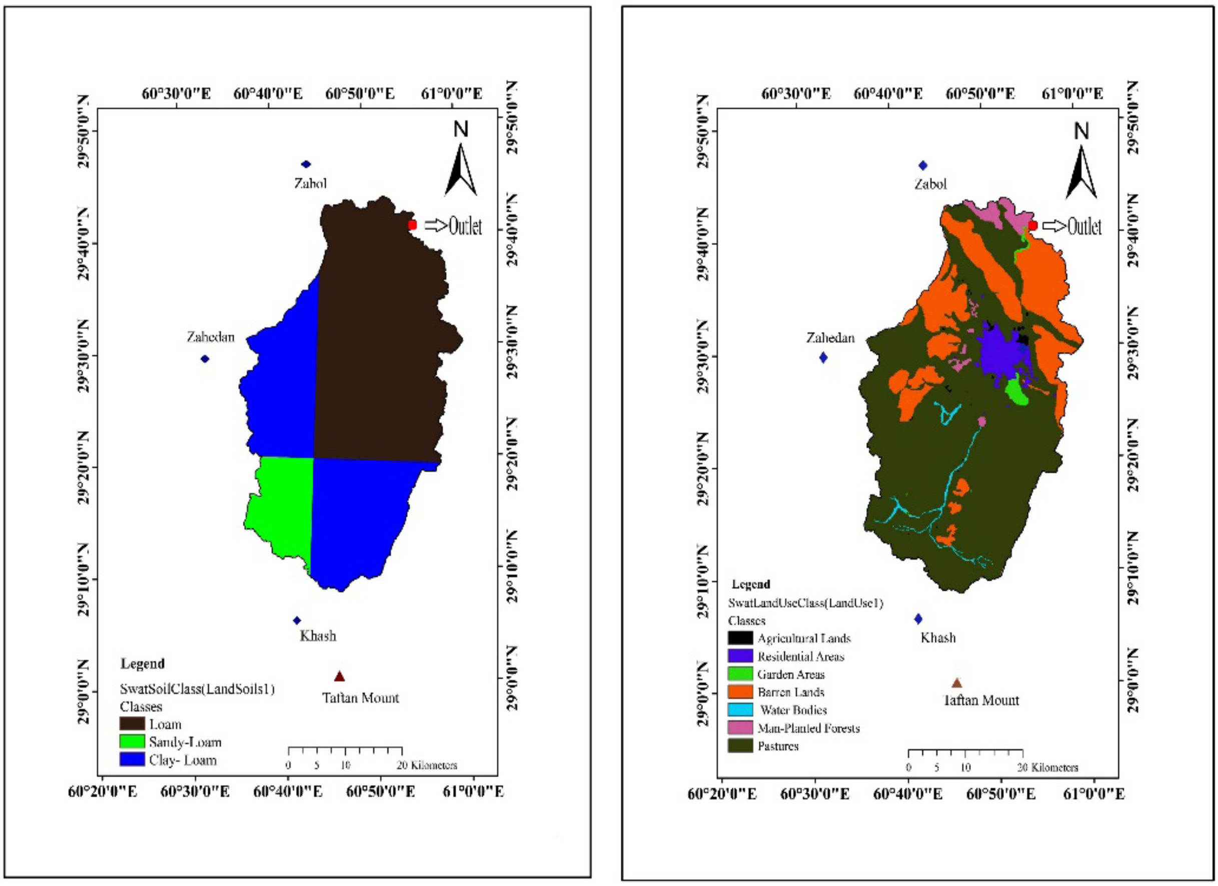

Figure 3) Soil map (left) and land-use map (right) of the Lar Watershed in Sistan and Baluchestan Province.

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map land use in the Lar Watershed (Figure 3). GEE is a web-based satellite image processing platform that enables free image processing. It utilizes graphical tools to simultaneously process numerous modified and mosaic images, ensuring efficient and rapid processing. Since a soil texture map specific to the study area was unavailable, the global soil texture map provided by the United States Department of Agriculture was utilized [31] (Figure 3).

Soil data is another critical input for any hydrological simulation model [35]. For watershed simulation, the SWAT model requires various physical and chemical soil properties such as available soil moisture, soil texture, bulk density, hydraulic conductivity, hydrologic groups, number of layers, organic carbon content, and more [32]. Due to the unavailability of a soil texture map for the study area, a global soil texture map with a resolution of 1000 meters, freely provided by the United States Department of Agriculture, was used in this research. Table 4 presents the hydrological soil groups within the Lar Watershed [30].

Digital Elevation Model Map

Using the DEM, the SWAT hydrological model can derive essential parameters such as the streamflow network, sub-basin number, hydrological response units, slope distribution, and watershed morphometry [36]. This study employed six DEMs with varying spatial resolutions of 12.5, 30, 50, 90, 450, and 1000-meters (Table 5). Figure 4 illustrates the DEM of the Lar Watershed, highlighting the water flow pathways segmented based on the different spatial accuracies.

Meteorological Data of SWAT Model: It comprises maximum and minimum temperatures, daily precipitation, maximum and minimum daily relative humidity, maximum and minimum daily wind speed, and daily solar radiation. This data is input into the SWAT model through the climatic subprogram or directly as measured data [22]. In this study, due to severe limitations in the availability of measured data resulting from inadequate equipment in the Lar Watershed, only daily precipitation and maximum and minimum daily temperatures from the overlapping period (1988-2017) were incorporated into the SWAT model.

Sensitivity Analysis, Calibration, and Validation of SWAT Model

Sensitivity analysis of parameters is conducted to assess the significance of input variables and their impact within a model [10]. This study employed a general sensitivity analysis method in the SWAT-CUP environment to conduct sensitivity analysis. This method determines the effect of each parameter on the output variable using t-stat and p-value coefficients. A parameter is considered highly sensitive if the absolute value of the t-stat coefficient (used as a

Table 3) Characteristics of the selected hydrometric station in the Lar Watershed of Sistan and Baluchestan Province.

Station Name	Type of Station	Height (m)	Longitude	Latitude	Station Code
Lar	Hydrometric	1145	60‹55° 15“	29‹40° 41“	53013

Table 4) Map of soil characteristics of the Lar Watershed in Sistan and Baluchestan Province.

Soil Type	Hydrological Group	Percent
Loam	D	53.93
Sandy-Loam	C	9.68
Clay-Loam	D	36.37

Table 5) Procedure for Generating Spatial Data of the Lar Watershed in Sistan and Baluchestan Province.

Location Data	Year of Preparation of the Map	Resolution (m)	Data Source
Digital Elevation Model	2021	12.5 × 12.5	www.asf.alaska.edu
	2022	30×30	girps.net
	2022	50×50	nbparsroya.blog.ir
	2022	90×90	girs.ir
	2022	450×450	Consultant Engineers for the Researchers of the Ideal Green Environment www.greengoalsco.com
	2021	1000×1000	US Geological Centre edcsns17.cr.usgs.gov
Land-Use	2021	30×30	earthengine.google.com
Soil Texture	2020	1000×1000	Global Texture Map www.nrcs.usda.gov

measure of parameter sensitivity) is equal to or greater than one, and the p-value for that parameter is close to zero [37].
The SUFI-2 algorithm method was used for calibration, which can be regarded as semi-automatic. This method determines parameter limits through a single calibration step involving a specific number of model runs (typically 500 to 1000) [31]. Subsequently, two indicators are employed to assess the accuracy and uncertainty of calibration [38]: A. The r-factor index represents the percentage of observational data falling within the %95 uncertainty range. B. The p-factor index is calculated as the mean thickness of the 95 PPU uncertainty band divided by the standard deviation of observational data.
Theoretically, the p-factor ranges from zero to one, while r-factor values range from zero to infinity. A p-factor value of one and an r-factor value of zero indicate that simulated and measured values are identical. The simulation accuracy is considered low when the r-factor and p-factor values deviate significantly from their ideal range [39].
The calibration and validation phases of hydrological models are designed to ensure the accuracy and reliability of these models in simulating and predicting hydrological processes. In the calibration phase, model parameters are adjusted using actual observational data to ensure that the model accurately simulates the actual behavior of the watershed. Then, during the validation phase, the model is tested with independent data to assess its ability to predict new and different conditions. These phases help improve the model's accuracy and build confidence in its results for scientific and managerial analyses [40].

Evaluating the Model Efficiency

In this study, the accuracy of the SWAT model discharge simulation was assessed by using the Nash-Sutcliffe coefficient (NS) and coefficient of determination (R^2) criteria based on various DEM accuracies. The following section elaborates on each coefficient and its calculation method.

Nash-Sutcliffe coefficient (NS)

This coefficient quantifies the relationship between measured and simulated values. It ranges from negative infinity to one, with an ideal value of one [41]. The NS is defined in Eq. (2):

$$NS = 1 - \left[\frac{\sum_{i=1}^{n}\left(Q_i^{abs} - Q_i^{sim}\right)}{\sum_{i=1}^{n}\left(\overline{Q}_i^{abs} - \overline{Q}_i^{sim}\right)}\right] \qquad \text{Eq. (2)}$$

Coefficient of Determination (R^2)

This metric signifies the proportion of observed data variance explained by the model's simulated values. It ranges from zero to one, with one value indicating perfect agreement between simulated and observed values [42]. The calculation is outlined in Eq. (3):

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(Q_i^{sim} - \bar{Q}_i^{sim}\right)\left(Q_i^{abs} - \bar{Q}_i^{abs}\right)\right]^2}{\sum_{i=1}^{n}\left(Q_i^{sim} - \bar{Q}_i^{sim}\right)^2 \sum_{i=1}^{n}\left(Q_i^{abs} - \bar{Q}_i^{abs}\right)^2} \qquad \text{Eq. (3)}$$

where the variables in Eqs. (2)-(3) represent $\bar{Q}_i^{abs}$ the mean observed discharge values ($m^3.s^{-1}$), $\bar{Q}_i^{sim}$ mean simulated discharge values ($m^3.s^{-1}$), Q_i^{abs} measured discharge values ($m^3.s^{-1}$), Q_i^{sim} simulated discharge values ($m^3.s^{-1}$) and n denote the number of observations.

Implementing the SWAT Watershed Model

In this research, SWAT version 2012 integrated with ArcGIS 10.3 was utilized. Following the preparation of maps and input data, the initial step involved constructing the watershed model. Subsequently, adjustments in the Lar Watershed's elevation were made to determine the sub-basin areas and their optimal values using the SWAT model. The hydrological response units within the watershed were formed based on Land-Use maps, soil textures, slope classes, and DEMs.

The modeling process also entailed employing the Hargreaves-Samani method for evapotranspiration calculations, the variable storage method to ascertain flow patterns, and the SCS method for discharge estimations. Climatic data, such as precipitation, temperature, and humidity, were incorporated into the SWAT model daily throughout the study period.

It is noteworthy that the initial three years (1988-1990) were devoted to model setup, followed by 18 years (1990-2005) for recalibration and the subsequent 12 years (2006-2017) for validation purposes.

It is essential to mention that in arid regions, due to limited access, gaps or improper distribution of monitoring systems, poor quality of available data, lack of investment and attention in equipping, completing, and developing monitoring systems, as well as the limited capability of hydrological models to study the unique hydrology of these areas, quantifying water resources has always been a severe challenge. According to the information provided in the article, only one hydrometric station is available in the study watershed, indicating a lack of an adequate monitoring network. Therefore, the SWAT model's capabilities were utilized in this study to assess discharge accuracy in the Lar Watershed. The complete research process is presented in Figure 5.

Findings

Simulation Results and Sensitivity Analysis

The simulated physiographic characteristics of the watershed and the monthly discharge graph of the Lar Watershed based on six different DEM spatial accuracies (12.5, 30, 50, 90, 450, and 1000 meters) are presented in Table 6 and Figure 6. Table 6 revealed that as the pixel size of the DEM increased, the heights of the physiographic characteristics did not consistently exhibit a decreasing or increasing trend. This lack of correlation between the physiographic values and the magnification of the DEMs is consistent with findings reported by other researchers such as Fard et al. (2022) [25], Chaplot (2005) [27], Ghafari (2011) [43], Jeirani et al. (2011) [44].

Among the physiographic parameters analyzed in Table 6, the area, number of sub-basins, number of HRUs, slope of the watershed, and mean slope of the waterway demonstrated greater sensitivity to changes in DEM accuracy. Previous studies by Peipei et al. (2014) [14], Sivasena Reddy et al. (2015) [42], and Lin et al. (2010) [45] have also

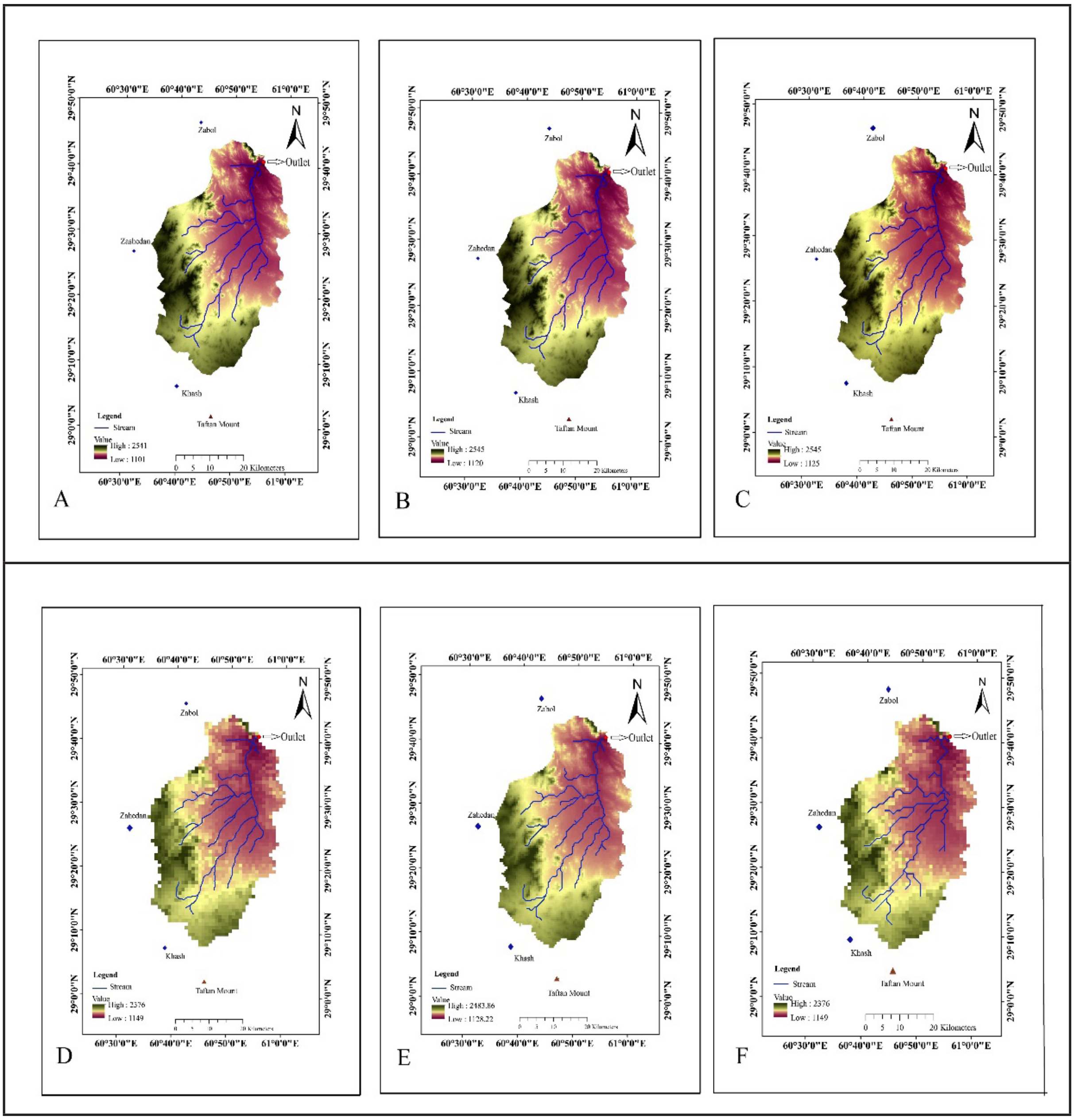

Figure 4) DEM map with accuracies of A: 12.5 m, B: 30 m, C: 50 m, D: 90 m, E: 450 m, and F: 1000 m along with the flow network of the Lar Watershed in Sistan and Baluchestan Province.

highlighted the impact of increasing DEM pixel size on the uncertainty of physiographic values, leading to higher errors in the measurements.

Furthermore, an increase in DEM accuracy was found to reduce the length of the main waterway and eliminate lower-ranking waterways in the Lar Watershed. This decreased drainage density and reduced discharge height [3,9,22,25,46] (Figure 6).

The discharge simulation using the SWAT model was followed by calibration and validation of the model using SWAT CUP software and the SUFI-2 algorithm. Sensitivity analysis tests were performed on several parameters before recalibration. Table 7 presents the most sensitive parameters for discharge simulation. Among these, three parameters were the most sensitive compared to the others, which included r_CN2.mgt (curve number for mean humidity conditions), v_ALpha_BF.gw (base

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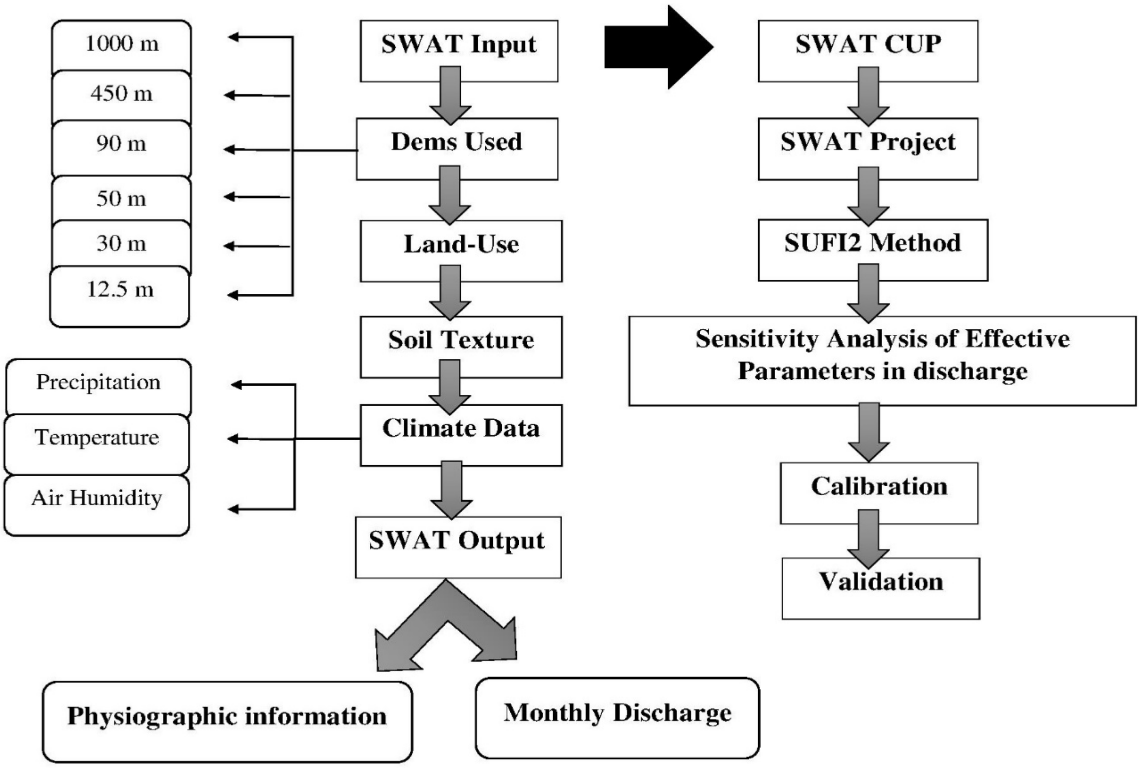

Figure 5) The process of making a model in research.

Table 6) Physiographic characteristics of the Lar Watershed of Sistan and Baluchestan Province under the influence of different accuracies of the digital elevation model (12.5, 30, 50, 90, 450, and 1000 m).

Characteristics of the Watershed	Accuracies of Digital Elevation Model (m)					
	12.5×12.5	30×30	50×50	90×90	450× 450	1000×1000
Watershed Area (km^2)	1643.56	1642.83	1642.83	1515.9	1504.6	1478.98
Number of Sub-Basins	37	37	35	33	35	1
Number of Hydrological Response Units	305	302	269	265	203	134
Maximum Height (m)	2541	2545	2545	2376	2483	2376
Minimum Height (m)	1105	1128	1128	1177	1131	1149
Mean Height (m)	1609.62	1626.08	1626.08	1603.52	1603.32	1599.21
Watershed Slope (%)	5	7	6	4	3	1
Mean Slope of the Waterway	22.8	21	18	10	9.8	6.73
Discharge Height (mm)	4.21	4.20	4.18	4.13	3.59	3.56
Drainage Density	1.3	1.29	1.26	1.22	1.16	0.46
Length of the Main Waterway (km)	43.45	35.2	33.37	25.99	14.05	3.02

[DOI: DOI: 10.22034/ECOPERSIA.12.4.329]

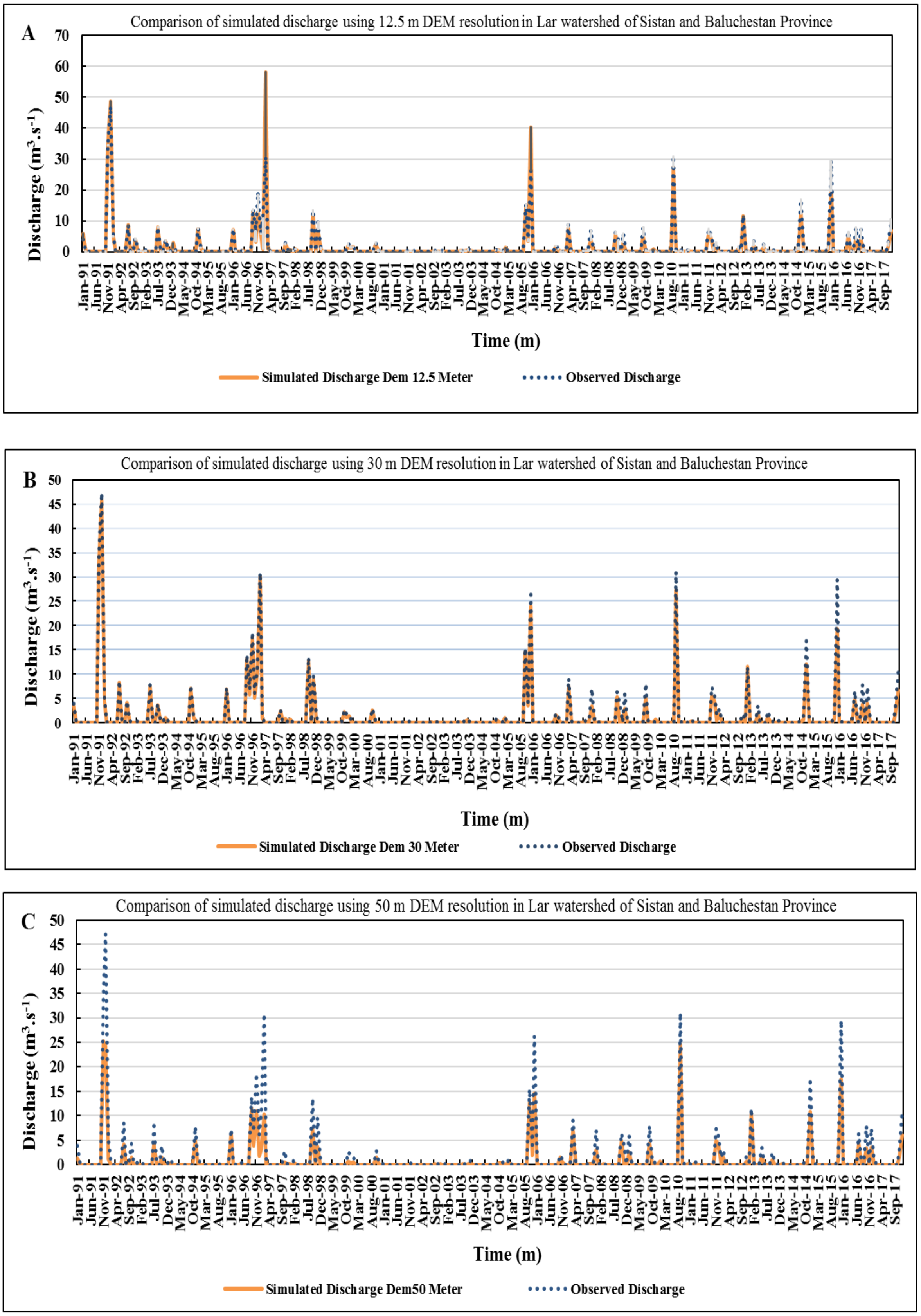

Figure 6) Comparison of simulated discharge using six DEM resolutions: A: 12.5m, B: 30m, C: 50m, D: 90, E: 450m, and F: 1000min the Lar Watershed of Sistan and Baluchestan Province.

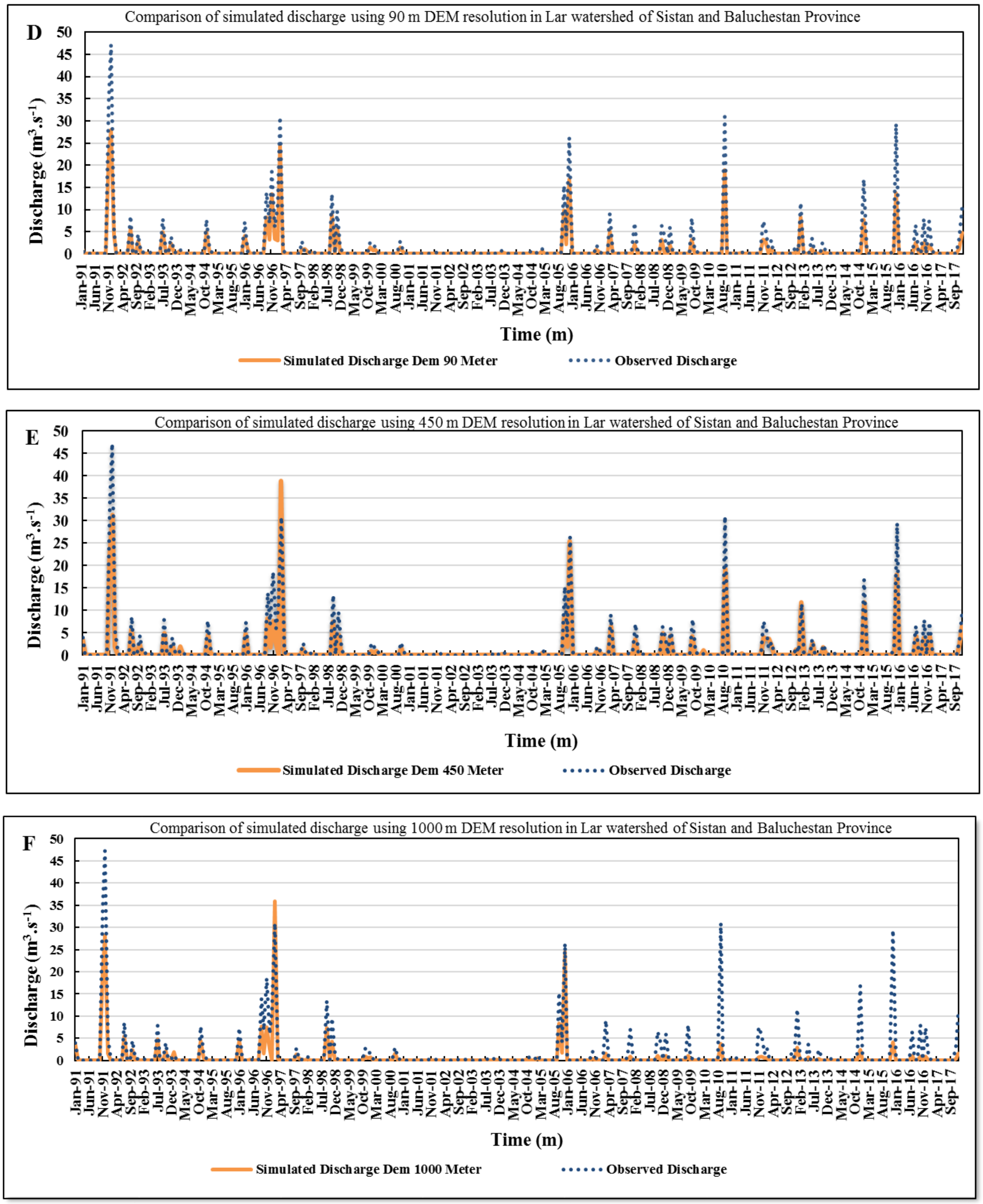

Figure 6 Continued) Comparison of simulated discharge using six DEM resolutions؛ A: 12.5m, B: 30m, C: 50m, D: 90m, E: 450m, and F: 1000m in the Lar Watershed of Sistan and Baluchestan Province.

flow return factor to the main waterway), and r_SOL_AWC.sol (mean usable water) [48]. The parameter r_CN2.mgt, influenced by moisture conditions, soil permeability (soil hydrological groups), and Land-Use, plays a crucial role in discharge simulation. Changes in this parameter significantly impact surface discharge, lateral flow, evaporation, and transpiration, affecting water balance components and flow simulation [19,49,50].

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The r_CN2.mgt parameter is recognized as a crucial SWAT parameter and has been consistently identified as the most sensitive parameter in discharge simulation across various research studies [3,20,44,46,51]. The second sensitive parameter, v_ALpha_BF.gw represents underground water conditions and base flow. A higher base water simulation results in a reduction in the v_ALpha_BF.gw factor [52]. The third sensitive parameter, r_SOL_AWC.sol, signifies the available moisture in distinct soil layers, governing deep infiltration, soil, and evapotranspiration [7]. While these susceptible parameters play pivotal roles in water balance and flow simulation, less sensitive parameters also contribute to completing the water circulation cycle and enhancing model calibration, thereby improving the accuracy of the hydrograph shape [41]. The results of the SWAT CUP implementation for different spatial accuracies of the DEMs, along with the determination of parameter values in the best simulation, are detailed in Table 8. Initially, the model calculated the relative changes in parameters for each hydrological response unit based on DEM, Land-Use, and soil maps within specified ranges. Subsequently, the SUFI-2 method was employed to modify these initial values, leading to the determination of appropriate parameter values after recalibration.

It should be noted that the calibration process plays a crucial role in improving the accuracy of predictions. As mentioned earlier, calibration involves adjusting the critical model parameters to ensure the simulation results align more closely with observed data. These parameters are related to hydrology, vegetation cover, and soil. This process is critical in arid regions using Digital Elevation Models (DEMs) of varying resolutions.

Table 8 illustrates the range of changes observed for the r_CN2.mgt coefficient in the sub-basins during calibration results was similar for DEM accuracies of 12.5 and 90 meters, as well as for the v_ALpha_BF.gw and r_SOL_AWC.sol coefficients at accuracies of 12.5 and 450 meters. Furthermore, differences in parameter values across sub-basins were evident when employing different DEM map accuracies.

Calibration and Validation of Discharge Simulation with Varying DEM Accuracy Resolutions (12.5, 30, 50, 90, 450, and 1000-meters)

The results of calibration and validation for each of the different numerical accuracies of Height (12.5, 30, 50, 90, 450, and 1000 meters) for the Lar Watershed using the SWAT model are presented in Tables (9) and (10).

In this study, the NS coefficient was used as the objective function because it has become one of the standard criteria in evaluating hydrological models due to its power and simplicity in assessing model accuracy. The calibration and validation results indicated that the NS values for the DEM maps with 12.5 and 1000-meter resolutions were underestimated in both stages. This indicates that using spatial data with either very high or very low resolution does not necessarily improve the performance of hydrological model predictions.

Tables 9 and 10 also show that the accuracy evaluation criteria for 30, 50, 90, and 450-meter DEM resolutions are close during the calibration and validation stages. Among the various DEM accuracies, the 30-meter resolution significantly outperformed the others, with NS values of 0.82 and 0.88 in the validation and calibration stages, respectively.

Discussion

The results shown in Figure 6 and Table 6, illustrating the simulated monthly discharge for different DEM resolutions over the study period (1991-2017), indicate an

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inverse relationship between the simulated discharge height and DEM resolution. As the DEM resolution increases, the simulated discharge height decreases, highlighting the importance of DEM accuracy for precise discharge simulation.

This finding aligns with the results of studies by researchers such as Fard et al. (2022) [25], Chaplot (2005) [27], Chaubey et al. (2005) [29], Kiyani Majd (2022) [31], Dehvari & Heck (2013) [46] and Moradi et al. (2015) [47].

Another critical reason is that as the cell size of the Digital Elevation Model (DEM) increases, the length of the mainstream decreases. In other words, with the increase in cell size, lower-order streams are eliminated, reducing the drainage density of the Lar Watershed.

This observation is also consistent with the findings of researchers such as Mokhtari Porzarandi [2], Jeirani et al. [43], Lin et al. [44], and Zarif Kar et al. [51].

Additionally, overall modeling results (Figure 6) showed that the SWAT model effectively simulates the monthly discharge of the Lar Watershed, particularly in terms of the timing of discharge peaks and recessions.

However, the model faced challenges in accurately capturing peak flows during specific years, which can be attributed to factors such as the omission of detailed topographic features, the small grid size on slopes, and inaccuracies in determining the amount of surface discharge in the DEM [19,44,46]. The presence of larger pixel sizes in DEMs may introduce errors in predicting topographic indices, which can undermine the accuracy of flow simulation results [16,21,22,41,54]. The findings indicate that DEM accuracy is crucial in hydrological modeling and discharge prediction precision.

In conclusion, among the various DEM accuracies considered, the simulated monthly discharge graph with a DEM accuracy of 30 meters displayed the closest agreement with the observed data chart. The sensitivity analysis on the model parameters highlighted the significance of critical parameters such as r_CN2.mgt, v_ALpha_BF.gw, and r_SOL_AWC.sol in influencing discharge simulation accuracy. By understanding how these parameters impact water balance components and flow simulation, researchers can fine-tune model calibration to achieve more accurate results. The influence of these parameters on surface discharge, lateral flow, and evapotranspiration underscores their importance in accurately capturing watershed dynamics.

Moreover, identifying less sensitive parameters that still play a role in refining the model's calibration underscores the complexity of hydrological modeling and the need for comprehensive parameter assessment. By considering the permissible range of changes for each sensitive parameter and aligning them with regional conditions and existing research findings, researchers can ensure that the model calibration process is robust and tailored to the specific characteristics of the study area. This approach enhances the model's ability to replicate real-world hydrological processes and produce reliable simulations of discharge behavior over time.

Overall, the sensitivity analysis results underscore the importance of effectively selecting and calibrating model parameters to improve the accuracy of hydrological simulations. By focusing on critical parameters and considering their influence on water balance and flow dynamics, researchers can enhance the reliability and predictive capabilities of the SWAT model in capturing the complexities of watershed behavior.

The findings of Table 8 highlight the influence of spatial accuracy in the DEM on the calibration results of critical parameters in hydrological modeling. The observed simi-

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Table 7) Selected parameters for recalibration after sensitivity analysis using p-value and t-stat indices for the Lar Watershed in Sistan and Baluchestan Province [31].

Rank	Parameter	Definition	A Selected Range of Suitable Answers by SWAT-CUP	Range of Parameter Changes
1	r_CN2.mgt	Initial SCS Discharge CN for moisture condition II	-0.2-0.2	0-0.3
2	v_ALpha_BF.gw	Baseflow alpha factor (d^{-1})	0-1	0-1
3	r_SOL_AWC.sol	Available water capacity of the soil layer (mm H2O.mm soil)	-0.2-0.1	-0.5-0.5
4	v_gw_DELAY.gw	Groundwater delay time (d)	30-450	0-100
5	v_CH_K2.rte	Effective hydraulic conductivity in the main	5-130	0-150
6	v_gw_GWHT.gw	channel alluvium (mm.h)	0-100	0-25
7	v_RCHRG_DP.gw	Initial groundwater height (m)	0-250	0-2

Note: The prefix 'r' in the parameters indicates changing the initial value of the parameter by applying a coefficient (+1 change value). In contrast, the prefix 'v' signifies replacing the parameter with a new value during recalibration.

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larities and disparities in parameter adjustments across sub-basins underpin the importance of carefully considering DEM resolutions for improved simulation outcomes. This underscores the significance of integrating spatial accuracies in DEMs during hydrological model calibration to enhance the representation of land surface characteristics and, consequently, improve model performance and predictive capabilities. Further exploration and refinement of parameter calibration procedures in response to varying DEM accuracies could significantly enhance the reliability and precision of hydrological simulations across diverse geographic settings.

The results indicate that the accuracy of the simulation decreases with the DEM resolution of 1000 meters, as also mentioned in the studies by Lin et al. [44] and Kavian and Mohammadi [21]. The close performance of the 30, 50, 90, and 450-meter resolutions can be attributed to the adjustment of calibrated parameter values for various DEM accuracies and the use of the SUFI-2 algorithm during calibration and validation, as supported by research from Fard et al. (2022) [25], Chaplot (2005) [27], Chaubey et al. (2005) [29], Abbaspour (2011) [38], Jeirani et al. (2011) [43], Lin et al. (2010) [44], Dehvari & Heck (2013) [46], Moradi et al. (2015) [47] and Wang & Lin (2010) [54].

An important point to consider is that an NS above 0.75 indicates excellent model performance, between 0.75 and 0.36 is considered satisfactory, and below 0.36 is unacceptable [15]. Based on the results, the SWAT model can simulate monthly streamflow in the Lar Watershed with acceptable to excellent accuracy, especially when using a 30-meter DEM resolution.

Conclusion

In this research, monthly discharge simulation in the Lar Watershed was conducted using the SWAT model and six spatial resolutions of the DEM (12.5, 30, 50, 90, 450, and 1000 meters) during the selected period (1991-2017). The Lar Watershed is a dry watershed with seasonal flow and lacks

Table 8) Determining the selected ranges of selected parameters in different DEM accuracies for the Lar Watershed in Sistan and Baluchestan Province.

Parameter	Unit	Best Selected Value of the Parameter Accuracies of Digital Elevation Model (m)					
		12.5	30	50	90	450	1000
r__CN2.mgt	Dimensionless	0.02-0.3	0.04-0.2	0.06-0.3	0.02-0.3	0.01-0.1	0.05-0.3
v__ALpha_BF.gw	(d^{-1})	0-0.5	0.02-0.4	0.1-0.8	0.2-0.7	0-0.5	0.03-0.6
r__SOL_AWC.sol	(mm H_2O.mm soil)	-0.5-0.5	-0.4-0.07	-0.4-0.1	-0.5-0.1	-0.5-0.5	-0.3-0.5
v__gw_DELAY.gw	(d)	17.8-97.8	50-93	10.3-70.6	35-100	6.6-96.6	12-100
v__CH_K2.rte	(mm.h)	1-50	2.3-46	10.1-79.8	17.7-62	86.4-150	67.03-150
v__gw_GWHT.gw	(m)	2-24.5	2-16.9	4.06-14.06	3.5-12.5	1-22.2	2.3-23.7
v_RCHRG_DP.gw	Dimensionless	0.1-0.6	0.1-0.7	-0.4-0.5	0.09-0.5	0.1-1.6	0.07-1.7

Table 9) The results of the simulated discharge calibration for the Lar Watershed in Sistan and Baluchestan Province, using the SWAT model, based on six different accuracies of the DEM.

DEM Criterion	12.5×12.5	30×30	50×50	90×90	450×450	1000×1000
R^2	0.78	0.83	0.89	0.85	0.77	0.78
NS	0.72	0.82	0.75	0.81	0.74	0.03
p-factor	0.40	0.39	0.41	0.44	0.43	0.30
r-factor	0.25	0.31	0.46	0.41	0.37	0.02

Table 10) The results of the validation discharge for the Lar Watershed in Sistan and Baluchestan Province, using the SWAT model, based on six different accuracies of the DEM.

DEM Criterion	12.5×12.5	30×30	50×50	90×90	450×450	1000×1000
R^2	0.76	0.89	0.89	0.88	0.86	0.86
NS	0.12	0.88	0.85	0.73	0.53	0.23
p-factor	0.18	0.47	0.40	0.46	0.45	0.35
r-factor	0	0.44	0.48	0.57	0.63	0

a base flow, often becoming completely dry during certain months. By examining the annual variations in precipitation and discharge, it became evident that the region experiences irregular and highly variable rainfall, increasing the likelihood of prolonged drought. Additionally, low precipitation intensity and losses from evapotranspiration, infiltration, and surface storage result in minimal water yields and no peak flow formation.

The simulation results indicated that the physiographic characteristics of the watershed did not uniformly follow a decreasing or increasing trend in response to changes in DEM spatial accuracy. Parameters such as area, number of sub-basins, number of HRUs (Hydrologic Response Units), watershed slope, and mean stream slope showed high sensitivity to changes in DEM accuracy. With an increase in DEM resolution, the length of the mainstream decreased, and

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the elevation of the watershed discharge also decreased. This was evident in the simulated plots and observations for the six DEM resolutions.

Furthermore, the SWAT model exhibited weaknesses in simulating peak flow points for DEM resolutions of 50, 90, 450, and 1000 meters, indicating that higher spatial accuracy may lead to inaccuracies in estimating topographic features, which weakens streamflow simulation results. The calibration process identified seven influential parameters using a general sensitivity analysis method (r_CN2.mgt, v_ALPHA_BF.gw, r_SOL_AWC.sol, v_gw_DELAY.gw, v_CH_K2.rte, v_gw_GWHT.gw, v_RCHRG_DP.gw), with the r_CN2.mgt parameter being the most sensitive. This parameter, which depends on humidity conditions, soil permeability, and Land-Use, significantly affects surface discharge, lateral flow, and evapotranspiration.

The evaluation of the calibration and validation results using the coefficients of determination, NS, r-factor, and p-factor for all six DEM accuracies showed that the performance of the DEM resolutions at 12.5 and 1000 meters was weaker than the others. This indicates that using DEMs with extremely high or low spatial resolution does not necessarily increase the accuracy of hydrological model simulations. Conversely, the performance evaluation statistics for DEM resolutions of 30, 50, 90, and 450 meters did not differ significantly due to adjusting calibrated parameters and using the SUFI-2 algorithm.

Based on the results of this research, DEM with a spatial resolution of 30, 12.5, 50, 90, 450, and 1000 meters showed the best performance for simulating the monthly discharge of the Lar Watershed. Considering the value of the objective function (NS) in the calibration and validation stages, it can be concluded that the SWAT model can simulate the monthly discharge of the Lar Watershed with acceptable accuracy.

This research showed that good results can be obtained by simulating watersheds with sufficient data and information over a long period. Executive managers can rely on this information and models to implement appropriate preventive measures at the right time, helping to protect the watershed and its population from risks such as droughts and their effects to some extent.

Digital Elevation Models (DEMs) are highly accessible and valuable resources in hydrological studies and serve as input for most related software. Understanding their characteristics and limitations is crucial for accurate hydrological modeling. As mentioned, their accuracy and precision significantly impact the models and software results. Therefore, more comprehensive and extensive studies should be conducted to assess their accuracy and reliability. For this purpose, the following suggestions can be used by other researchers at the national or international level.

- A recommendation is to compare digital elevation models with real-world data by conducting more extensive studies using a greater range of hydrological software in different watersheds with varying climatic conditions.
- More data must be used to reveal better the effect of different digital height accuracy in calibrating comprehensive models such as SWAT.
- Investigate the effect of the cell size of the elevation digital model on the calculation of other watershed issues such as topography, soil characteristics, lithology, and other relevant parameters.
- Appropriate meteorological and hydrometric stations should be established in the watershed and appropriate positions so that the watershed can be simulated using advanced models.

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