

## Erosion Estimation in Ungauged Basins by Using the Integrating Model Technique

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### □ ABSTRACT □

The aim of this research is to estimate the sediment yield of ungauged basins by using the integrating model technique. A Geographical Information System (GIS), coupled with the Universal Soil Loss Equation (USLE) model by applying spatial program with advanced language programming (Visual Basic 6), is used to facilitate database development, manipulation, and output display. The 403 km<sup>2</sup> watershed is divided into 200 x 200 m grid cells, and gross soil erosion for each cell is first predicted by the USLE model. The Arc/Info GIS utilities are used to calculate the total mass of sediment moving from each cell to the nearest stream network. In addition, a watershed of (36) effective rainstorms is simulated; the sediment yield ranges between (16 and 1908 tons) for rainfall ranging between (15.5 and 79.9) mm; the results have demonstrated that the eroded sediment yield is closely related to rainfall

**Keywords:** GIS, USLE, Sediment yield modeling, SCS, Runoff, Simulation, DEM.

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## تقدير الإنتاج الرسوبي للأحواض المائية غير المرصودة باستخدام تقنية النماذج التكاملية

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### □ الملخص □

يتناول البحث الحالي تقدير الإنتاج الرسوبي للواديان غير المرصودة وذلك باستخدام تقنيات النماذج الرقمية الحاسوبية المتكاملة، حيث تم في البحث الحالي الربط بين نظام المعلومات الجغرافية (GIS) مع نموذج حاسوبي تم بناؤه لتقدير الإنتاج الرسوبي من خلال برنامج أُعد لهذا الغرض وباستخدام لغة برمجة (Visual Basic 6) وباستخدام معادلة فقدان التربة (USLE). تم استخدام حوض مائي غير مرصود كنموذج للدراسة بمساحة (403 km<sup>2</sup>) حيث تم تقسيمه إلى شبكة من الخلايا بأبعاد (200 x 200 m) تعتمد في حساب الإنتاج الرسوبي لها وباستخدام معادلة فقدان التربة (USLE) ثم يتم حساب صافي الرسوبات المنقول من خلال شبكة البزل في حوض الدراسة مع كمية الإنتاج الرسوبي عند منفذ الحوض باستخدام نظام (Arc/Info GIS). وقد تم في البحث الحالي محاكاة الإنتاج الرسوبي لـ (36) عاصفة مطرية مؤثرة وتراوحت كمية الإنتاج الرسوبي بين (16-1908) tons لهطول مطري يتراوح بين (15.5 – 79.9 mm)، وبينت النتائج بشكل واضح بان الإنتاج الرسوبي مرتبط مع الهطول المطري بعلاقة تم استنتاجها للحوض المدروس.

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## Introduction:

Sediment yield estimation in the watershed areas of rivers and water surface bodies is considered an important issue in the hydraulic and sediment model design of control canals against floods, sediment estimation in reservoirs, and navigation canals. It is an important parameter in the evaluation of the sediment effects on the projects and activities occurring in land use. Estimation of annual sediment yield produced from single rainfall event requires application many approaches in this subjects to get an acceptable and logical results. These approaches were classified especially into two classes : single event approach and the average annual approach knowing that the most project designs requires quantitative estimation of the transported sediment volumes resulted from single rainfall event.

One of the common methods is the modified universal soil loss equation (MUSLE) suggested by (William and Berndt) [1]. This equation was developed to estimate the sediment yield produced from single rainfall event and represent an alternative to the previous equation (USLE) suggested by (Wischmeir and Smith) [2]. The USLE does not defined the hydrological processes like rainfall, infiltration, runoff and the main erosion processes like detachment of soil particles as a result of rainfall drop power and sediment transport. It also cancels the gully and bank erosion.

Main consideration of hydrology is the rainfall-runoff relationship of a watershed. The response of a watershed to rainfall is observed as the runoff at the basin outlet. For the gauged basins, this is recorded as hydrograph (discharge vs. time graph). The unit hydrograph of the basin is the surface runoff hydrograph caused by a unit excess rainfall distributed uniformly over the area, and its determination in hydrology. For gauged basins unit hydrographs are determined from observed storm data; hyetographs and corresponding hydrographs. For the ungauged basins there are several techniques for derivation of unit hydrographs synthetically. SCS unit hydrograph method [3] is one of these techniques, different than the other techniques, flexibility of SCS methodology enables it to be adapted to new technologies such as digital elevation modeling (DEM) in Geographic Information Systems (GIS) [4, 5] which have been widely used in water resources field. The hydrograph and drainage information derived from DEMs, surface drainage, channel network, drainage divides, and other hydrographic data from DEMs has established itself as a result of increasing availability of square-grid DEMs and GIS software products that derive this data from (DEM) The automated techniques are faster and provide more precise and reproducible measurements than traditional manual techniques applied to topographic maps.

## Location of Study:

Study area is the Sweedi Valley, one of the important valleys in the west bank of Mosul Dam Lake north of Iraq. The morphological characteristics of the Sweedi basin are that it has an area of (403 km<sup>2</sup>), main basin slope (0.0103 m/m), basin parameter (85.15 km), shape factor (2.7), sinuosity factor (1.05), main basin elevation (435.4 m), main stream length (34.54 km), average overland flow (0.95 km). and drainage density (1.136 km<sup>-1</sup>). Figure (1) shows Iraq map, and satellite image explains the location of study area.



Figure (1): Location map of study area.

## Methodology:

The predicting model for watershed area in a certain site is considered an important tool to study area in detail. Such a model is defined as a simple compound system in which the behavior of this system is represented by a number of equations contributing to the logical aspects and relations between the variables to predict the required results, [6]. The aim of such a model is to have the best understanding of the watershed performance in addition to presenting a suitable tool to get the specific data concerning the flow. The Simulation process in the model is considered an alternative tool rather than carrying out comprehensive continuous case studies and experiments which are often so costly and difficult to verify. In this research, a computer model is used to predict a conceptual model for the study site. This process is one of the essential steps in the modeling procedure. The conceptual model is a simple representation for the study site through predicting the watershed border and the surface runoff movement over the basin of the main stream in the valley as well as the topography of the basin and soil type in the study site. Numbers of assumption and simplification are adopted to get the conceptual model. The study of watershed area is divided into many parts in case of non homogeneity in the physical characteristics of the area. These characteristics can be represented using some specified symbols such as points, curves, and polygons to illustrate all the information which defines the conceptual model, including boundary conditions. These characteristics can be converted into digital maps by using (GIS) system and feeding of the watershed modeling program work on the principle of finite difference method aimed at studying the watershed area to complete the second part of conceptual model in order to simulate the morphological characteristics of the study of the watershed area, surface runoff over basin and produce the surface runoff hydrograph at watershed outlet.

Sediment yield modeling is more complicated than other types of hydrologic modeling due to the required detailed information concerning the amount and type of precipitation, runoff, and the movement of water before the sediment movement can be modeled. The objective of this research is to develop a conceptual model which could mathematically simulate overland flow, erosion-sediment routing and estimate the sediment yield of the outlet of watershed. Figure (2) explains the Flow chart of the research methodology.

### 1. Obtaining a Digital Elevation Model (DEM)

The digital contour data with a scale of 1:50000 are used to obtain a digital elevation model of the Sweedi Valley basin area by using Geographic Information Systems (GIS). The river network and the boundary of the basin are obtained from the 1:50000 scaled hardcopy map sheets by onscreen digitizing as described in Figure (3), and the (Dem) of Sweedi Basin is given in figure (4) below.

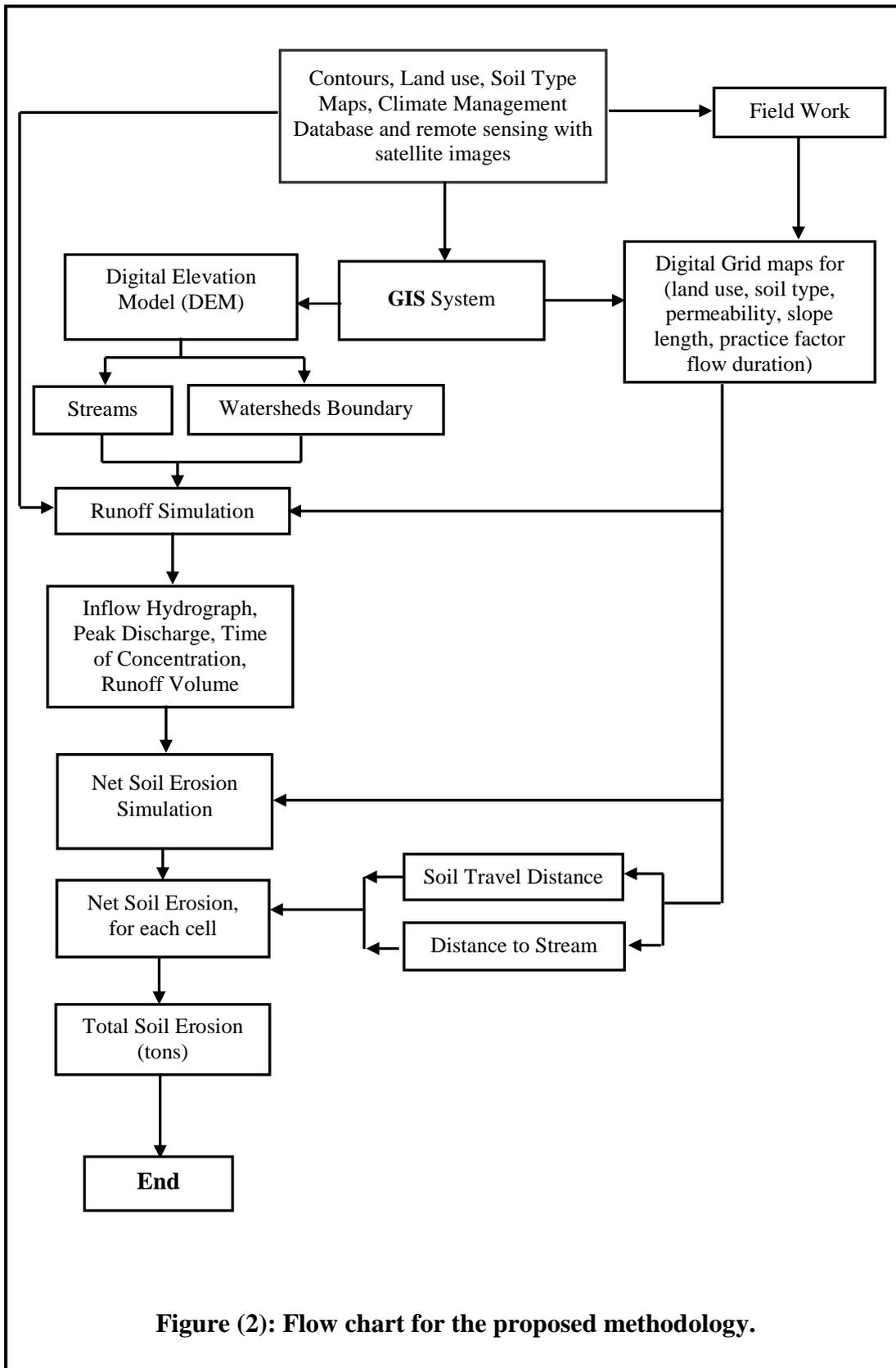
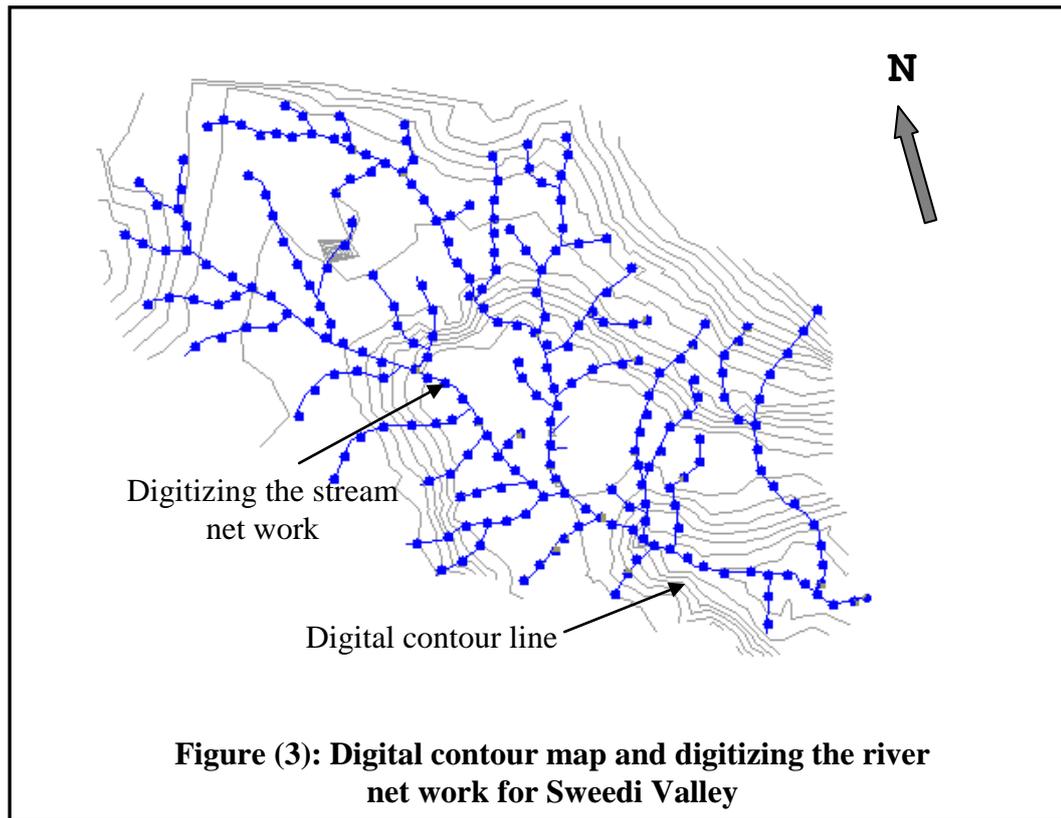
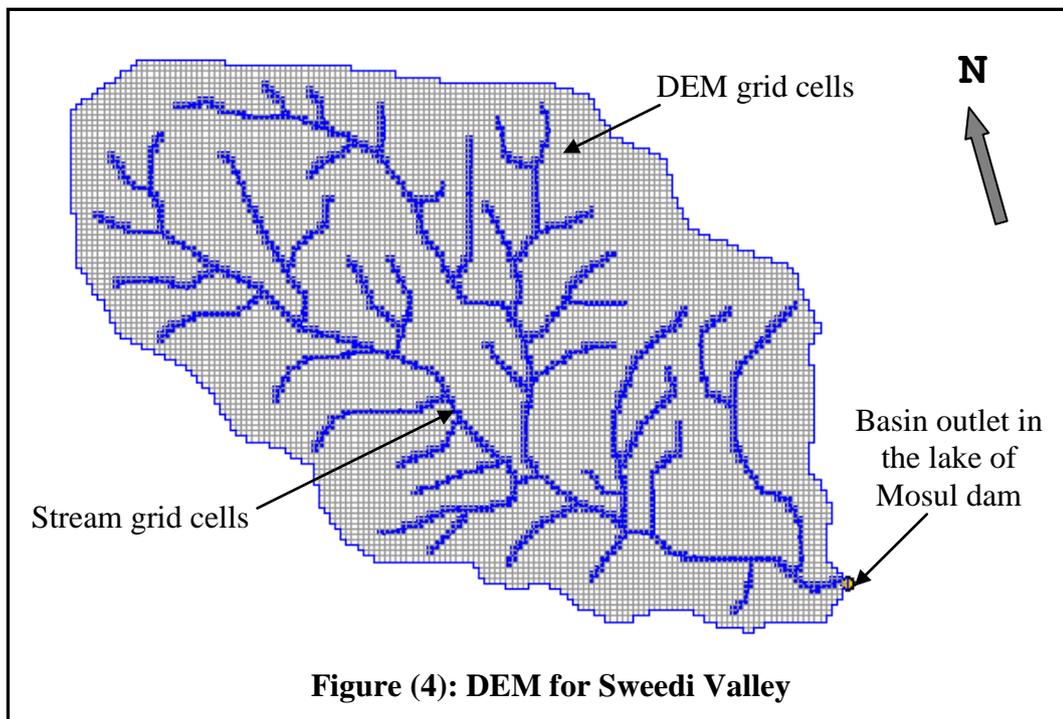


Figure (2): Flow chart for the proposed methodology.



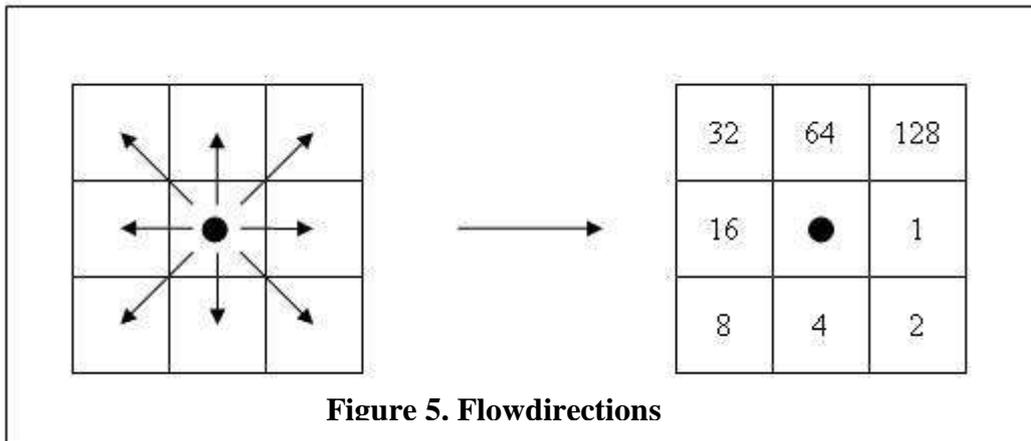
**Figure (3): Digital contour map and digitizing the river net work for Sweedi Valley**



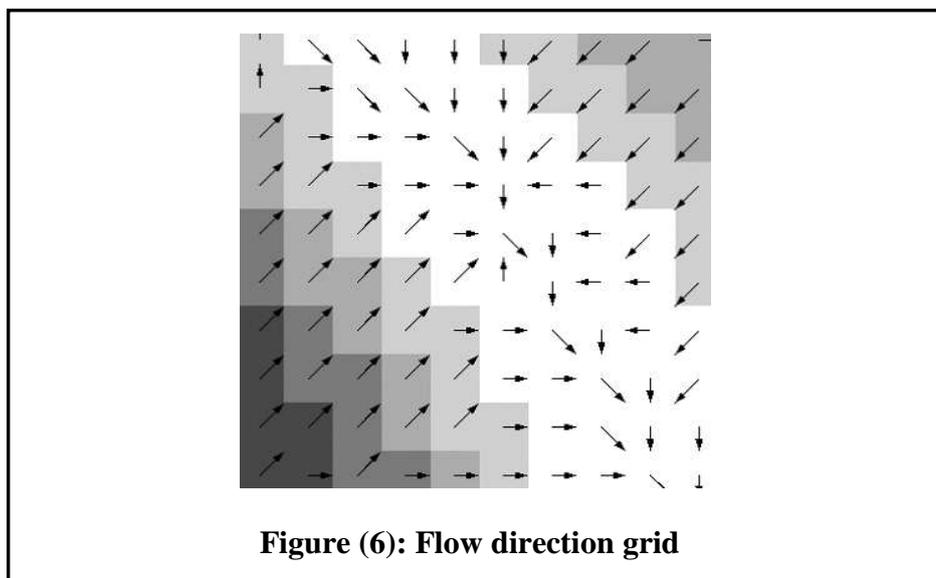
**Figure (4): DEM for Sweedi Valley**

## 2-Flowlength Grid

The flow length grid (FlGrid) represents each cell, the total travel length of the water droplet from that cell to the basin outlet along the direction of flow. Inputs are required for calculating flowdirection grid (FdGrid). In a square grid environment, each grid cell is surrounded by eight cells as described in Figure (5), and direction of flow of each cell can be represented by assigning a number representing one of the eight directions. Using GIS tools flow direction value of each cell in the basin is calculated by the DEM of the basin then a grid containing these values is obtained and named as flowdirection grid, FdGrid.



The flow direction grid can be computed by the active DEM region using a custom version of the TOPAZ model distributed with Geographic Information System [7]. The flow direction grid is then imported as a DEM point attribute, and is used to define the flow regime of the entire domain as illustrated in Figure (6) below.



## Integrating Models Computations

### Runoff

Owing to simplicity and compatibility with remote sensing and GIS, the runoff component is estimated using SCS curve number method [3] as follows:

$$R = \frac{(P - 0.2S)^2}{(P + 0.8S)} \dots\dots\dots 1$$

$$R = 0 \text{ if } P < (0.2 * S)$$

Where,

R = Runoff (mm)

P = Precipitation (mm)

$$S = (25400 / CN) - 254 \dots\dots\dots 2$$

Where,

CN = Curve number

The curve numbers could be derived from the information on land use / land cover and hydrological soil groups. The curve numbers are provided for moderate antecedent soil moisture conditions (ASM-II), to convert into ASM-I and ASM-III conditions, regression equations are developed from the data available in the Hand book of Hydrology using Curve fit software.

$$CN-I = 0.3358 * 1.009^{CN-II} * CN-II^{1.038} \dots\dots\dots 3$$

$$CN-III = 3.5610 * 0.9961^{CN-II} * CN-II^{0.8101} \dots\dots\dots 4$$

Where, CN-I, -II, -III represents curve numbers for antecedent moisture condition I, II and III respectively. ASM = Antecedent Soil Moisture.

To compute the total runoff over the grid cell in cubic meters,

$$V = (R / 1000) * \text{grid cell area (in m}^2) \dots\dots\dots 5$$

### Peak runoff rate

The peak runoff rate (Qp) can be computed as suggested in EPIC (Erosion Productivity Impact Calculator) model:

$$Q_p = 3.97 * A^{0.7} * S^{0.16} * \left( \frac{R}{25.4} \right)^{0.903 * A^{0.017}} * LW^{-0.19} \dots\dots\dots 6$$

Where,

A = Area of the cell (km<sup>2</sup>)

S = Length of the cell along slope (m/km)

R = Runoff depth (mm)

LW = Length to width ratio of the cell

All the grid cells in the present study are square cells having length to width ratio of 1.0.

## Erosion

The erosion component is divided into detachment, transport capacity and net detachment. Details are given below:

### Detachment (D)

To compute detachment of soil particles, Universal Soil Loss Equation (USLE) or its variants are often used with a modification in energy component. We have assumed that the surface runoff is the major component that governs the soil detachment and its transport. Hence we have retained the basic structure of Revised Universal Soil Loss Equation (RUSLE) as follows:

$$D = \lambda * K * LS * C * PP \dots\dots\dots 7$$

Where,

D = Soil loss

$\lambda$  = Erosive energy component

K = Soil erodibility factor

LS = Slope length factor

C = Cover factor

PP = Erosion control practice factor

The  $\lambda$  component could be explained by modifications as suggested by various authors as (from Erosion Productivity Impact Calculator (EPIC) model documentation):

$$\lambda = 0.79 * (V * Qp)^{0.65} * A^{0.009} \quad \text{For MUSS (Small watershed version of MUSLE)} \dots\dots\dots 8$$

Where,

V = Storm runoff volume (m<sup>3</sup>)

Qp = Peak runoff rate (m<sup>3</sup>/sec)

A = Area of the grid cell (ha)

The other parameters like K, C, LS, P factors are computed as defined in the RUSLE manual, and convert these factors into a digital map (DEM grid file) representing the distribution of these characteristics in the study area by using Geographic Information System (GIS).

### The K factor

Soil Erodibility is the function of physical characteristics of soil and its management, including both land and crop management. The erodibility index (K) can be obtained from an already developed nomograph\*. The erodibility index is calculated for each soil series in this study, using the following equation:

$$K = (2.1 M^{1.4}) 10^{-4} (12-a) + 3.25 (b-2) + 2.5 (c-3) \dots\dots\dots 9$$

• where M = particle size parameter (% silt + % very fine sand) or (100 - % clay)

• a = % organic matter

• b = soil structure class (1 for very fine granular; 2 for fine granular; 3 for medium to coarse granular; and 4 for blocky, platy or massive);

• c = soil permeability class (1 for rapid; 2 for moderate to rapid; 3 for moderate; 4 for slow to moderate; 5 for slow; and 6 for very slow)

All M, a, b and c values were extracted from soil reports of individual soil series.

According to this equation, the K value is calculated on the basis of the organic matter content, the type of soil structure, the soil permeability and the soil texture.

**The LS factor**

In this study, the slope length for different types of land use is determined, using information from the field survey. Data on aspect, land use and slope maps are overlaid to map the slope length. L and S were treated as a combined factor to find the LS index. The LS factor is computed for slope gradients of less than 8%, using the following equation.

•  $LS = (1/22.13)^n (0.0065 + 0.045 s + 0.0065 s^2)$  ..... 10

• where, LS = slope length in meters

• s = slope gradient in %

• n is slope length exponent and table (1) content values of n.

**Table (1) Values of n**

<i>slope</i>	1%	1-3 %	3-5 %	5 %
<i>n</i>	.2	.3	.4	.5

• When the slope had a gradient of more than 8%, the following equation is used.

•  $LS = \{ (1/22.13)^{0.5} \} \{ (0.17 s) - 0.55 \}$  ..... 11

**The C factor**

The cover factor (C) is defined as the eroded soil percent of the land having a special vegetation cover to the eroded soil of bare soil. This value ranges between 0.15 and 0.25 for the present study area.

**The PP factor**

Erosion control factor (PP) is considered as function of land use and is often used in agricultural lands, [8]. The pp value depends on the gradation of the surface topography, slope, cultivation method, and roughness of land. Its value usually is taken as (1) in the case of the unavailability of data on the lands. Use of comprehensive activities in the basin is nonexistent. No agricultural activates are spotted in the present study of the watershed area of Sweedi valley; therefore, pp value is taken to be (1).

**Slope of Land Element**

A slope map can be produced using the slope operation in geographic information system (GIS). According to (GIS) user manual, slope of cell at location X, Y is calculated as an average as follows. This method is developed by Zevenbergen and Dunn [9] who classify this method as a quadratic surface method. Equation (12) and (13) are used to calculates the average change in elevation for each unit distance in X and Y direction. For example, Figure (7) below shows the simple grid file, and the procedure below explains it, using equation (12 and 13) to calculate the slope of grid (Z5) in Figure (7).

$$S_x = \frac{(Z3 + Z6 + Z9) - (Z1 + Z4 + Z7)}{3} * C_x \dots\dots\dots 12$$

$$S_y = \frac{(Z1 + Z2 + Z3) - (Z7 + Z8 + Z9)}{3} * C_y \dots\dots\dots 13$$

Where,  
 Z1..Z9 = Elevation in 3\*3 window in Figure (7),  
 Cx = Pixel size in x direction,  
 Cy = Pixel size in y direction.

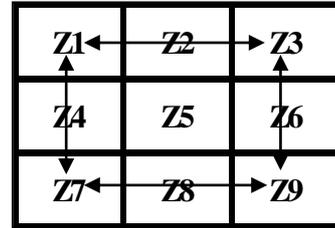


Figure (7): Basic approach to calculating slope.

Calculate the slope for x , y as follow,

$$S = \frac{\sqrt{(S_x)^2 + (S_y)^2}}{2} \dots\dots\dots 14$$

If  $S < 1$  slope percent =  $100 * S$   
 Otherwise slope percent =  $200 - 100/S$

Slope degree is calculate as in equation (15) below.

$$Slope\_degree = \tan^{-1}(S) * \frac{180}{\pi} \dots\dots\dots 15$$

**Transport Capacity (T)**

It is a well known phenomenon that all detached sediments will not be transported till the end of watershed. It depends on the transport capacity of the flow. The transport capacity equation given in [10] is used to account for surface cover variations.

$$T = Q^D * C * \sin(S) * 10^{-6} * A \dots\dots\dots 16$$

Where,  
 T = Transport capacity of the flow (tons)  
 Q = Runoff (mm)  
 C = Cover factor (dimensionless)  
 S = Slope of the land element (%)  
 A = Area of the cell (m<sup>2</sup>)

**Net Detachment (N)**

It is true that all detached sediments will not be transported down the stream. The transport capacity of the cell limits the net detachment, and the detachment excess of transport capacity will be deposited in the cell under consideration. As the transportation of sediments detached (D) is limited to transporting capacity, the net detachment (N) from the cell will be:

$$N = D \text{ if } (D < T)$$

$$N = T \text{ if } (D > T)$$

### Sediment Transport from Grids to Streams

As illustrated in Figure 2, two steps (variables, D and L) are required to route the gross eroded sediment in each cell to the closet adjacent stream. A soil transport model is derived from field measurements [11].

$$N_d = N * (1 - 0.97^{L_e/L}) \dots\dots\dots 17$$

Where:

$N_d$  = mass moved from each cell to the closest stream network .

$L_e$  = the least-cost distance from a cell to the nearest stream network.

$L$  = the maximum distance that sediment with mass  $M$  may travel (meters). This variable was calculated by the equation detailed in [11].

$$L = 5.1 + 1.79 * M \dots\dots\dots 18$$

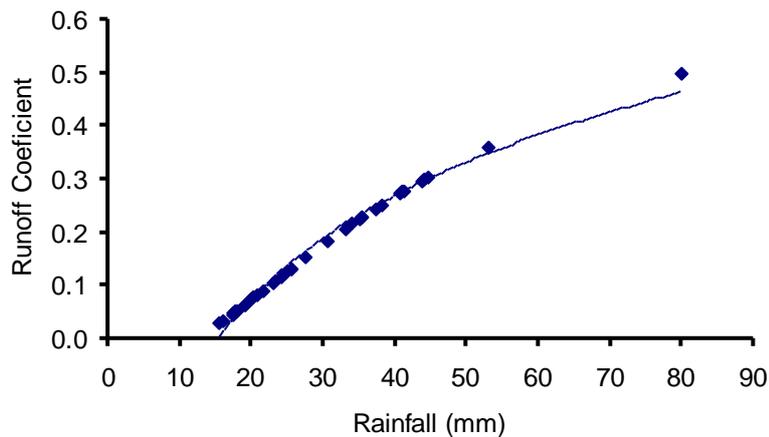
### Results Analysis and Discussion:

The runoff process is considered one of the important modern tools in runoff simulation, especially in the ungauged basins to predict flood peaks and runoff volume used for hydraulic structure design. A relation between rainfall depth and runoff coefficient for all the adopted recorded rainfall storms in the present research work shown in table (2) is drawn in Figure (8) in which the rainfall depth is less than (14 mm) and does not produce any runoff due to the infiltration process

**Table (2): Simulation of runoff and sediment yield result for (36) effected storms**

Storm No.	Rainfall Duration (min)	Rainfall (mm)	Runoff Coefficient	Peak Flow (m3/s)	Sediment Yield (Tons)
1	30	15.5	0.029	13	16
2	100	16	0.034	13	19
3	60	17.3	0.046	25	28
4	130	17.4	0.048	25	29
5	30	17.8	0.052	25	32
6	120	18	0.054	25	33
7	180	19.1	0.065	30	43
8	240	19.1	0.065	39	43
9	150	20	0.075	41	52
10	140	20	0.075	41	52
11	30	20.3	0.078	42	55
12	310	20.7	0.082	38	59

13	360	21.6	0.092	45	69
14	300	22.9	0.105	57	85
15	135	24	0.117	61	100
16	60	24.6	0.124	85	110
17	180	25.4	0.132	62	121
18	240	25.4	0.132	80	121
19	150	27.5	0.154	107	155
20	300	30.5	0.183	123	210
21	600	33	0.207	112	263
22	270	34	0.217	152	285
23	180	35	0.226	145	308
24	360	35.3	0.228	147	315
25	120	35.3	0.228	190	315
26	60	35.3	0.228	196	315
27	350	37.2	0.245	196	361
28	420	38.1	0.253	184	383
29	120	40.6	0.273	254	450
30	300	41	0.276	234	460
31	447	41.1	0.277	205	463
32	600	43.7	0.297	201	536
33	360	44	0.300	225	545
34	180	44.5	0.303	325	558
35	720	53	0.362	280	831
36	530	79.9	0.497	637	1908



**Figure (8): Rainfall depth and Runoff Coefficient relationship.**

Using a statistical program, an empirical relation to estimate runoff coefficient depends on the rainfall depth predicted as follows:

$$C = 0.28 \ln(P) - 0.762 \dots\dots\dots 19$$

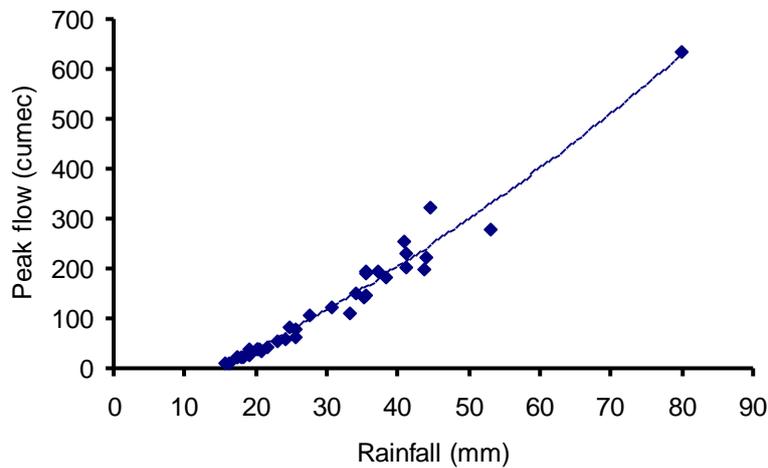
Where:

C= runoff coefficient

P= rainfall depth in (mm)

Runoff coefficient for the present study watershed area is calculated and ranges between 0.029 for rainfall depth 15.5 mm and 0.497 for a depth 79.9 mm. Figure (9) shows a relationship between peak discharge and rainfall depth for Sweedi valley, and a statistical relation to predict flood discharge in the flowing hydrograph at the exit of the basin is calculated as follows:

$$Q_p = 0.039P^2 + 6P - 95 \dots\dots\dots 20$$



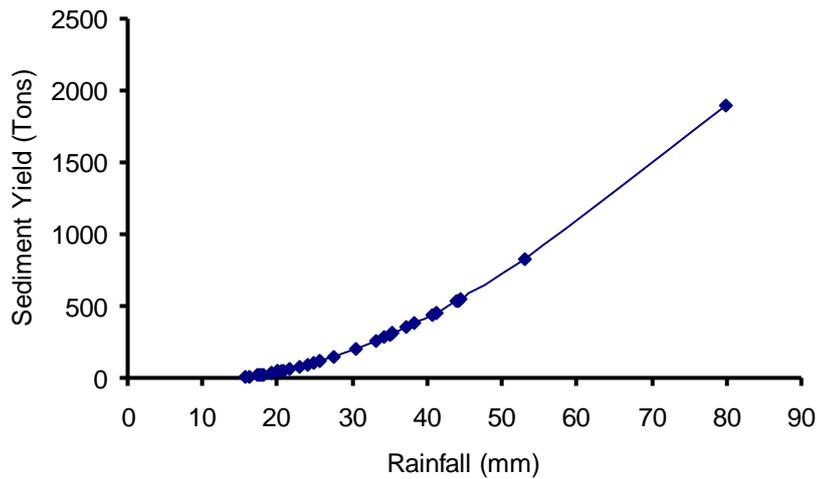
**Figure (9): Rainfall depth and peak discharge relationship.**

Where,  $Q_p$  = Peak flow ( $m^3/s$ )

The sediment yield of Sweedi valley is simulated and have been a function of rainfall depth. The sediment yield value for Sweedi valley has been (16-1908) tons for rainfall depth rate (15.5-79.9) mm. In table (2), it is clear that the eroded sediment yield and transported from the watershed is closely related to rainfall depth. Using a statistical program, a relationship to estimate sediment yield from Sweedi valley is predicted as follows:

$$\text{Sediment yield (tons)} = 0.0058 P^{3.0311} \dots\dots\dots 21$$

Where P = rainfall (mm)



**Figure (10): Rainfall depth and sediment yield relationship.**

### Conclusions:

Runoff and sediment yield is defined as the response of catchment's area to rainfall, and it is the result of many effects of the rainfall storm and the characteristics of watershed area. For this reason, the mathematical relation describes the correlation between different values of the system and can be defined as a model. The model is becoming one of the important tools used in hydrology, especially in ungauged basins such as the model prediction in the present research aimed at simulating surface runoff and sediment yield for the Sweedi valley. The field measurements take time, require field work, professional field work staff members, and field work equipment. This may increase the time interval needed to obtain the required results and then increase costs in comparison with the computer model which reduces time and cost by obtaining precise results. Integrating a GIS into a sediment production and transport model is a logical and effective way for predicting soil erosion and overland sediment transport across a watershed. This approach allows land managers to identify problem areas and conduct risk assessment before making management decisions.

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