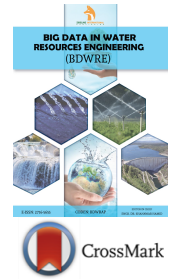


ZIBELINE INTERNATIONAL
PUBLISHING

ISSN: 2716-5655 (Online)

CODEN: BDWRAP

Big Data In Water Resources Engineering (BDWRE)

DOI: <http://doi.org/10.26480/bdwre.02.2020.43.48>

RESEARCH ARTICLE

ESTIMATING SEDIMENT YIELD AT TARBELA DAM AND FLOOD FORECASTING THROUGH CONTINUOUS PRECIPITATION-RUNOFF MODELING OF UPPER INDUS BASIN

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ARTICLE DETAILS

Article History:

Received 11 January 2020

Accepted 15 February 2020

Available online 19 March 2020

ABSTRACT

The live water storage of the reservoirs is decreasing by the sedimentation, which is affecting the reservoir's capacity and cause a severe problem for the irrigation system at the downstream side. Floods occur at the downstream by the poor management at upstream due to the heavy rainfall and snow melting. For annual accumulations of sediment load and estimation of the peak flow at Tarbela reservoir near Besham Qila station having area of 170,000 km² was selected. Estimation of the peak flow and sediment yield at the Tarbela reservoir, SWAT (distributed hydrological model) was used. The expected decrease in reservoir storage capacity was also estimated with the SWAT model. For runoff modelling, calibration was done for three years (2004-2006) and validation was also done for three years (2007-2009). Nash-Sutcliffe Efficiency (NSE) and Standard Error of Estimate existed the statistical indices to evaluate the results. Coefficient of determination (R²) was found as 0.75 for the calibration period and 0.80 for the validation. Whereas, NSE for calibration was observed 0.69 and 0.70 for the validation. Monthly mean sediment yield was about 0.13 BCM estimated at the Tarbela reservoir near Besham Qila.

KEYWORDS

Upper Indus Basin, SWAT, Sedimentation, Calibration, Tarbela Dam, Validation, Runoff.

1. INTRODUCTION

Precipitation at watershed and land surface features produces water by collaboration of both. Watershed is a hydrological model in which depth of precipitation and the character of watershed control the amount and nature of water delivered by the watershed. Heavy rainfalls, snow melting and poor watershed management in the upstream are the major roots of floods in downstream side, due to which deposition of sediments also occur, which decline the reservoirs functioning capacity gradually (Khan et al., 2008; Nearing et al., 1989). By the sediments deposition levels of flood rise in the reservoir head and a huge flux of sediment into the canals head are the problems in the recent decades. Plenty of people has been died and migrated in few decade's due to floods and damaged approximately \$800,000 US during the 1991-2001 decade (Khan et al., 2008; Rostamian et al., 2008).

Pakistan was hit by numerous floods between 1950 to 2015 in four provinces of Pakistan i.e. Punjab, Sindh, Khyber Pakhtunkhwa Khan, Baluchistan, the federal government managed tribal areas, Gilgit Baltistan,

and Azad Jammu and Kashmir (AJK) with the sediment deposition problems (FFC, 2014). All reservoirs are continuously silted up and active storage capacity is decreasing in the world, but South Asia, South America and Africa are more sensitive (Atkinson, 1996; Umar et al., 2016). Approximately 200 x 10⁸ tons of sediments are reaching to oceans each year (Lal, 2003) and 1% of total reservoir capacity (4000 km³) calculated as loss of storage (Mahmood, 1987). Since the beginning of the 20th century, the calculated storage capacity (5976 km³) of 2,300 reservoirs worldwide has lost 567 km³ and 1.53 x 10¹¹ tons of annual sedimentation by the erosion (Umar et al., 2016; Sayed et al., 2014).

Tarbela is considered the prime earth embankment reservoir across world, which was built in 1976 on the Indus river holding a catchment area, around 168,000 km² and height is approximately 470 feet above sea level with a live storage capacity of 9.7 MAF (Khan et al., 2008; Lal, 2003; Abid et al., 2010). In 1976, 13.69 MAF was the initial gross storage capacity of this dam. By the increasing sediment load and excessive runoff resulted by poor management plans at upstream are responsible

Quick Response Code



Access this article online

Website:
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DOI:
10.26480/bdwre.02.2020.43.48

for the reduction in storage capacity. In this regard during the transport of chemical pollutants reservoir is facing deterioration in water quality, drop in performance and damage to turbines (Khan et al., 2008; Umar et al., 2016; Lal, 2003).

For sustainable development surface runoff, soil erosion and sediment yields modelling are essential. Recently for evaluation of watershed, in response of aiding tool and techniques, Geographical Information System (GIS) and remotely sensed data are the watershed parameters for mathematical hydrological modeling (Cheema et al., 2014; Zakaullah et al., 2015). For soil erosion different models were used by the scientists, those were validated and recommended for different and complex study areas.

In this study, estimation of peak flows and sediment transport, Soil and Water Assessment Tool (SWAT) is used. SWAT is most commonly used model across the world as reported which was able to guarantee the confidence of additional dispensing techniques in sediments, high surface flows and chemical contaminants in amalgamated watersheds (Phomcha et al., 2012; Neitsch et al., 2005).

Recently, studied the SWAT model to seek out the consequences of extensive impacts of various management performs on loads (Bracmort et al., 2006). To predict the flows, Hydrologists used SWAT model globally for water resources with sort of lands and environmental characteristics. Some researchers used SWAT model however, in Upper Indus Basin (UIB) very less work was published for the sediment load (Khan et al., 2008; Radcliffe et al., 2009). The high surface flow in the Himalayan region is due to the high precipitation rate in the Indus river basin throughout the year.

Massive harm of industrious soil and water flow within the basin is due to the faulty farming practices and deforestation in addition to hilly topography. By using appropriate modelling methods based on hydrological simulation studies, an excellent basin management plan is needed to develop (Cheema and Bastiaanssen 2010). Moreover, considering the above issues, the application of existing models and hydrological behavior of the basin, SWAT-2012 integrated with remote sensing and GIS to assess the flow and sediment load within the upper river basin.

Furthermore, for the catchment station, model related data was available at gauging station for precipitation, surface flow and sediment load with time-series. To assess the applicability of the model these parameters have been used to assess peak flow and sediment load in the Himalayan region for the Indus River watershed (Khan et al., 2008; Fadil et al., 2011). A well-calibrated and validated SWAT model was the main aim of the study. That could be helpful to evaluate the maximum runoff and sediment yields at the Tarbela dam.

2. MATERIALS AND METHODS

2.1 Study Area

Indus River is most important river in south Asia having total base length of 2880 km and drainage zone of 912,000 km² spreading across the border of Pakistan and Asian countries i.e. India, China and Afghanistan (Figure 1). The UIB (upstream) of Tarbela Dam has base length of 1125 km long with a drainage zone of 168,839 km² (Cheema and Bastiaanssen 2010). However, Tarbela dam is the main for the UIB, which is like a backbone in making a budget of sediment load for the basin.

The dominate climate region of UIB is high mountain range in the northern part of basin. The climate is semi-arid to arid according to the rainfall and subtropical to tropical dry according to the temperature variation till Indus meets to the Arabian Sea (Khan et al., 2008; Zakaullah et al., 2015; Cheema and Bastiaanssen 2010; Ludwig et al., 1998). The monsoon causes heavy precipitation, which cause flooding at downstream and accumulation of snow at high altitudes.

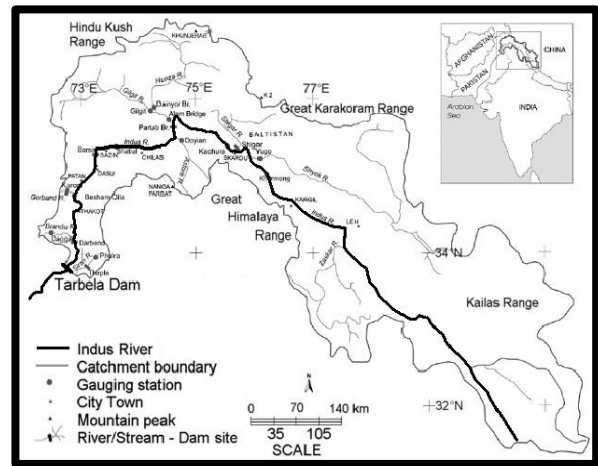


Figure 1: Location and origin of the Indus River in UIB.

2.2 SWAT Model

Department of Agriculture Research Services, The United States (US) has made a watershed scale model SWAT for long term variable management conditions to influence land management practices on soil erosion, land use and water, sediments and agricultural waste in complex large waters (Yang et al., 2009). Hydrology, climate, sediment yield, temperature of soil, development of crop, nutrients, pesticides, and agrarian performs are the eight major parameters of the model. The flow of water, transportation of the sediments, development of crop and nutrients cycling, etc. are openly modelled by SWAT model (Rostamian et al., 2008; Bicknell et al., 1993; Phomcha et al., 2012; Kumar et al., 2015). The preprocessing and interface of soil, DEM and land usage are the spatial data sets for the model. DEM was used to calculate sub-basin parameter i.e. slope topography of watershed. Soil characteristics and qualities were estimated by the soil data. Land and soil ecological processes and vegetation information on ground were estimated by the land cover data. Surface runoff was calculated on hourly and daily time steps used by the SWAT. For hourly and the daily computation, the Green and Ampt equation and exponential SCS curve number (CN) method were used respectively (Bicknell et al., 1993; Ludwig et al., 1998).

Three GIS models from the field of the agricultural economy (ProLand), ecology (YELL) and hydrology (SWAT-G) were used for integrated river basin management, in a mountainous mesoscale watershed of Aar (Fohrer et al., 2002; Moriasi et al., 2007).

2.3 Materials

2.3.1 Digital Elevation Model (DEM)

For the current study area, DEM data sets were freely downloaded from Shuttle Radar Topographic Mission (SRTM) website with 90m×90m resolution. These data sets were useful for study of the basin and land surface terrain patterns of drainage were analyzed by these Figure 2.

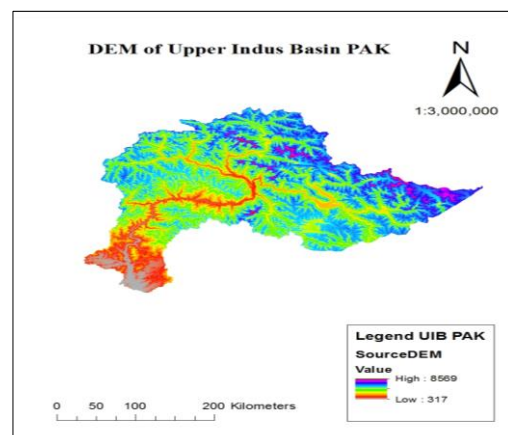


Figure 2: Digital Elevation Model of the Upper Indus River Basin

2.3.2 Land Use Data Sets

In SWAT model Land use map is one of the crucial and most significant input parameters which affects the flow, evapotranspiration and erosion of soil in the basin (Phomcha et al., 2012). For each sub-basin in the SWAT model each Hydrological Response Units (HRU) was determined through superimposition of land practice maps and soil types. The flow was quantized separately for each HRU and routed at obtaining entire flow for the watershed. These parameters helped for the apparent account of water balance. Accuracy of load forecasting was obtained by (Phomcha et al., 2012; Fadil et al., 2011).

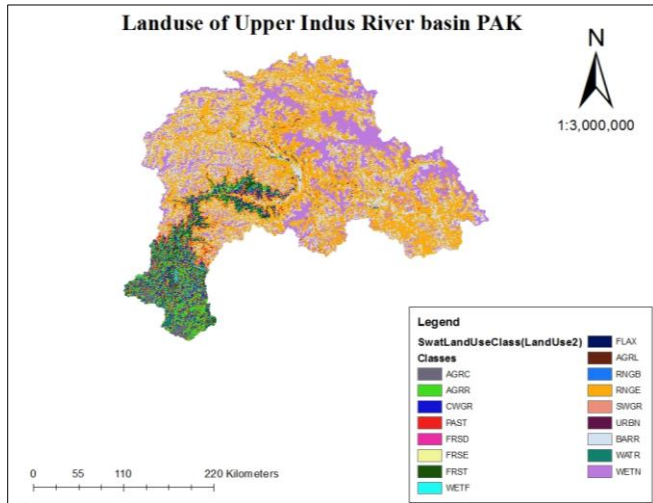


Figure 3: Land use map of Upper Indus River basin

2.3.3 Soil Data Sets

In SWAT model soil data is also essential to find the runoff in the basin which will greatly affect the sediment yield in the reservoir silting up. In soil data sets chemical and physical properties i.e. soil texture, soil moisture contents, hydraulic conductivity, density and organic contents for each soil type at different layers were under consideration. The data was also helpful in determining the range of hydrological characteristics found within each sub-basin (Radcliffe et al., 2009; Yang et al., 2009; Santhi et al., 2001; White, 2005).

2.3.4 Metrological Data Sets

In SWAT model precipitation (rainfall, snow melting), temperature deviation, wind velocity, radiation of sun and relative humidity were counted for the long-term hydrological modelling (Morgan et al., 1990; Cheema and Bastiaanssen 2010; White, 2001). The Metrological data from weather stations (i.e. Astore, Besham, Gupis, Bunji, Chillas, Hunza, Gilgit and Skardu) in research basin area were obtained from Pakistan Meteorology Department (PMD). The climate data sets were processed using the input format of the model. For the SWAT model .dbf files was required, that was made by using Microsoft Access 2013 for each set of temperature and precipitation.

2.3.5 Flow and Sediment Data Sets

Daily flow data at Tarbela dam for 2004-2010 was obtained from the Surface Water Hydrology Project of WAPDA Lahore. For calibration from 2004-2006 and validation from 2007-2009 was done by using these data sets.

2.4 Methods

2.4.1 Model Structure

In almost every hydrological model, for the hydrological cycle water balance equation-1 is the compulsory key as in SWAT model. In this model shallow water table and unsaturated zone beyond the impervious layer was considered as an element. To predict the hydrology of watershed in the SWAT model the following equation 1 was used (Khan et al., 2008; Phomcha et al., 2012; Fadil et al., 2011; Arnold et al., 2005).

$$SW_t = SW_o + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (1)$$

In above equation SWt was the resultant water soil contents obtained by sum of the SWo as initial water soil contents and summation of hydrological parameters i.e. R_{day} (daily precipitation), Q_{surf} (surface flow), E_a (evapotranspiration), w_{seep} (moisture in vadose zone), Q_{gw} (return runoff amount), all these sets were taken on i days and measurements were in mm, t was time taken for the data sets in days in this study 180 days (6 years study period) were taken. Estimation of the flow was done by the Soil Conservation Services (SCS) curve number method equation 2 (Arnold et al., 2005; Arnold et al., 1998).

$$Q_{surf} = \frac{(R_{day}-0.25)^2}{(R_{day}+0.25)} \quad (2)$$

Where, Q_{surf} (surface runoff on daily basis), R_{day} (depth of rainfall). S is the retention parameter; all measurement units were mm. While, S was calculated using the following equation 3.

$$S = 25.4 \left(\frac{1000}{CN} - 1 \right) \quad (3)$$

Where, CN is curve number, S (mm/day) is soil water drainable volume per unit area.

The curve number for moisture conditions I and III were calculated using following equations 4 and 5 respectively.

$$CN1 = CN2 - \frac{20(100-CN2)}{(100-CN2 + e^{[2.533-0.0636*(100-CN2)])}} \quad (4)$$

$$CN3 = CN2 \times e^{[0.00673(100-CN2)]} \quad (5)$$

Where, CN1, CN2 and CN3 are the curve number for moisture condition I, II and III respectively. The lateral flow was predicted by using the following equation 6.

$$q_{lat} = 0.024 \left(\frac{2SSC \sin \alpha}{\theta_d L} \right) \quad (6)$$

Where, q_{lat} (lateral flow), S (capacity of soil water), SC saturated hydraulic conductivity (mm/h); L (length of flow in m), α (slope of the land) and θ_d (drainable porosity).

2.4.2 Routing in SWAT

Routing in SWAT through stream network for the flows and sediments load were determined by the water loading, sediment, pesticides and nutrients to the main channel. Surface water, sediment load, nutrients and organic contents were the major four dividing components for routing in the main channel, further flow was routed through the Muskingum routing method.

For predicting soil erosion from watersheds, modified universal soil loss equation 7 (MUSLE) was used as under (Renard et al., 1997; Kumar et al., 2015).

$$Sed = 11.8(Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \quad (7)$$

Where, Sed is metric tons sediment yield, Q_{surf} is the mm H₂O/ha flow volume, q_{peak} is peak cumec flow, area_{hru} is sub-region hectare area, K_{USLE}, C_{USLE}, P_{USLE}, LS_{USLE}, CFRG are factors of the soil erodibility, cover and management, support practice, topographic factor and coarse fragment respectively. Landscape component and channel component were two components of sediment routing. The maximum transported amount of sediment for each segment was determined as peak channel velocity function and was calculated as equation 8.

$$V_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}} \quad (8)$$

Where, q_{ch,pk} is the (m³/s) rate of peak flow and A_{ch} is m² channel flow cross-sectional. The peak flow rate is defined as follow by equation 9.

$$q_{ch,pk} = prf \cdot q_{ch} \quad (9)$$

Where, prf is rate of peak flow factor adjustment and q_{ch} is the mean flow rate (m^3/s). The maximum transported sediment from a reach segment was quantized by equation 10.

$$Conc_{sed,ch,i} = C_{sp} \cdot V_{ch,pk} \cdot spexp \tag{10}$$

Where, $Conc_{sed,ch,max}$ is the maximum transported water-sediment (ton/m^3 or kg/l), C_{sp} is the user defined coefficient, $V_{ch,pk}$ is peak velocity of channel in m/s and $spexp$ is also user defined sediment re-entrained exponent parameter, normally it is between 1 and 2.

Comparison was made between the equation 10 based on calculated maximum sediment concentration and sediment concentration in the channel at the start of the time step, $Conc_{sed,ch,i}$. If $Conc_{sed,ch,i}$ is greater than $Conc_{sed,ch,max}$ then the dominant process is the deposition in the range and the net deposited sediment was quantized by the above mentioned equation 10. If $Conc_{sed,ch,i}$ is less than $Conc_{sed,ch,max}$ then dominant process is the degradation in the reach and the net re-entrained sediment load was calculated by the following equations 11 and 12.

$$Sed_{dep} = (Conc_{sed,ch,i} - Conc_{sed,ch,max}) \cdot V_{ch} \tag{11}$$

$$Sed_{deg} = (Conc_{sed,ch,max} - Conc_{sed,ch,i}) \cdot V_{ch} \cdot K_{ch} \cdot C_{ch} \tag{12}$$

Where, Sed_{dep} sediment deposited in metric tons, Sed_{deg} re-entrained sediment amount in metric tons, V_{ch} water volume in m^3 , K_{ch} and C_{ch} are erodibility cover factors for the channel. The concluding sediment amount in the reach was determined as equation 13.

$$Sed_{ch} = Sed_{ch,i} - Sed_{deg} + Sed_{dep} \tag{13}$$

Where, Sed_{dep} and $Sed_{ch,i}$ are sediments in suspension and sediments in suspension at start time period respectively in metric tons. The transported sediment reaches out was calculated by the following equation 14.

$$Sed_{out} = Sed_{ch} \cdot \frac{V_{out}}{V_{ch}} \tag{14}$$

Where, Sed_{out} is transported out of the reach sediment (metric tons), V_{out} in m^3 outflow volume during the time step.

2.5 Calibration, Validation and Efficiency of Model

Any ambiguity or compassion program can easily be associated to SWAT through a generic interface (SWAT-CH tool). SWAT CH tool was used to calibrate and validate the peak flow coming into the Tarbela dam daily. Calibration period consisting of 3 years i.e. 2004-2006 and the period from 2007-2009 was made for validation. Model based results can be evaluated by many methods. In this study model efficiency was assessed using the R^2 and three suggested statistical coefficients i.e. Nash-Sutcliffe Efficiency index (NSE), Percent Bias (PBIAS) and Root Mean Square Error (RMSE) observations standard deviation ratio (RSR). The reliability among actual and simulated data set were obtained by R^2 following the best fit line. It ranges from zero to 1.0, in this study for calibration, it was 0.75 which is considered reliable. NSE, the normalized statistical method was used to predict the comparative amount of noise in comparison to information as equation 15.

$$NSE = 1 - \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - Y_i^{mean})^2} \tag{15}$$

Where n is total observation taken, Y_i^{obs} , Y_i^{sim} , Y_i^{mean} are the i^{th} streamflow, simulated and mean observed values respectively (Moriassi et al., 2007). PBIAS is the tendency of simulated to observed value as larger or smaller (Gupta et al., 1999). The optimal value is 0 and ranges from 10 to 10; negative values directed the overestimation bias, while positive showed the model underestimation bias value as equation 16.

$$PBIAS = \left(\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim}) \times 100}{\sum_{i=1}^n Y_i^{obs}} \right) \tag{16}$$

Based on the recommendation, RMSE-observations standard deviation ratio (RSR) was established and calculated as follow by equation 17 (Singh et al., 2005).

$$RSR = \frac{\sqrt{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}}{\sqrt{\sum_{i=1}^n (Y_i^{obs} - Y_i^{mean})^2}} \tag{17}$$

The smaller RSR value indicates accuracy of the model simulation. The life expectancy of the Tarbela dam was determined using equation 18 by (Kumar et al., 2015).

$$\text{Life of Tarbela Dam} = \frac{\text{Capacity of Tarbela Dam (BCM)}}{\text{Rate of Sediment Deposition (BCM/Year)}} \tag{18}$$

3. RESULTS AND DISCUSSION

3.1 Calibration of Model

SWAT calibration for the three years from 2004 to 2006 was done between Available Water-soil Content (AWC) and Soil Evaporation Compensation Factor (SECF) using monthly runoff data noted at the outlet of the research. To achieve the model calibration numerous replication runs were applied. The ranges of the sensitive calibrated parameters are shown in Table 1. The parameters were repeatedly adjusted for better results.

Table 1: Description and ranges of sensitive parameters.

Sr. No.	Sensitive Parameter	Description of Parameter	Calibrated Range
1	SPCON	Linear re-entrainment parameter for sediment and peak flow routing in channel	0.006
2	SPEXP	Exponential re-entrainment parameter for sediment and peak flow routing in channel	1.5
3	PRF	Peak rate adjustment for main channel	0.9
4	CH_COV1	Factor for channel erodibility	0.3
5	CH_COV2	Factor for channel cover	0.8
6	USLE_P	The support practice factor	0.01

Emphasizes on the previous literature review was also done instead of relying on the sensitivity analysis for finding the complex factors of the model for the flow assessing i.e. R^2 , NSE and PBIAS were used for checking SWAT estimation as used (Bracmort et al., 2006; Santhi et al., 2001; Vanliew et al., 2007). The NSE and R^2 values were found 0.69 and 0.75 respectively, which advocates satisfactory results for the calibration period. Calibrated monthly observed and simulated runoff has been plotted for visual comparison in Figure 4.

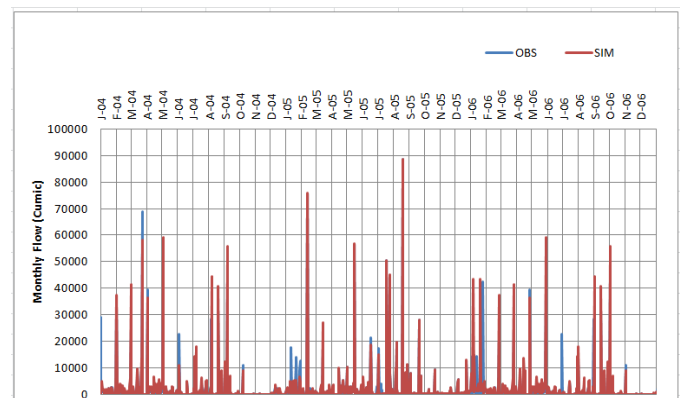


Figure 4: Visual comparison of monthly runoff during the calibration period 2004-2006.

Figure 4. Showed the overestimated peak runoff for calibration period. The modeled total runoff was found to be 500 to 89000 $m^3 \text{ sec}^{-1}$ against the observed runoff 1000 to 70000 $m^3 \text{ sec}^{-1}$.

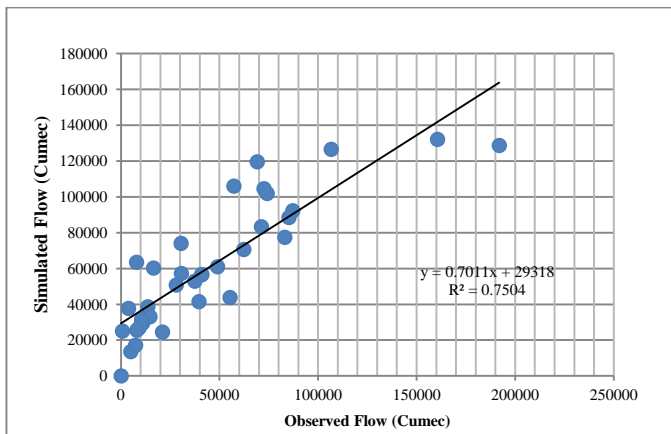


Figure 5: Regression analysis of river flow for the calibration at Besham Qila (2004-2006)

The best fitted line was made between the actual and simulated flows in cumec. R² and NSE values of the monthly time flows were 0.75 and 0.69, respectively, as shown in Figure 5.

3.2 Validation of the model

In modelling, model validation is considered as last step which was done between sediment production and estimating peak flow. It was carried out at monthly surface runoff for three years 2007-2009. In the validation period, most events showed the over-estimated peaks surface runoff (Figure 6).

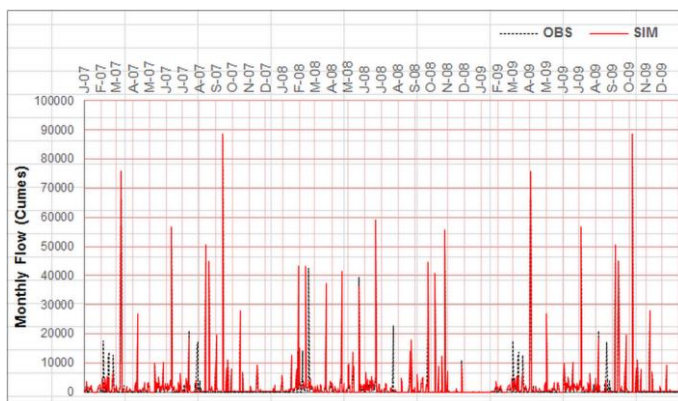


Figure 6: Comparison of monthly actual and simulated flows for the validation period 2007-2009.

For monthly peaks flow, values of the R² and NSE were obtained as 0.8 and 0.68 respectively as shown in Figure 7.

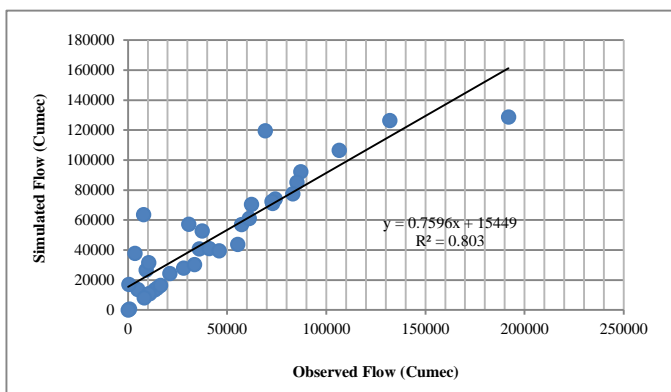


Figure 7: Regression plot of monthly observed and simulated flow for validation period at Besham Qila (2007-2009)

The mean sediment yields on monthly basis are displayed in Table 2, the highest rate was in the month of august i.e. 83.58 tons ha⁻¹.

Table 2: Average monthly basin values for sediment yield												
Mo nth	1	2	3	4	5	6	7	8	9	10	11	12
Sed. Yield	32	72	45	51	17	26	70	83	29	3.	7.	22
	.9	.7	.8	.5	.6	.6	.3	.5	.0	7	9	.4
	5	9	2	0	5	4	4	8	3	9	2	5

*Sediment yield is in (tons ha⁻¹)

3.3 Sediment Yield Calculation

Total sediment yield potential = Area × Average sediment yield

Area of watershed = 7580494.5 hectare

Total average monthly sediment yield simulated by the Model = 38.76 Tons ha⁻¹

Total sediment yield potential = 7580494.5 ha × 38.76 Tons ha⁻¹

Total sediment yield potential = 293819966.82 Tons

Total sediment yield potential = 0.13 BCM

The average sedimentation rate for Tarbela dam was estimated 0.13 BCM using the SWAT model. The gross, live and dead storage capacity of Tarbela reservoir in BCM as determined by WAPDA in 2010 were 10.393, 8.695 and 1.698, respectively. If the sediment load will be continued at rate of 0.13 BCM, then silting up period for the Tarbela reservoir is next 79.94 years reference to 2010.

4. CONCLUSIONS

Pakistan is a country with hilly areas in the north and flat land with a huge irrigation web in the mid of the country and ultimately ends at Arabian Sea in the south. For rainfall distribution it is arid to semi-arid and for temperature it is tropical to subtropical. Snow melting and heavy rainfall in the north erode the soil and cause problems in downstream. Reservoir storage capacity is highly affected due to anthropogenic activities in reservoirs yielding. In this study, runoff simulation and sedimentation yield were assessed by SWAT model in Indus watershed. The model gave correct estimates of sediment yield at Besham Qila station showing strong footing for future calculations. The model was calibrated for the three years (2004-2006) and showed good performance with R²=0.75 and NSE= 0.69 for peak runoff. The model was validated for the period of three-year (2007-2009) and performed well with R² and NSE 0.8 and 0.70 respectively. In nutshell, the modelling outcomes of this study concluded that the SWAT model divulged the reasonably well sediment load yield and runoff from the intermediate watershed area in the study area. For the research area of the watershed (7580494.5 ha) and total average monthly sediment load modeled (138.76 Tons ha⁻¹), the total potential for sediment yield was estimated as 0.13 BCM. It is the alarming situation for Pakistan that with the increasing sediment yield reservoirs of the Indus Basin is silting up. With this estimation agriculture sector, hydropower sector and water inhabitants will be on the hit point by the shortage of the Water. Now the Government of Pakistan should make policies to prevent the environment by plantings trees on the upper Indus, so that erosion can be minimized, and precipitation increased. In this way, sediment potential will be minimum and live storage of the reservoirs will be increased. With a few enhancements in the input data performance of the model could be enhanced.

ACKNOWLEDGEMENT

The authors are thankful to the Faculty of Agricultural Engineering and Technology-University of Agriculture Faisalabad, Pakistan for providing facilities for the successful completion of the current study work. Precision Lab of Center for Advanced Studies in Agriculture and Food Security (CAS-AFS)-UAF is also highly acknowledged for providing a conducive environment for research work.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

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