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Assessment of Runoff and Sediment Yield in the Tilaya Reservoir, India Using SWAT Model

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Abstract: In this paper the Soil and Water Assessment Tool (SWAT) was used to simulate the runoff and sediment that is coming into the Tilaiya Reservoir, Jharkhand, India. In this twenty first century, it is widely accepted that climate change would significantly affect many hydrologic systems which in turn would affect the water availability, overland flow and the flow discharges in rivers. Surface runoff estimation in a catchment based on the rate of storm precipitation and also discharge estimation at outlet is important in hydrologic studies. The research was conducted using a 10-year historical stream-flow record from 1991-2000; the data from 1991 to 1995 was used for calibration and the data from 1996 to 2000 was used for validation. From the sediment inflow data that we obtained from the SWAT model output, the reservoir life was calculated i.e. the time required to fill the reservoir up to its dead storage; in the study it was found out to be 89 years from the year 2000.

Key words: Runoff, sediment, reservoir, SWAT, rivers.

Introduction

Deposition of sediment in reservoirs is a serious issue to be noted in recent years. Deposition in reservoirs reduces the storage capacity and cause serious problems in case of the stability and operation of the dam. An important factor in reservoir design and operation is its sedimentation problem. Sediments are generally delivered to the reservoir from two main sources: (i) the main stream channel entering the reservoir and (ii) the valleys on both sides of the reservoir.

Sediment yield is the amount of sediment that has been transported to the basin outlet over a period of time. If there is a reservoir at the downstream end of the basin, these sediments would enter into the reservoir. The sediment yield is also referred as the amount which enters into a reservoir at the downstream end of the basin (Morris and Fan, 1998). It is observed that all the eroded and transported sediments does not reach the basin outlet because of deposition and trapping at various places in the upstream basin reaches. Due to the erosion and sedimentation problems, quantification of sediment yield in reservoirs is a very important factor for river morphology studies and water soil conservation measures planning.

With the rapid urbanization and economic development, water scarcity and deterioration of water quality have become increasingly severe in many river basins. Solving these problems with effective water management strategies is crucial for the sustainability of economic development to meet the water demand for the growing population. The aim of water management in different watersheds may vary. For example objective of some watersheds is to harvest water throughout the year for drinking purpose and irrigation whereas the objective of some other watershed is to reduce the peak rate of runoff to minimize the soil erosion and sediment yield or to increase groundwater recharge. Hence watershed

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modelling is very much essential for sustainable development. Most important feature of a hydrological model is its accuracy in estimating the surface runoff adequately because the surface runoff process affects the transport of sediments and agricultural chemicals. Distributed watershed models have become very common in recent years and are applied to implement management strategies in the areas of water resource allocation, flood control, impact assessments for land use and climate change, and pollution control. Most of these models' basic approach is similar in their attempt to incorporate the heterogeneity of the watershed and the spatial distribution of topography, vegetation, land use, soil characteristics, rainfall and evaporation.

Over the past decades, complex water resource systems such as simulations are being used to identify the impact of climate change and land use on water availability in river basins (Muttiah and Wurbs, 2002; Cao et al., 2006). A dramatic increase in the use of distributed hydrological models could be seen over the past few years to simulate hydrological process and to estimate the soil erosion and non-point source pollution (Tripathi et al., 2004). In the recent years, several distributed hydrological models has been developed such as Agricultural Nonpoint Source Model (AGNPS) (Young et al., 1989), Soil and Water Assessment Tool (SWAT) (Arnold and Allen, 1996; Arnold et al., 1998) and Areal Nonpoint Source Watershed Response Simulation (ANSWERS) (Beasley, 1980) which are integrated within GIS environment for predicting runoff and sediment yield.

SWAT is a very efficient distributed model, developed to predict runoff, erosion, sediment and nutrient transport from watersheds (Arnold and Fohrer, 2005). In this model SWAT, the concept of Soil Conservation Services (SCS) and Curve Number (CN) equation is utilized to predict storm runoff; thus implicitly assuming an excess infiltration value. Because of this limitation, it may fail to predict Variable Source area correctly.

Researchers such as Arnold et al. (1999) reported that SWAT performed well during a monthly streamflow simulation in the Texas Gulf basin with drainage areas ranging from 10,000 to 110,000 km^2. Other researchers like Van Liew and Garbrecht (2003) showed that SWAT is capable of providing adequate hydrologic simulations related to the impact of climate variations on water resources.

The SWAT has got many parameters to be calibrated; hence its calibration should be done very carefully. The calibration of such a distributed parameterized watershed model deserves the attention and careful consideration of researchers, especially concerning uncertainty. According to former researchers Abbaspour et al. (2004) the primary sources of uncertainties include simplifications in the conceptual model; Abbaspour (2005)—unaccounted processes occurring in the river basin; Beven and Freer (2001)—inclusion of processes that actually do not occur in the model; Van and Meixner (2006)—processes unknown to the modeller and not included in the model either; Van et al. (2008)—errors in input parameters or data; and Abbaspour et al. (2008)—nonunique parameters. It has been used as an effective tool to simulate the impact of climate change and human activities on hydrological and biogeochemical cycles in a variety of catchments and has been very popular among the researchers of the world such as Arnold and Fohrer (2005); Gossain et al. (2005); Benaman and Shoemaker (2005); Tripathi et al. (2005); Kou et al. (2007); Tolson and Shoemaker (2007); Wu and Johnston (2007); Easton et al. (2008) and Xu et al. (2009). In the above mentioned studies, the model was applied mainly for predicting runoff and sediment yield on monthly and annual basis.

In the present study, ArcSwat is used as it can model saturation excess response to rainfall as it takes into account the topographic effect on hydrology. In this study the runoff and the sediment inflow data was obtained using the SWAT model and at the same time the reservoir life was also calculated.

SWAT Model Description

The Soil and Water Assessment Tool (SWAT) is a river basin or watershed scale model. The model was developed by the United States Department of Agriculture – Agricultural Research Service (USDA – ARS). The SWAT model is applied successfully all over the world, mostly with limited data sets (Arnold et al., 1996). It is developed to predict the effects of land management practices on water, nutrients, sediments and agricultural yields in large complex watersheds with varying soil characteristics, land use and management conditions over long time duration. The model is physically based, uses readily available input data, computationally efficient and it enables users to study long term effects.

SWAT is a distributed rainfall-runoff model and it needs the river basin to be subdivided into smaller discrete calculation units for which the spatial variation of the major physical properties are limited, and hydrological processes can be treated as being homogeneous. The total basin behaviour is the result of the discredited smaller sub-basins. The maps of soil, land cover and surface slope within each sub-basin, are used to define unique combinations and each combination will be considered as a homogeneous unit, i.e. Hydrological Response Unit (HRU). Hence, SWAT subdivides the river basin into units that have similar characteristics in soil, land cover and surface slope. Such units are located in each of the considered sub-basins. The water balance components for each HRU are computed on a daily time step.

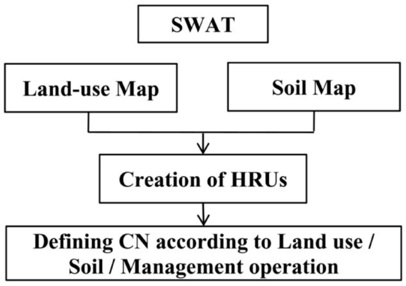

Figure 1: Framework for the SWAT model.

Study Area

The Tilaiya dam was constructed across the Barakar River, at Tilaiya in Koderma district in the Indian state of Jharkhand. It is one of the four multi-purpose dams included in the Damodar Valley Corporation (DVC). It was the first one to be constructed in the first phase of the Damodar Valley Corporation (DVC) and was opened in 1953. Figure 2 shows the map of DVC and the location of Tilaya Dam. The study area (Barakar catchment), which is a part of the Damodar catchment, is located between 24°00′ to 24°30′ N latitude and 85°00′ to 87°00′E longitude (Figures 3a and 3b). The Tilaiya Reservoir has a catchment area of 984 km^2 and is situated upstream of the Mython dam in the DVC system. Figure 3(a) shows the schematic diagram of entire DVC system and Figure. 3(b) shows the entire Damodar Basin.

SWAT Model Input Set Up

SWAT model is data driven model; its accuracy and operation depends on different types of data ranging from

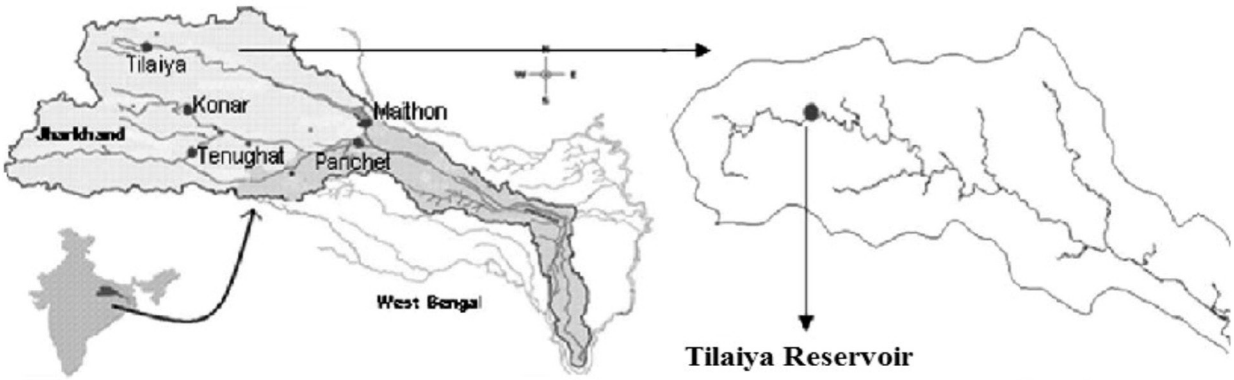

Figure 2: Map of DVC.

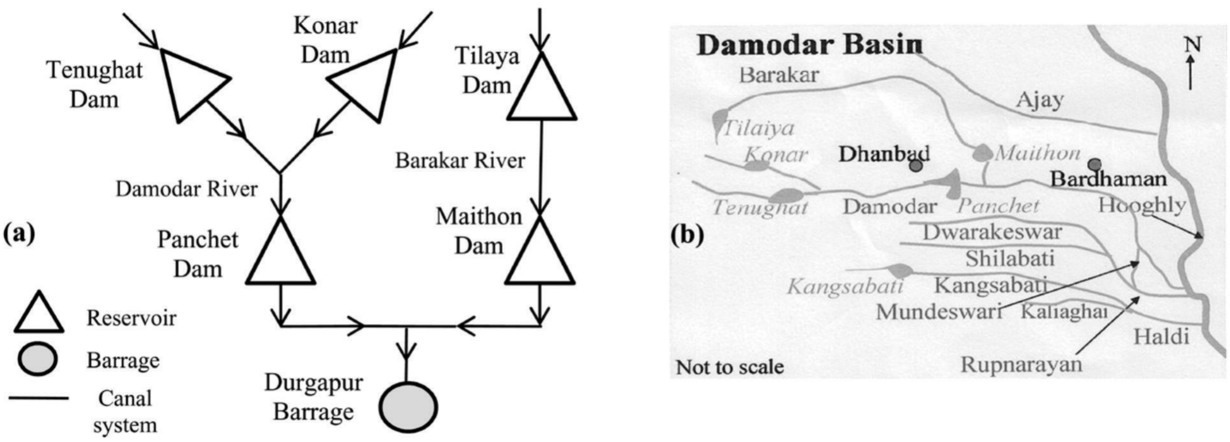

Figure 3: (a) DVC system and (b) Damodar Basin.

topography, land use, soil, climate, etc. The sources of various data collected are mentioned below and different processes to integrate them in the SWAT model for simulation are also mentioned.

DEM: The DEM (Digital Elevation Model) map for the study region has downloaded from SRTM (Shuttle Radar Topography Mission) database (Figure 4a).

Land Data: Land use map for the study region has been downloaded from the USGS Land Cover Institute (LCI) database (Figure 4b, Table 1).

Soil Data: Soil dataset has been downloaded from FAO data-map – Digital Soil Map of the world website and it was also reprojected in the same projection after creating the subset using the Arcmap Software (Figure 5a, Table 2).

Table 2: Soil use detail

Soil	*Area [ha]*	*Area [acres]*	*% Area*
Sandy loamy soil	76628.7909	189353.5738	88.79
Loamy sandy soil	9094.0472	22471.8452	10.54
Sandy clayey loamy soil	584.9831	1445.5226	0.68

Weather: SWAT requires daily values for precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed for modelling of various physical processes. Soil and rainfall being the

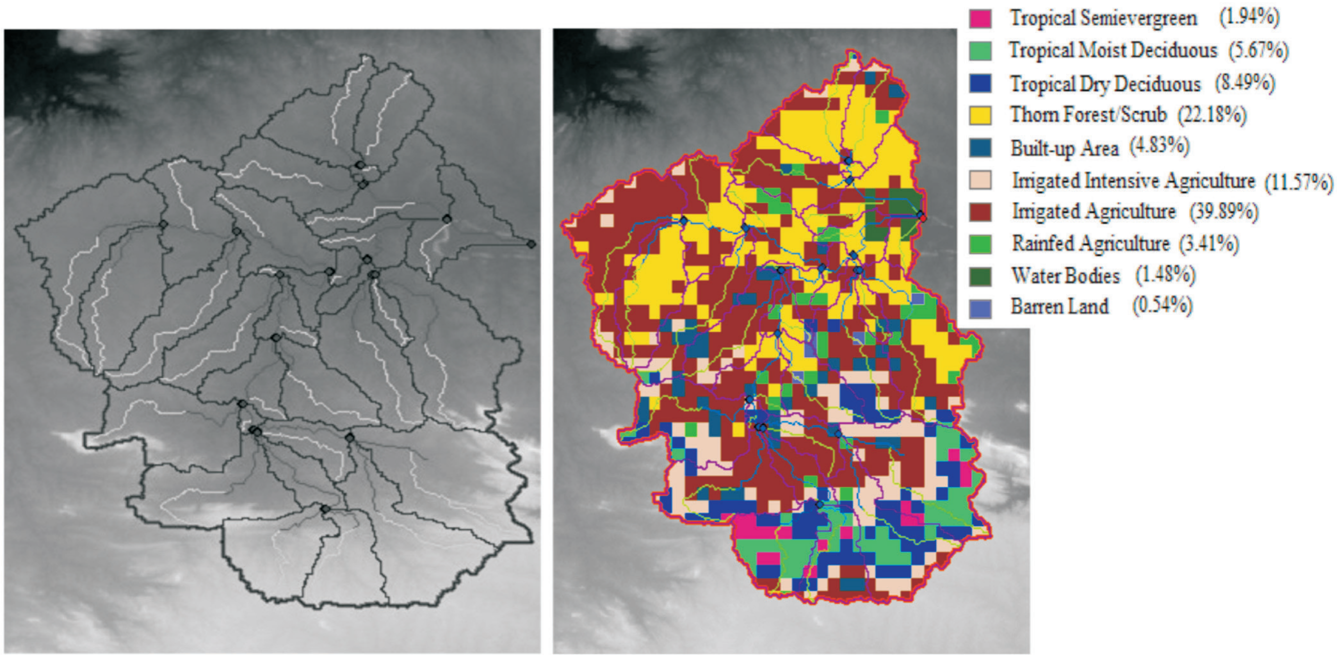

Figure 4: (a) Digital elevation model (DEM) map with delineated watershed and (b) Land use map.

Table 1: Land use detail

Land use	*Area [ha]*	*Area [acres]*	*% Area*
Tropical semi-evergreen → FRSE	1677.3251	4144.7543	1.94
Tropical moist deciduous → FRSD	4895.1326	12096.1173	5.67
Tropical dry deciduous → FRST	7328.6945	18109.5705	8.49
Thorn forest/Scrub → WETL	19141.9930	47300.8217	22.18
Built-up area → WETN	4171.7061	10308.4943	4.83
Irrigated intensive agriculture + Irrigated agriculture + Rainfed agriculture → AGRL	47350.0243	117004.2776	54.87
Water bodies → WATR	1273.1986	3146.1374	1.48
Barren land → BARR	469.7471	1160.7685	0.54

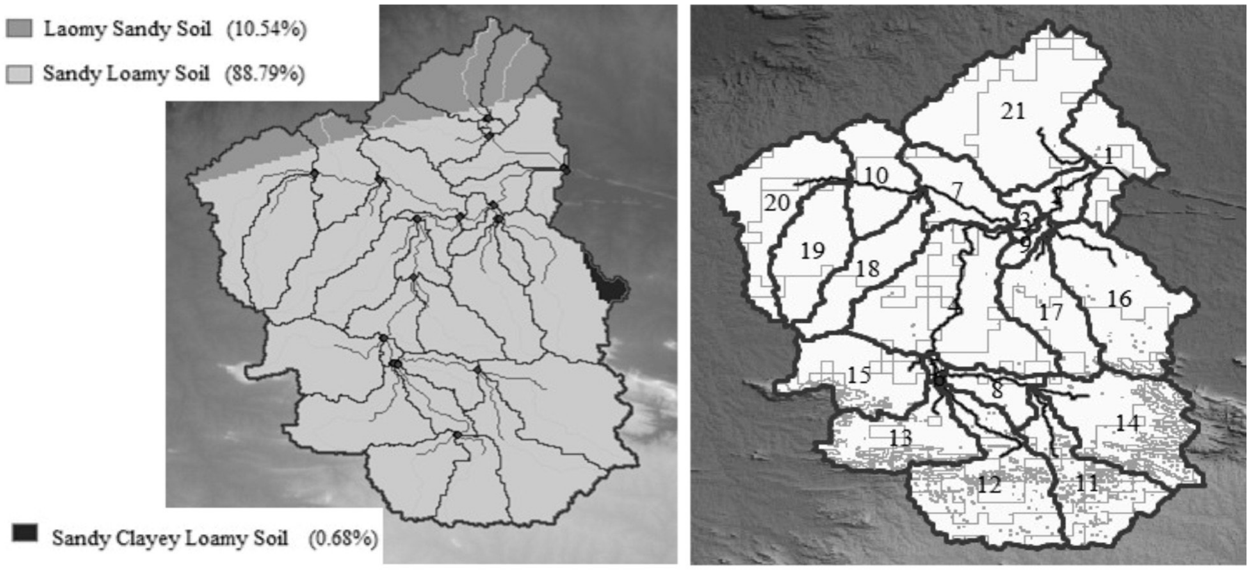

Figure 5: (a) Soil use map and (b) HRU distribution map.

most important input data. Weather data were collected from the database of waterbase.org website.

Preparation of thematic layers: The satellite data are interpreted to derive thematic information on land use and land cover. This, in combination with conventionally measured climatic parameters like precipitation, temperature, etc. and topographic parameters like height, contour slope and drainage network, are used to obtain necessary inputs. The extracted information from remote sensing is stored as geo-referred database in GIS. The DEM, stream network, land use and land cover, and hydrological soil group maps for providing inputs to the SWAT model were prepared.

Results and Discussions

A river basin can be divided into sub-basins by discretization schemes. In the present work, the study area was Tilaya catchment (Figures 2 and 3). Figure 3 is showing the entire DVC system and the river network basins of the whole DVC system. In order to get a reasonable resolution of soil properties, land use and management practices, the basin was further divided into a total of 21 HRUs (Figure 5b).

The HRU was created using the help of the Digital Elevation Map (DEM) of the Tilaiya catchment area as well as other inputs such as the land use map and the soil use map. At first the inlet and outlet points were selected in the DEM map used in the ArcGis software. With the help of the slopes from the DEM projections the stream network was created and once the outlet was specified the initial stream network and sub-basin outlets were defined. The software also provides the option of defining streams based on a drainage area threshold or importing pre-defined watershed boundaries and streams.

Watershed delineation was more defined in this section by fixing the outlet point of discharge for the sub-basin and for the whole watershed. Sub-watershed outlets are the points in the drainage network of a sub-watershed where the stream flow exits the sub-watershed area. The point where the Barakar river meets the Tilaiya reservoir has been considered as the outlet point for the whole watershed. Outlet for the whole watershed was defined manually. It is convenient to select the most down-stream outlet of each target watershed to determine the whole basin. The area of the sub-basin was cut short from previous defined sub-basin area after defining the outlet. The calculation of sub-basin parameters section contains functions for calculating geomorphic characteristics of the sub-basins and reaches, as well as defining the locations of reservoirs within the watershed.

Topographic report was created which contained the summary and distribution of discrete land surface elevations in the sub-basins. Now outlet is selected manually at the point where your watershed outlet is located. The movement of water depends on the soil type and vegetation cover. The amount of rain lost due to interception storage on the plants depends on the type of vegetation and has a significant effect on the infiltration capacity of the soil. Dense vegetation covers the soil from raindrop impact and reduces the problem of erosion. As vegetation cover decreases, the surface runoff increases resulting in increasing sediment transportation to the streams.

For each of the delineated sub-basins, land use and soil data were defined for modelling of various hydrological and other physical processes. The prepared land-use from digital maps was given as input to the model. The load predictions will be good and accurate if each HRU is considered obtaining the total effect of different land cover crops and soils. The total runoff depends on the actual hydrologic condition of each land cover/crops and soil present in the watershed. Therefore, the impact of each type of land use is considered in this modelling to calculate runoff and sediment load in the basin. After the overlay of the land-use, soil maps and slope, the distributions of the Hydrological Response Units (HRUs) were determined (Figure 5b).

ArcView interface to SWAT was utilized to obtain the model input and for watershed parameterization. It helped to provide a graphical support for the disaggregation scheme and allowed the construction of the model input from digital maps. In the beginning the input model parameters are directly obtained from the database (e.g. parameters concerning soil property, crop property, rainfall, etc.) or estimated by AVSWAT based on input maps and database (e.g. curve number, manning roughness coefficients).

Sensitivity Analysis

Sensitivity analysis determines the degree of effect that the model parameter has on the output and thus reducing the number of parameters for calibration. The analysis was carried out by changing the value of one parameter and keeping the others constant. Sensitivity of the parameters was assessed in relation to the runoff and sediment yield (Table 3).

Table 3: Sensitive parameters from sensitivity analysis

Parameter_Name	*Fitted value*	*Min value*	*Max value*
R__CN2.mgt	0.0750	-0.20	0.20
V__ALPHA_BF.gw	0.8125	0.00	1.00
V__GW_DELAY.gw	161.2500	30.00	450.00
V__GWQMN.gw	0.3750	0.00	2.00

For sediment yield, GWQMN and ALPHA_BF were the most sensitive parameters. The base low factor hugely affects the erosion thus directly affecting the sediment yield.

Model Calibration

The model was calibrated using monthly inflow to Tilaiya Reservoir data i.e. monthly surface runoff for the years 1991 to 1995. Both the calibration and validation was carried out using monthly inflow data to the Tilaiya Reservoir. The different calibrated values of Manning's '*n*' for different condition, such as for overland flow, channel flow and effective hydraulic conductivity of channel alluvium were considered as 0.12, 0.04 and 0.55 mm/hr respectively for the watershed.

The roughness values were kept within the range as suggested in SWAT model. Moreover, the sediment routing factor and the coefficients of sediment routing equation and the exponent of re-entrainment parameter for channel sediment routing were taken as 0.10, 0.02 and 1.3, respectively. These values were almost same as in Betrie et al. (2011), which reported the values of routing factor, linear parameter and exponent as 0.12,

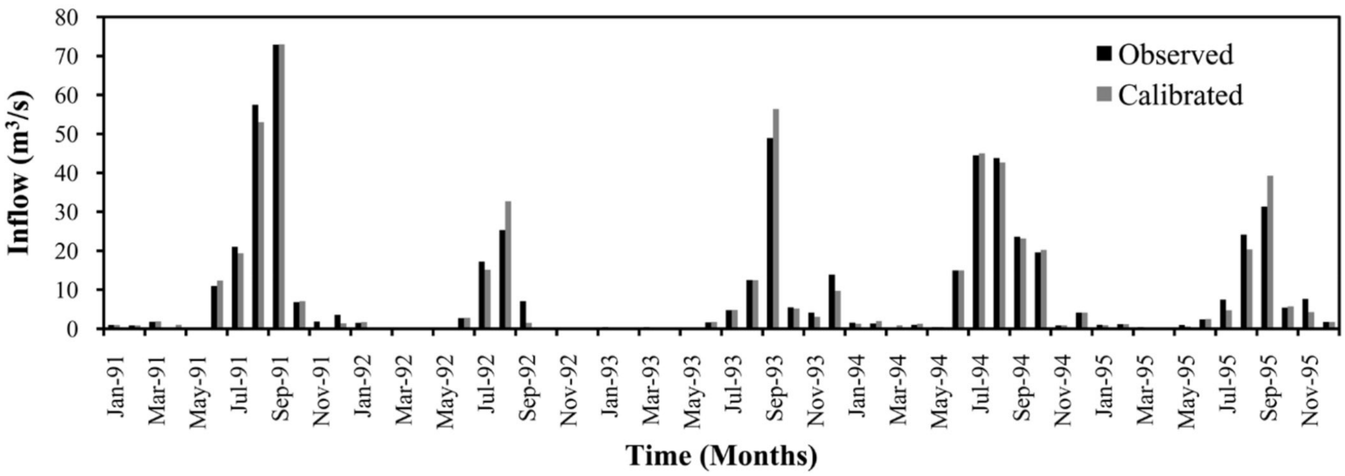

Figure 6: Comparison of observed and simulated monthly runoff for the calibration period 1991-1995.

0.01 and 1.2 respectively in sediment routing equation. The time series of the observed and simulated monthly runoff (Table 4 and Figure 6) for the calibration period were plotted for visual comparison. From these figures, it can be observed in general that the model was calibrated well. In most of the months it can be seen that the simulated flow is more than the observed flow; however the deviation is very small. From Table 4 also it is evident that the model was satisfactorily calibrated.

Table 4: Comparison of the calibrated value

	Calibration	
Statistical parameters	*Observed*	*Simulated*
Mean (m^3/s)	9.41	9.27
Peak (m^3/s)	72.87	72.96
Sum (m^3/s)	564.79	556.69

Model Validation

The model validation was carried out for monthly surface runoff for the years 1995 to 1997. A graphical representation of the observed and simulated monthly flows (Figure 7) is shown. The graph shows that the peaks of the surface runoff over-estimated in most of the events. Though here also the difference is very small; thus we can say that the model is validated. The same may be inferred after taking a look at Table 5.

Table 5: Comparison of the validated value

	Validation	
Statistical parameters	*Observed*	*Simulated*
Mean (m^3/s)	11.05	11.69
Peak (m^3/s)	76.68	80.36
Sum (m^3/s)	663.440	701.75

Reservoir Inflow

The actual monthly inflows to Tilaiya Reservoir for the calibration and validation periods (average monthly) are compared with the simulated monthly inflows to Tilaiya Reservoir (Figure 8). It can be seen from Figure 8 that the observed and simulated flow matches well and almost all the data fall within the 30% deviation line. The magnitude and temporal variation of simulated inflows matches well with the observed inflow for calibration and validation periods, except for a few months. Hence we can conclude that the model is reasonably validated.

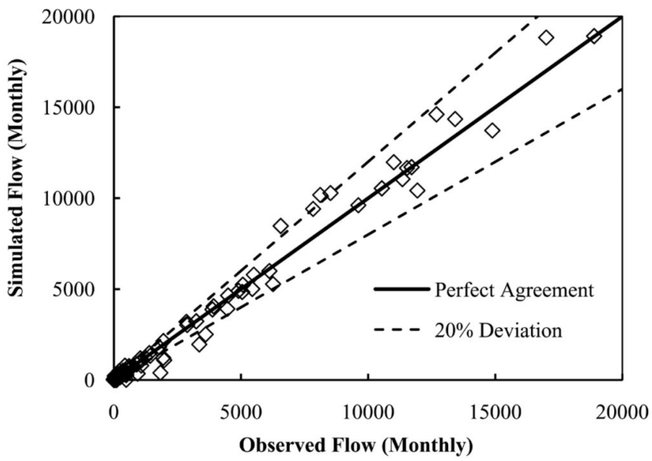

Figure 8: Reservoir inflows to Tilaiya Reservoir for the calibration and validation periods (average monthly).

Sediment Yield

For better understanding and accuracy of the validation, the daily flow of one year, 1997, has been selected for the monsoon season (June, July, August, September and October) and compared as shown in Figure 9. It can

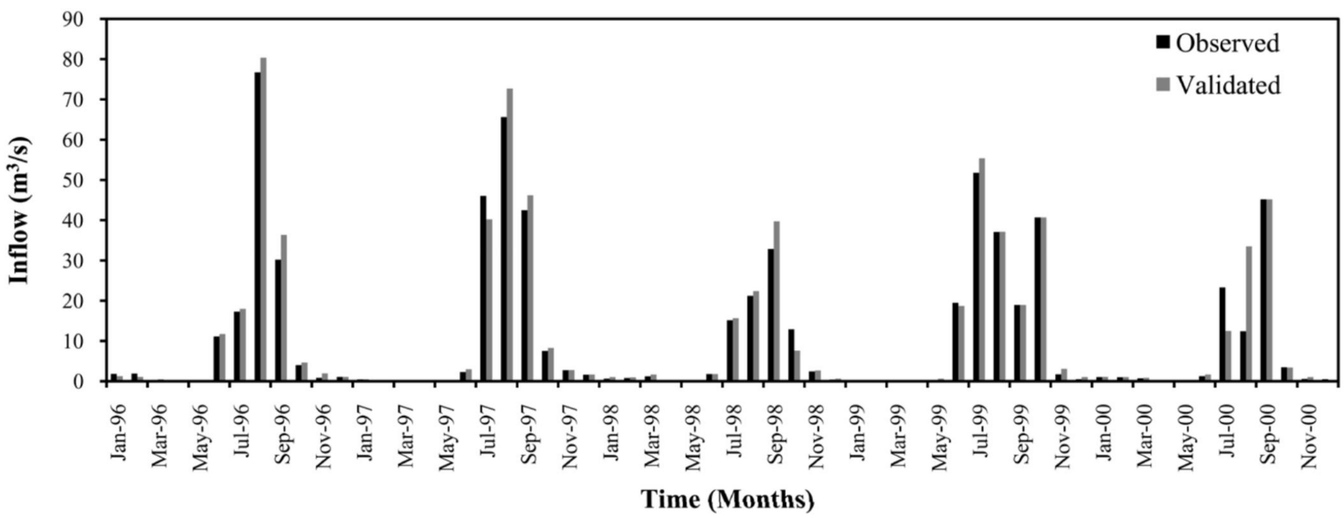

Figure 7: Comparison of observed and simulated monthly runoff for the validation period 1996-2000.

be seen from Figure 9 that here also the observed and simulated flows match well and almost all the data fall within the 30% deviation line.

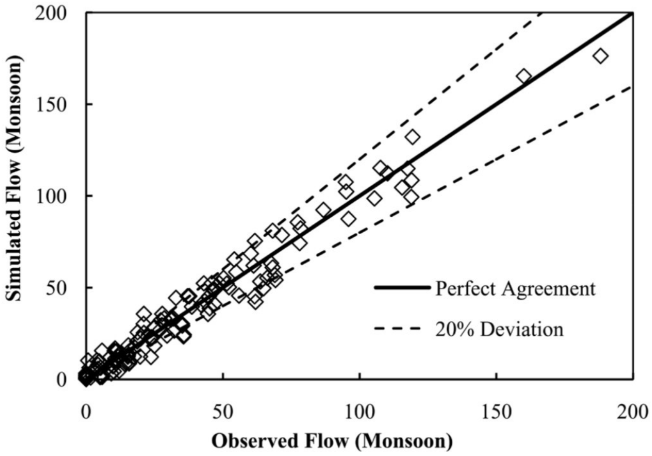

Figure 9: Daily reservoir inflows to Tilaiya Reservoir for monsoon season of the year 1997.

The differences may be due to the nature of rains and soil condition over the watershed. In a catchment the sediment yield is directly related to surface runoff; due to this phenomenon, the simulated sediment yield is related to the trends of simulated surface runoff. From the graphical representation shown above, it is evident that the model-calibrated parameters for the Tilaya reservoir catchment represented quite realistically the hydrological behaviour of the catchment. There is a marginal difference; however it may be because of the inaccuracies involved in the model presentation of the subtle differences in curve number (CN2), management practices, channel, soil, and subsurface water properties. Hence, the SWAT model can be used for the simulation of the studied watershed.

Reservoir Life

The average sedimentation rate for the Tilaiya Reservoirs during the study period (1991-2000), obtained from the model, was 0.83 Mm^3/year. The average sedimentation rate of Tilaiya reservoir based on 1991 survey was 1.02 Mm^3/year; however the planning stage sedimentation rate of Tilaiya is not available. As mentioned earlier, the DVC is the first river valley project in Eastern India that tackles soil and water conservation problems in an integrated manner and Tilaya reservoir is a part of the DVC system. In these sub-watersheds, treatment such as afforestation, trenching, bunding, terracing, vegetative barriers, sediment basin, farm pond and different kinds of check dams were constructed. These treatments may have resulted in the decrease of the reservoir sedimentation rate, and also indicates that the conservation measures adopted in the catchment area were effective.

A management plan was developed for treating the sub-watersheds to verify how the reservoir sedimentation and its life was effected by the management practices (soil and water conservation measures). These sub-watersheds were treated sequentially considering the proximity of sub-watersheds to the reservoirs and average annual sediment loss. Initially all sub-watersheds near the reservoirs with high priority class were treated, and their impact on reservoir sedimentation was investigated. Application of the management plan had increased the life of Tilaiya reservoir by 29 years. The study clearly indicates that the SWAT model can be used for hydrological modelling, identification and management of critical erosion-prone areas to control reservoir sedimentation rate. The average sediment deposition rate calculated from the model output was 0.83 Mm^3/yr for the Tilaiya catchment for the base period (1991-2000). In the present study the period of silting up to dead storage was worked out as 89 years, starting from the year 2000. The soil and water assessment tool (SWAT) model was used to accurately simulate runoff and sediment yield at different spatial scales because of the close agreement between the simulated runoff and sediment yield and their observed counterparts. The SWAT model gave us the siltation rate for the Tilaiya catchment and the capacity of the catchment is known. From there the reservoir life was manually calculated.

So according to our study, the Tilaiya reservoir should be filled to dead storage by the year 2089. Trap efficiency was computed based on difference between sediment inflow and outflow of the reservoir and from the capacity inflow ratio curve suggested by Brune (1953).

Conclusion

The soil and water assessment tool (SWAT) model can be used to accurately simulate runoff and sediment yield at different spatial scales because of the close agreement between the simulated runoff and sediment yield and their observed counterparts. In all cases, there was less than 10% deviation between the measured and model simulated runoff, sediment yield and reservoir inflows. This study shows that the SWAT model can be used for hydrological modelling and to identify critical sub-watersheds. Furthermore, the model is a useful tool to select a management plan for reducing reservoir sedimentation rate. The SWAT model ArcSwat was tested for the study. Since the basic conceptual methodology of the model differed in terms of creating hydrological response unit (HRU) and distribution of curve number (CN), the models response was different to runoff and soil erosion. SWAT created HRUs from the combination of land use/soil types and runoff was modelled on the basis of Curve Number (CN) defined for HRU. Conceptually the model implicitly assumed infiltration excess response to rainfall. The topographic effect and consequently the saturation excess mechanism was ignored in the modelling process.

The ability of SWAT to replicate hydrologic and/or pollutant loads at a variety of spatial scales on an annual or monthly basis has been confirmed in numerous studies. However, the model performance has been inadequate in some studies, especially when comparisons of predicted output were made with time series of measured daily flow or pollutant loss data. These weaker results underscore the need for continued testing of the model, including more thorough uncertainty analyses, and ongoing improvement of model routines. Some users have addressed weaknesses in SWAT by component modifications, which support more accurate simulation of specific processes or regions, or by interfacing SWAT with other models. Both of these trends are expected to continue. The SWAT model will continue to evolve in response to the needs of the ever increasing worldwide user community and to provide improved simulation accuracy of key processes. A major challenge of the ongoing evolution of the model will be meeting the desire for additional spatial complexity while maintaining ease of model use. This goal will be kept in focus as the model continues to develop in the future.

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