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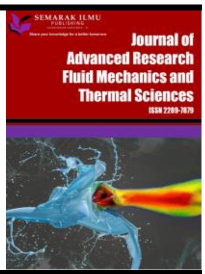

Hydrological Modelling of Sediment Yield in the Upper Basin Region of Kirkuk City Watershed

Ameer Hashim Hussein[1,*], Thair Jabbar Mizhir Alfatlawi[2], Reham Alwash[3]

[1] Al-Mussaib Technical Institute, Al-Furat Al-Awsat Technical University,51009 Babylon, Iraq
[2] Department of Civil Engineering, University of Babylon, Babylon, Iraq
[3] School of Civil Engineering and Built Environment, Liverpool John Moores University, Liverpool, United Kingdom

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ABSTRACT

Mountain sedimentation and undue erosion provide significant challenges for dams since materials accumulate within reservoirs that hold water, reducing the capacity for storing living water, which is the most important goal of dam building. Iraq is one of the nations that will have a big problem getting sufficient water because its water requirement continues to climb, and the supplying countries provide less water to Iraq. The present research focuses on the upper basin of the Kirkuk City watershed in northeastern Iraq. The largest watershed region, spanning approximately 420 km^2 within Al-Sulaymaniyah and Kirkuk Provinces. The objective is to quantify and foresee the sediment yield in this basin using 43 years of daily environment information and various rainstorm events with various intensities. The model was adjusted and confirmed by comparing it to the monthly mean surface flow and sediment readings obtained at the Kirkuk gauging station. The Soil and Water Assessment Tool (SWAT) model was utilized to simulate the upper basin region of Kirkuk City. The aforementioned model uses the geographic information system (GIS) software to analyse necessary information from GIS layers of the electronic contour modelling kind of soil, using of land, and coverage by integrating it with the appropriate climatic information. The kinematic erosion (KINEROS) and runoff model can simulate intricate watershed behaviour by precisely adjusting for the geographical variation of soils, distribution of rainfall sequences, and vegetation. The hydrological features of the Kirkuk city basin reveal that the subdivisions with the highest erosion rates cannot transport the debris or deposits to the reservoir, primarily due to propagation damages, percolating, and other smaller barriers. The optimal curve number (CN) was determined to be between 84 and 88, while the land cover factor (C) ranged from 0.005 to 0.04. The model validation results indicate that the Kirkuk Dam reservoir received a total volume of water estimated at 118.7 million cubic metres (MCM) and a total silt yield of 0.85 million tonnes. The "KINEROS" simulation modelling for the sediment yield closely matches the upper basin of Kirkuk watershed's deformation and sedimentation behaviour during singular rainfall events; this is particularly true for parts of watersheds located near the watershed area entrance.

* *Corresponding author.*
E-mail address: inm.ame@atu.edu.iq

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1. Introduction

A great amount of research has been conducted on the subject of highland sediment yield and erosion. The works presented are examples of research projects with a wide range of goals, methodology, and other relevant elements. A comprehensive awareness of the amount of sedimentation moved from the upstream region due to highland erosion, and the extent to which it reaches the watershed is essential for efficiently managing the basin and the reservoir. Sedimentation significantly impacts reservoir longevity, which is crucial for flood prevention and water consumption [1,2]. Several of the following research examines various terms associated with the deposition patterns in the watershed.

Flow rates decline with time due to the stream's ability to move silt, which is diminished, leading to settling [3]. Typically, a delta forms in the reservoir's headwater section, marking the depositional phase's beginning. Tiny fragments of silt could be carried nearer to the dam by concentration flows [4,5].

In order to model the quality of water issues in the middle Cong catchment of Vietnam, Arnold and Fohrer [6] implemented the soil and water assessment tool (SWAT) modelling. The present research findings indicate that the catchment is not affected by sediments much; rather, the primary concern is the nitrate loading. It analyzed the sediments output volume from the Angered Valley in Ethiopia to predict the reservoir's operational lifespan; this was done using a farming nuisance polluting model [7].

Omran [8] proposed two measures to enhance the longevity of the reservoir: reducing the amount of sediment entering the reservoir and eliminating sediment from the reservoir. The significance of this study is evident in its recommendation and implementation of the calibration and verification procedure based on local conditions. This study was conducted on the sedimentation process in the AL-Adhaim dam watershed. It is particularly important as many hydrologic prediction models rely on generic constraints and parameters.

The sedimentation distribution over the watershed is quite comparable throughout the whole basin [9]. This results from the ongoing process of completing the operation throughout its time, as well as the characteristics of the underlying topography. Over 60 years since the commencement of operations, it was discovered that the sedimentation thickness at the upstream section of the reservoir might reach up to 220 cm. Mahamid and Hani [10] utilized the Arch Views Soil and Water Assessment Tool (AV-SWAT) approach to simulating the Mojib Dam watershed region. The Mojib dam built in 2003 and is located on the King High-way between the Madiba and Karika Jordan Governorates. It was chosen for assessing an amount to the sedimentation accumulated in its Basin from November 2003 to December 2006.

In numerous instances, sediment yields are substantial, necessitating the implementation of conservation or prevention strategies in drainage to mitigate long-term sediment production [11]. The sediment yield rate is the sediment yield per unit of drainage area, which is the proportion of eroded material that travels through the drainage network to a downstream control point [12]. The delivery ratio is between the quantity of sediment yield and the gross erosion in the watershed area; it is a metric that connects the gross soil erosion and sediment yield [13].

Various computational and probabilistic approaches exist for estimating sediment yield. However, their practical use is often restricted to small regions due to the extensive data needed, including hydrological information, physiographic characteristics of the area, and detailed measurements to determine parameters for the equations [14]. The Universal Soil Loss Equation (USLE) technique and its revised version (RUSLE) can be used to forecast soil erosion under different land management strategies [15]. The sediment yield at the outlet is determined by combining the sediment delivery ratio with the soil loss erosion levels. The updated Universal Soil Loss Equation (MUSLE); The prediction model developed by Williams [16] in 1995 is designed to estimate the amount of sediment that is carried out of the watersheds. This updated model enhances the accuracy of sediment yield estimation, eliminates the requirement for delivery ratios, and enables the application of the model to specific storm events.

The erosion of soil and yield of sediment from watersheds exhibit significant disparities. Erosion is the process by which soil particles become dislodged, moved, and deposited in different locations. While it is accurate to say that not all eroded materials from a watershed end up in the stream system, some remain within it [17]. The soil particles that become detached from relatively flat fields, where there is minimal or no water flowing over the surface, only travel short distances and do not get carried to a lower location in the watershed [18]. The objective of the research on sediment source analysis is to calculate the yearly gross erosion, which refers to the aggregate quantity of deposited particles eroded within the upper basin of Kirkuk city watershed in a given year. The annual erosion of the gross (*AE*) is determined by the contributions of different sediment sources, including erosion of upland (*UE*), erosion of gully (*GE*), and erosion of local bank (*BE*), as follows:

$$AE = UE + GE + BE \tag{1}$$

Usually, the main source of sediment, highlands eroding *UE*, should be approximated at every particular location due to massive loss or eroded banks *BE* and erosion of gully *GE*. Recent and current satellite images and field studies help one to ascertain, for example, The yearly quantity of sediment carried by the river's flowing sideways and the upriver migration of headcounts. In steady fluvial systems, the study of sediment sources emphasizes highland erosion losses from snowmelt and rainfall.

2. Sediment Yield Calculation

Various mathematical and stochastic approaches exist for estimating sediment yield. However, their practical use is often restricted to small geographical areas due to the complicated data requirements. These include hydrological information, physiographic features of the area, and the need for extensive data measurements to determine parameters for the equations [19]. The Universal Soil Loss Equation (USLE) technique and its revised version (RUSLE) developed by Asres and Awulachew [20] are used to forecast soil erosion under different land management strategies. The sediment delivery ratio is used in conjunction with the soil loss erosion measurements to calculate the quantity of sedimentation transported to the outflow. The updated Universal Soil Loss Equation (MUSLE) is a predictive model that estimates sediment yields at the outlet of a watershed [16]. This updated model enhances the accuracy of sediments yield estimation, eliminating the requirement for transmission ratio, and enables the application of the model to specific storm events.

Wischmeier and Smith [21] created the universal soil loss equation (USLE) to estimate the amount of soils erosion in USA watersheds in agriculture. The USLE uses rainfall energy to predict the average annual gross erosion. It can also estimate the typical yearly yield of sediment by using the transport ratio, which is the ratio of sediment yield at a channel point to upstream erosion in large watersheds. Estimating the delivery ratio accurately is often challenging in many locations due to the lack of available measured data. Moreover, the USLE is deemed unsuitable for water quality modelling. MUSLE is an altered iteration of the USLE created by Suresh [22]. In MUSLE, the factor of energy rainfall is substituted with a factor of runoff. This change enables the formulation to be utilized to predict the yield of sediments. It eliminating the requirement for transport ratios and applies the formulation to specific storm occurrences [23]. The revised version of the USLE is:

$$S_Y = 11.8(Q_{RF} * Q_{PF})^{0.56} K_e . T_s . C_m . S_p . C_{cf} \quad (2)$$

where S_Y is the sedimentation yields' (tons); Q_{RF} is the runoff volume (m^3); Q_{PF} is the peak-flow rating (m^3/sec); K_e is the factor of soils erosion (metric ton m^2 h/ [m^3-metric ton cm]); T_s is the parameter of topography; C_m is the management and cover factor; S_p is the parameter of supported practical and C_{cf} is the parameter of coarsely fragments. For every Hydrologic Response Unit (HRU), the SWAT models' calculate the runoff volume Q_{RF}, using Eq. (2) as:

$$Q_{RF} = q_R * A_{HRU} \quad (3)$$

where q_R is the accumulating excess of rainfall or runoff (mm); A_{HRU} is the hydrologic response unit area (Km^2).

The formula used above reflects two primary elements: hydrological components, specifically Q_{RF} and Q_{PF}, and the erodibility of the surface of the land system, which can be further split into two sub-factors. The first sub-factor is the physical characteristics of the land surfaces, including the soil's eroded characteristics and potential for erosion. The second sub-factor is the implementation of watershed approaches to management aimed at reducing erosion of soil, such as maintaining cover vegetation over the surface land and implementing methods to preserve soil [24].

3. Methodology

3.1 Study Area Description

The Kirkuk City basin is situated in the northeastern region of Iraq, namely on the Kirkuk stream, approximately 17 kilometres north-east of Kirkuk City. The Khasa stream is a little river that joins the Zaghitun Waterways and ultimately flows into the Adhaim Dam Reservoir.

The Soil and Water Assessment Tool (SWAT) model delineates and characterizes the upper basin of Kirkuk city watershed, as shown in Figure 1. This is achieved by analyzing the Digital Elevation Model (DEM) layers mapping and a satellite image (Landsat TM) corresponding to digitally projected administrating Iraqi mapping layers.

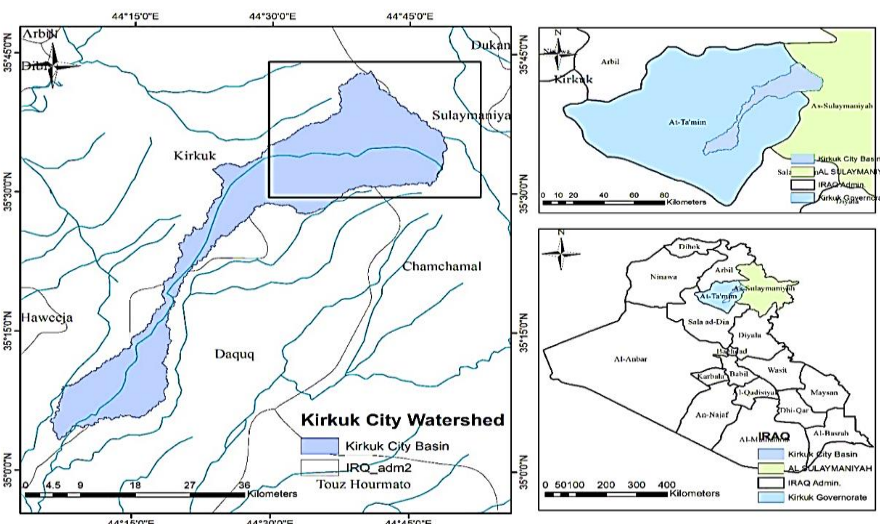

Fig. 1. The Upper Basin location of Kirkuk City

The utility software Global Mapper Edition (18) is utilized to acquire a comprehensive topographical characterization and study of the Kirkuk city reservoir and the bulk of its watershed region, as depicted in Figure 2. Additionally, a 3-D assessment is conducted and presented in Figure 3.

Clay and silt soils have decomposed. Although the Upper Kirkuk City Series dominates the area, the topsoil is distinguished by weathering gravel and transported (debris) soils distinct from the rocks beneath them [25].

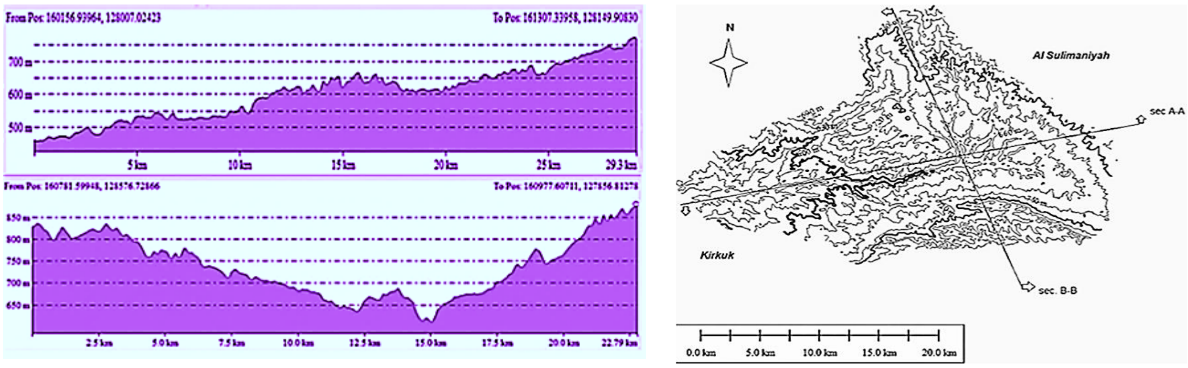

Fig. 2. Topographical arrangement of the upper basin of the Kirkuk watershed

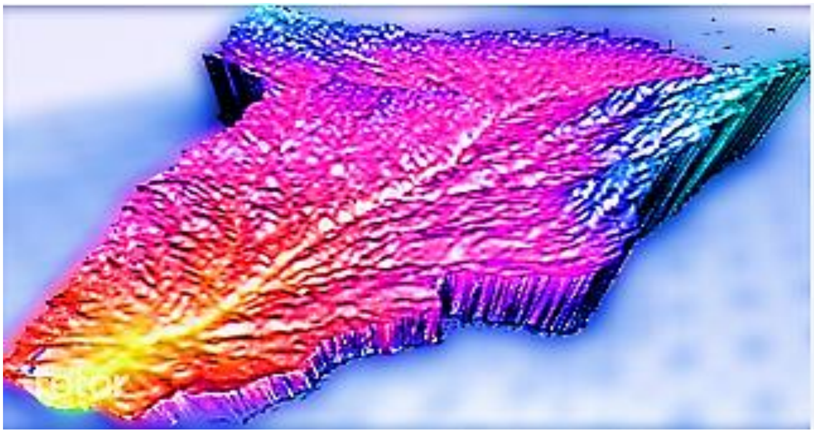

Fig. 3. The 3D Topographical analysis of the Upper basin of the Kirkuk watershed

Physiographical geography demonstrates that the region is a fragile barrier in Iraq that is categorized as a mountain zone. This region, which represents the compressional bending of lesser tertiary, is located in the centre of the problematic platform in Iraq. A site's contents include alluvial deposition; modern river raised beds, and Paleogene–Neogene massive Molas's sediments from the Bakhtiaria subgroup (Muqadaas and Bai-Hasan) and Farses group (Fatiha and Injiana). The region has a topography that slopes westward and is steep.

Weather information was gathered from Kirkuk Geophysical Observatory recordings from 1945-2023, published by the Iraqi Meteorologist Organization. Table 1 presents an overview of environmental variables [25].

Table 1
Lists of the Climatical parameter to the Kirkuk City Reservoir station [25]

Climatical parameter	Max. quantity	Min. quantity	Av. quantity
Rainfall (mm/month)	811.3	179.2	378.3
Evaporations' (mm)	405.2	39.6	---
humidity (%)	75	33	42
Speed of wind	35	-	2.3
Evaporation (free surface water/year) mm	---	---	1753.3
Temperatures 0C	47.86	-3.7	25.8

The research region is characterized by a range of soil forms determined by the underlying rock parents that have undergone decomposition through weather. The silty claystone rock outcrops, belonging to the Middle Bakhtiaria's inception, typically exhibit weathering formations of clay and silt soils. The area is primarily composed of conglomerates (higher Bakhtiaria Series). However, the top soils consist of weathered gravel and alluvium soils, which vary depending on the underlying rocks.

3.2 Sedimentation Yield's Model

The simulation was connected to a geographic information system (GIS). This database system enables the administration of multiple categories of geographically dispersed information by integrating layers to assist users in synthesizing and interpreting the data. Sediment modelling difficulties in reservoirs fall into four primary groups:

i. Water and sedimentation yield in the catchment (as in the current investigation).
ii. Transport of sediment, depositing, and the patterns of scouring in the region above the dam under various operating regulations.
iii. Customized deposition patterns and scouring around hydraulic infrastructure.
iv. deposition, transport, and scouring in the waterway beneath the dams.

Therefore, GIS does not generate additional information but enhances the clarity of linkages by modifying the existing information. GIS can incorporate eroding or sedimentary debris models using graphical user experiences or shells programmed in various languages computers. The interfacing provides the users with the ability to perform several tasks. These include defining a study area, selecting management practices, choosing conservation of water and soil practice like strip cropping, terraces, and contouring, accessing the database of GIS to assign attributes to modeling factors, executing the model to modify attribute table, and analysing and displaying the findings [26,27]. An instance of these models connected to Geographic Information Systems (GIS) is the SWAT model, utilised in the current research.

3.3 SWAT-Based Hydrological Modelling of The Kirkuk City Reservoir

The necessary information must be collected daily for the SWAT model, enabling the prediction of simulation findings on a daily, monthly, and yearly schedule.

In order to obtain more precise and authentic findings, it is essential to utilise a continuously updated meteorological database to reflect the gathered daily trends. In this study, the upper basin of Kirkuk station climate was chosen to gather the daily climatic information recording from 1981 to 2023. Daily precipitation data for the period were gathered from records of Kirkuk climatological station with an average annual rainfall equal to 395.2 mm. Figure 4 disaggregates maximum and minimum daily precipitation data.

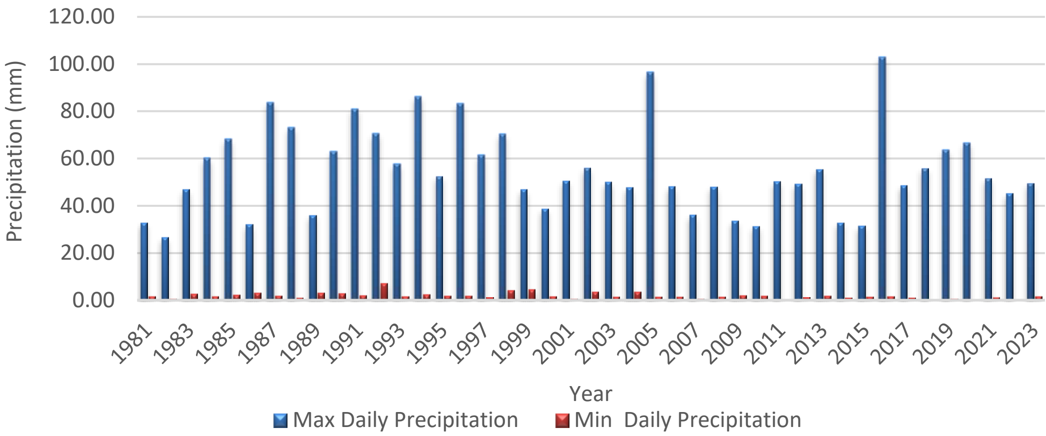

Fig. 4. Disaggregation of maximum and minimum daily precipitation data for (MSK)

The analysis of 42 years climatological data in this study reveals a distinct influence on the functioning of the model's everyday temperature. It computes a range of variables, including evaporated form, snow melting, and topsoil temperature at various depths. Particularly in sub-basins modelling, data from storm events are utilised to expand models for kinematic runoff and erosion (KINEROS2).

The satellite data contains information gathered from many sources, such as the Pleiades satellites for classified land cover and digital elevation models (DEM) for subdivision variable extraction.

In this work, an electronic representation of the upper basin of the watershed was successfully recovered at a depth of 25 metres, as depicted in Figure 5. The Digital Earth Model (DEM) is essential for executing the model using GIS technology. Panoramic photos satellites from 2023 verified site observations, as shown in Figure 6.

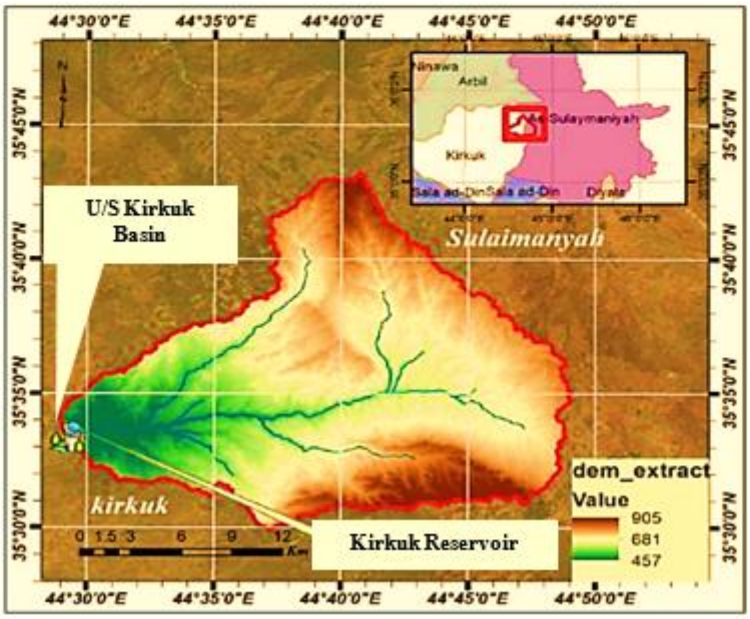

Fig. 5. Geospatial representation of the topography in the designated research region

Fig. 6. Satellite imagery of the designated region

The map of the soil developed by the Food and Agricultural Organization (FAO), which is among the world's largest international organizations', is the most recent system of classification and is comparable with GIS. It was issued in 2019 at a scale of 1/5,000,000. Figure 7 illustrates the two categories of soils recognized by the FAO's soil mapping layers for the studying region within the SWAT models: Gypsics Xerosol and Calcics Xerosol which exhibit distinct characteristics [28].

Fig. 7. FAO's harmonised world soil database's characterization of the studying region

3.4 SWAT Model (Soil and Water Assessment Tool)

The SWAT model is a widely used, process-based hydrological model designed to simulate the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds over long periods. It uses daily weather data, including precipitation, temperature, wind speed, humidity, and solar radiation, to predict water flow, sediment transport, and nutrient dynamics. The model operates at the sub-basin level and accounts for various land uses, soil types, and topographical features.

In this study, the SWAT model was employed to provide a comprehensive understanding of the long-term hydrological behavior of the Kirkuk City Watershed. By utilizing 42 years of daily climatic data, the model generates critical outputs related to water discharge, evapotranspiration, and sediment yield across the sub-basins, identifying key areas with high sediment transport potential. These outputs offer valuable insights into the watershed's overall hydrological performance, which supports the planning and management of water resources in the region.

3.5 KINEROS Model (KINematic Runoff and EROSion Model)

The KINEROS model is an event-based, physically based hydrological model designed to simulate the processes of surface runoff and erosion during single storm events. Unlike SWAT, which focuses on long-term hydrological trends, KINEROS is highly effective in analyzing the short-term impact of high-intensity rainfall events on sediment transport and runoff generation. It uses rainfall input data to simulate the movement of water and sediment within a watershed at a high temporal resolution.

In this study, the KINEROS model was applied to model a single storm event scenario in specific sub-basins identified by the SWAT model. By focusing on a high-intensity rainfall event, KINEROS provides a detailed understanding of the short-term sediment transport dynamics and the effects of extreme weather on the watershed. This detailed analysis complements the SWAT model’s long-term outputs, giving a more complete picture of sediment behavior under different temporal conditions.

3.6 Integration of SWAT and KINEROS Models

The integration of both models in this study allowed for a more comprehensive assessment of the sediment yield in the Kirkuk City Watershed. SWAT identified critical sub-basins with high sediment generation potential based on long-term data, while KINEROS was used to simulate the detailed impact of specific storm events on these sub-basins. This combined approach enhances the accuracy of sediment yield predictions and provides valuable information for water resource management and sediment control strategies in the region.

4. Results And Discussion

The SWAT modelling findings provide an assessment of how both land cover and land use impact the reactions of a watershed to hydrology and sedimentary rock, based on the relevant climatological data and the designated research region. The SWAT and KINEROS2 items frameworks have the capability to generate intricate watershed visualisations, taking into consideration the specific characteristics of soils, patterns of the vegetation, and distribution of rainfall.

As depicted in Figure 8 for parts of the watershed and Figure 9 for channels, sub-watershed No. 2 has a higher level of erosion and is particularly conducive to sediment accumulation than No.4 after that. Channels that are more attached to the reservoir in the main pathway have a greater capacity to carry material to the upper basin of the Kirkuk watershed. The yearly transported sediment volumes through these channels amount to 2.54×10^3 ton.

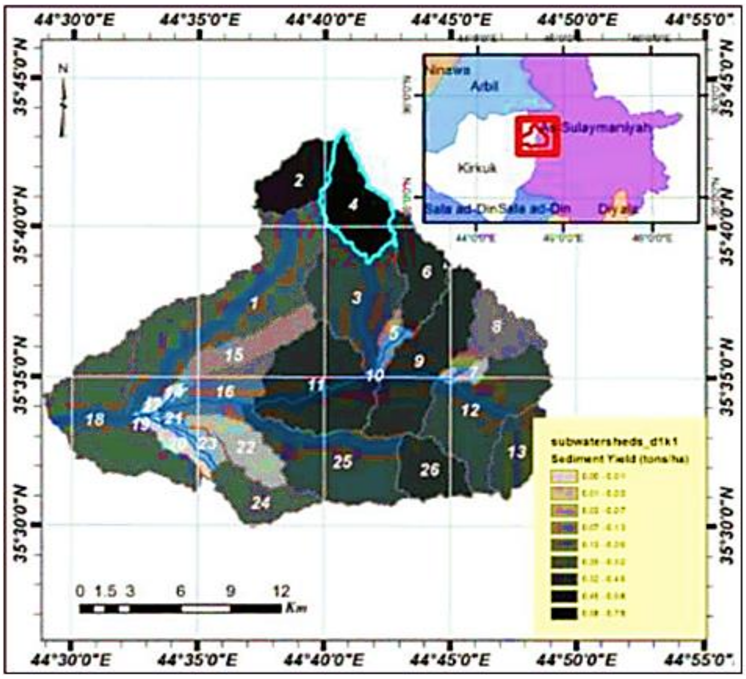

Fig. 8. Sedimentation yields' for Sub-Kirkuk Reservoir (year)

In accordance with the SWAT results, the watershed characteristics of the watershed region of Kirkuk City show that the subdivisions with the highest rate of erosion (No. 2, 3 and 4) are unable to transport the damaged rock or debris to the catchment area because of conveyance damages, infiltration, and other more minor challenges that they face.

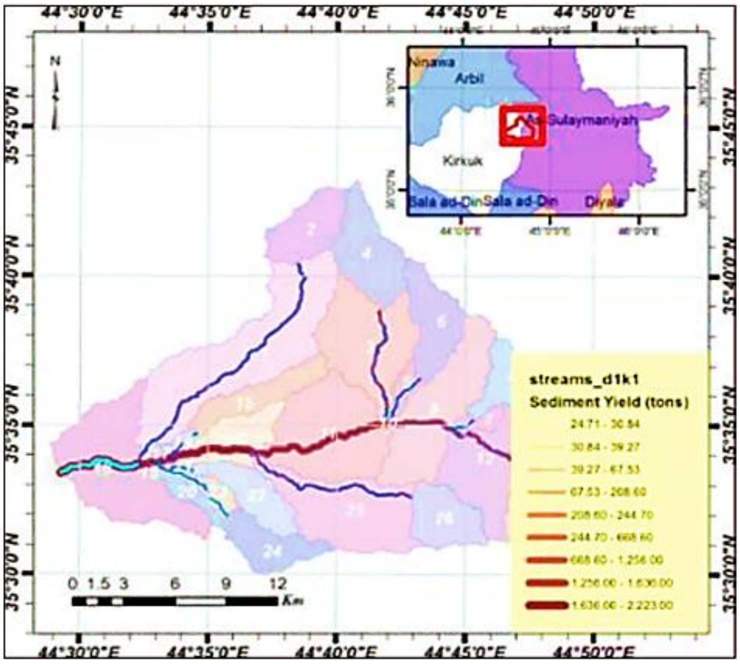

Fig. 9. Sedimentation yield in Rivers (year)

For the purpose of this investigation, Region 1 has been chosen to replicate the sediment yield in the major catchment of Kirkuk City. This decision was made based on the geographical position of the catchment and its capacity to transport materials to the catchment in a manner that is consistent with all of the necessary characteristics. As shown in Figure 10, Region 1 comprises subdivisions No. 1 and 2, which come together to cover a total area of 70 km^2 and are situated near to the watershed.

The KINEROS2 simulation simulates thunderstorm scenarios in the (Region 1) catchment. The rainfall has a depth of 70 mm and lasts for 10 hours (MOT-IMOS). This scenario mimics rainstorms that occur in the upstream Kirkuk city catchment, which can range from 52 mm to 85 mm in depth and last from 4 hours to 1 day. The magnitude of these rainstorm's can be recognized by the quantity of loaded runoff in the lower exit of the basin, as depicted in Figure 11.

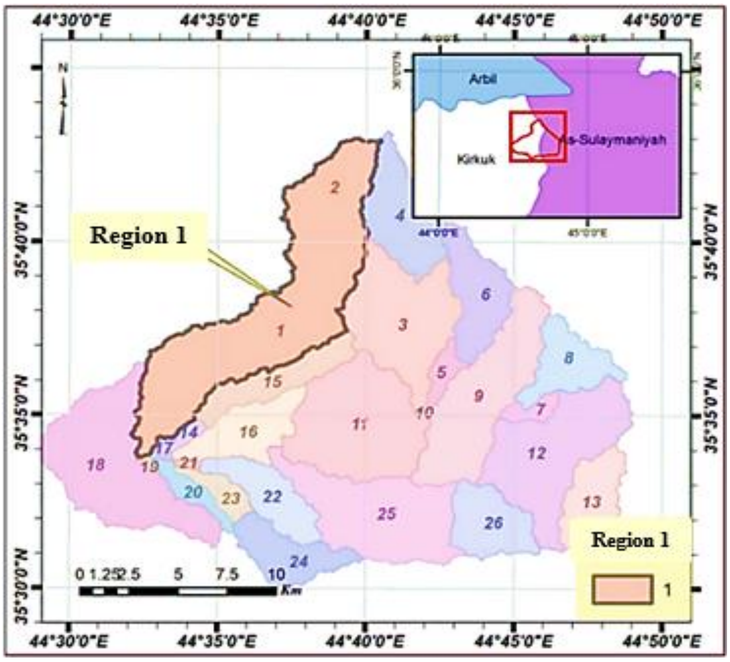

Fig. 10. The kinematics erosion and runoff influence the watershed boundary in Region 1

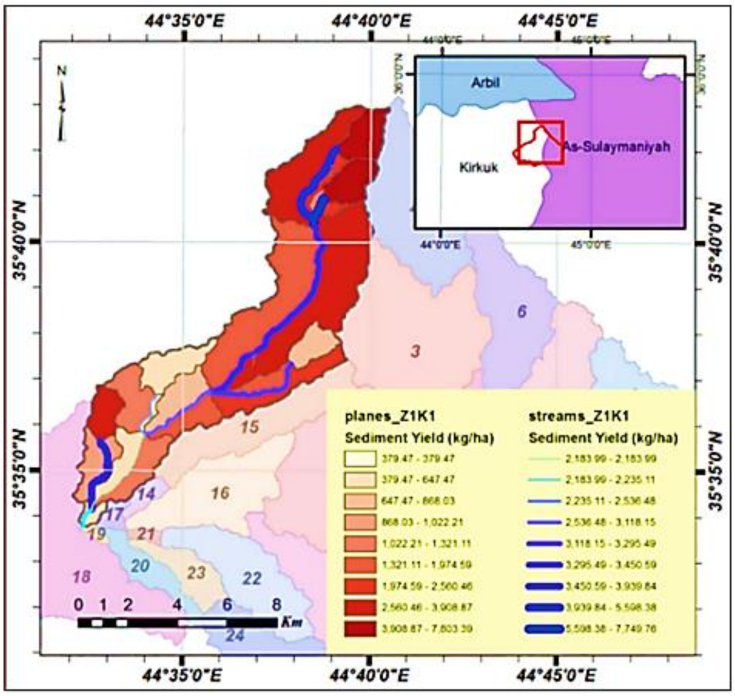

Fig. 11. Heavy discharge in the bottom released of the catchment

The KINEROS2 simulation provides outcomes for the yield of sediments in the sub-basin (Region 1), illustrating the processes of deposition, transportation, and erosion through electronic geographic information distribution. These results are visualized in Figure 12. Additionally, Figure 13 and Figure 14 display hydro graphs illustrating the overall sediment yield and maximum outflow hydrograph, further supporting the findings.

The sedimentation yield accumulating at the outlet of the watershed was estimated based on the hydrographs obtained for the totally sediments yield (Kg/sec) and full outflow (m3/sec) shown in Figure 6 to Figure 13. The total sediment yield is determined to be 27,273.65 tons, with a sediments concentrations of 70.89×103 parts per million (ppm), as stated in Table 2. The model provides soil erosion data for each subbasin of the watershed. This is done by calculating the average yearly sediment yield and dividing it by the average yearly soil erosion. The resulting average delivery ratio is presented in Table 3.

Fig. 12. Distribution of the sedimentation yields in the stream and catchment for the (Region 1)

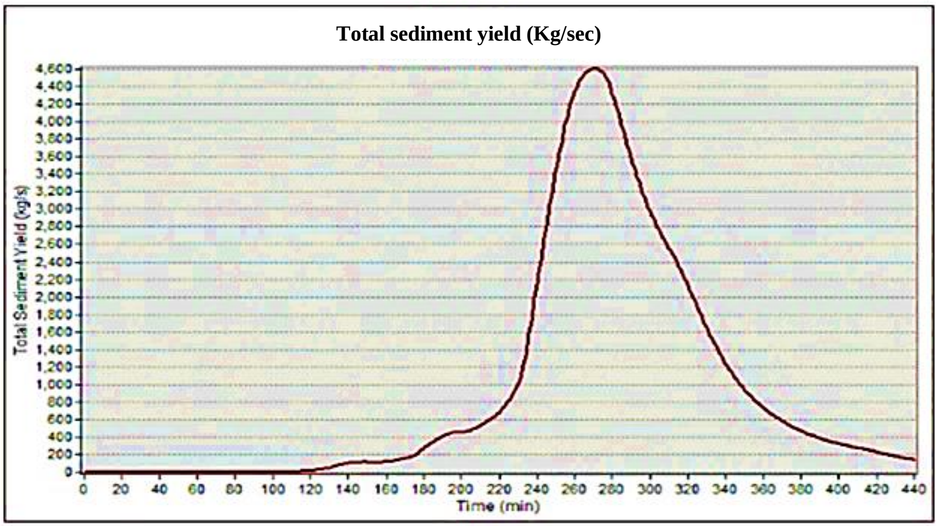

Fig. 13. Hydrograph for the sedimentation yields' (Region 1)

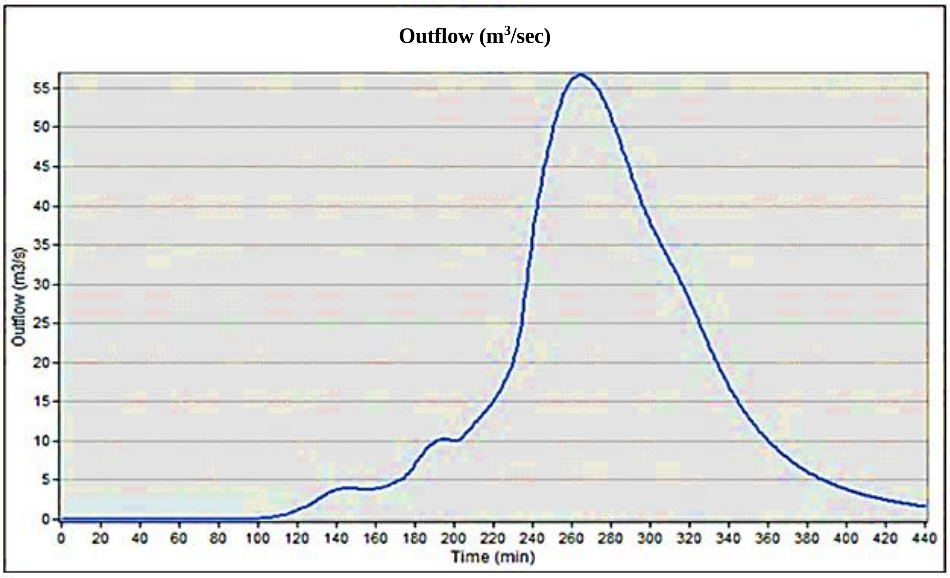

Fig. 14. Hydrograph for the peak outflow (Region 1)

Table 2
Dispersion of silt particles and concentrations of sediment for Region 1

Totally outflow (m^3)	Size of particle sediments (mm)	Sedimentation Yields' (tons)	Concentrations (ppm)
351,565.9	0.005	4563.67	13.32*103
	0.054	6889.21	22.45*103
	0.31	15,820.77	42.351*103
	Accumulated sediments	27,273.65	78.12*103

Table 3
Delivery ratio, Soil erosion, and Sediment yield for each subbasin

Sub-basin	SYLD (Ton/ha)	Soil erosion (Ton/ha)	Delivery Ratio	Sub-basin	SYLD (Ton/ha)	Soil erosion (Ton/ha)	Delivery Ratio
1	1.95	2.12	0.92	14	5.31	5.91	0.90
2	2.35	2.47	0.95	15	1.24	2.21	0.56
3	1.15	1.42	0.81	16	0.03	0.04	0.75
4	1.26	2.17	0.58	17	0.01	0.02	0.50
5	1.12	2.54	0.44	18	0.00	0.01	0.00
6	1.31	1.80	0.73	19	1.98	2.95	0.67
7	1.15	1.32	0.87	20	3.14	3.82	0.82
8	1.98	2.95	0.67	21	0.71	0.84	0.85
9	0.65	0.81	0.80	22	1.13	1.34	0.84
10	0.04	0.19	0.21	23	1.16	1.43	0.81
11	2.11	2.43	0.87	24	0.84	0.91	0.92
12	0.06	0.23	0.26	25	1.32	1.86	0.71
13	0.08	0.26	0.31	26	1.07	1.29	0.83

The results provide a clear understanding of the importance of sediment management to ensure the sustainable operation of hydraulic infrastructure such as dams and water catchment systems. These findings can be used to support future infrastructure planning, helping to implement effective strategies to reduce sedimentation and ensure the sustainability of water resources amid current environmental challenges.

These results represent an initial step towards more effective sediment management and highlight the need for further field studies to support future planning and improve water resource management practices.

Ethical Statement

i. The manuscript has not been submitted to another journal for simultaneous consideration.
ii. The submitted work is original and has not been published elsewhere.
iii. Results are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation (including image-based manipulation).
iv. A plagiarism test was made on the manuscript.
v. No permissions are required to secure copyrighted material.

Conflict of Interest

The authors have no conflict of interest.

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