Assessment of sediment yield for Wala dam catchment area in Jordan

A.Z. Ijam[1] and E.R. Tarawneh[2]
Civil and Environmental Engineering Department,Faculty of Engineering, Mu'tah University, Mu'tah, Jordan.
e-mails: (1) azijam@yahoo.com, (2) esraatarawneh@yahoo.com

Abstract: This study presents an application of the Soil and Water Assessment Tool (SWAT), associated with Geographic Information System (GIS) to simulate the hydrology, soil erosion and sedimentation of Wala dam catchment (2000 km^2) in Jordan. Model calibration (for the period May 1972 to October 1979) and verification (for the period October 1990 to September 1998) were carried out using flow rate and sediment yield data observed at Wala flow station and the results were satisfactory with acceptable statistical measures. Simulated results predicted average sediment yields of 143780 ton/year and 123100 ton/year for the prediction periods November 2002-December 2007 and 2008-2020, respectively. Predicted results indicated that the western and northern sub-basins yield more water to the dam reservoir and are more susceptible to soil erosion and sediment yields. The study suggested soil conservation and sediment reduction measures to control soil loss and maintain storage of water in Wala dam reservoir. The present work could assist in quantifying sediment yields in the long-term as well as in identifying the most susceptible areas within the catchment in order to assist policy makers in taking cost-effective management decisions.

Key words: Sediment yield; Reservoirs; Dams; Water yield; Jordan.

1. INTRODUCTION

During recent decades, studies and simulation models have been developed all around the world in order to estimate, analyze or predict runoff, soil erosion, and sediment yield and to relate the spatial variability of land characteristics to runoff generation and erosion. The first world map of soil erosion intensity was produced in 1990 by the international soil reference and information center (FAO, 2005). Many attempts have been made to develop predictive erosion models; the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) is one of them. The application of this model in several countries has shown promising results in the assessment of erosion, runoff, and sediment yield, under a wide range of soil types, land-uses, and climate conditions (Arnold and Fohrer, 2005).

 Rodriguez et al. (2005) selected Nazas river basin in Mexico to carry out a study to assess SWAT performance, and concluded that the curve number (CN) is the most important parameter in defining runoff volume and maximum annual peak runoff rate. Licciardello et al. (2005) have reported the results of a SWAT model for an experimental semi-arid watershed in Sicily, Italy, calibration and validation were carried out using the Universal Soil Loss Equation, and confirmed that the vegetation factor (C) is the most important calibration parameter for sediment yield assessment. Mishra et al. (2007) have evaluated the effect of sediment control structures on sediment transport in Banha watershed in north-east of India using SWAT model, the results showed that the sediment loss could be reduced by more than 64% by adopting check-dams as barriers for sediment. Setegn et al. (2009) confirmed the applicability of SWAT model to estimate sediment yield within each sub-basin of the lake Tana basin in Ethiopia, and the most sediment contributing areas in the basin are identified.

The impacts of land use change on sediment yield have received increasingly widespread concern. Asres and Awulachew (2010) presented SWAT model for a case study of the Gumera watershed in the Blue Nile basin in Ethiopia, vegetation filter strips of various widths were used to reduce sediment production from critical micro-watersheds. Cai et al. (2011) investigated the

impacts of land-use change on sediment yield in the upper Huaihe river basin in China using SWAT model, it was concluded that the rainfall-sediment yield relationship is sensitive to the types of land use and rainfall. Phomcha et al. (2012) applied SWAT to model Lam-Sonthi watershed in central Thailand, the model identified 40% of the entire watershed as serious soil erosion areas, and the results revealed that the combination of reforestation and mulching was the most effective treatment in reducing sediment yields. Mbonimpa et al. (2012) used SWAT to assess the impact of continuous corn farming on sediment and phosphorus loading in Upper Rock river watershed in Wisconsin, USA. Simulations indicated that conversion of corn-soybean to continuous corn caused 55% and 35% increase in sediment yield and total phosphorous loss, respectively. Fiseha et al. (2012) investigated the hydrological behavior of the Upper Tiber river basin in central Italy using SWAT model, it was confirmed that the model can be used for the prediction of the impact of climate and land use changes on water resources planning and management. Hasan et al. (2012) presented flow and sediment yield simulations for Bukit Merah reservoir catchment, Malaysia using SWAT model. Results showed that sediment yield increase will exacerbate the reservoir operation problem. Ayana et al. (2012) applied SWAT model to simulate the sediment yield from the Fincha watershed in Ethiopia, it was found that the model accurately tracked the measured flows and simulated the monthly sediment yield well.

On Jordan scale, Harza (1978) utilized sediment deposition in Kafrain and King Talal reservoirs to adjust the constants of the equation which was developed from selected reservoir survey data in the semi-arid climate of the southwestern of USA (USBR, 1987), aiming at developing a similar formula suitable for estimating sediment yield in reservoirs of Jordan. However, the resulted equation gives rough estimate and is useful only for preliminary design because catchment area alone is not a good parameter on which sediment yield is based, since factors such as geology, slope, rainfall, land-use, and vegetation cover are crucial in determining soil erosion and sedimentation. Special attention has been given to soil erosion problems in Amman Zarga basin (Al-Sheraideh et al., 2000; Malkawi et al., 2002), and the associated troubles in reducing King Talal reservoir storage (Numayr, 1999).

Concerning the present study area, studies have seemed to be limited and the only engineering study being on hand at this juncture is the consulting study that was undertaken by Howard and Humphreys (1992). The study included Mujib catchment (4600 km^2) and Wala catchment (2000 km^2), and involved an analysis for daily flow duration curves and sediment rating curves based on daily flow records at Mujib station (1964 to 1989) and Wala station (1963 to 1989). From this analysis, the mean annual sediment transport has been estimated as 263600 m^3 and 316500 m^3 at Mujib and Wala, respectively. The consulting study included groundwater recharge model using MODFLOW model (McDonald and Harbaugh, 1988), and investigated the effect of sediment blanket forms on the reservoir bed. The adverse effect of the sediment on the recharge process was clearly identified. To mitigate sedimentation problem, removal of the deposited sediment has been suggested to be carried out during drought or low water periods, but these measures have not been implemented since the operation of the reservoir.

This study uses the comprehensive watershed model: Soil and Water Assessment Tool (SWAT2000), in a Geographic Information System (GIS) environment to simulate the hydrology, soil erosion, and sedimentation of Wala dam catchment area, to estimate the water and sediment loads delivered to Wala dam reservoir, and simulating the spatial variability in runoff and sediment generation within the area to produce soil erosion and sediment yield maps of the study area.

2. DESCRIPTION OF THE STUDY AREA

Among the major hydrologic basins of Jordam, Mujib basin occupies a considerable irregular-shaped area about 7% of the area of Jordan (about 6600 km^2). It comprises two major watersheds,

Mujib and Wala, both drained by a distributed stream network. Wala watershed occupies the upper part of Mujib basin, covering a triangular shaped region of nearly 2000 km^2. The area encompasses several intermittent wadis draining westerly from the highlands in the east, northeast and north to the lowlands of Jordan valley. The confluence of these wadis forms wadi Wala being one of the two major tributaries of the Mujib stream system, the other is wadi Mujib that drains Mujib watershed.

Wala dam is a 52 m height roller compacted concrete dam, constructed on wadi Wala, about 40 km south of Madaba with a storage capacity 9.3 x 10^6 m^3. The dam has been in use since November 2002 for purposes of groundwater recharge. The groundwater water recharge provides water to the springs and pumping wells of Al-Heidan.

The area for which this study has been implemented is Wala dam catchment area in Jordan. The main water resources in the area originate from a continuous system of springs increasing in a downstream direction, and the surface water resources that are exclusively used for agriculture (Al-Balawi, 2003). Wala area comprises semi-arid to arid plateau lands having a predominant Mediterranean climate characterized by hot dry summer and cold wet winter with significant seasonal and daily temperature variations. Precipitation tends to decrease rapidly eastward depending on aerographic effects; this characteristic greatly affects the hydrological conditions of the area and all related watershed processes. Agriculture in Wala catchment area is characterized by a highland agriculture with major crops such as wheat and barely planted in the non-irrigated regions. In addition, some kinds of trees are mainly grown in the irrigated areas.

3. SEDIMENT YIELD MODELS

Sediment yield studies estimate the amount of sediment that leaves an area over a period of time, therefore, they involve erosion processes as well as sediment deposition and delivery to a point of interest. Several mathematical deterministic models are available to estimate sediment yield, but mostly, their applications are limited to small areas because of the numerous data requirements including hydrological information, physiographic characteristics of the area, and extensive field measurements to determine parameters for the proposed equations (Sadeghi et al., 2007). In contrast to mathematical models, empirical models are simpler as they require mostly rainfall data and maps (topographic, soil, and vegetation). One of the most used empirical models is the Modified Universal Soil Loss Equation (MUSLE) that has been developed by Williams (1975) to derive a sediment yield estimation model based on rainfall and runoff characteristics. The MUSLE has been subjected to modifications and presented by Williams (1995) for individual hydrologic response units (HRUs) as:

$$SY = 11.8 \left(Q \cdot Q_p \cdot A_{hru} \right)^{0.56} \cdot K \cdot LS \cdot C \cdot P \cdot f_{CFRG} \tag{1}$$

where:
SY is sediment yield (tons),
Q is the runoff volume (mm) as computed by curve number method,
Q_p is peak flow rate (m^3/sec) as estimated by the rational method,
A_{hru} is the area of the HRU (ha), and K, LS, C, P, and f_{CFRG} are, respectively, the soil erodiblity, topography, cover management, support practice, and coarse fragments factors. Methods of estimation of these factors are given by Williams (1995), Das (2000), Suresh (2000), and Neitsch et al. (2005).

In the present study, Equation 1 has been utilized to estimate the sediment yield of Wala watershed at its outlet, i.e. at Wala dam reservoir. A detailed review on the equations and assumptions of the surface runoff, flow routing, erosion estimate, sediment yield and sediment routing can be found in the theoretical documentation of the SWAT model by Neitsch et al. (2005).

4. SWAT MODEL

4.1 ArcView/SWAT model

SWAT is a comprehensive watershed model developed by the USDA Agricultural Research Service and integrated into GIS to be capable of simulating a high level of spatial detail by allowing the division of a watershed into a large number of sub-basins (Gassman et al., 2003). It can predict the impact of land characteristics and management practices on water, sediment and agricultural yields in watersheds of different sizes with varying soils, land-use and management conditions. The required maps and databases include digital elevation model (DEM), different GIS layers, and several database files, and their assignment is represented in Figure 1.
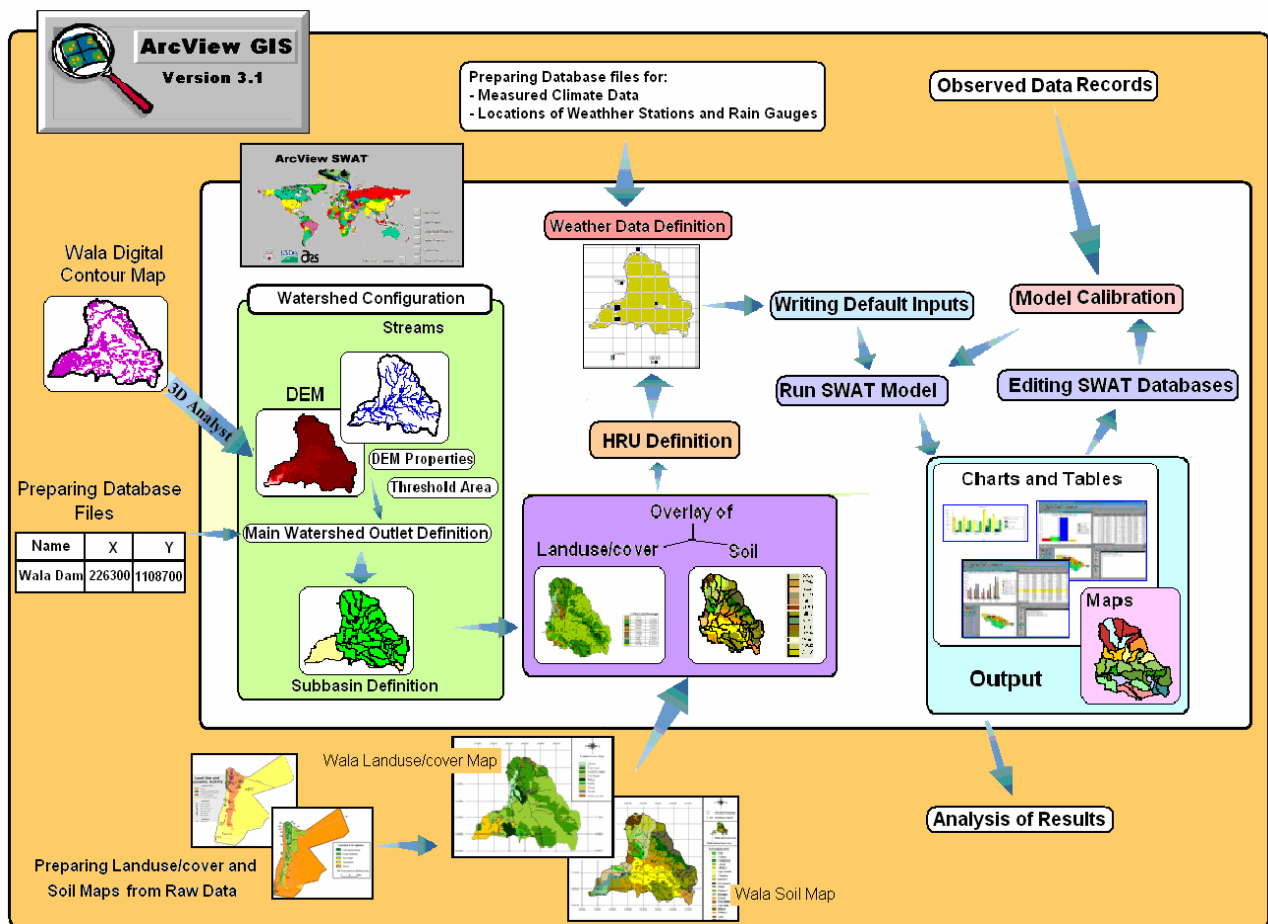
Figure 1. The process of using ArcView/SWAT with reference to Wala watershed.

4.2 Model calibration

In this study, several model runs were carried out for different periods during the years 1970 through 2000 to experience SWAT performance in modeling Wala watershed. All these runs were built on the default model conditions and parameters, and thus default outputs were obtained. In most SWAT models, water flow is a major variable upon which most other processes depend, therefore, a sketchy comparison was made between simulated and measured streamflow values, indicating that the model simulated the general streamflow trends, but discrepancies were found between observed and simulated values. However, this is normal in modeling, as it is unrealistic to expect the model to automatically set all input parameters to ideal values. Hence, model input modification was a necessity to increase the accuracy and reliability of outputs, the required

modifications were controlled by model calibration, but prior to this, the quality of the observed data for the whole period was checked to select the most suitable period for model calibration and verification.

SWAT inputs are physically based and can be obtained from existing land properties and conditions, but there is still some uncertainty in the inputs that are sometimes difficult to be well defined, such as the curve number (CN) and the USLE cover factor (C), which have been used as calibration parameters in this study to compensate for any expected uncertainty in land-cover and soil definition. The typical procedure for SWAT model calibration is to calibrate streamflow and sediment in succession. It is very important at this juncture to state that specific measures (qualitative and quantitative) of model performance have been employed to decide when the results are acceptable and when to stop the calibration. The qualitative assessment has been made in the preliminary stage by visual comparison between measured and simulated results through graphs, then the calibration has been assessed quantitatively using the following statistical indicators: The mean of residual errors (M), The Variance of residual errors (VAR), The standard deviation of residual errors (SDEV), The mean of absolute residual errors (MA), The root mean of squared residual errors (RMS), and The linear correlation coefficient (r). In addition, literature shows that Nash-Sutcliffe model efficiency (E_{model}) (Nash and Sutcliffe, 1970) is usually used to quantify the closeness of fit between SWAT-modeled results and observed data. Efficiencies equal to 1 indicate a perfect fit, while values equal to 0 indicate that the model prediction is not better than the average of the observed data.

4.3 Model components

The main components of the model as applied for Wala watershed, are:
1. Wala watershed delineation; The digital contour map of Wala watershed (Tarawneh, 2007) has been processed using the 3D analyst of ArcView GIS to create a raster DEM grid of 25m resolution, Wala catchment has been delineated into 43 sub-basins as shown in Figure 2.
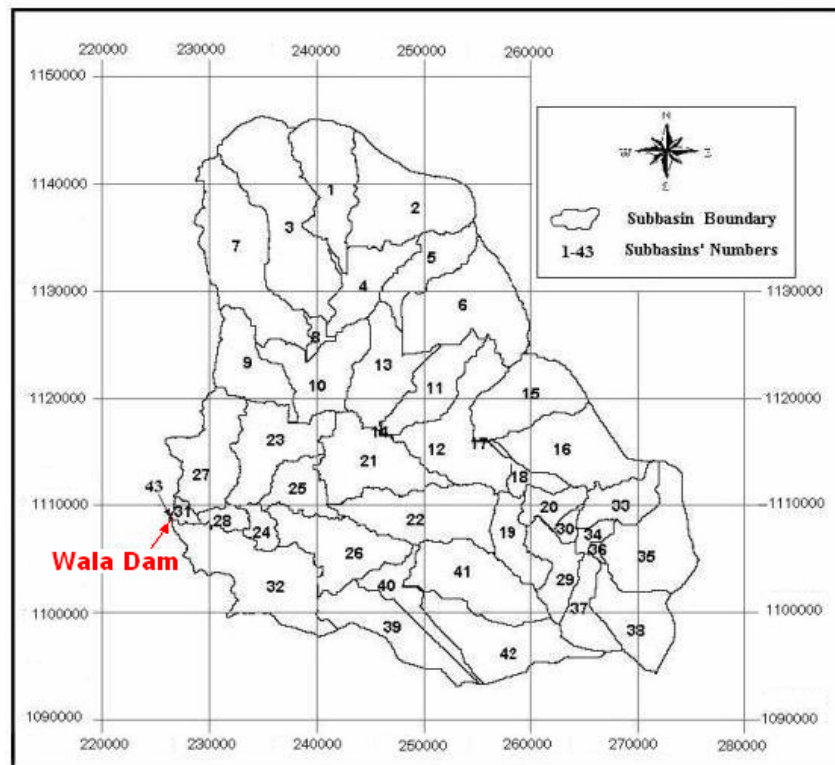

Figure 2 . Wala catchment area sub-basins as configured by SWAT.

2. Wala vegetation and land use definition; Land use and vegetation data from the national soil map and land-use project (MOA, 1994), which have offered some refinement for the broad classification presented by Royal Jordanian center. SWAT has produced Figure 3 that shows Wala sub-basins with their respective land-use cover, and the percentage of each category with respect to the catchment area.

3. Wala vegetation and land use definition; Land use and vegetation data from the national soil map and land-use project (MOA, 1994), which have offered some refinement for the broad classification presented by Royal Jordanian center. SWAT has produced Figure 3 that shows Wala sub-basins with their respective land-use cover, and the percentage of each category with respect to the catchment area.

4. Wala soil definition: A vector map and database for Wala watershed soils have been prepared during this study depending on the information provided by the national soil map and land-use project (MOA, 1994). Each sub-basin has been characterized by one or more soil units, as appears in Figure 4.

5. Hydrologic response units distribution: The first level of watershed subdivision creates sub-basins, which can be subjected to further discretization into multiple hydrologic response units (HRUs) consisting of unique combinations of land-use/cover and soil. The benefit of HRUs is the increase in accuracy they add to the prediction of sub-basin loading. SWAT has generated detailed reports regarding the number and distribution of HRUs in each sub-basin, and the respective land cover/soil classes (Tarawneh, 2007).

6. Weather data definition: The climatic variables required by SWAT include daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity, these are obtained from Qatraneh and Errabbah weather stations as being the nearest stations for which the required statistical dataset can been prepared (Tarawneh, 2007). Each sub-basin has been linked to one of them, whichever is closest, to account for any missing sub-basin weather data. The rain gauges option has been chosen to assign available measured rainfall data for five rain gauges through Wala watershed (Diban, Dhab'a, Amman Airport, Madaba and Wala rain gauges). During the simulation, each sub-basin has been linked to the gauge which is closest to its centroid. The Qatraneh and Errabbah stations have not been included as rain gauges although rain data are available for them, the reason is that these stations are remoter than the five rain gauges listed above, thus they will be excluded by default because of the presence of closer gauges.
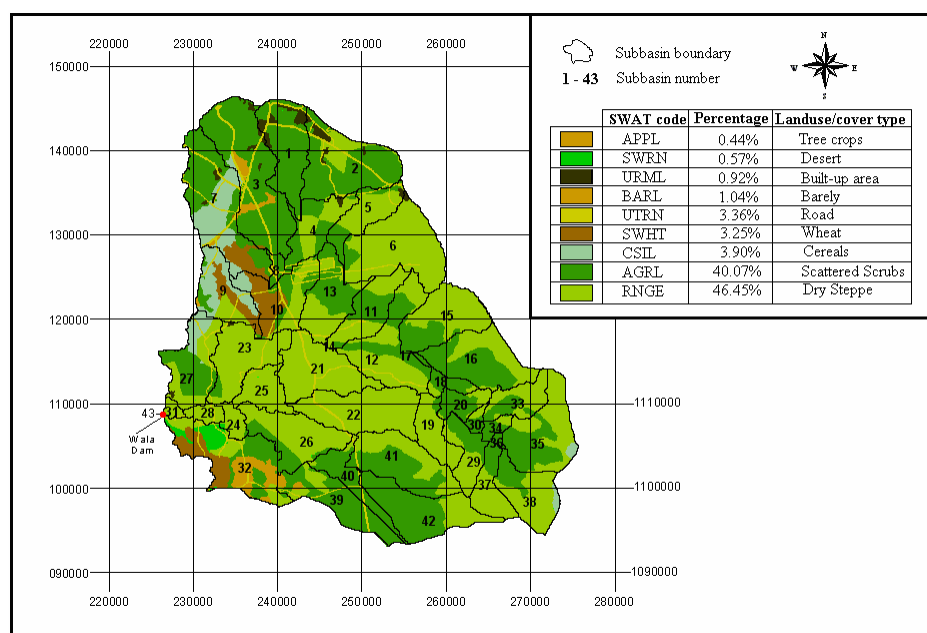

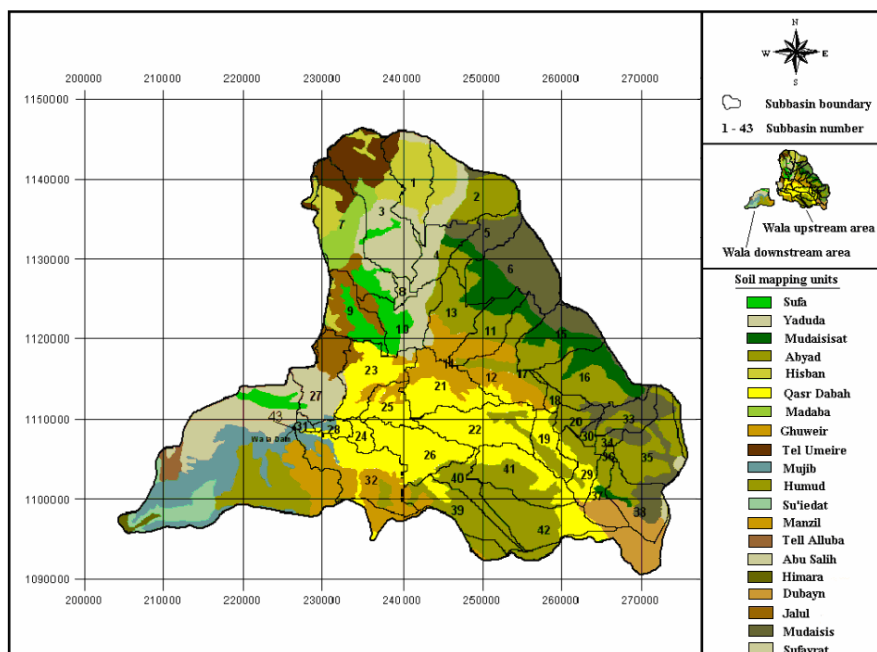*Figure 3. Land-use/cover map of Wala Dam catchment area as defined by SWAT.*

Figure 4. Wala watershed soil map.

5. RESULTS AND DISCUSSION

The Wala watershed SWAT model has been executed and a variety of results has been generated, and in light of these results, the model inputs have been subjected to further modifications during the calibration process. The calibrated inputs have been employed to run the model again for verification and validation periods.

5.1 Streamflow calibration

Calibration of streamflow has been performed depending on observed flow measurements at Wala gauging station (CD0038), provided by Water Authority of Jordan (WAJ), for the period May 1972 through October 1979 because for this period, better quality data are available for model setup and calibration. Firstly, the model has been executed and calibrated for annual flows, and then the calibration has been fine-toned for temporal changes of monthly flows. The initial annual simulation has shown a general overestimation of flow values, thus the (CN) has been selected as a calibration parameter for its significant effect on flow computation, and the sub-basins' (CN) values have been varied iteratively within a reasonable range during several runs until satisfactory agreement has been gotten between simulated and observed flow values. Table 1 represents the values of the statistical indicators, mentioned before, using the observed and calibrated average annual flow values at the outlet of Wala catchment area. As can be seen in Figure 5, good correspondence has been obtained between observed and calibrated annual flows.

Once average annual flow has been calibrated and found realistic, more scenarios have been created to check whether the temporal changes in flow are reasonable as well. Adopting the calibrated set of parameters, the model has been run on a monthly basis for the same period, and again, the optimum scenario has been selected according to the previous statistical criteria. Table 1 summarizes the obtained statistics, by which it might be noticed that larger values of some statistical measures have been accepted for the monthly calibration in comparison with the annual statistics, this is because the great variation in the monthly observed flows makes it difficult to obtain better calibration. To be more satisfied with the results in such cases, it is recommended to apply the concept of relative errors (Zheng and Bennet, 2002). Relative errors have been obtained

by dividing the statistical measures by the difference between the maximum and minimum observed flows as reported in Table 1. Figure 6 represents the observed and calibrated monthly flows. The model efficiency is higher for annual simulation than for monthly, which is probably due to the elimination of some differences in observed and simulated flows by an averaging process within the year. The optimum (CN) values obtained after model calibration on HRUs level range from 78 to 85.
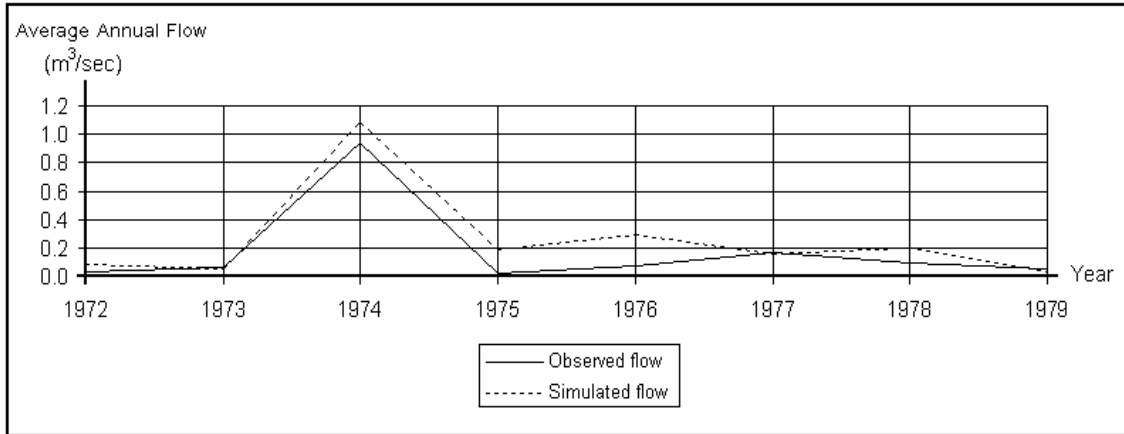

Figure 5. Comparison between observed and simulated annual flows.

Table 1. Calibration statistics for streamflow.

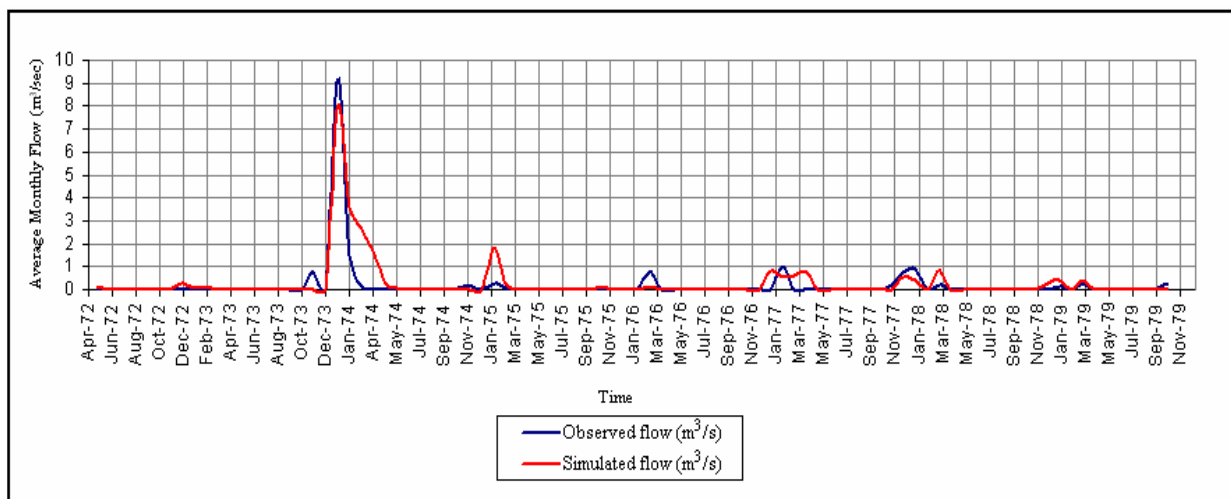| Statistical indicator	Annual simulation	Monthly simulation	Relative error
M	0.08 (m^3/sec)	0.09 (m^3/sec)	0.01
VAR	0.01 (m^3/sec)^2	0.23 (m^3/sec)^2	0.03
SDEV	0.1(m^3/sec)	0.48 (m^3/sec)	0.05
MA	0.09 (m^3/sec)	0.19 (m^3/sec)	0.02
RMS	0.12 (m^3/sec)	0.49 (m^3/sec)	0.05
R	0.97	0.88	
E_{model}	0.83	0.75	

Figure 6. Comparison between observed and simulated average monthly flows for the calibration period.

5.2 Sediment load calibration

The required observed sediment loads have been acquired from the sediment rating curve that was prepared by (Howard and Humphreys, 1992) for Wala gauging station during the preliminary

design studies of Wala dam. The USLE cover factor has been adjusted to match observed and simulated sediment loads through several iterations, for which the previous model performance indicators and the context of relative errors have been applied. Table 2 summarizes the statistics of the optimum simulation, and Figure 7. depicts the monthly variation of observed and simulated results for the period of calibration. The optimum values of the USLE cover factor obtained on HRUs level range from 0.003 to 0.19. All calibration statistics, either for flow or sediment, are acceptable and indicate that SWAT is able to simulate the study area and predict flows and sediment loads well, depending on the optimum set of parameters.

Table 2. Calibration statistics for sediment loads.

Statistical Indicator	Relative Error
M	0.02
SDEV	0.05
MA	0.02
RMS	0.05
r	0.97
E_{model}	0.75
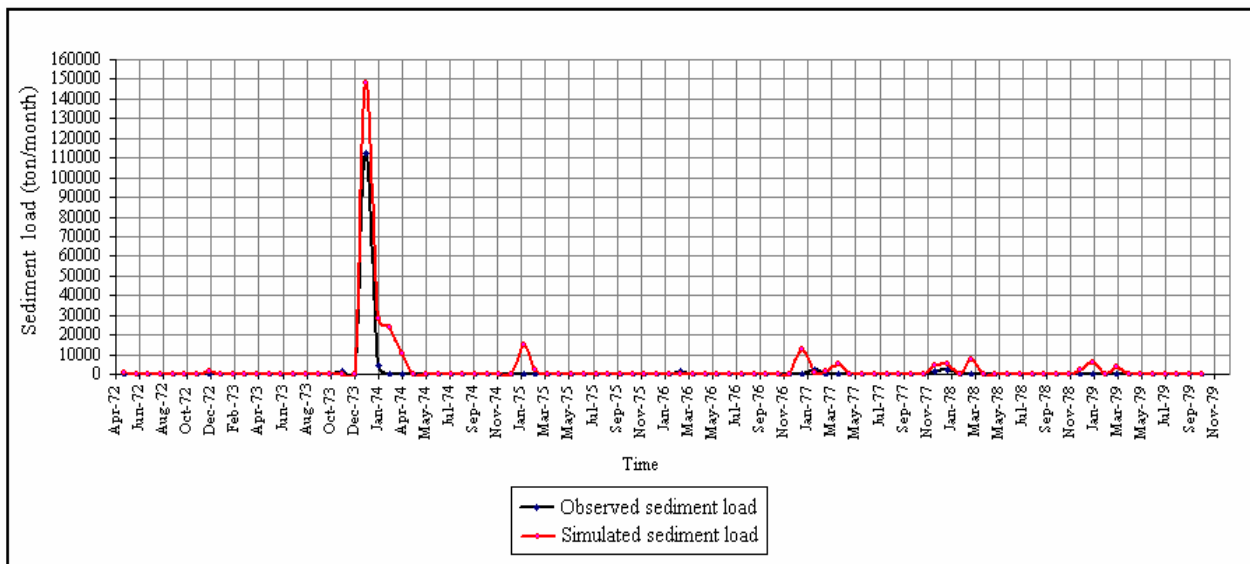
Figure 7. Comparison between observed and simulated monthly sediment loads for the calibration period.

5.3 Model verification

The calibrated parameters are used to check the model capability of reproducing measured flow and the corresponding sediment loads at Wala gage station. The period October 1990 to September 1998 is selected as having better quality data records. The temporal variations of monthly and simulated results for verification period are depicted in Figures 8 and 9 for flow and sediment load, respectively. A reasonable match can be noticed from these figures, giving more support toward utilizing SWAT to model Wala watershed and achieve the intended modeling objectives.

6. WALA SWAT MODEL AS A PREDICTION TOOL

The calibration and verification results afford credibility for using the calibrated model for prediction purposes; the model has been utilized for two different prediction periods as follows.
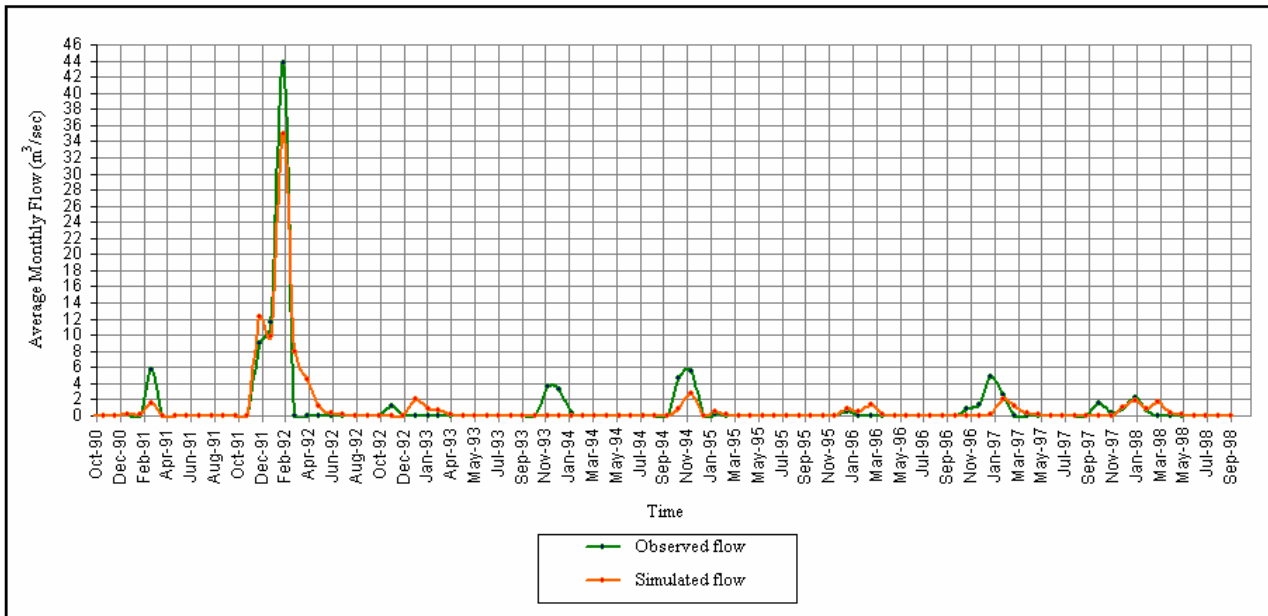
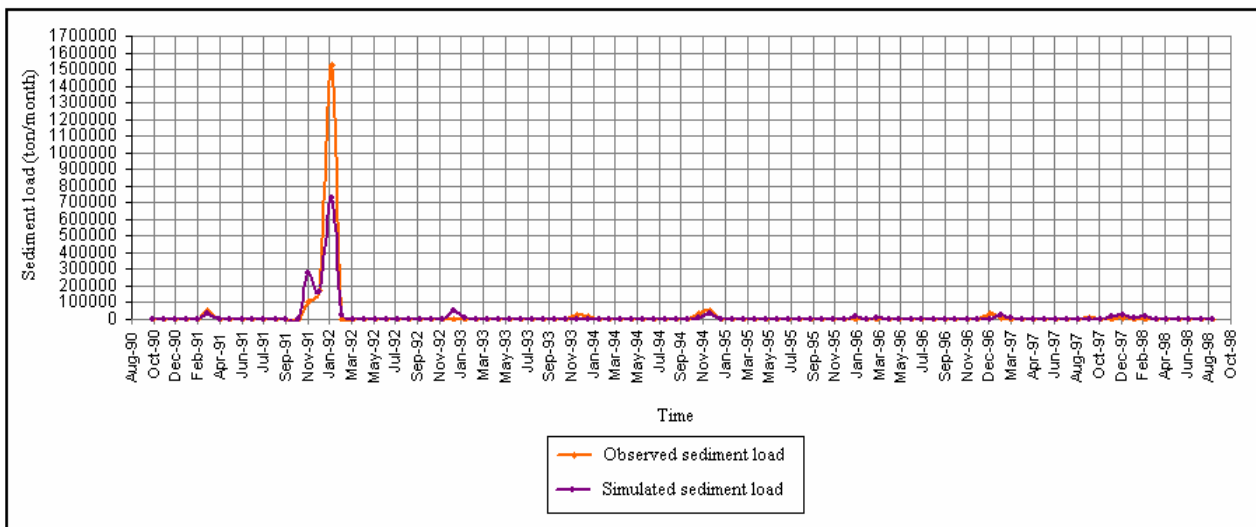*Figure 8. Comparison between observed and simulated monthly flows for the verification period.*

Figure 9. Comparison between observed and simulated monthly sediment loads for the verification period.

6.1 Prediction period (2002-2007)

Unfortunately, no or very limited flow and sediment measurements at Wala gage station are available for the period after the construction of Wala dam. For this period, the prediction extends from November.2002, the date on which Wala dam has been in operation, to December 2007. Daily rainfall data are available and are used in the SWAT model. The model has been run both annually and monthly for the mentioned period and several types of outputs have been produced. Figures 10 and 11 represent the predicted values of average annual flow and sediment yield. It can be concluded from figures above that the same trend has been gotten in flow and sediment yield simulation; this indicates that the two processes are strongly related. The maximum flow and sediment yield correspond to the year 2003, this is because the rainfall records provided for this year contain high values. Depending on the simulated sediment yields, a total amount of 742860 ton expected to be transported to Wala dam reservoir during the period November 2002-December.2007; this amount is equivalent to a volume of 571431 m^3 of sediments, assuming a bulk density of 1.3 ton/m^3 for sediments deposited in the reservoir. Monthly flow and sediment yield

have been simulated for the same period and the results also show similarity in the trend between water flow and sediment, as can be noticed in Figures 12 and 13. From Figure 12, SWAT shows a good performance in simulating the seasonal variation in flow as expected according to the climate of Jordan, where most precipitation occurs during the months November to February.
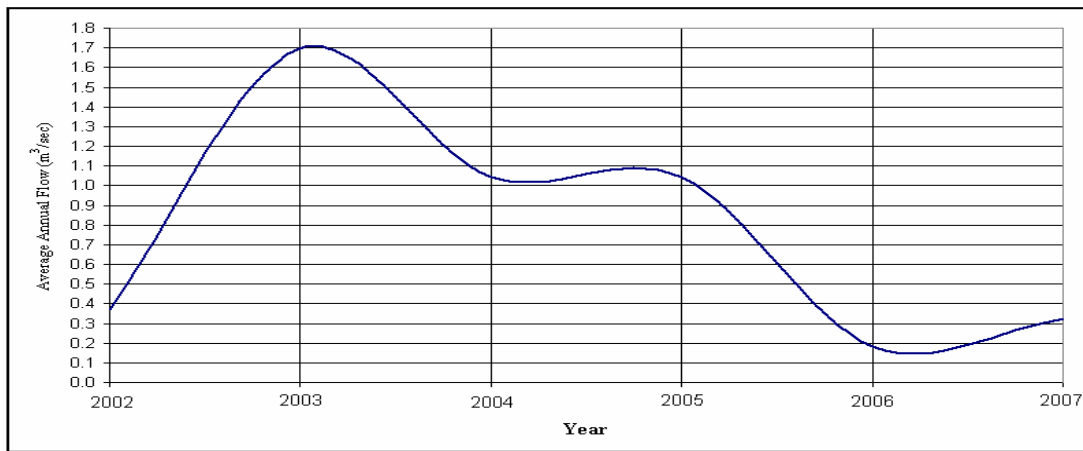

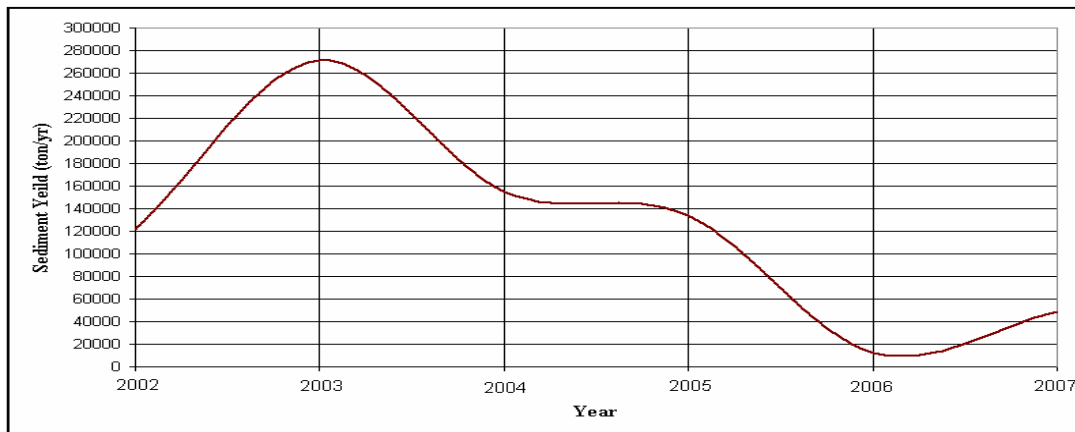*Figure 10. Average annual flow as predicted by SWAT at Wala Dam location (2002-2007).*

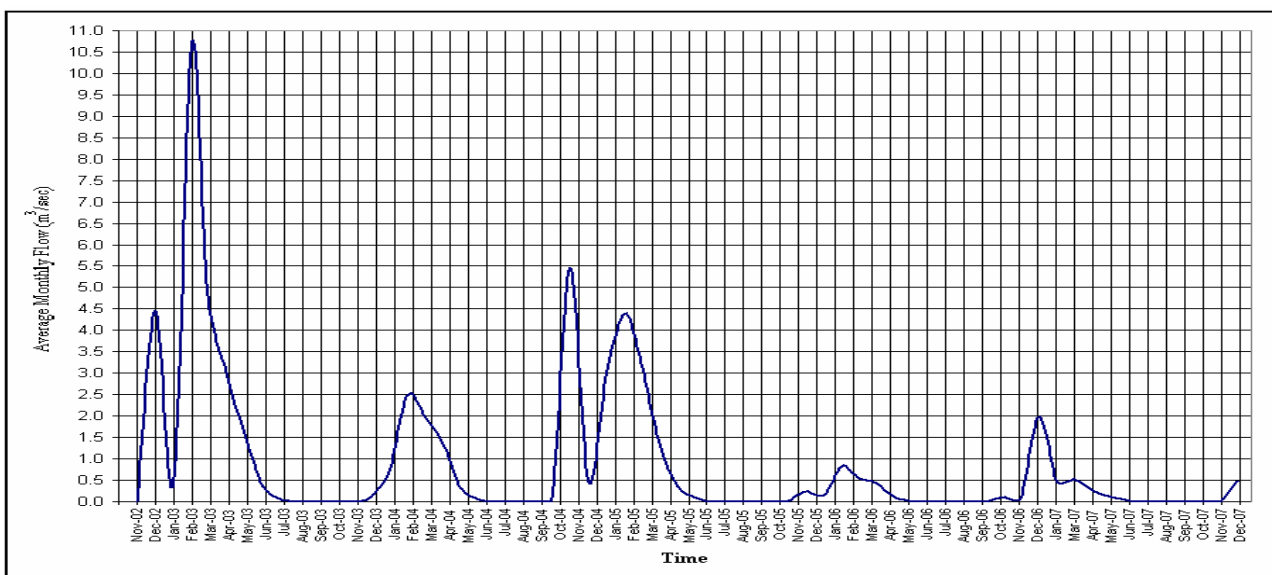*Figure11. Annual sediment yield as predicted by SWAT at Wala Dam location (2002-2007).*

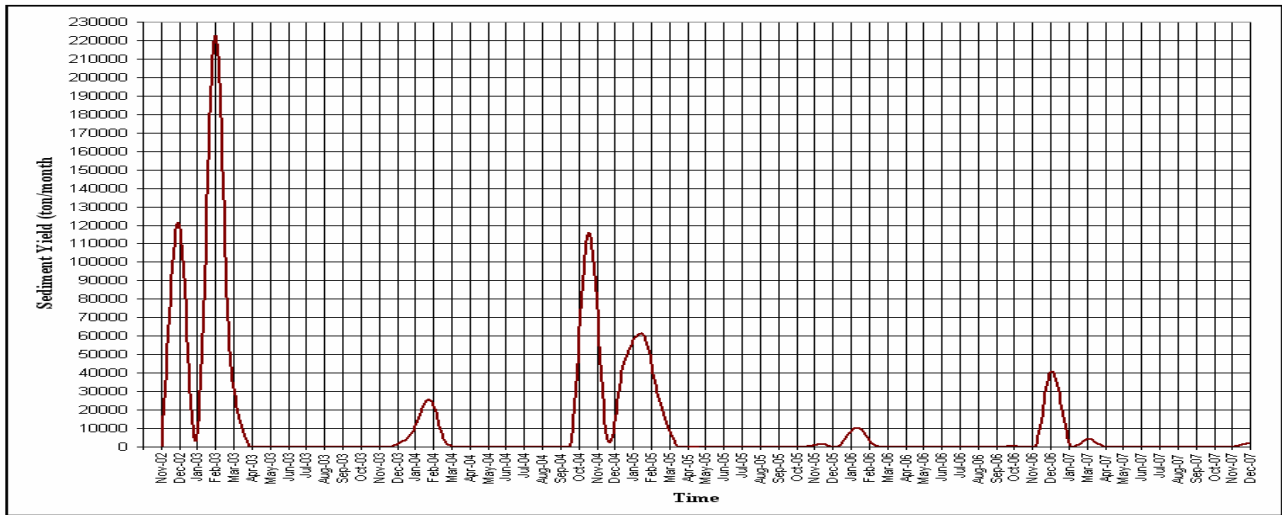*Figure 12. Monthly flow as predicted by SWAT at Wala dam location.*

Figure 13. Monthly sediment yield as predicted by SWAT at Wala dam location.

The amount of soil erosion per unit area is calculated using the USLE. Figure 14 displays the average annual soil erosion for the years 2002 to 2007. The sub-basins which show greater susceptibility to soil erosion mostly lie in the western and northern parts of the area. Various characteristics of climate, topography, soil and land-cover conditions cause this differentiation in soil erosion in different sub-basins.
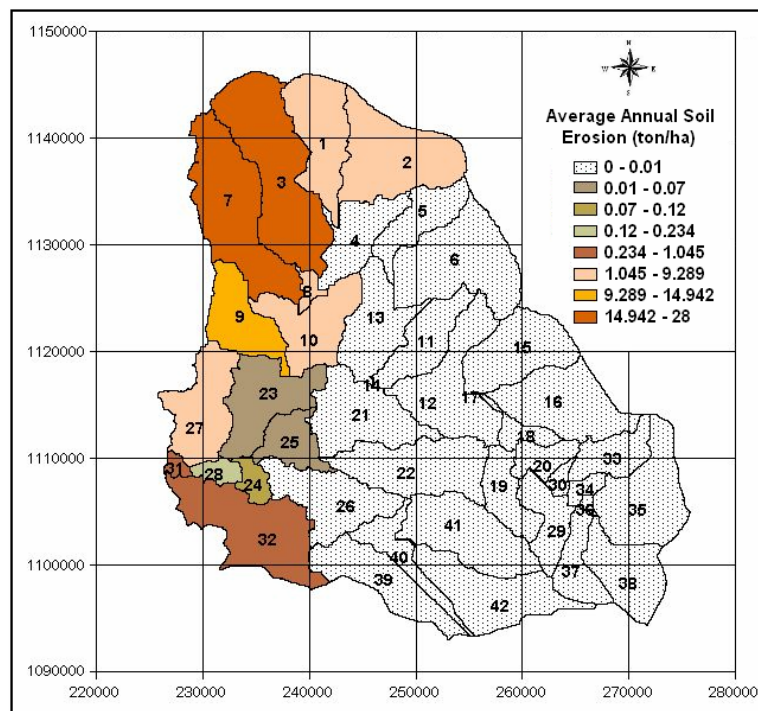

Figure 14. Average annual soil erosion simulated for the period 2002-2007.

It is very imperative for this study to determine the partial contribution of each sub-basin within Wala dam catchment area to the total loads received by Wala dam reservoir, either water or sediment yield. The resulting average annual loads of water and sediment originating from each sub-basin and received by Wala dam reservoir are shown in Figures 15 and 16, respectively. It is obvious that the sub-basins that contribute the greatest amounts of water and sediment are located in the north and west of the area. This result is expected as more precipitation is received by the northern and western regions, causing greater runoff, streamflow and soil erosion to be generated.

In addition, the geographical arrangement and closeness of these areas with respect to Wala dam increase the chance to deliver more loads; this is also concluded by computing the delivery ratios from each sub-basin to Wala dam reservoir.
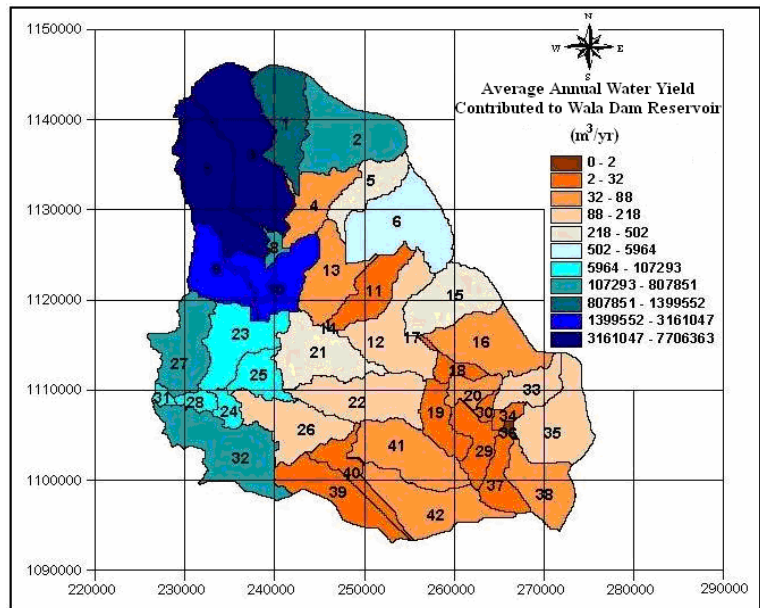

Figure 15. Average annual water yield contributed to Wala dam reservoir from each sub-basin for the period 2002-2007.
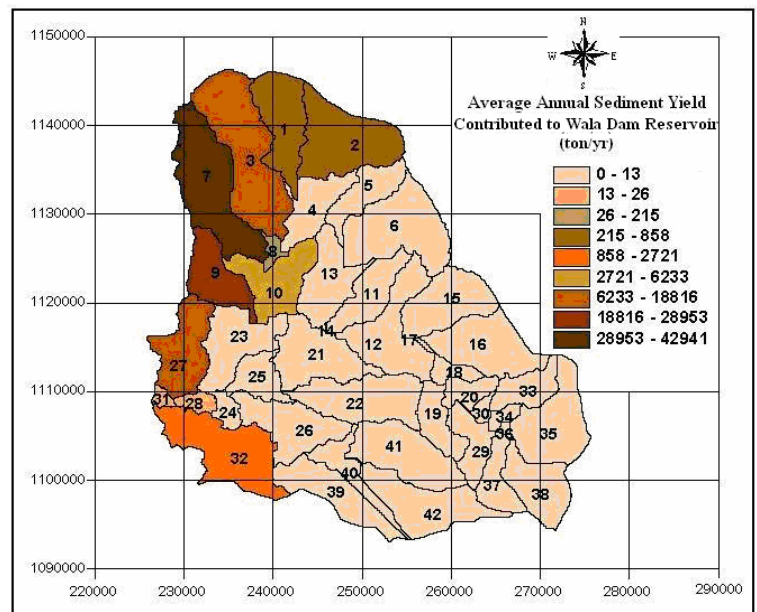

Figure 16. Average annual sediment yield contributed to Wala dam reservoir from each sub-basin for the period 2002-2007.

6.2 Prediction period (2008-2020)

The prediction has been extended to simulate the period 2008-2020 depending on weather data that have been generated using the provided weather generator that utilizes Markov chain model to generate precipitation. In Markov model, each day is defined as wet or dry by comparing a random number between zero and one generated by the model to monthly wet-dry probabilities assigned in the weather generator. If a day is classified as wet, the amount of precipitation is generated from a

skewed distribution (Neitsch et al. 2005). Figures 17 and 18 depict the annual flow and sediment yield at Wala dam location for the years 2008-2020, in addition to the average values for the whole period. Promising results have been obtained with respect to the quantity of sediment yield at Wala dam location (an average value of 123100 ton/year), which is equivalent to average 94700 m^3/year (considering a sediment density of 1.3 ton/m^3), warning of a real threat of reducing the operational life of the dam by decreasing its active storage and adversely affecting the reservoir's ability to recharge the groundwater aquifer due to sediment deposition and the resulting clogging at the bottom. Returning back to the results for the period 2002-2007, the average annual sediment load is about 143780 ton/year; this amount is somewhat comparable to that obtained for the period 2008-2020, and thus the predictions of the model give some insight regarding the expected storage loss due to sediment accumulation in the reservoir.
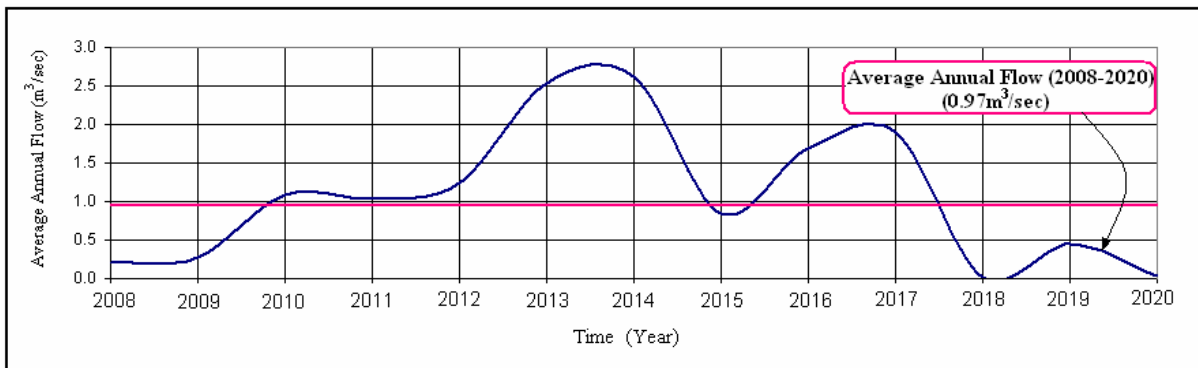

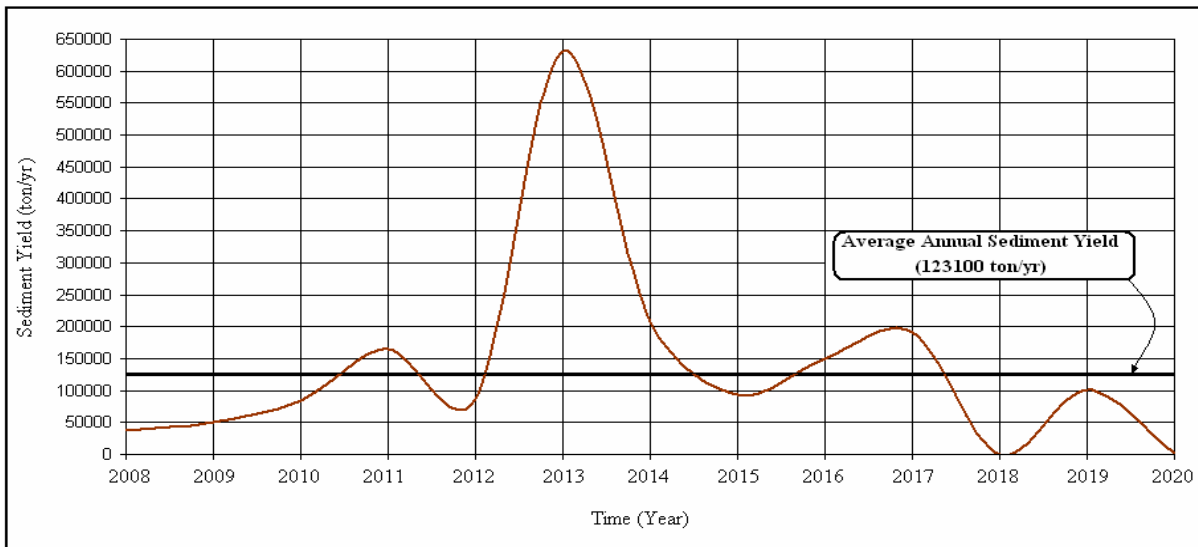*Figure 17. Average annual flow as predicted by SWAT at Wala Dam location (2008-2020).*

Figure 18. Annual sediment yield as predicted by SWAT at Wala Dam location (2008-2020).

7. CONCLUSIONS

Results indicate that SWAT can be used to simulate the hydrological processes and sedimentation of Wala dam catchment area to produce reasonable estimates of monthly and annual streamflows and sediment yields. The model calibration was evaluated and all statistical measures have shown good performance of SWAT to simulate Wala watershed. Inputs and outputs of the model indicate that the northern and western parts of the study area receive greater amounts of rainfall, generate larger runoff volume to streams, are more susceptible to soil erosion, and yield greater water and sediment to Wala dam reservoir. Management and conservation practices are

recommended to be applied for these parts of the catchment area; several practices can be suggested comprising land contouring, terracing in the hilly regions, and planting certain kinds of trees. The study revealed that the model, with its corresponding optimum set of parameters, is able to predict water flow and sediment yield values, which might be beneficial for future planning and management. The built SWAT model can be utilized to simulate different scenarios to examine the effect of different types of management practices and land-cover/uses in mitigating the problems of soil erosion and sedimentation in cooperation with the concerned agencies.

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