Predicting Sedimentation at Mujib Dam Reservoir in Jordan

Abbas Z. Ijam [1] ***and Mohammad H. Al-Mahamid*** [2]

Civil and Environmental Engineering Department, Faculty of Engineering, Mu'tah University, Mu'tah, Jordan.
[1] Professor of Civil and Environmental Engineering, E-Mail: abbasa@mutah.edu.jo
[2] Water and Environment Engineer, E-Mail: m_mahamid1981@yahoo.com

ABSTRACT

Reservoir sedimentation is a severe problem facing dams causing the decrease of active water storage which is the main purpose of the construction of dams. Mujib dam, constructed in Jordan in 2003, was selected to estimate the quantity of sedimentation in its reservoir. Arc-View Soil and Water Assessment Tool (AVSWAT) model was used to simulate Mujib dam catchment area. The results of this study identified the quantity of water and sediment inflow to the reservoir. They also identified the regions of high soil erosion, sediment yield and delivery ratio in order to manage these regions by applying techniques which reduce these values in sequence to decrease the sediment yield reaching the reservoir.

KEYWORDS: Sediment yield, Erosion, Water-Soil model, Dams, Mujib, Jordan.

INTRODUCTION

There are many reservoirs that can no longer perform their design functions because much of their original active storage volume has been filled by sediment. For hydropower projects and water supply schemes, any loss of storage increases the risk of failure to meet the design objectives in extreme dry periods. Jordan suffers from limited water resources and an increasing demand for water due to the increase in population growth rate, so the water authorities in the last two decades started water harvesting projects, especially dam projects in many regions. Mujib dam is one of these projects, constructed for facing water problems in Jordan. The useful life of dams and future planning for water resources depend on sedimentation in reservoirs.

There are a number of studies on sediment measurements which have been conducted to estimate the deposit of sedimentation in reservoirs. The U.S. geological survey (USGS, 2005) has completed a number of reservoir sediment studies in Kansas using a combination of bathymetric surveying, sediment coring, chemical analysis and statistical analysis. The results indicated that decreases in total water storage capacity ranged from less than 5% to about 55%. Aynekulu et al. (2006) reported that the lifetime of two dams in Ethiopia is almost five times shorter than that considered during the design phase. Perault et al. (2002) used historical field measurements of sediments in the College Lake in Virginia, USA and confirmed the loss of storage capacity of the lake until it is completely filled in.

Attempts have been made to develop predictive erosion and sediment models (Lane et al., 2000; Vicente and Confield, 2004; Salas and Shin, 1999; Kaur et al., 2003; Logan et al., 2005; Jain et al., 2005; Arnold et al., 1995). Applications of these models in several countries have shown promising results in the assessment of erosion, runoff and sediment yield, under a wide range of soil types, land uses and climate conditions.

In Jordan, the first sediment data were obtained in

Accepted for Publication on 21/7/2012.

1962 (Khatib, 1973), and the main purpose of these data was to construct a stream load-rating curve. Lara (1980) from US Bureau of Reclamation conducted the first sedimentation survey for King Talal reservoir by using sonic depth recording equipment. Surveys were conducted annually from 1981 to 1993 by Jordan Valley Authority, the primary purpose of these surveys was to measure the reduction of active storage by sedimentation in the reservoirs (Malkawi et al., 2002). Harza (1978) has used sediment deposition measurements in Kafrien and King Talal reservoirs to approximate a relationship, $Q_s = 6290\ A^{-0.418}$, to estimate sediments in reservoirs in Jordan, where Q_s is the sediment inflow rate (m^3/year/km^2) and A is the catchment area (km^2). Sheraideh et al. (2000) have estimated the sediment yield at Amman-Zerqa basin in Jordan using Agricultural Non-Point Source (AGNPS) model in order to enhance the reservoir capacity of King Talal dam. Malkawi et al. (2002) had implemented remote sensing and GIS assisted modeling of soil induced erosion hazards on Amman-Zarqa basin, the study implemented Revised Universal Soil Loss Equation (RUSLE) and Stehlike's model. It was found that areas in the central and western parts of the basin have the highest erosion potential.

In the present study, Mujib dam reservoir is chosen as a case study in applying the Modified Universal Soil Loss Equation (MUSLE) model with the use of Geographical Information System (GIS) and Digitized Elevation Model (DEM) software.

MODELING OF SEDIMENT YIELD

Sediment yield is simply defined as the final and net result of detachment, transport and deposition processes occurring to the point of interest where sediment yield information is needed (Lane et al., 1984). There are several factors which affect the sediment yield; the main factors are: land use, soil type, catchment size, climate and rainfall (Suresh, 2000). Wischmeir and Smith (1965 and 1978) developed the Universal Soil Loss Equation (USLE) for predicting gross soil erosion from agricultural watersheds. MUSLE is a modified version of the USLE, developed by Williams (1975). In the modified model, the rainfall energy factor is replaced by a runoff factor, this modification allows the equation to be used for predicting sediment yield, eliminates the need for delivery ratios and allows the equation to be applied to individual storm events (Neitsch et al., 2002).

The modified universal soil loss equation is:

$$Sed = 11.8\ (Q_{surf}\ q_{peak}\ A) \cdot K \cdot C \cdot P \cdot LS \cdot CFRG \quad (1)$$

where Sed is the sediment yield on a given day in (metric tons), Q_{surf} is the surface runoff volume in (mm.ha), q_{peak} is the peak runoff rate in (m^3/sec), A is the area of the sub-region in (km^2), K is the soil erodibility factor in (metric ton.m^2.hr/(m^3.metric ton.cm)), C is the cover and management factor, P is the support practice factor, LS is the topographic factor and CFRG is the coarse fragment factor. Detail on methods of estimating the different factors is given in the Soil and Water Assessment Tool (SWAT model) theoretical documentation published by (Neitsch et al., 2002).

SWAT model is a river basin, or watershed, scale model developed for the USDA Agricultural Research Service (ARS). SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. The model is physically based, is computationally efficient and enables users to study long-term impacts. The SWAT model uses ARCVIEW interface, so AVSWAT is selected for modeling the sediment yield for Mujib dam reservoir in Jordan in the present study.

DESCRIPTION OF THE STUDY AREA

Mujib Basin

Mujib hydrological basin is located in the middle of Jordan and covers 7000 km^2. It largely comprises semi-arid to arid plateau land. Mujib basin contains two main valleys: Wadi Al-Mujib and Wadi Al-Wala. Wadi Al-Mujib contains four dams: Mujib dam, Siwaqa dam, Qatraneh dam and Sultani dam (Figure 1). In this study, Mujib dam catchment area covers an area of 1311 km^2 lying between the desert highway and the King's highway. Topography of the catchment varies widely, in the range from 200 m to 1200 m above mean sea level. As in most semi-arid areas, temperatures exhibit large seasonal and diurnal variations, with daily temperatures ranging from a maximum of around 43°C in August to a minimum of -5°C in January. Annual precipitation decreases rapidly eastwards from over 300 mm near the escarpment to less than 150 mm in the center of the basin and to less than 50 mm in the extreme south-east. The soil map for Mujib dam catchment area was obtained from the National Soil Map (Ministry of Agriculture, 1994) and digitized using ArcView Software. The area contains 13 subregions, each of which has approximately uniform soil properties. The study area contains three types of major vegetation regions: desert region, dry steppe region and scrub/woodland region.

Mujib Dam

Mujib dam is a roller compacted concrete, RCC dam with earth-fill abutments. The total length of the dam is 765 m and it is of 62 m maximum height. The storage capacity of the dam reservoir is 32 MCM. The reservoir length is 5 km, it is of 1100 m maximum width, 194 m maximum water level and 189 m full supply level. The RCC part of the dam is 467 m long and constructed as a stepped spillway with a design flood of 5839 m^3/sec determined from flood analysis employing a 10^4 year return period. The dam is provided with a drainage gallery and a bridge over the dam crest, 300m long, to connect King highway of Madaba-Karak. The reservoir yield is 16.8 MCM to provide water to the southern Ghor irrigation project, the Arab Potash company the Dead Sea chemical complex and to the developments on the east shore of the Dead Sea.

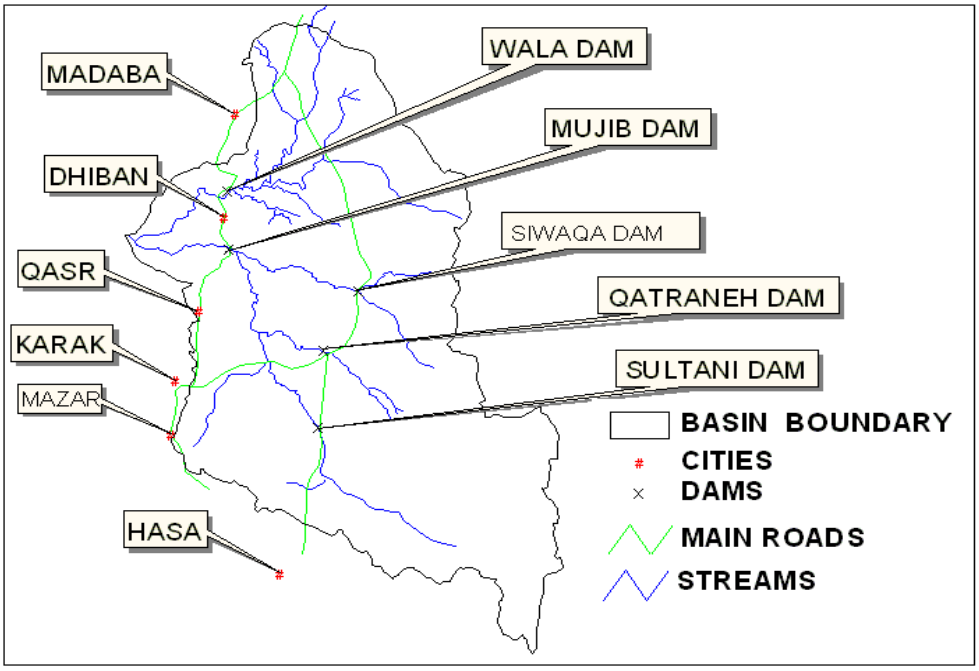

Figure 1: Mujib basin and existing dams

MODELING OF THE STUDY AREA

Data Preparation

The data required for the model contain maps or layers and data base files. The data preparing steps are:

1. The digital elevation model is created using Arc-View GIS 3.1 version for Mujib watershed and the adjacent regions as shown in Figure 2.
2. The land cover map shown in Figure 3 is digitized using Arc-View in order to enable us to use it in the model. The study area contains three types of land cover: dry steppe, scrub/woodland and desert. These types are close to: dry steppe of shrubland (RNGB), agricultural land of scattered scrubs and woodland (AGRL) and desert area(SWRN) consequently as loaded in the default SWAT data base according to USGS definitions.
3. The soil GIS layer for the area is shown in Figure 4. The National Soil Map of Jordan provides important data for each subregion such as: silt, sand and clay contents. Additional data are prepared for each subregion such as: soil type, hydraulic conductivity, soil available water content, soil hydrologic group, soil moisture bulk density and soil erodibility factor.
4. Daily precipitation data file for four rainfall gauges (Dhiban, Qatraneh, Rabbah and Mazar gauges), and weather generator data file for two stations (Qatraneh and Rabbah stations) are provided to the SWAT model.

Modeling Procedure

The modeling steps are summarized below:

1. The first step after preparing all required data is watershed delineation. The model utilizes the provided DEM and streams layer to delineate the area into subbasins as shown in Figure 5. Then, the model estimates the related data for streams layer and subbasins layer, such as: area of subbasins, average slope of subbasins, length and cross-sectional dimensions of streams and field slope length.
2. The model will overlay the soil and landcover layer on the subbasins layer and create a description report which includes each subbasin and its landcover and soil types within the subbasin.
3. The hydrologic response unit (HRU) is defined to allow the model to subdivide the study area into regions having unique soil and land cover properties.
4. Loading the daily precipitation and weather stations data files into the model.
5. The SWAT database is linked to the layers data in order to find all the parameters necessary for estimating the sediment yield at each HRU (Al-Mahamid, 2007).
6. Running the model for the period of simulation.

RESULTS AND DISCUSSION

In practical model application, model input parameters are never completely defined and are always associated with various uncertainties, so after a model of a specific site is constructed through assembly of the appropriate input files, it is generally necessary to calibrate the model. Calibration is a process in which model input parameters are adjusted until model output variables match field observed values to a reasonable degree. But the calibrated model must be capable of reproducing a set of field observations independent of that used in the model calibration, this step is called the verification process, then the calibrated model becomes capable of predicting future conditions with sufficient precision and this step is called the validation process.

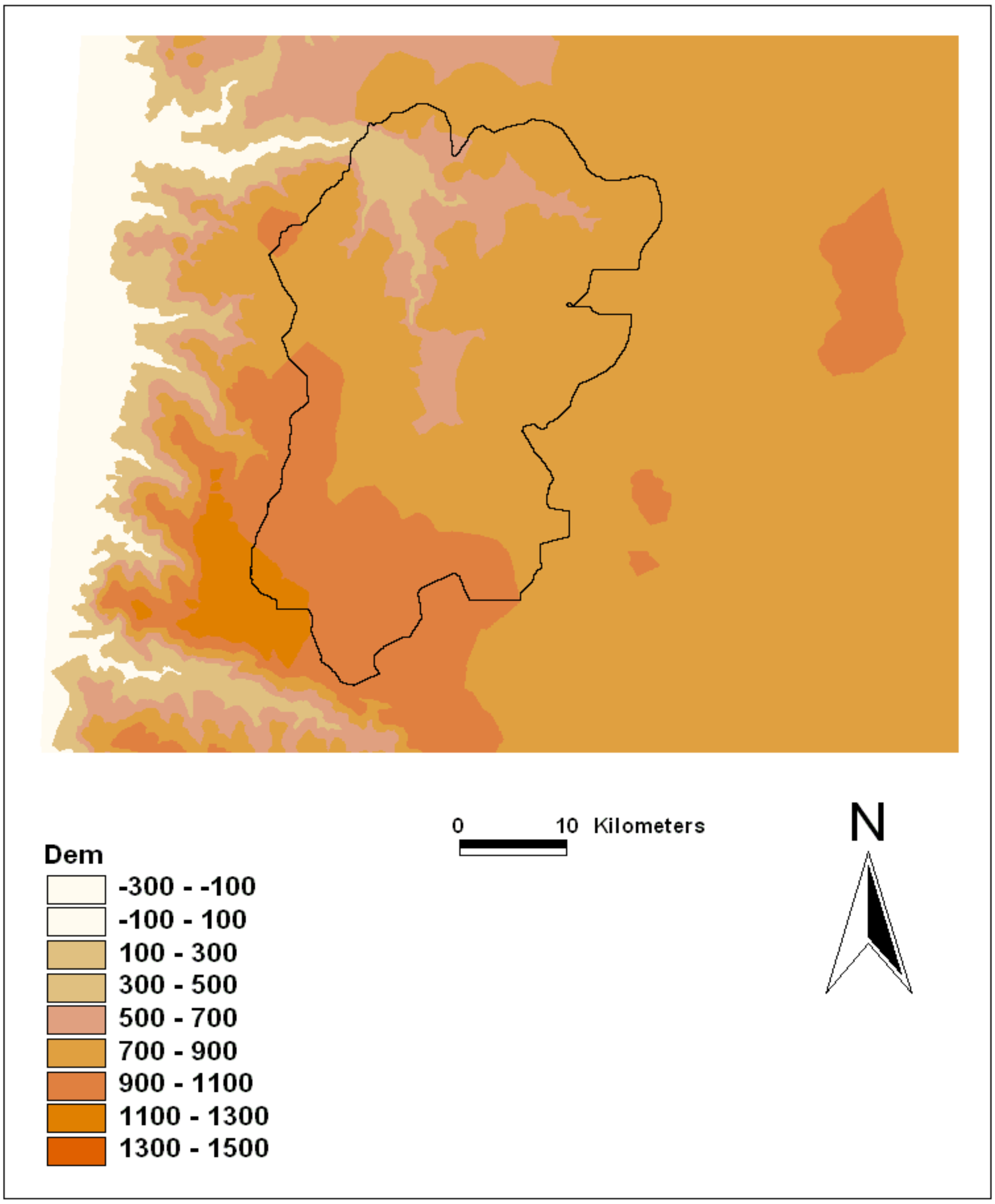

Figure 2: Digital elevation model for Mujib watershed and adjacent regions

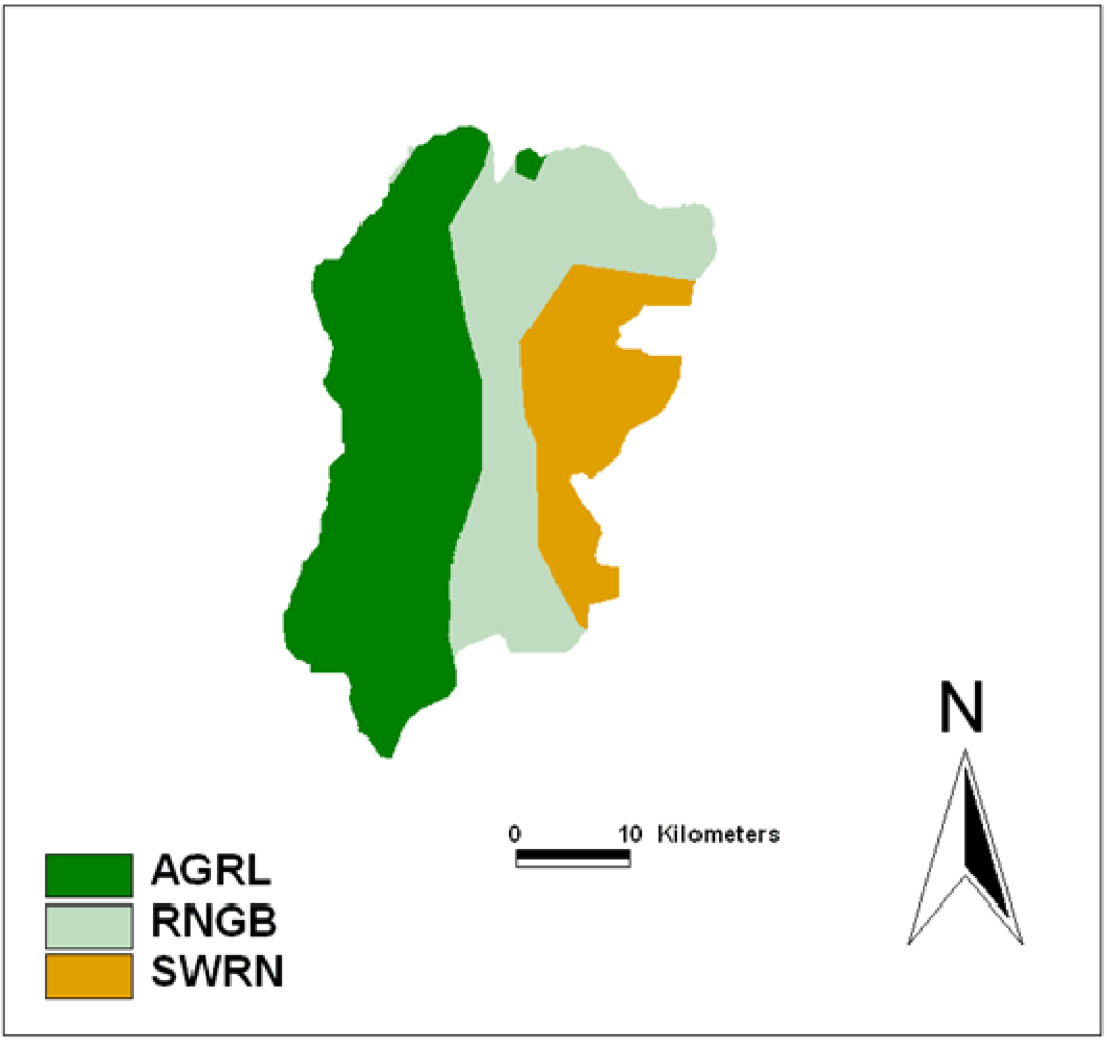

Figure 3: Generated land cover layer. (AGRL: Agricultural land of scattered scrubs and wood-land, RNGB: Dry steppe of shrub-land, SWRN: Desert area)

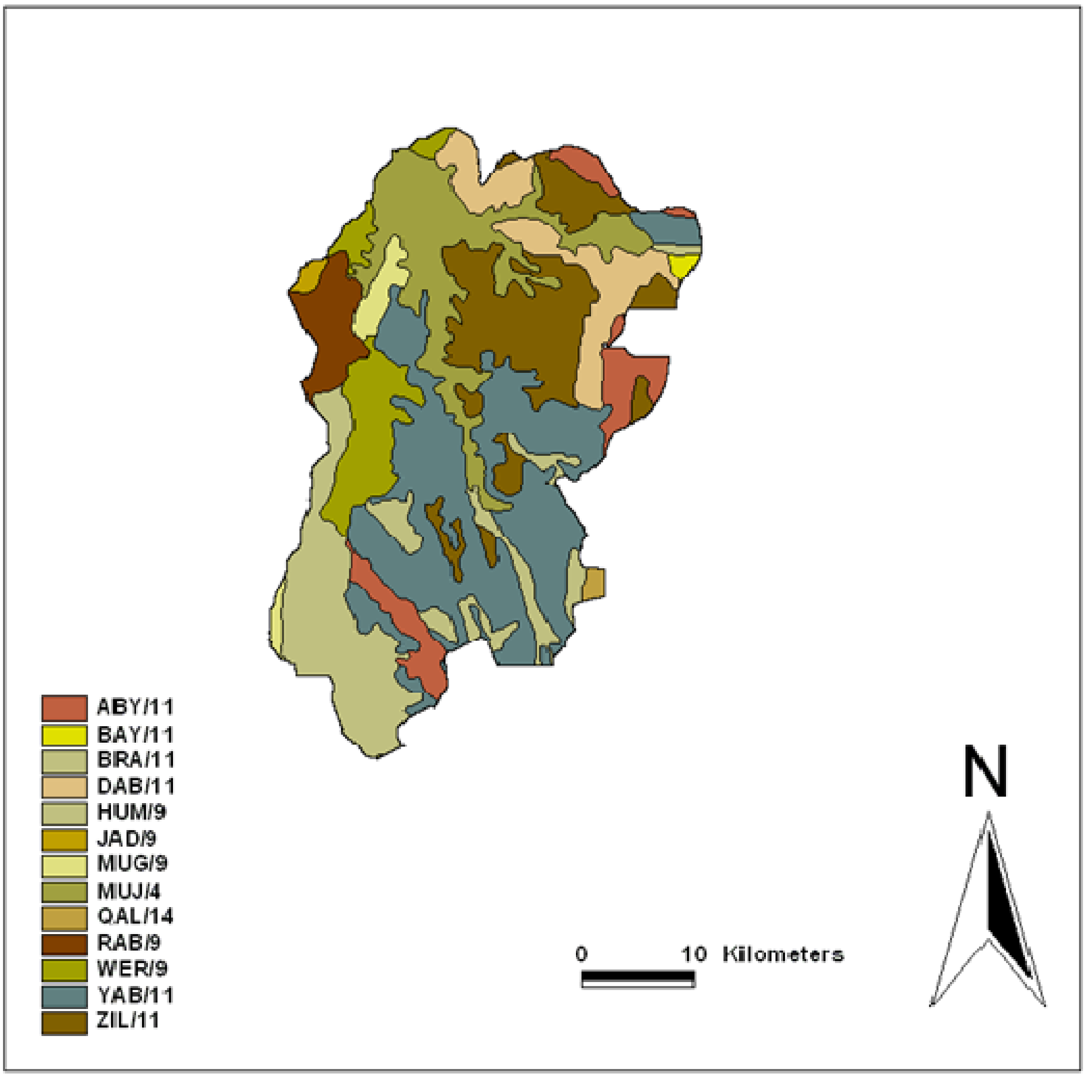

Figure 4: Soil map of the region (MOA, 1994)

Model Calibration

The calibration process is divided into two parts: stream flow calibration and sediment yield calibration, and the model has been run on a monthly basis. And due to the great variations in the monthly observed flows, it is decided to apply the concept of relative error as a statistical parameter in calibration as recommended by (Zheng and Bennet, 2002). The relative error is obtained by dividing the root mean squares of residual errors (RMS) by the difference between the maximum and minimum observed values.

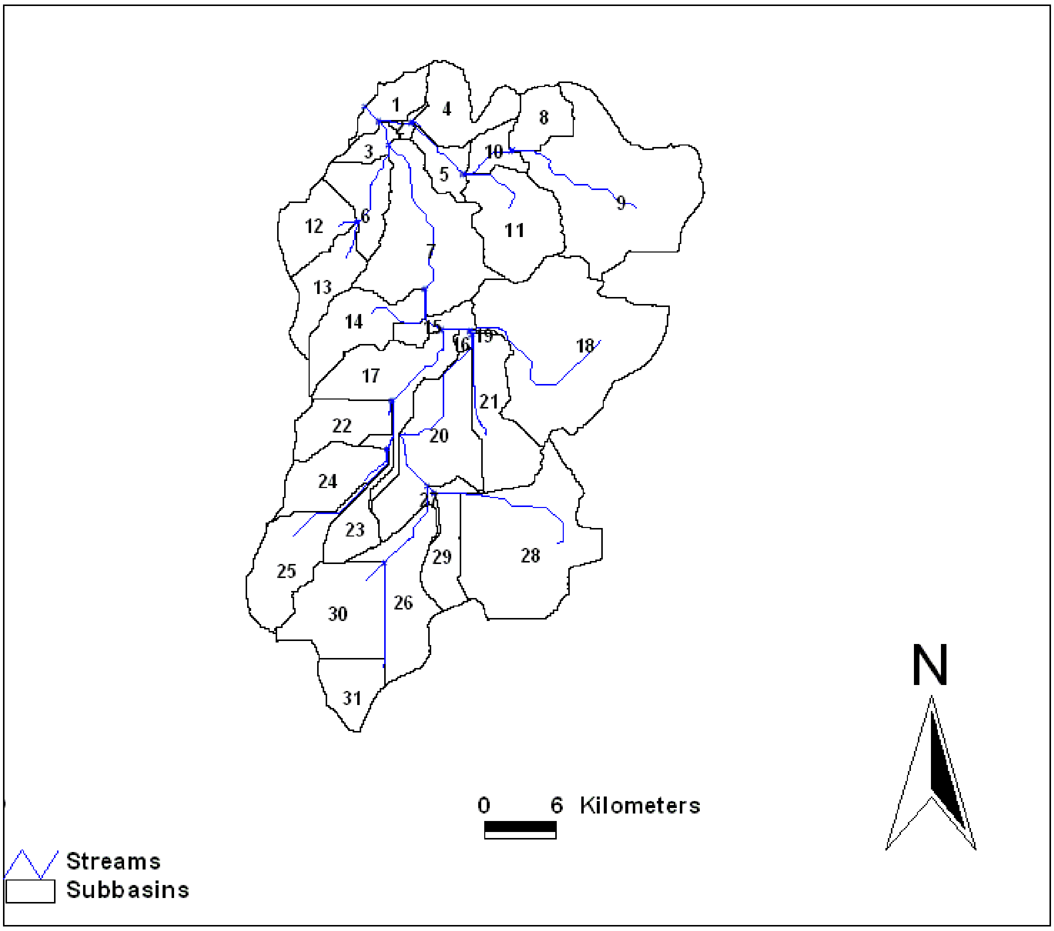

Figure 5: Subbasin delineation of the catchment area

Stream Flow Calibration

The surface runoff volume is estimated using the Curve Number, (CN), method, in which the CN is a function of the soil permeability, land use and antecedent soil water conditions. The CN input parameter has been used as a calibration parameter in this study to compensate for any expected uncertainty in land use and soil definition. The typical procedure for SWAT model calibration is to calibrate stream flow and sediment yield in succession. The optimum curve number (CN) values are obtained after calibrating the model using the better quality observed data available for the monthly average surface flow for the period January/1971 through December/1975 at the dam site (Howard and Humphreys, 1992). The optimum CN values for the 31 subbasins of the study area and on hydrologic response units (HRU) level range from 84 to 91. The relative error of the (RMS) is 4.7%. Comparison between observed data and calibrated stream flow results is shown in Figure 6.

Sediment Yield Calibration

The land cover and management factor (C) has been used as a calibration parameter to calibrate the model with respect to sediment yield at watershed outlet (at Mujib dam reservoir). The sediment loading curve prepared by Howard and Humphreys (1992) for Mujib gauging station is used in this calibration process. The cover factor (C) has been adjusted to match observed and simulated yield through several iterations. The optimum values of the USLE cover factor obtained on hydrologic response units (HRU) level range from 0.0033 to 0.202. The relative error of the (RMS) is 4.3%. Comparison between observed data and calibrated sediment yield are shown in Figure 7.

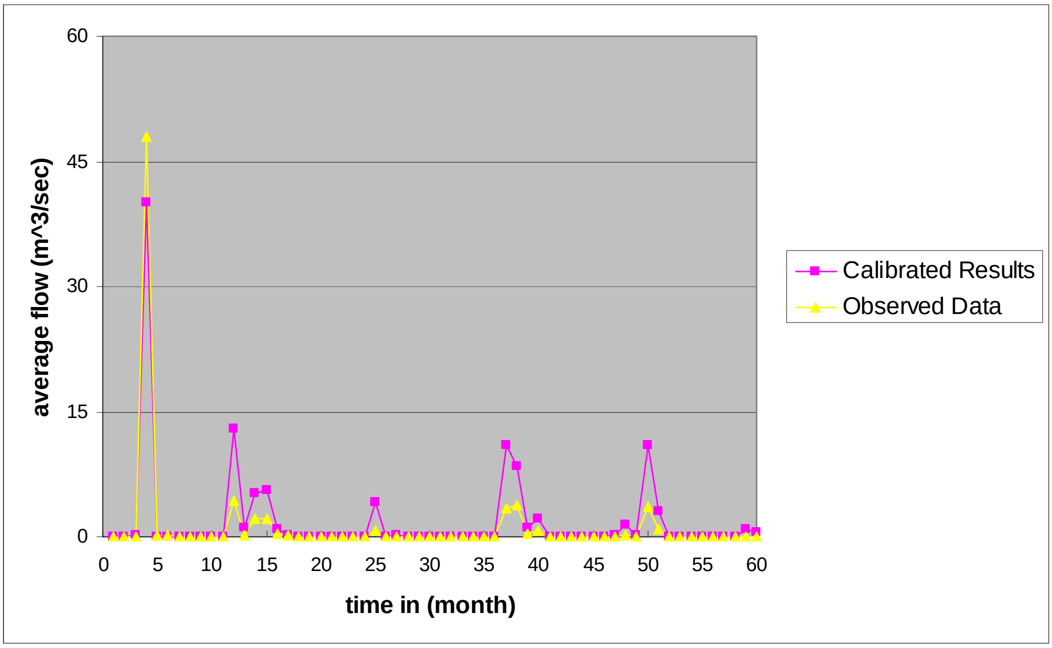

Figure 6: Comparison between calibrated flow results and observed flow data

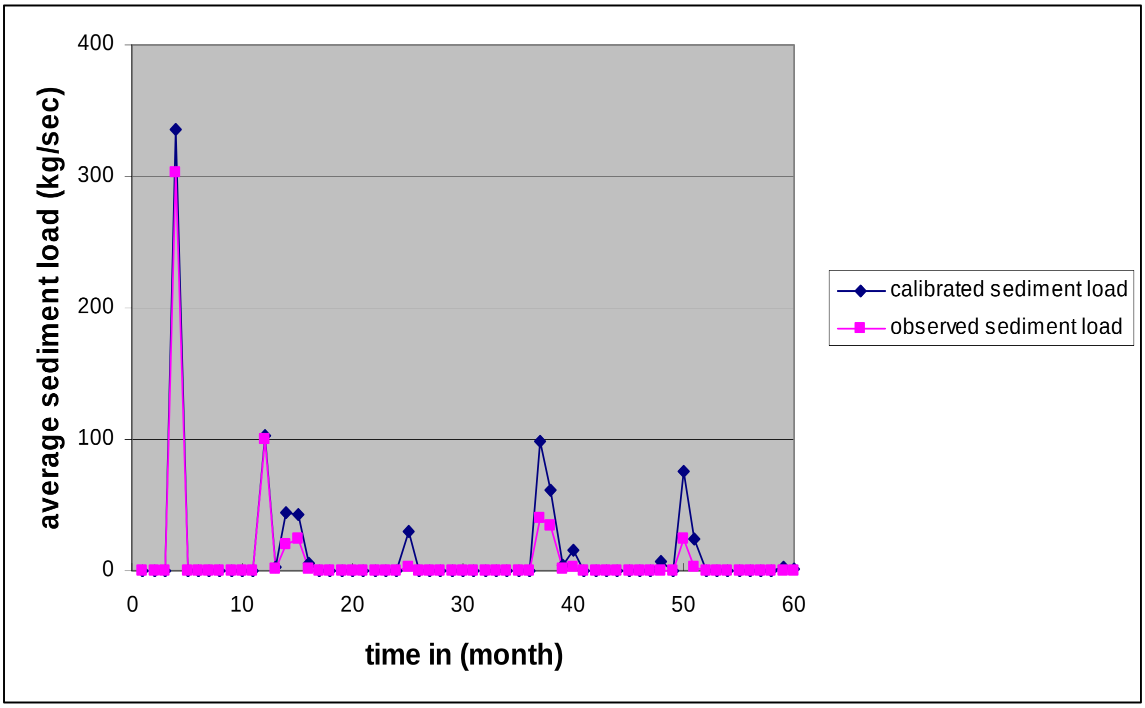

Figure 7: Comparison between calibrated and observed sediment yield

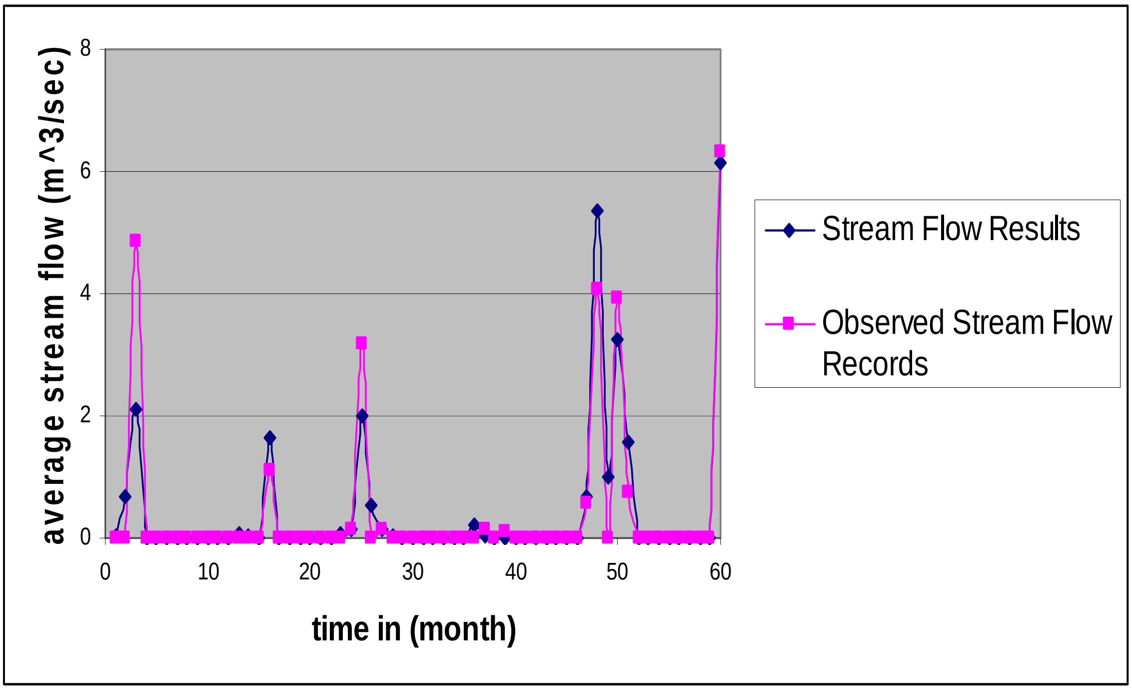

Figure 8: Model verification comparison for stream flow

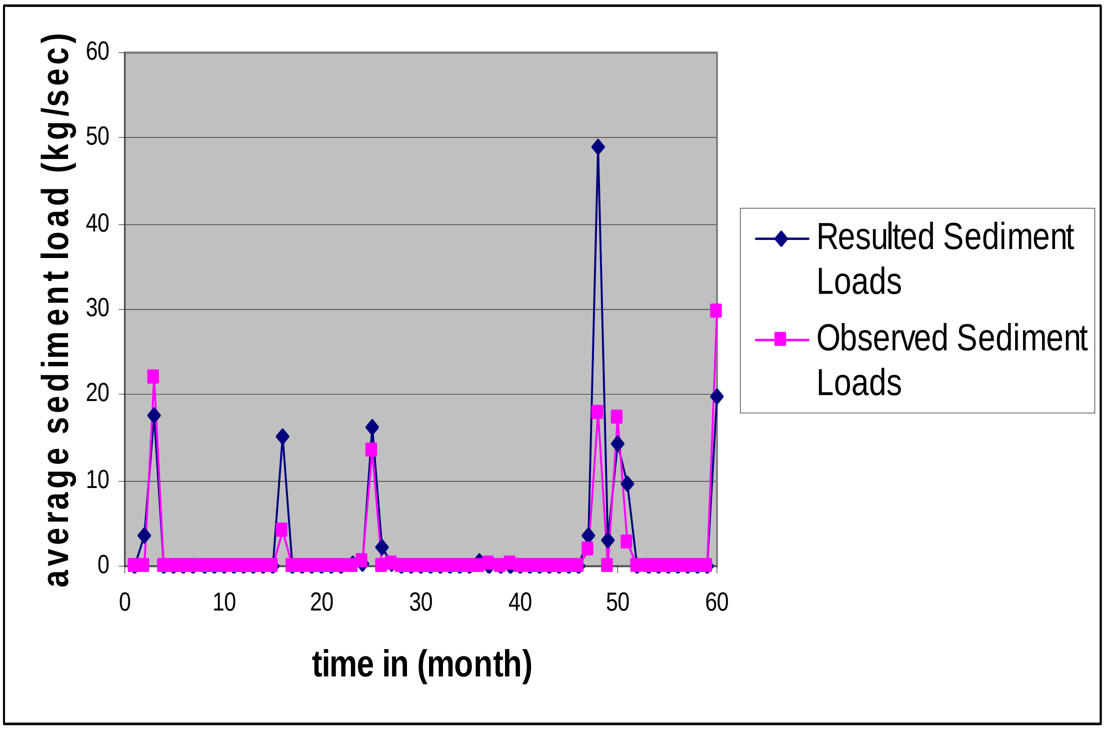

Figure 9: Model verification comparison for sediment yield

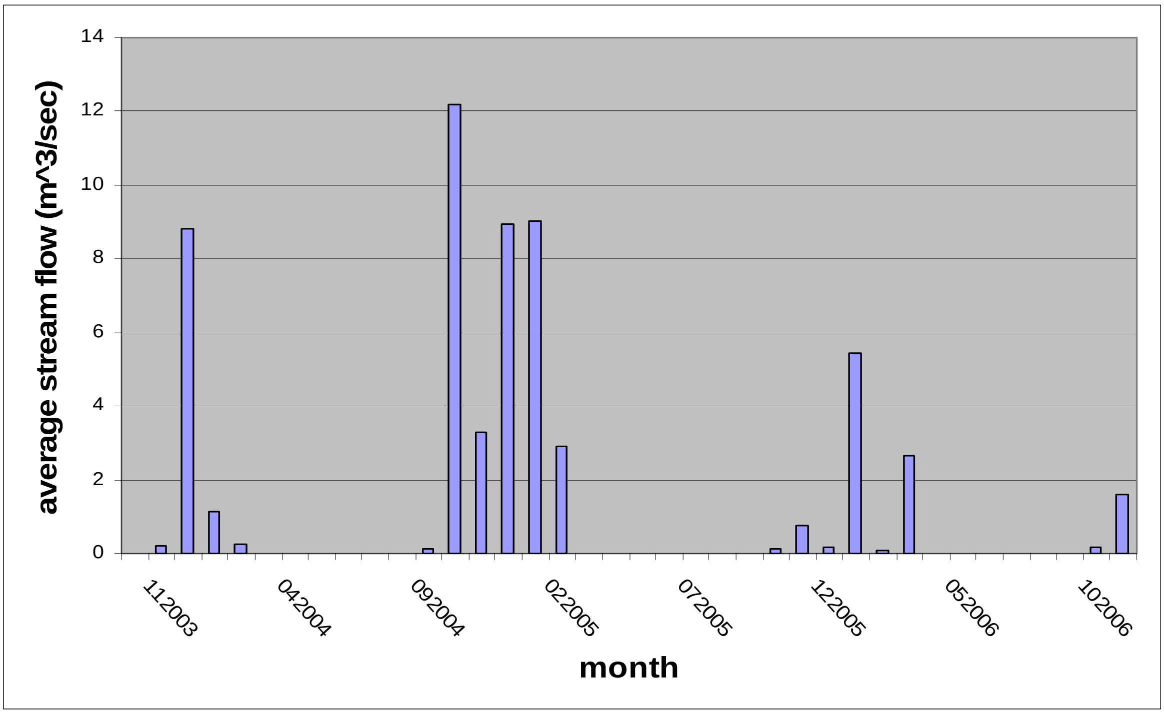

Figure 10: Predicted average monthly stream flow

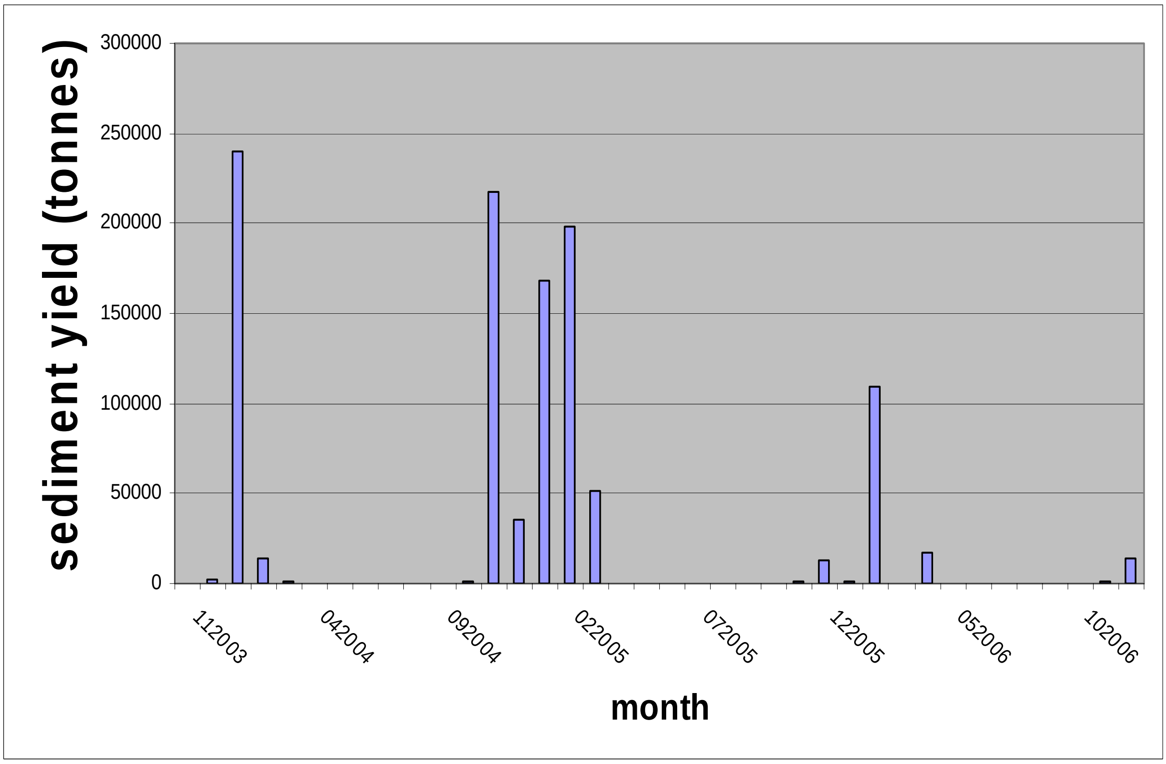

Figure 11: Predicted monthly sediment yield

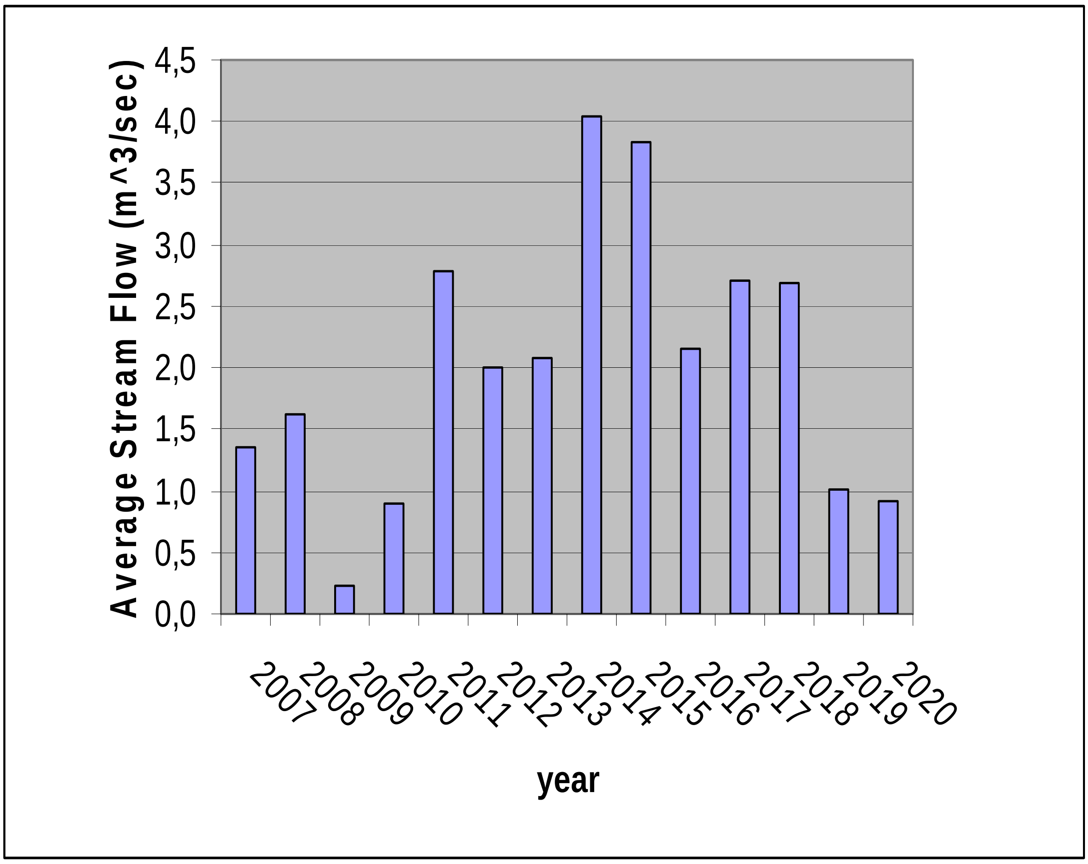

Figure 12: Predicted yearly stream flow

Model Verification

The calibrated parameters are used to verify the model capability of reproducing measured flow and the corresponding sediment yield at Mujib gauge station. The period January/1976 to December/1980 is selected as having a better quality data record. The stream flow and sediment yield results with the observed data are shown in Figures 8 and 9, respectively. The relative errors of the RMS for stream flow and sediment yield results are 7.6% and 9%, respectively. A reasonable acceptance of results can be assumed from these figures and errors, giving more support toward utilizing SWAT to model Mujib dam watershed and achieve the intended objectives.

Model Prediction

Unfortunately, no measurements at Mujib gauge station are available for the period after the construction of the dam. The first period for prediction starts from November/2003, the date on which Mujib dam has been in operation, to December/2006. For this period, good quality data is available for the daily rainfall. The predicted average monthly flow is shown in Figure 10, the magnitudes represent the flow out from subbasin 1 where the location of the dam reservoir occurs. Due to the large amount of rainfall in November/2004 the average stream flow rate reached a maximum value of 12.2 m^3/sec.

The total monthly sediment yield is shown in Figure 11, the maximum sediment yield occurred in January/2004 and reached 239800 tons; while the average stream flow in this month was not the maximum. This difference is due to that the sediment yield depends on the sediment concentration in addition to the quantity of flow, also the sediment yield depends on the source of flow, in other words it depends on the physical parameters of the subbasins and the contribution of these subbasins in stream flow reaching the reservoir. The total sediment yield that reached the reservoir during the simulation period (Nov./2003 to Dec./2006) is 1084844 tons, with an average of 341887 tons/year. Using a bulk density of 1.3 ton/m^3 for sediment deposition, then the average annual sediment yield equals 263000 m^3/year, this is equivalent to 200m^3/year/km^2, while using the equation derived by (Harza, 1978) to estimate the sediment yield in Jordan's reservoirs gives 313 m^3/year/km^2. This large difference is due to that the later estimate depended only on the catchment area; whereas in the present study the physical characteristic parameters of the area are taken into consideration as stated in equation(1).

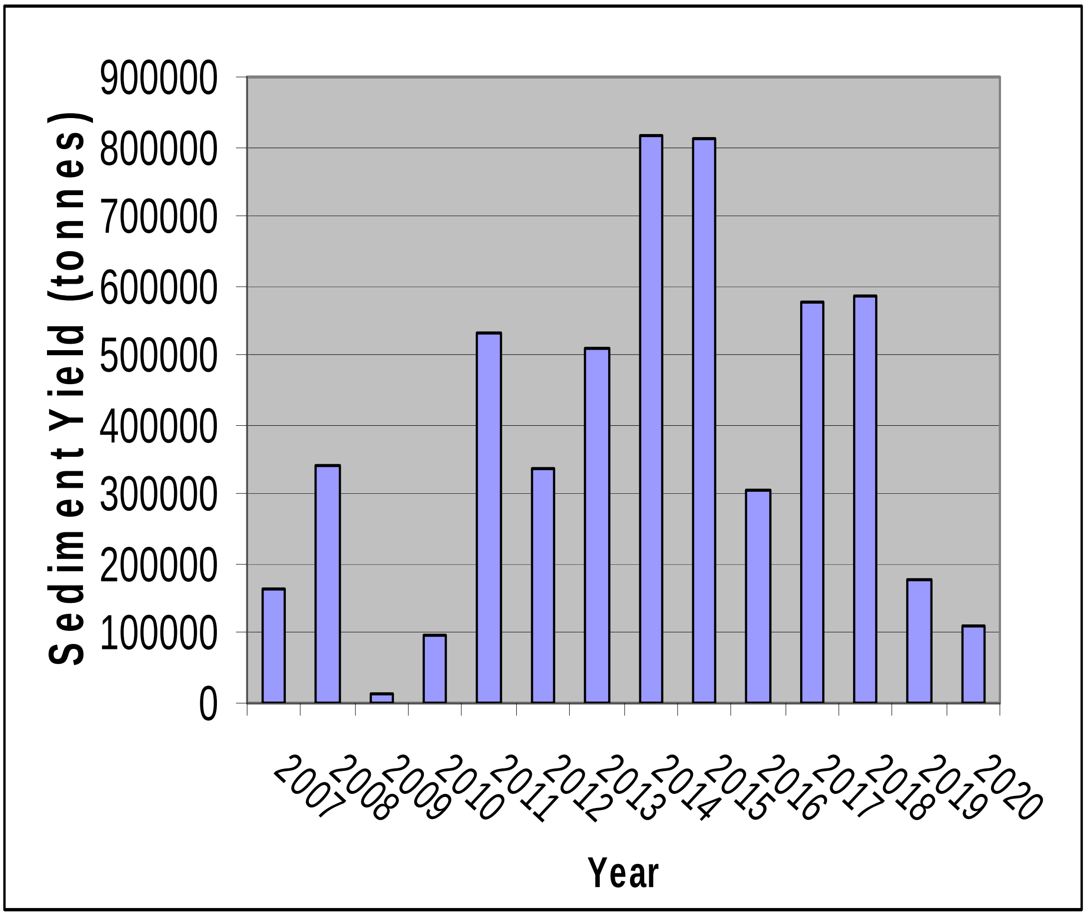

Figure 13: Predicted yearly sediment yield

The model results indicated that the subbasins which have maximum water and sediment yields are located westwards of the area, this occurred because these subbasins have a higher curve number and a higher land use management factor, a maximum precipitation and a high elevation region with high length slope factor.

The model application is extended to simulate the period 2007 to 2020 depending on weather data generated using the provided weather generator that utilizes Markov Chain model to generate daily precipitation data. Figures 12 and 13 depict the annual flow and sediment yield at Mujib dam reservoir for the simulated period. Results show that a total sediment of about 5.37 Million tons reaches the dam reservoir with an average of 383850 tons/year, which is equivalent to an average of 295269 m^3/year, assuming a bulk density of 1.3 ton/m^3 for sediment deposited in the reservoir, or 225 m^3/year/km^2 of the study area. This quantity of sediment is a real threat of reducing the operational life of the dam reservoir by decreasing its active storage. Returning back to the results for the period 2003 to 2007, the average annual sediment yield is about 341887 tons/year, this amount is somewhat comparable to that obtained for the period 2007 to 2020, and thus the predictions of the model give some insight regarding the expected storage loss due to sediment accumulation in the reservoir.

CONCLUSIONS AND RECOMMENDATIONS

SWAT model has been successfully used to estimate the sediment yield at Mujib dam reservoir in Jordan. The model required extensive data for the study area, these data were classified into digital maps and data files. Model calibration was evaluated using the curve number (CN) and the land cover management factor (C), the optimum values were determined with acceptable errors. Model verification and comparison with observed data confirmed the capability of SWAT model to predict the water flow and sediment yield to Mujib dam reservoir. Analysis of the model indicates that the subbasins which have maximum water and sediment yields are located westwards of the study area, this occurred because these subbasins have a higher curve number and a higher land cover management factor, as well as a maximum precipitation and a high length slope factor.

It was predicted that the average annual sedimentation in the Mujib dam reservoir is about $300x10^3$ m^3/year, this is a real threat of reducing the operational life of the dam due to decreasing its active storage. Management and conservation practices are recommended to be applied for the subbasins with high quantities of erosion and sediment yield. Several practices can be suggested comprising land contouring, terracing in the hilly regions and planting certain kinds of trees. Sediment traps can also be constructed, like small check dams and sediment detention basins. The study revealed that the model is able to predict water flow and sediment yield, which might be beneficial for future planning and management. The 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 with the concerned agencies. A field measurement program of sediment yield at the dam site is recommended to gain more confidence in the validity of the proposed model in predicting future sediment accumulation.

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