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Sedimentation Yield Analysis of Kamthikhairy Dam Reservoir using SWAT and SWAT-CUP Algorithm

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Abstract: ***Sedimentation is an immense problem that has threatened water resources development in the Kamthikhairy dam reservoir, Nagpur, Maharashtra. Sediment yield is becoming a major problem now days which leads to siltation in reservoir and not only reduces the capacity of dam but also can affect the power generation and safety of dam as well as aquatic life. In current scenario all the dams in India are facing this problem. An insight into sedimentation mechanisms plays an important role for managing the reservoir operations efficiently in the governing region. The objective of the study is to analyze the sedimentation of the reservoir using Remote sensing and Soil and Water assessment Tool (SWAT). The SWAT can be the powerful tool to analyze the sedimentation in the reservoir. The calibration using SWAT-CUP algorithm will help to make the simulation more accurate to the observe results.***

Keywords: ArcGIS, Remoe Sensing, SWAT, SWAT-CUP

I. INTRODUCTION

The sedimentation deposition of reservoirs in India has become a serious problem due to the increasing population, agricultural activities, poor soil conservation, and deforestation. Sediment deposition creates many problems in the reservoirs. The accumulation of sediments in reservoir has led to a decline in lake water storage capacity, navigation problems, and other water quality and environmental issues.

To overcome the problems caused by the accumulation of reservoir sediments and to use these sediments, it is important to estimate the sediment volume (quantity) and its distribution in these reservoirs. This is not only used to assess the capacity of reservoirs but also to ensure the safest route of navigation through these reservoirs. The assessment of reservoir sediment deposits is important for the operational planning and management of these reservoirs.

RS data has proven to be a useful tool for monitoring reservoir sediment deposits. Besides, GIS analysis tools are used to combine satellite observations with field measurements to assess sediment deposits in reservoirs and to successfully apply them in different parts of the world. Therefore, this study aims to estimate the total amount of accumulated sediment and its distribution on the reservoir bed using RS and GIS techniques.

Typically, the reservoir is designed to accommodate the estimated settling rate. Remote sensing and GIS technology is a new method for assessing sediment yields that provide high-precision results and spatial data over time.

II. METHODOLOGY AND EXPERIMENTATION

The SWAT model is a semi-physical model that helps to generate the different hydrological parameters including flow and sediment using different equations like SCS-CN and MUSLE. The SWAT model is comprised of major three sections like Digital Elevation map processing which includes the fill operations in which the DEM voids get filled with the respective values using the interpolation method. After the Fill operation, flow accumulation and flow direction are performed to generate the streams, and the watershed is delineated.

The second section includes the generation of hydrological response units (HRU) using Land-use and Land-cover maps and Soil maps. The third section includes the climate data input and creating the weather input tables for a successful SWAT model. After the input data, the model is set up for the initial requirement of Digital elevation map (DEM), Land use and Land cover map (LULC), Soil map, and weather input data in which the daily precipitation, maximum and minimum temperature, relative humidity, wind speed and solar radiation along with streamflow data for the complete model.

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Table 1: Data Source

Sr. No.	Data	Resolution	Sources
1	Digital Elevation Map	30 Meter	SRTM
2	Land-Use/Land-Cover Map	100 Meter	DAAC decadal landuse
3	Soil Map	100 Meter	FAO soil map
4	Climate Data	Daily	Global Weather data and IMD
5	Observed Sediment Data	Daily	More Dam Authority and NMMC

A. Digital Elevation Map

Digital Elevation Model is the geographic grid of an area where the contents of each grit cell describe the elevation of any point at a given location and specific spatial resolution in the form of a digital form. It is one of the essential spatial inputs necessary for delineation of the watershed into several sub-basin based on elevation in the SWAT model.

The SRTM DEM of 30m resolution was processed for the extraction of flow direction, flow accumulation, stream network generation, and delineation of the watershed and sub-basins. The topographic parameters such as terrain slope, channel slope, or reach length were derived from the DEM.

B. Land use and Land Cover Map

Change in land use and vegetation affect the water cycle and its influence is a function of the density of plant cover and morphology of plant species. Water types include wetlands or open water. Land use shows how people use the landscape whether for development, conservation, or mixed uses.

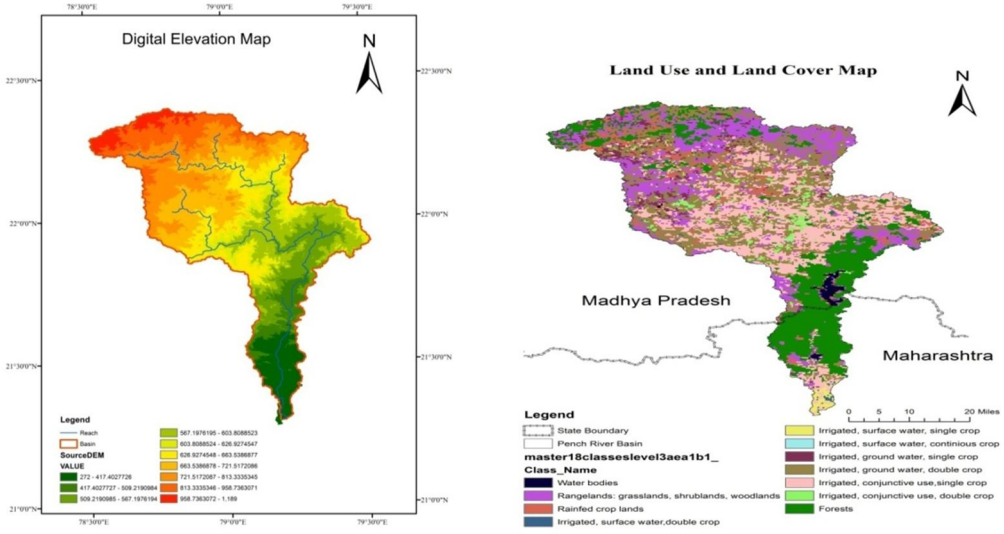

Figure 1: Digital Elevation Map and Land Use and Land Cover Map

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Table 2: LULC Parameters

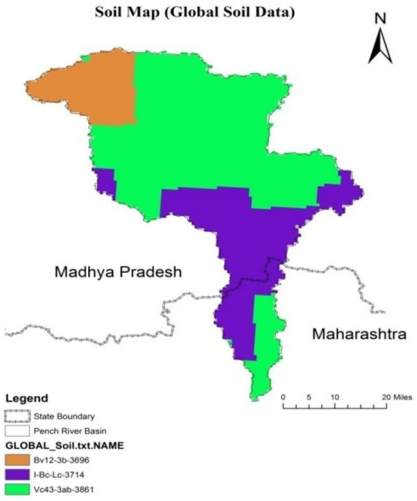
Land use and Landcover	Class code	Area [ha]	Area[acres]	%Area
Range-Brush	RNGB	86126.4598	212822.7884	18.18
Agricultural Land-Generic	AGRL	18393.4018	45451.0154	3.88
Residential-Med/Low Density	URML	7250.4229	17916.1575	1.53
Agricultural Land-Generic Crops	AGRC	132587.3243	327629.9077	27.98
Forest-Mixed	FRST	111544.3857	275631.7543	23.54
Agricultural Land-Generic Crops	AGRR	113017.5731	279272.074	23.85
Barren	BARR	2414.773	5967.0247	0.51
Water	WATR	2510.3681	6203.2452	0.53

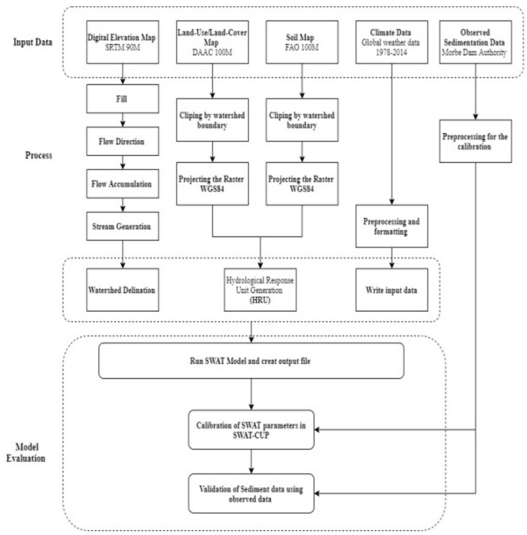
D. Soil Data

The soil map was obtained mainly from the FAO (Food and Agricultural Organization). The soils are compared with the watershed area to use their properties to define HRUs. The soil associations are characterized in terms of the estimated proportions of the component soil units, the presence of phases, and the estimated proportions of these soil units in one of 5 texture-slope classes such as Shallow coarse soil: 8.60%, medium black soil: 5.65%, deep black soil: 2.87%, clayey medium black soil: 7.06%, clayey Lumi: 74.90%.

Table 3: Soil Data Table

Class code	Area [ha]	Area[acres]	%Wat.Area
Bv12-3b-3696	59218.2958	146331.3699	12.5
Vc43-3ab-3861	284470.7844	702941.5319	60.03
I-Bc-Lc-3714	130155.6284	321621.0654	27.47





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SWAT (Soil and Water Assessment Tool) is a model developed by the United States Department for Agriculture, Agricultural Research Service (USDA-ARS) and it is a river basin scale model developed to quantify the impact of land management practices in large, complex catchments (Neitsch et al., 2001). SWAT is a deterministic, physically-based, continuous simulation, watershed model. The SWAT was developed principally to compute runoff and loadings from rural especially agriculture-dominated watersheds and predicts the long term impacts of the land management practices on water, sediment in watersheds with varying soils and land cover.

The semi-distributed model divides the watershed into multiple sub-basins up to ten thousand which are called hydrologic response units (HRUs). The amount of water, sediment, nutrient, and pesticide loadings to the main channel from each sub-catchment is controlled by the land phase of the hydrologic cycle. Aggregation of input data can be facilitated using a GIS interface (either Geographic Resources Analysis Support System (GRASS) or Arc View) available with the model. The Arc View interface developed for the SWAT model requires land use/land cover, soils, and DEM data as spatial inputs and can be used to prepare the input files. SWAT computes the volume of surface runoff using the SCS curve number method or Green and Ampt infiltration method; while the amended Rational Formula or the SCS TR-55 is used to count the peak runoff rate.

The SWAT model has become widely accepted as an effective tool to predict the effects of watershed management on runoff, sediment, nutrients, etc. SWAT considers the base-flow contribution to total streamflow by routing a shallow aquifer storage component to the stream.

E. Hydrologic Water Balance

Water balance is the key for the simulation of hydrology within a watershed. SWAT uses two phases for the simulation of hydrology, land phase, and routing phase. The land phase simulation calculates the amount of sediment, water pesticide, and nutrient loading in the main channel in each basin. The routing phase defines the movement of water, sediment, etc. in the outlet through the channel network of the watershed. The hydrologic cycle of the SWAT model is based on the water balance equation, which considers the unsaturated zone and the shallow aquifer above the impermeable layer as a unit.

$SWt = SWo + \sum t\ (Rday - Qsurf - E_a - w_s\square\square ep - Q_gw)_i$

The equation is the important equation to predict the watershed of the hydrology used by SWAT.

Where;

t is the time in days,

SWT and SWo are the final and initial soil water content respectively (mm),

R_day is the amount of precipitation on the day I (mm),

Qsurf is the amount of surface runoff on the day I (mm),

GQ is the amount of return flow on the day I (mm).

F. Surface Runoff

The estimation of surface runoff can be performed by the model using the Soil Conservation Service (SCS) curve number method, (S.M.Ghoraba) This method is widely used for the prediction of the approximate amount of runoff from a given rainfall event.

CN1 = CN2-(20(100−$CN2$) (100−$CN2$+e(2.533−0.0636∗(100−$CN2$)))

CN3 = CN2*(0.0063(100−CN) (4)

Where;

CN1 is the moisture condition I curve number,

CN2 is the moisture condition II curve number, and

CN3 is the moisture condition III curve number.

G. Model Setup

1) *Watershed Delineation by SWAT:* Click on Watershed Delineator Automatic Watershed delineation, Once the watershed delineation window is activated, click on the open file button in the DEM setup portion, and then click on select from map, and then select the project DEM. Click OK. You will see that the name of the DEM will change to Source DEM. Then proceed to create flow direction and flow accumulation grids. By leaving the default DEM-based option unchanged in the stream definition portion, click on the flow direction and flow accumulation button. After flow direction and flow accumulation are complete, the area box will be populated by some numbers. This is the critical stream area threshold that will be used to define the stream network. Steps:

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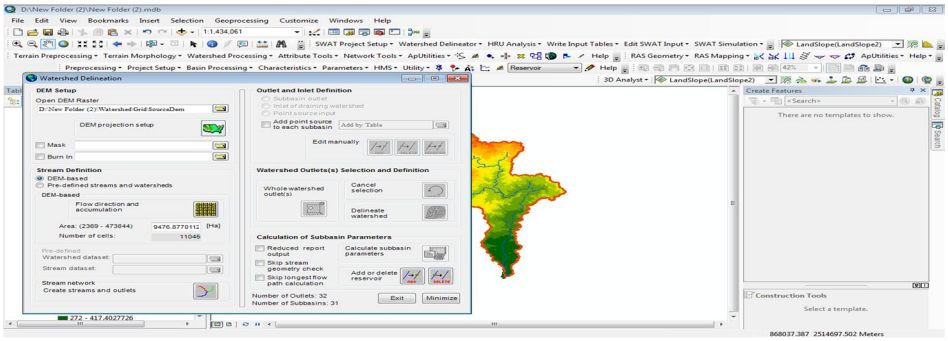
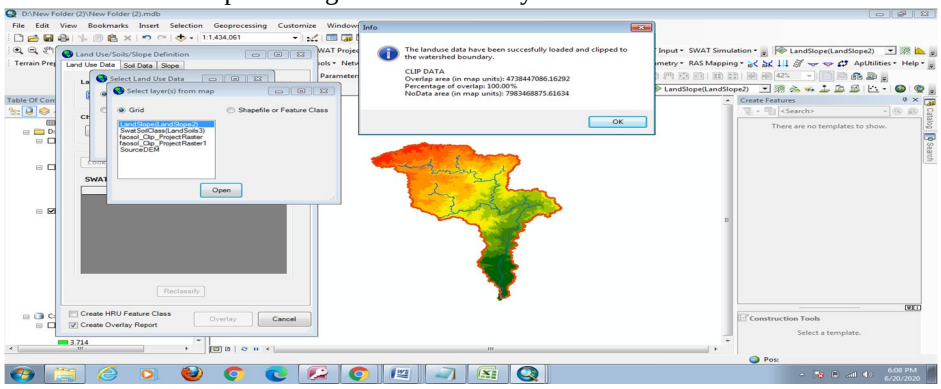
a) DEM projection setup
b) Stream definition
c) Outlet and Inlet definition
d) Watershed Delineation
e) Subbasin parameter calculation



Click the create stream and outlets button to create a stream network, sub-basins, and outlets for each of the sub-basin. Next, in the watershed outlets selection and definition, click on the select whole watershed outlet button, and then select the desired outlet location using the cursor. If the outlet does not exist at the point you are interested in, use the add button in edit manually frame to add the point, and then do the selection using the outlet button. After the outlet is selected, the Delineate watershed button will be activated in green. After the watershed is delineated, the polygon feature class with sub-basins is added to the map document. Click on the calculate sub-basin parameters button to populate the watershed feature class with necessary attributes for the SWAT model. After all, attributes are calculated, click OK on the final message box. Now open the attribute table and you will see that it has more attributes as shown below. The delineating watershed and creating sub-basins for a specific threshold table is done. Exit the watershed delineation window by clicking on EXIT.

H. HRU (Hydrological Response Unit)

When you install Arc-SWAT, a raster with STATSGO soil data for the entire United States is stored where the Arc-SWAT is installed. Browse to the MDB file, and add the raster to the map document. Next, the raster is clipped to the DEM for the study area. Clipping is done by using the Arc-Tool box in Arc Map. Use the original DEM as the mask during the clipping. To use this clipped soil raster, it should have the same coordinate system as the other data in the map document. The soil grid has geographic coordinates and then the project raster is done by using the Arc-Tool box. When the soil analysis is done, it is ready for HRU analysis. On the Arc-SWAT toolbox click on the HRU Analysis- Land use/soils/slope definition. The land use/soils/slope definition window has three tabs for land use, soil, and slope each. Click on the open file button to load the land use data. After that select the land use data from the disk, and open the file button to load the land use data. In the next window, select the land use data from the disk and click open. The program will clip the data before using it in the project. Land use data typically comes with numbers for each land use type and is used in a look-up table to relate these numbers to specific land-use types. Click the look-up table and select the soil map. This will create a detailed description of each land use number in the SWAT land use classification table. Lastly, click on the reclassify to finish the land use data processing of the HRU analysis.



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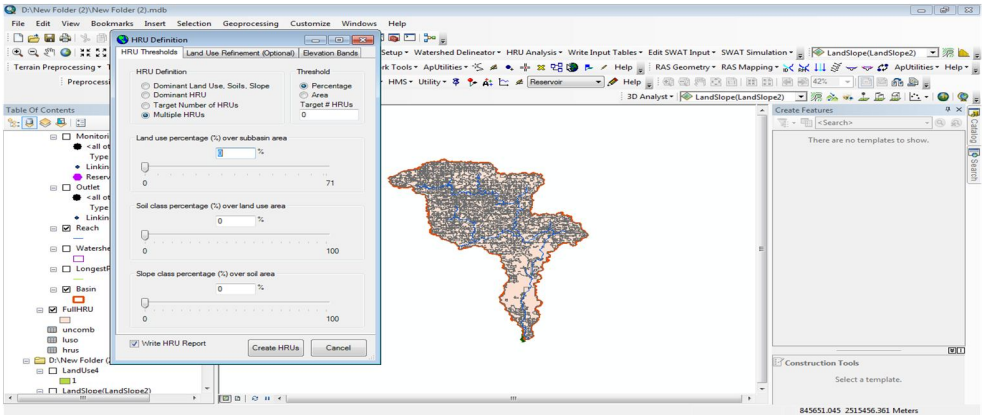
After processing land use data, click on the Soil data tab. After that click on the open soils grid button, land soils dataset from disk, and browse to the clipped projected soil raster that was just created, and click Select. This step will input the raster and then clip that raster to the watershed area. This process sometimes takes a long time depending on the size of the watershed. After that the soil data are loaded, choose VALUE as the grid field and click OK. This will add all numerical values present in the land soil dataset to the SWAT soil classification table. The next step is to link these values to a certain soil type. To use the lookup table, it is necessary to define the attribute in the lookup table that corresponds to the soil type. Finally, click on reclassify which will finish the soil data processing for the HRU analysis. The next step is to assign slope attributes to each HRU. Click on the slope tab. To keep the process simple, use the single slope option, and click to reclassify. This will complete the processing of land use, soil, and slope data for HRU analysis. Close the land use/ soil/ slope definition window. Leave the default options of multiple HRUs in the HRU definition. Several hours will be added to the map document that would be described in the HRU report generated by this process.



I. Write Input Table

After all, geo-processing is done on DEM, land use, and slope data to create sub-basins and HRUs, the next step is to create input files for SWAT including weather data. Weather Data to create weather input for SWAT, click on Write input tables-weather station. There are two options to input weather data. The first option is to use the weather geo-database from SWAT, and the second option is to use your custom database. For this exercise, we will just use the internal weather geo-database within SWAT. Next, in the Rainfall data tab, leave the simulation option checked with the daily precipitation time step selecting a simulation option means that the will be generated through the internal weather generator within SWAT. Similarly, for Temperature, relative humidity, solar radiation, and wind speed, leave the simulation option checked. Finally, click OK. This will create a weather database for the study area

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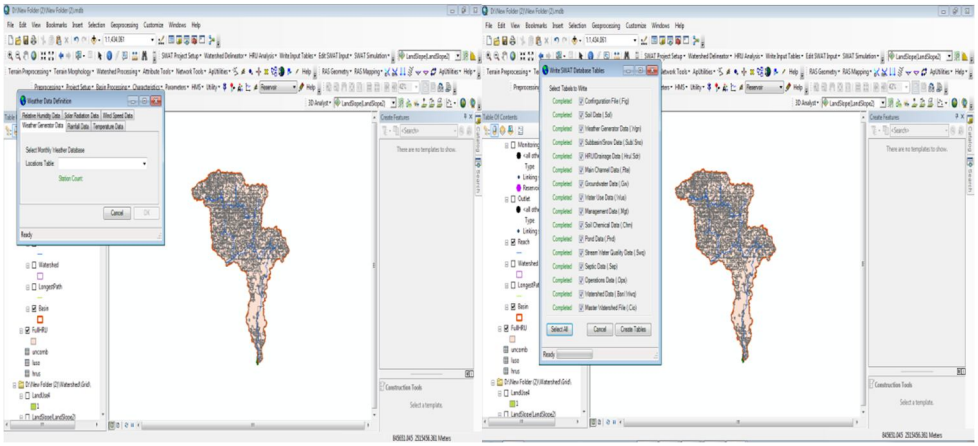

Other input files after generating weather database, create all other input files by selecting write input table, and write SWAT input tables. A new window will be displayed known as 'Write SWAT Database Tables'. Then click on select all and click on create tables. Also, choose YES in all the subsequent messages which will be showing up on the screen.

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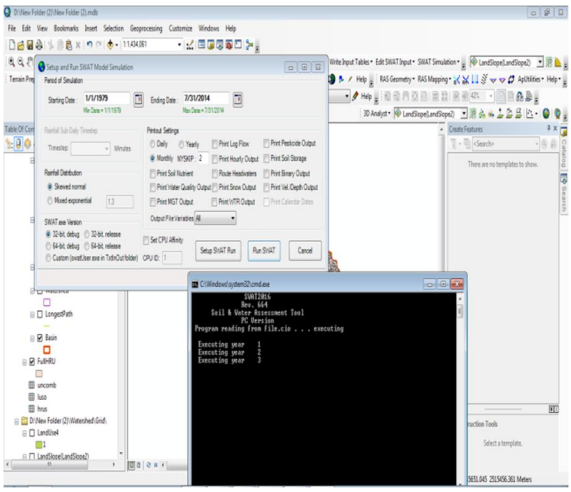
J. SWAT Simulation



To run SWAT Simulation click on SWAT Simulation and run SWAT output to set the period of simulation from 01/05/2003 to 31/12/2013 and change the printout settings to daily, and leave the options unchanged. After getting the finished SWAT setup message, click on Run SWAT. While the SWAT is running, a DOS window is shown on the screen for the progress, and after the simulation is done, the final message of the SWAT simulation is done is displayed on the screen. After the successful simulation message, close the SWAT Simulation setup window and read and visualize the model output.

K. System Performance Analysis

The SWAT model gives the sediment inflow and outflow in mg/lit at the outlet point of the sub-basin. The total sediment deposited at the reservoir can be determined by how much sediment is consolidated at the reservoir by subtracting the outflow from the inflow. The graph below shows the correlation between the sediment of the Penchch dam derived from the SWAT-Model without calibration and sediment derived from the observed data. The model is evaluated using the correction coefficient R^2.

$$R^2 = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{[n(\Sigma x^2) - (\Sigma x)^2][n(\Sigma y^2) - (\Sigma y)^2]}}$$

The Coefficient of determination R^2 can be determined from the above equation and the value can range from 0 to 1. The value 1 shows complete correlation and a value near 1 can be considered as a good correlation. The graph below shows a correlation of about 0.81. The value represents a good degree of correlation, but to improve that we can calibrate the output of the SWAT model using the SUFI2 algorithm of SWAT-CUP.

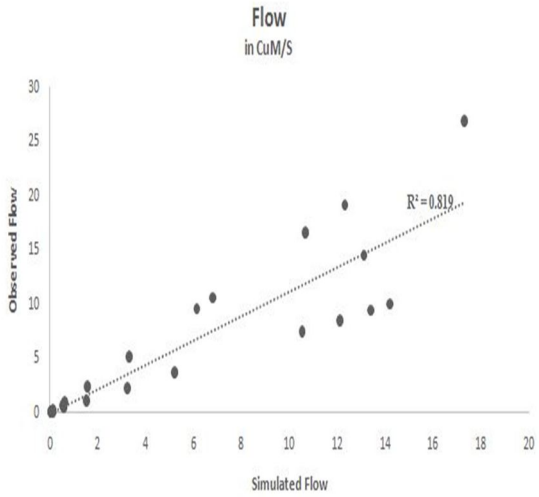


Fig: The graph of observed VS SWAT simulated sediment with a coefficient of determination of 0.81

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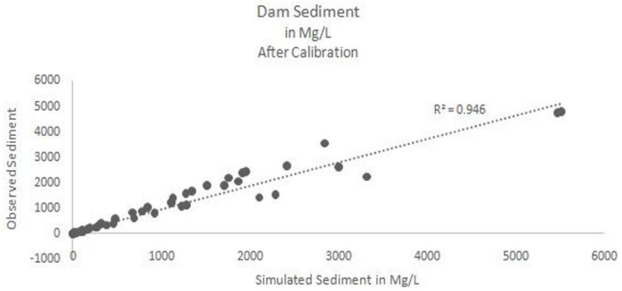
The sediment derived from the SWAT is calibrated using SWAT-CUP for different parameters which are from.SOL group. The. SOL group of SWAT parameters represent the soil-related parameters like Soil Hydrologic group, Maximum rooting depth of soil profile (mm), Soil CaCo3, Soil ph-value, Electrical conductivity, USLE equation soil erodibility (K) factor, Moist Soil Albedo, Clay content(%s soil weight), Saturated hydraulic conductivity (mm/hr), Depth of soil surface to the bottom of layer (mm), Moist bulk density (Mg/cu.M) for different maximum and minimum value to match the output values of the sediment derived from different observed data and parameters. The coefficient of determination after calibration shows around 0.9469 shows a very good correlation.

Parameters	Description	Values	
		Min	Max
r__CN2.mgt	Initial SCS runoff curve number for moisture condition II	-0.2	100
v__ALPHA_BF.gw	Baseflow Alpha Factor (1/day)	0	1
v__GW_DELAY.gw	The Delay time	30	450
v__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H2O)	0	2
v__SNAM.sol	Soil Name	0.1	100
r__HYDGRP.sol	Soil Hydrologic group	0	100
r__SOL_ZMX.sol	Maximum rooting depth of soil profile (mm)	0	100
r__SOL_CAL().sol	Soil CaCo3	0	50
r__SOL_PH().sol	Soil PH value	3	10
r__SOL_EC().sol	Electrical conductivity	0	100
r__USLE_K().sol	USLE equation soil erodibility (K) factor	0	1000
r__SOL_ALB().sol	Moist Soil Albedo	0	1
r__SOL_CLAY().sol	Clay content(%s soil weight)	0	100
r__SOL_K().sol	Saturated hydraulic conductivity (mm/hr)	0	100
r__SOL_Z().sol	Depth of soil surface to the bottom of the layer (mm)	0	100
r__SOL_BD().sol	Moist bulk density (Mg/cu.M)	0	100

After getting the desired output, the calibration of the model is important for certain parameters like soil and land-use classes. The sedimentation is majorly dependent upon the SOL parameters and RCH. For calibration of the model, SWAT-CUP is used. The SWAT-CUP is equipped with the four algorithms for calibration i.e. SUFI2, GLUE, ParaSOL, and PSO. From the various kinds of literature, the SUFI2 is suitable for analyzing and calibrating the sediment parameters. For calibrating the sediment value of Pench dam the following parameters are used. The following table shows the minimum and maximum thresholds for all the factors along with a description. Table: List of SWAT Model parameters for calibration along with a description and maximum and minimum values for calibration in SUFI2 algorithm. The upper and the lower limit of each parameter are referred from the SWAT handbooks for each parameter. The parameters which are responsible for the sediments are most of them from. Sol group i.e. soil group and it is important to calibrate the soil parameters. The parameters like rooting depth of soil profile (SOL_ZMX) and soil surface depth (SOL_Z) are the major parameters responsible and important to calibrate for assessing the soil and sediment in the reservoir. The CN value of moisture zone II is also important to calibrate as the land-use data is responsible for soil fragment and looseness



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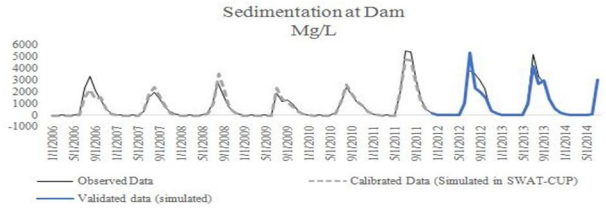
The graph below shows the final sediment values including the data for calibration and validation. The sudden increase in the sediment can be seen after the monsoon of 2011 which represents the full working condition of the Pench dam, as the year 2011 is the year of attaining the fully functional level of Pench Dam. The year 2011 shows the actual sediment deposition and the data can be seen increased after the year 2011. The study is important to analyze the change in the reservoir water capacity as the sediment may reduce the capacity after saturating the dead storage.



III. RESULT AND DISCUSSION

YEAR	Sediment yield in MCM
1982	0.05194512
1983	0.1222586
1984	0.0381975
1985	0.0796892
1986	0.500515941
1987	0.053229.4
1988	0.1000183
1989	0.142745
1990	0.1415361
1991	1.076426783
1992	0.299541695
1993	2.17868947
1994	0.504554603
1995	0.733694296
1996	0.629837096
1997	0.723472382
1998	0.803517424
1999	0.4469532
2000	0.132218959
2001	0.887013779
2002	0.68538317
2003	1.417188101
2004	2.220433626
2005	1.698641289
2006	0.033526.89
2007	0.107482
2008	0.0620514
2009	0.1037938
2010	0.114345
2011	0.1140119
2012	0.08846138
2013	0.0814514
2014	0.0143729
TOTAL	**16.30044141**

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IV. CONCLUSION

The SWAT model and SWAT-CUP algorithm model is developed and applied to case study of Kamthikhairy Dam in Pench river basin in Maharashtra state, India. SWAT model calculated sediment yield data based on spatial datasets (DEM, Land cover changes, and soil map) and weather data. This sediment yield data obtained from the SWAT analysis was used as target data in SWAT-CUP model to validate the SWAT output data

The conclusions from SWAT analysis for the present study are given below:

A. It was observed that, the rate of sediment yield varied between 0.071 MCM/year in 1985 to 2.22 MCM/year in 2014
B. The Average rate of sediment yield was found to be 0.51 MCM / year from SWAT model.
C. For the duration between 1982 to 2014 almost 8.03% of the gross storage of dam was reduced due to problem of sediment yield.

The conclusions from SWAT-CUP for the present study are given below:
SWAT-CUP is a program for calibration of SWAT models. The program could be used to perform calibration, validation, sensitivity analysis (one-at-a-time, and global) and uncertainty analysis. The program links SUFI2, GLUE, ParaSol, MCMC, and PSO to SWAT. Any of the procedures could be used to perform calibration and uncertainty analysis of a SWAT model. SWAT-CUP also has graphical modules to observe simulation results, uncertainty range, sensitivity graphs, watershed visualization using Bing map, and statistical reports

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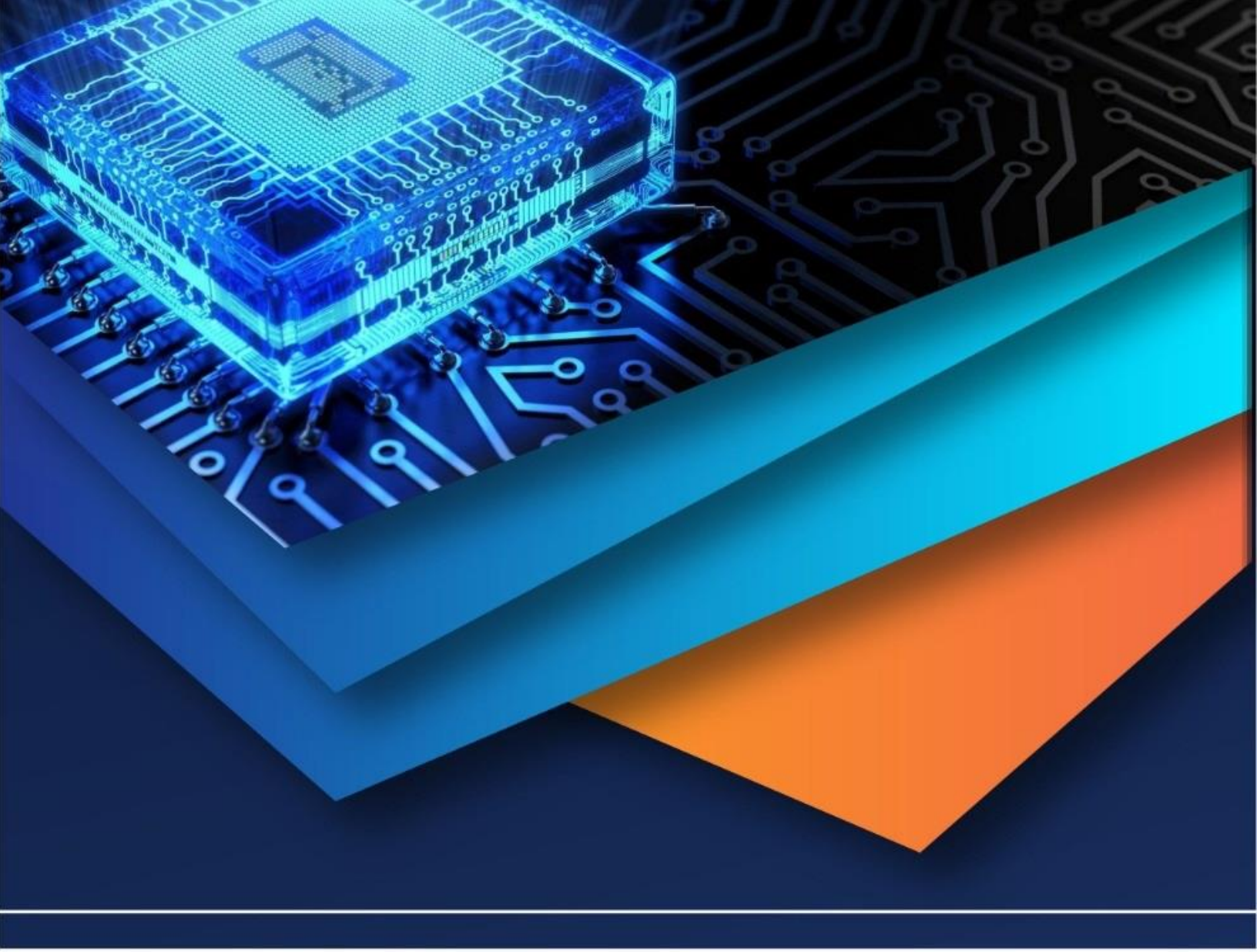

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