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A Computer Program for Estimating the Sediment Load Entering the Right Side of Mosul Dam Reservoir

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ABSTRACT

Mosul Dam is one of the important dams in Iraq, it suffers like other dams from the problem of sediment accumulation in the reservoir. The daily surface runoff was estimated from three main valleys (Sweedy, Crnold, Alsalam) in the right bank of the reservoir during the period 1/1/1988 - 31/8/2016 by applying SWAT model. The model performance was assessed and the results were good. The daily sediment load was estimated by three methods, Bagnold method was adopted in SWAT, while Toffaletti and Einstein methods were programed by MATLAB. The averages annual sediment load from the main valleys to the reservoir were 1.08×10^3 - 27.32×10^3, 0.08×10^4 - 10.41×10^4 and 0.44×10^5 - 28.66×10^5 tons for Bagnold, Toffaletti and Einstein methods respectively. The valley Sweedy is the main supplier of sediments to the right side of the reservoir with 89%.

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برنامج حاسوبي لتخمين حمل الرسوبيات الواصلة الى الضفة اليمنى لبحيرة سد الموصل

الخلاصة

سد الموصل واحد من السدود المهمة في العراق ويعاني كغيره من السدود من مشكلة تراكم الرسوبيات في البحيرة. قدر حجم السيح السطحي اليومي لثلاثة وديان رئيسة (سويدي، كرنولد، السلام) تصب في الضفة اليمنى لبحيرة السد وللفترة 1988/1/1 – 2016/8/31 عن طريق تطبيق برنامج (SWAT). اجريت معايرة النموذج لتقدير الجريان السطحي وحمل الرسوبيات، وجرى تقييم لأداء النموذج وكانت النتائج جيدة. قدر حمل الرسوبيات اليومي باستخدام ثلاثة طرق، طريقة باكنولد في برنامج (SWAT)، بينما برمجت طريقتي توفاليتي واينستاين باستخدام برنامج (MATLAB). تراوح معدل حمل الرسوبيات السنوي المجهز من الوديان الى البحيرة 1.08×10^3 - 27.32×10^3 و0.08×10^4 - 10.41×10^4 و0.44×10^5 - ×*10^5 طن لطرق باكنولد وتوفاليتي واينستاين على التوالي على طول فترة الدراسة. يعتبر وادي سويدي المجهز الاساس للرسوبيات لبحيرة السد من ضفتها اليمنى بنسبة تبلغ حوالي 89%.

1. INTRODUCTION

Water is the life, and rivers are the means of transmitting life as they contain water. Rivers and various water courses are important natural resources that supply land and thus the entire human race with water. Notes the importance of watercourses in the fact that the first human civilizations arose on the banks of rivers, their prosperity and sustainability were derived from the continued flow of water in those streams.

Due to the lack of water in the water courses located on the surface of the earth and also due to the emergence and intensification of the phenomenon of drought in these watercourses and the increasing demand for water, it has called for the build of large-scale hydraulic constructions on these streams to control the water. Storage of water behind dams in rivers and open canals is used in human use, agriculture, industry and other wide uses [1].

The storage process in addition to its benefits, but accompanied by some of the problems and negatives, the most important of which is the deposition of sediments at the dam or lake of the structure, the most important disadvantages of this process is the decrease in the volume of reservoirs of the dam and thus reduce its efficiency, in addition to the impact of sediments on power plants. Furthermore, storage of sediments containing contaminants in the reservoir and subsequent chemical

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reactions to these sediments due to long-term storage can cause an actual problem over the quality of the stored water.

Mosul Dam is one of the most important dams in Iraq, it suffers from the problem of the deposition of sediments in the reservoir of dam. The dam is located on the Tigris river in northern Iraq about 50 km north of Mosul and 80 km from Turkey and Syria [2].

Several studies have been conducted to estimate surface runoff and sediments resulting from rain using hydrological models such as WEPP, SWAT and HEC-HMS. Rasheed et al. [3] studied the sediments production of Sweedy Valley in the right Bank of Mosul Dam Reservoir by linking the Geographic Information System (GIS) with a computer model built using Visual Basic 6 and Universal Soil Loss Equation (USLE). Ijam et al. [4] conducted a study on Mujib dam in Jordan for the purpose of estimating the surface runoff and sediment load using the Soil and Water Assessment Tool (SWAT). Mohammad et al. [5] used SWAT model, while Fadhel [6] used Water Erosion Prediction Project (WEPP) to estimate the surface runoff and sediments of three valleys (Sweedy, Crnold, Alsalam) located on the right bank of the Mosul Dam Reservoir. Bussi et al. 2013 [7] estimated soil erosion and sediment transport on Rambla del Poyo, Valencia, Spain using the conceptual model TETIS. A study was carried out by Sa'adallah [8] to estimate the sediment transported to Tigris river from Alkhooser river which located in Ninawa using SWAT model. Evans et al. [9] tested the abilities of Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) to estimate surface erosion and sediment routing on House Creek watershed in Fort Hood, Texas. USA. Zende et al. [10] estimated surface runoff and sediment load using SWAT for Yerala river basin located in Peninsular, India. Mustafa et al. [11] studied the amount of surface runoff and sediment load coming from six valleys (Al Akhdher, Al Fuhaimy, Al Qasir, Al Rihana, Al Skarh, Gedah) to the left bank of Haditha Dam reservoir in Anbar, Iraq by SWAT model. Further studies were conducted to find the Universal Soil Loss Equation factors to estimate soil erosion. Kiran et al. [12] estimated the amount and severity of the erosion in Bankura District, West Bengal, India, using the USLE model. Al-Saleh et al. [13] used GIS and Remote Sensing (RS) to study soil erosion in Dahr al-Jabal area, Al-Suwayda, Syria by applying a mathematical model within the GIS environment based on the USLE. Al-Abadi et al. [14] studied soil erosion in northern Kirkuk along the left side of Altin Kobry watershed using the Revised Universal Soil Loss Equation (RULSE) based on GIS.

The objectives of this study can be summarized by applying SWAT model after the calibration and validation prosses on the main valleys that pour into the right bank of the Mosul Dam Reservoir for the purpose of estimating the amount of surface runoff during the study period 1/1/1988-31/8/2016, and then estimating the amount of sediments using Bagnold method in SWAT model simulation, as well as using Einstein and Toffaletti methods using MATLAB codes, and determining which valleys are the main supplier of sediments.

2. STUDY AREA

The study area covered the right-side valleys of Mosul Dam Reservoir located in 50 km north of Mosul, Iraq, there are several main valleys pour directly into the reservoir, it also included Alkhooser seasonal river basin located in 45 km north-west of Mosul, for the purpose of calibration and validation SWAT model. The three main valleys Sweedy, Crnold and Alsalam pour directly in the right bank of Mosul Dam Reservoir. The elevations of valleys area are 330 to 780 m. The watershed of Sweedy valley is the largest, it is 390.7 km^2 and located in north of the pumping station for Northern Algazzera Irrigation project, the pump station suffers from the deposition of the sediments nearby, which affect work and efficiency of the pump station. The second valley is Crnold located in north of Einzalah mount, it's area 65.35 km^2. The third Valley is Alsalam located in south of Einzalah mount and north of Batma mount within the fold of Rafan and its area 43.28 km^2 [6]. These valleys were encoded by the symbols R1, R2 and R3, respectively, while the calibration and validation watersheds were encoded by the symbols (A) and (B) respectively, as shown in Fig. 1.

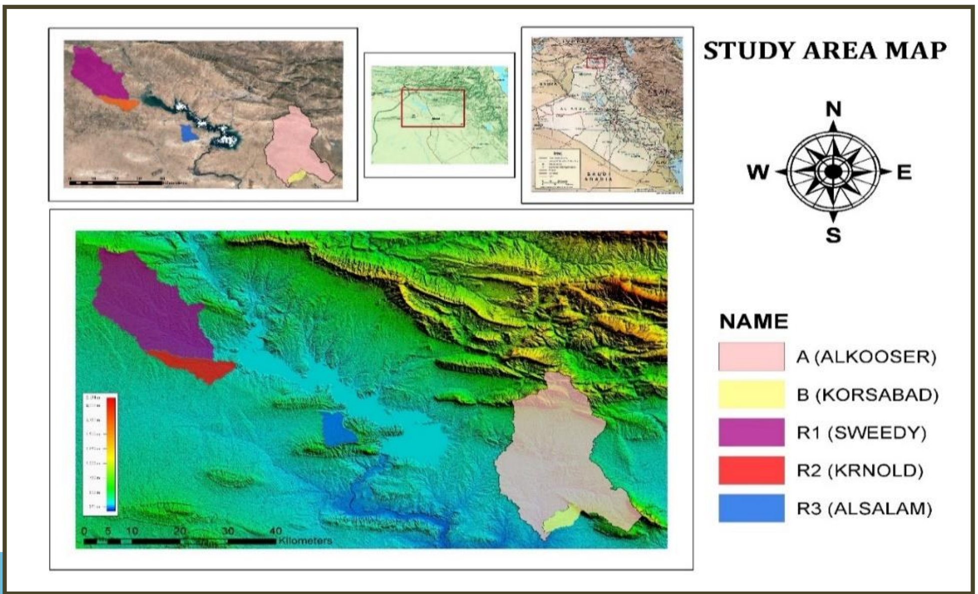

Fig. 1. Study area map.

The calibration and validation watersheds are part of Alkhooser seasonal river basin, located northwest of Mosul. The watershed (A) located at the top of the waterfalls site, it is area 696 km^2, was used to calibrate the model which has field measurements of the surface runoff and sediment load. The watershed (B) located northeast of the waterfalls, it is area 38.3 Km^2, which is part of watershed (A) was used to validate the model [8]. Table 1 shows the morphological characteristics of the main three valleys and the calibration and validation watersheds. The Digital Elevation Model (DEM) with resolution of 30*30 m produced by ASTER was adopted as an input in SWAT simulation to determine the study area terrain.

The Soil of Sweedy valley is silty loam and silty clay loam, it is clay, silty loam and loam for Crnold, and is clay, loam and silty clay loam for Alsalam [6]. The Harmonized World Soil Database (HWSD) was adopted to determine the types and data of the study area soils. This map contains a rich database of all necessary information that required in SWAT model simulation.

The three valleys are covered by winter crops (wheat and barley), grasslands and pastures, as well as some barren areas. The Sweedy Valley is covered by natural pasture and grass with 58.8%, while winter crops (wheat and barley) covers 38.5% of the valley, where the rest is Barren land, while most of Crnold and Alsalam are covered by natural pasture and grass by more than 90% and the remaining is winter crops in addition to barren land, these ratios were determined based on satellite images. The Global Land Use Map (Globcover2009_L4_V2.3) was adopted for the purpose of determining the land use for the study area.

The daily climate data for two weather stations near the study area (Mosul and Dohuk Stations) were adopted for the purpose of generating the SWAT weather database for the daily continuous. The daily database included rainfall, wind speed, relative humidity, maximum and minimum temperatures, and solar radiation. The average annual precipitation of the study area was 369 mm along the study period.

2.1. SWAT Calibration

The Watershed (A) was used for the purpose of calibrating the model which has field measurements of surface runoff and sediment load by [15]. Mohammad [15] set up a surface runoff and sediment load measurement station at the outlet of the watershed (A). The watershed was used to calibrate the model because located near the area around the reservoir [5,6]. SWAT calibration for the surface runoff estimation was carried out by changing curve number values (CN) within acceptable limits until the best results were obtained when comparing the observed and simulated surface runoff values, the best results were obtained by reducing the CN value 4%. The performance of the model was assessed using four statistical criteria, they were Regression coefficient (R^2), Nash and Sutcliffe Model Efficiency (NSE) and the Index of Agreement (IOA). The values of R^2, NSE and IOA were 0.99, 0.64 and 0.89 respectively, as shown in Table 2. The model was calibrated for sediment load estimation then was assessment with the same statistical criteria, where R^2, NSE and IOA were 0.99, 0.99 and 0.99 respectively, as shown in Table 3.

2.2. SWAT Validation

Field Measurements of watershed (B) which conducted by Mohammad [16] were used to validate the model for surface runoff estimation. The performance of the model was assessed using four statistical criteria. R^2, NSE and IOA were 0.98, 0.86, and 0.96 respectively, as shown in Table 4.

Table 2
The observed and simulated values of the surface runoff and the statistical criteria values for the calibration.

No.	Date of Storm	Rainfall (mm)	Observed Runoff (mm)	Simulated Runoff (mm)	R^2	NSE	IOA
I	19/02/2003	19	1.26	1.76			
II	21/02/2003	18	1.83	2.32	0.99	0.64	0.89
III	15/01/2004	9	0.18	0.07			

Table 3
The observed and simulated values of sediment load and the statistical criteria values for the calibration.

No.	Date of Storm	Rainfall (mm)	Observed sediment (kg/m^3)	Simulated sediment (kg/m^3)	R^2	NSE	IOA
I	19/02/2003	19	1.85	1.91			
II	21/02/2003	18	2.1	2.14	0.99	0.99	0.99
III	15/01/2004	9	0.6	0.54			

Table 4
The observed and simulated values of the surface runoff and the statistical criteria values for the validation.

No.	Date of Storm	Rainfall (mm)	Observed Runoff (mm)	Simulated Runoff (mm)	R^2	NSE	IOA
I	04/01/2003	14	0.312	0.12			
II	19/02/2003	19	3.75	2.85	0.98	0.86	0.96
III	17/01/2004	16	1.66	1.69			

3. SURFACE RUNOFF ESTIMATION

SWAT model estimate surface runoff by one of two methods, the first method is Green and Ampt method which requires a lot of information about the soil and measurements of rainfall depths with time in high resolution, for example every hour, these values are not available in the measurement stations of the study area. The second method is Curve Number Method, which is the most widely used in surface runoff estimation and has been adopted in this study for its compatibility with available rainfall and soil data. This method is based on soil characteristics, land use and hydrological conditions [17].

4. SEDIMENT LOAD ESTIMATION

Many studies and researches conducted to estimate the impact of rainfall and surface runoff on detach and transport the sediments. The importance of the subject and the extent of its negative effects and with the evolution in the computer sciences led to move clearly and largely to adopt the simulation models to represent many of natural phenomena in various fields, including hydrology, which is a complex science in various subjects, such as surface runoff and the amount of sediment transported which cause many problems in the areas where is transported or deposited [18].

4.1. Watershed Sediments Estimation

SWAT model estimates the process of soil erosion caused by rain using Modified Universal Soil Loss Equation (MUSLE). This method represents the use of MUSLE produced by [19] which is development of USLE which found by [20] as mentioned [21]. The USLE equation depends on the intensity of rainfall without taking into account the amount of infiltration if it is high or low. In the high infiltration, there is little runoff and therefore less erosion, while in the low infiltration there is a high runoff and therefore a larger erosion. The modification of the USLE equation convert the calculation of the erosion by the rain intensity to the surface runoff, while the other elements of the equation remained same. This development of the equation improved the sediment estimation process [22].

4.2. Channel Sediment Load Estimations

The sediment load delivered from the channels of the three valleys (Sweedy, Crnold, Alsalam) were estimated using three methods Bagnold, Einstein and Toffaletti.

4.2.1. Bagnold Method

The study done by Williams [23] have been used the formula presented by Bagnold [24] formula which adopts Stream Power theory to find the sediment load transferred in terms of slope and flow velocity of the channel, SWAT model uses this method for estimating the amount of sediments transferred in the channel from watershed. The sediment estimation equation is based on the maximum flow velocity [8].

4.2.2. Einstein Method

Einstein departed from the concepts of previous theories. His physical treatment of the problem considered at least two basic ideas which break with the past: 1. the critical criterion avoided, because the critical condition for initiation of sediment motion is difficult to define, and 2. the bed-load transport is related to the turbulent flow fluctuations rather than to the average values of forces of the flow exerts on the sediment particles. Consequently, the beginning and ceasing of sediment motion is expressed with the concept of probability, which relates instantaneous hydrodynamic lift forces to the particle's submerged weight.

Based upon experiments, Einstein found that there exists an relationship between the bed material and the bed load, where there is a steady and intensive exchange of particles exists between the bed materials and the bed load, and the particles are transported along the bed in a series of steps, the average step length is proportional to the particle size, and the rate of deposition per unit area depends upon the transport rate past a given section as well as the probability that the hydrodynamic forces are such that the particle may be deposited. The total sediment discharge is calculated by collecting the discharge values of the bed load sediments with the discharge of the suspended sediments as this is an indirect method in calculating the total sediment load. Einstein method assumes that flow resistance is due to the surface roughness of the particles and the roughness of the gathering form of these particles [25]. A code in MATLAB was built to include all the equations and steps of the solution of this method, in addition to encode all the Figures and curves of this method in the code.

4.2.3. Toffaletti Method

Toffaletti presented a procedure for the determination of sediment transport based on the concept of Einstein theory. In his method, he first replaced the actual channel for which the sediment discharge is to be calculated by an equivalent two-dimensional channel of width equal to that of real stream and depth equal to the hydraulic radius of the real stream. Then he divided the flow depth into four zones to calculate the sediment load in it.

The main differences between Toffaletti and Einstein methods are that utilized: 1. the velocity distribution in the vertical, 2. a combination of several of Einstein correction factors into one, and 3. a relation of stream parameters (Sediment Transport for an Individual Grain and Intensity of shear on Individual Grain Size) to sediment transport at other than the two grain diameters above the bed [25]. This method was also programmed using MATLAB.

4.3. SWAT and the Codes Simulation

The SWAT program was used in this study to estimate the surface runoff and also sediment loads resulting from the impact of rain storms on the three valleys that pour into the right bank of the reservoir after calibrating and validating the model using the watershed (A) and (B), respectively and obtaining the related results. Projects were created in SWAT model for each valley separately. The topographic map (DEM) with resolution 30×30 m, the soil type map (HWSD) and the land use map

(Globcover2009_L4_V2.3) insert in the model to determine the topography, soil type and land use of the valleys. A continuous daily simulation was conducted throughout the study period 1/1/1988 - 31/8/2016.
SWAT model divides each main basin into many subbasins and then calculates the surface runoff and the sediment load, as well as other data such as the discharge and sediments that flow in its channels until reaching the outlet of the basin. SWAT provides us with a data file generated from the daily simulation that includes many information as well as many other files that contain the data of the channels, including the slop, width and length of these channels.

A continuous daily simulation was carried out throughout the study period to estimate the sediment load using Toffaletti and Einstein methods using thcodes designed in MATLAB to simulate these methods. The resulting discharge from the simulation of SWAT model was used as an input in the codes because they were designed to estimate the sediment load only, as well as data for the dimensions of the channel and its other characteristics and other required data for each method.

Table 5
The annual values of the maximum, minimum, average and total surface runoff for the study period of the three valleys.

Valley Code	Max Runoff (mcm)	Years of Max Runoff	Min Runoff (mcm)	Years of Min Runoff	Avg. Runoff (mcm)	Total Runoff (mcm)
R1	53.8, 54.4	1993, 2016	0.02 - 0.94	1999, 2000, 2007 - 2009, 2012	13.6	392.95
R2	6.8, 6.66	1993, 2016	0.003 - 0.13	1999, 2000, 2007 - 2010, 2012	1.37	39.76
R3	4, 4.25, 4.3	1988, 1993, 2016	0.004 - 0.025	1999, 2000, 2008, 2009	1.08	31.22

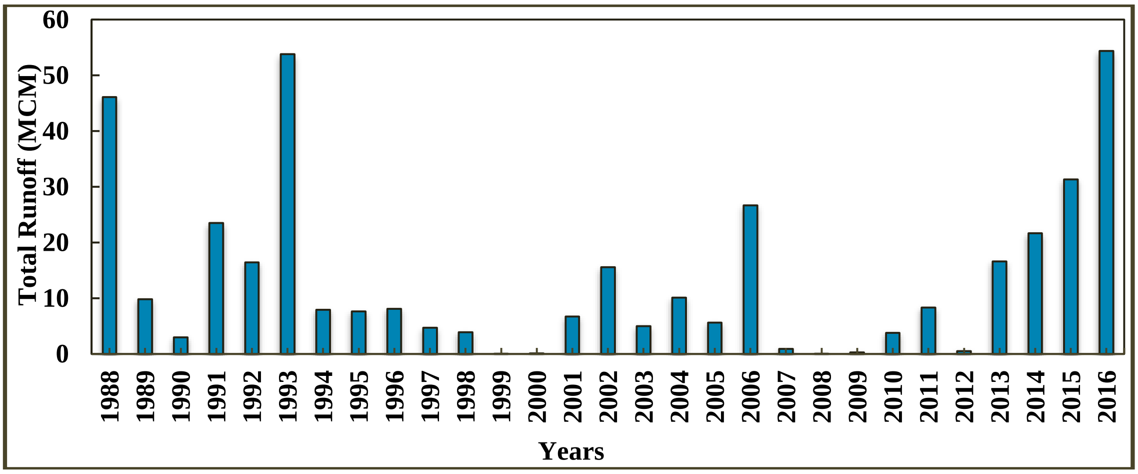

Fig. 2. Annual surface runoff of Sweedy valley.

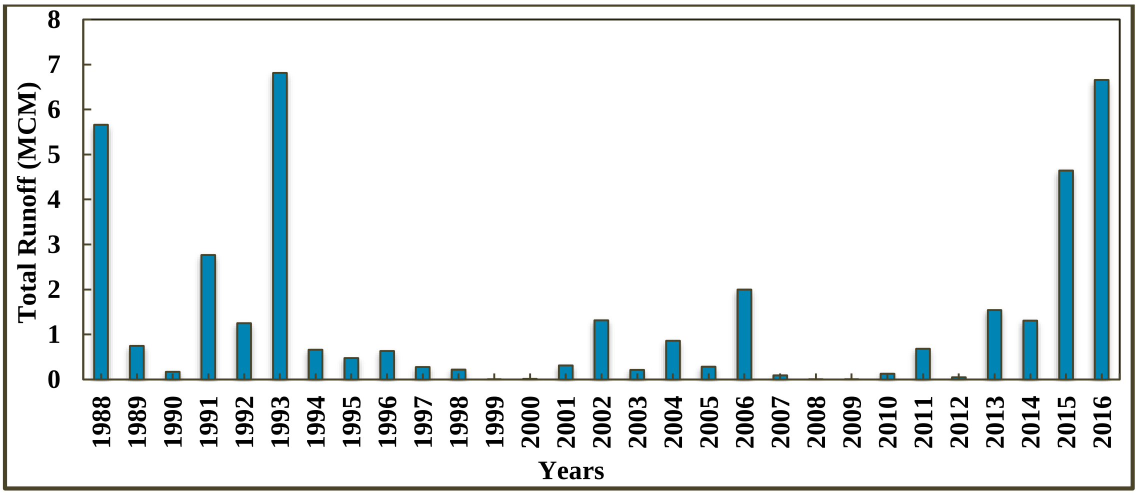

Fig. 3. Annual surface runoff of Crnold valley.

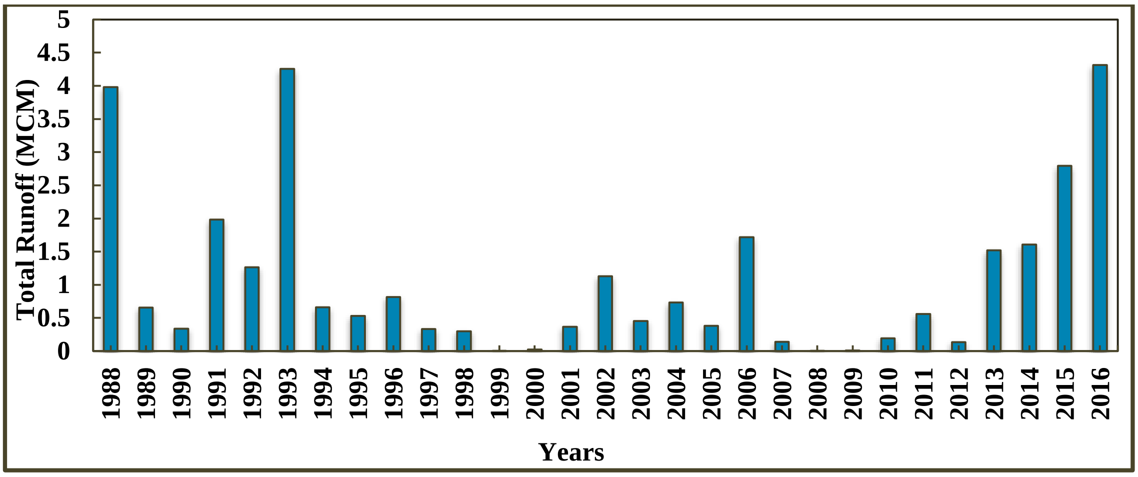

Fig. 4. Annual surface runoff of Alsalam valley.

Table 6
The values of the averages annual sediment load and totals sediment load over the study period of the three methods and the three valleys.

Valley Code	Bagnolds × 10^3 (ton)		Toffaletti × 10^4 (ton)		Einstien × 10^5 (ton)	
	Avg. Sed. Load	Total Sed. Load	Avg. Sed. Load	Total Sed. Load	Avg. Sed. Load	Total Sed. Load
R1	27.32	792.21	10.41	301.75	28.66	831.12
R2	1.08	31.45	0.08	2.26	0.44	12.81
R3	1.17	34	3.96	114.94	2.97	86.01

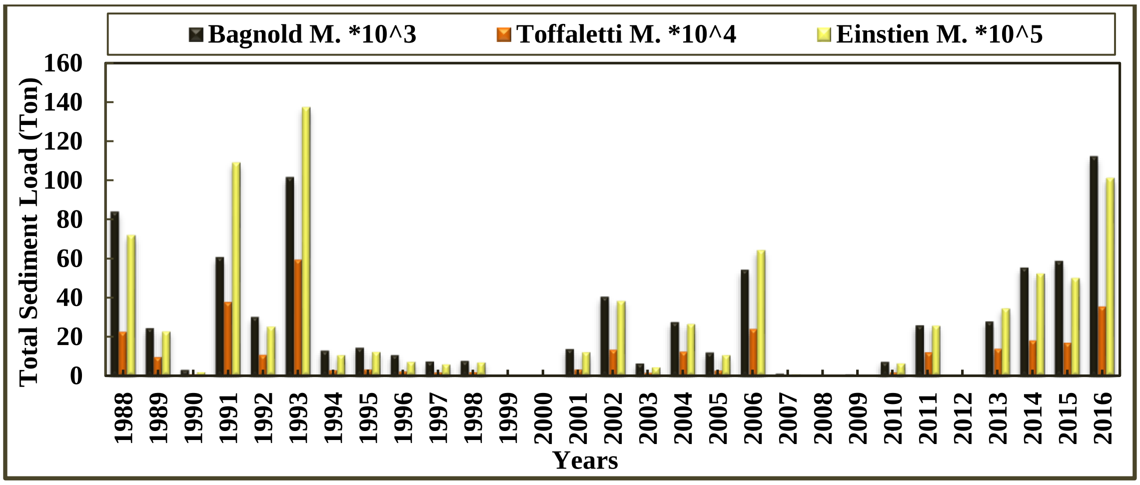

Fig. 5. Annual sediment load of Sweedy valley.

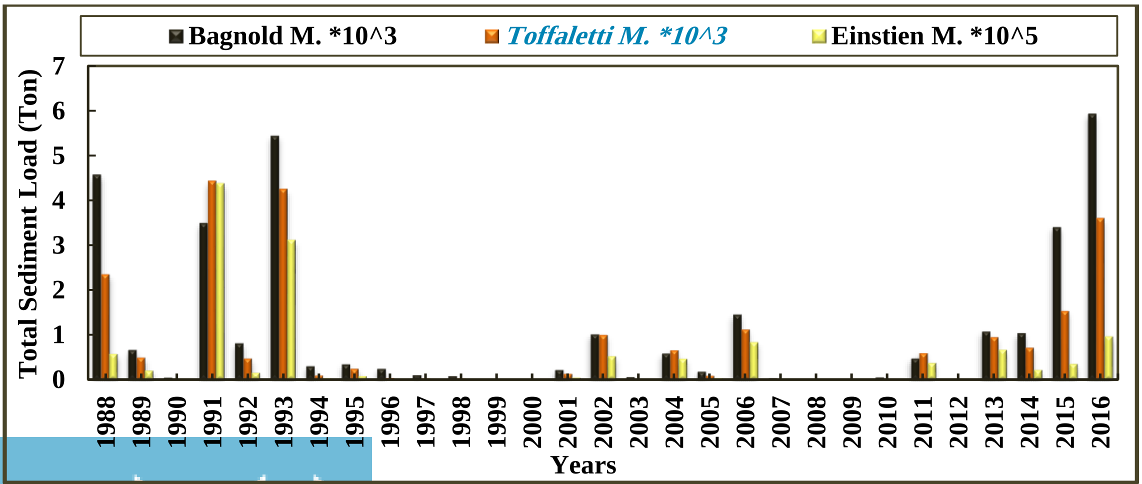

Fig. 6. Annual sediment load of Crnold valley.

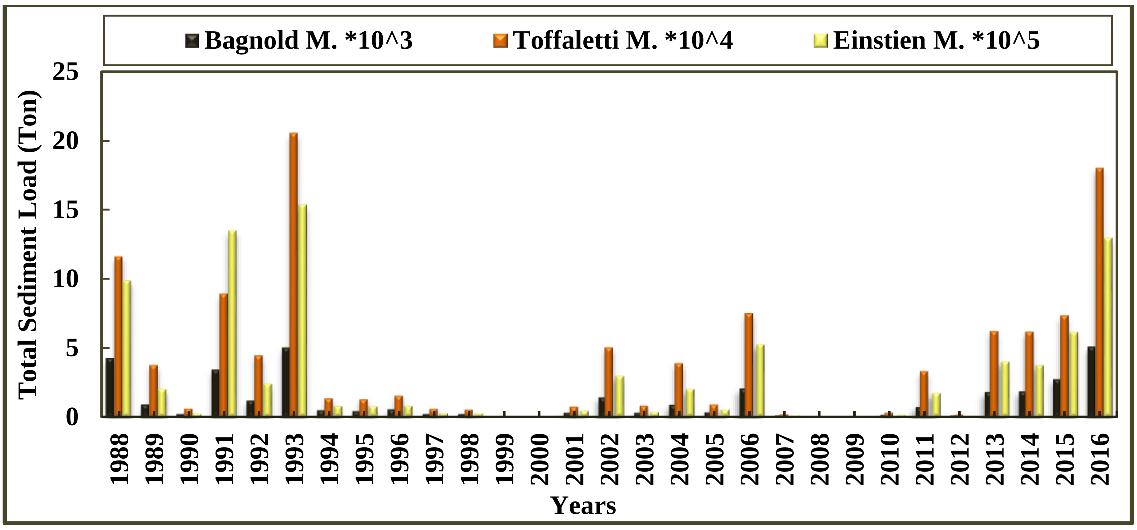

Fig. 7. Annual sediment load of Alsalam valley.

5. RESULTS AND DISCUSSION

The maximum surface runoff of Sweedy valley were 53.8×10^6 m^3 and 54.4×10^6 m^3 for the years 1993 and 2016, while the minimum amounts ranged between 0.02×10^6 m^3 and 0.94×10^6 m^3 for the years 1999, 2000, 2007, 2008, 2009 and 2012. Table 5 shows the annual values of the maximum, minimum, average and total surface runoff for the study period of the three valleys. Figs. 2- 4 shows the annual surface runoff of Sweedy, Crnold and Alsalam respectively.

The average sediment load along the study period for Sweedy valley was 27.32×10^3, 10.41×10^4 and 28.66×10^5 tons for Bagnold, Toffaletti and Einstein methods, respectively. The total sediment load during the study period was 792.21×10^3, 301.75×10^4 and 831.12×10^5 tons, respectively. Table 6 shows the values of the averages annual sediment load and total sediment load over the study period of the three methods and the three valleys. Figs. 5-7 shows the annual sediment load along the study period for the Sweedy, Crnold and Alsalm Valleys, respectively.

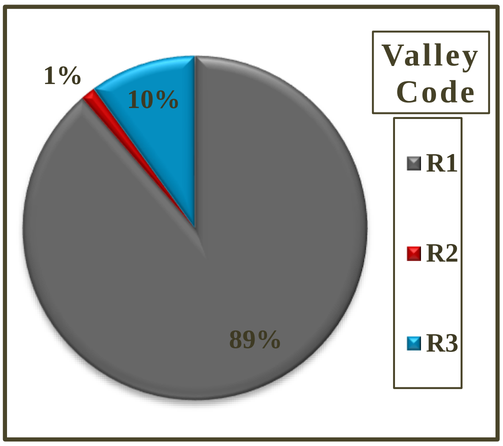

Fig. 8. The percentage of sediment load delivered to the right side of the lake using the average of the three methods used in this study.

The results of this study indicate that Sweedy valley is the main supplier of sediments to the Mosul Dam reservoir from its right side with 89%. Its large area 390.7 km^2 plays a large role in increasing the amount of surface runoff and sediment load. Fig. 8 shows the percentage of sediment load delivered to the right side of the reservoir using the average of the three methods used in this study, Figs. 9-11 show the percentages of sediment load delivered from the three valleys using Bagnold, Toffaletti and Einstein method, respectively.

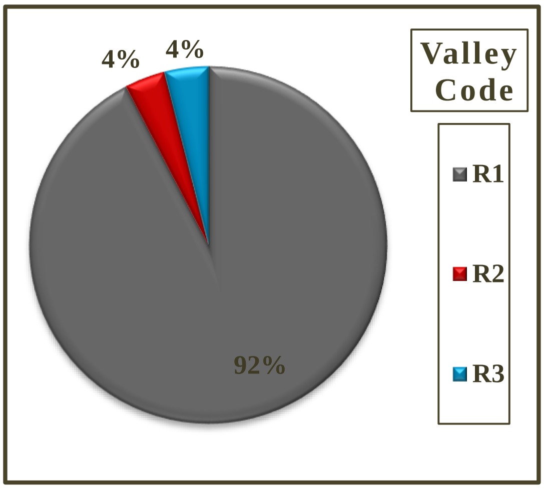

Fig. 9. The percentages of sediment load delivered from the three valleys using Bagnold method.

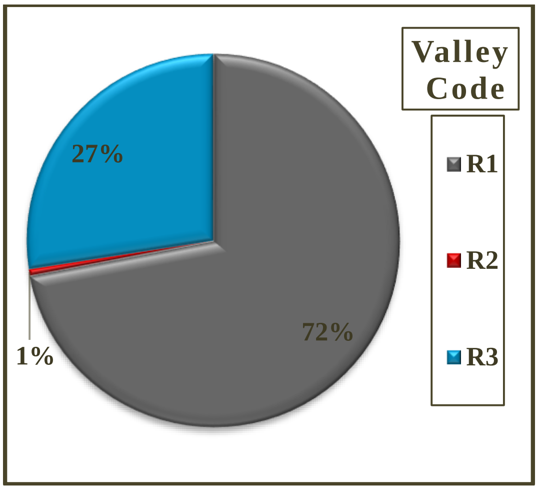

Fig. 10. The percentages of sediment load delivered from the three valleys using Toffaletti method.

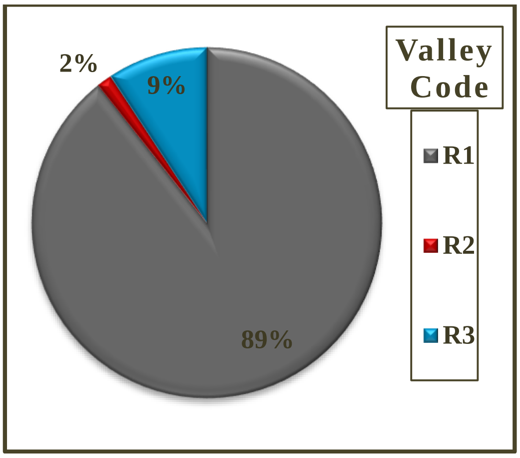

Fig. 11. The percentages of sediment load delivered from the three valleys using Einstein method.

Table 7 shows the annual sediment load for the years 1994 to 2012 estimated by Ref. [6] also Bagnold, Toffalletti and Einstein methods used in this study for the three valleys Sweedy et al. [6] used WEPP model to estimate the surface runoff and sediment load. The annualsediment load was estimated using the three methods in this study for the years 1988 to 2008 to comparing them with the results of the study presented by [5], they used SWAT model for purpose of sediment load estimation for the three valleys, as shown in Table 8. We notice that there is a difference in the values of the annual sediment load when compared with the results of the studies presented by [5,6]. In general, we note that Einstein method gives a higher estimate of the sediment load while Bagnold method gives a lower estimate of sediment load, according to the characteristics of the results of this study indicate that Sweedy valley is the main supplier of sediments to the Mosul Dam reservoir from its right side with 89%. Its large area 390.7 km^2 plays a large role in increasing the amount of surface runoff and sediment load. Fig. 8 shows the percentage of sediment load delivered to the right side of the reservoir using the average of the three methods used in this study, Figs. 9-11 show the percentages of sediment load delivered from the three valleys using Bagnold, Toffaletti and Einstein method, respectively. Valley, while Bagnold method gives the closest results.

Table 7
Averages annual Sediment Load for Sweedy, Crnold and Alsalam Valleys for the period 1994 to 2012.

Valley Code	(Fadhil, 2013) × 10^3 (ton)	Bagnolds × 10^3 (ton)	Toffaletti × 10^4 (ton)	Einstien × 10^5 (ton)
R1	17.4	12.47	4.179	11.95
R2	1.6	0.26	0.021	0.121
R3	1.3	0.41	1.46	0.84

Table 8
Averages annual Sediment Load for Sweedy, Crnold and Alsalam Valleys for the period 1988 to 2008.

Valley Code	Mohammad et al. × 10^3 (ton)	Bagnolds × 10^3 (ton)	Toffaletti × 10^4 (ton)	Einstien ×10^5 (ton)
R1	35.6	24.12	9.78	26.79
R2	4.9	0.93	0.073	0.49
R3	2.2	1.04	3.51	2.73

6. RECOMMENDATIONS

1. It is recommended to use SWAT model to estimate surface runoff and sediment load after calibrating and validating the model using field measurements and inserting the necessary data in the model. The model provides us with tables of many results related to water flow and sediments as well as water quality.
2. Sweedy valley is the main supplier of sediments to Mosul Dam Reservoir from the right side with about 89%. Therefore, the reduction of sediment load coming from this valley will largely reduce the sediment coming to the right side of the reservoir. So, it is recommended to use all methods to reduce the soil erosion and sediment transport process in this valley.

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