water

MDPI

Article

Watershed Sediment and Its Effect on Storage Capacity: Case Study of Dokan Dam Reservoir

Mohammad Ezz-Aldeen [1], Rebwar Hassan [1], Ammar Ali [2], Nadhir Al-Ansari [1,*] and Sven Knutsson [1]

[1] Department of Civil, Environmental and Natural Resources Engineering, Lulea University of Technology, 971 87 Lulea, Sweden; mohezz@ltu.se (M.E.-A.); rebwar.hassan@ltu.se (R.H.); Sven.Knutsson@ltu.se (S.K.)
[2] Department of Water Resources Engineering, Baghdad University, Baghdad 10071, Iraq; ammali_75@yahoo.com
* Correspondence: nadhir.alansari@ltu.se; Tel.: +46-920-491-858

Received: 28 May 2018; Accepted: 26 June 2018; Published: 28 June 2018

check for updates

Abstract: Dokan is a multipurpose dam located on the Lesser Zab River in the Iraq/Kurdistan region. The dam has operated since 1959, and it drains an area of 11,690 km^2. All reservoirs in the world suffer from sediment deposition. It is one of the main problems for reservoir life sustainability. Sustainable reservoir sediment-management practices enable the reservoir to function for a longer period of time by reducing reservoir sedimentation. This study aims to assess the annual runoff and sediment loads of the Dokan Dam watershed using the soil and water assessment tool (SWAT) model to evaluate the relative contributions in comparison with the total values delivered from both watershed and Lesser Zab River and to identify the basins with a high sediment load per unit area. These help in the process of developing a plan and strategy to manage sediment inflow and deposition. The SUFI-2 program was applied for a model calibrated based on the available field measurements of the adjacent Derbendekhan Dam watershed, which has similar geological formations, characteristics and weather. For the calibration period (1961–1968), the considered statistical criteria of determination coefficients and Nash–Sutcliffe model efficiency were 0.75 and 0.64 for runoff while the coefficients were 0.65 and 0.63 for sediment load, respectively. The regionalization technique for parameter transformation from Derbendekhan to Dokan watershed was applied. Furthermore, the model was validated based on transformed parameters and the available observed flow at the Dokan watershed for the period (1961–1964); they gave reasonable results for the determination coefficients and Nash–Sutcliffe model efficiency, which were 0.68 and 0.64, respectively. The results of SWAT project simulation for Dokan watershed for the period (1959–2014) indicated that the average annual runoff volume which entered the reservoir was about 2100 million cubic meters (MCM). The total sediment delivered to the reservoir was about 72 MCM over the 56 years of dam life, which is equivalent to 10% of the reservoir dead storage. Two regression formulas were presented to correlate the annual runoff volume and sediment load with annual rain depth for the studied area. In addition, a spatial distribution of average annual sediment load was constructed to identify the sub basin of the high contribution of sediment load.

Keywords: Dokan Dam; runoff; sediment load; SWAT

1. Introduction

Most of the dams, storage schemes, and different hydraulic structures around the world suffer from sedimentation problems. For dams and reservoirs, this effect is mainly concerned with the design capacity and operation schedule. The main source of reservoir sediments is the main river flow in addition to the runoff water, carrying the sediment load from watersheds and valleys surrounding the reservoir.

After a long period of dam operation, it is usually necessary to evaluate the current storage capacity of the reservoir relative to that in the design stage. The runoff and sediment load delivered to the reservoir could be estimated based on measured values of continuous river flow. Schleiss et al. [1] highlights and discusses the main matters concerning reservoir sedimentation. The reservoir sedimentation problem should be considered from the early stages of planning design and operation. In addition, the sedimentation process can create problems downstream from the dam which should also be considered in the planning and design stages.

Physically based models are usually used in cases where runoff and sediment load data records are not available. These models are of two types, which are referred to as single storm models and continuous simulation models. The Areal Non-Point Source Watershed Environment Response Simulation (ANSWERS) is developed by Beasley et al. [2]; and the European Soil Erosion Model (EUROSEM) was improved by Morgan et al. [3]; all of those models mentioned are examples of the former models. Examples of the latter are the spatially distributed erosion and sediment yield component, chemicals, runoff and erosion from agricultural management systems CREAMS (Science and Education Administration; Department of Agriculture, Washington, WA, USA) which are proposed by Knisel [4]; the SHESED model (the hydrologic and sediment transportation model of hydrological modeling system (SHE)) which is proposed by Wicks and Bathurst [5]; and the soil and water assessment model (SWAT) that was developed by Arnold et al. [6]. The SWAT model is the most commonly used model and, for this reason, a number of researchers have modified this model for different purposes (see [7,8]). Durao et al. [9] estimates the transported nutrient load in the Ardila River watershed in Spain by applying the SWAT model in order to identify the contribution of this load to the whole watershed. The model is applied to simulate long-period data; the real daily precipitation data is considered for the period 1930–2000. The considered flow data for model calibration and validation extend from 1950 to 2000, and nutrient data stretch from 1981 to 1999. The results indicate that the main source of diffusion prolusion comes from the main tributaries of Spain. Wang et al. [10] tests the possible conservation practices within a rangeland watershed using the agricultural policy/environmental extender (APEX). The model is calibrated and validated for both flow and sediment yield for the Cowhouse Creek watershed in north Texas. The analysis of the scenario extends from 1951 to 2008. It shows that a significant reduction reaches to 58.8% of overland sediment losses from the area covered by a range brush to range grass. This reduction is due to the replacement of shrub species with herbaceous species within the subareas. Samaras and Koutitas [11] evaluates the effect of land-use changes in a watershed on coastal erosion for a selected area in north Greece. They apply both the SWAT model and a shoreline evolution model, a shoreline evolution model, for this purpose. The simulation is applied before and after land use change using three formulas of sediment transportation. The result indicates that a reduction in crop/land use cover from 23.3% to 5.1% leads to a reduction in both watershed sediment yield and sediment discharge at the outlet by (56.4%) and (26.4 to 12.8%), respectively. This study can be considered as a suitable tool and guide for future work in the same field. Samaras and Koutitas [12] studies the effect of climate change on sediment transport and morphology. The study is applied to a selected sandy coast area and its watershed in North Greece. Both SWAT models are implemented for the watershed and PELNCON-M is implemented for the coastal area to achieve the study aims. Two scenarios are employed; the first one is considered to be an extreme rise in the precipitation depth on the watershed, and the second one is considered to be an extreme rise in waves in the coastal area. Results of the first scenario shows a significant effect on erosion, sediment transport, sediment yield and discharge at the watershed outlet, while the second scenario indicates a lower effect on the coastline variation. Arnold [13] developed the SWAT + CUP model (SWAT Calibration and Uncertainty Programs, Swiss Federal Institute of Aquatic Science and Technology, Zurich, Switzerland), which provides a semi-automatic tool for decision-making for the SWAT model by applying both manual and automated calibration and incorporating both sensitivity and uncertainty analysis. A number of previous studies [14–17] were applied using the SWAT model to estimate runoff, sediment yield and/or other soluble materials for ungagged watersheds based on neighboring or similar property watersheds. Another technique is used for flow and erosion, and sediment transport is the distributed mode. Juez et al. [18] simulates the hydro-sedimentary response of the Western Mediterranean catchment to a representative rainfall storm. The simulation combines the distributed flow surface model with the empirical model for infiltration, the Soil Conservation Services Model (SCS), and the erosion model, which is the Hillslope Erosion Model (HEM), considering water depth and flow as a 2D model. The present model is a tool for analyzing the hydro-sedimentary process at a temporal and special scale.

Most countries in the Middle East suffer from water shortage problems, where the annual allocation per capita does not exceed 500 m^3 [19]. For this reason, water is essential to life, socioeconomic development, and political stability in this region. Future prospects are negative; therefore, this problem is expected to be more chronic and severe in future [20]. Iraq used to be considered to be a relatively rich country in terms of its water resources, until the mid-1970s, because of the presence of the Tigris and Euphrates Rivers [21]. Due to regional and internal problems in Iraq, the estimation of the overall water required is about 75–81 billion cubic meters (BCM) [22], while the available quantity is 59–75 BCM and will drop to 17.61 BCM in 2025 [23]. In view of this situation, it is very important to know the actual storage capacity of the reservoirs—which are unknown now—so that prudent water resources planning can be done. The sedimentation rate of several reservoirs was recently investigated in Mosul and Dohuk. This is the third reservoir to be dealt with in Iraq. The bed of the Dokan Dam reservoir (located in the northeast of Iraq) is surveyed by Hassan et al. [24], and this studied the bed sediment using 32-bed samples distributed spatially over the reservoir. The results indicate that the bed sediments of the reservoir are composed of silt (48%), clay (23%), gravel (15%) and sand (14%).

All reservoirs in the world suffer from sediment deposition. This is one of the main problems for reservoir life sustainability. Sustainable reservoir sediment-management practices enable continued reservoir functioning for a longer period by reducing reservoir sedimentation. Iraq suffers from water shortage problems, especially after the construction of a series of storage reservoirs in source countries (Turkey, Syria and Iran), so the evaluation of the actual live storage capacity of dams is important for the prudent management of the operation schedule. The aim of this study is to assess the annual runoff and sediment loads of the Dokan Dam watershed (ungagged area) using a SWAT model set-up based on the parameter transformation technique of the modeling-gauged Derbendekhan watershed to learn the hydrological behavior of the area and to assess its contribution to the total values pouring into the reservoir. Moreover, the set-up model helps us to find the spatial distribution of erosion and annual sediment yield for the sub basins. This will help us to find the sub basins with a high sediment yield and evaluate effective factors for them. These assessments help in the process of developing a plan and a strategy for managing the sediment inflow and deposition.

2. Study Area

2.1. Location and Topography

The considered study area is the watershed of the Dokan Dam reservoir, situated in the northeast of Iraq (Figure 1). Dokan dam is a concrete arch dam located in the Lower Zab River, about 65 km southeast of Sulaimaniyah city and 295 km north of Baghdad, the capital city of Iraq. The dam height is about 116 m at maximum river depth, having a total storage capacity of 6.87×10^9 m^3 (6.14×10^9 m^3 live storage and 0.73×10^9 m^3 dead storage) at normal operation level of 511 m.a.s.l. [22]. The dam has been built to serve irrigation, power generation, water supply and flood control needs. Due to the limited observed data of flow at the Dokan Dam watershed and the unavailability of sediments load data, the second watershed considered for this research is the Derbendekhan Dam watershed; it is the nearest watershed to the study area. The properties of the Dokan and Derbendikhan watersheds are shown in Table 1. The digital elevation model (DEM) with 30 m resolution is considered to identify the watershed boundary, classification of overland and channel flow, slopes and other properties.

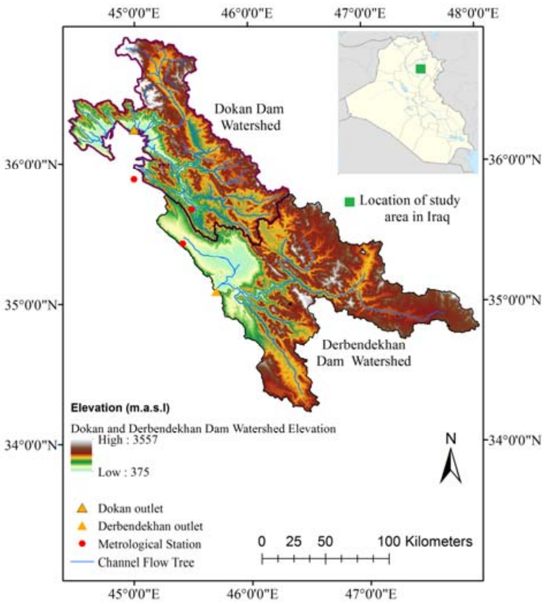

Figure 1. Topographic map of the watershed areas of the Dokan and Derbendekhan Dams and their locations in Iraq.

Table 1. Properties of the Dokan and Derbendekhan watersheds.

Watershed	Area (km^2)	Max. Elevation (m.a.s.l)	Min. Elevation (m.a.s.l)	Average Slope (%)	Maximum Annual Rain (mm)	Minimum Annual Rain (mm)
Dokan Dam	11,690	3557	489	26.5	1125	182
Derbendekhan Dam	15,280	3332	375	23.3	970	174

2.2. Soil Type and Land Use

The exposed rocks at the Dokan and Derbendekhan watershed areas are mainly limestone and minor exposures of dolomitic limestone, dolomite, and Quaternary alluvial deposits [25,26]. Based on the Reconnaissance Soil Map of the three Northern Governorates, Iraq [26] and the Food and Agriculture Organization of the United Nations (FAO) soil map [27], both watersheds are located on a common extended type of soil classification. Samples for different soil classes were taken depending on the soil map of the study area. A map of soil types is prepared for this study as a shape file for each watershed to be used in the SWAT model (see below for model details). The soil samples analysis includes grain size distribution in different types, organic matter content and hydraulic conductivity. The analysis of soil samples indicates that the area generally consists of four major soil types. Most of the area (85.6%) is covered by gravelly sandy mud; 6.9% is gravelly mud; and 7.5% of two types of muddy gravel (the main differences between the two types are the percent of gravel, which is 74% and 56% for types 1 and 2, respectively). Figure 2 shows the shape file of soil type considered in the SWAT model for the Dokan watershed.

The land use map for the years (1976–1979) [28] and available satellite image (NASA's Landsat GeoCover, 2007, with a spatial resolution of 14.25 m) indicates that the winter plants and pastures represent the main part of the land use map of the studied area. This depends on rainfall as a main source of irrigation water. The other parts are forests, vegetables and urban areas (villages). The land use change is limited (see Table 2). This is mainly due to the geological nature of both watersheds. In addition, the topography of the area does not enhance any changes. It is noteworthy to mention that rain is the main source of irrigation. For these reasons, the land cover did not change widely through the study period since the operation of the dam from the year 1959 to the year 2014. The Dam and the studied watershed are located away from the main cities, so changes in the urban and rural areas are limited. Table 2 shows the percentage of different land use cover for the two periods of the available land use map.

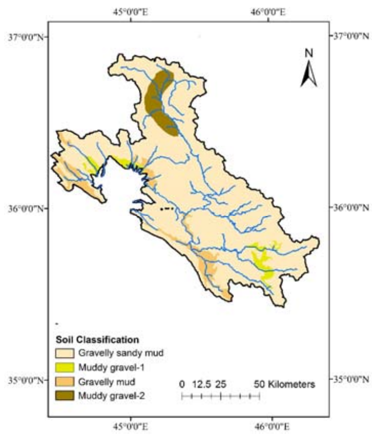

Figure 2. Soil type classification of the Dokan Reservoir watershed.

Table 2. Percentages of different land use types for two years of the studied period.

Year	Winter Plant and Pasture	Forest	Vegetables	Urban Area (Village)
1976–1979	77.3	22.0	0.5	0.2
2007	82.7	15.6	1.6	0.1

Due to the small difference between the percentage of land cover for the two available years, a map of land use for the study area is prepared as a shape file (Figure 3). The area consists of four types of land use/cover. Winter plants (pasture) and forests of different types of trees cover the main part of the study area, while the remaining small area is planted with vegetables near the reservoir boundary and/or in urban areas (villages).

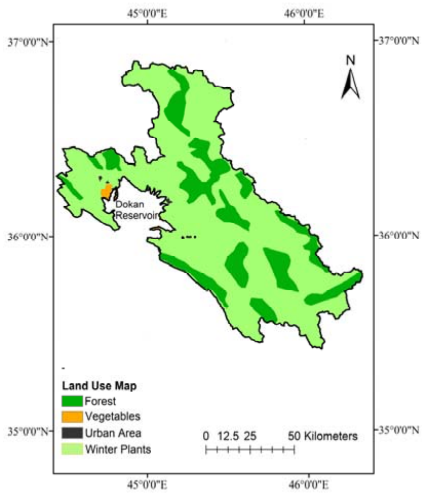

Figure 3. Land use and land cover classification of the Dokan Reservoir watershed.

3. Applied Model

The soil and water assessment tool (SWAT) is a physically based continuous simulation model for short or long times that can be applied to large river basins and complex watersheds. It was developed by the US Department of Agriculture, Agricultural Research Service [6]. The model is an efficient tool to estimate the flow and sediment load in addition to different chemical and nutrient materials. The model divides the watershed into sub basins based on their DEM date and hydrological response units (HRU); each unit has the same soil type, land use and land slope.

The hydrological simulation is based on the topographical terrain, soil type, land use and hydrological data of daily precipitation, maximum and minimum temperature, wind speed, relative humidity and solar radiation. The flow can be estimated based on a water balance equation; this equation is simulated in the SWAT model by different modular: the land phase and routing phase [14]. For the land phase, the soil water balance calculation is based on the following form [29]:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{sur} - E_a - w_{seep} - Q_{qw}) \quad (1)$$

where,

SW_t: Water content of the soil (mm);
SW_0: Initial water content (mm);
R_{day}: Depth of precipitation (mm);
Q_{sur}: Equivalent depth of surface runoff (mm);
E_a: Evapotranspiration depth (mm);
w_{seep}: Depth of water seepage out of considered surface profile (mm);
Q_{qw}: Equivalent depth of return flow (mm).

The Penman–Monteith method is considered for potential evapotranspiration estimation. The required input data to estimate the potential evapotranspiration (PET) using the Penman–Monteith method are daily solar radiation, air temperature, relative humidity and wind speed. The formula of this method considers three effective factors for evapotranspiration, which are the required energy to sustain evaporation, the required strength to remove the water vapor and the aerodynamic in addition to resistance of the surface. The Penman–Monteith method is in the following form [29]:

$$\lambda E = \frac{\Delta(H_{net} - G) + \rho_{air} \cdot c_p \cdot [e_z^o - e_z]/r_a}{\Delta + \gamma \cdot \left(1 + \frac{r_c}{r_a}\right)} \quad (2)$$

where,

λE: Latent heat flux density (MJ/m^2/day);
E: Evaporation rate (mm/day);
Δ: Saturation vapor pressure-temperature slope (de/dt) (kPa/Co);
H_{net}: Net radiation (MJ/m^2/day);
G: Density of heat flux to the ground (MJ/m^2/day);
ρ_{air}: Density of the air (kg/m^3);
c_p: Specific heat at constant pressure (MJ/kg/day);
e_z^o: Saturated vapor pressure of air at height z, (kPa);
e_z: Water vapor pressure of air at height z (kPa);
λ: Psychrometric constant (kPa/Co);
r_c: Resistance of plant canopy (s/m);
r_a: Diffusion resistance of the air layer (s/m).

Also, the different parameters of land management are recognized based on soil type, land use and land cover. The soil water content and soil infiltration can be estimated by two methods based on the available data, either by the Green–Ampt infiltration equation or curve number methods. The Green–Ampt equation requires rainfall data of a sub daily interval, which is not available in Iraqi weather stations, so the curve number method is utilized throughout this work using the following form [29]:

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)} \quad (3)$$

where,

Q_{surf}: Equivalent depth of surface runoff (mm);
R_{day}: Rainfall depth of the considered day (mm);
S: Retention parameter (mm).

The value of S can be estimated by the following equation [29]:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (4)$$

where, CN is the curve number of that considered day.

The second process includes the estimation of soil erosion from the overland due to rainfall detachment and surface runoff in addition to channel erosion and deposition. The sediments, routing in both the overland and channel flow, are estimated based on rainfall data, soil properties, land use/land cover and topography. The maps of soil type and land use are required with the digital elevation model (DEM) data to identify the topography of the watershed and to classify it into overland and channel sediment flow. The modified universal soil loss equation (MUSLE) is considered in the following form [29]:

$$sed = 11.8 \times \left(Q_{surf} \cdot q_{peak} \cdot are_{hru}\right)^{0.56} K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \quad (5)$$

where,

sed: Yield of sediment for the considered storm or day (ton.);
Q_{surf}: Volume of surface runoff (mm/ha);
q_{peak}: Greatest surface runoff rate (m^3/s);
are_{hru}: Hydrologic response unit area (ha);
K_{USLE}: Soil erodibility factor of Universal Soil Loss Equation (USLE);
C_{USLE}: Cover and management factor of USLE;
P_{USLE}: Soli practice factor of USLE;
LS_{USLE}: Topographic factor of USLE;
$CFRG$: Factor of coarse fragment.

4. Model Calibration and Validation

4.1. Runoff and Sediment Load Calibration

Although the mathematical and conceptual models are considered widely in hydrological studies to simulate different events, such as runoff flow, sediment and both suspended and dissolved material transport, they still require calibration with measured values to ensure the accuracy of the model outputs.

Two types of dataset are prepared to be applied to SWAT model. The metrological (climate) data include daily precipitation, maximum and minimum temperature, wind speed, relative humidity and solar radiation; hydrometric data are also present. The second dataset is the topography data, which includes the DEM map.

In view of the limited available measurements of flow and unavailable sediment records of the Dokan Dam watershed, the available data of the Derbendekhan Dam watershed (the adjacent watershed to Dokan, Figure 1), were considered for both flow and sediment model calibration. Due to the similarity in the geological formation, soil type, land use, topographical and watershed characteristics (Table 1), the parameters of the calibrated watershed can be transformed to an ungauged watershed model [17]. To calibrate the results of the SWAT model for both runoff and sediment, the SWAT-CUP software is applied. It is an efficient tool to adjust different parameters of the SWAT model to obtain optimal local results and create an uncertainty analysis of SWAT model parameters to provide an easy and quick method of calibration and standardized calibration [30]. The considered software for the model is the Sequential Uncertainly Fitting version 2 (SUFI-2, Swiss Federal Institute of Aquatic Science and Technology, Zurich, Switzerland). In this program, all the uncertainty parameters can be used in the model calibration, including uncertainly in driving variables, parameters of the conceptual model and considered data [30]. Different statistical criteria can be considered in the model objective function to evaluate model performance, such as the determination coefficient, Nash–Sutcliff model efficiency, root mean square error and Chi-square. The determination coefficient is considered to be effective criteria to obtain the optimal values of flow and sediment concentration between the observed and measured data.

The SWAT project for the Derbendekhan watershed is set-up including the required DEM data, soil type land use, as shown in Figures 1–3, respectively, and meteorological data based on the nearest stations to the area as shown in Figure 1. The monthly average flow rate data at Derbendekhan station are considered for model calibration. To obtain an enhanced calibration of the model and for more understanding of the model's performance, the monthly recorded flow data are separated into base flow and surface runoff [14]. The recursive digital filter technique [31] is used to obtain a monthly separation based on the original daily separation technique. The separated monthly runoff from the total flow as measured values is applied in SUFI-2 to calibrate the model parameters. The statistical criterion of the determination coefficient is used as an objective function criterion. Besides this, the Nash–Sutcliffe model is employed to evaluate the model performance. For monthly runoff flow, the highest obtained values are 0.75 and 0.64 for the coefficient of determination and Nash–Sutcliffe model, respectively. The model uncertainty was measured using two factors: the P-factor reflects the percentage of measured data bracketed by 95% prediction uncertainty (95PPU). This means that one minus the P-factor represents the presence of poorly simulated values. The R-factor is another measurement of model uncertainly equal to the average thickness of the 95PPU band divided by the standard deviation of measured data. For the runoff calibration period, the P-factor is 0.78 and the R-factor is 1.27. Figure 4 shows the observed and simulated runoff at the Derbendekhan watershed outlet and the uncertainty band (95PPU) for the period (1961–1968).

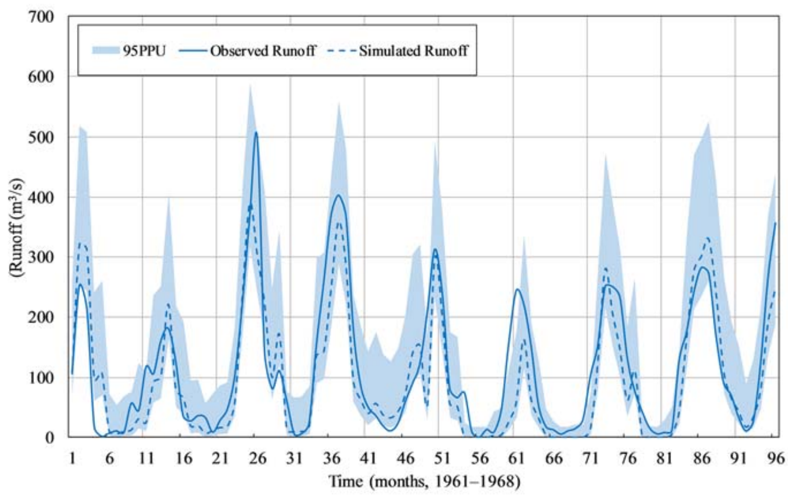

Figure 4. Monthly observed and simulated runoff at the Derbendekhan outlet and 95PPU for the period 1961–1968.

The available measured sediment concentration data of the Diyala River at Derbendekhan station, as presented by Assad [32], were utilized to calibrate the SWAT model parameters for the same period of runoff flow calibration. Figure 5 shows the measured and optimal simulated values of sediment load concentration at Derbendekhan outlet. The same statistical criteria are implemented, and the optimal resultant values are 0.65 and 0.63 for determination coefficient and Nash–Sutcliffe model efficiency, respectively, while the P-factor and R-factor equal to 0.68 and 2.27 respectively.

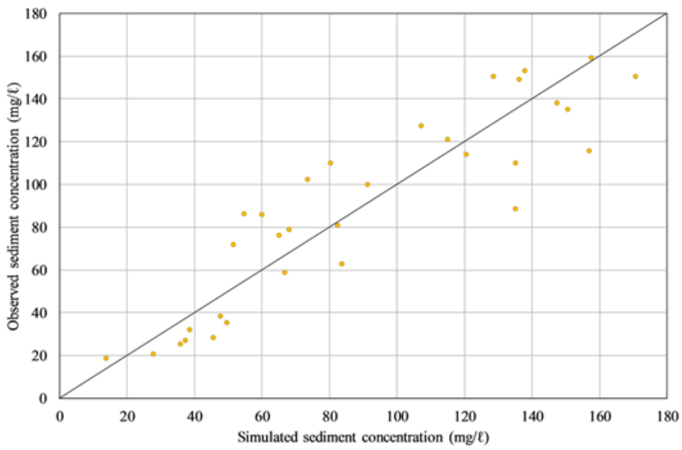

Figure 5. Observed and simulated sediment concentration for period (1961–1968) at the Derbendekhan watershed.

The most effective parameters are selected for the runoff and sediment model calibration as proposed by [28] in addition to other parameters. The resultant best-fitted values (optimal values) of the parameters and the considered range are shown in Table 3. Parameters listed in Table 3 are also mentioned in other previous literature [14,33].

Table 3. The range, optimal (fitted) values and sensitivity analysis of considered parameters.

Parameter	Description	Min_Value	Max_Value	Fitted_Value
V_GWQMN.gw	Threshold depth in shallow aquifer (mm).	0	2	1.698
V_CH_COV1.rte	Channel erodibility factor.	0.05	0.6	0.38715
R_USLE_K(**..**).sol	USLE, equation soil erodibility (k) factor.	−0.8	0.8	−0.1168
R_LAT_SED.hru	Sediment conc. In lateral and ground flow.	0	5000	2525
R_SPCON.bsn	Linear par. for calculating max. amount of sediment that can be re-entrained during channel sediment routing.	0.0001	0.01	0.008743
V_SPEXP.bsn	Exponential Par. for calculating max. amount of sediment that can be re-entrained during channel sediment routing.	1	2	1.549
V_GW_REVAP.gw	Groundwater "revap" coefficient.	0.02	0.2	0.07166
V_ALPHA_BF.gw	Base flow alpha factor (days).	0	1	0.555
V__CH_COV2.rte	Channel cover factor.	0.001	1	0.281719
V_GW_DELAY.gw	Groundwater delay (days).	0.02	0.2	0.07166
R_SOL_BD(**..**).sol	Moist bulk density.	−0.5	1	−0.3755
R_USLE_C(**..**)plant.dat	Min value of USLE-C factor for land cover/plant.	−0.5	0.5	0.151000
R_CH_N2.rte	Manning's "n" value for the main channel.	−0.5	0.5	−0.279
R_USLE_P.mgt	USLE, support practice parameter.	0	1	0.941
R_SOL_K(**..**).sol	Saturated hydraulic conductivity.	−0.5	0.5	0.177
R_CN2.mgt	SCS runoff curve number.	−0.2	0.2	0.198
R_SOL_AWC(**..**).sol	Available water content of the soil layer.	−0.5	1	0.5005

Note: **R**: Relative, **V**: Replace. **(..)** for different soil or plant type.

4.2. Runoff Validation

A SWAT model project is set-up for the Dokan Dam watershed, the main part of the study area. The limited recorded data of the monthly flow rate at the outlet of the Dokan watershed and the absence of any sediment load measurements leads to utilizing the regionalization technique to transfer the effective parameters from the adjacent gauged (Derbendekhan) watershed. Due to its similarity in geological formation, soil type, land use, watershed characteristics and weather data, the effective hydrological parameters obtained from the Derbendekhan (gauged) watershed can be transformed to the Dokan (ungauged) watershed. The process of parameter transformation is called regionalization. There are a number of presented methods for the regionalization of the watershed hydrological parameters: Kokkonen [34] applies the regression approach, while Parajka et al. [35] employs kringing and a similarity approach and Heuvelmans et al. [36] investigates the application of artificial neural nets and other methods. Since the Derbendekhan watershed is adjacent to the Dokan watershed (Figure 1), and the physical, topographical properties and rainfall are similar (Table 1) along with the geological formation, land use/land cover, and soil type, both watersheds have similar flow and sediment parameters. In this case, the effective parameters can be transformed from a donor watershed to an ungauged watershed. The fitted values of the Derbendekhan parameters calibrated by the SUFI-2 program are transferred to the Dokan watershed SWAT project. The SUFI-2 program is implemented for the calibration, uncertainly analysis and regionalization of the considered parameters of the SWAT model for the Debendekhan watershed for runoff and sediment load of concentration. Here, the SUFI-2 algorithm is used for the calibration, validation and measurement of the uncertainty for input data, model and sensitive parameters. The degree of uncertainty is measured by two values: P-factor and R-factor. The percent of measured values bracketed by 95% prediction uncertainly represent (95PPU), which is the P-factor while the ratio of 95PPU thickness divided by standard deviation of measured values is equal to the R-factor. When the simulated values are exactly the measured ones, the value of P-factor equals 1 and the value of R-factor equals zero [37].

Based on the transformed parameters, the simulated runoff flows are compared with measured values at the Dokan watershed outlet after the separation of the base flow for the period 1961–1964 (Figure 6) to evaluate the effectiveness of the transformation of the hydrological parameters. For the validation period of runoff, the obtained values of the determination coefficient and Nash–Sutcliffe model efficiency are 0.68 and 0.64, respectively, indicating that the transformation process is successful. The P-factor and R-factor for the model uncertainty also indicate a reasonable model performance: the P-factor is 0.71 and R-factor is 0.97.

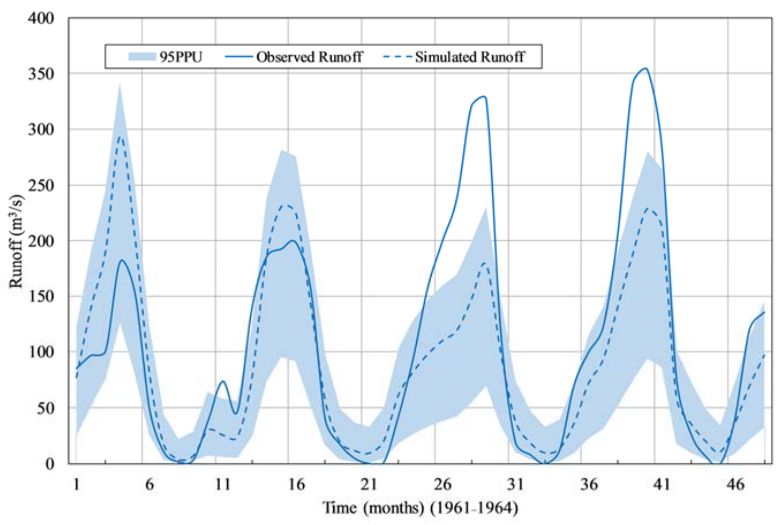

Figure 6. Monthly observed and simulated runoff at the Dokan outlet and 95PPU for the period 1962–1965.

5. Results and Discussion

After Durbendekhan SWAT project calibration for runoff and sediment data, the best-fitted values of the hydrological watershed parameters are transformed by the regionalization technique to the Dokan SWAT project, the main project of the study. The sensitivity analysis is also studied for the most effective parameters on both the runoff and sediment load. The sensitivities are accomplished to identify the effective parameters on runoff and sediment load values for the watershed. The parameter sensitivity is estimated in the SUFI-2 model based on the multiple regression system presented by Abbaspour [38] to evaluate the effect of the considered parameter value (b_i) on the objective function (g); its sensitivity is in the following form:

$$g = \alpha + \sum_{i=1}^{m} \beta_i b_i \quad (6)$$

This formula calculates the average changes in the objective function due to the change in a given parameter while other parameters are changing. The comparative significance and sensitivity of each parameter are estimated based on the statistical criteria of the *t*-stat and *p*-value. The *t*-stat value is obtained from the coefficient of a parameter in the multiple regression analysis divided by its standard error. If the coefficient value is large in comparison to the standard errors, this mean that the parameter is sensitive. The *p*-value can be obtained by comparing the *t*-stat value with the student's distribution table [37]. The *p*-value of each term test is the null hypothesis, in which the coefficient is not affected. If the *p*-value is less than 0.05, it indicates that the null hypothesis can be rejected. The *t*-stat and *p*-values of different effective parameters are shown in Table 4. The parameters are arranged from low to high sensitivity, i.e., from low *t*-stat value or high *p*-value. The result of the test indicates that the soil water content, soil curve number at normal conditions (CN2) and the soil saturated hydraulic conductivity are the most effective parameters while threshold depth in a shallow aquifer, the channel erodibility factor and soil erodibility (k) factor in USLE have the lowest effect on runoff and sediment load simulation.

Table 4. Effective parameters arranged from low to high sensitivity based on *t*-stat and *p*-value.

Parameter	Absolute *t*-Stat	*p*-Value
GWQMN.gw	0.61	0.54
CH_COV1.rte	0.62	0.54
USLE_K(..).sol	0.77	0.44
LAT_SED.hru	0.78	0.43
SPCON.bsn	0.92	0.36
SPEXP.bsn	0.97	0.33
GW_REVAP.gw	0.98	0.33
ALPHA_BF.gw	1.20	0.23
CH_COV2.rte	1.25	0.21
GW_DELAY.gw	1.25	0.21
SOL_BD(..).sol	1.34	0.18
USLE_C(..)plant.dat	1.96	0.05
CH_N2.rte	2.08	0.04
USLE_P.mgt	3.69	0.03
SOL_K(..).sol	9.34	0.02
CN2.mgt	11.57	0.01
SOL_AWC(..).sol	16.05	0.00

Note: (..) for different soil or plant type.

The model is applied for the study period to estimate the runoff and sediment load reaching the Dokan Reservoir. The considered years of simulation have begun since the operation of the dam in 1959 to the year of the bathometry survey (2014) carried out by [39]. The resultant annual runoff volume that enters the Dukan Reservoir from the HRUs ranges from 300 to 4600 MCM (Figure 7), depending on rainfall intensity, depth and distribution through the rainy season. The runoff average volume from the watershed represents 35% of the live storage capacity of the dam, indicating that watershed runoff makes a significant contribution to reservoir inflow.

The SWAT model is an efficient tool to estimate the runoff hydrograph, but, in some hydrological studies, such as scheduling reservoir operations to supply the demand rate, the assessment of water resource income only is required. A regression formula is determined based upon the input–output data of SWAT model of the study area. This is a simple and quick tool to correlate the annual runoff depth with annual rainfall with good correlation ($R^2 = 0.9$) results without the need for more detailed input data as required in SWAT projects. The relationship used is in the following form:

$$Run_{Ann} = 0.075 \times R_{Ann}^{1.21} - 1.92 \ \mathrm{R}^2 = 0.90 \ (for \ R_{Ann} > 16 \ \mathrm{mm}) \tag{7}$$

where

Run_{Ann}: Annual runoff depth mm);
R_{Ann}: Annual rainfall depth (mm).

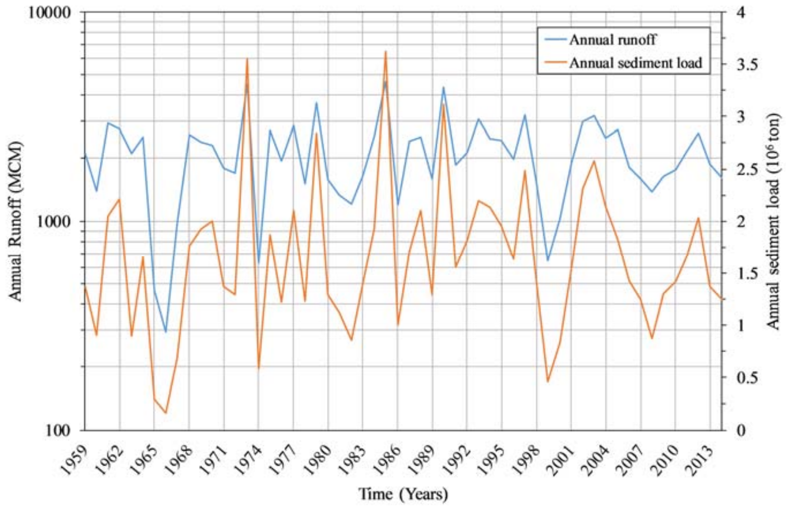

Figure 7. Annual runoff volume and sediment load delivered to the Dokan Reservoir for the period 1959–2014.

The formula is suitable when the annual runoff depth is greater than 15 mm to avoid negative runoff; this value is already much lower than the minimum historical recorded value.

The sediment load delivered to the Dokan reservoir is also estimated based on MUSLE programmed into the SWAT model for each single storm. The results are presented here annually. The average annual sediment load concentration is 650 mg/ℓ. This concentration can be considered relatively low in comparison with other locations or measurements in the region as proposed by [40,41] as well as the worldwide rate [42]. This is due to the nature of the rocks of the area and the effect of plant cover, such as winter pasture and plants and some forest trees throughout the region which reduce the detachment of soil particles transported with runoff flow. The estimated annual sediment load delivered to the Dokan reservoir from the watershed ranges from 3.6 to 0.16 $\times$ 10^6 ton for studied period, Figure 7. The average annual value is 1.63 $\times$ 10^6 ton.

The sediment trap efficiency of the reservoir is estimated based on the method presented by Garg V. and Jothiprakash V. [43]. This depends on reservoir storage capacity and annual inflow. The trap efficiency of the Dokan reservoir changes through the study period from 1 to 0.985.

Based on the results obtained from the simulation model, the estimated sediment load volume deposited in the reservoir for the considered period is about 10% of the dead storage capacity. This value is for the watershed only, which is considered a reasonable value and does not affect the designed project life. However, the Lesser Zab load should be also considered to evaluate the total amount of sediment load delivered and deposited within the reservoir. The total amount of sediment deposited in the Dokan reservoir for the period (1959–2014) is 209 MCM [38]. This means that the sediment load delivered into the reservoir from the watershed based on simulated results is about 34% of the total sediments deposited within the reservoir, which mean that the watershed sediment contribution is an effective value.

Due to the huge amount of data required, including topographical, metrological and hydrological data, different maps of soil, and land use to estimate the sediment load based on the applied model, a simple regression formula is used. It is based on simulated values to correlate the sediment load per unit area of the Dokan watershed with annual runoff depth in the following form:

$$Sed_{Ann} = 0.056 \cdot R_{Ann}^{1.195} - 7.33 \ \mathrm{R}^2 = 0.97 \ (for \ R_{Ann} > 60\mathrm{mm}) \quad (8)$$

where

Sed_{Ann}: Annual sediment load per unit area, (ton/km^2);
R_{Ann}: Annual rainfall depth (mm).

The formula is suitable when the annual runoff depth is greater than 60 mm; this value is already lower than the minimum historical recorded value in Dokan area.

A special distribution map of average annual sediment yield per unit area of sub basins is also prepared (Figure 8a). It can be noticed that the annual sediment load contribution ranges from 13 to 950 ton/km^2 approximately. The rate of erosion and sediment yield depends on a number of factors: topography, soil type, land cover and rainfall intensity. Comparing the sub basins of different soil types and land uses, in both the annual sediment yield map (Figure 8a) and the sub basin slope map (Figure 8b), it can be noticed that the most effective factor for the sediment yield is the land slope rather than other factors. This can be clearly noticed in that some basins have the same soil type and land use but a higher slope gives higher sediment yield. Sub basins having an average slope between 25 to 45% represent the area of high sediment yields from 400 to 950 t/km^2; however, when the sub basin slope is less than 20%, the sediment yield per unit area is reduced to about 40 t/km^2.

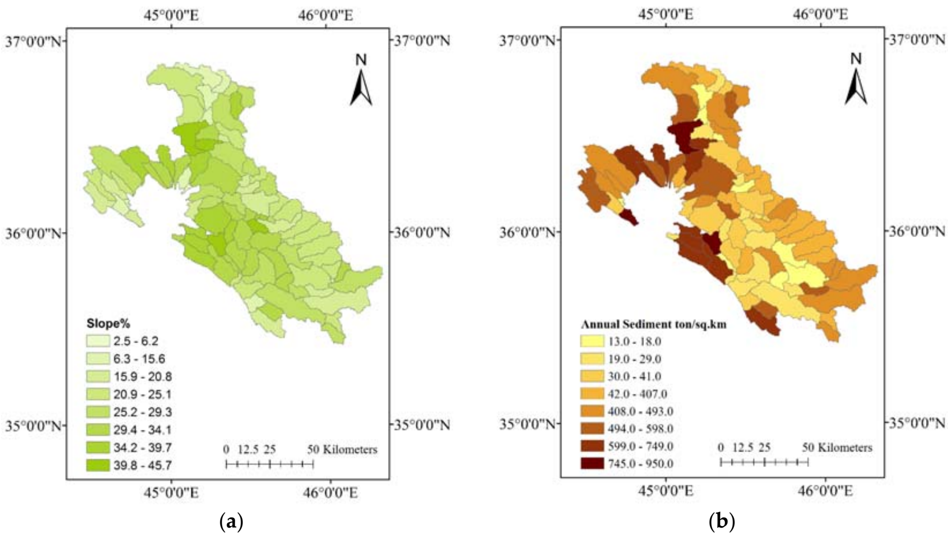

Figure 8. (**a**) Spatial distribution of average annual sediment load for the Dokan watershed sub basins; (**b**) average slope of sub basins.

This map is a tool that can enable decision-makers to apply a suitable method to reduce the erosion load, especially from high erosion rate areas. Depending on the selected area, the treatment may include practicing strip planting, terracing, or contour forming to reduce the effect of slope on surface runoff flow velocity, erosion and sediment transport capacity.

6. Conclusions

The soil and water assessment tool (SWAT) model is applied to assess the runoff and sediment delivered from the Dokan Dam watershed. Due to the limited recorded flow data and the absence of sediment measurements data at a station near the inlet of Dokan Reservoir, the model is calibrated for both runoff and sediment load for the Derbendekhan watershed adjacent to the Dokan watershed. The regionalization technique is employed to transfer the calibrated parameters of the SWAT project from a gauged (Derbendekhan) to an ungauged (Dokan) watershed. The resultant monthly runoff flow for the Dokan SWAT project is based on transformed parameters which were compared with measured values to evaluate the regionalization technique and model performance. The determination coefficient (R^2) and Nash–Sutcliffe model efficiency (Eff.) are 0.68 and 0.64, respectively, indicating a reasonable model performance with this technique. The average watershed contribution for annual runoff represents 35% of the dam life storage; this percentage is considered effective in the dam operation schedule. The total sediment load delivered to the Dokan reservoir from the watershed for the studied period is about 72 MCM. This load forms about 10% of the dead storage capacity of the reservoir. Generally, the total sediment load delivered and deposited in the reservoir for the period of dam operation is considered acceptable within the allowed limits. The map of special distribution of annual sediment load yield per unit area of each sub basins is presented; the average slopes map reflects a good agreement with the map of annual sediment load yield in comparison to other effective factors to be considered. This indicates that the land slope is the most effective factor on erosion and sediment transport. This can be used for soil conservation treatment to reduce the erosion rate.

Author Contributions: M.E.-A. and R.H. did the field, methodology and modelling, A.A. helped in the modelling, N.A.-A. and S.K. did the supervision.

Funding: This research received no external funding.

Acknowledgments: The authors would like to express their thanks to John McManus (University of St. Andrews, St. Andrews, UK) and Ian Foster (Northampton University, Northampton, UK) for reading the manuscript and for their fruitful discussions and suggestions, and to Lulea University of Technology for some of the financial support for this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Schleiss, A.J.; Franca, M.J.; Juez, C.; De Cesare, G. Reservoir Sedimentation—Vision Paper. *J. Hydraul. Res.* **2016**, *54*, 595–614. [CrossRef]
2. Beasley, D.B.; Huggins, L.F.; Monke, E.J. ANSWERS: A model for watershed planning. *Trans. ASAE* **1980**, *23*, 938–944. [CrossRef]
3. Morgan, R.P.C.; Quinton, J.N.; Smith, R.E.; Govers, G.; Poesen, J.W.; Auerswald, K.; Chisci, G.; Torri, D.; Styczen, M.E.; Folly, A.J. The European soil erosion model (EUROSEM): A dynamic approach for predicting sediment transport from fields and small catchments. *Earth Surface Process. Landf.* **1998**, *23*, 527–544. [CrossRef]
4. Knisel, W.G. *CREAMS: A Field-Scale Model for Chemical, Runoff and Erosion from Agricultural Management Systems*; USDA Conservation Research Report; Conservation Model Development: Washington, WA, USA, 1980.
5. Wicks, J.M.; Bathurst, J.C. SHESED: A physically based, distributed erosion and sediment yield component for the SHE hydrological modelling system. *J. Hydrol.* **1996**, *175*, 213–238. [CrossRef]
6. Arnold, J.G.; Srinisvan, R.; Muttiah, R.S. Large area hydrologic modeling and assessment. Part I: Model development. *Am. Water Resour. Assoc.* **1998**, *34*, 73–89. [CrossRef]
7. Easton, Z.M.; Fukal, D.R.; White, E.D.; Collick, A.S.; Ashagre, B.B.; McCartney, M.; Awulachew, S.B.; Ahmed, A.A.; Steenhuis, T.S. A multi basin SWAT model analysis of runoff and sedimentation in the Blue Nile, Ethiopia. *Hydrol. Earth Syst. Sci.* **2010**, *14*, 827–1841. [CrossRef]

8. Swami, V.A.; Kulkarni, S.S. Simulation of runoff and sediment yield for a Kaneri Watershed Using SWAT Model. *J. Geosci. Environ. Protect.* **2016**, *4*, 1–15. [CrossRef]
9. Durao, A.; Leitao, P.C.; Brito, D.; Fernandes, R.; Neves, R.; Morais, M.M. Estimation of Transported Pollutant Load in Ardila Catchment Using the SWAT Model. In Proceedings of the International SWAT Conference, Toledo, Spain, 15–17 June 2011.
10. Wang, X.; Amonett, C.; Williams, J.R.; Fox, W.E.; Tu, C. Assessing Impacts of Rangeland Conservation Practices Prior to Implementation: A Simulation Case Study using APEX. In Proceedings of the International SWAT Conference, Toledo, Spain, 15–17 June 2011.
11. Samaras, A.G.; Koutitas, C.G. The impact of watershed management on coastal morphology: A case study using an integrated approach and numerical modeling. *Geomorphology* **2014**, *211*, 52–63. [CrossRef]
12. Samaras, A.G.; Koutitas, C.G. Modeling the impact of climate change on sediment transport and morphology in coupled watershed-coast systems: A case study using an integrated approach. *Int. J. Sediment Res.* **2014**, *29*, 304–315. [CrossRef]
13. Arnold, J.G.; Youssef, M.A.; Yen, H.; White, A.Y.; Sheshukov, A.M.; Sadeghi, D.N.; Moriasi, D.N.; Steiner, J.L.; Amatya, D.M.; Haney, E.B.; et al. Hydrological processes and model representation: Impact of soft data on calibration. *Trans. ASABE* **2015**, *58*, 1637–1660.
14. Emam, A.R.; Kappas, M.; Linh, N.H.K.; Renchin, T. Hydrological Modeling and Runoff Mitigation in an Ungauged Basin of Central Vietnam Using SWAT Model. *Hydrology* **2017**, *4*, 1–17.
15. Emam, A.R.; Kappas, M.; Linh, N.H.K.; Renchin, T. Hydrological Modeling in an Ungauged Basin of Central Vietnam. *Hydrol. Earth Syst. Sci. Discuss.* **2016**, 1–33. [CrossRef]
16. Prabhanjan, A.; Rao, E.P.; Eldho, T.I. Application of SWAT Model and Geospatial Techniques for Sediment-Yield Modeling in Ungauged Watersheds. *J. Hydrol. Eng.* **2014**, *20*, C6014005. [CrossRef]
17. B'ardossy, A. Calibration of hydrological model parameters for ungauged catchments. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 703–710. [CrossRef]
18. Juez, C.; Tena, A.; Fernández-Pato, J.; Batalla, R.J.; Garcia-Navarro, P. Application of A Distributed 2d Overland Flow Model for Rainfall/Runoff and Erosion Simulation in A Mediterranean Watershed. *Cuadernos de Investigación Geográfica* **2018**. (In Spanish) [CrossRef]
19. Al-Ansari, N. Hydropolitics of the Tigris and Euphrates Basins. *Engineering* **2016**, *8*, 140–172. [CrossRef]
20. Bazzaz, F. Global climatic changes and its consequences for water availability in the Arab world. In *Water in the Arab Word: Perspectives and Prognoses*; Roger, R., Lydon, P., Eds.; Harvard University: Cambridge, MA, USA, 1993; pp. 243–252.
21. Al-Ansari, N.; Knutsson, S. Toward Prudent management of Water Resources in Iraq. *Adv. Sci. Eng. Res.* **2011**, *1*, 53–67.
22. World Bank. *Iraq. Country Water Resources, Assistance Strategy: Addressing Major Threats to People's Livelihoods*; Water, Environment, Social and Rural Development Department: Washington, DC, USA, 2006.
23. UNESCO. *Iraq's Water in the International Press*; UNESCO Office for Iraq: Erbil, Iraq, 2010.
24. Hassan, R.; Al-Ansari, N.; Ali, S.A.; Ali, A.A.; Abdullah, T.; Knutsson, S. Dukan Dam Reservoir Bed Sediment, Kurdistan Region, Iraq. *Engineering* **2016**, *8*, 582–596. [CrossRef]
25. Karim, K.H.; Al-Hakari, S.H.S.; Kharajiany, S.O.A.; Khanaqa, A.P. Surface Analysis and Critical Review of the Darbandikhan (Khanaqin) Fault, Kurdistan Region, Northeast Iraq. *Kurdistan Acad.* **2016**, *12*, 61–75.
26. Berding, F. *Reconnaissance Soil Map of the Three Northern Governorates*; FAO Erbil Coordination Office: Erbil, Iraq, 2001.
27. Food and Agriculture Organization of the United Nations. *The Digital Soil Map of the World and Derived Soil Properties*; Version 3.6; FAO: Rome, Italy, 2003.
28. Ministry of Agricultural and Irrigation, Republic of Iraq. *Map of Soil and Land Use*; Ministry of Agricultural and Irrigation: Baghdad, Iraq, 1990.
29. Neitsch, S.L.; Arnold, J.G.; Kiniry, J.R.; Williams, J.R. *Soil and Water Assessment Tool*; Theoretical Documentation Version 2009; Texas Water Resources Institute: College Station, TX, USA, 2011.
30. Abbaspour, K.C.; Vejdani, M.; Haghighat, S. SWAT-CUP Calibration and Uncertainty Programs for SWAT. In Proceedings of the International Congress on Modelling and Simulation (MODSIM 2007), Melbourne, Australia, 10 December 2007.
31. Smakhtin, V.U. Estimating continuous monthly baseflow time series and their possible applications in the context of the ecological reserve. *Water SA* **2001**, *27*, 213–218. [CrossRef]

32. Assad, M.N. Sediments and Sediment Discharge in the River Diyala. Master's Thesis, Baghdad University, Baghdad, Iraq, 1978.
33. Salimi, T.E.; Nohegar, A.; Malekian, A.; Hosseini, M.; Holisaz, A. Runoff simulation using SWAT model and SUFI-2 algorithm. *Casp. J. Environ. Sci.* **2016**, *14*, 69–80.
34. Kokkonen, T.; Jakeman, A.; Young, P.; Koivusalo, H. Predicting daily flows in ungauged catchments: Model regionalization from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina. *Hydrol. Process.* **2003**, *11*, 2219–2238. [CrossRef]
35. Parajka, J.; Merz, R.; Bloschl, G. A comparison of regionalisation methods for catchment model parameters. *Hydrol. Earth Syst. Sci.* **2005**, *9*, 157–171. [CrossRef]
36. Heuvelmans, G.; Muys, B.; Feyen, J. Regionalisation of the parameters of a hydrological model: Comparison of linear regression models with artificial neural nets. *J. Hydrol.* **2006**, *319*, 245–265. [CrossRef]
37. Tang, F.F.; Xu, H.S.; Xu, Z.Z. Model calibration and uncertainty analysis for runoff in the Chao River Basin using sequential uncertainty fitting. *Procedia Environ. Sci.* **2012**, *13*, 1760–1770. [CrossRef]
38. Abbaspour, K.C. *SWAT-CUP: SWAT Calibration and Uncertainty Programs—A User Manual*; Swiss Federal Institute of Aquatic Science and Technology, Eawag: Dubendorf, Switzerland, 2015.
39. Hassan, R.; Al-Ansari1, N.; Ali, A.; Ali, S.; Knutsson, S. Bathymetry and siltation rate for Dokan Reservoir, Iraq. *J. Lakes Reserv. Res. Manag.* **2017**, *20*, 1–11. [CrossRef]
40. Walling, D.E. *The Impact of Global Change on Erosion and Sediment Transport by Rivers: Current Progress and Future Challenges*; United Nations Educational, Scientific and Cultural Organization: Paris, France, 2009.
41. Basson, G. *Sedimentation and Sustainable Use of Reservoirs and River Systems*; International Commission on Large Dams: Paris, France, 2009.
42. Mahmood, R. *Reservoir Sedimentation: Impact, Extent, Mitigation*; World Bank: Washington, DC, USA, 1987.
43. Garg, V.; Jothiprakash, V. Trap Efficiency Estimation of a Large Reservoir. *J. Hydraul. Eng.* **2008**, *14*, 88–101. [CrossRef]

© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).