ASSESSMENT OF CATCHMENT SOIL EROSION & SEDIMENT MANAGEMENT IN HIRAKUD RESERVOIR USING REMOTE SENSING AND GIS

A DISSERTATION

Submitted in the partial fulfillment of the requirements for the award of the degree
of

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in

Water Resources Development and Management

By

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CANDIDATE’S DECLARATION

I hereby certify that the work, which is being presented in this dissertation, entitled **“ASSESSMENT OF CATCHMENT SOIL EROSION & SEDIMENT MANAGEMENT IN HIRAKUD RESERVOIR USING REMOTE SENSING AND GIS”** in fulfillment of the requirement for the award of the degree of Master of Technology, submitted in the Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee is an authentic record of my own work which is carried out under the supervision of Prof. Deepak Khare and Dr. Santosh Murlidhar Pingale.

I have not submitted the matter embedded in this for award of any other degree.

Rajendra Kumar Mishra

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

The live storage capacity of a reservoir which is the utilizable storage gets reduced due to continuous sedimentation from the catchment since impounding. The reservoirs are used for flood control, irrigation, hydropower production, water supply for industries and multi-functional utilization. Proper monitoring of sedimentation is required for efficient water utilization. Hirakud reservoir is impounded in 1957. After 62 years of operation for proper monitoring of the reservoir, a cost effective measure has been adopted, without adopting the conventional hydrographic surveys. Therefore, in the present study, an attempt has been made to assess the quantity of sediments in Hirakud reservoir from its catchment area by using Soil and Water Assessment Tool (SWAT). The result of the SWAT model have been found in good agreement during calibration (R^2=0.772, NSE =0.655, PBIAS=15) and validation (R^2=0.85, NSE= 0.83, PBIAS= -16.9) periods. The quantity of sedimentation has been found to be 39.35 Mm^3/year. Further, the remote sensing technique has been applied to estimate water spread area for different time periods (2016 to 2018) of maximum level and minimum level and some intermittent level of Hirakud reservoir. SWAT model results have been compared with results obtained in remote sensing based water spread area estimation. Comparing with the original capacity of the reservoir in 1957 which was 8135 Mm^3 and capacity in the year 2016 to 2018 was found to be 5406.54 Mm^3. The total reduction in capacity is 2729 Mm^3 in 62 years which gives amount of sedimentation 44.01 Mm^3/year, which gives a 10% higher value. It means the deposition of sediments comes from higher intensity of rainfall, which doesn't coincide with SWAT model result which runs on daily basis runoff simulation.

Keywords: Sediment, SWAT, Hirakud reservoir, Elevation capacity curve, Remote Sensing and GIS

LIST OF ABBREVIATIONS

CN = Curve number

CN2 = SCS runoff curve number for moisture condition II

CO_2 = Carbon Dioxide

Δ = The slope of saturation vapor pressure-temperature curve

DEM = Digital Elevation Model

Δt = Time step

E = The depth rate evaporation (mm d-1)

ET = Daily evapotranspiration (mm)

GW = Groundwater (mm)

GWP = Global Warming Potential

HCFC = Hydrogen Carbon Fluorine Chlorine

HRU = Hydrology Response Unit

IPCC = Inter Governmental Panel on Climate Change

Lat_F = Lateral Flow (mm)

LAT_TIME = Lateral flow travel time

LCM = Land Cover Map

MCM = Million Cubic Meter

NSE = Nash-Sutcliffe Index

PBIAS = Percentage Bias

RMSE = Root Mean Square Error

RSR = Standardizes root mean square error using the observed standard deviation

SWAT = Soil Water Assessment Tool

UNEP = United Nations Environment Program

URML = Urban low/medium density

LULC = Land use land cover

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CHAPTER – 1

INTRODUCTION

1.1 Background

Reservoirs are constructed at the outlet of the watershed to get enough of drainage into it for a multi-functional utility like flood control, irrigation, hydropower drinking water supply, supply of water for industrial purposes. As most of the catchment of the river is prone to agriculture or forest, down the years sediment is generated from the erosion and accumulates through drains at the outlet of the watershed and deposited inside the reservoir. For few years, the sediments are deposited in dead storage level and then it occupies the live storage reducing the capacity of the reservoir. When the reservoir is more than 50 years of operation the siltation creates a major loss of capacity. Soil erosion is a natural process of geomorphology but due to change of land use/land cover (LULC) causes accelerated soil erosion (Abebe and Sewnet 2014; Merina et al 2016; Tamene et al. 2016).

1.2 Statement of the Problem

Sedimentation generation and transportation in the catchment of the reservoir is a complex process and depends upon various parameters like type of soil, soil slope, texture of soil of catchment, intensity of rainfall, LULC change, practices of irrigation, crop pattern, etc. and area of the catchment. The sedimentation problem is a major issue of the world and around 40,000 reservoirs are facing storage loss of 0.5 to 1% yearly (Marina et al 2016). Statistical analysis conducted in 21 selected reservoirs in India and annual storage loss was reported 0.5% to 1% average with some high as 2%. Hirakud dam was taken up for construction in the year 1947 with a concept to overcome the flood control in the Mahanadi Delta region 9500 Km^2 and irrigation to 1,08,385 ha of Rabi and 159,106 ha of Kharif crop and a power generation of 307.5 MW. The Hirakud dam comes to operation in 1957 and 62 years already passed since 2017. So, the quantification of the sedimentation volume of the reservoir using geospatial techniques is very important for the successful performance of the dam. Hydrographic survey of the reservoir is not economical to study the annual sedimentation yield for monitoring and control and reduction of sediments to the reservoir because, it is not cost effective. For enabling frequent monitoring of reduction in capacity of reservoir hydrological modeling and remote sensing methods can be utilized to get accurate results.

1.3 Research gap

(a) Since now very few studies have been done to assess the sedimentation from the catchment of Hirakud dam for identification of erosion prone areas and actual sediments deposited since 62 years inside the reservoir.

(b) An economical silt reduction procedure to be followed is yet to be evolved for sedimentation management of the reservoir.

(c) There is no study on annual sedimentation yield computation and with use of water spread area calculation through high resolution spectral image data. Also, there are no findings on elevation capacity curve and calculation of sediments yield from the catchment by using SWAT which requires different data which includes daily precipitation, DEM, Soil, slope, and LULC.

1.4 Objective of study

1. Soil erosion assessment from the catchment of Hirakud reservoir by using SWAT model.
2. To estimate sediment yield of the catchment of the reservoir using SWAT.
3. To study the reduction of capacity of reservoir by capacity elevation curve and comparison with SWAT model result.

1.5 Significance of the study

The Hirakud reservoir is impounded in the year 1957. So, the assessment of reservoir capacity is essential to know the exact reduction in capacity. The hydrographic survey is not economical for the purpose hence hydrological survey and remote sensing survey is adopted for an economical concept. The study is for the comparison of annual sediment yield to the Hirakud reservoir by both methods.

1.6 Organization of the thesis

Chapter 1 - Provide the introduction and objective of study.

Chapter 2- Provides a brief literature review about sedimentation and it's problem in Hirakud dam.

Chapter 3- Description of study area and data available for analysis.

Chapter 4- describes methodology adopted in the assessment of erosion from the catchment and estimation of water spread area of the reservoir by using remote sensing technique.

Chapter 5- provides the results and discussion about SWAT model results and water spread area estimation by using remote sensing. Finally, reduction in volume of storage of the reservoir since impounding of reservoir has been presented.

Chapter 6- describes brief summary of the present study and conclusion drawn from the analysis carried out.

Chapter – 2

LITERATURE REVIEW

2.1 General

Rathore et al (2006) studied assessment of sedimentation in Hirakud reservoir using remote sensing technique. Hirakud Reservoir's original utilizable and gross volumes were 5818 and 8136 m M^3, respectively. Minimum draw down level and full reservoir level (FRL) for reservoir were 179.83 m and 192.02 m. Linear Imaging Self Scanning (LISS) – III data covering elevation range between 180.68 and 191.89 m, were used to determine the water spread area. Revised live storage capacity was 4842 Mm^3. Silt index for the live storage area was 2.623 ha m (100 km^2 per year (0.376% of live storage or 21.9 Mm^3 per year). Total live storage lost in sedimentation was 984 Mm^3 (16.90% of live storage).

Reservoir's original utilizable and gross volumes were 5818 Mm^3 and 8136 Mm^3 respectively. Design silt index was 2.5 ha m (100 km^2 year)$^{-1}$. Total live storage loss between 1957 and 2001 was 984 Mm^3. In percentage terms, total and yearly losses in live storage were 16.9% and 0.376% of live storage volume respectively. Silt index for live storage zone was 2.623 ha m per 100 km^2 per year which was higher than design silt index. Mukhaerjee et al. and Joshi (2007) studied to evaluate the changes in water spread area and capacity loss, five satellite overpass data were used (October 15th 1988, December 20th 1988, February 24th 1989, March 18th 1989 and May 1st 1989).

- The live and gross storage capacities of the reservoir were estimated to be 6151.30 Mm^3 during 1989, since the dead storage has been estimated as zero.
- The capacity loss of 1953.70 Mm^3 (24.10 %) from 1957 to 1989.
- Annual rate of siltation is found to be 61.05 Mm^3, since impoundment of reservoir in 1957 to 1989.

The high-level technical committee (HTLC) in 2007 have been constituted to study various aspects of water usage for Hirakud reservoir (HTLC, 2007) and have reported benefits of Hirakud dam, which includes a) Pre-construction period – 8 floods in 10 years and b) Post-construction period – 3.30 floods in 10 years. Choudhury et al., (2010) made a report on

Hirakud Dam, Odisha State Resource Centre, Forum for policy dialogue on water conflicts in India. The gross storage in year 2000 was decreased to 5,896 Mm^3 from 8,141 Mm^3 in 1957 (originally). The Hirakud dam project was designed as a multipurpose project, with provisions to supply water for irrigation, power generation, drinking water, navigation and fishery but there was no industrial water allocation in the initial plan, though a handful of industrial units were drawing water from the reservoir. However, since 1991 there have been a lot of disputes between the dam officials and farmers over the provision of providing water to the industries as famers are said to be falling short of irrigation water because of water being supplied to the industries and factories.

2.2 Reservoir Sedimentation Process

Sediment is the prime solitary nonpoint causes of pollution derived chiefly from the physical and chemical disintegration of weathered rocks in the earth’s crust. This fragmented material is later transported by the force of the wind, water, or ice, and / or by the action of gravity force on the particle itself, or by the combination of these transporting agents. When the transporting mediator is water, the sediment is termed as “Fluvial Sediment” and the act of moving or removing the particles from their resting place is called “erosion”. The material named “Alluvium” if transported and deposited by rivers, when it is named “Loess” if conveyed and deposited by wind, and “Glacial Drift” if it is transported and deposited by glaciers (Qamar et al. 2012). Among other agents; water, wind, and ice are contributing more in transporting and depositing sediment as a form of soil erosion. However, their progressive detachment, transport, and deposition of sediment within the drainage basins are worsening more also by some other sorts of human activity. In these days, for instance, development efforts like the expansion of cultivable land, urbanization, roads and highway construction, mining together with deforestation can be listed as the principal sources of sediment just aside with natural factors. The sediment particle yielded from the catchment ranges in size from boulders to colloidal fragments and vary in their shape from rounded to angular. Regarding its causes, the incoming sediment particle size has a significant effect upon density. Thus, sediment deposit composed of silt and sand will have higher densities than those in which clay predominates. The general classifications of sediments according to size proposed by the American Geophysical Union (Vanoni, 1975) are shown in Table 2.1.

Table 2.1: Classification of sediments according to their size (Vanani, 1975)

Sediment type	Size in Milimeters
Clay	Less than 0.004
Silt	0.004 to 0.062
Sand	0.062 to 2.0

When a natural stream enters a given reservoir, it exhibits a release of stream load due to the sudden changes of flow velocities. This sudden decline of velocities in turn, reduces the rate of dissipated energy aligned with the bed and water spread area of the reservoir per unit downstream length, which is usually called stream power. The amount of sediment transported by this flow were also gets reduced and form a deltaic deposit on the reservoir mouth.

At the outset, reservoir sedimentation issues were considered using the notions of 'live' and 'dead' storage. 'Live' storage is to mean that the storage available above the lowest intake level while 'dead' storage is referred to us that the storage below the lowest intake level. Here, erroneously the assumption was made that reservoir sedimentation would fill the dead storage first before beginning to fill the live storage. It was later realized that sedimentation affects both live and dead storage with often more live storage lost than dead storage. The longitudinal accumulation of sediments both in the live and dead storage can be subdivided in to three main deposition zones; Topset bed, Forest bed, and Bottomset bed (Morris and Fan, 2010). The topset bed characterized by the deltaic deposit of larger sized sediment particles that settle rapidly. The Foreset, bed is resulted from the progressing shape of the deltaic deposit. Whereas, the Bottomset bed, which is a residual part of longitudinal sediments deposition zone, is composed of fine sediments that are carried by non-stratified flows of density currents.

Morris and Fan (2010) categorizes longitudinal reservoir sedimentation into four basic patterns of deposition (Figure 2.1). When a natural stream enters a quiescent pool of water, it results in the abrupt decline of velocity. In consequence, the phenomenon of siltation occurs in the mouth of the reservoir, which is usually termed as a deltaic deposit. Hence, this delta deposit contains the coarser fractions (d ≥ 0.062 mm) of the incoming sediment load or large portion of finer sediment for instance silt materials. The wedge-shaped sediment deposits, however, are bulkrest at the dam and be fall thinner stirring upward. Such an arrangement is typically grounded by the transport of fine materials to the dam face by the action of turbidity currents. If the water is conveyed frequently through the gate of the reservoir, the head of the delta propagates towards the dam face and the deposition appears wedge-shaped, which is reflected on the equilibrium state for certain reservoirs over a longer period (Lai and Shen 1996). Tapering deposits is a common pattern of deposit in longer reservoirs that normally held at a high pool level and it happens when fine sediment deposit attains a progressive movement towards the dam face through the action of flowing water. Whereas, uniform deposits are unusual but can be found in a narrow reservoir with repeated water flux and a small fill of fine sediments that can produce nearly uniform deposition depths.

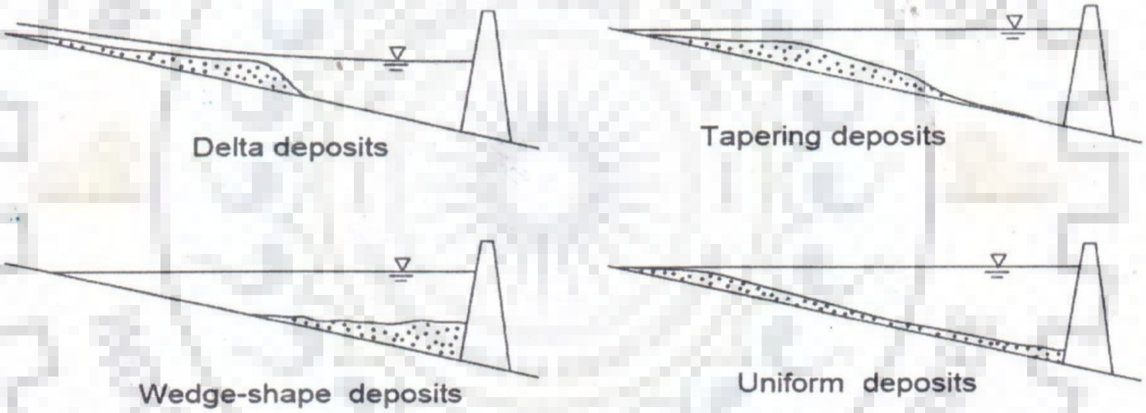


Figure 2.1 Basic types of longitudinal deposit (Morris and Fin, 2010)

These longitudinal profiles of sediment deposits differ with one another due to a number of factors, among them; characteristics of sediment inflow and reservoir operations are the major ones (Morris and Fan, 2010). However, the process of reservoir sedimentation also governed by other factors for example flood incidence, sediment yield of the catchment, channel geometry, transport rate of sediment, and so forth.

2.3 Reservoir Sedimentation Control Methods

To maintain sustainability of storage reservoirs, three control, strategies need to be followed (Qamar et al. 2012), (1) Control of reservoir silting: This erosion control measure is aiming at minimizing catchment sediment yield, sediment inflow rate, sediment deposition rate, or a combination of these three measures through sediment trapping strategy. Minimizing sediment yield can be achieved in a form of soil conservation practices both applied in the river and in the reservoir’s catchment. Structural or mechanical measures such as check dams and diversion canals are used to reduce the flow velocity, increase reservoir surface water area, and help to dispose of flush runoff (Morgan, 1995).

In contrast, non-structural measures like vegetative practice and land tillage works are used in minimizing the intensity of potential precipitations. Minimizing sediment, inflow in to the natural channels and reservoirs can be achieved by implementing exclusively engineering practices that include sediment – trapping reservoirs, river regulation works, slope and bank training works, by pass structures, and off-stream storage reservoirs. Reservoir operations like sediment sluicing and venting of turbidity currents are also the other important control measures need to be assessed in minimizing sediment deposit within the reservoir reach. Sediment stepping, in general, can be considered as a highly valuable method in reducing the sediment yield rate over the catchment but there are still many drawbacks such as high cost incurrence, siltation, sustainability problems, and restricted benefits. Thus, integrated watershed management practice with erosion control priority would be carried out widely to control reservoir sedimentation. (2) Removal of deposited sediments: This is a strategy adopted in dealing with desilting reservoir sedimentation by following one of the strategies between hydraulic removal of sediment through flushing and siphoning method or implementing mechanical methods such as dredging and digging of sediments through machineries. (3) Compensation of reservoir sediments: This approach can be used to compensate reservoir siltation is a form of reconstructing the dam wall by providing new sluice facilities or by changing management operation of the given reservoir. Besides, raising the dam height can be considered as another option in compensating reservoir siltation because it provides relief in maintaining the economic life for some predefined periods. However, implementing the above strategies and measures if it was found inefficient, costlier, and ineffective, then, abandoning the old reservoir and constructing a new one could be the last and mandatory option. Here, among other strategies, hydraulic flushing is given much emphasis in this study.

According to White (2001), hydraulic flushing is by fact distinct to sluicing operation. Here, flushing is the scouring of previously deposited sediments with accelerated flows hydraulically through the bottom outlets of the dam, while sluicing is an operation undertaken to bypass incoming sediment laden water during high flood events, it is the operation usually applicable to medium, and small sized sediment particles typically silt and clay. Expelling turbidity current is a sediment desilting techniques where by discharging off muddy flows carried by the currents in the course of bottom outlets. Hence, there are two general categories of flushing operations in removing sediment, deposition from reservoirs (Fan, 1985). These are empty or free flow flushing, which engages emptying the reservoir to the level of the bottom outlet with riverine flow through the pool, and pressure flushing, which requires less drawdown but is also less effective. The second method is not commonly used.

Emptying or free flow – flushing exhibits more generalized effect, which expands both along the length and across the banks of the reservoir basin (Qamar et al. 2012). During such operations, the bottom outlets are opened and the water levels in the reservoir are getting down for certain periods of time. The drawdown can be either steady when the sluice gates are gradually but partly opened and the operation termed as fully controlled flushing, or quick when the gates are suddenly and fully opened and the flushing operation is resembled to be uncontrolled. The governing factors that influence the efficiency of sediment flushing include topographic setup of the proposed reservoir, the conveyance capacity of the bottom outlets, reduced level of these outlets, inflow sediment characteristics, reservoir operation, the time duration of flushing, the standard flushing discharge,

2.4 Previous studies of reservoir sedimentation and flushing

Ijam and Mahamid (2012) applied AVSWAT model to forecast reservoir sedimentation at Mhjib Dam in Jordan. This model was utilized in delineating the watershed, Quantifying stream discharge and sediment inflows and determining sediment yield rate over the catchment together with its potential region of erosion. The modified version of USLE and Stehlike's models were implemented in conjunction with ArcGIS interface. The simulation results acknowledges factors like curve numbers, land cover, precipitation and slope length are good indicators of the locations of maximum runoff and sediment yield potential sources of the sub basin. Accordingly, the annual sedimentation rate over the year is found to be 300 x 10^3 m^3 at Mhjib Dam Reservoir.

Ahn (20011) used GSTARS4 to sedimentation and flushing, studies of the Xiaolangdi Reservoir, sited on the major tributary of Yellow River in China. According to the study, the sediment concentration of the reservoir was in the order of 10-100 Kg/m^3 during regular operation periods and 100-300kg/m^3 at times of flushing operations. The constituting part of fine sediments usually clay materials were found to be around 20 - 70% in the reservoir. However, the model was run for quasi-steady and unsteady simulations with three and half year's area- specific coefficients to compute the transport potential and channel geometric change. Besides, the model was adjusted by Han's (1980) transport function and with the unit stream power equation. The simulation results showed that the computed volume of reservoir sedimentation, channel cross-section, elevation, bed material size, and gradation of flushed sediments were generally in good agreement with unsteady computation results then steady flow simulations.

Chaudhary and Rehman (2010) review 50 worldwide reservoirs in the attempt of assessing their experience of sediment flushing operation. The summary result indicated that among them only six reservoirs were flushed their sediments successfully with high flushing efficiency. However, all the rest of representative reservoirs were found to be low efficient. Besides, it was found in the study that the flushing data were not documented well and even not available.

Ji (2006) applied numerical model studies to evaluate sediment control and flushing methods, which supposed to reduce, and possibly eliminates the dredging operation of Nakdong River Estuary Barrage (NREB) in South Korea. The simulation scenario was developed and examined based on flow duration curve, stage storage curve, and tidal elevation data collected over a period of 1998 to 2003. The quasi-steady analysis results indicated that at high flow, the water level differences with and without dredging, were immaterial as compared to significant water level change at low flow condition due to tidal effects. The analysis of flushing curves and past records of annual dredging sediments (665,00 m^3) indicated that sediment flushing is possible at the NREB 2.5. The sediment transports function can be treated in different ways during mathematical modeling of reservoir sedimentation. The suspended load can be treated either of equilibrium or non-equilibrium transport model depending on the sediment concentration and the carrying capacity of the streamflow. The concentration of sediment and the carrying capacity of the flow usually exhibit in excess or deficit those results in a self-adjustment of the channel by depositing or scouring the beds and banks. If the difference between the instantaneous sediment concentration and sediment carrying capacity is being neglected, then it belongs to the equilibrium sediment transport model (NIH, 1978-79). Otherwise, it belongs to non-equilibrium or non-saturated sediment transport model. The former kind of model is developed and adopted in the USA and European countries. However, the later was adopted in Japan, the Netherlands, France, and China.

Chapter – 3

STUDY AREA AND DATA COLLECTION

3.1 Study area

The Hirakud reservoir is located between 19^{o} N to 24^{o} N latitude and 80^{o} E to 84^{o} E longitude (Fig.3.1). The Hirakud dam is constructed across Mahanadi and is located 15 km from Sambalpur in Odisha, India. The project is a multipurpose project with objectives namely irrigation, power generation and flood control. Powerhouses are located at Burla and Chiplima. The reservoir is located in Jharsuguda, Bargarh and Sambalpur districts of Odisha and spreads upto 58 km from dam and water spread area of 742 km^{2}. Mahanadi delta in Puri and Cuttack districts of Odisha is protected from floods by the project.

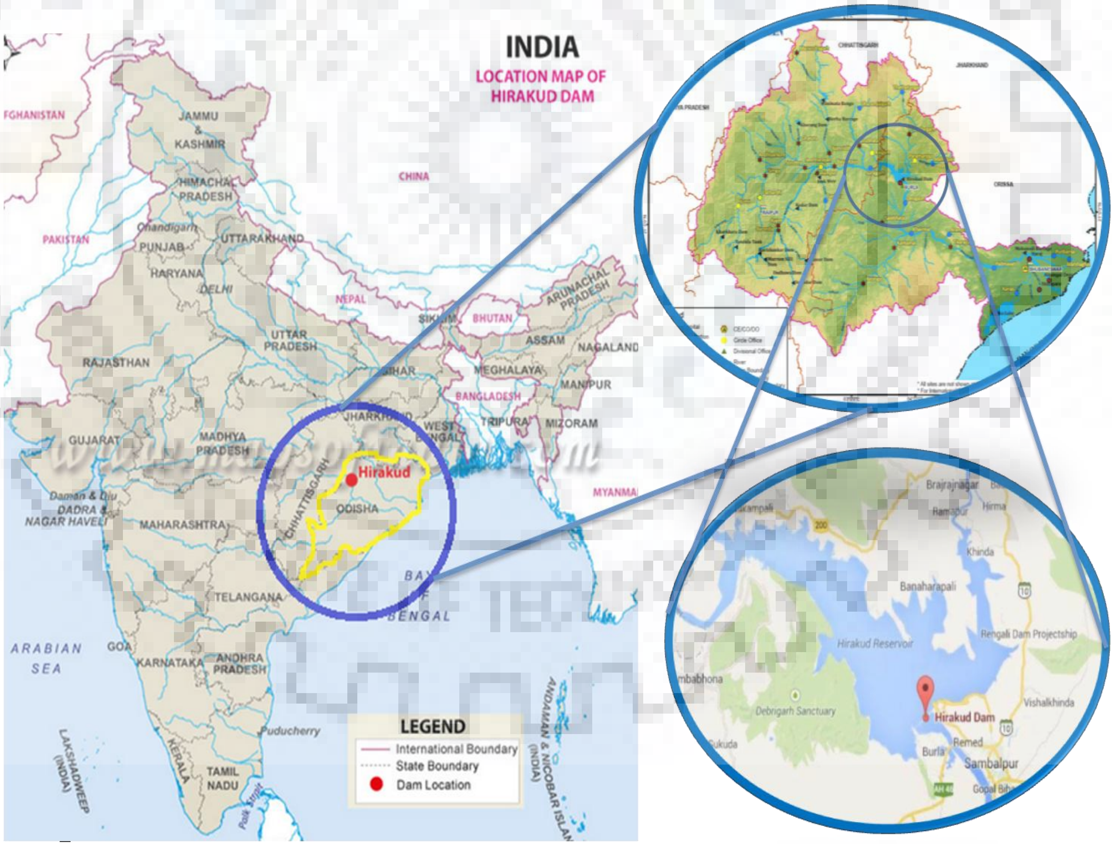


Figure 3.1 Study area

The temperature of the zone varies from 10^{o}C to 36^{o}C being maximum in the month of April and May and winter temperature in the month of December and January (Fig. 3.2). The month of July and August shows the highest rainfall with 28 days of rainfall with the highest precipitation of 288 mm. The lowest rainfall observed in December and November (Fig.3.3).

The catchment of the Mahanadi upto the Hirakud reservoir is 83400 km^2 from which 89% comes in Chhatisgarh state and other 11% in Madhya Pradesh (0.8%), Bihar, Maharashtra (0.3%) and Odisha (8.8%). The dam is divided into 2 parts 4.8 km is a concrete dam and 21 km is earth dam, which constitutes the composite dam of 25.8 km. two observation towers namely Gandhi Minar and Jawahr Minar are constructed in the left and right dyke. The salient features of the Hirakud dam is presented in Table 3.1

Table 3.1 : Details of Hirakud reservoir

1.	Length of the concrete dam	4.8 km
2.	Total length of earth dam	25.8 km
3.	Area of irrigation in both Rabi & Kharif	235477 ha
4.	The reservoir lake water spread area in FRL	743 km
5.	Total area covered for construction	506.36 km^2
6.	Water spread area at MDDL	274 km^2
7.	Hydropower generation capacity	307.5 MW
8.	Total estimated expenditure of dam	100.02 crores
9.	The top level of the dam	195.68 m
10.	The RL of FRL	192.02 m
11.	The RL of MDDL	179.80 m
12.	The earth consumed in earth dam	18100,000 m^3
13.	Total quantity of concrete consumed is 4.8 km dam	1070,000 m^3
14.	Initial height of dam at the time construction	60.96 m
15.	Gross capacity of the dam (original)	81.36 Mm^3
16.	Original dead storage capacity	2318 Mm^3
17	Design flood discharge spillway capacity	42450 Mm^3

. **Table 3.2** : Details of catchment area of Hirakud reservoir

State	Catchment area up to dam (ha)	% area	Total catchment (ha,)	%area
Chhattisgarh	74,970	89.9	74,970	52.9
Madhya Pradesh	130	0.1	130	0.1
Maharashtra	250	0.3	250	0.2
Bihar	650	0.8	650	0.5
Odisha	7400	8.8	65,600	46.3
Total	83400	100.0	141600	100.0

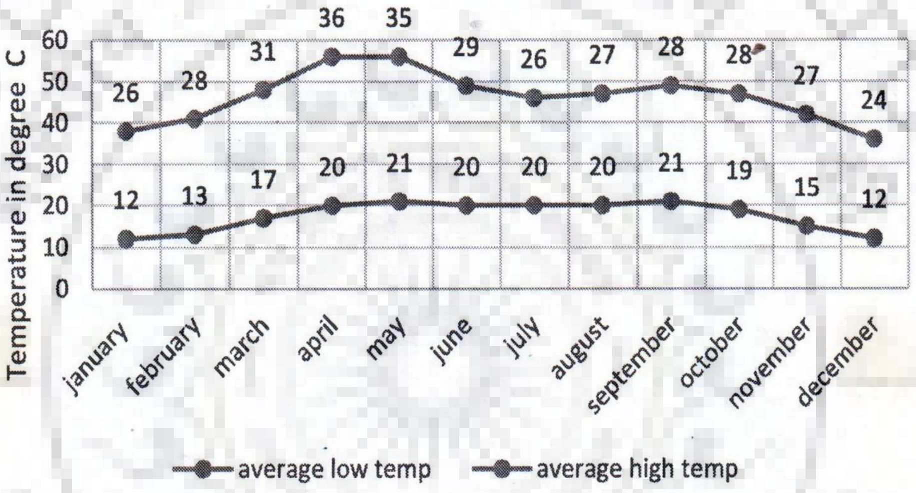


Figure 3.2: Average monthly temperature for Hirakud

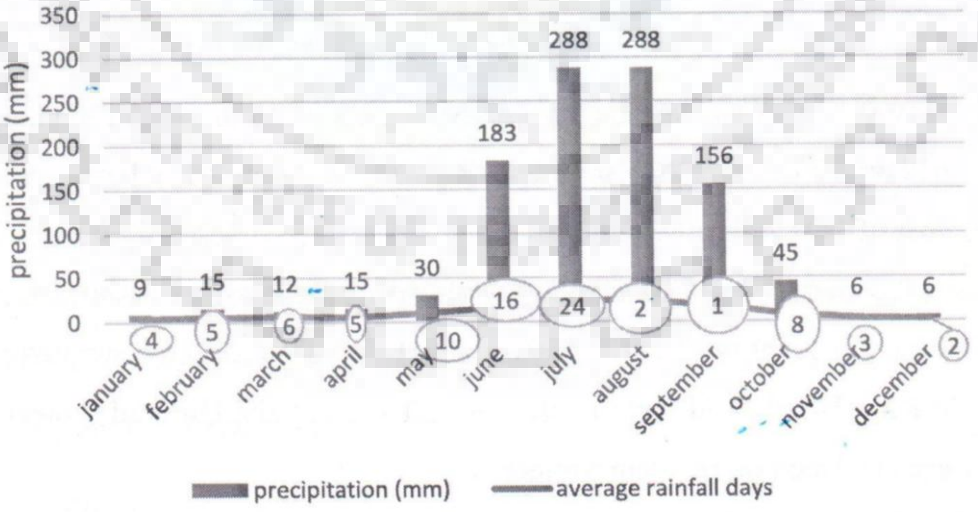


Figure 3.3: Showing average rainfall in months of the year, the values inside circle showing the number of days of rainfall in a month

3.2 DATA COLLECTION

From USGS earth explorer, SRTM DEM of Hirakud catchment area has been downloaded and study area delineated. LULC, soil (NBSS and LUP, scale 1: 2,50,000), and slope maps have been collected from different sources (i.e., global website and Government of India website). The soil map collected from National Bureau of Soil Survey and Land Use Planning (NBSS and LUP).Gauge discharge data of 3 stations in Mahanadi catchment has been collected from Government of Odisha, Water Resources Department, and RL of the Hirakud reservoir has been collected from India WARIS web site from April 2005 to April 2019. NECP CFSR data have been used for knowing the temperature, precipitation, relative humidity, to wind spread, solar radiation for 36 years (1979 to 2014).

The high-resolution satellite imageries have been downloaded from USGS earth explorer for 8 different time periods (July 2016, 18th June 2017, 22nd June 2017, 9th August 2017, 12th April 2018, 23rd August 2018, 5th September 2018, 22nd November 2018). The water spread areas of the reservoir in different dates corresponding to different elevation have been prepared. The original capacity of Hirakud reservoir data at the time of impounding and original elevation to the water spread area of the reservoir have been collected from Water Resources Department, Govt. of Odisha.

Chapter – 4

METHODOLOGY

The methodology adopted in the present study subsequently discussed in the following sections and presented in Fig. 4.1.

4.1 SWAT model description

SWAT is the acronym for Soil Water Assessment Tool, a river basin, or watershed, scale model developed by Dr. Jeff Arnold for the USDA Agriculture Research Centre (ARS) (Neitsch *et al*., 2005). SWAT model is mainly used to predict the impact of land-management practices on water, sediment, and agricultural chemical yields in large basins with varying soils, land use, and management over long periods of time (Neitsch et al. 2001). SWAT operates on a daily time step and uses physiographical data such as elevation, land use, and soil properties as well as meteorological data and river discharge data for calibration. The hydrological processes included in the model are surface runoff, evapotranspiration (ET), percolation, infiltration, aquifers flow (shallow and deep), and channel routing (Arnold et al. 1998). The SWAT model uses the Natural Resource Conservation Service Curve Number (NRCS-CN) method for estimating surface runoff (Q_{surf}) (SCS 1972). The water balance of a given watershed is given by:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (1)$$

Where, SW_t = final soil water content (mm); SW_0 = the initial soil water content on day *i* (mm); t = time in days; R_{day} = rainfall (mm); Q_{surf} = surface runoff (mm); E_a = evapotranspiration (mm); W_{seep} = percolation (mm); and Q_{gw} = return flow (mm).

Sediment yield in SWAT is estimated with the modified soil loss equation (MUSLE) developed by Williams and Berndt (1977). The sediment routing model consists of two components operating simultaneously: deposition and degradation. The deposition in the channel and floodplain from the sub-watershed to the watershed outlet is based on the sediment particle settling velocity. The settling velocity is determined using Stoke’s law (Chow et al., 1988) and is calculated as a function of particle diameter squared. The depth of fall through a reach is the product of settling velocity and the reach travel time. The delivery ratio is estimated for each particle size as a linear function of fall velocity, travel time, and flow depth. Degradation in the channel is based on Bagnold's stream power concept (Bagnold, 1977) and (Williams, 1980).

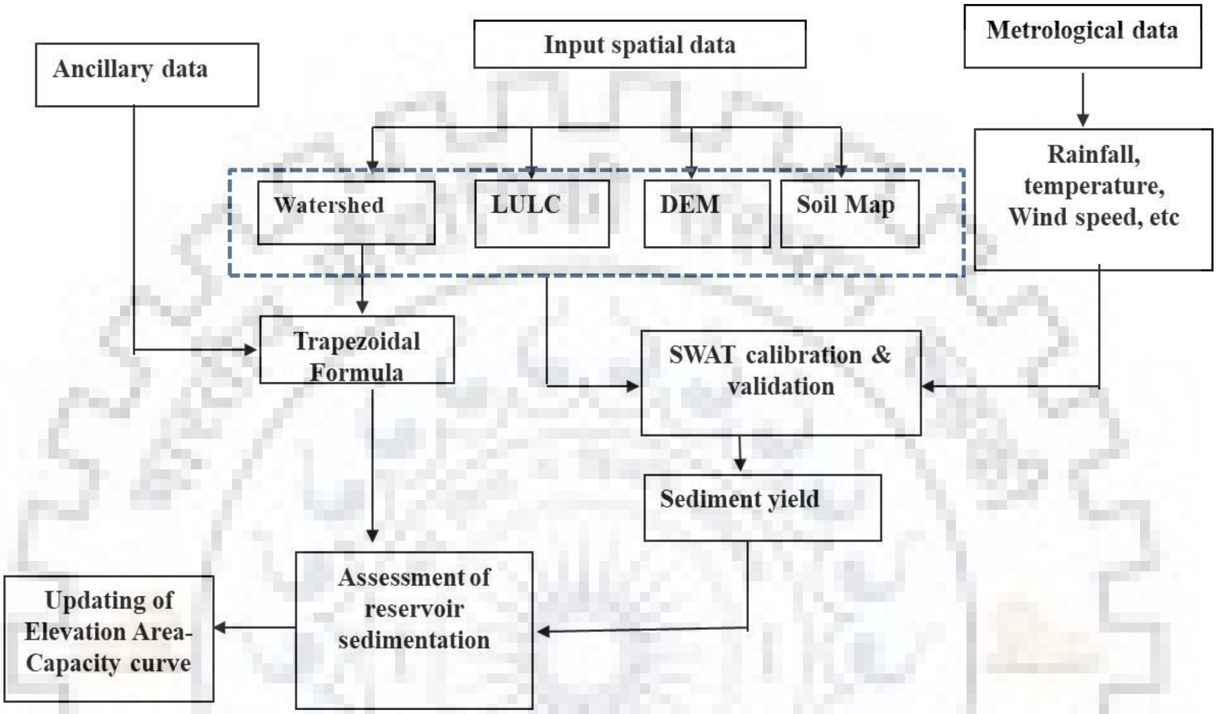


Figure 4.1 : The methodology adopted in the present study

Modified USLE equation is used to calculate the sediment in the SWAT model 2016 version. The modified USLE equation is

$$\text{Sedimentation} = 11.8\,(Q_{surf} \text{ x } q_{peack} \text{x} area_{hru})^{0.56} \text{ X } K_{USLE} \text{ X } C_{USLE} \text{ X } L_{USLE} \text{ X CFRG}$$

Where, Sed. = Sediment in a given day

Q_{SURF} = Surface runoff volume mm / hectare

q_{peak} = Peak runoff rate m^3/sec

$area_{hru}$ = The area of Hydrological Response Units

K_{usle} = USLE erodibility factor

C_{usle} = USLE cover management factor

P_{usle} = USLE support practice factor

L_{susle} = USLE topographic

4.2 SWAT model set up

In the present study, SWAT model has been used to simulate the runoff and sediments yield from the study area. In SWAT, a watershed is divided into several sub-watersheds based on stream drainage areas (Fig.4.2). Further, the sub-watersheds are divided into a number of hydrological response units (HRUs). HRUs are defined as unique combinations of land cover, soil, and/or slope classes distributed over a sub-watershed. Each HRU is assumed spatially uniform in terms of land use, soil, topography, and climate, and a single HRU can be found at different locations within the sub-watershed. All model computations are performed at the HRUs level. The runoff is predicted separately for each HRU and routed to obtain the total runoff at the outlet of a watershed (Her et al., 2015).

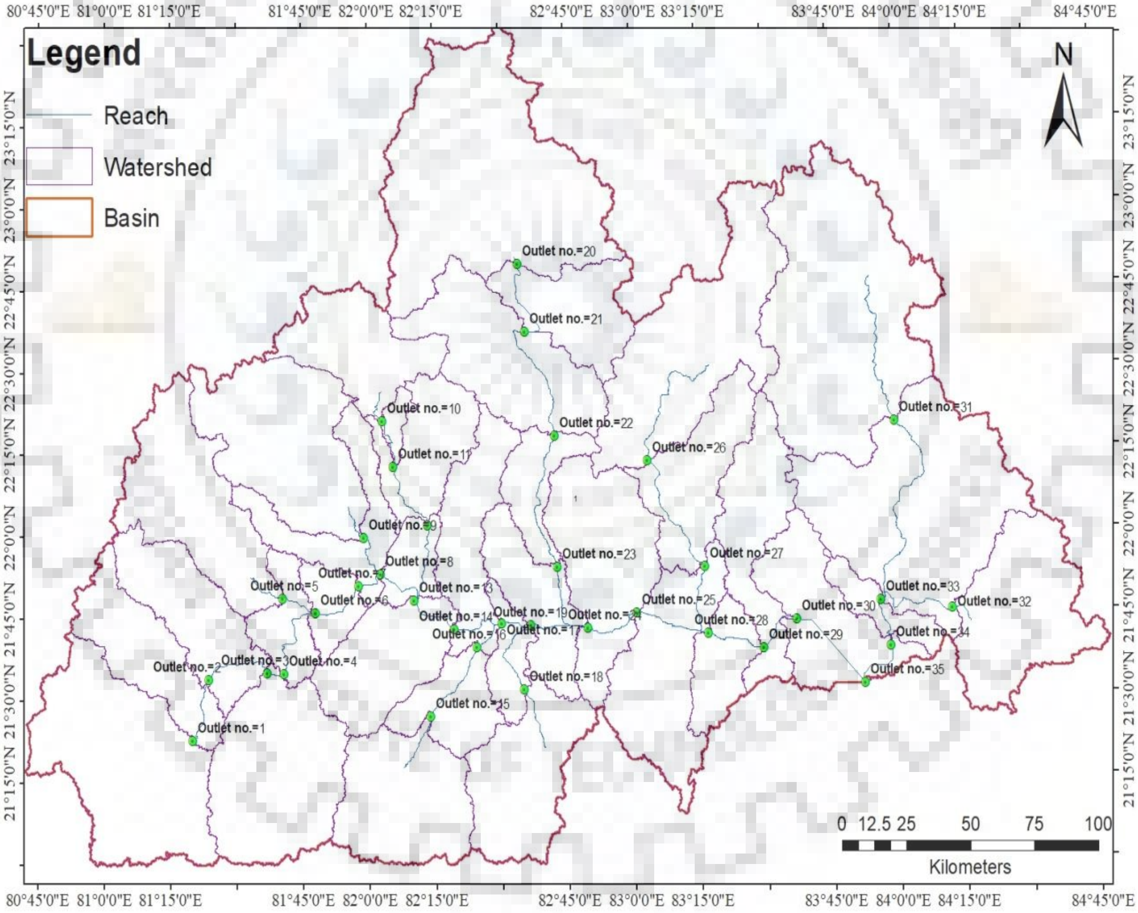


Figure 4.2: Inlet and outlet delineation map

The different inputs of the study area such as SRTM 90 m resolution DEM, slope soil map and land use have been used in this study (Fig.4.3 to 4.6). The database collected has been updated by soil FAO (Food and Agriculture Organization on the United Nations). Then the

Hirakud soil database has been incorporated into the SWAT model. The LULC map is also reclassified as per the look-up table of the SWAT model and incorporated as model input. Land, soil and slope threshold (2%, 2% and 3%, respectively) have been used to increase the number of HRU (Hydrological Response Units) to give an accurate result. Daily gridded hydro metrological data has been collected from India Meteorological Department for 40 years (1975 to 2014). SWAT model has been set up and run for 36 years (1979 to 2014) with a warming up period of 3 years to simulate daily runoff and sediment simulations.

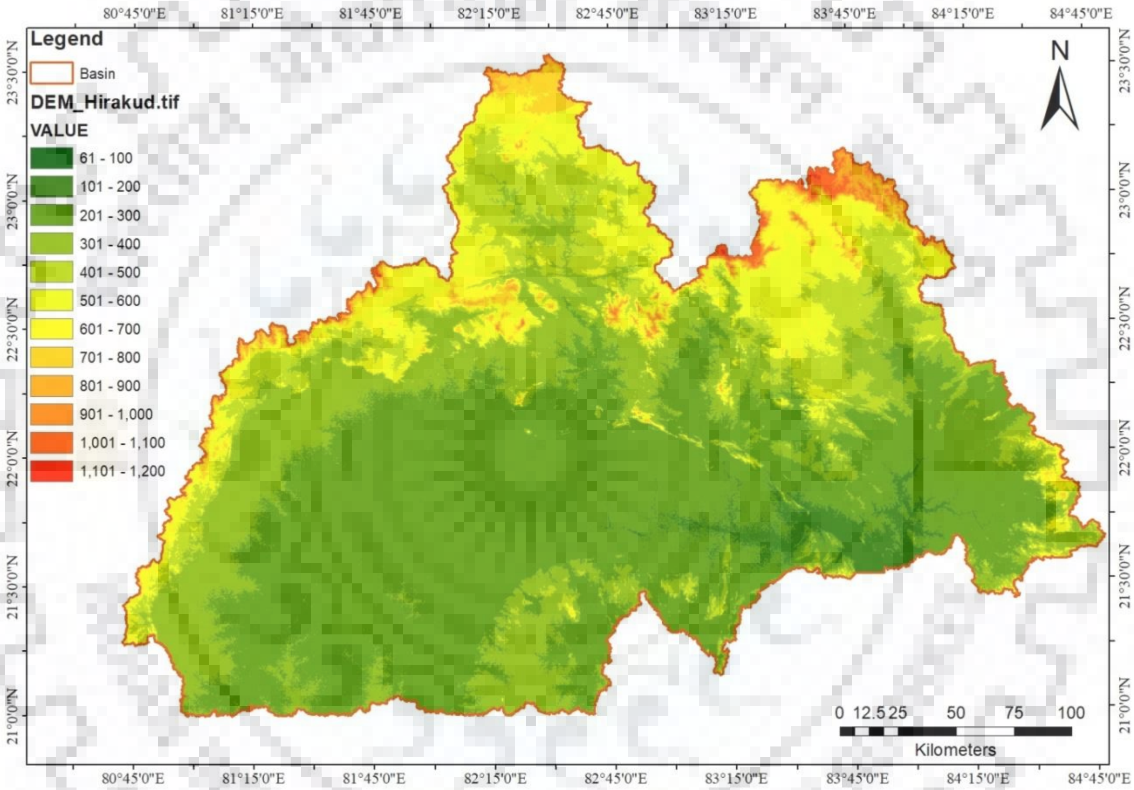


Figure 4.3: Digital elevation model

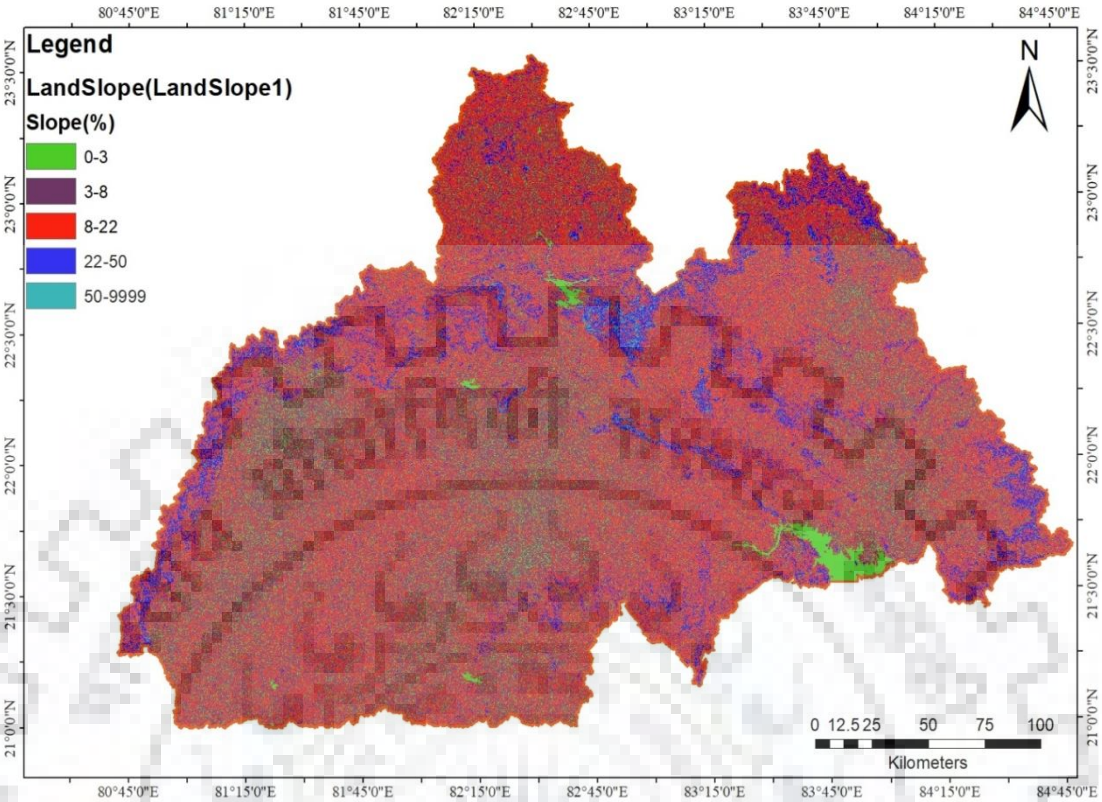


Figure 4.4 Slope map

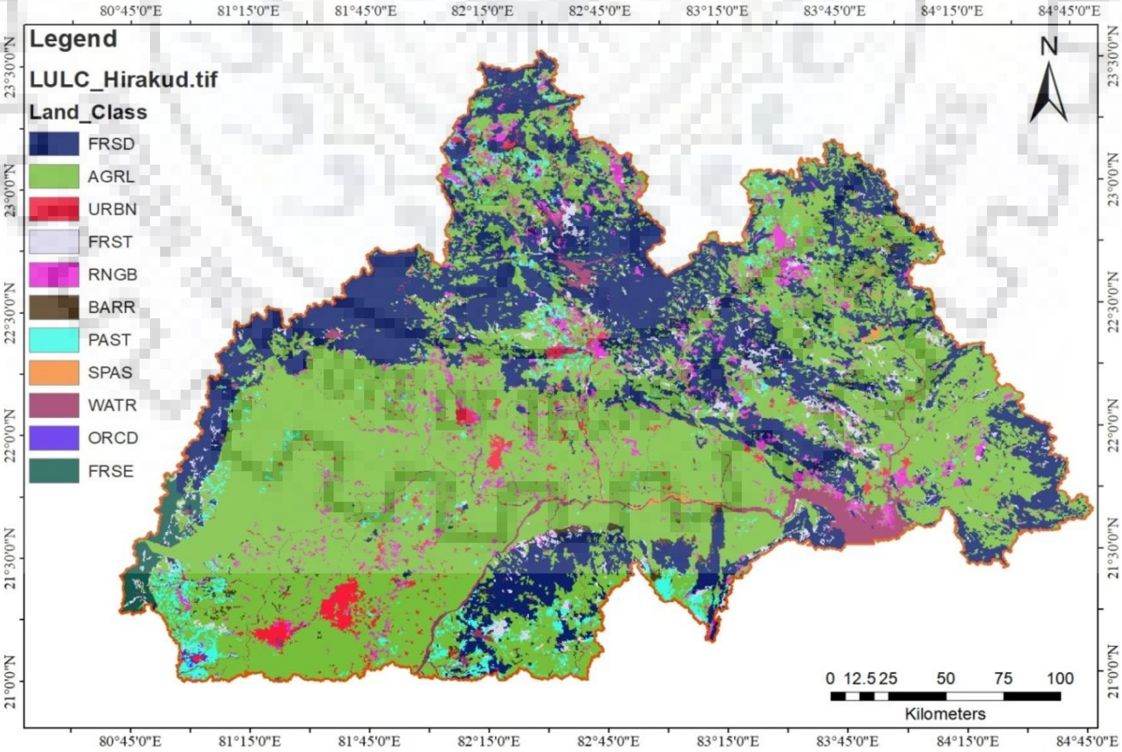


Figure 4.5: LULC Map

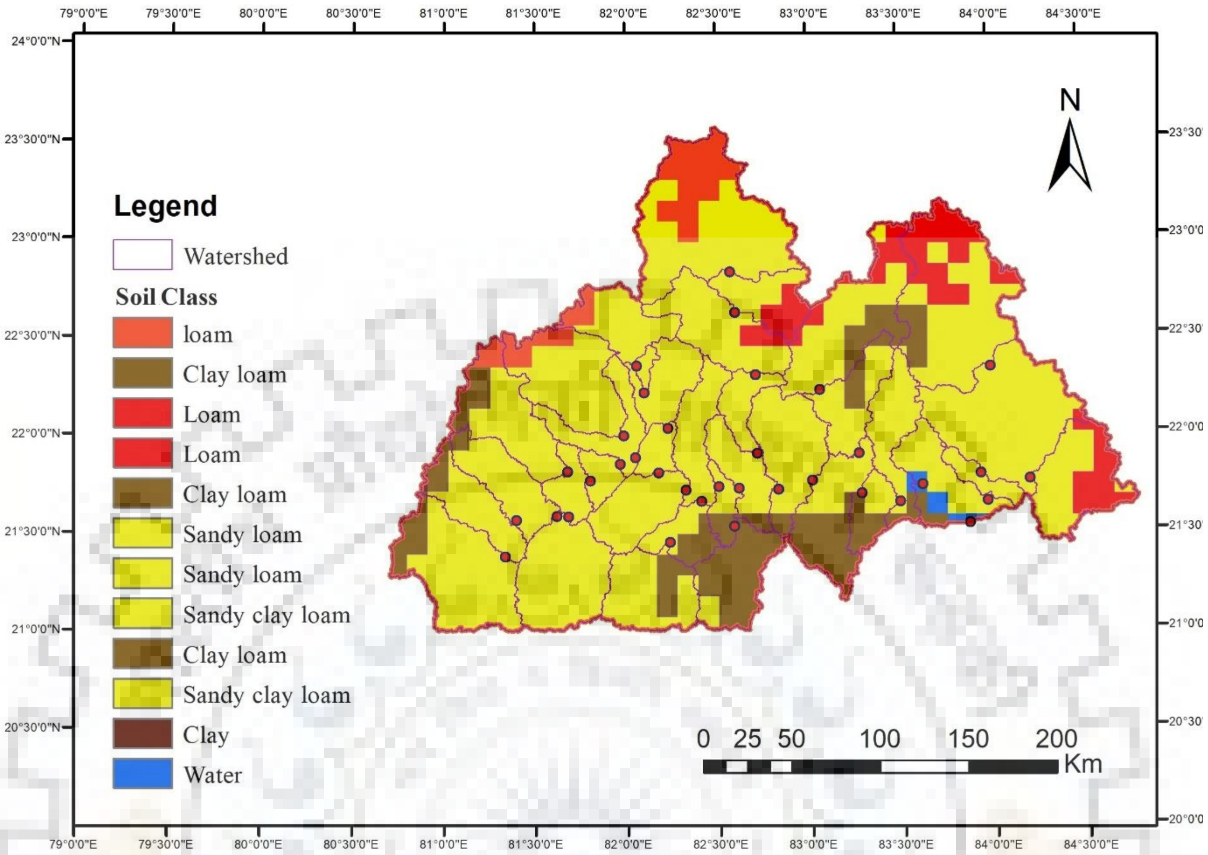


Figure 4.6 Soil class map

4.3 Calibration and validation of model

Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters). It is a necessary process to identify key parameters and parameter precision required for calibration (Ma *et al*., 2000). Model calibration is the process of estimating model parameters by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions. Model validation involves running a model using input parameters measured or determined during the calibration process.

Two time periods datasets were selected for the calibration (2000 to 2001) and the validation (2002 to 2003), which allows the model to cycle multiple times in an attempt to minimize the effects of the user's estimates of initial state variables, such as soil water content and surface residue. In addition, the period from 1997-1999 was used as a model warm up period. The SWAT-CUP has been used for the SWAT model calibration and validation

(Abbaspour, 2015). The performance of the calibrated parameters was evaluated by graphic comparisons and statistics indices, Coefficient of determination (R^2), Nash-Sutcliff efficiency (NSE), percentage bias (PBIAS) and ratio of the root mean square error to the standard deviation of measured data (RSR) (Moriasi *et.al.*, 2002).

4.4 Estimation of water spread area and volume of sediments by remote sensing

The original capacity of the reservoir was measured in the 1st year of water impounding in the year 1957. The imageries for different time periods have been processed by using ERDAS IMAGINE software. Initially, the different layers of imageries have been stacked to create high-resolution imageries, and then the Hirakud reservoir catchment area has been masked with catchment boundary. Further, the unsupervised classification technique has been applied to classify the selected satellite imageries using ERDAS. Finally, the water spread areas for selected imageries have been calculated using the ERDAS software. The revised elevation capacity curve has been developed to find out the reduction in capacity of the reservoir and to find out the quantity of silt deposited in the reservoir since impounding.

Chapter 5

RESULTS AND DISCUSSION

The results obtained through the methodology adopted have been subsequently discussed in the following sections:

5.1 Calibration and validation

Two time periods datasets were selected for the calibration (2000 to 2001) and the validation (2002 to 2003). In addition, the period from 1997-1999 was used as a model warm up period. The calibration result of the SWAT-CUP shows that the optimal parameters of sensitivity analysis are reasonable (Table 5.1). It may be noted that the values for the optimized model parameters were obtained in the field for the specified soils, land cover and climate conditions. Any substantial change in these field conditions could alter the values of

Table 5.1: Calibration and validation parameter

Parameter/Name	Fitted Value	Minimum value	Maximum value
1:R__CN2.mgt	-0.0924	-0.2	0.2
2:V__SURLAG.bsn	10.3725	0.05	24
3:V__CH_N2.rte	0.2092	-0.01	0.3
4:V__ESCO.hru	0.0810	0	1
5:V__SLSUBBSN.hru	62.7800	10	150
6:V__GWQMN.gw	585.0000	0	5000
7:V__EPCO.hru	0.3670	0	1
8:V__GW_REVAP.gw	0.1030	0.02	0.2
9:R__SOL_AWC(..).sol	0.1788	-0.2	0.2
10:V__GW_DELAY.gw	26.5000	0	500
11:V__ALPHA_BF.gw	0.9170	0	1
12:V__REVAPMN.gw	427.5000	0	500
13:R__SOL_K(..).sol	-0.1564	-0.2	0.2
14:R__SOL_ALB(..).sol	-0.1988	-0.2	0.2
15:V__SPEXP.bsn	1.2155	1	1.5
16:V__CH_ERODMO(..).rte	0.8710	0	1
17:V__CH_COV2.rte	0.5285	-0.001	1
18:V__SPCON.bsn	0.0093	0.0001	0.01
19:V__USLE_C{..}.plant.dat	0.2181	0.001	0.5
20:R__USLE_P.mgt	0.1732	-0.2	0.2
21:V__TLAPS.sub	-9.5800	-10	10

these parameters and affect the best model result. Thus, the model result discussed in this section should be interpreted as accurate only for this set of 21 parameters, 15 numbers for discharge simulation and 6 numbers for sediment load simulation.

The result of the SWAT model have been found in good agreement during calibration (R^2=0.772, NSE =0.655, PBIAS=15) and validation (R^2=0.85, NSE= 0.83, PBIAS= -16.9) periods (Table 5.2). The observed and simulated mean monthly discharge during calibration and validation is shown in Figure 5.1 to 5.4, respectively. The high R^2 and NSE in the calibration and validation suggest that the calibrated model can describe the stream flow of the basin. Thus, we can be confident the calibrated model with set of optimized parameters can be applied to examine the hydrological responses of the basin under the land-cover change and climate change scenario.

Table 5.2: Evaluation coefficients for SWAT calibration and validation

Period	Evaluation statistic			
	R^2	NSE	PBIAS	RSR
Calibration (2000-2001)	0.772	0.655	15	0
Validation (2001-2003)	0.850	0.833	-16.9	0

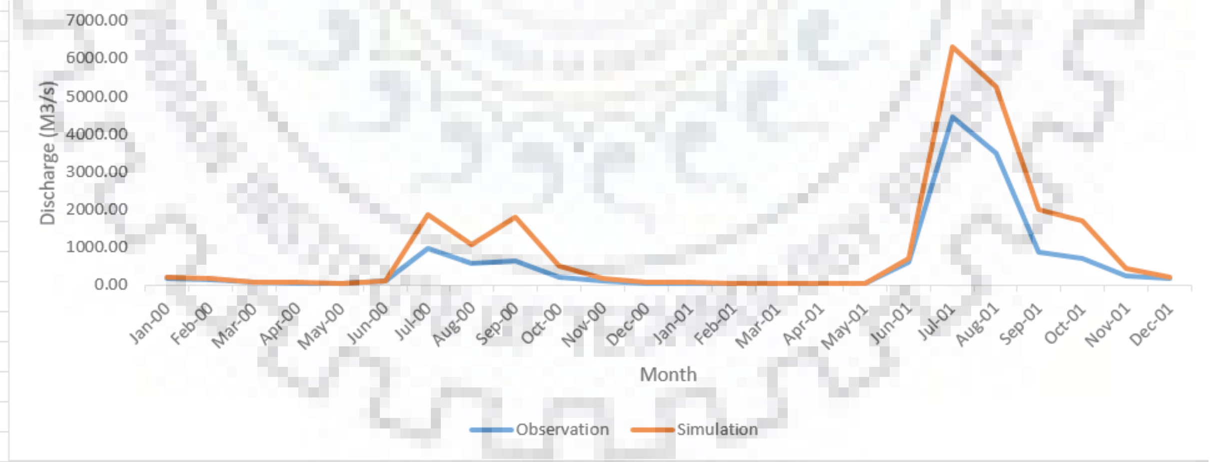


Figure 5.1: Mean monthly simulated and observed discharge at the Hirakud basin outlet during calibrated period (2000 -2001)

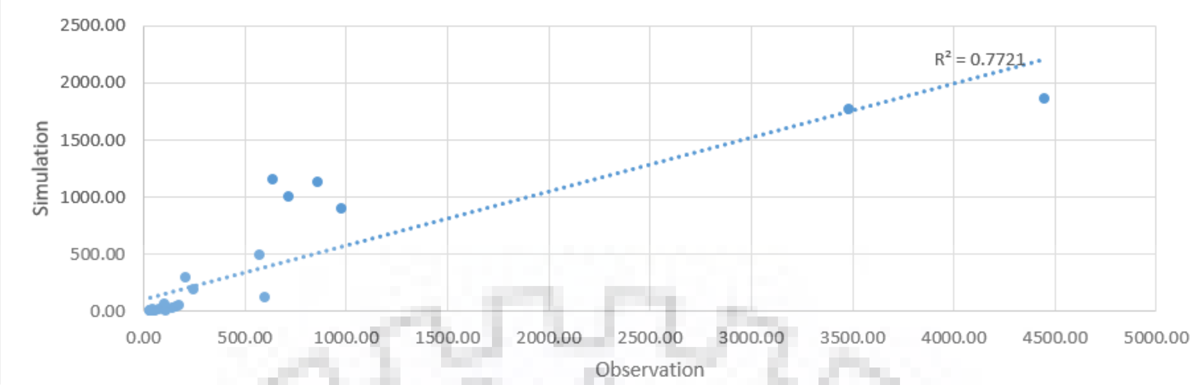


Figure 5.2: Scatter plot of monthly simulated and observed discharge during the calibration period (2000-2001)

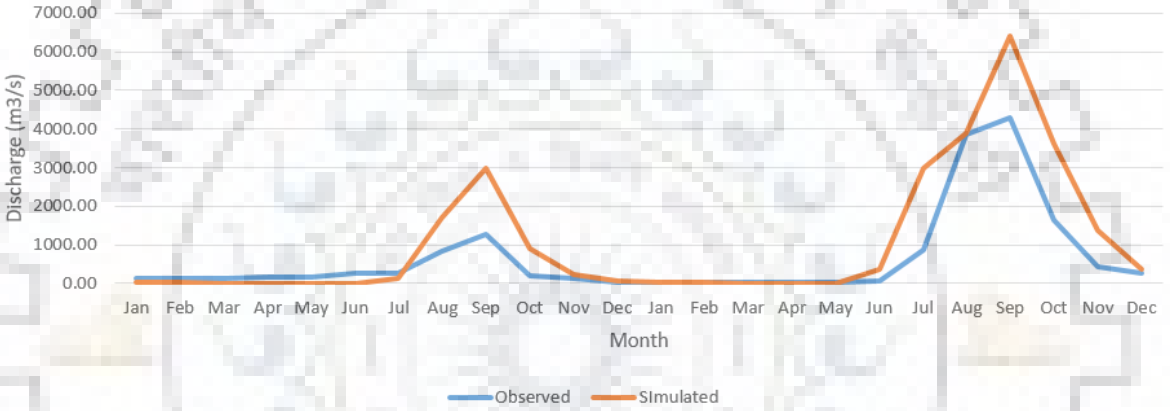


Figure 5.3: Mean monthly simulated and observed discharge at the Hirakud outlet during the validation period (2002-2003)

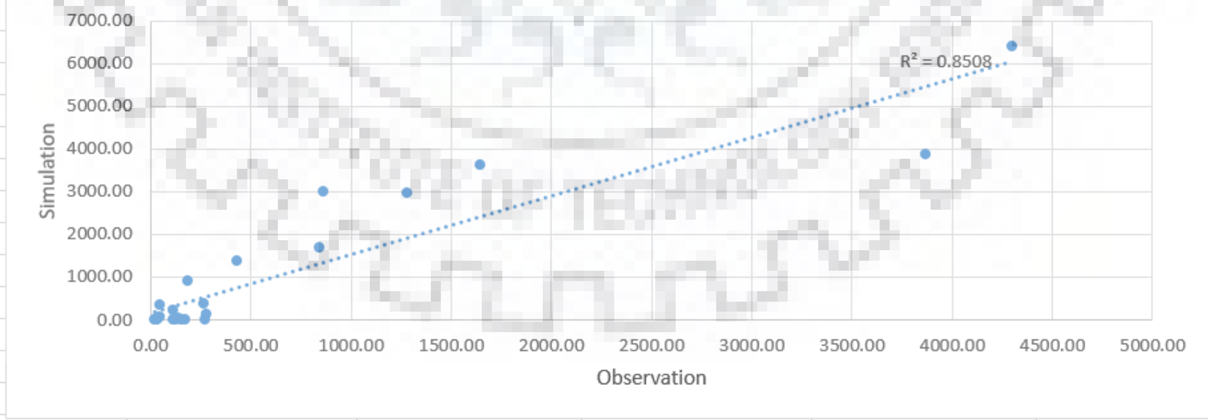


Figure 5.4: Scatter plot of daily simulated and observed stream flow during the validation period (2002-2003)

5.2 SWAT model results

The delineated catchment area of the Hirakud reservoir has been found 66272 km^2 and, number of sub-watershed and HRU found to be 35 and 857, respectively. By average CN value 81.46, average surface runoff and sediment yield in 36 years has been found to be 512.18 mm/year and 194.35 tones/ha, respectively. Hence, total sediment yield in a catchment has been found 1288990400 tons. Taking the average density of sandy loamy site which is more than 60% covered by Hirakud catchment is having specific weight 1.30 tons per m^3. Hence, the sediment deposited will have a volume of 991.5 Mm^3 which gives annual sediment yield 30.98 Mm^3. Taking the actual catchment of Hirakud 84300 km^2 and the annual sediment yield is 39.35 Mm^3. The details of simulated surface runoff and sediment yield are presented in Fig. 5.5 to 5.6 and Table 5.3.

The sediment loss from the land scape is dependent upon many factors. Sediment over estimate in SWAT is most commonly due to inadequate biomass production. This often occurs in specific land uses, if upland sediment yield is excessive than a particular land use must be erosion prone. Especially the land use under agriculture gives more erosion and > 60% of the Hirakud catchment is erosion prone as it is used for agriculture land and mostly belongs to sandy loam type of soil. SWAT also modifies sediments to occur for in stream deposition and erosion of stream banks and channels. Often there is no data to differentiate upland sediment and in-stream sediment. Stream may be either a net source of sediment or a sink. Stream sediment modification is impacted by physical channel characteristics (slope width depth channel cover).

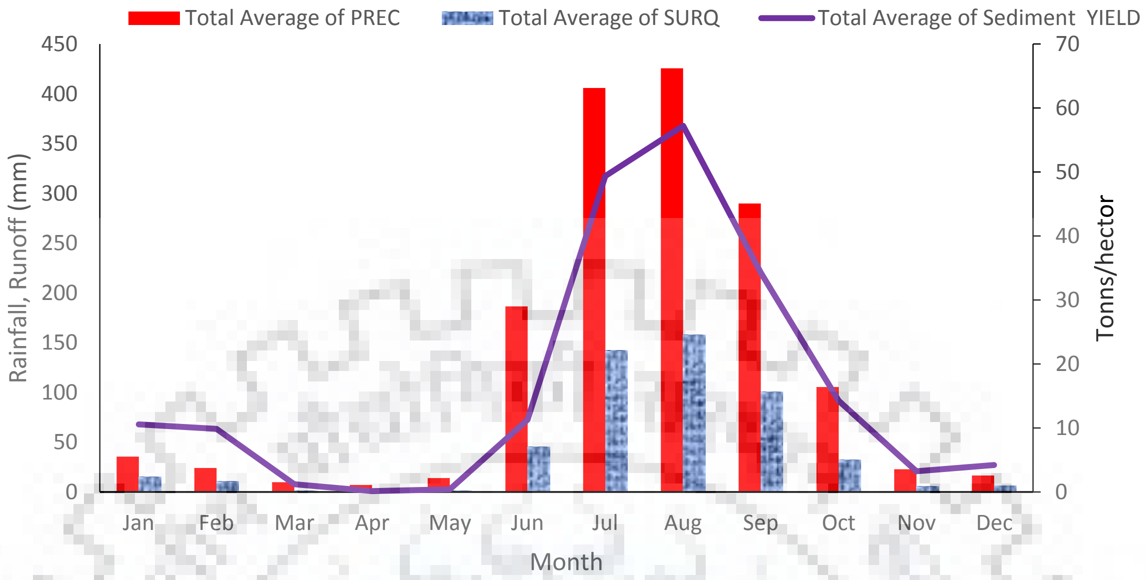


Figure 5.5: Monthly simulated sediment yield (1982-2014)

Table 5.3: Average monthly sediment yield

Month	Average rainfall, mm	Average surface runoff, mm	Average sediment yield, ton/ha
Jan	35.57	15.42	10.56
Feb	24.15	10.84	9.86
Mar	9.81	1.47	1.21
Apr	7.04	0.22	0.13
May	14.09	1.30	0.41
Jun	186.45	45.51	11.28
Jul	405.81	142.15	49.37
Aug	425.64	157.90	57.22
Sep	289.88	100.90	34.24
Oct	105.53	32.42	14.28
Nov	22.90	5.92	3.24
Dec	16.64	6.53	4.21

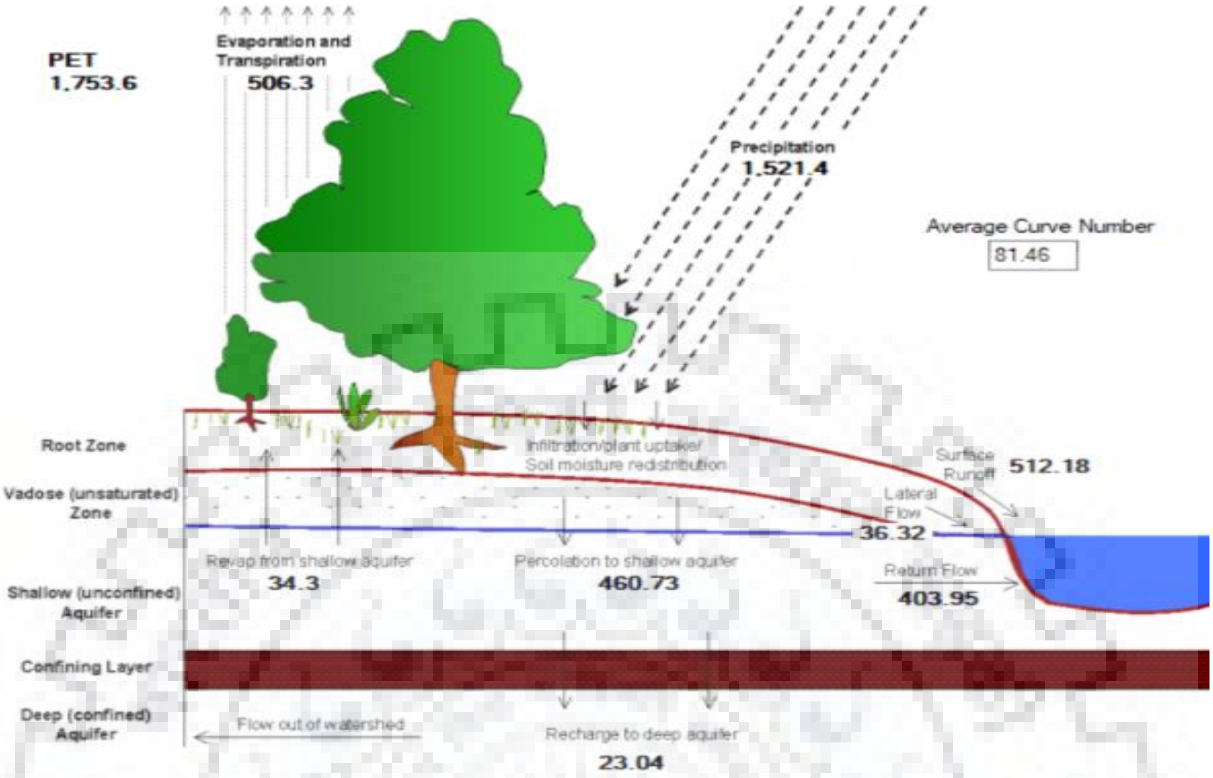


Figure 5.6(a): Simulated water balance components by SWAT

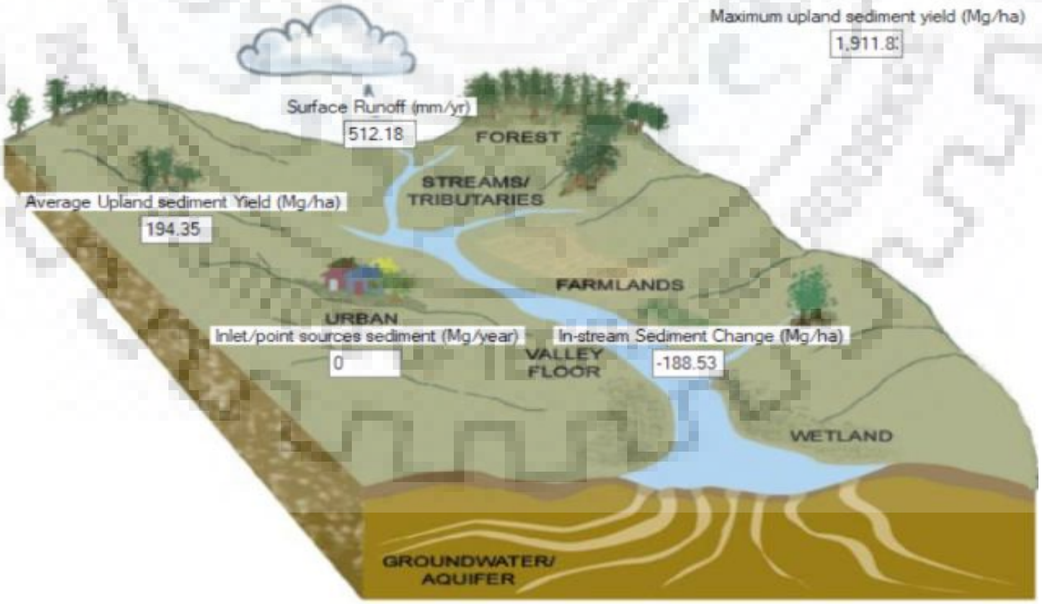


Figure 5.6(b): Simulated water balance components by SWAT

5.3 Water spread area and volume of sediments

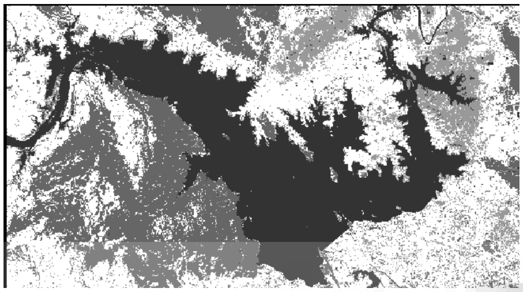
The elevation and water spread area for different time period satellite imageries have been calculated by remote sensing technique and ERDAS software (Table 5.4 & 5.5, and Fig.5.7).

Table 5.4: Elevation Level

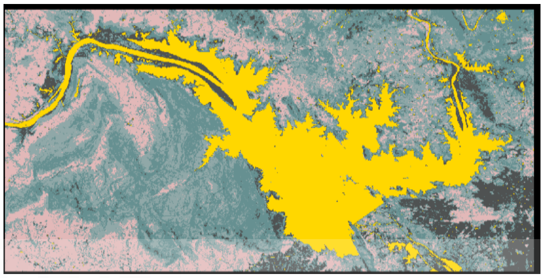
Date	Elevation, m
1st January 2016	181.35
18th January 2017	182.88
22nd July 2017	184.60
9th August 2017	185.92
12th April 2018	187.45
23rd August 2018	188.97
5th September 2018	190.50
22nd November 2018	192.02

Table 5.5 Water spread area of 1957 (observed) and water spread area 2017-18 (Remote sensing

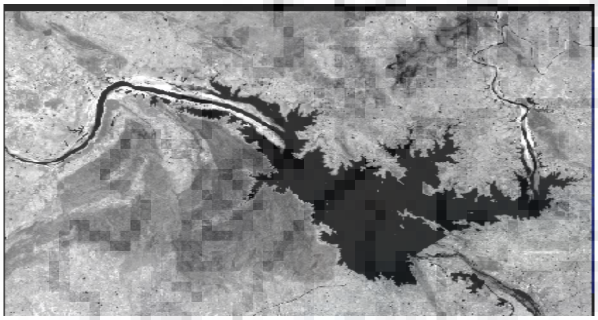
R.L. in m	**Original parameter**			**ERDAS IMAGINE 2017-2018**		
RL (m)	**Area (km^2)**	**Capacity (Mm^3)**	**Construction capacity**	**Area km^2**	**Capacity**	**Cumulative capacity**
179.83	277.66	405.26	2262.12	-	-	938.82
181.35	322.04	456.59	2718.79	211.6	296.39	1235.21
182.88	366.56	524.36	3243.07	249.02	326.9	1562.11
184.40	416.49	596.26	3839.33	292.9	412.5	1974.61
185.92	466.46	672.45	4511.78	349.67	485.3	2459.91
187.45	525.50	754.45	5266.14	410.31	574.57	3034.45
188.97	582.50	843.13	6104.17	482.76	679.7	3714.14
190.5	651.97	942.37	7051.94	554.87	790.03	4504.18
192.02	727.31	1053.06	8135.15	630.80	902.36	5406.54



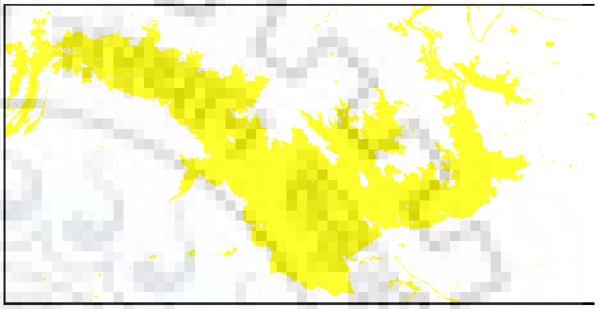
1st July 2016 (Area: 211.6 sq.km)



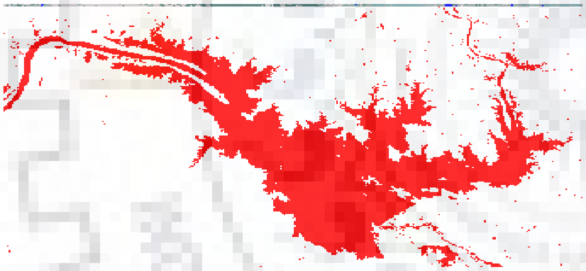
18th June 2017 (Area249.02sqkm)



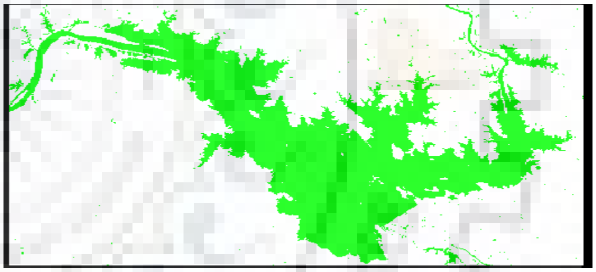
22nd July 2017 (Area 292.9sq.km)



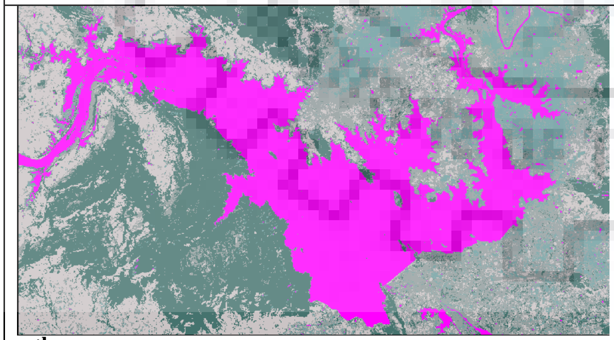
9th August 2017 (Area 344.67 sq.km)



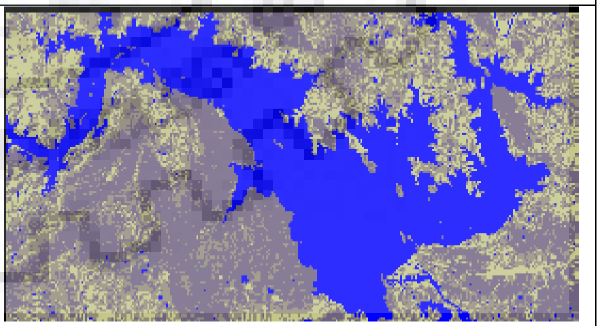
12th April 2018 (Area 410.31 sq.km)



23rd August 2018 (Area 482.76 sq.km)



5th Sept. 2018 (Area 554.87 sq.km)



22nd Sept. 2018 (Area 630.80 sq.km)

Figure 5.7: Water spread of Hirakud dam (2017-18)

The capacity has been determined by the trapezoidal formula $(A_1 + A_2 + \sqrt{A1\ x\ A2})\,\frac{h}{3}$

A_1 & A_2 = Water spread area of successive elevation.
h = Elevation difference between 2 water spread area.

It is calculated that the gross storage capacity of the reservoir is decreased and calculated.

$$\frac{8135-5406}{8135} \text{ x } 100 = 0.33 \quad = 33\%$$

Original live storage capacity in 1957 = 5826 Mm^3

Life storage in 2018 = 5406 – 938 = 4468 Mm^3

Decrease in live storage since 62 years = 23%

Total decrease in capacity since 2018 = 8135 – 5406 = 2729 Mm^3

44.01 Mm^3 / year

The storage capacities have been estimated for different elevations (Table 5.5). The elevation capacity curves give a difference of capacity and compare the capacity of the reservoir in 1957 (original) and 2017–2018 (present) (Fig. 5.8 and 5.9). It has been found that the capacity of the reservoir has reduced by 2729 Mm^3 in 62 years. The results have also been compared with the result of India WARIS which gives the capacity of the reservoir in 4th October 2017 is 5378 Mm^3 which has been found within acceptable limits (0.5% error).

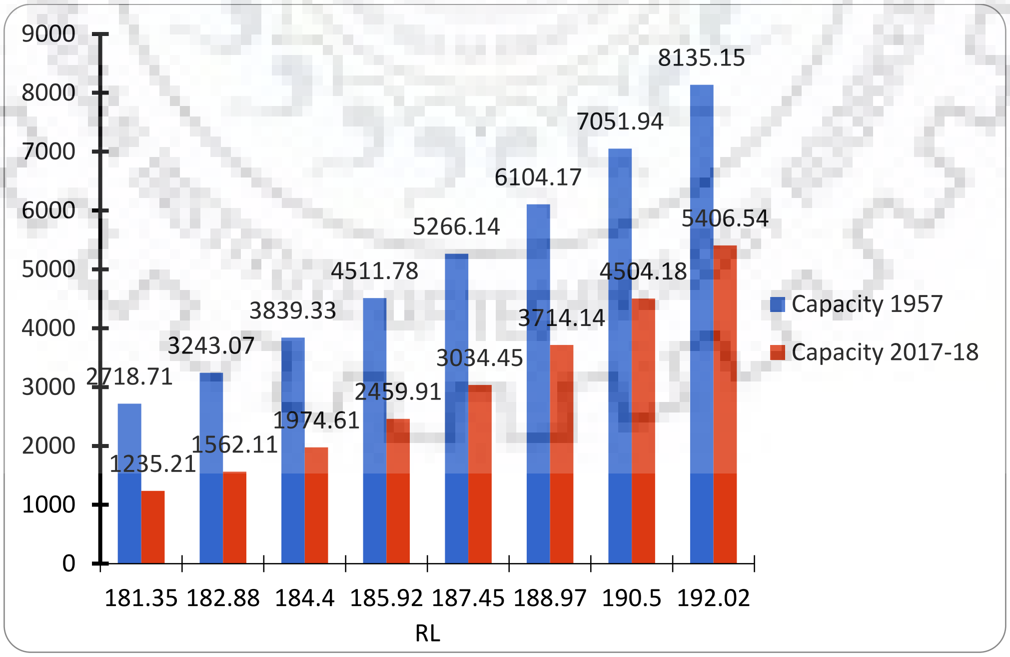


Figure 5.8: Elevation capacity curve

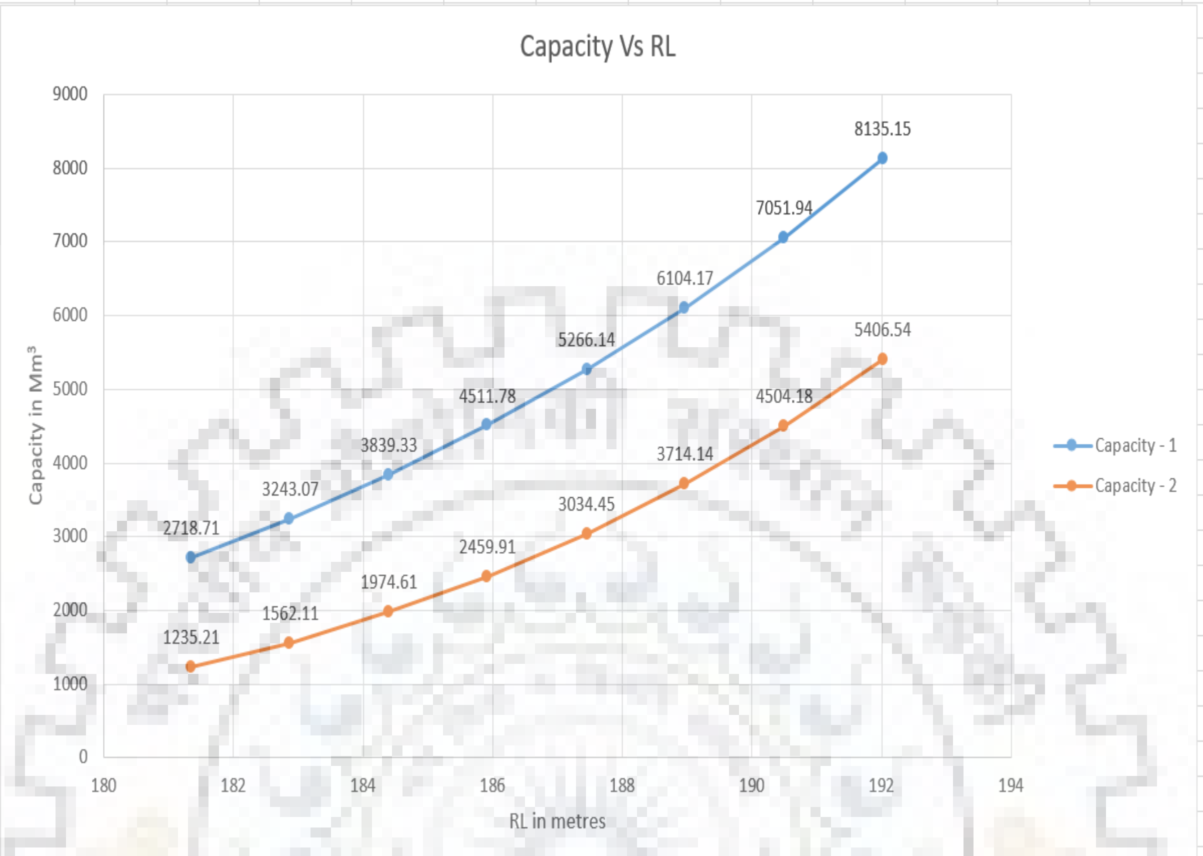


Figure 5.9: Capacity Vs RL

CHAPTER – 6

SUMMARY AND CONCLUSION

Annual sediment yield from the catchment of the reservoir has been assessed by using SWAT model. It has been found to be 39.35 Mm^3. By remote sensing method, the reduction in the capacity of Hirakud reservoir has been found to be 2729 Mm^3 in 62 years. Hence, the annual sediment yield has been estimated as 44.01 Mm^3. Hence, it can be concluded that the SWAT model under-estimates the sediment yield (4.06Mm^3), because it calculates the sediment yield by simulating daily runoff and never takes the effect of the sudden storm of high intensity causing more sediment yield due to climatic change. Hence, the SWAT model requires calibration and validation with climatic parameters to get more accurate result. Innovative erosion prevention measures can be adopted thorough out the catchment area of study area to reduce the soil erosion. Check dam construction, gabion construction, soil slope stabilization methods, land contouring, terracing, planting of trees are some of the solutions to soil erosion. This paper is certainly attempt to encourage other researchers to address the economic and effective management of watershed and the reservoir by utilization of SWAT model and ERDAS for planning and reducing soil erosion and sediment load for the existing reservoirs or storage structure to be planned along the stream.

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