

Modelling and Assessment of Streamflow and Sediment Yield using SWAT under Varying Accuracy and Resolution of Input Data

Rawaa AAlfatah AAlhusein^{a,b*}, Khairul Nizam Abdul Maulud^{a*}, Mahmoud Saleh Al-Khafaji^c, Siti Fatin Mohd Razali^a, Zaher Mundher Yaseen^d, Mohd Nazish Khan^e & Mohammad Suhail^f

^aDepartment of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

^bSurvey Department, Centre of Studies and Engineering Designs, Ministry of Water Resources, Baghdad, Iraq

^cDepartment of Water Resources Engineering, College of Engineering, University of Baghdad, 10071, Baghdad, Iraq

^dCivil and Environmental Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia

^eDepartment of Physical Geography and Natural Resources, Samarkand State University named after Sharof Rashidov, 15 Boulevard, Samarkand, 140104, Uzbekistan

^fCentre of Applied Remote Sensing and GIS Applications, Samarkand State University named after Sharof Rashidov, 15, Boulevard, Samarkand -140104, Uzbekistan

*Corresponding author: knam@ukm.edu.my

Received 12 September 2025, Received in revised form 21 October 2025
 Accepted 1 January 2026, Available online 30 May 2026

ABSTRACT

Digital Elevation Models (DEM) and Land Use/Land Cover (LULC) are critical inputs for the SWAT model, providing a spatial framework for hydrological simulations. However, the combined influence of their sources and resolutions on hydrological outputs such as streamflow and sediment yield remain not widely explored. This study systematically evaluated the impacts of seven DEMs and four LULCs, varying in spatial resolution and source, through 28 SWAT model configurations. These models underwent monthly calibration and validation to assess performance and the influence of input variables. Results highlighted that DEM resolution is crucial for watershed delineation, while source has minimal impact. Finer DEMs consistently delineated larger areas, with SRTM yielding slightly broader regions. Maximum altitude correlated directly with DEM resolution, whereas minimum altitude showed an inverse relationship. Finer DEMs generated more Hydrological Response Units (HRUs), with Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) yielding the highest HRU count. LULC resolution significantly influenced HRU numbers based on the number of classes. Streamflow analysis revealed no clear linear relationship between DEM and LULC resolutions; the most accurate predictions did not always stem from the highest-resolution data. For sediment yield, finer DEMs generally produced higher outputs, with ALOS-30 m and SRTM 90 m yielding the highest sediment levels, 0.4% and 0.2%, respectively. However, no consistent trend emerged for LULC's impact on sediment yield. These findings underscore the importance of carefully selecting input resolutions for SWAT modelling and provide crucial insights to bridge existing knowledge gaps in hydrological modelling.

Keywords: Climate Resilience; Environmental Sustainability; Hydrological Modelling; Sustainable Development; Water Resource Management.

INTRODUCTION

Water is a vital resource upon which all life depends. Efficient management of watershed is essential to ensure the long run conservation and provision of this vital resource for future generations (Duan et al. 2021). The remotely sensed data in hydrological models are essential for the precise, full, and current updates of the most important parameters used in water-scarce areas of management (El-Bagoury and Gad 2024). The use of digital imagery, including Digital Elevation Model (DEM) and Land Use/Land Cover (LULC) details, has become an important part of hydrological modelling methodologies (Gholami et al. 2024). These datasets are created with specific levels of precision and resolution, both temporal and spatial (Tang, Wang, and Chen 2024). Among the feasible options, Soil and Water Assessment Tool (SWAT) is likely to be the most commonly used and efficient method for constructing watershed simulators (Al-Khafaji and Al-Chalabi 2019). It is important to analyze how satellite information with different spatial resolutions affects the performance of hydrological simulations (Alfieri et al. 2021). Generally, more detailed input data yields more accurate and reliable modeling outputs (Zhu et al. 2023).

Significant research has been conducted to determine the optimal resolution as well as source of DEMs. These studies often rely on widely available remote sensing data, such as the Shuttle Radar Topography Mission (SRTM), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and Light Detection and Ranging (LiDAR). DEMs can also be made using topographical maps or just terrain measurements. These contribute together to the larger understanding of data-driven modeling.

Sukumaran and Sahoo (2020) studied the effect of DEM resolution (30 m. to 1000 m.) on hydrological simulation response for the Upper Narmada basin in India, extent is 4923 km². Results revealed that surface runoff in the mountainous catchment was not very sensitive to various resolutions of DEM, whereas sediment yield showed marked responses to different input DEMs. Nazari-Sharabian, Taheriyoun, and Karakouzian (2020) employed SWAT in assessing the influence of DEM resolution and topography on streamflow. Found that the higher model resolution produced higher streamflow. The authors also observed the accuracies of the results would probably be affected by time-sliced reduction in computing. Śliwiński, Konieczna, and Roman (2022) observed that as the resolution of DEM became coarser, accuracy toward the results in the Zgłowiączka catchment 64 90 km² also coarsened.

Numerous studies have analyzed the impact of LULC resolution regarding hydrological modelling outcomes. El

Harraki et al. (2021) used SWAT to estimate the effect of LULC spatial resolution on streamflow prediction. The study compared a global ESA-CCI (300 m resolution) data set to a higher resolution database (20 m) to see how the quality of LULC affects the models' performance. Results suggested that an increase of spatial detail did not bring improvements in forecasting streamflow and was unable to support that larger numbers of delineated HRUs ensured increased precision. The study demonstrated that SWAT could predict streamflow accurately with a coarse dataset (300 m). It also stressed that higher-resolution LULC data are not always better in improving statistical performances. Similarly, Ait M'Barek et al. (2022) evaluated impact of three LULC at 300, 30 and 10 m on output of SWAT model. They concluded that even if low resolution LULC can provide the optimal results, it can save time and calibration efforts.

Only a few studies have investigated how DEM as well as LULC resolutions work together to interact the prediction of the surface streamflow. Saleh Al-Khafaji and Saeed (2018) utilized SWAT model to analyze the relationship between them, and tested five DEM resolutions with four LULC resolutions. Results suggested that estimates of surface streamflow are highly sensitive to both of them. Similarly, Fan et al. (2020) valued the effects of LULC maps with spatial resolution of 250, 1000, and 2500 meters in combination with different DEM datasets. Results show that changes in LULC resolution have a greater effect on streamflow measurements than changes in DEM. The observed sensitivity can be attributed to the curve number, which serves as a critical parameter in the modelling of streamflow. It was also concluded that a DEM resolution of up to 100 meters is typically appropriate for hydrological modelling.

It can be inferred from the literature that previous studies have not clearly emphasized the effects of satellite data from different sources and resolutions on the performance of hydrological model simulations. Specifically, the cumulative effects of DEM sources and resolutions, combined with LULC resolutions, on the estimation of streamflow and sediment have yet to be thoroughly investigated. The uncertainty may stem from the different features of the watersheds. Moreover, an analysis of the relationship between the watershed characteristics and the source as well as resolution of geographic input data is essential for the progression of watershed modelling. This study addresses this gap by examining two key questions: (1) how does the spatial resolution of input data affect hydrological modelling results and (2) how does the source of input data influence these outcomes?

CASE STUDY AND DATA EXPLANATION

STUDY AREA

The Bakerman Dam watershed is situated in the northern part of Iraq, positioned between the coordinates of latitude $36^{\circ} 49' 39''$ N and longitude $43^{\circ} 38' 09''$ E, and is characterized by a semi-arid climate (Figure 1). It covers about 724 square kilometers and lies on the Khazer River, a major tributary of the Great Zab River. The Bakerman Reservoir catchment is characterized by the altitudes 1000–2000 m above sea level, with an average altitude of around 1050 m in downstream area (Bellier 1977). As it is located in a semi-arid hydrological area. Most precipitation

comes in the winter, starting in November and going until May (Al-Hussein et al. 2022a). The region experiences hot, dry summers with minimal rainfall, while winter precipitation occasionally includes snowfall that contributes to hydrological inputs. Seasonal temperature variations are significant, with summer high temperatures and winter temperatures occasionally descending below the freezing. Moderate wind speeds are common and play a notable role in increasing evaporation rates. During the hot and arid summer months, evaporation rates rise due to higher temperatures and increased solar radiation. Overall, annual evaporation levels are high, with peak river flows occurring in winter from rainfall and snowmelt, and reduced flows in the dry summer period (Al and Hasan 2022).

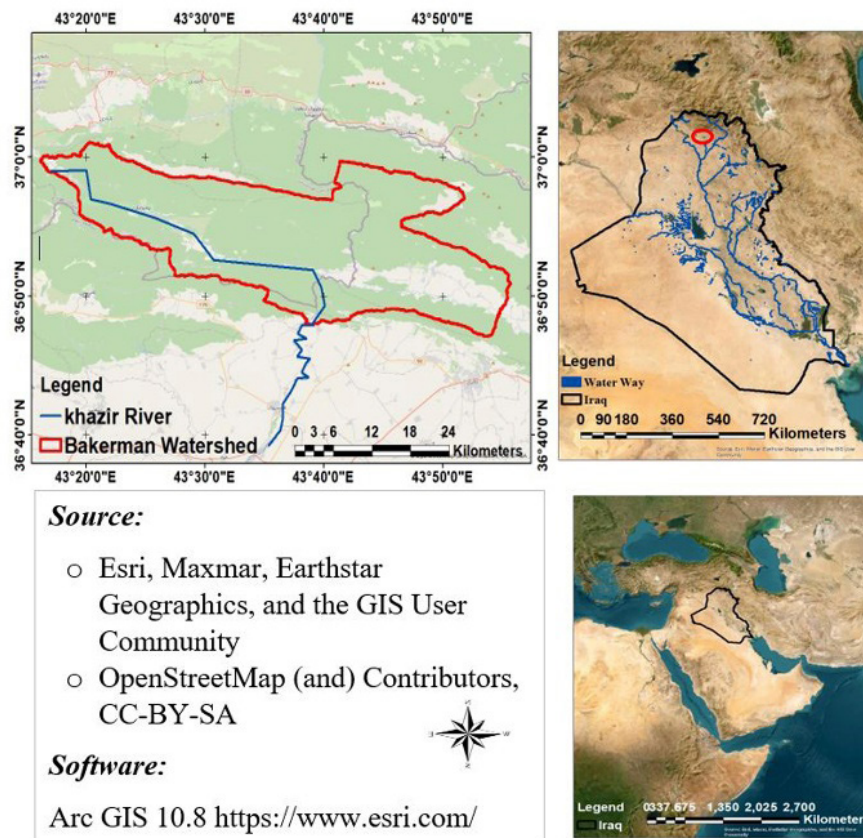


FIGURE 1. Location map of Bakerman Watershed.

INPUT DATA

DIGITAL ELEVATION MODEL (DEM)

DEMs are currently readily available via a multitude of online platforms, offering high-resolution topographic data suitable for a range of applications (Yin et al. 2021). In this research, seven DEMs of four different spatial resolution and from four different sources were used: GMTED 250

(U.S. Geological Survey 2011)(U.S. Geological Survey 2011)(U.S. Geological Survey 2011), ASTER 90 & 30 (NASA/METI/AIST/Japan Spacesystems 2019), SRTM 90 & 30 (U.S. Geological Survey (USGS) 2014)(U.S. Geological Survey (USGS) 2014)(U.S. Geological Survey (USGS) 2014) and ALOS 30 & 12.5 (Japan Aerospace Exploration Agency (JAXA) 2021). These DEMs are shown in Figure 2 and the names of DEMs, resolutions, vertical accuracy and sources are listed in Table 1.

LAND USE AND LAND COVER (LULC)

Data pertaining to LULC are currently accessible from a multitude of sources, presenting openly accessible datasets that offer both global and regional coverage at varying resolutions to accommodate a range of applications (Mehra and Swain 2024). In this research four types of LULC

images of different spatial resolution were used: MODIS 500 m (Friedl 2022),ESA 300 m (ESA Land Cover CCI project team 2016), GLC 100 m (Copernicus Global Land Service 2020) and ESRI 10 (Impact Observatory 2021). The names of LCs, resolutions and sources are listed in Table 2. The LULC classes and their percentages listed in Table 3. These LCs are shown in Figure 3.

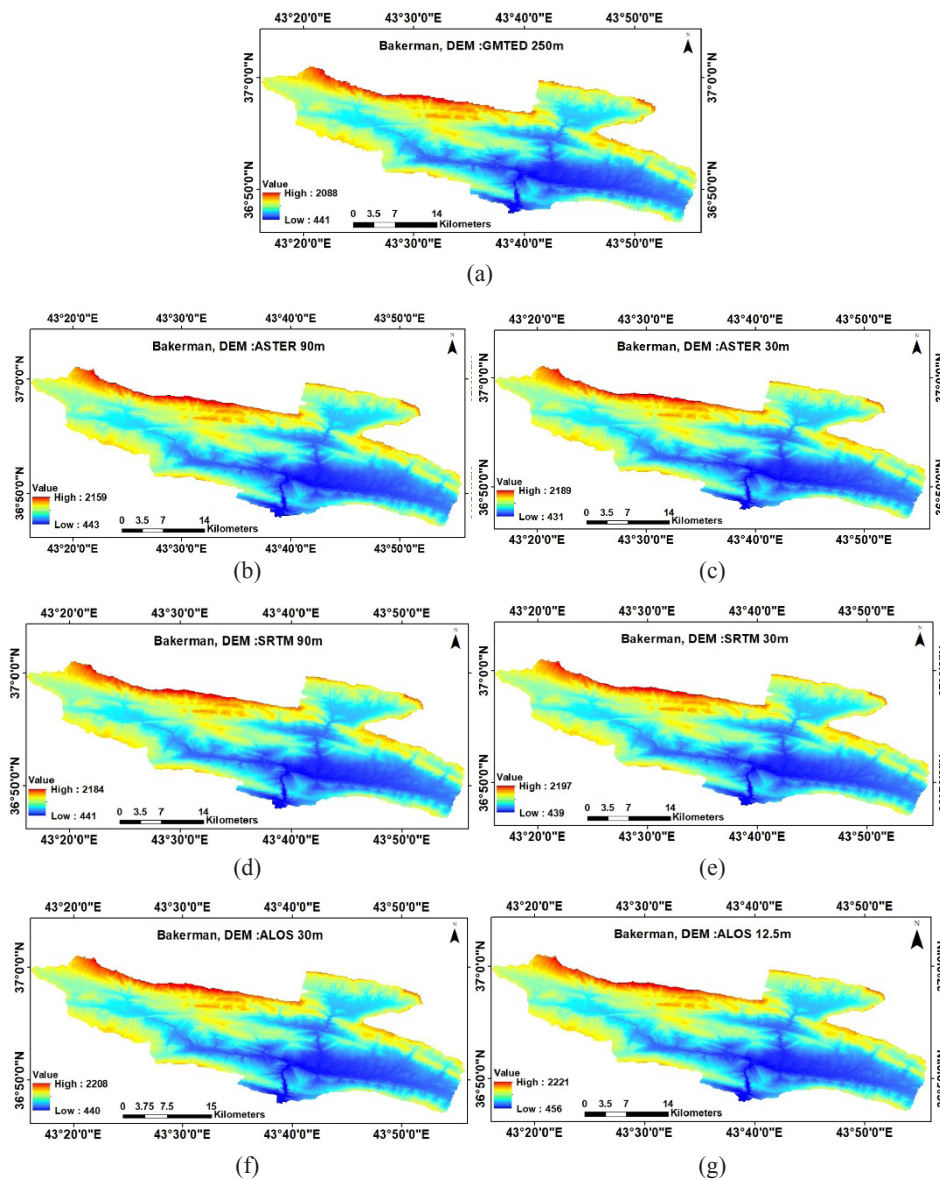


FIGURE 2. DEMs of Bakerman: (a) GMTED 250 m, (b) ASTER 90 m, (c) ASTER 30 m, (d) SRTM 90 m and (e) SRTM 30 m, (f) ALOS 30 m and (g) ALOS 12.5 m.

TABLE 1. Input DEMs in SWAT models Bakerman watershed.

No.	Name	Spatial Resolution (m)	Vertical Accuracy (m)	Source
1	GMTED	250	between 10 and 25	https://earthexplorer.usgs.gov/
2	ASTER	90	20	https://www.earthenv.org/DEM
3	ASTER	30	10 to 15	https://search.earthdata.nasa.gov/search/
4	SRTM	90	16	https://earthexplorer.usgs.gov/

continue...

...cont.

5	SRTM	30	8 to 10	https://earthexplorer.usgs.gov/
6	ALOS	30	5 to 10	https://asf.alaska.edu/datasets/daac/alos-palsar-radiometric-terrain-correction/
7	ALOS	12.5	5 to 7	https://asf.alaska.edu/datasets/daac/alos-palsar-radiometric-terrain-correction/

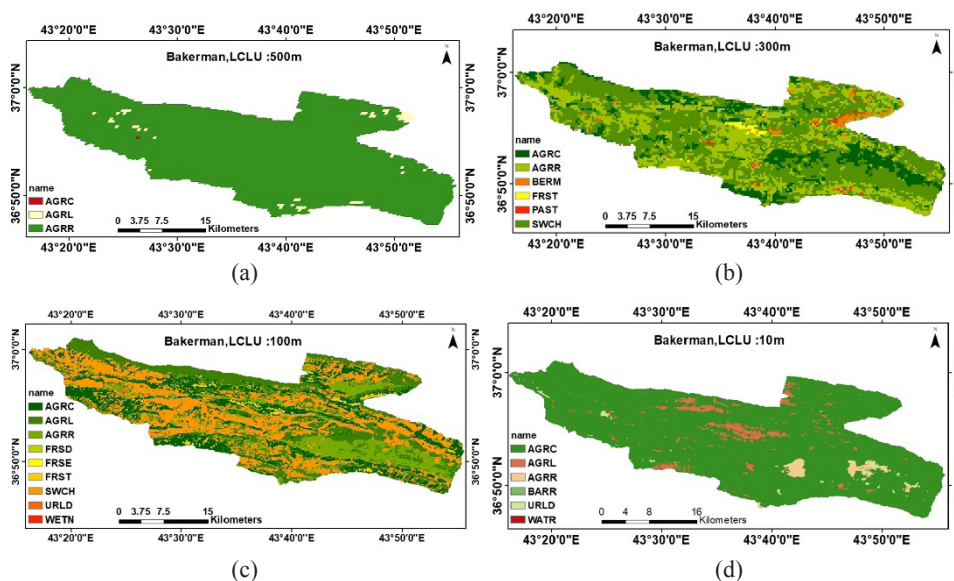


FIGURE 3. LULCs of Bakerman: (a) 500 m, (b) 300 m, (c) 100 m and (d) 10 m.

TABLE 2. Input LULCs in SWAT models Bakerman watershed

No.	Name	Spatial Resolution (m)	Source
1	MODIS	500	https://earthexplorer.usgs.gov/
2	ESA	300	https://esa-worldcover.org/en
3	GLC	100	https://land.copernicus.eu/en
4	ESRI	10	https://livingatlas.arcgis.com/landcover/

TABLE 3. The LULC types and percentage of Bakerman Watershed.

No.	LULC:10		LULC:100		LULC:300		LULC:500	
	Class	%	Class	%	Class	%	Class	%
1	WATR	0.02	SWCH	35.29	AGRC	14.08	AGRC	0.03
2	AGRL	4.92	AGRL	25.48	SWCH	52.91	AGRL	1.69
3	AGRR	1.66	AGRR	14.25	AGRR	30.01	AGRR	98.28
4	URLD	1.03	URLD	0.11	FRST	0.76	-	-
5	BARR	0.04	WETN	0.00	BERM	1.52	-	-
6	AGRC	92.34	FRST	2.17	PAST	0.72	-	-
7	-	-	FRSE	0.02	-	-	-	-
8	-	-	FRSD	0.01	-	-	-	-
9	-	-	AGRC	22.66	-	-	-	-

SOIL DATA

The Food and Agricultural Organization of the UN (FAO, 2003) offers a geographic database that comprises two distinct soil layers, specifically at depths of 100–30 cm and 30–0 cm, which collectively encompass five thousand unique soil types. The distribution is accessible in vector form at a scale of 1:500,000 (Food and Agriculture Organization of the United Nations (FAO) 2024). Figure 4 shows the soil maps used in SWAT models for the Bakerman watershed. Table 4 shows the soil classes and their percentages.

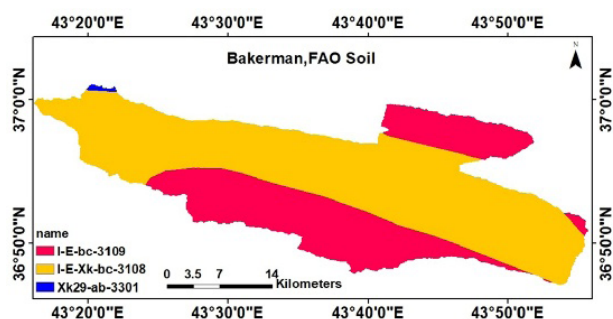


FIGURE 4. FAO soil map of Bakerman (Food and Agriculture Organization of the United Nations (FAO) 2024)

TABLE 4. Input soils in SWAT models Bakerman watershed (Food and Agriculture Organization of the United Nations (FAO) 2024)

No.	Type	%
1	I-E-bc-3109	34.86
2	I-E-Xk-bc-3108	64.95
3	Xk29-ab-3301	0.19

WEATHER DATA

The weather data provided by National Aeronautics and Space Administration (NASA) is frequently used in the field of hydrological modelling, especially in conjunction with the SWAT model. NASA provides detailed, high-quality resources for climate throughout the world. These datasets cover different weather variables such as rainfall, temperature, solar radiation and wind speed. With respect to SWAT modelling, the use of NASA weather data demonstrates a considerable advantage, particularly in regions where limited number of ground-based observations are available. There have been numerous studies in various fields, related to the reliability of this NASA-derived weather data and particularly hydrological modelling at semi-arid locations. Rocha et al. (2023) emphasized the significance of NASA's data on enhancing the model's competitiveness within arid regions. In an identical manner,

Khalid, Ahmed, and Abdullah (2024) explained that NASA product represents a fundamental source for weather data generation in semi-arid regions. The SWAT model has two approaches to incorporating weather data, gauged and simulated. In this research, the utilized weather data, which was gauged, served as the basis for the simulations conducted. The data downloaded on September 15, 2024 from (<https://power.larc.nasa.gov/data-access-viewer/>)

HYDROLOGICAL DATA

The dominant reason for discharges of the Khazer River is high precipitation and snow melting in spring. The river is an important water resource for cultivation which forms the primary source of livelihood in the area. However, water is also directly tied to the changes in climate as well as over-extraction and upstream damming impacting its flow regimes (Al-Hussein et al. 2022b). The observed income flow collected from the National Center for Water Resources Management/ Baghdad for Bakerman on daily time step.

METHODOLOGY

OVERVIEW OF THE RESEARCH METHODOLOGY

The methodological procedure of this research was a systematic, pattern- and scenario-based manipulation of SWAT in a user-friendly approach for SWAT simulation on the catchment area, properly parameterized with the help of SWAT-CUP that involved rigorous model calibration/validation. Figure 5 provides a complete overview of the research process, from set-up and starting point for the project to interpretation of findings. The research was structured into six distinct phases:

1. Project Setup, this involved the setting of boundaries of the study area as well as gathering of four main spatial datasets (DEMs, LULC, Soil, and Weather).
2. Preprocessing, during which the input data were prepared for SWAT, i.e., Watershed Delineation and HRUs generation.
3. To be executed is Weather Data Processing by making use of the WGN (Weather data generator) in order to generate the required time series inputs.
4. Model Calibration & Validation - the most important processes, through the use of SWAT-CUP to conduct parameter sensitivity analysis and calibration against observed values with

- statistical indicators (NSE, R2, and PBIAS) until a threshold level of fit is obtained.
5. Simulation and Scenario Analysis: the 28 models (corresponding to different DEM-LULC combinations) have been implemented for model simulation, followed by an assessment of the effect of such input resolutions.
 6. Conclusion Explanation, including interpretation of results in terms of the variance between model predictions in order to justify decisions or communicate interpret findings.

STREAMFLOW SWAT SIMULATION MODEL

SWAT was established in the beginning of the 1990s by the USDA Agricultural Research Service. Its development aimed to provide a comprehensive, process-oriented model capable of predicting the effects of land management practices on water flow, sediment transport, and agricultural chemicals in large and complex watersheds. The SWAT model operates on a continuous temporal scale, emphasizing the interrelationships within climate, use of land, soil traits,

and topographical features (Rocha et al. 2023b). The theoretical framework integrates empirical and physically based formulas to efficiently simulate streamflow, infiltration, nutrient cycling, and sediment yield (Sisay et al. 2023). The model divides the watershed into sub-basins, which are further partitioned into Hydrologic Response Units (HRUs) — unique combinations of land use, soil type, and slope characteristics. SWAT utilizes the Curve Number (CN) method, which is an established empirical technique to evaluate surface streamflow in relation to land cover, soil characteristics, and preceding moisture conditions (Kumar, Singh, and Shrestha 2016). Together, its historical development, conceptual framework, and computational structure make SWAT an effective tool for assessing water management and land-use impacts at the watershed scale (Khaleghi and Hosseini 2024). The Curve Number (CN), the Penman-Monteith formula, and the variable storage technique were employed for streamflow modeling, facilitating the computation of all water balance components for 28 models for the study watershed. Table 5 shows the constructed scenarios with different DEM and LCLU inputs for the Bakerman SWAT models.

TABLE 5. SWAT Bakerman scenarios.

Scenario	DEM (m)	LULC (m)	Scenario	DEM (m)	LULC (m)
1	250	500	15		100
2	(GMTED)	300	16		10
3		100	17	30 (ASTER)	500
4		10	18		300
5	90 (ASTER)	500	19		100
6		300	20		10
7		100	21	30 (ALOS)	500
8		10	22		300
9	30 (SRTM)	500	23		100
10		300	24		10
11		100	25	12.5 (ALOS)	500
12		10	26		300
13	90 (SRTM)	500	27		100
14		300	28		10

SENSITIVITY ANALYSIS AND UNCERTAINTY

In the present investigation, SWAT-CUP 2012 was employed for the calibration and validation of all models, utilizing Sequential Uncertainty Fitting 2 (SUFI-2) method. Before calibrating, the SWAT model was set up for each case by delimiting the watershed boundaries, breaking stream networks and HRUs, all using combinations of DEMs and LULC maps available. The climatic data for input (daily precipitation, temperature, average relative humidity, wind speed and solar radiation) was included

from NASA after validating it with available local meteorological stations in order to make the simulation environment more realistic. The simulation lasted for the entire period of record, with a 3-year model warm-up applied to reach antecedent conditions before calibration.

The main performance criterion used was Nash–Sutcliffe Efficiency (NS) and coefficient of determination (R^2) were the supporting criteria for model evaluation. Values of NS and $R^2 > 0.5$ are considered to be satisfactory, those greater than 0.75 are considered as indicating good perform (Clark et al. 2021). The connection between SWAT

and SWAT-CUP was formed at the file input/output interface during project's setup, for tuning physical-dependent parameters automatically and comparing model simulated streamflow to observations.

SWAT-CUP conducted 300 iterations in the first run. All 28 models calibrated differently and were validated and sensitivity analysed separately based on different input datasets. Calibration was used to identify the key hydrological parameters affecting the streamflow and sediment production, whereas sensitivity analysis ranked these parameters according to their relative importance. The model was calibrated and validated with monthly

discharge records to maintain the time coherence and avoid the high flow bias.

Calibration was done using parameter set developed by by Abbaspour et al. (2015) and Mitova et al. (2024), plus other parameters tested via sensitivity analysis. Validation was performed using the best fitting parameter ranges found during the last calibration iteration. The P-factor and R-factor were used as criteria for judging the adequacy of calibration iterations, which was not needed when the P-factors are 0.6 or higher and that R-factor can reach acceptable values.

RESERCH METHODOLOGY

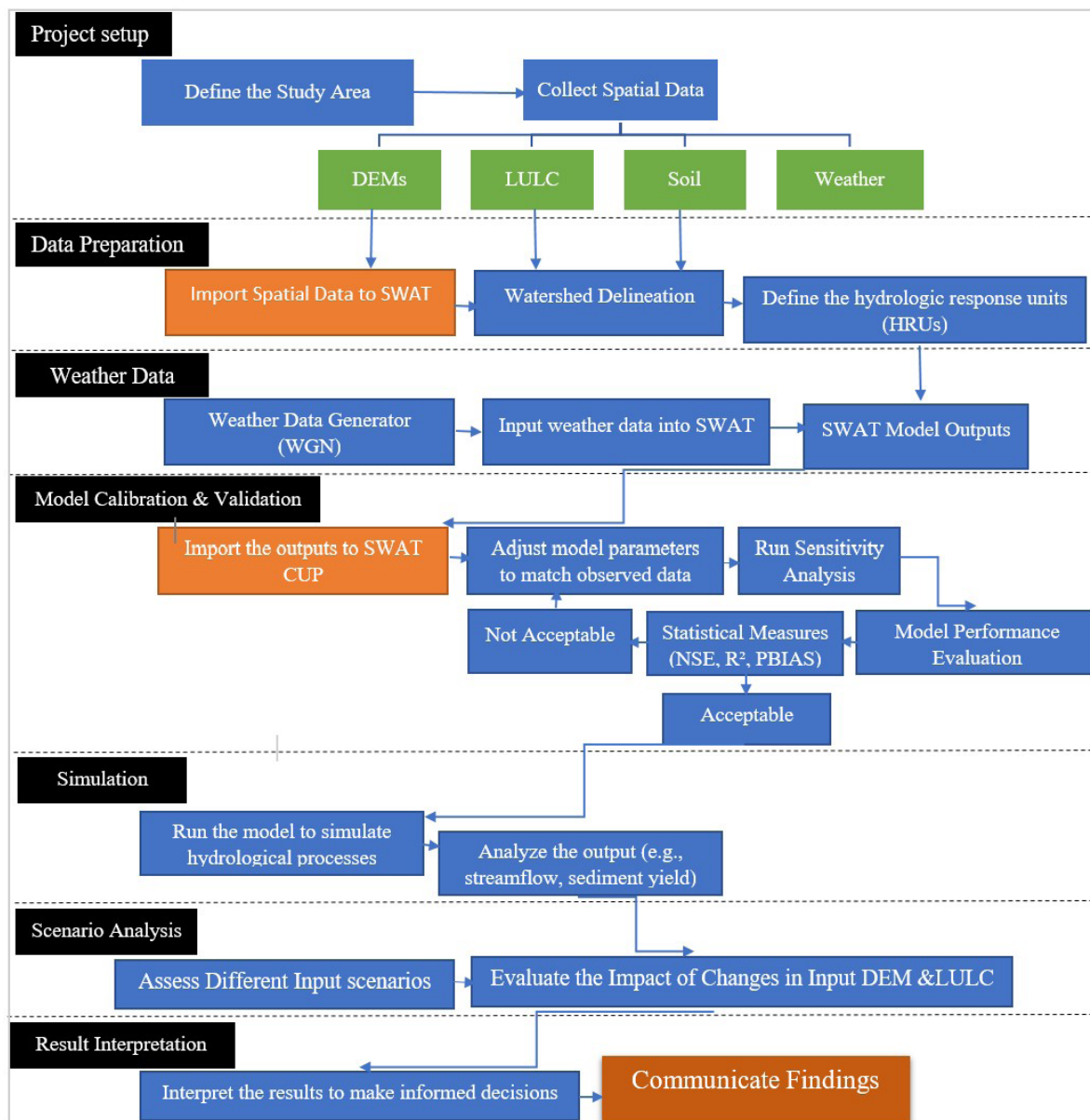


FIGURE 5. Research Methodology

MODELING RESULTS AND DISCUSSION

WATERSHED DELINEATION

The initial phase of the SWAT method entails the delineation of the watershed. Accordingly, the delineation results of the Bakerman watershed derived from different DEM analyses were compared to evaluate the effect of DEM resolution on delineation variables. This comparison demonstrates that the spatial resolution of a DEM has a substantial impact on watershed delineation, consistent with the findings of Datta et al. (2022) and Al-Khafaji, Saeed, and Al-Ansari (2020), as it influences the degree of detail in the representation of terrain. The higher the resolution of the DEM, the more detailed and accurate topographic features are represented, such as watershed boundaries, flow path and stream network delineation. On the other hand, coarse resolution may over-generalize the elevation data that smaller features are lost and incompletely defined (thus discontinuity). These ripple led to finally different terrain factors derived from different resolution DEMs. The influences of various spatial resolutions and sources for DEM on watershed delineating process are presented in Figure 6.

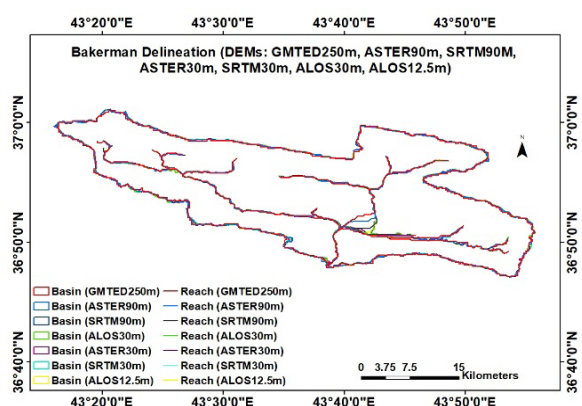


FIGURE 6. The watershed delineation with DEMs of different spatial resolutions and from different sources.

The influence of DEM sources, although at the same spatial resolution, has also been observed and suggests that source influences process. For instance, SRTM has smoother delineation edges than ASTER does in the spatial resolution of 90 meters. In addition, when considering the watershed delineation results at 30 m resolution of SRTM and ALOS, it was found that both had nearly the same resultant output due to their smoother boundaries compared with those from ASTER. This discrepancy is due to varying accuracies of input data, processing algorithms and elevation determination methods. There can be difference in vertical accuracy, noise and representation of terrain

features in DEMs derived from different sources. These differences affect watershed delineation, stream network generation, and flow accumulation, as each source interprets terrain characteristics differently.

The analysis was also expanded to the differences in watershed delineations across DEMs due to changes in their spatial resolution as provided by the data sources. The study found that changes of spatial resolution in the same source generated results with offset for ASTER, SRTM and ALOS. Similar and consistent in the results of the previous studies which have also concentrated on sub-basin delimitation.

WATERSHED AREA

The demarcation of the considered catchment area for the DEM-BM reveals that the system resolution considerably effects on computed watershed area. It is observable that finer-scale resolution of DEM has consistently greater watershed areas generally as reported by Buakhao and Kangrang (2016) and Chaubey et al. 2005). The function clarifies the dependency existing between the DEM spatial resolution and that of the calculated watershed. High resolution DEMs can be used to model finer scale land forms such as small channels, ridges and depressions which would represent more accurate representation of the basin. Smoothing in lower-resolution DEMs, on the other hand, may render such smaller contributing areas ineffective in hydrological modeling and result in underestimation of total watershed area.

The impact of DEM sources at identical spatial resolutions has also been documented. At a 90-meter resolution, ASTER produced a slightly larger watershed area compared to SRTM. At a finer resolution of 30 meters, both ALOS and SRTM generated larger watershed areas than ASTER.

Different DEM sources, even when sharing the same spatial resolution, can affect watershed delineation in SWAT due to variations in data acquisition methods, processing algorithms, and vertical accuracy.

The analysis was subsequently broadened to examine the effect of changing spatial resolution within the same DEM source on the variations observed in watershed area across different sources.

The investigation revealed that modifications to the spatial resolution from a single source produced only minor variations. The study found a small but consistent effect on the spatial resolution from changes in the single source. The spatial resolution difference between ALOS and SRTM has produced changes in watershed area that are very close, whereas the ASTER shows more differences. Moreover, all previous studies were also performed at the sub-basin

scale and consistent results were obtained throughout the analyses. The calculated values of the areas are given in Table 6.

TABLE 6. Total area of Bakerman watershed.

No.	DEM Name	Spatial Resolution (m)	Area (km ²)
1	GMTED	250	744.46
2	ASTER	90	746.66
3	ASTER	30	746.99
4	SRTM	90	746.51
5	SRTM	30	747.52
6	ALOS	30	747.44
7	ALOS	12.5	747.85

WATERSHED ELEVATION

Among the objectives of this study was to assess the effect of DEM resolution on altitude values in the Bakerman Catchment. Results reveal that under different DEMs, minimum elevations are usually overestimated and maximum ones underestimated. This phenomenon arises

because coarser DEMs result in a smoothing of the terrain and thus loss of detail with regard to abrupt elevation changes and topographic features. With decreasing resolution depressions and peaks, which are smaller than a cell size, are degraded by averaging or combining into surrounding topography therefore estimates of minimal and maximal elevation become higher/lower. The results obtained align with the findings presented by Reddy and Reddy (2015) and Tan et al. (2015).

The effect of different DEM sources, all with the same spatial resolution, was also explored. Analysis showed that DEM sources differences had little impact on the maximum and minimum elevation values. Likewise, varying spatial resolution in the same DEM source had little influence on watershed elevation values. Inconsistencies in data collection techniques, vertical precision and processing can cause slight variations in representation of terrain features which can result in small differences resultant elevation values. All previous investigation also conducted at the sub-basin scale share one feature: Hypsometric integral has showed an almost identical pattern. Figure 7 the effect on watershed elevation of using DEMs with different spatial resolutions and from different sources. The calculated elevations are listed in Table 7.

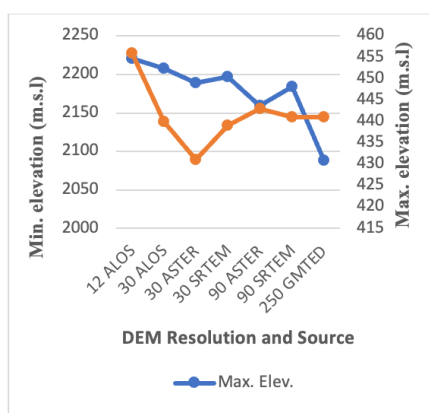


FIGURE 7. Bakerman Watershed Elevations.

TABLE 7. Elevations of Bakerman watershed

No.	DEM Name	Spatial Resolution (m)	Elevation (m.a.s.l)			Std.Elev.
			Max.	Min.	Mean	
1	GMTED	250	441	2088	1085	316.424
2	ASTER	90	443	2159	1088	319.576
3	ASTER	30	431	2189	1090	322.324
4	SRTM	90	441	2184	1089	320.059
5	SRTM	30	439	2197	1090	321.189
6	ALOS	30	440	2208	1093	320.343
7	ALOS	12.5	456	2221	1108	321.475

HRU ANALYSIS

THE IMPACT OF DEM RESOLUTION

This indicates that NHRUs are directly proportional to DEM resolution, which agrees with the results of Rocha et al. (2022) and Saleh Al-Khafaji and Saeed (2018). The slope can be considered the main factor affecting the number of HRU related to a given DEM. The increased resolution better captures the fine features of the landscape, allowing for a more accurate representation of slope and topography. This enhancement leads to delimiting more classes of slope and terrain features, and therefore generating a larger number of HRUs. While coarser DEM are inclined to be generalized for terrain resulting in reduction of slope and topography variation, which subsequently reduces the total number of HRUs.

The effect of different DEM sources with the same spatial resolution was studied. The characterisation of terrain features from different origins is variable and can bear on the number of HRUs in SWAT. Slope calculations and terrain classification is different because of the differences in elevation accuracy of DEM sources, data processing methods and noise level. These variations influence the classification of slope categories and their interactions with land use and soil data, thereby altering the total number of HRUs. The analysis revealed that ASTER generally produces a higher number of HRUs compared to other DEM sources.

Subsequent analysis examined the impact of changing the spatial resolution within the same DEM source on the variations in NHRUs across different sources. The investigation revealed that adjustments in spatial resolution within a single source produced only minor differences; however, ASTER showed more noticeable discrepancies in the number of HRUs generated. The computed NHRUs are presented in Table 8. A critical inspection of Table 8 further reinforces these findings. For instance, increasing the resolution from 250 m (GMTED) to 12.5 m (ALOS) results in a substantial growth in HRUs from 224 to 532 for the 10 m LULC case, reflecting the sensitivity of HRU generation to DEM granularity. Among the 30 m datasets, ALOS and SRTM produce comparable HRU counts (864 and 867, respectively), indicating that at finer resolutions, DEM source differences exert a diminishing influence on HRU variability. However, ASTER consistently exhibits slightly higher HRUs than other DEMs at equivalent resolutions, suggesting that its terrain representation accentuates slope variability and contributes to finer delineation of sub-basin units. These differences, while moderate, can lead to perceptible changes in hydrological response simulations, particularly for erosion and runoff modeling.

THE IMPACT OF LULC RESOLUTION

The results indicate that LULC significantly impacts HRUs, which is matching the outcomes of Regasa and Nones (2023) and Afonso de Oliveira Serrão et al. (2022). The resolution and classification of LULC data play a pivotal role in ascertaining the quantity of HRUs within SWAT. Higher-resolution LULC data capture finer spatial details, while a greater number of land use classes enhances the representation of land cover variability. The interaction of these factors increases the diversity of combinations among land cover, soil, and slope, thereby resulting in a larger number of HRUs. In contrast, a reduction in the resolution or a decrease in the number of classes results in diminished heterogeneity, which consequently leads to a reduced number of HRUs.

The analysis indicates a direct correlation between LULC resolution and HRUs, contingent upon the condition that the quantity of LULC classes is either held constant or augmented with increased resolution. The transition from a resolution of 500 meters to 300 meters, and then to 100 meters, leads to a notable rise in the number of HRUs. Nevertheless, the utilization of SENTINEL-2 data (10 meters resolution) results in a comparatively low quantity of HRUs, mainly due to the limited diversity of its land use classes.

As evidenced in Table 8, the effect of LULC resolution on HRU formation is particularly evident across all DEM datasets. When LULC classes increase from 12 to 23 (at 300 m resolution), the HRUs approximately double for most DEMs—for instance, ASTER 30 m rises from 263 HRUs at 500 m LULC to 665 at 300 m LULC. Such a sharp increase underscores the importance of the diversity of subject matters as premise for definition of hydrological units. In contrast, the decrease in HRUs at finest 10 m LULC resolution (ASTR 30 m for example drops from 884 to 510) suggests that high spatial resolution does not necessarily lead to larger HRU differentiation if class diversity is limited. This result underlines that it is the joint effect of spatial and thematic resolution that determines HRU generation efficiency rather than spatial accuracy alone. These results highlight the importance of a compromise between spatial resolution and land cover classification richness which guarantees realistic hydrological response in SWAT.

TABLE 8. HRUs of Bakerman watershed

No.	DEM Name	Spatial Resolution (m)	LULC	LULC	LULC	LULC
			(500m) 12 Classes	(300m) 23 Classes	(100m) 22 Classes	(10m) 9 Classes
Number of Hydrological Response Units (NHRUs)						
1	GMTED	250	224	528	648	338
2	ASTER	90	238	599	758	408
3	ASTER	30	263	665	884	510
4	SRTM	90	244	599	779	423
5	SRTM	30	264	652	867	504
6	ALOS	30	261	652	864	520
7	ALOS	12.5	261	671	882	532

STREAMFLOW EVALUATION

Preliminary simulations of Bakerman streamflow, conducted before calibration, exhibited a low base flow. The sensitivity of the model to different DEM and LULC datasets was evaluated through a comparative analysis of observed streamflow against simulated streamflow. The validation and calibration of the model were done utilizing the NS as the key goal function within SWAT-CUP, while the R^2 was employed as a supplementary indicator. Hydrographs derived from the calibrated and validated results of 28 models were analyzed, showing that NS and R^2 values displayed a high degree of consistency. The model exhibiting the best NS value throughout the validation time was selected. The best validation performance was achieved using ESA data at 300 m resolution and ASTER at 90 m, yielding NS and R^2 values of 0.81 and 0.88, respectively. The SWAT model for the Bakerman watershed may produce less accurate streamflow estimates when using very high-resolution DEM/LULC data, as finer resolutions introduce a larger number of

hydrologic parameters that require optimization relative to the observed flow. This finding is consistent with the results presented by Alawi and Özkul (2023) and Al-Khafaji et al. (2020). Figure 8 illustrates the results obtained from the most accurately calibrated and validated SWAT models pertaining to the Bakerman watershed.

The analysis reveals a trend of modest increases in streamflow quantities associated with higher DEM resolutions. When comparing DEMs of identical resolution from different sources, no consistent trend was observed at the 90 m resolution. At a resolution of 30 meters, ALOS consistently yielded marginally elevated streamflow values across all LULC datasets, with SRTM following, and ASTER exhibiting the lowest streamflow amounts. Furthermore, analyses of DEMs from the same source but with different resolutions (such as ASTER 30 m vs. 90 m and SRTM 30 m vs. 90 m) showed that the higher-resolution 30 m DEMs consistently produced slightly greater streamflow values than their 90 m counterparts. Figure 9 shows the systematic quantification of streamflow prediction uncertainty across 28 input scenarios.

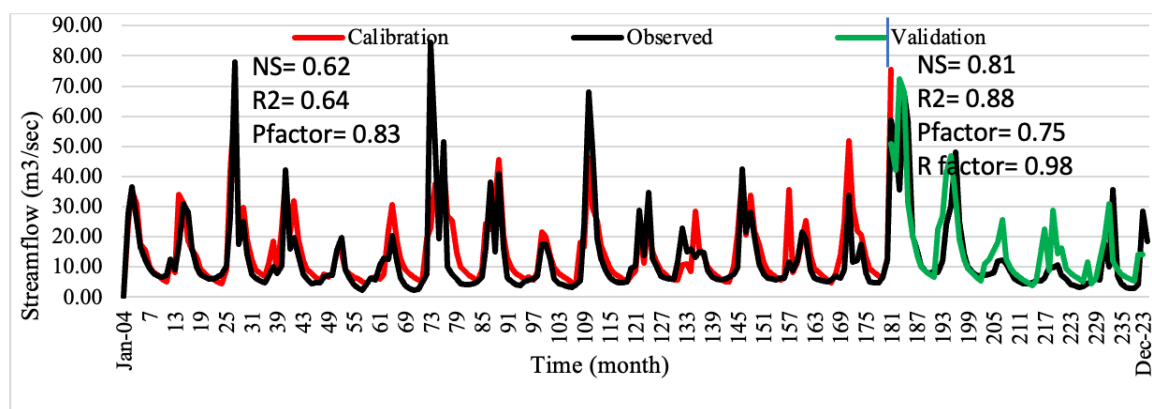


FIGURE 8. The best calibrated and validated SWAT model of Bakerman.

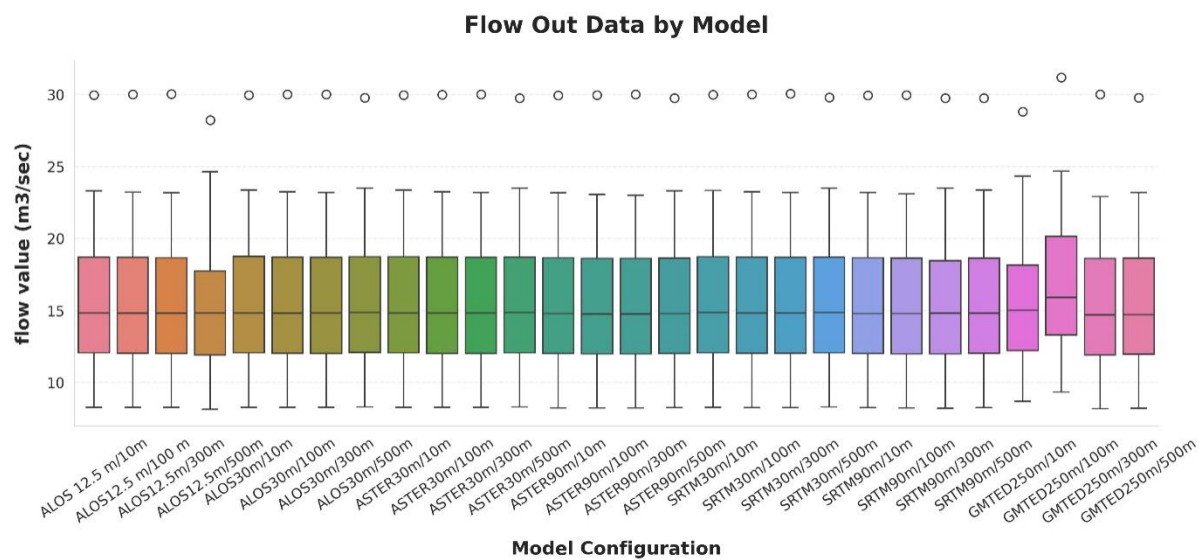


FIGURE 9. Systematic Quantification of Streamflow Prediction Uncertainty across 28 Input Scenarios.

SEDIMENT EVALUATION

The varying spatial resolutions of DEM affect sediment output in SWAT by influencing slope calculations as well as the delineation of drainage patterns. Increased resolution yields also improved the visual appearance of slopes and topography, resulting in more accurate estimates of slope gradient and increased fidelity in determining flow paths. Greater sediment yield and erosion rates are obtained due to the finer spatial resolution in the level of detail, as from 250 m to 12.5 m. Conversely, larger gridded DEMs are highly likely to sand down details of the land surface, meaning slopes and flow velocities will be underestimated. This in turn results in a decrease of sediment output, coinciding with the findings of Akbar et al. (2024) and Lin et al. (2010).

Different DEMs, with the same spatial resolution, were tested for their effect on sediment yield within a specific LULC. The representation of land relief in various sources based on data acquisition mode, vertical accuracy, and processing procedures may affect sediment yield considerably. Fluctuations in slope calculation and flow path region demarcation are necessary as an input to a sediment transport model. Even small differences in slope gradient and drainage network integrity between DEM sources can result in different fluvial erosion rates and

sediment delivery. At 30m, ALOS generally provided the highest sediment output value, followed by ASTER and SRTM which was lowest. The SRTM gave sediment values a little higher than ASTER at 90 m and this was an average value.

Further analysis was carried out to determine the effect of changing pairs of spatial resolutions to the respective DEM source on the results obtained. The results showed that changing spatial resolutions within the same source would produce differences, albeit not significantly, while more profound differences occur in the case of SRTM datasets compared to ASTER.

Finally, an analysis of the effect of LULC data resolution as well as the number of classes show on sediment output was carried out. The data shows that there are no systematic trends between LULC resolution and sediment yield. However, the analysis of 10 m, 100 m, and 300 m for LULC data shows that increased resolutions would lead to results with higher sediment output. However, the trend loses its consistency in the case of the 500 m. To explain that the lack of consistency in the case of 500m and certain pair ratio data can be attributed to the spanning scale issues likely caused by the difference in data sources used. Figure 10. Sediment prediction uncertainty quantified systematically across 28 input scenarios.

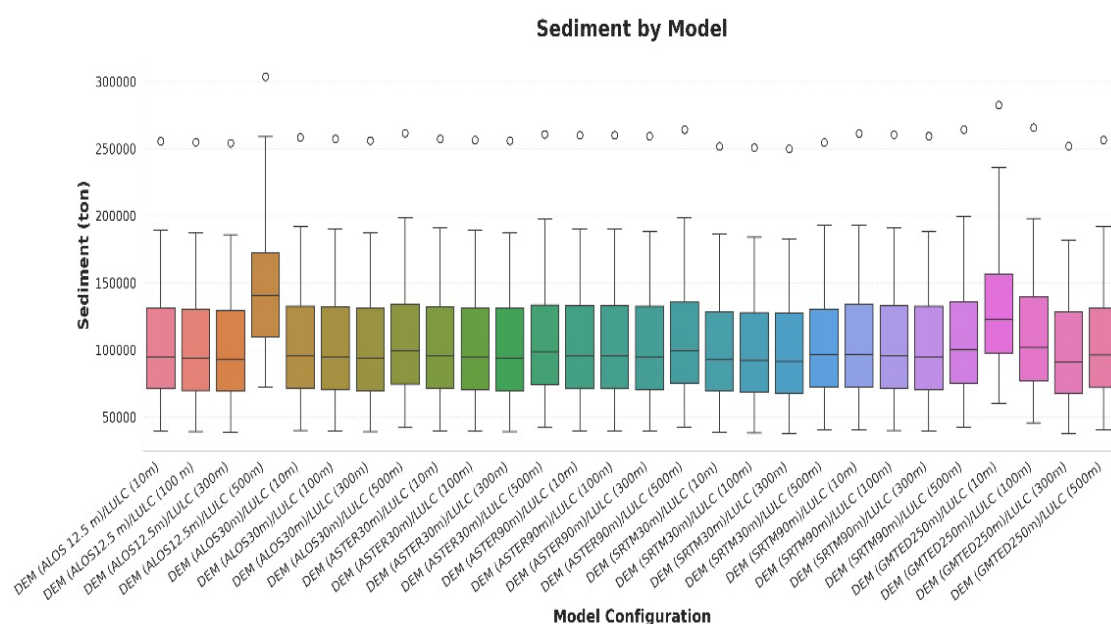


FIGURE 10. Systematic quantification of sediment prediction uncertainty across 28 input scenarios.

DISCUSSION

This study highlights the influence of DEM and LULC attributes on the hydrological model outputs and provides valuable insights into their combined influences to predict streamflow and sediment yield. Previous studies have also reported similar results, emphasizing that HRU and sediment estimating being sensitive to DEM and LULC (Al-Khafaji and Saeed 2018; Regasa and Nones 2024). The findings show that the spatial resolution of DEM, which is critical in watershed definition and HRU identification as well as sediment yield estimation, is significantly more important than the source of DEM. This result is in agreement with studies indicating that higher resolution DEMs contribute more to topographic representation and subsequent hydrologic responses than DEM source alone (Aouissi, Ennajeh, and Benabdallah 2017; Saksena and Merwade 2015). Similarly, HRU counts are influenced by LULC data, while the influence on sediment yield is not necessarily monotonous. Variations in sediment yield resulting from LULC have also been observed by Ait M'Barek et al. (2023), who stressed the importance of thematic richness and resolution in hydrological modeling. Outflow underlying predictions and input resolution had no strong relation among each other, emphasizing the complexity of hydrological processes and that several drivers interact with each other during model calibration and validation. This complexity has already been reported previously and suggests that input data quality as well as the calibration strategy is

crucial for streamflow simulations (Al-Khafaji, Saeed, and Al-Ansari 2020b; Saksena and Merwade 2015).

The results of this study are an issue of great concern in a variety of disciplines like civil, environmental and water resource engineering. Reliable DEM and LULC information is essential for planning of infrastructure, prediction of flooding risk and controlling the watershed. This is especially important in semi-arid and arid regions where intense precipitation can lead to flash flooding, necessitating efficient water management solutions.

What is even more problematic is that the sediment yield prediction is dependent on the DEM resolution, which has substantial implications for erosion and sedimentation control in waters and river basins. To optimize engineering solutions, such as sediment traps, check dams, and silt fences, it is crucial to understand the relationship between the DEM's resolution and the evaluation of sediment yield. As a result of applying DEM data, of seemingly higher quality, users can predict sediment load with higher accuracy, making the hydraulic infrastructure more durable and efficient. Some of the most recent research on this topic suggests that the DEM's resolution is one of the critical elements in sediment and erosion model application, outlining its importance in watershed and infrastructure control and management. (Aouissi et al. 2017; Setargie et al. 2022).

Furthermore, the importance of LULC in hydrological modeling has real-life implications regarding land use development and urban planning. Practitioners working in land use planning can benefit from this study as an approach

to assessing the influence of different land cover on runoff and infiltration rates and thus, on the deployment of green infrastructure schemes. Finally, the paper emphasises the need for standardized land use and land cover classification systems to enhance hydrologic assessments consistency and reduce model undesirables.

The results of this study greatly improve the development of an accurate hydrological model and support engineering attempts for sustainable water resources management. In the future, there is a need to examine the integration of emerging technologies such as remote sensing, machine-learning and AI-based methods in order to improve DEM and LULC data quality for better prediction performance of hydrological models. This work serves the progress for resilient water infrastructure and sustainable watershed management approaches by solving uncertainties on data resolution and source in engineering applications.

The analysis of uncertainty was extended from parameter related statistics obtained with SUFI-2 to incorporate both sources of input data and model structural uncertainty. A major source of error is a DEM and LULC data as indicated by the main conclusions of this study: differences in source, complexity and resolution have a direct impact on certain important modelling inputs such as watershed delimitation, HRU quantity and CN value. Contrarily, the natural variability in input DEM resolution and vertical accuracy (e.g., ASTER vs. SRTM) constitutes an initial input-related uncertainty that precedes any one specific simulation run. Moreover, limited or interpolated meteorological data, especially in the semi-arid and topographically complex Bakerman watershed, adds uncertainty to the exact spatial distribution and amount of precipitation. Finally, model structural uncertainty should be recognized as SWAT is a real world simplified model and there are components that it could not accommodate well and the complex hydrologic processes such as lateral groundwater flow or extreme localized preferential paths may not be captured fully representing an intrinsic limitation associated with the model domain. Bakerman of interest, results on prevailing sensitivity of input data resolution and type correspond with – but fundamentally differ from – previous findings using global SWAT modeling studies. By including this comparative context, the robustness of our results increases and emphasizes hydro-climatic dependence of input uncertainty.

A direct linkage between DEM resolution, watershed delineation and sediment yield is an important observation not unique to the semi-arid region. The reasons for this sensitivity to the increase of topographic factors such as slope length and steepness [LS-factor] in the Modified Universal Soil Loss Equation [MUSLE]) are essential in the SWAT model on all landscapes. Comparison to

Highland/Tropical Regions: While it is found in all higher relief and mountainous regions. For instance, in the work by Dile et al. (2024), on an Ethiopian highland watershed also shows a scale-dependent impact. Discovered that the 0–30-m DEMs improved sediment yield simulations in relatively smaller sub-basins, but decreased at the larger scale. This corroborates with congregated conclusion that high resolution data is the key to physically based outputs such as sediment yield, either in a semi-arid or a tropical region. Comparison with Temperate Regions: A comparable work by Reddy and Reddy (2015b) in the Kaddam watershed, India found that daily sediment yields from each sub-watershed decreased at coarser DEM resolutions. Their results directly could validate the findings on the geometric influence of resolution by comparison with their very high resolution data.

The fact that the simulated streamflow prediction did not appear to be directly influenced by the input resolution (a potential reason being the well-known, and generally dominant even for fully distributed variables, role that calibration plays in defining reliability of model output for integrated variables) is interesting. Comparison with Mountainous/Complex Terrain -This phenomenon has been continuously presented in the literature from complex terrain. A study by Jin et al. (2024) in the Appalachian region of the United States found that all three DEM resolution scenarios performed well for streamflow in calibration.

The fact that the role of LULC data as it relates to HRU counts and impact on sediment yield remains variable among sources emphasizes uncertainties resulting from differing LULC classification approaches. Comparison among different data sources: The uncertainty of the LULC data source is one of the universal problems internationally. The study by Alawi and Özkul (2023b) in the Kokcha watershed, a mountainous region of Afghanistan, found that LULC data from two sources led to approximately an identical and only minor deviation in final streamflow results after calibration and validation. This supports the statement that although LULC affects HRU layout, these specific impacts on overall responses are damped out by the model structure and calibration. Comparison with tropical dynamics: However, in a very dynamic tropical environment such as the Periyar River Watershed, the investigation of Sadhwani et al. (2022) observed that, although flow and sediment yield varied by LULC change scenarios, the effect at the watershed outlet was sometimes considered no significant when taking into consideration of its upland large heterogeneous character. This is more evidence that a simple straight forward connection between LULC source/resolution and output can be difficult, with it differing greatly based on catchment scale and model calibration.

Overall, findings from the Bakerman watershed are very likely to be applicable as they reflect some general (theoretical) sensitivities of SWAT. The DEM resolution dependency of sediment yield is a global topographic control, but the relative insensitivity of streamflow to both DEM and LULC sources is due to model calibration under unit conversion, an emergent property related to scale aggregation rather than statistical under-parameterization that holds in semi-arid, tropical and temperate domains.

CONCLUSION

The findings of this study provide critical insights into the combined effects of DEM and LULC sources and resolutions on SWAT model performance, underscoring their pivotal role in hydrological modelling and water resource management. One of the most significant conclusions is that DEM resolution exerts a decisive influence on watershed delineation, while the DEM source has comparatively minimal impact. Higher-resolution DEMs consistently delineated larger watershed areas, with SRTM generating marginally broader extents than ASTER. Interestingly, estimates of maximum altitude rose in tandem with DEM resolution, whereas minimum altitude values exhibited the opposite trend, reinforcing the sensitivity of topographic representation to resolution choice.

A critical assessment of the results reveals that the generation of HRUs is influenced by both the spatial and thematic resolution of input data rather than resolution alone. Finer DEMs consistently increased the number of HRUs due to improved representation of terrain variability; however, this relationship was not strictly proportional, as variations in DEM source accuracy and slope classification also played a role. Similarly, higher-resolution LULC data with a greater number of land cover classes enhanced the heterogeneity of HRUs, but the 10 m SENTINEL-2 dataset, despite its fine spatial detail, produced fewer HRUs because of its limited class diversity. This indicates that HRU generation depends on a balanced interaction between DEM resolution, LULC classification detail, and data quality, rather than on resolution alone. Therefore, selecting datasets should involve consideration of both spatial precision and thematic richness to achieve realistic model representation without unnecessary computational complexity. Sediment yield analysis highlighted another key dimension, showing that finer-resolution DEMs generally produced higher sediment estimates. Notably, ALOS 30 m and SRTM 90 m DEMs recorded the greatest sediment loads within their respective resolution groups. In contrast, the influence of LULC resolution on sediment yield proved less consistent, suggesting that other factors,

such as soil parameters and climate variability, may exert stronger controls. Collectively, these results emphasize that resolution alone is not a guarantee of accuracy, but rather that careful consideration of input data characteristics is essential. The study contributes vital evidence to bridge gaps in hydrological modelling knowledge, offering guidance for future applications of the SWAT model in advancing sustainable water resource management and climate resilience.

Finally, the findings of this study have direct and significant practical and policy implications for the Bakerman watershed. This analysis confirms that while DEM and LULC resolution both introduce uncertainty, land use changes are the more influential structural factor governing the watershed's hydrological response, particularly concerning sediment yield. This underscores the need for policymakers to prioritize regulatory mechanisms for land-use planning over simply acquiring the highest resolution DEM data. Furthermore, demonstrating that optimal prediction accuracy was achieved with mid-to-coarse resolution data provides a pathway for resource optimization, advising water managers that reliable streamflow modeling can be conducted with readily available, computationally efficient datasets, thereby accelerating decision-making processes related to water allocation and flood risk management.

ACKNOWLEDGEMENT

The authors would like to express their sincere appreciation to Earth Observation Centre, Institute of Climate Change Universiti Kebangsaan Malaysia (UKM)

DECLARATION OF COMPETING INTEREST

None.

REFERENCES

- Abbaspour, K. C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H. & Kløve, B. 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology* 524: 733–752. <https://doi.org/10.1016/j.jhydrol.2015.03.027>
- Afonso de Oliveira Serrão, E., Silva, M. T., Ferreira, T. R., Ataíde, L. C. P., dos Santos, C. A., de Lima, A. M. M., da Silva, V. P. R., de Sousa, F. A. S. & Gomes, D. J. C. 2022. Impacts of land use and

- land cover changes on hydrological processes and sediment yield determined using the SWAT model. *International Journal of Sediment Research* 37(1): 54–69. <https://doi.org/10.1016/j.ijsrc.2021.04.002>
- Ait M'Barek, S., Bouslihim, Y., Rochdi, A. & Miftah, A. 2022. Effect of LULC data resolution on hydrological and erosion modeling using the SWAT model. *Modeling Earth Systems and Environment* 9(1): 831–846. <https://doi.org/10.1007/s40808-022-01537-w>
- Ait M'Barek, S., Bouslihim, Y., Rochdi, A. & Miftah, A. 2023. Effect of LULC data resolution on hydrological and erosion modeling using the SWAT model. *Modeling Earth Systems and Environment* 9(1): 831–846.
- Akbar, A. Q., Mitani, Y., Nakanishi, R., Djameluddin, I. & Sugahara, T. 2024. Impact assessment of digital elevation model (DEM) resolution on drainage system extraction and the evaluation of mass movement hazards in the upper catchment. *Geosciences* 14(8): 223.
- Al, A. Y. & Hasan, H. M. 2022. River islands of Khazir River: A geomorphological study along the area from Nedoush Valley to the Upper Zap. Dlm. *IOP Conference Series: Earth and Environmental Science* 1120: 12006.
- Alawi, S. A. & Özkul, S. 2023a. Evaluation of land use/land cover datasets in hydrological modelling using the SWAT model. *H2Open Journal* 6(1): 63–74.
- Alawi, S. A. & Özkul, S. 2023b. Evaluation of land use/land cover datasets in hydrological modelling using the SWAT model. *H2Open Journal* 6(1): 63–74.
- Alferi, L., Avanzi, F., Delogu, F., Gabellani, S., Bruno, G., Campo, L., Libertino, A., Massari, C., Tarpanelli, A. & Rains, D. 2021. High resolution satellite products improve hydrological modeling in Northern Italy. *Hydrology and Earth System Sciences Discussions* 2021: 1–29.
- Al-Hussein, A. A. M., Khan, S., Ncibi, K., Hamdi, N. & Hamed, Y. 2022a. Flood analysis using HEC-RAS and HEC-HMS: A case study of Khazir River (Middle East—Northern Iraq). *Water* 14(22): 3779.
- Al-Hussein, A. A. M., Khan, S., Ncibi, K., Hamdi, N. & Hamed, Y. 2022b. Flood analysis using HEC-RAS and HEC-HMS: A case study of Khazir River (Middle East—Northern Iraq). *Water* 14(22): 3779.
- Al-Khafaji, M., Saeed, F. H. & Al-Ansari, N. 2020a. The interactive impact of land cover and DEM resolution on the accuracy of computed streamflow using the SWAT model. *Water, Air, & Soil Pollution* 231(8). <https://doi.org/10.1007/s11270-020-04770-0>
- Al-Khafaji, M., Saeed, F. H. & Al-Ansari, N. 2020b. The interactive impact of land cover and DEM resolution on the accuracy of computed streamflow using the SWAT model. *Water, Air, & Soil Pollution* 231(8): 416.
- Al-Khafaji, M. S. & Al-Chalabi, R. D. 2019. Assessment and mitigation of streamflow and sediment yield under climate change conditions in Diyala River Basin, Iraq. *Hydrology* 6(3): 63.
- Al-Khafaji, M. S. & Saeed, F. H. 2018. Effect of DEM and land cover resolutions on simulated runoff of Adhaim watershed by SWAT model. *Engineering and Technology Journal* 36(4A): 439–448.
- Aouissi, J., Ennajeh, R. & Benabdallah, S. 2017. Impact of DEM data resolution on SWAT model in runoff simulation. Dlm. *Euro-Mediterranean Conference for Environmental Integration*, 815–817. Springer.