Sediment Yield Assessment for Tannur Dam Reservoir in Jordan

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Abstract
Reservoir sedimentation is caused from erosion process in the catchment area, the sediment build up in the reservoir, reduce its capacity and affect the aim for which the dam was constructed. This study presents an application of the Soil and Water Assessment Tool (SWAT) to simulate the water and sediment yield for Tannur dam reservoir in Jordan. The model was calibrated and verified using the monthly average surface flow and sediment measurements at Tannur gauging station. The optimum curve number (CN) was found in the range 82 to 86 and land cover factor (C) in range 0f of 0.003 to 0.03. Model validation results estimated the total volume of water of 110.5 MCM and total amount of sediment yield of 0.8 million ton reached Tannur dam reservoir during the period from October 2003 to December 2009. Total sediment yield of 2.5 million ton was predicted for the period 2010-2030. Subbasins 14 and 30 are more susceptible to soil erosion and sediment yields. 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.
Keywords: Sediment yield, Erosion, Reservoirs, Tannur dam, Jordan

1. Introduction

Sedimentation is an important consideration in the design and management of reservoirs for water supply, hydroelectric power, flood control, and other purposes. A dam and reservoir project on a stream results in deposition of sediment, which over time may significantly decrease its storage capacity. The problem confronting the project planner is to estimate the rate of deposition and the period of time before the sediment will interfere with the useful functioning of the reservoir. In many situations, sediment yields are high and conservation or erosion control measures in the drainage area are important for a reduction in the long-term sediment production. The sediment yield can be defined as the portion of eroded material that does travel through the drainage network to a downstream control point, the sediment yield per unit of drainage area is the sediment yield rate. The gross soil erosion and sediment yield are related together by delivery ratio which is defined as the ratio between the amount of sediment yield and the gross erosion in the watershed area.

Several mathematical and stochastic models are available to estimate sediment yield, but mostly, their applications is limited to small areas because of the numerous data requirements including hydrological information, physiographic characteristics of the area, and extensive data measurements to determine parameters for the proposed equations. The Universal Soil Loss Equation (USLE) methodology and its revision (RUSLE) (Renard et al., 1997) predict soil erosion for alternative land management practices. A sediment delivery ratio is combined with the soil loss erosion amounts to obtain the sediment yield at the outlet. The Modified Universal Soil Loss Equation (MUSLE) (Williams, 1995) predicts sediment yields at the watershed outlet, this modified model improves the sediment yield estimate, eliminates the need for delivery ratios, and allows the model to be applied to individual storm events.

The MUSLE has been presented by Williams (1995) as:

$$SY = 11.8\ (Q_v . Q_p)^{0.56} . K . LS . C . P . f_{cfrg} \qquad (1)$$

Where,

SY is sediment yield in (tons), Q_v is volume of runoff (m^3), Q_p is peak flow rate (m^3/sec),
K, LS, C, P, and f_{cfrg} are, respectively, the soil erodibility, topography, cover management, and coarse fragments factors. Methods of estimation of these factors are given by Neitsch et al. (2005)

SWAT model computes the volume of runoff, Q_v, in equation (1) for each individual Hydrologic Response Unit (HRU) as:

$$Q_v = Q . A_{hru} \qquad (2)$$

Where,

Q is the runoff in mm as computed by the Curve Number method, and
A_{hru} is the area of the HRU in hectares.

Many attempts have been made to develop predictive erosion and sediment yield software using USLE and MUSLE models; Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) is one of them. Several applications of this model have shown promising results in the assessment of erosion, runoff, and sediment yield (Arnold and Fohrer, 2005). Rodriguez et al. (2005), Licciardello et al. (2005), Stegen et al. (2007), Hasan et al. (2012), and Ayan et al. (2012) have confirmed the applicability of SWAT to estimate flow and sediment yield from different scales of watersheds. Asres and Awulachew (2010), Cai et al. 2011), Phomcha et al. (2012), Mbonimpa et al. (2012), and Fiseha et al. (2012) have applied SWAT model to assess the impacts of land use and climate change on soil erosion and sediment yield. On Jordan scale, special attention has been given to soil erosion problems in Amman Zarga basin (Al-Sheraideh et al., 2000) and (Malkawi et al., 2002), and the associated troubles in reducing King Talal reservoir storage (Numayr, 1999). Abdulla et al. 2007 have employed an Automated Geospatial Watershed Assessment (AGWA) tool to evaluate the sediment yield in a semi-arid region case study, Kufranja Basin-Jordan, And the sediment yield has been calculated at three proposed dam sites in the basin. SWAT has been successfully applied to estimate the sediment yield in Mujib dam reservoir in Jordan (Ijam amd Mahameed, 2012) and the results well compared with flow and sediment measurements. Concerning the present study area, studies have seemed to be limited and the only engineering study being on hand is the consultant study that was undertaken by Howard and Humphreys (1994). The study involved an analysis for daily flow duration curves and sediment rating curves based on daily flow records at Tannur dam station.

This study has been accomplished using the comprehensive watershed model (SWAT) to simulate the hydrology, soil erosion, and sedimentation of Tannur dam catchment area, considering the probable inverse effect of sedimentation in impairing Tannur dam function of water supply storage. 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).

2. Description of the Study Area

Tannur dam is located on Wadi Hasa at Jebel Tannur, approximately 26 km upstream of Dead Sea and 200 km south of Amman, with reservoir capacity of 16.8 MCM. The Hasa basin covers an area of approximately 2800 km^2 and comprises a semi-aeid plateau of the downstream end of the catchment and flat arid desert terrain at the upstream end of the catchment. The study area in this work covers an area 580 km^2 lies between the desert highway and Kings highway. Wadi Hasa has predominately a Mediterranean type climate, characterized by hot dry summer and cool to cold wet winter. As in most semi-arid areas, the temperature exhibits large seasonal and diurnal variations. Annual precipitation resulting largely from orographic effects decreases rapidly eastward from over 250 mm in the western edge of the carchment, down to less than 50 mm in the extreme east of the catchment. The summer in Wadi Hasa is high temperature and zero rainfall from June to September, and the winter starts from October to May with low temperature. The highest region lies at the south western region at elevations between 1000 m and 1520 m a.m.s.l, while the lowest rgion lies at the north western region near the dam site at elevation between 360 m and 920 m a.m.s.l.

3. SWAT Model Application

The type of data for SWAT modeling of the study area is maps or layers and database files; such as soil and digital contour maps. ArcView 3.1 and AVSWAT2000 are used to prepare the required data. The digital contour map has been processed using the 3D analyst of ArcView GIS to create a raster digitized elevation model (DEM) grid of 25 m resolution, Tannur catchment has been delineated into 31 subbasins. The DEM calculates the required parameters such as area, length, slope, slope length factor, etc.. Land use and vegetation data are obtained from the National Soil Map Project (MOA, 1994). Figure 1 shows Tannur catchment subbasins with their respective land use cover. Soil map has been prepared using data provided by the national soil map and land use project (MOA, 1994). Each subbasin has been characterized by one or more soil units as shown in Figure 2. Each subbasin can be further subdivided into multiple hydrologic response units (HRU_s) consisting of unique combinations of land use/ cover and soil. The benefit of HRU is the increase in accuracy it adds to the prediction of subbasin loading. The required climatic variables include daily precipitation, maximum/ minimum air temperature, solar humidity. There are three rainfall gauges within the study area, Hasa Fosfat, Hasa Tannur, and Abur station, their rainfall data files are used by weather generator model to generate daily climate data for the subbasins.

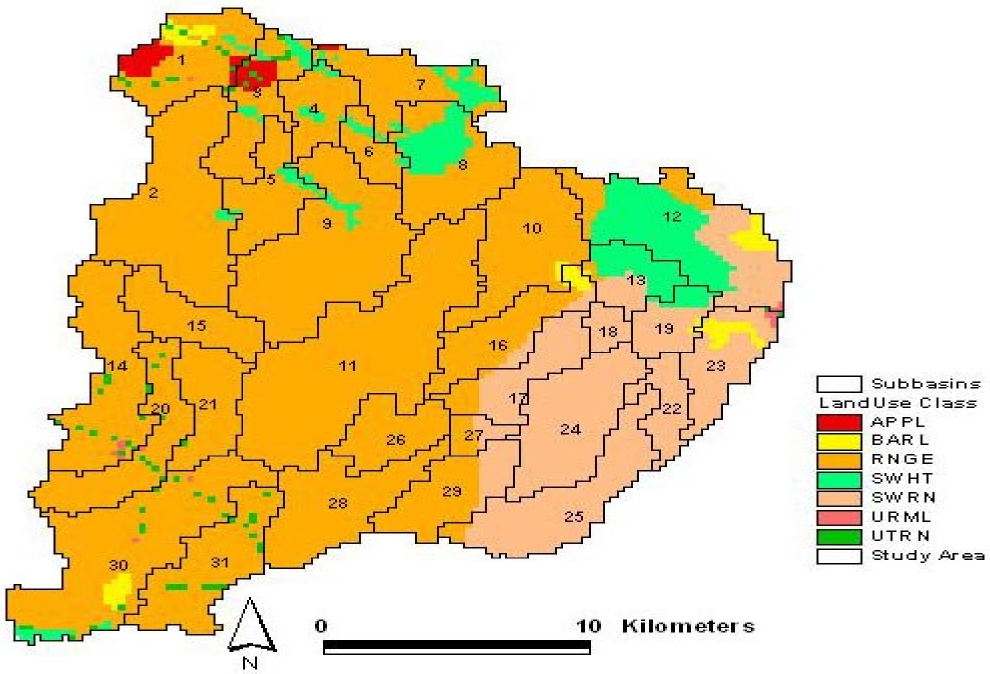

Figure 1. Land-Use/ Cover Layer as Defined by SWAT

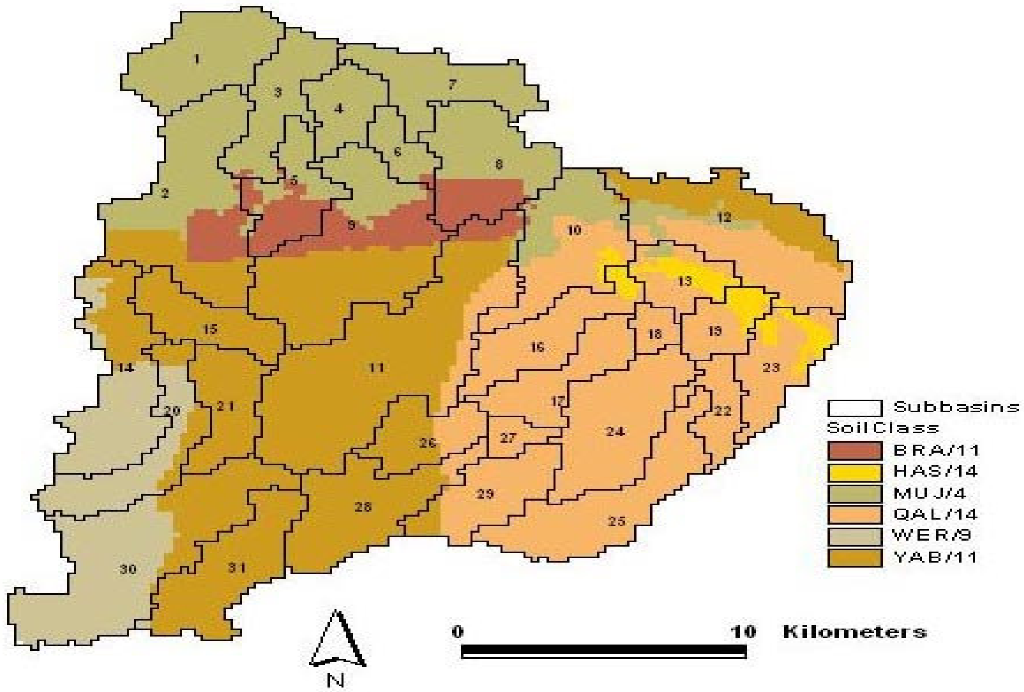

Figure 2. Soil Layer of the Watershed Area

4. Results and Discussion

The SWAT model has been executed and a variety of results has been generated, and in the 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 for verification and validation periods.

4.1 Calibration Process

The curve number (CN) and land cover factor (C) have been used as calibration parameters to calibrate stream flow and sediment load in succession, using the monthly average surface flow and sediment data for the period Jan. 1978 to Dec. 1983 at Tannur gauging station (Howard and Humphreys, 1994). The calibration has been assessed quantitatively using the linear correlation coefficient and the relative error as statistical indicators. The optimum curve number (CN) values rang from 82 to 86 with linear correlation coefficient 0.91 and relative error 0.1. The observed and calibrated average monthly flow at the dam reservoir site are shown in Figure 3. The sediment rating equation that was prepared by Howard and Humphreys (1994) for Tannur gauging station has been used in the present work for the sediment load calibration. The optimum values of the land cover factor (C) range from 0.0031 to 0.03 with linear correlation coefficient 0.88 and relative error 0.096. The observed and calibrated monthly sediment load at the dam reservoir site are shown in Figure 4. Calibration results are acceptable and indicate that SWAT is able to simulate the watershed and predicts flow and sediment load well depending on the optimum set of parameters obtained.

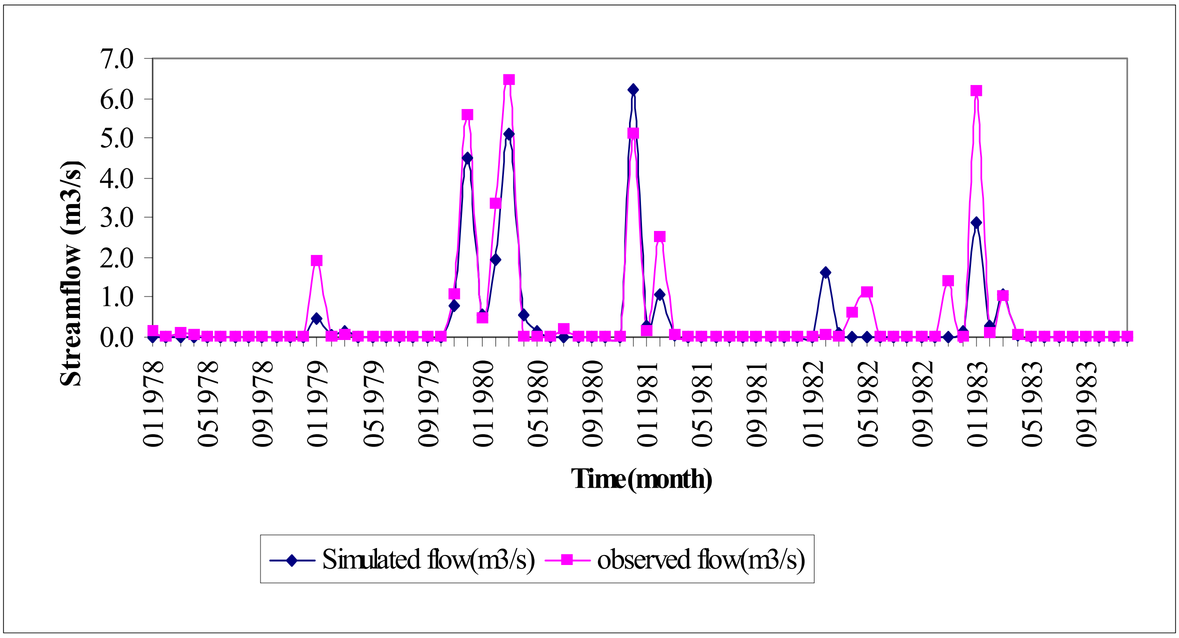

Figure 3. Comparison Between Calibrated and Observed Flow

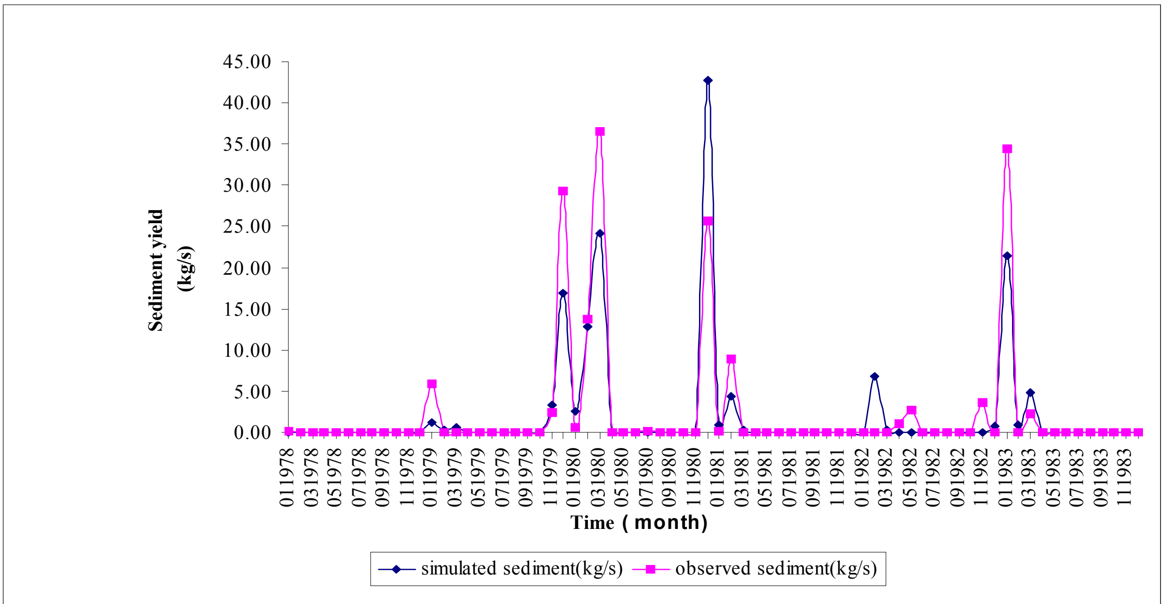

Figure 4. Comparison Between Calibrated and Observed Sediment Yield Values

4.2 Verification Process

Data for the period Jan. 1984 to Dec. 1988 at Tannur station is used for verification process. The variation of observed and simulated results are shown in Figures 5 and 6 for flow (with correlation coefficient 0.83) and sediment load (with correlation coefficient 0.88) respectively. The verified results give more support toward utilizing SWAT to model Tannur dam watershed and achieve the intended modeling objectives.

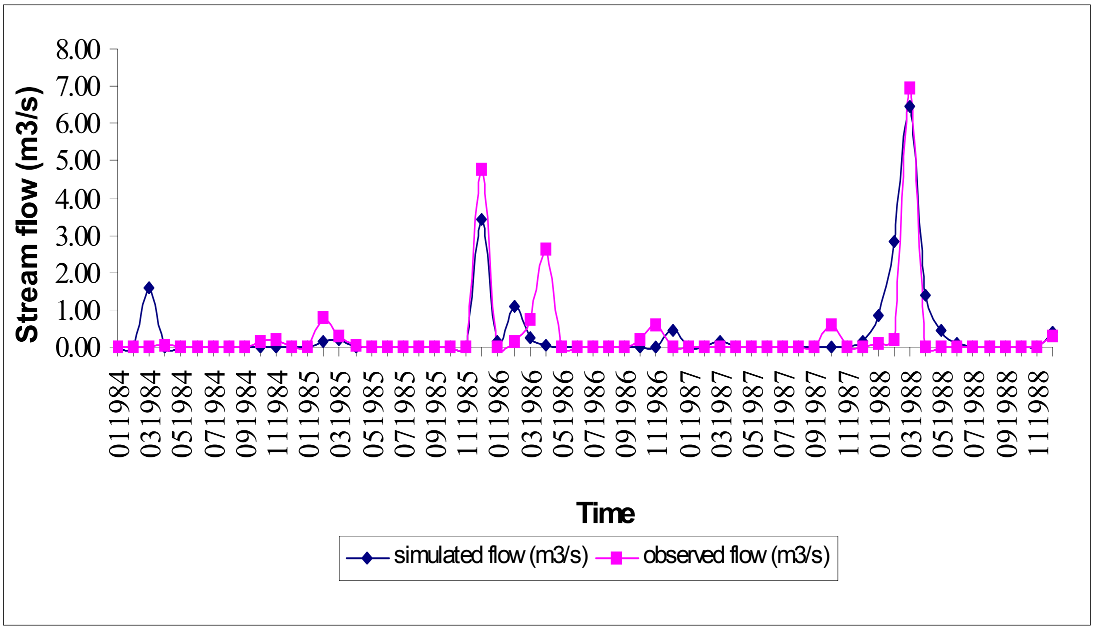

Figure 5. Comparison Between Simulated and Observed Flow for Verification Process

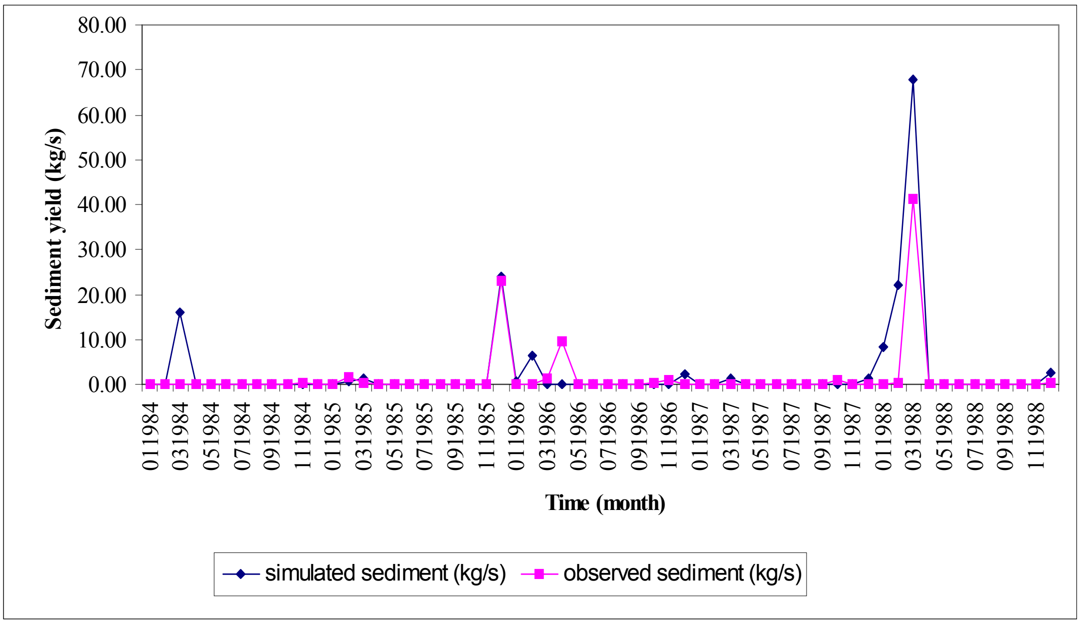

Figure 6. Comparison Between Simulate and Observed Sediment Yield Values for Verification Process

4.3 Validation Process

The validation process period extends from Oct. 2003, the date on which Tannur dam has been in operation, to Dec. 2009. Daily rainfall data are available at the three gauges within the study area. Figures 7 and 8 represent the simulated values of average monthly flow and sediment yield, the same trend is noticed in flow and sediment yield simulation, therefore the two processes are strongly related. The maximum values correspond to Dec. 2003, this is because high amount of rainfall in this month. The total volume of water yield in the reservoir during the validation period is 110.5 MCM, with an average annual rate of 17.65 MCM. This compares well with the average annual water yield of 16.8 MCM reported by Howard and Humphreys (1994). The total amount of sediment yield in the reservoir for the same period about 0.8 million ton, with an average annual rate of 113.3×10^3 ton, this is close to 106×10^3 ton as was estimated by Howard and Humphreys (1994). The average yearly sediment yield in Ton/hectare from the subbasins of Tannur watershed during the validation period is shown in figure 9.

Model results include soil erosion for each subbasin of the watershed, by dividing the average yearly sediment yield by the average yearly soil erosion, the average delivery ratio is obtained as listed in table 1. It is noted that the maximum soil erosion occurred in subbasins 14 and 30, because these subbasins have high water yield and high land slope.

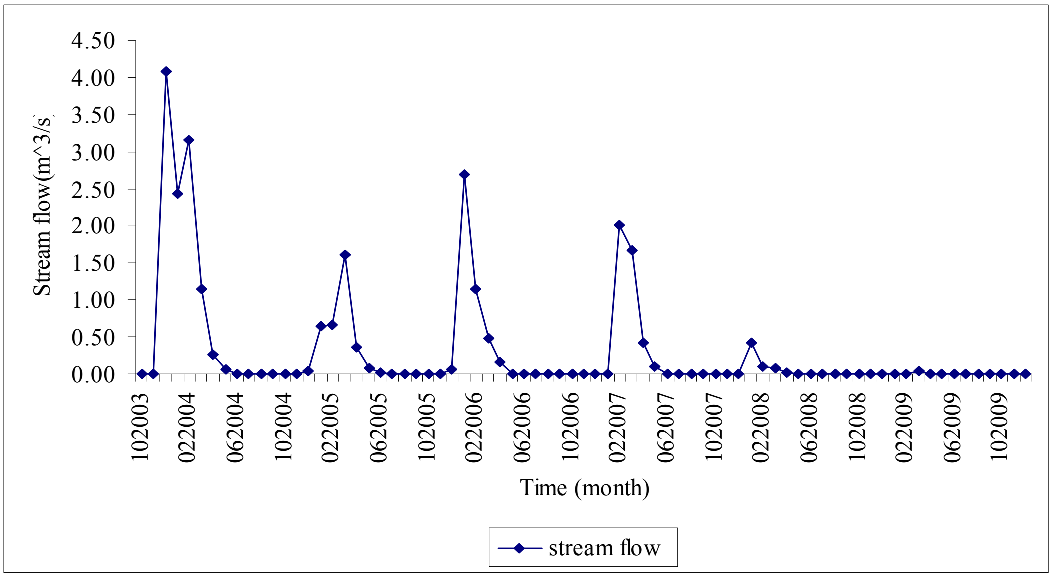

Figure 7. Average Monthly Stream Flow Results for Validation Process

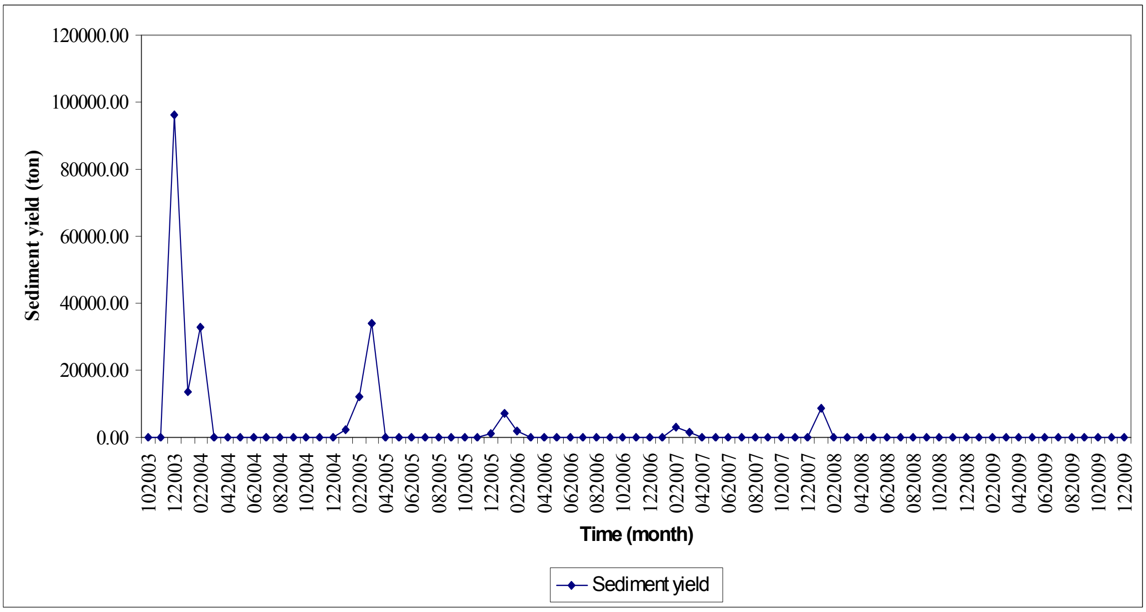

Figure 8. Average Monthly Sediment Yield Results for Validation Process

4.4 Pridiction Process

The model has been used to simulate the period 2010-2030 depending on weather generation data built within SWT model. The total amount of sediment yield in the reservoir during the simulation period about 2.5×10^6 ton with an average annual rate of 123.7×10^3 ton, this compares well with the predicted value during the verification period. For the period from Oct. 2003 to Dc. 2030, the average sediment yield is 118.5×10^3 ton/year, this equivalent to a volume of 91×10^3 m^3/year assuming a bulk density of 1.3 ton/m^3 for sediment deposited in the reservoir. The model has predicted that the reservoir storage is reduced by 0.6 MCM at end of 2009, and will be reduced by 2.5 MCM at the end of 2030.

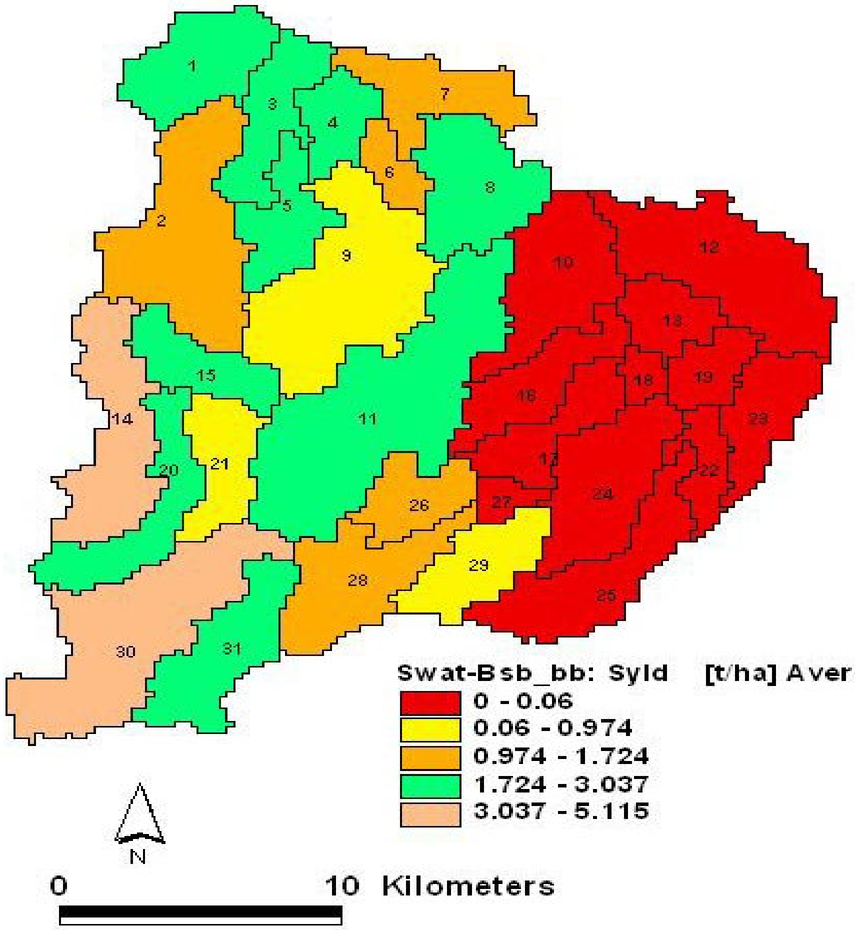

Figure 9. Average Yearly Sediment Yield in Ton/hectare for Validation Process

5. Conclusions and Recommendations

The sediment yield at Tannur dam reservoir has been successfully estimated using the Soil and Water Assessment Tool (SWAT) model. Extensive data for the study area were used, these data were classified into digital maps and data files. The curve number and the land cover management factor were used and optimized during the calibration process with acceptable errors. The model has been verified and comparison with observed data confirmed the capability toward utilizing SWAT to model Tannur dam watershed. The validation process was applied for the period Oct. 2003 to Dec. 2009, the same trend was noticed in flow and sediment yield simulation, therefore the two processes are strongly related. Results of erosion and sediment yield for each subbasin of the watershed during the validation period were shown, and the maximum rates occurred in subbasins 14 and 30 because these subbasins have high water yield and high land slope. The model application has been extended to include a prediction process for the period 2010-2030, and the average annual amount of sediment yield was 1.24 x 10^3 ton, this is a real threat of reducing the operational life of the dam reservoir 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 such as land contouring, terracing in the hilly regions and planting certain kinds of trees.

Table 1.
Sediment yield, Soil erosion, and Delivery ratio for each Subbasin

Subbasin	SYLD (Ton/ha)	Soil erosion (Ton/ha)	Delivery ratio
1	1.84	2.02	0.91
2	1.11	1.38	0.80
3	1.16	2.08	0.56
4	2.25	2.38	0.94
5	1.04	2.43	0.43
6	1.22	1.72	0.71
7	1.16	1.22	0.95
8	1.88	1.92	0.98
9	0.55	0.71	0.78
10	0.03	0.07	0.38
11	2.01	2.32	0.87
12	0.05	0.12	0.41
13	0.06	0.13	0.48
14	4.99	5.73	0.87
15	1.14	1.95	0.59
16	0.01	0.02	0.31
17	0.00	0.02	0.05
18	0.00	0.01	0.08
19	0.00	0.02	0.05
20	3.04	3.71	0.82
21	0.60	0.64	0.94
22	0.00	0.01	0.00
23	0.00	0.01	0.08
24	0.00	0.01	0.08
25	0.00	0.01	0.08
26	1.14	1.34	0.85
27	0.01	0.02	0.30
28	1.16	1.33	0.87
29	0.81	0.97	0.83
30	5.12	5.65	0.90
31	2.04	2.41	0.84

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