Assessment of Soil Erosion and Sediment Yield for Prioritization of Watersheds Using Soil and Water Assessment Tool (SWAT)

Submitted in partial fulfilment of the requirements of the degree of

DOCTOR OF PHILOSOPHY
in
WATER RESOURCES ENGINEERING

By

P. SHYAMSUNDER

Roll No:701605

Supervisor

Prof. K V JAYAKUMAR
Department of Civil Engineering

WATER & ENVIRONMENT DIVISION
DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
WARANGAL– 506004
TELANGANA, INDIA

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NATIONAL INSTITUTE OF TECHNOLOGY WARANGAL

WARANGAL-506004

DEPARTMENT OF CIVIL ENGINEERING

CERTIFICATE

This is to certify that the dissertation entitled "**Assessment of soil erosion and sediment yield for prioritization of watersheds using Soil and Water Assessment Tool (SWAT)"** is bonafide record of work carried out by **P. Shyamsunder (Roll No: 701605),** submitted to the faculty of **Civil Engineering** in partial fulfilment of the requirements for the award of the degree of **Doctor of Philosophy** in **Water Resources Engineering.**

(K.V. JAYAKUMAR)
Thesis Supervisor
Professor (HAG)
Department of Civil Engineering
National Institute of Technology
Warangal-506004

DISSERTATION APPROVAL FOR Ph.D

This dissertation entitled **"Assessment of soil erosion and sediment yield for prioritization of watersheds using Soil and Water Assessment Tool (SWAT)"**by **P. Shyamsunder (701605)** is approved for the degree of **Doctor of Philosophy** in **Water Resources Engineering.**

Examiners

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Supervisor

____

Chairman

____

Date: ______________

Place: Warangal

DECLARATION

I **(P. Shyamsunder)** bearing **Roll No-701605** hereby declare that the dissertation titled **"Assessment of soil erosion and sediment yield for prioritization of watersheds using Soil and Water Assessment Tool (SWAT)"** under the supervision of **Prof. K.V. JAYAKUMAR** is submitted in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy in Water Resources Engineering. I declare that this written submission represents my ideas in my own words and where other's ideas or words have been included, I have adequately cited and referenced the original sources. I also declared that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea / data / fact / source in my submission. I understand that any violation of the above will be cause for disciplinary action by the institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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Roll No: 701605
Date: __________

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
AMC	Antecedent Moisture Condition
CIWR and HRSRC	China Institute of Water Resources and Hydropower Research's Sediment Research Centre
C/I	Capacity to Inflow
C/W	Capacity to Watershed
C/O	Capacity to Outflow
CDF	Cumulative Distribution Function
CN	Curve Number
CWC	Central Water Commission
CWPRS	Central Water and Power Research Station
DEM	Digital Elevation Model
GHG	Green House Gases
GIS	Geographical Information System
GoI	Government of India
GPS	Global Positioning System
HEC-RAS	Hydrologic Engineering Centre – River Analysis System
HWSD	Harmonized World Soil Database
HRU	Hydrological Response Unit
ICP-MS	Inductively Coupled Plasma-Mass Spectrometry
IMD	Indian Meteorological Department
LULC	Land Use/ Land Cover
MoWR	Ministry of Warer Resources
MSL	Mean Sea Level
MUSLE	Modified Universal Soil Loss Equation
NASA	National Aeronautical Space Administration
NSE	Nash-Sutcliffe Efficiency coefficient
NRSC	National Remote Sensing Centre
NSE	Nash Sutcliffe Efficiency
PBIAS	Percent Bias
PET	Potential evapotranspiration

RCM	Regional Climate Model
RD & GR	River Development and Ganga Rejuvenation
RS	Remote Sensing
RUSLE	Revised Universal Soil Loss Equation
SCS-CN	Soil Conservation Service Curve Number
SRL	Sediment Research Laboratory
SRTM	Shuttle Radar Topography Mission
STREL	Sediment Transport and River Engineering Laboratory
SUFI2	Semi Automated Fitting Tool
SWAT	Soil and Water Assessment Tool
SWAT-CUP	SWAT calibration and Uncertainty Program
T_e	Trap Efficiency
USDA	United States Department of Agriculture
USDANRCS	United States Department of Agriculture Natural Resources Conservation Service
USGSSL	United States Geological Survey's Sediment Laboratory
USLE	Universal Soil Loss Equation
WRI & EC	Water Resources Information and Education Centre
XRF	X-ray fluorescence

ABSTRACT

Deposition of sediment is a natural phenomenon of any storage structure or reservoir by which the reservoir's storage capacity is lost year after year thus affecting the very economy of the community for whom the reservoir is intended to serve. It is required to take sufficient restoration measures to arrest the sedimentation, otherwise, the storage capacity of the reservoir will be reduced at a faster rate. This thesis provides the analysis of the field studies using the hydrographic surveys conducted on the Wyra, a medium irrigation reservoir built across Wyra, a tributary of river Krishna. Conducting of the survey during the period of good rains would give good results. The objectives of the study are to assess status of sedimentation, rate of annual sedimentation in the reservoir and to arrive at the trap efficiency (T_e) of the reservoir. 'T_e' is very useful for estimating the remaining useful life span of the reservoir, the deposition of the sediment pattern in the reservoir. The rate of sedimentation was about 6.86 ha.m/100km^2/year, which is greater than that considered at the time of construction of the project.

The thesis also presents the analysis of the results obtained by the SWAT model programming, for estimating the runoff and the sediment yield by using the data collected at the Konijerla hydrometric station of Wyra reservoir for the period of 1991 to 2019. To calibrate, the data from 2011 to 2016 is used and to validate, the data from 2017 to 2019 is used by the SWAT model. The watershed of Wyra basin consists of 26 sub-basins. and47 HRUs. From the study, it can be noted that the sub-basin 5 is yielding about 18.8% of the sedimentation. Two other sub-basins, though less in area, were generating more sediments. It is further noticed that through the seasonal sediment analysis, the sedimentation was increased by 12% in the month of August for wet years. On the whole, the sedimentation had increased by 10.60% in the wet years and it was decreased by 18.78%, in the dry years. The calibration and the validation of the SWAT model for the periods for the various parameters used had shown satisfactory results. It can be concluded that the SWAT model can be very useful for the analysis of both the runoff and the sedimentation including the management of reservoir capacity.

CHAPTER 1

INTRODUCTION

1.1 General

Water is the most valuable resource and soil is the foundation of survival for all living beings. The sedimentation of reservoir takes place when top soils as well as disintegrated or weathered rock formations in the watershed or catchment begin to erode by the force of flood water duly transporting sediment from the upper basins to the streams then entering the storage reservoir due to gravity, eventually becomes stable as over-bank deposits, delta deposits, and bottom set beds.

At the reservoir mouth, where the river first enters the reservoir area, the moving suspended silt is deposited. This deposition may spread across the reservoir's mouth and bed. "Backwater deposit" refers to silt deposition that happens at a reservoir's mouth. Then, the formations of deposition are named according to the position, shape, or size of the sediment particles. "Over bank deposits" are sediments with medium grained composition, "bottom set beds" are sediments with fine grained composition, and "delta deposits" are sediment deposits made up of coarse-grained sediments that settle down within the reservoir zone.

Economic and agricultural losses are the most common types of on-site consequences and reduction in the capacity due to silt accumulation is the most major off-site effect of soil erosion. According to Dosskey et al. (2005) and Krishna Rao et al., (2015), the primary non-point source of pollution in rivers and reservoirs is the sediment-laden floodwater that rushes with greater momentum. Agricultural lands that receive a lot of rainfall are also susceptible to severe erosion.

Forest fires, deforestation, improper digging methods, overgrazing, rash land-use land changes and agricultural practices contribute to the transportation of sediment inflow into the streams. The features that affect the sedimentation in the upstream of reservoir are the shape, size and length of watershed, geological formation, land use pattern, mining activities, rainfall intensity, climatic factors and peak discharge. Assessing and managing the amount and quality of water resources both spatially and temporally is necessary for their proper use (Garg and Jothiprakash 2008 a; Jain and Kothyari 2000).

A stream's natural propensity is to deposit the majority of its silt in the reservoir beds, which typically obstructs the flow due to which potential energy is developed reducing the consumption of energy of the flow. When flow velocity decreases, sediment momentum within the reservoir zone also decreases, resulting in a significant reduction in the loss of head owing to the friction.

1.2 The Problem Statement

The goal of this research is to further improvise the comprehension of the relationships between potential controlling factors and the sediment output to reservoirs. A clear and better understanding of the variables that affect sediment yield to reservoirs can be explored to calculate the likelihood of lifespan of a reservoir and the most effective conservation of soil and water mitigation strategies to reduce reservoir sedimentation to a considerable extent possible. The size, shape and length of scattered watersheds with their climatic - geological formations including land use - land cover can be examined using physically based modelling techniques which include both current and potential sources of sediment. Of the software models developed recently by the United States Department of Agriculture (USDA), the Soil and Water Assessment Tool (SWAT) model is one of the best.

1.2.1 Adverse effects of sedimentation

The downstream water environment, the ecological environment of the region, and the water security are all affected very badly by the sedimentation. When the sedimentation discharge and river runoff are compared, the former may be considered a crucial analysis in surface river processes to measure the loss of soil resources and degradation of land along the river system (Siyam et al., 2005; Tan et al., 2019; Erskine et al., 2002). Scientific management of water and soil resources, as well as the ecological environment of rivers, can be based on an evaluation of the changes and effects of sediment loads in rivers during the past few decades.

1.2.2 The backwater and sediment carrying capacity

The backwater of the reservoir increases the cross-section of the river when the flow of water is entering into the reservoir area. As a result, the velocity of the flow of water declines, and the sediment-carrying capacity of the water downstream decreases. The apparatus and ancillary structures are being subjected to abrasion by the sediment, which is partially moving downstream through the outlet structures.

1.2.3 Sedimentation and the degeneration of stream bed

The environmental ecosystem is out of balance due to the deposition of the sediment upstream of the reservoir water-spread area, while the downstream areas are being inundated by the fine sediments, which causes the stream bed to deteriorate with silt, frictional flow, and loss of various nutrients, ultimately resulting in a shortage of food for the stream habitat.

1.2.4 Seasonal sedimentation analysis

The study analyses the sedimentation by season, which offers important insights into the spatial and temporal patterns of sedimentation over the seasons of the year. This knowledge is essential for creating reservoir management strategies that would reduce the environmental harm due to sedimentation. Understanding how much sediment gets accumulated in a reservoir is essential for ascertaining its effects both on the reservoir and the environment. The study highlights the significance of considering reservoir seepage and evaporation losses when assessing the sediment load.

The use of the SWAT model in the study provides a systematic and comprehensive approach to estimating sediment analysis. It enables the integration of various physical processes and environmental variables, such as precipitation, temperature, land use, and soil characteristics, to simulate the impact of sedimentation on the environment and water resources. Understanding the dynamics of sedimentation and the factors that affect its occurrence requires a seasonal analysis of sedimentation.

The seasonal sediment analysis provides valuable information on the spatial and temporal variation of sedimentation, which would assist in formulating effective management strategies to mitigate the impact of sedimentation on the reservoir and the environment. The findings of the study would further improve our knowledge of processes of the sedimentation, sediment transport, and deposition of sediment patterns, which has significant implications for the management of medium irrigation reservoirs.

1.3 Significance of the Problem

Verstraeten & Poesen (2000) conducted studies on a number of the world's major rivers. They examined the trend of sediment discharge of 145 major rivers and discovered that nearly half of them had significantly decreased (by 47%), primarily as a result of a loss in reservoir storage capacity. Additionally, only 5% of the rivers in their analysis had an increasing tendency in the discharge of silt.

As per the Central Water Commission (CWC, 2015) study report, India experiences around 9900 M tonnes of soil erosion per year as a result of "sheet erosion." The investigation also revealed that by the year 1992, Nizam Sagar Reservoir in the current Telangana state, which was constructed in 1930 and had an initial capacity of 841.18 Mm3, had lost up to 60.74% of its storage capacity. Moreover, owing to the sedimentation, on an average, 239 reservoirs in India would lose, about 0.44% of their gross storage capacity annually. This is undoubtedly an alarming and worrying situation that requires a thorough investigation as well as prompt implementation of the necessary preventive measures.

Sediment growth in reservoirs causes a number of issues, including increased flood risks, storage capacity depletion and downstream river bed degradation; other issues, such as decrease in water quality, and increased difficulty in operation and maintenance of reservoir resulting in escalation of maintenance cost (Le Roux, 2018; Gyamfi et al., 2016; Kothyari et al., 1994; Kothyari et al., 1996; Kothyari et al., 2002;

Siyam, et al., 2005). Irrespective of the size and function of the ponds or reservoirs, the runoff from the rivers with different formations, carrying suspended sediment flows into the water bodies which reduces the velocity of the flow and settles on the bed of the river (Verstraeten & Poesen, 2000). Understanding the pattern and underlying causes of soil and water loss due to variations in river sediment loads is crucial for the sustainable development of any area. (Yang and colleagues, 2008; Van et al., 2005).

Observed data on river sediment concentration are generally not available or inadequate, especially in less developed countries (Mulu & Dwarakish, 2015). While the sediment is suspended in the water, gravity causes it to continuously settle down; nevertheless, a portion of the material is continuously lifted upward and maintained in suspension by the turbulence of the water flow. To keep the sediment suspended, the two need to be in balance (Issa et al., 2015; Chitata et al., 2014; Krishna Rao et al., 2015). However, human activity has disrupted these two variables. When building and maintaining water conservation projects, river sediment is a crucial indicator that needs to be taken into account. It has to do with matters like river-bed erosion and sedimentation, reservoir storage capacity, flood management, and aquatic ecology (Kothyari et al., 2002; Lewis et al., 2013; Miao et al., 2011: Shrivastava et al., 2004).

Studies on the sedimentation of 43 reservoirs of major, medium and minor scale have revealed that the rate of siltation varies between 0.34 to 27.85 ha-m/100km2/year, 0.15 to 10.65 ha-m/100km2/year and 1.00 to 2.30 ha-m/100km2/year for major, medium and minor reservoirs respectively (Shangle 1991). In semi-arid areas where reservoirs were primarily developed for irrigation and water supply as well as electricity generation or flood control, silt building in reservoirs will have negative environmental and economic effects if proper soil and water conservation measures are not taken. The reservoir capacity loss in arid areas can range from 6000 to 8000 m^3/km^2 per year.

An intriguing and important part of managing and controlling river silt is comprehending its features of spatial (geographical) and temporal dispersion. Sediment movement and deposition is a complicated phenomenon that can be affected by multiple hydraulic and hydrological factors. The dominant factors that influence the sedimentation process are sediment properties, the quality of water entering into the reservoir, the characteristics and mode of operation of the reservoir.

Because of the frequent, high-intensity rains, which promote erosion because the soils are bare and exposed at the beginning of the season, large amounts of sediment can be produced and transported in semi-arid locations. Continuous soil erosion has caused the cultivated layer to become shallower, leading to decrease in the fertility of the soil. The cultivated lands in many areas of the region have been washed away or submerged to varying degrees (Issa et al., 2015; Chitata et al., 2014).

The primary data issue facing research on changes in river sediment load is this. For river sediment, the majority of the time, just the concentration of suspended particles was observed; the transported sediment load was not measured. (Mishra, 2007; Arekhi et al., 2012; Markose & Jayappa, 2016; Jiang et al., 2015; Van Liew et al., 2005; Samantaray et al., 2022; Himanshu et al., 2019; Singh et al., 2019).

It was recommended to use both theoretical and empirical methods to determine the T_e for tiny ponds in order to estimate high sediment yield. While Brown's technique overestimated the T_e of Gobindsagar Reservoir (Bhakra Reservoir) on Satluj River in Bilaspur district of Himachal Pradesh, in the Himalayan area of India, modified Brune's equations through regression analysis produced better T_e values (Garg & Jothiprakash, 2008a, b). Tan et al. (2019) found that the estimated values of T_e for large reservoirs in the upper Yangtze River were comparable to the measured T_e. These findings were derived from the analysis of four distinct empirical models that included the capacity to inflow ratio (C/I) and capacity to watershed ratio (C/W).

SWAT, introduced by Arnold et al. (1993), serves as a valuable tool for assessing the potential impacts of various management practices on water quality, sediment yield, and pollution loading in watersheds. This model operates on a continuous time scale, utilizing daily time steps, and takes a semi-distributed approach to simulate hydrological and water quality processes within a watershed. It plays a crucial role in formulating effective planning strategies, particularly in the context of integrated basin models (de Vente et al., 2013).

SWAT is an eco-hydrological model extensively employed to simulate the effects of diverse land use management strategies. It possesses the capability to assess the impacts of climate change on both water quality and quantity within agricultural catchments (Neitsch et al., 2011). Researchers worldwide have extensively utilised the Soil and Water Assessment Tool (SWAT) for estimating sediment yield on a daily and monthly basis (Briak et al., 2016).

1.4 Motivation of the Work and Research Gap

Not many studies have been carried out and reported on the problem of sedimentation in medium irrigation reservoirs. This prompted the taking up of the current study. Having sedimentation information is essential for effectively obtaining the capacity-outflow (C/O) ratio, rather than the capacity-inflow (C/I) ratio. For realistic results, it is necessary to consider the reservoir's evaporation and land use changes while also planning the treatment of watershed areas. Through the literature review, the research gap identified was that of estimating the trap efficiency (T_e) duly considering all the losses of capacity which could otherwise greatly impact the estimation of sediment load.

1.4.1 Sedimentation in medium irrigation reservoirs

Operation of the dams significantly alters the flow regime characteristics and sedimentation when compared to an unregulated time period. Sedimentation reduces the capacity of the reservoir over time which in turn decreases the useful life of the reservoir. Research on sedimentation is necessary to forecast future losses in storage capacity, remaining useful life, and the effects of sediment on reservoirs, rivers, and the environment. The majority of earlier studies focused on the major irrigation reservoirs and the large dams but the small and the medium irrigation reservoirs were not given adequate importance in sedimentation studies, which created a knowledge gap about sedimentation in these small and medium irrigation reservoirs. This study aims to fill such gaps by concentrating on a medium irrigation reservoir in the Krishna River basin.

The research gap was determined from the literature review to be the estimation of T_e using the relationship between T_e and C/O ratio rather than C/I ratio. In order to estimate the sediment load accurately, it is also vital to be aware of the evaporation and seepage losses in the reservoir. If these factors are not taken into consideration, the computation will differ noticeably.

In order to precisely interpret the parameters in small lakes and reservoirs, further study is required on the prediction of T_e for small reservoirs with varying geometric and hydraulic properties. Additionally, an inventory of data bank must be prepared.

The study on the seasonal analysis of the sedimentation gives the details on the special and temporal pattern of the sedimentation throughout all the seasons of the year and over the entire watershed area of the basin. This information is essential for the efficient management of reservoirs because it enables the identification of times when sedimentation is more obvious and the corresponding adjustment of management strategies. The seasonal sedimentation analysis provides in-depth information about the seasonal variance of sedimentation including the topographical features of the entire watershed area of the basin., which is crucial for creating successful management strategies for reservoirs and their operation. In order to obtain a thorough understanding of sedimentation in the medium irrigation reservoir, the study used the SWAT model to estimate sediment load by carrying out a seasonal sediment analysis.

SWAT simulates runoff and sedimentation by considering how land use changes affect water, sediment, and nutrient yields in the watersheds. In order to forecast the effects of land use changes and management practices on water quality and quantity, the model considers various processes, including rainfall, infiltration, runoff, erosion, and sediment transport. The results of the study would make it possible to create management plans that would effectively reduce the effects of sedimentation on the reservoir, river and ecosystem.

1.4 Scope and Objectives of the Study

This thesis aims to determine the impact of runoff and sediment yield on the Wyra River and develop a sediment management strategy for the region. The study focuses on understanding the variation in sediment yield from different sub-basins of the Wyra watershed which would enable management strategies for effective control of sedimentation in the river. To achieve this objective, the following specific objectives have been identified:

(i) To assess the sedimentation status from the outlet of the Wyra Reservoir using satellite data, the location of which is shown in Fig. 1.1,

(ii) To assess the variability of sediment yield among the sub-basins in the watershed and identify areas with high erosion rates that require site-specific management interventions. This objective will help to identify the sub-basins that contribute the most sediment to the river network and, hence, to the reservoir. By identifying these sub-basins, the study can inform targeted management interventions to reduce erosion rates and minimize sediment yield.

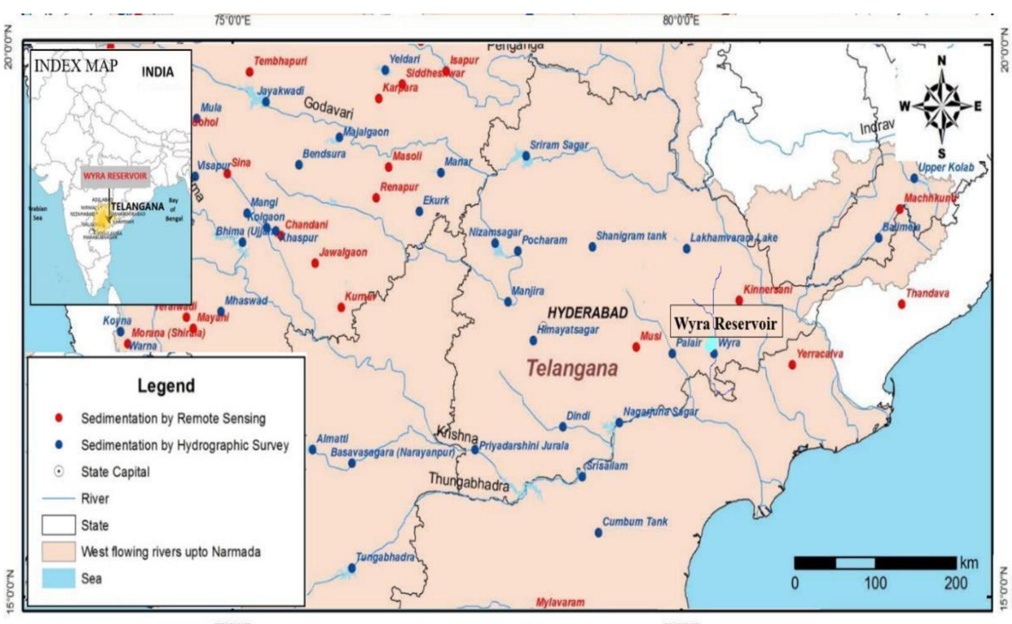


Fig. 1.1 Location Map of Wyra Reservoir

(iii) To determine the sediment yield from the outlet of the Wyra watershed is another objective of this study. The sediment yield is the amount of sediment that is transported by the river network and ultimately deposited in the reservoir. By accurately determining the sediment yield, the study can provide insights into the sedimentation processes in the reservoir and how they are influenced by watershed characteristics.

(iv) Estimating soil erosion rates using an identified model, for predicting erosion rates and how they vary across different sub-basins Soil erosion is a critical process that contributes to sediment yield in the watershed.

(v) Analysing seasonal sediment erosion by removing the climate change impacts is another important objective of the study. Seasonal variation in sediment yield is a critical factor that influences sedimentation processes in the reservoir. By removing the impacts of climate change, the study can provide insights into the natural seasonal variation in sediment yield and how it varies across different sub-basins. This information can inform management strategies that target specific seasons to mitigate sedimentation impacts.

To summarize, the study aims to provide a comprehensive understanding of sedimentation processes in the Wyra watershed by determining sediment yield, assessing variability among sub-basins, estimating soil erosion using different models, and analysing seasonal sediment erosion by removing climate change impacts. By achieving these objectives, the study can inform management strategies to mitigate the impact of sedimentation on the environment and water resources in the region.

1.5 Organisation of the Thesis

After introducing the problem taken up for the study and discussing about the significance of the problem, the objectives of the study are introduced in this Chapter. A detailed review of the literature related to various methods of sedimentation, and the models used to identify the model to be used in the study are presented in the Chapter 2. Chapter 3 presents the methodology related to the sedimentation, the model selected and seasonal analysis. Further, the description of the study area, data needed and available for the study area are also presented in this chapter. The results, discussions and calculation of sedimentation through empirical formula are presented in Chapter 4. Chapter 5 contains the summary of the study, the conclusions arrived, recommendation from the study and suggestions for further research activities. This Chapter also reports the contribution from this study.

CHAPTER 2

LITRATURE REVIEW

2.1 Overview

In this chapter, the current state of the research about sediment transport models is presented and it consists of a description of the features of the most used model concepts. The chapter reviews the research carried out around the world about the model concepts developed. An historical and also chronological description of the modelling of non-uniform sediment transport is part of the first section, in which the most used models are cited. Afterwards, the most relevant ones for the present research are more deeply described, including their mathematical formulations.

Reservoir sedimentation is steady growth of received river sediment load. It is a universal and natural occurrence. Flowing water transports sediment from the upper basin to streams. Forest fires, deforestation, improper digging methods, overgrazing, and rash land-use land changes and agricultural practices all contribute to transport sediment into streams, finally into the artificial reservoirs (Ouyang et al., 2010).

Verstraeten and Poesen (2000) found that it would be extremely difficult to compute T_e for small reservoirs with changing hydraulic and geometric parameters because the requisite runoff data were not available during the survey periods and that additional research on the prediction of T_e was therefore required. By assessing the sediment load, one can calculate T_e, which is defined as percentage of the sediment yield of the watershed trapped in the reservoir. It can also help to determine the quality of the sedimentation of reservoir.

The silting rate of a reservoir will be lower if the T_e is high. The features that affect the T_e of reservoir in the upstream are the shape, size, length, watershed characteristics, geological formation, land use pattern, mining activities, rainfall intensity, climatic factors and peak discharge (Ella, 2005). Based on the data from the Revised Universal Soil Loss Equation (RUSLE), the sediment T_e computed for a reservoir on the Wisloka river at Krempna, Poland, was on average 30% greater than the value determined by bathometric measurements (Michalec & Tarnawski, 2007). Major rivers like the Yangtze, Yellow River, Indus, Brahmaputra, Krishna, Ganga, and Mekong have had steady attention in recent years due to their sediment issues.

For lakes and ponds, the empirical and theoretical approaches and their use to determine the T_e were recommended by Garg and Jothiprakash (2008a) for calculating high sediment output. For the Gobindsagar Reservoir (Bhakra Reservoir) on the Satluj River in the Bilaspur district of Himachal Pradesh, in the Himalayan region of India, the Brown's technique overestimated the T_e whereas the regression analysis by the modified Brune's equations produced improved T_e estimates. The T_e for the Pong Reservoir on the Beas River in the district of Kangra, Himachal Pradesh, India, was determined by appropriately modifying the accepted empirical methods; the computed T_e values were closer to Brune's median curve (Garg & Jothiprakash, V. 2008b).

By adapting the original methods proposed by Churchill (1948) and Brune (1953) for a 5-year study period for the Burdekin Falls Reservoir in Australia, T_e was estimated based on daily flow volumes with reasonably good results that took into account shorter residence times and higher intra-annual flow variability (Lewis, et al., 2013). T_e estimate becomes challenging if the reservoirs are without upstream flow measurement facilities. The estimation of T_e by modifying the various methods would be more convenient when the downstream outflow data is used (Mulu & Dwarakish 2015).

The backwater of the reservoir increases the cross-section of the river when the water is flowing into the reservoir. As a result, the water flow velocity declines, and the sediment carrying capacity of the water to the downstream decreases. Sediment growth in reservoirs causes a number of issues, including increased flood risks, storage capacity depletion, and downstream river bed degradation including adverse effects on aquatic ecosystems; other issues, such as decrease in water quality, increased difficulty in operation leading to increased expenses of reservoir maintenance.

The following definitions are available in the literature (Graf, W. H. 2011; Garde & Rangaraju, 2000):

Suspended load can be used for either (i) the material moving in suspension in a fluid, being kept up by the upward components of the turbulent currents or by colloidal suspension, or (ii) the material collected in or computed from samples collected with a sampler. (a sampler is a sampler which attempts to secure a sample of the water without separating the sediment from the water). Where it is necessary to distinguish between the two meanings above, the first may be called the true suspended load.

Bed load may be used to designate either coarse material moving on or near the bed, or material collected in or computed from samples collected in a bed load sampler or trap. Bed material load is part of the sediment load of a stream which is composed of particle sizes found in appreciable quantities in the shifting portions of the streambed. Wash load is that part of the sediment load of a stream \which is composed of particle sizes smaller than those found in appreciable quantities in the shifting portions of the streambed.

Additional references to studies from India and other tropical countries are provided in the Table 2.1 given below showing the authors, the models used along with the location of study area:

Table 2.1 Literature Review (Authors, Model Used, and Study Area)

Sl. No.	Authors	Literature Review	Model Used	Study Area
1	Daramola et al., (2019)	Study used SWAT in GIS to predict sediment yield in North Central Nigeria. Model predicted annual sediment yield as 255.8 tons/ha/yr and 8.31x10^9 tons between 1985-2010. Highest sediment concentration was in sub-basins 29, 20, and 19. Properly calibrated SWAT in GIS is suitable for modeling hydrology and predicting sediment yield.	SWAT	North Central Nigeria.

2	Acharyya et al., (2022)	Monsoon variability impact on hydrology in Subarnarekha River basin. SWAT model simulates discharge rate and estimates erosion effectively. SWAT is model useful for water management in areas with limited data.	SWAT	Subarna-rekha India
3	Kositsa-kulchai et al., (2012)	Calibration and validation of model parameters using time series data Predicted and observed sediment yields showed good agreement R2 and ENS statistical measures used to evaluate model performance	SWAT	Fincha Watershed
4	Bartley et al., (2012)	This paper presented 750 entries of water quality data from 514 different geographical sites around Australia covering 13 different land uses. This paper tests many of the assumptions regarding use of water quality data in previous modelling applications. The paper will form the most comprehensive analysis of water quality data from Australia for use in water quality models.	Water Quality	Australia
5	Himanshu et al., (2019)	Assessment of sediment yield The study emphasizes the importance of sustainable river management practices to ensure the long-term health of river ecosystems	SWAT	Tungabha - dra River Basin India
6	Mishra A. et al., (2007)	Assessment of sediment transport SWAT can be a useful tool for studying how check dams can be used to manage and control sediment loss from small watersheds located in sub-humid climate conditions.	SWAT	Banha Watershed Northeast India

7	Sanjay et al., (2010)	The study area was an intermediate watershed of Satluj river in Western Himalayan region. The model performance was evaluated with statistical and graphical methods and showed moderate accuracy in runoff and sediment yield simulation.	SWAT	Satluj India
8	Setegn et al., 2010	SWAT model tested for sediment yield prediction in Ethiopian watershed. Good agreement found between observed and simulated sediment yield. Data from ten years of meteorological, flow, and sediment used for calibration and validation.	SWAT	Ethiopian Watershed
9	Shrivasta-va et al., (2004)	Assessment of runoff and sediment yield by SWAT model could be used for developing a multiple year management plan for the critical erosion prone areas of a small watershed.	SWAT	Eastern India
10	Xu et al., (2009)	SWAT was used to simulate runoff and sediment transport into Miyun Reservoir, Beijing. The model was validated for feasibility of simulating catchment-scale processes in arid and semi-arid North China. SWAT accurately simulated daily and monthly runoff, with a Nash-Sutcliffe coefficient greater than 0.6 and 0.9.	SWAT	Miyun Reservoir Beiging, China
11	Yao et al., (2023)	High Resolution Sentinel-2 satellite imagery is used to estimate reservoir sedimentation rates and storage capacity losses. The same have been validated on eight reservoirs located in the central and western regions of the United States.	High-Resolution Seninel-2 Satellite and Water Level Data	United States

2.2 Erosion Process

Erosion is the process of the detachment and transportation of soil, rock, and other materials from one location to another by the forces of water, wind, and gravity. Erosion is a natural process that is influenced by various factors, including the type of soil or rock, vegetation cover, land use, and climatic conditions. The erosion process can be divided into several stages: detachment, transportation, and deposition.

The erosion process can have significant impacts on the environment and human activities. Excessive erosion can lead to soil degradation, loss of vegetation, decreased agricultural productivity, and increased sedimentation in rivers and lakes. Effective erosion management requires an understanding of the erosion process and the implementation of appropriate management strategies. Some of the strategies that can be used to manage erosion include implementing conservation tillage practices, planting vegetation, constructing sediment basins and stabilizing stream banks. By understanding and managing the erosion process, we can help to protect the environment and ensure the sustainability of human activities (Morris & Fan, 2009).

(a) **Detachment**: The first stage of the erosion process is the detachment of particles from the soil or rock surface which is caused by the forces of raindrops, wind, or flowing water.

(b) **Transportation**: The second stage of the erosion process is the transportation of the detached particles by the forces of water, wind, or gravity, which is divided into three types: sheet, rill, and gully erosion.

(c) **Deposition**: The final stage of the erosion process is the deposition of the transported particles which occurs when the forces of transport are insufficient to keep the particles in motion.

2.3 Factors Affecting Soil Erosion

Several factors influence soil erosion, which include climate, soil, topography, vegetation, management practices. The basic energy input required to drive erosion processes is provided by rainfall and runoff. Soil erosion by water is affected by the steepness (gradient), slope length, and shape, which modify the energy of the hydrologic inputs. Soil erosion is a natural process, but it can be accelerated by human activities. The following are some of the factors that contribute to soil erosion:

i. Water
ii. Wind
iii. Soil Characteristics
iv. Vegetation Cover
v. Land Use Practices
vi. Slope Steepness and Length
vii. Human Management Practices
viii. Climate
ix. Soil Moisture
x. Soil Organic Matter Content

2.4 Erosion and Sediment Transport Models

Erosion and sediment transport models are mathematical tools used to simulate and predict the movement of soil and sediment in rivers, lakes, and other water bodies. These models are based on physical principles and data on the hydrological, geomorphological, and sediment characteristics of the study areas The models can be used to assess the impacts of erosion and sedimentation on aquatic ecosystems, infrastructure, and water quality, as well as to design effective erosion control and sediment management strategies (Bogen & Bonsnes, 2003).

2.5 Principles of Sediment Transport

Sediment transport is the process of moving solid particles, such as sand, gravel, and silt, from one location to another by the forces of water, wind, and gravity. Sediment transport is a complex process influenced by various factors, including particle size, flow velocity, water depth, and channel geometry. Understanding these principles is essential for managing rivers, coastlines, and other water bodies.

The principles can be divided into three main categories: initiation, transport and deposition.

(a) **Initiation**: The initiation of sediment transport is the point at which particles begin to move due to the forces of water, wind, or gravity. The forces required to initiate sediment transport depend on the particle size, shape, and density, as well as the characteristics of the fluid that is carrying the sediment. The threshold velocity, or critical shear stress, is the minimum velocity required to initiate sediment transport. The threshold velocity varies with particle size and shape, as well as the density and viscosity of the fluid.

(b) **Transport**: Once sediment is initiated, it can be transported by various mechanisms, including bedload, suspended load, and dissolved load. Bedload is sediment that moves along the bed of a river or stream, in contact with the bottom, by rolling, sliding, or bouncing. Suspended load is sediment that is carried by the fluid, but not in contact with the bottom. Dissolved load is sediment that is carried in solution. The type and amount of sediment transport depend on the flow velocity, water depth, and particle size distribution.

(c) **Deposition**: The deposition of sediment occurs when the forces of transport are insufficient to keep the sediment particles in motion, and they settle out of the water column. The amount and location of deposition depend on the flow velocity, sediment size, and channel geometry. Deposition can occur in the channel or on the floodplain, and the deposited sediment can form bars, islands, and deltas.

These principles are important for managing rivers, lakes, and coastal areas. Effective sediment management requires an understanding of the principles and the use of appropriate management strategies to control sediment transport and deposition.

2.6 Methods for Sediment Analysis

Various methods of sediment analysis are briefly given below:

(a) **Sediment Yield Monitoring:** This involves measuring the amount of sediment that is being transported in a river or stream over a period of time by using sediment samplers placed in the watercourse and then analyzed.

(b) **Sediment Budget Analysis**: This involves assessing the sources and sinks of sediment in a river or stream system by measuring the amount of sediment that enters the system that is transported downstream, and the amount that is deposited along the way.

(c) **Sediment Transport Modelling**: This involves using computer models to simulate the movement of sediment in a river or stream system by predicting where the sediment will be deposited and where erosion is likely to occur.

(d) **Particle Size Analysis**: This involves measuring the size and distribution of sediment particles in a sample by the methods of sieving, laser diffraction, and sedimentation analysis.

(e) **Sedimentation Rate Analysis**: This involves measuring the rate at which sediment is deposited in a particular area using sediment traps or by analysing sediment cores from the area of interest.

(f) **Sediment Source Identification**: This involves identifying the sources of sediment in a river or stream system by geochemical analysis and sediment fingerprinting.

(g) **Sediment Concentration Monitoring**: This involves measuring the amount of sediment that is suspended in a river or stream by using turbidity meters or other instruments that measure the optical properties of the water.

(h) **Sedimentation Depth Analysis**: This involves measuring the depth of sediment that has accumulated in a particular area by using sediment cores or by analysing the sediment profile in the area of interest.

(i) **Sediment Flux Analysis**: This involves measuring the amount of sediment that is being transported in a river or stream over a set amount of time using sediment samplers.

(j) **Sedimentation Rate Monitoring**: This involves measuring the rate at which sediment is accumulating in a particular area using sediment traps or by analysing sediment cores from the area of interest.

(k) **Sediment Trap Efficiency:** The sediment which is transported through the channels, finally settles down by gravity at the mouth, in the bottom set beds and overbanks of the reservoir followed by the estimation the trap efficiency (T_e) of the reservoir.

(l) **Trap Efficiency Advantages:** T_e is basically useful in arriving at the balance useful life span of the reservoir and the pattern of sediment deposition in the reservoir.

2.7 Recent Developments in Sediment Analysis

The recent developments in sediment analysis have focused on the development of new analytical techniques, the integration of different analytical methods, and the use of sediment analysis in environmental management.

a) **Development of new analytical techniques:** The development of new analytical techniques involves the use of advanced instrumentation and technology to improve the accuracy and precision of sediment analysis. One example is the use of laser diffraction to measure particle size distribution, which is faster and more accurate than traditional sediment sieving methods.
Another example is the use of X-ray fluorescence (XRF) spectroscopy to measure metal concentrations in sediment, which is non-destructive and allows for the simultaneous analysis of multiple metals (Timothy et al., 2021).

b) **Integration of different analytical methods:** The integration of different analytical methods involves the combination of different analytical techniques to provide a XRF more comprehensive analysis of sediment. For example, the combination of spectroscopy with other techniques, such as Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), can provide a more accurate measurement of metal concentrations in sediment. The integration of different analytical methods also allows for the assessment of multiple parameters in sediment, such as particle size, organic matter content, and metal concentrations, in a single analysis.

c) **Use of sediment analysis in environmental management:** The use of sediment analysis in environmental management involves the assessment of sediment quality to inform management decisions. Sediment analysis can be used to identify potential contaminants in sediment, such as metals and organic pollutants, and evaluate the ecological health of aquatic systems. Sediment analysis can also be used to assess the effectiveness of management strategies, such as dredging and sediment capping, in reducing contaminant concentrations in sediment (Elirehema, 2001).

2.8 Estimation of Reservoir Sedimentation

Reservoir sedimentation refers to the accumulation of sediment in a reservoir, which can reduce the storage capacity of the reservoir and affect its function. The estimation of reservoir sedimentation is an important task for reservoir management and planning, as it can help to assess the future storage capacity and lifespan of the reservoir, and to plan for sediment management strategies.

The estimation of reservoir sedimentation can be done using direct measurement, indirect measurement, and modelling.

a) **Direct measurement**: Direct measurement involves physically measuring the depth and volume of sediment in the reservoir using bathymetric surveys. This method provides accurate and reliable data on the sediment accumulation in the reservoir, but it can be time-consuming and expensive.

b) **Indirect measurement**: Indirect measurement involves estimating the sediment accumulation in the reservoir based on sediment yields from upstream sources, sediment trap data, and sediment concentration data. This method can provide a rough estimate of sediment accumulation in the reservoir, but it may not accurately reflect the sediment transport processes in the reservoir.

c) **Modelling**: Modelling involves using mathematical models to simulate the sediment transport processes in the reservoir and to estimate sediment accumulation over time. There are various types of sediment transport models, namely empirical, conceptual, and physically-based models. These models use data on the hydrological, geomorphological, and sedimentological characteristics of the reservoir and the upstream watershed to simulate sediment transport processes and estimate sediment accumulation. Modelling is a cost-effective and efficient method for estimating sedimentation, but it requires detailed data and expertise in modelling.

Regardless of the methods used, the estimation of reservoir sedimentation requires data on the sediment sources, transport processes, and accumulation rates. This data can be obtained through field surveys, monitoring programs, and modelling. The data can then be used to estimate the sediment accumulation over time and to develop sediment management strategies.

2.9 Soil Erosion Models

Soil erosion models are mathematical tools that simulate the soil erosion process, and they are used to evaluate the impact of different factors on soil erosion. There are several types of soil erosion models, including empirical, conceptual, and process-based models. Empirical models are based on statistical relationships between soil loss and the different factors that affect it. These models are simple and easy to use, but they may not be accurate if the data used to develop them are not representative of the conditions under study.

Conceptual models are based on a conceptual representation of the soil erosion process. They are more complex than empirical models and can consider the spatial and temporal variability of the soil erosion process. However, they may not accurately represent all the processes involved in soil erosion.

Process-based models are based on the physical processes that control soil erosion. These models simulate the interaction between soil, water, and vegetation to predict soil erosion. They are the most accurate type of soil erosion models, but they are also the most complex and require detailed input data.

2.10 The Universal Soil Loss Equation (USLE) Model

USLE is a commonly used model for predicting soil loss due to erosion. It was developed in the 1960s by the US Department of Agriculture's Soil Conservation Service, and has since been widely used to estimate soil erosion in agricultural fields, forests, and other land use systems. The USLE model considers several factors that contribute to soil erosion, including rainfall erosivity, soil erodibility, slope length and steepness, vegetative cover, and erosion control practices. The Eqn. (2.1) is expressed as:

$$A = R * K * LS * C * P \tag{2.1}$$

where: A = average annual soil loss in tonnes per hectare per year; R = Rainfall erosivity factor; K = Soil erodibility factor; LS = Slope length and steepness factor; C = Cover and management factor; and P = Erosion control practice factor

Each of these factors is assigned a numerical value based on specific characteristics of the land use system being modelled. The equation is typically used to estimate soil loss for a specific land area over a one-year period. The USLE model has been widely used to guide soil conservation efforts and to assess the effectiveness of various erosion control practices. However, like all models, the accuracy of the USLE model depends on the quality of the data used to estimate the various factors in the equation (Rubianca et al., 2018).

The USLE model has been widely used for many years and has been proven to be a useful tool for land management and conservation planning. However, it has some limitations. For example, it assumes that erosion occurs uniformly across a plot of land, which may not always be the case. Additionally, it does not account for factors like wind erosion or channel erosion, which can be significant in some environment conditions. Despite these limitations, the USLE model remains a valuable tool for predicting and managing soil erosion.

2.11 Modified Universal Soil Loss Equation (MUSLE) Model

MUSLE is an improved version of the USLE developed by the US Department of Agriculture. The MUSLE model considers the effects of both sheet and rill erosion, and also considers the effects of conservation practices such as contouring and terracing. The MUSLE model is widely used for predicting soil loss from agricultural lands. The MUSLE model considers several factors that influence soil erosion, including rainfall erosivity, soil erodibility, slope length and steepness, cover and management practices, and conservation practices. The Eqn. (2.2) for MUSLE is:

$$Q_{sed} = 11.8 \times (V\varphi \times Q_p \times A_{hru}^{0.56} \times K \times L \times S \times C \times P \times CFRG \qquad (2.2)$$

where Q_{sed} is the sediment yield on a given day (metric tons); Vφ is the volume of stream flow (m³); Q_p is the peak flow rate (m³/s) of the storm; A_{hru} is the area of the HRU; L and S are topographic factors that describe hill slope length and hill slope steepness (dimensionless); K is soil erodibility in (Mg ha h ha−1 MJ−1 mm−1); C and P are cover-management practices and support practices factors that describe land use, respectively; CRFG is the coarse fragment factor.

Gross erosion is roughly estimated by MUSLE for soil loss caused by sheet, rill, and rain splash, but erosion caused by landslides and gullies cannot be computed using these equations. The erodibility factor indices were obtained using the MUSLE in a Geographic Information System (GIS) framework.

Like USLE, MUSLE is an empirical model that estimates soil erosion based on several factors, including rainfall erosivity, soil erodibility, slope length and steepness, crop management, and conservation practices. However, MUSLE also incorporates factors such as channel erosion, which is important for estimating sediment yield and channel stability (Saleh et al., 2010).

The MUSLE model can be used, i) To predict soil loss from agricultural lands under various land use and management scenarios, ii) To identify areas that are prone to soil erosion, and iii) To develop effective conservation practices to reduce soil loss and maintain soil productivity.

The MUSLE model includes the following factors:

a) **Rainfall erosivity factor**: The erosive power of rainfall is a function of rainfall intensity, duration, and frequency. The model uses a rainfall erosivity factor (as per the Eqn. 2.2) to quantify the erosive power of rainfall.

b) **Soil erodibility factor**: The erodibility of soil is the susceptibility of soil to erosion. The model includes a soil erodibility factor (K) that accounts for soil texture, structure, and organic matter content.

c) **Slope length and steepness factor**: The length and steepness of a slope influence the amount of runoff and the velocity of water flow. The model includes a slope length and steepness factor (LS) to quantify the effect of slope on soil erosion.

d) **Cover and management factor**: Vegetation cover and land use management practices can affect soil erosion by reducing the impact of raindrops on soil, increasing infiltration, and reducing runoff. The model includes a cover and management factor (C) to quantify its effect on soil erosion.

e) **Support practice factor**: Support practices, such as terracing, contour plowing, and conservation tillage, can also reduce soil erosion by reducing slope length and increasing infiltration. The model includes a support practice factor (P) to quantify its effect on soil erosion (Wu et al., 2020).

2.12 Sediment Transport Equations

Sediment transport equations are mathematical models that estimate the movement of sediment in rivers, streams, and other water bodies. These equations are used to predict the rate and direction of sediment transport, as well as the amount of sediment that will be deposited or eroded in a given area over time (Joseph et al., 2022).

There are several types of equations, each with its own set of assumptions, limitations, and mathematical formulations. One of the most commonly used equations is the Einstein-Brown equation, which relates the sediment transport rate to the shear stress of the water and the size of the sediment particles. This equation assumes that sediment transport is dominated by bed load, where particles roll or bounce along the bottom of the stream.

Other equations used include the Ackers-White equation, the Meyer-Peter-Müller equation, the Wilcock-Crowe equation and the choice of equation depends on the specific characteristics of the stream or river (Chenguang et al., 2023).

2.13 Runoff Mechanism

During the runoff process, sediment particles are detached from the soil surface and transported along with the water, resulting in soil erosion (Liu et al., 2023). The detachment of soil particles can occur through various mechanisms. The first mechanism is raindrop impact, where raindrops strike the soil surface with enough energy to detach soil particles.

The detachment of soil particles by raindrop impact is largely determined by the erosivity of rainfall, which is the ability of rainfall to cause erosion. The second mechanism is surface flow, where water flows over the soil surface, carrying soil particles along with it. The surface flow erosion process is determined by the slope gradient and length of the slope, the texture and erodibility of the soil, and the hydraulic properties of the soil (Yin et al., 2022). Several factors can influence the transport capacity of water for sediment particles, including the water velocity, turbulence, and sediment concentration.

The Soil Conservation Service Curve Number (SCS-CN) method developed by the United States Department of Agriculture's Natural Resources Conservation Service (USDANRCS) (formerly known as the Soil Conservation Service) is used to predict runoff in a runoff model, such as SWAT. While it is theoretically consistent with both infiltration excess theory and saturation excess theory, it is most commonly used in a way that assumes infiltration excess as the primary runoff mechanism.

2.14 Selection of the Model

Measuring and sampling sediment transportation can be time-consuming and costly which necessitates for an alternative such as the use of hydrological model representing the drainage basin for the climatic and physical conditions. This model is designed to simulate rainfall-runoff relationships under different temporal and spatial dimensions, establishing relationships between various hydrological components (Cheng et al., 2018).

Physically based models predict the distribution, magnitude and behaviour of a process with limited observations in which the equations used can relate changes in water properties within a given reach to those across the surface (Tulus et al., 2018). Empirical models are a summary of field or experimental observations which are useful in predicting soil erosion, the effects of climate, soil properties, topography and crop management but they are specific to a particular site requiring long-term data.

Spatial variability is handled by dividing a drainage basin into smaller geographical units, such as sub-basins, land cover classes, elevation zones or a combination of them. The sub-basins are further divided into Hydrological Response Units (HRUs). Among the various project dependent selection criteria, the following three are being considered (Onishi, Y. 1994).

a) Whether the model can provide the necessary outputs that are required for the specific project.

b) Whether the model can adequately simulate the hydrological processes that are required to estimate the desired outputs.

c) Whether the necessary input data can be obtained within the time of the project and cost constraints.

The physically-based distributed model SWAT is a well-established model among the models mentioned above.

2.15 Reason for Selection of the SWAT Model

The following are few reasons to select the SWAT model

(i) The model provides satisfactory results when calibrated and simulated on the Indian river basins.

(ii) The model offers advantages which include modularity, computational efficiency, the ability to predict long-term impacts as a continuous model and the ability to use readily available global datasets.

(iii) The model simulates the hydrological processes in the watersheds.

(iv) The model has the capability to operate at the watershed scale level by combining multiple sub-basins.

(v) The model allowed for variations in topography, land use, and management practices within the watershed.

2.16 SWAT - the strengths and the weaknesses

Studies have identified that the main strengths and weaknesses of SWAT model (Liu & Jiang 2019; Kuti & Ewemoje 2021; Karakoyun et al., 2022; Setegn et al., 2010; Pandey et al., 2021; Rostamian et al., 2008; Roti et al., 2018; Chandra et al., 2016).

Despite its complexity, the SWAT model offers several benefits. It can support decision-making in land management by simulating the impacts of various practices on water quality and quantity, such as cropping patterns, fertilizer and pesticide applications and irrigation timing.

Some of the shortcomings of the model identified in the literature are: (a) The model requires extensive data inputs, which can be time-consuming and resource-intensive to collect and process; (b) Users may face challenges in selecting appropriate parameters for the model, as these can be difficult to determine and can significantly affect the accuracy of the calculations; (c) The process of selecting coefficients for the model can be subjective, as it may depend on the expertise and judgement of the user, which can introduce variability and uncertainty into the results; and (d) SWAT may have limitations in simulating short-term events, as the model is designed to operate on a longer time scale and may not accurately capture rapid changes in hydrological processes.

When predicting hydrology, sediment yield, and water quality, it is essential to consider uncertainties in the predictions. The main sources of uncertainties in these predictions include:

a) Simplifications in the **Conceptual model** are common and can arise due to several factors. In general, simplifications and assumptions can lead to uncertainties in the predictions.

b) **Hydrological models** can exclude certain processes occurring in a watershed, which can affect the predictions. Some examples of such processes include:

(i) **Wind erosion**: The model may not consider the effects of wind erosion on soil erosion and sediment transport. Wind erosion can lead to soil loss in some regions, particularly in arid and semi-arid environments.

(ii) **Landslides**: Landslides can result in soil erosion and sediment transport, but the model may not explicitly account for this process.

(iii) **Vegetation dynamics**: The model may not capture the complex interactions between vegetation and hydrological processes. For example, changes in vegetation cover and type can affect evapotranspiration rates, and soil moisture dynamics.

(iv) **Anthropogenic activities**: Human activities, such as urbanization, mining, and agriculture, can alter the hydrological processes in a watershed.

c) **Hydrological models** can include certain processes that are known to occur in a watershed. Some examples of such processes include:

(i) **Reservoirs**: The hydrological regime of a watershed can be altered by regulating flow and sediment transport.

(ii) **Water diversions:** This can reduce the flow of a river, affecting downstream hydrological processes.

(iii) **Irrigation:** This can impact soil moisture dynamics and groundwater recharge, which can in turn affect hydrological processes such as runoff and infiltration.

(iv) **Farm management affecting water quality**: This can impact water quality by affecting nutrient and sediment transport. Errors in the input variables such as rainfall and temperature

d) In general, the uncertainties associated with these processes can lead to inaccuracies in the predictions of hydrological models.

2.17 Limitation of SWAT in Terms of Sediment Analysis

One of the major limitations of SWAT in terms of sediment analysis is that it assumes uniformity in soil properties and topography across a given watershed. This assumption may not always be valid, particularly in areas with complex topography and variable soil properties. As a result, the model may not capture the spatial variability of sediment sources within a watershed.

Another limitation of SWAT is that it relies on empirical relationships to estimate sediment transport capacity, rather than physical processes modelling. For example, the model may not consider the effects of cover crops on soil erosion and sediment transport. (Khandelwal et al., 2019).

2.18 SWAT Model Development and an Interface with ArcGIS

The SWAT model operates on a daily time step, which allows for the simulation of long-term effects of land management practices and climate on water resources. The model is semi-distributed, which means that it divides the watershed into sub-watersheds which are further divided into HRU’s, which have a unique combination of soil, land use and slope and consider the interactions between them (Panagopoulos et al., 2017).

The major components of the SWAT model include hydrology, weather, erosion, plant growth, nutrients, pesticides, land management, and stream routing. The hydrology component simulates the movement of water including infiltration, evapotranspiration, and runoff. The weather component provides data on temperature, precipitation, and other meteorological variables. The erosion component simulates the movement of sediment and nutrients, while the plant growth component models the growth and development of vegetation. The nutrient and pesticide components simulate the movement of these chemicals, while the land management component simulates the effects of land use changes and management practices. Finally, the stream routing component simulates the movement of water and sediment.

The SWAT model is provided with an interface in ArcGIS, which allows users to define watershed hydrologic features and storage as well as organize and manipulate spatial and tabular data. The interface provides tools for inputting data, running simulations, and visualizing results. It also allows users to customize model inputs and parameters to suit their specific needs (Huang et al., 2020; Duan et al., 2017).

2.19 Structure of the SWAT Model

The United States Department of Agriculture (USDA) and Texas A&M University have developed the SWAT model (USDA ARS 2018). According to Gao et al. (2019), the SWAT model is a free and all-inclusive environmental modelling program that can be used for both small, medium and large catchments. The SWAT model is a popular tool for estimating the runoff and the sediment yield of a catchment area, which may be easily applied to GIS-based interfaces and further connects to the tools such as sensitivity, calibration, and uncertainty analysis (Kiros et al. 2015).

The present study is based on SWAT model which integrates the Geographic Information System (GIS) with attribute database to estimate the runoff and sediment yield of Wyra catchment area. SWAT is a physically based distributed parameter model which has been developed to predict runoff, erosion, sediment and nutrient transport from agricultural watersheds under different management practices. In the present study the catchment area has been delineated using the Digital Elevation Model (DEM) and then divided into sub-basins and these sub-basins are further divided into hydrological response units (HRUs).

The SWAT model is a continuous time series model that is initially designed to function on a daily time step. Being process-based and computationally efficient, this model can simulate continuously for extended periods of time (Iskender & Sajikumar, 2016). The land use map and soil map extracted from the world land use data and HWSD (Harmonized world soil database) raster world soil map respectively. Weather, hydrology, soil characteristics, erosion and sedimentation, plant development, nutrients, pesticides, bacteria and pathogens and land management are some of the main elements of a SWAT model.

SWAT model divides a watershed into smaller sub-basins and subsequently these sub-basins are further divided into hydrologic response units (HRUs). Within the sub-basin, each HRU has a lumped land area with similar land use, management, slope, and soil characteristics (Rostamian et al. 2008; Arnold et al. 2012; Zettam et al., 2017).

The calculated flow, sediment yield, and nutrient loading obtained for each sub-basin are then routed through the river system (Wu et al., 2018, 2020). Channel routing is simulated using either the variable storage or Muskingum method. Surface runoff from daily rainfall is estimated using a modified SCS curve number method. Peak runoff predictions are based on a modification of the Rational Formula (Chow et al, 2016). The watershed concentration time is estimated using Manning's formula, considering both overland and channel flow (Liu et al., 2015).

The model's approach to runoff estimation and routing provides valuable information for water resource management and planning. The soil profile in the SWAT model is divided into multiple layers to account for various soil water processes such as infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers (Fang et al., 2014). Sediment yield in SWAT modelling was estimated using the MUSLE.

2.20 Hydrological Component of SWAT

The hydrological component of SWAT is divided into two main phases: the land phase and the routing phase. The land phase is responsible for simulating the hydrological processes on land, while the routing phase simulates the movement of water and associated substances in the channel network of the watershed.

The land phase of SWAT includes several hydrological components, such as canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff, ponds, and tributary channels return flow. Ponds are small depressions on the land that temporarily store water. Tributary channels return flow refers to the return flow of water from tributary channels to the main channel (Chauhan et al., 2022).

The routing phase of SWAT simulates the movement of water and associated substances through the channel network of the watershed. This includes the routing of flow, sediment, nutrients, and pesticides from each sub-basin through the river system to the outlet. The routing phase uses the variable storage or Muskingum method to simulate channel routing. Sediment yield is estimated using MUSLE and sediment routing is simulated using a deposition and degradation model.

2.21 Potential Evapotranspiration

SWAT offers three different methods for calculating potential evapotranspiration (PET): Penman-Monteith, Priestley-Taylor, and Hargreaves. Each method has specific requirements for climate variables. The Penman-Monteith method requires solar radiation, air temperature, relative humidity, and wind speed. The Priestley-Taylor method requires solar radiation, air temperature, and relative humidity. The Hargreaves method only requires air temperature (Wang et al., 2019, 2020).

2.22 Sediment Component of SWAT

Soil erodibility factor (K-factor) is an important parameter in the Soil and Water Assessment Tool (SWAT) model, which is used to estimate soil erosion in agricultural watersheds. The K-factor is a measure of the exposure of soil to erosion by water, and it is influenced by several soil properties such as soil texture, organic matter content, and soil structure. In SWAT, the K-factor is calculated based on the soil texture and the organic matter content of the soil using an empirical equation developed by USDA. The K-factor is a dimensionless parameter that is used in USLE to estimate soil erosion. Soil conservation practices such as conservation tillage, cover crops, and crop rotation can help reduce the K-factor and minimize soil erosion (Ramesh et al., 2021).

2.23 Cover and Management Factor

The Cover and Management Factor (C-factor) is an important parameter in SWAT model, which is used to estimate soil erosion in agricultural watersheds. The C-factor represents the effect of land use and management practices on soil erosion. It considers the amount and type of vegetation cover, crop management practices, and soil conservation practices. The C-factor ranges from 0 to 1, where 0 indicates bare soil and 1 indicates complete vegetative cover.

In the SWAT model, the C-factor is estimated based on the land use and management practices in the watershed. The C-factor is determined using lookup tables that provide default values for various land use and management practices. The SWAT model provides a useful tool for assessing the impact of land use and management practices on soil erosion and for designing effective soil conservation strategies (Srinivasan et al., 2010; Ma et al., 2018).

2.24 Support Practice Factor of SWAT model

The Support Practice Factor (P-factor) is used to estimate soil erosion in agricultural watersheds. The P-factor represents the effect of soil conservation practices such as terraces, grassed waterways, and diversions on reducing soil erosion. It considers the effectiveness of these practices in reducing soil loss and sediment delivery to downstream water bodies. The P-factor ranges from 0 to 1, where 0 indicates no soil conservation practices and 1 indicates complete effectiveness of soil conservation practices in reducing soil erosion.

In the SWAT model, the P-factor is estimated based on the type and effectiveness of soil conservation practices implemented in the watershed. By implementing soil conservation practices with high P-factor values, such as terraces and grassed waterways, farmers can effectively reduce soil erosion and sediment delivery to downstream water bodies (Pandey et al., 2015; Zhang et al., 2018).

2.25 Some of the Sediment Studies in India by using SWAT model

Mahendra et al., (2019) used the SWAT model to estimate sediment yield in the Kali River Basin. The study found that the average annual sediment yield in the Kali River Basin was 1.25 t/ha/yr, with a total sediment yield of 14.8 million tonnes over the study period. The study found that the average annual sediment yield in the Kali River Basin was 1.25 t/ha/yr, with a total sediment yield of 14.8 million tonnes over the study period.

The study by Verma et al., (2021) used the SWAT model to assess soil erosion and sediment yield in the Kosi River Basin. The study found that the annual average soil erosion in the Kosi River Basin was 6.23 t/ha/yr, with a total sediment yield of 186.82 t/ha/yr. The results also showed that the soil erosion and sediment yield were higher in the upper catchment areas compared to the lower areas. The major factors contributing to soil erosion and sediment yield in the Kosi River Basin were found to be rainfall, slope, land use, and soil characteristics.

Mishra et al., (2019) used the SWAT model to estimate sediment yield in the Mahanadi River Basin. The study found that the annual sediment yield in the Mahanadi River Basin ranged from 32.5 to 143.7 million tons, depending on the sub-basin and land use type. The study focuses on the effective sediment management.

The study on the evaluation of the sedimentation pattern in the Loktak lake by Singh et al., (2020) used the GIS and remote sensing techniques to evaluate the sedimentation pattern while the study on sediment yield assessment in the Upper Tapi Basin by Chandra et al., (2016) used SWAT model simulation which concluded that the sediment yield from Burhanpur sub-catchment at Tapi River was about 80% of the Hathnur reservoir. However, if proper soil conservation measures were implemented, then the sediment yield could be reduced by up to 20%. Similarly, the study on the estimation of sediment yield in both the Wainganga river basin as well as Yamuna river basin using SWAT model, it was found that the agricultural activity itself accounted for major sediment yield (Lal et al., 2019).

2.26 Sediment Research in the International Context

Sediment research has implications on the sectors, viz. agriculture, forestry, mining, urban development, and water management. International organizations such as the United Nations (UN) and the World Bank (WB) have recognized the importance of sediment research and its role in sustainable water resources management (https://www.hydrosedi.net/). The UN Water Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS) report highlights the need for research and innovation to address sediment related issues in water resources management.

Similarly, the WB has highlighted the importance of sediment management in the context of sustainable development, highlighting the need for a coordinated approach to address the issues which primarily include the sediment related challenges (https://unesdoc.unesco.org/ark:/48223/pf0000183153). Examples of these programs include the United States Geological Survey's Sediment Laboratory (USGSSL) and the China Institute of Water Resources and Hydropower Research's Sediment Research Center (CIWR and HRSR) (https://unesdoc.unesco.org/ark:/48223/pf0000150719). Sediment research is an area of study in the international context, with implications for sustainable water resources management, human health, and the environment (Liu et al., 2023).

2.27 Sediment Research in the Indian Context

Sediment research is a major problem in India, where sediment related problems are a major concern in many parts of the country. Sediment can block waterways, reduce the storage capacity, increase flooding, and degrade aquatic habitats. In addition, sediment carrying pollutants such as nutrients, pesticides, and heavy metals, which can have negative impacts.

The Ministry of Water Resources (MoWR), Government of India (GoI), River Development, and Ganga Rejuvenation (RD&GR) has established the Sedimentation Research Laboratory (SRL) to conduct research and develop strategies to manage sediment related problems in rivers and reservoirs. The SRL has been involved in a range of sediment related research activities, including sediment monitoring, modelling, sediment transport analysis and sedimentation management planning by suggesting sediment control methods (https://pib.gov.in/PressReleasePage.aspx?PRID=1888318).

Several Indian universities and research institutions are also involved in sediment research. For example, the Indian Institute of Technology (IIT) Delhi has a Sediment Transport and River Engineering Laboratory (STREL) that conducts research on sediment transport processes in rivers and their impacts on river morphology and aquatic habitats. Similarly, the National Institute of Hydrology (NIH) has a Sedimentology Division that conducts research on sedimentation processes in rivers, lakes, and reservoirs (Singh et al., 2018).

In addition, the Central Water and Power Research Station (CWPRS) in Pune, Maharashtra is involved in sediment research. The CWPRS conducts research on sediment transport and sedimentation in rivers, reservoirs, and canals and develops innovative strategies for sediment management. Sediment research is important in India, with implications for sustainable water resources management, human health, and the environment (Bhattacharya et al., 2016; Sharma & Garg 2018). Collaborative efforts between these stakeholders can help address sediment related challenges and ensure sustainable water resources management in India (Kothyari, 2011).

2.28 Summary

In this chapter, an overview of the literature on Sediment analysis methods are presented. It is seen that anthropogenic activities are severely affecting the hydrological variables of water and physical variables of watershed along the river basins. Besides, climate change is expected to affect the magnitude and frequency of extreme events and likely to cause more intense degradation of soil and the ecological and hydrological atmosphere in general. One of the measures to mitigate the sediment erosion changes is through the treatment of watersheds restoring the natural behaviour in the river basin. Therefore, it is of great importance to understand the sediment erosion at river scale.

CHAPTER 3
METHODOLOGY AND STUDY AREA

3.1 General

This chapter discusses the methodology adopted for the study and details of the study area. The systematic approach and techniques employed for the analysis of sediment dynamics within the context of SWAT model are discussed. An insight into the data collection, processing and modelling procedures essential for the assessment of sediment transport in the watersheds are also presented. The movement of sediment in watershed has major implications for the environment and ecology.

It is necessary to understand the dynamics of sediment transport for the management of land and water sustainability, especially in areas that are prone to soil erosion, water body sedimentation and the deterioration of aquatic ecosystems. To address these challenges, this chapter outlines the steps involved in sediment analysis, including hydrographic survey, determination of T_e, application of SWAT, relevant data collection, model calibration and validation including sensitivity analysis.

Hydrometeorological information, like rainfall (daily), temperatures (minimum and maximum), wind speed, sunshine hours, humidity, observed river discharge and suspended sediment load/concentration are collected and analysed. The analyses make the data suitable for integrating into predictive models. After the process of parameterizing the model by converting the findings of the data analysis into model parameters, the model is then prepared for the sensitivity analysis, calibration, validation, and simulation studies using various model parameters.

The sensitivity analysis enables the identification of model parameters that have significant influence on outcomes, for further refining the accuracy of the model. Calibration and validation processes validate the performance of the model against real world observations, ensuring its reliability in simulating complex interactions.

Multiple simulations are run involving changes in parameters and the model comprehensively explores a range of scenarios, offering a holistic perspective on possible outcomes. The ultimate goal is to derive meaningful conclusions that shed light on the hydrometeorological dynamics of the basin and offer necessary insights into its behaviour under different conditions.

This iterative process of data collection, parameterization, simulation and analysis serve as a robust framework for understanding, predicting and managing the complex interplay of hydro-meteorological factors within the basin. The recommendations arising from these comprehensive analyses hold practical significance for water resource management, flood prediction, erosion control, and to develop environmental protection strategies.

3.2 Study Area

Wyra reservoir, located across the Wyra river, a tributary of Munneru, which itself is a tributary of river Krishna, was chosen for the study. The reservoir is located near the Wyra town, in the Khammam district of Telangana. Constructed during the year 1929, Wyra reservoir supplies water for drinking as well as crops for an ayacut about 7463 Ha (i.e., 2430 Ha and 5033 Ha under right and left canals respectively).

With a catchment area of approximately 710 km2, the reservoir experiences intense storms and releases substantial amounts of silt due to the steep topography of the watershed. Fig. 3.1 shows the location map with the catchment area of Wyra.

Table 3.1 displays the key characteristics of Wyra Reservoir together with other fundamental information including the year it was built, its catchment area, the length of time data was available, its average rainfall, and its decreasing capacity during the years 1930, 2002, and 2018.

The data for the study includes various spatial data like DEM, LULC, Soil Map generated from SRTM, BHUVAN and satellite data and prepared in ArcGIS on 1:12500 scale with the resolution of 30 m. Several collateral data like weather files (from 1991 to 2019) from rain gauge stations and climate stations have been collected.

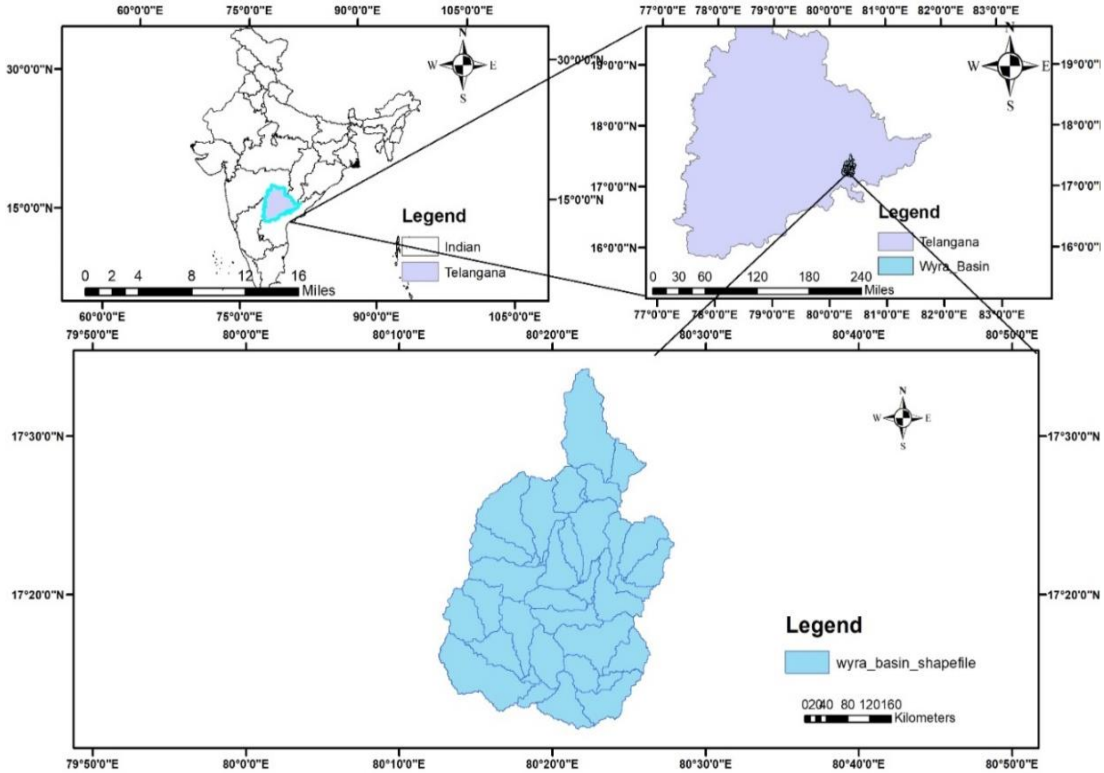


Fig. 3.1 Location map of Wyra reservoir with Watershed

3.3 Physiography

Physiography of the Wyra reservoir basin can be broadly divided into three different unit: (i) moderate to gentle sloping alluvial plains, (ii) gently sloping pediments to gently sloping alluvial plains, and (iii) level to nearly leveled, alluvial plains.

3.4 Hydrometeorology

Wyra river basin has a tropical monsoon climate with three seasons, the monsoon (*Kharif*, between late June to October), the cooler *Rabi* (November to February) which is dry except occasional rain in November and in the coastal region, and the hot summer season (March to mid-June). The rainfall occurs almost entirely during the south-west monsoon months (June to September) with an average annual rainfall of about 860 mm with significant regional variations, in the basin.

Table 3.1 Salient features of Wyra reservoir

Sl. No.	Description of Item or Activity	Area in km^2	% of Area
Classification of Catchment Area			
1	Forest area	211.34	29.78
2	Water spread area of reservoir and other tanks	31.48	4.44
3	Area covered by villages and towns including plain cultivated area	466.86	65.78
	Total:	709.68	100
4	Latitude	17° 11' 45''N	
5	Longitude	80° 22' 30''E	
6	Year of construction	1929	
7	Period of data availability	1999 to 2021	
8	Average annual rainfall (mm)	1147	
9	Area of reservoir at FRL +95.77m	18.15 km^2	
10	Gross capacity @ FRL +95.77m during 1930 Gross capacity @ FRL +95.77m during 2002 Gross capacity @ FRL +95.77m during 2018	70.07 Mm^3 55.76 Mm^3 42.48 Mm^3	

3.4.1 Temperature

The study area is situated in semi-arid climatic region conditions and hence the temperature reaches up to extreme levels. The average monthly temperature in the study area is shown in Fig.3.2. The temperature generally fluctuates during pre-monsoon to post-monsoon periods. After February, the temperature progressively rises and by the month of May and June it reaches maximum before the onset of the monsoon. On an average, maximum and minimum temperatures reach about 38°C and 26°C.

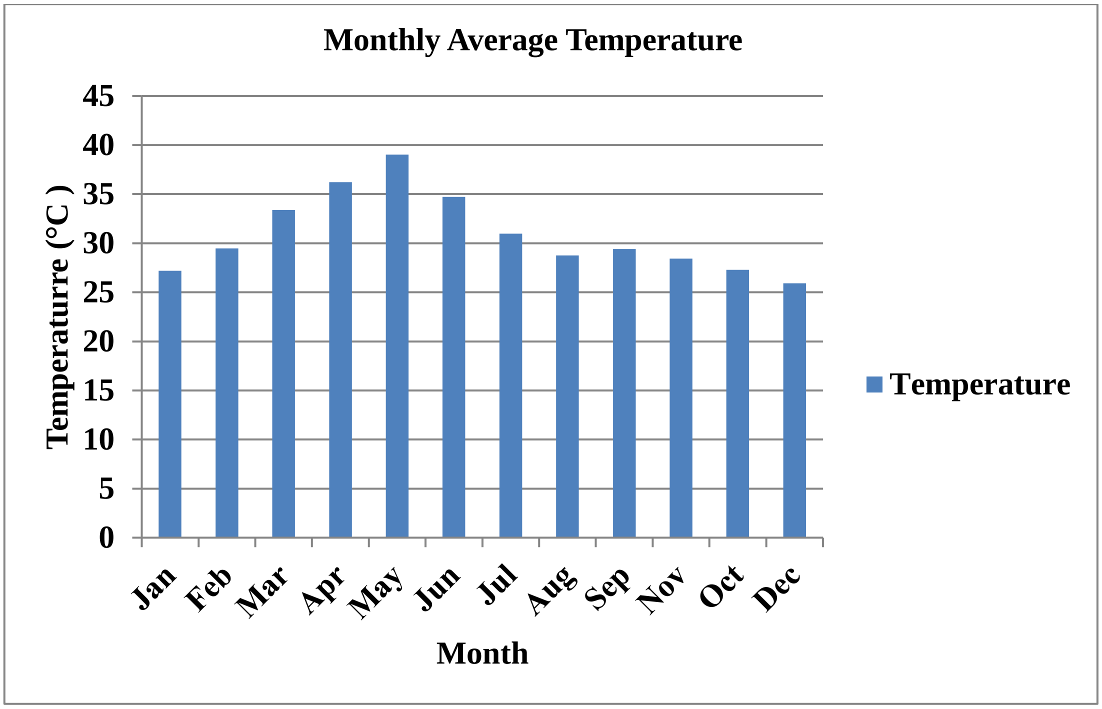


Fig. 3.2 Averaged monthly temperature of Wyra basin

3.4.2 Wind

Around 72% of days between May and September each year are windy days with a mean wind speed of 38km/hour. These winds are the carries southwest monsoon system, starting from mid-June till mid-September.

3.4.3 Relative humidity

During the monsoon months, the monthly mean relative humidity is about 80% and overall average relative humidity is about 58%. Except during the monsoon months, the atmosphere is generally dry in the afternoons being drier than the mornings.

3.4.4 Rainfall

The rainfall data reveal both the seasonal and annual variation. Based on available rainfall data, the average yearly rainfall for the present study area is computed as about 750 mm. The average monthly rainfall is shown in Fig. 3.3.

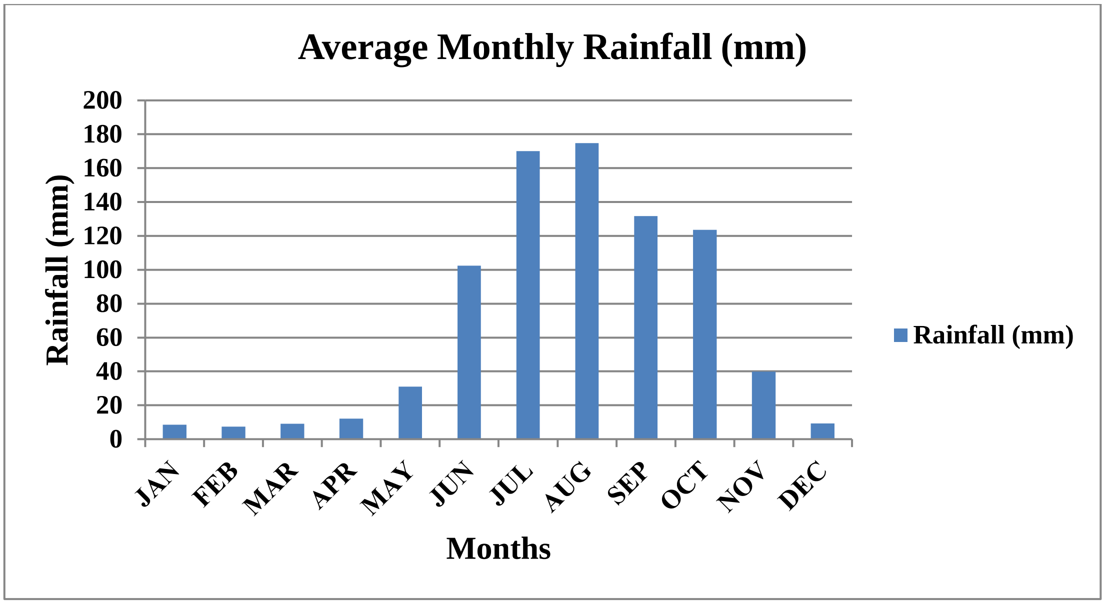


Fig. 3.3 Average monthly rainfall Wyra basin

3.5 Data Collection

The data required for this research study can be categorised into two main types: spatial data and time series data. Spatial data include DEM, LULC information, and soil map relevant to the study region. 30m resolution DEM data of the study area (downloaded from the Earth explorer website: https://earthexplorer.usgs.gov/). The following webpage was used to download the LULC data: https://power.larc.nasa.gov/data-access-viewer/.. The research area's various land use types are identified and categorised into six groups using remote sensing and visual interpretation. Soil data of the Wyra watershed area were downloaded from the NASA website: https://power.larc.nasa.gov/data-access-viewer/. These crucial datasets were acquired from the Water Resources Information and Education Center (Include the website) website, which gives a comprehensive collection of historical weather and water-related information.

For the estimation of sediment yield within the study area, the research employed specialised models and software tools. The GIS software ArcGIS 10.2 was used in managing and analysing spatial data. Extension of the SWAT, namely, ArcSWAT 2005 version 2.3.4, was used in the study.

ArcSWAT can streamline the input data preparation for the SWAT model, thereby enhancing the accuracy and effectiveness of the estimation process. This software can be used to create Thiessen polygons, for delineating the catchment areas for the meteorological stations located within the watershed.

By integrating this suite of tools, software and datasets, the study attempted to estimate sediment yield within the study area. The combination of spatial data, time series (temporal) data, and the chosen software enabled to carry out systematic analysis, develop an understanding of the hydrological and environmental dynamics.

3.5.1 Meteorological data

The meteorological data necessary for the study included precipitation on daily basis, air temperature minimum and maximum, wind speed, solar radiation, and relative humidity. Despite the non-availability of some of the above datasets, which is a common occurrence, the SWAT model has the capability to generate substitute data using a weather generator.

To facilitate this data generation process, monthly statistical values were used. These statistical data, derived from the raw daily data, serve as an input for the creation of daily values. For instance, precipitation, temperature, and other parameters were analysed for their monthly patterns, thus forming the basis for the subsequent generation of daily values.

Most of the data needed were collected from Konijerla gauging station. These datasets were prepared in text format for processing and analysis. Other information for calculation of potential evapotranspiration (PET), using the Penman-Monteith equation were collected from different websites.

3.5.2 Sediment data

Suspended sediment data, were collected at limited number of locations in the river, although over a relatively short timeframe. The observed sediment data of Wyra river were obtained from the Wyra river management. Using this observed sediment data, the additional sediment values required for the study were generated through the application of a sediment rating curve. This procedure was instrumental in facilitating both calibration and sensitivity analysis.

3.6 Hydrographic Survey

The hydrographic or bathymetric survey consisted of conducting soundings on the predetermined basic range lines by the echo-sounder, the water depth and its referencing position is recorded at every point and then the capacity of the reservoir is estimated, using the contour map.

3.6.1 Range lines

The basic range lines were used to split the reservoir's full water-spread region into 12 sub-areas, as shown in Fig. 3.4.

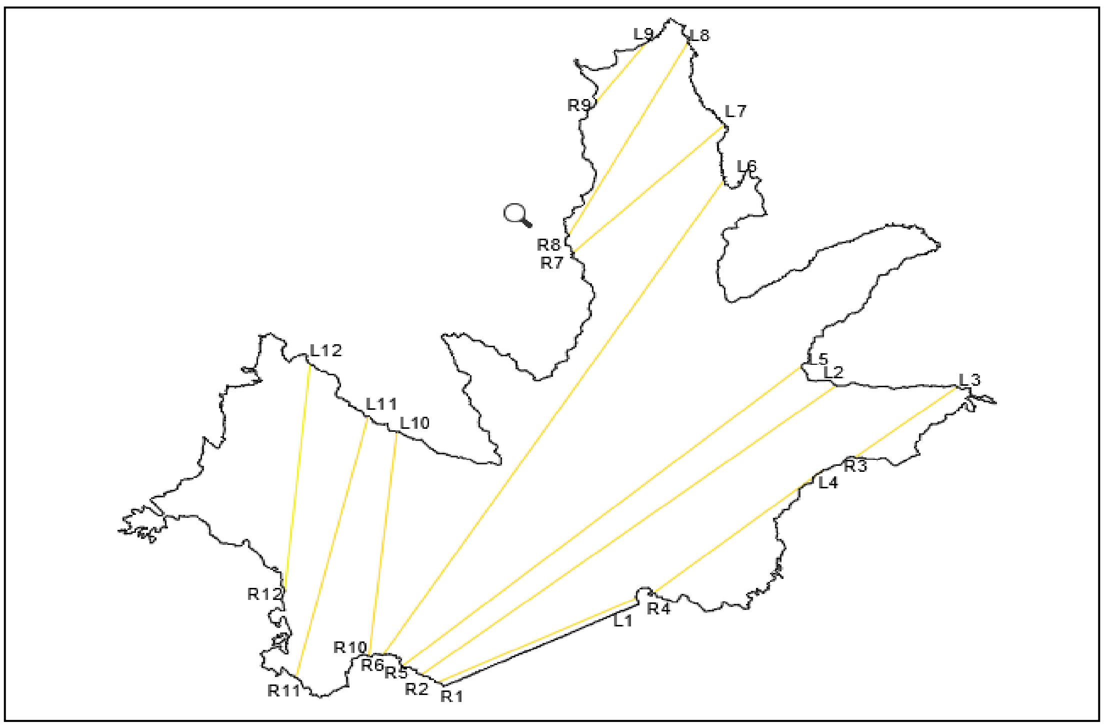


Fig. 3.4 Plan showing the range lines of Wyra Reservoir – 2018

3.6.2 Pre-survey planning

Pre-survey planning include the following steps (i) Importing background image of reservoir; (ii) Georeferencing the image; and (iii) Drawing survey lines/paths.

3.6.3 Hydrographic survey – 1980

The Wyra reservoir was constructed with an original capacity of 70.07 Mm^3 at F.R.L. +95.77m. The first hydrographic survey was carried out in the year 1980 and the capacity at full reservoir level (FRL) +95.77m was calculated to be 62.20 Mm^3, and the capacity loss from the initial stage was calculated to be 7.87 Mm^3.

3.6.4 Hydrographic survey – 2002

The second hydrographic survey was conducted during the year 2002 and the capacity at FRL +95.77m was worked out to 55.76 Mm^3 and the loss in the capacity was computed to be 14.31 Mm^3.

3.6.5 Hydrographic survey – 2018

The FRL of the reservoir is +95.77 metres but during the survey, the water level was +93.48 metres. The National Remote Sensing Centre (NRSC) provided satellite imagery to augment the data on the variations in water levels. The imageries along with the details are presented in the Table 3.2, the capacity at FRL +95.77m was 42.41 Mm^3 and the loss in the capacity was computed to be 27.66 Mm^3.

Table 3.2 Details of Satellite imageries from NRSC Laboratory

S. No	Elevation (m)	Date of Pass	Satellite	Sensor	Path-Row
1	+93.55	22.01.2018	RESOURCESAT-II	LISS-IV	102-61-A
2	+94.11	09.01.2015	RESOURCESAT-II	LISS-IV	101-60-D
3	+95.66	30.11.2017	RESOURCESAT-II	LISS-IV	101-60-D

3.6.6 Echo-sounder

The soundings in the reservoir were conducted with Seafearer Indicator type echo-sounder which was fitted to one side of the boat. Special arrangements were made to hold the transducer of the echo-sounder in a fixed position at any required depth. The transducer was kept at a depth of 0.2m below the surface of water. The equipment amplifies the echo to measure the intervening time interval and to convert this automatically into units of depth in meters. The maximum depth reading capacity of the instrument is 120 m.

3.6.7 Hand-held GPS

Hand-held GPS was used for taking the position of all the important points like dam coordinates, end points of range-lines, range-line interval and other ground control points.

3.6.8 Navisoft survey software

Range lines and grids were tracked with this software by using its 'Planning and Presentation' option. Data will be gathered, processed, and stored using the "Survey" menu. There after a file with the extension [. RAW] contains all of the data. The raw data is converted for additional data processing using the product file [. PRD]. The Data edif menu was used to alter the data visually. Lastly, the profile, overview, and cross-sectional views are provided by this software. Using both Navisoft and Surfer software facilitated the bathymetric survey's conduct and allowed for the timely acquisition of the required results.

3.6.9 Surfer software

Surfer software is a graphics software that uses only grids. The XYZ grid data is interpolated into a regularly spaced grid format (.grd file) from its uneven spacing. Surfer creates the Surfer plot, or contour map, using the grd.file. Surfer creates wireframe maps, contour maps, and other maps using gridded data.

Figure 3.5 displays the Wyra reservoir's contour map, which shows contour lines at various altitudes ranging from 84 to 93 metres.

3.6.10 Post-survey processing using the software

Post survey processing of the results obtained using Navisoft and Surfer software include:

(i) Removing errors through filtering, smoothing

(ii) Filling missing values manually or through interpolations

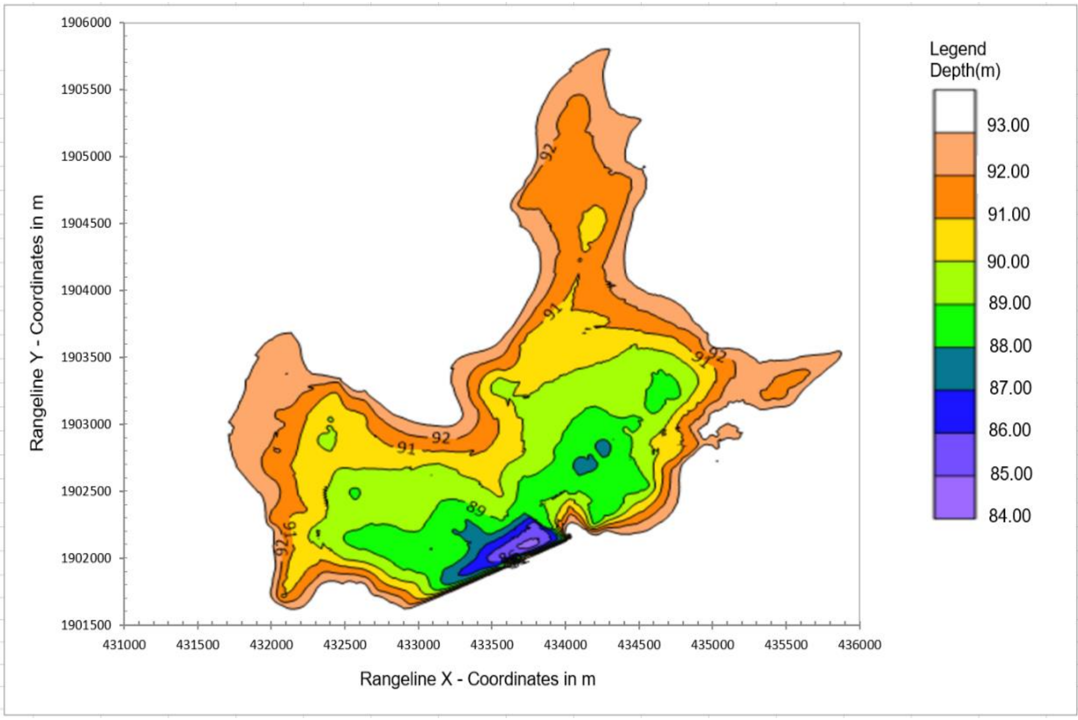


Fig. 3.5 Contour map of Wyra based on hydrographic survey-2018

(iii) Data exporting to other common formats

(iv) From the data, reduced levels were obtained along the ranges, and the data file was generated in Microsoft Excel for the position X, Y and corresponding depth (Z).

(v) After obtaining the field data, the data is processed in the lab to create wireframe, contour, and grid maps using the Surfer programme.

(vi) Using the grid file, contour map at every 1m interval was generated as.

(vii) Calculating reservoir volumes from the surface areas.

The report of hydrographic surveys conducted in 1980, 2002, and 2018 as well as temperature and rainfall data collected from 1991 to 2019 form the basis of the current study. Further, the data with the source of information for Precipitation, Temperature, Wind, Humidity, DEM, LULC, Soil and Hydrographic Survey are tabulated in the following Table 3.3.

Table 3.3 Data with Source of Information

Sl.No.	Data	Source
1	Precipitation Data	Indian Meteriological Dept. (IMD)
2	Temperature Data	Indian Meteriological Dept. (IMD)
3	Humidity Data	Indian Meteriological Dept. (IMD)
4	Wind Data	Indian Meteriological Dept. (IMD)
5	DEM (30m)	https://earthexplorer.usgs.gov/
6	Land use and Land Cover (LULC)	https://esa-worldcover.org/en
7	Soil data	https://power.larc.nasa.gov/data-access-viewer/
8	Hydrographic Survey	Collected from the Dam Authorities

3.6.11 Estimation of Runoff

For the Deccan Plateau region, the runoff was determined using the Inglis and DeSouza formula, Eqn. (3.1), where R is the yearly runoff and P is the annual rainfall in millimeters.

$$R = \frac{P}{254}(P - 17.8) \qquad (3.1)$$

3.7 Estimation of Reservoir Capacity

Using the Surfer software, the collected field data were processed to create wireframe, contour, and grid maps. Using the data file, a grid file was created, which is necessary to construct a contour map at a 1-meter interval. The reservoir's capacity was calculated using the areas of several contours. Eqn. (3.2) provided the prismoidal formula, which was used to compute the capacity.

$$\mathbf{V} = \frac{\mathbf{H}}{\mathbf{3}}\left(\mathbf{A1} + \mathbf{A2} + \sqrt{\mathbf{A1} * \mathbf{A2}}\right) \qquad (3.2)$$

where V = Volume/capacity; H = Contours Interval

A1 = Lower contour area; A2 = Upper contour area

3.8 Trap efficiency (T_e)

Calculating the T_e has emerged as a crucial aspect of reservoir sedimentation. Numerous laboratory and field studies were conducted to examine the reservoirs' T_e and sediment output variations. Brune's method, modified, for determining T_e turned out to be the most successful empirical formula so far, producing values that were closer to the actual measured values.

3.8.1 Factors affecting T_e

T_e primarily depends on the parameters like inflow sediment characteristics, particle size distribution which monitors flocculation, detention storage time, runoff volume, peak discharge, base flow and reservoir characteristics like topology, surface area, shape, nature of out-lets, initial storage volume, water releases (Verstraeten and Poesen, 2000).

3.8.2 General equation for T_e

T_e is defined as the proportion of the catchment/watershed area's sediment yield that is trapped in the reservoir, and it is particular to that reservoir. T_e is defined as the percentage of settled incoming silt to total incoming silt, and it is provided by Eqn. (3.3).

$$T_e = \frac{V_i - V_o}{V_i} \text{x} 100 \qquad (3.3)$$

where V_i is the incoming sediment and V_o is the discharged sediment.

In order to derive T_e using the C/I ratio, Brune's methodology was refined and improved by Dendy (1974), Gill (1979), Heinemann (1981), and Garg & Jothiprakash (2008a). T_e was represented as closely as possible to the three curves of Brune for coarse, medium, and fine-grained sediments. But because the equations for Dendy and Heinemann's approaches were developed using data for small reservoirs, their applicability is limited.

3.8.3 Brown's equation for T_e

Brown's T_e (1943) is the ratio of the reservoir capacity 'C'(Ha.m) to catchment area 'A'(km^2), as given by Eqn. (3.4) (Gill, 1979; USACE, 1989; Campos, 2001).

$$T_e = 100 \times [1 - \frac{1}{\left[1+2100x\frac{kC}{A}\right]}] \qquad (3.4)$$

where k is a constant or the coefficient that depends basically on the time of detention-storage, sediment grain size, the reservoir shape, the sluice position, the operation of the gates. When 'k' value is taken as 1.0, 0.1 and 0.046 for the sediments which are coarse, medium and fine-grained respectively. However for the present study 'k' value is taken as 0.1 since the sediment considered as medium grained.

But if the runoff produced by respective watersheds differs due to differing hydrological parameters, reservoirs with the same catchment/watershed (C/W) ratio would provide varied T_e values. Taking into consideration the aforementioned restriction, Brune created an empirical relationship that employed the storage capacity (C) to annual inflow (I) ratio (C/I ratio) to calibrate the reservoir T_e. The study was based on field observations conducted across 44 reservoirs in the United States, with C/I ratio values ranging from 0.0016 to 2.00.

3.8.4 Brune's equation for T_e

The ratio of storage capacity (C) at full reservoir level (FRL) to annual inflow (I) into the reservoir (C/I ratio) is used by Brune to develop an empirical relationship for calibrating the reservoir T_e. The study was based on field observations conducted over 44 reservoirs in the USA, with values of C/I ratio ranging from 0.0016 to 2.00. For normal ponded reservoirs, the results were plotted as three enveloping curves: the median curve for medium-grained sediments, the primarily colloidal and dispersed fine-grained sediment envelop curve, and the primarily highly flocculated and coarse-grained sediment envelop curve. The T_e was determined using Eqn. (3.5).

$$T_e = K * Ln(C/I) + M \qquad (3.5)$$

C/I = capacity–inflow ratio where ‘C’ (million m^3) is capacity of reservoir at FRL
I= annual inflow into reservoir (million m^3) and K and M are coefficients dependent on C/I ratio

For normal ponded reservoirs and the T_e, Brune had plotted the three enveloping curves: the median curve for medium-grained sediments, the primarily colloidal and dispersed fine-grained sediment envelop curve, and the primarily highly flocculated and coarse-grained sediment envelop curve. Table 3.4 lists the values of K and M that correlate to the C/I ratio. It should be noted that if the C/I ratio is less than 1.00, the reservoir's storage was fully refilled for that year; if it is more than 1.00, the reservoir is a holdover storage reservoir.

From this, it can be inferred that the average retention time of the reservoir's sediment-laden water is determined by the C/I ratio. Therefore, a longer retention period results in a larger C/I ratio and more silt accumulation. Brune's approach, however, will only work with reservoirs that are typically ponded; it will not work with semi-dry, flood-water retarding, or desilting reservoirs.

Table 3.4 Values of K and M corresponding to C/I ratio

C/I ratio	K	M
0.002 to 0.03	25.025	158.61
0.03 to 0.10	14.193	119.3
0.10 to 0.70	6.064	101.48

3.8.5 Dendy’s equation for T_e

Dendy (1974), has modified and improved Brune’s methodology for obtaining T_e as given in Eqn. (3.6).

$$T_e = 100[0.97^{0.19^{\log\left(\frac{C}{I}\right)}}] \qquad (3.6)$$

3.8.6 Gill’s equation for T_e

Gill (1979), using C/I ratio, the T_e can be expressed as nearer to the three curves for coarse, medium and fine-grained sediments respectively by Brune, as given as given in Eqn. (3.7)

$$T_e = \frac{100\frac{C}{I}}{(0.012 + 1.02\frac{C}{I})} \quad (3.7)$$

3.8.7 Heinemann's equation for T_e

Heinemann (1981), developed another relationship using the Brune's approach for T_e as given in Eqn. (3.8)

$$T_e = \frac{100K}{(0.012+1.02K)} \quad (3.8)$$

where K=sedimentation index (SI) x acceleration due to gravity (g) and "SI" is given by Eqn. (3.9)

$$SI = \frac{\left(\frac{C}{I}\right)^2}{L} \quad (3.9)$$

where, L is dam/reservoir length, measured from the centre of the axis of the dam to the farthest point of the spread of water. The applicability of both the Dendy (1974) and Heinemann (1981) methods is restricted because the equations were developed using data for small reservoirs.

3.8.8 Garg and Jothiprakash equation for T_e

Garg and Jothiprakash (2008b) have derived the modified equations for the correlations given by Brune for coarse and medium grained sediments. However, for the present study, only median curve for medium grained sediments were considered as given by Eqn. (3.10).

$$T_e = \frac{\frac{C}{I}}{\left[0.00013+0.01\times\frac{C}{I}+0.0000166\times\sqrt{\frac{C}{I}}\right]} \quad (3.10)$$

3.9 Data Analysis

Daily precipitation data including maximum and minimum air temperature for the period from 1975 to 2018 (that is 44 years of simulation period) were obtained from the website of the Indian Meteorological Department (IMD) to calibrate and validate the simulated results of the SWAT model including carrying out sensitivity analysis of the model. SWAT May 28 VER 2020 Rev 681 model is being used for the present study.

3.10 SWAT Model Description

The SWAT model was selected for the study due to its ability to assess the effect of land management practices on water, sediment, agricultural and chemical yields from a watershed. The model uses readily available inputs and is computationally efficient for large basins. The required data was collected and processed to meet the input requirements of the model. The program computes fluxes for each hydrologic response unit (HRU), aggregates the results to sub-basin outputs, and routes sub-basin outputs through a river reach within the channel network. The hydrologic components of the model are based on the water balance equation given by Eqn. (3.11) (Arnold et al., 1998).

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right) \qquad (3.11)$$

where SW_t is the soil water content at time t; SW_0 is initial soil water content; t = time (in days); R_{day} is the amount of precipitation on day; Qsurf is the amount of surface runof on day; E_a is the amount of evapotranspiration on day; W_{seep} is the water percolation to the bottom of the soil profile on day; Q_{gw} is the amount of water returning to the ground water on day.

The SWAT model analyses components such as weather, surface runoff, ET, irrigation, sediment transport, nutrient, pesticide yield, groundwater flow, and crop growth. The sub-basins of the model are subdivided into eight components, including hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. SWAT simulates various hydrological processes, including surface runoff, infiltration, ET, lateral flow, percolation, and channel routing. The model first delineates a basin or watershed and then subdivides it into smaller units known as sub-basins, which are further divided into HRU's. The hydrologic cycle has two phases: the land phase and the water or routing phase. The first phase deals with water, sediment, nutrients, and pesticides into each sub-basin, while the second phase deals with how they travel through the watershed's network of channels.

3.11 Hydrology Modelling

To analyse, manage and reduce the continuous sedimentation in reservoirs, it is essential to carry out hydrological modelling in the watershed area of the drainage basin. The calibration and validation of the SWAT model parameters are fundamental for hydrological modelling (Shivhare et al. 2018).

Hydrological modelling is used to predict the impact of changes in land use, climate, and water management practices on watersheds. The process involves the use of mathematical models to simulate the movement of water through various components of the hydrological cycle, such as rainfall, evapotranspiration, runoff, infiltration, and groundwater flow.

There are different types of hydrological models which can be used depending on the specific research. For example, rainfall-runoff models are used to simulate the movement of water from rainfall to streams, while sedimentation models are being used to study the transportation of sediment and the estimation of sediment yield data were based on the RUSLE equation using the SWAT model. In hydrological modelling a wide range of data sources such as satellite imagery, ground-based sensors, and historical records are used to calibrate and validate the model.

3.11.1 Surface runoff/overland flow

SWAT makes use of two methods to estimate surface runoff. The first method is the SCS curve number, (1972) procedure and the second method is the Green-Ampt (1911) infiltration method. Both methods have been widely used and proven to be effective in estimating surface runoff. In the computation of surface runoff, SWAT employs both daily and hourly time intervals. For daily time steps first method is used whereas for hourly time steps, Green and Ampt equation is applied.

3.11.2 Potential evapotranspiration (PET)

Several approaches have been formulated for calculating PET. Within the SWAT model, three such methods are incorporated to assess PET, viz. i) The Penman-Monteith method, ii) The Priestley-Taylor method and iii) The Hargreaves method. However, the first method is being used in the study.

3.11.3 Sediment routing

The results were routed to their respective reach and catchment outlet through the channel network. The work of Abbaspour et al. (2009) provided the necessary framework for carrying out this analysis. Sediment transport in the channel network is a function of two processes, deposition and degradation, operating simultaneously in the reach. There are two options in SWAT to compute deposition and degradation in the reach. The first and traditional way is to keep the channel dimensions constant so that SWAT will compute deposition and degradation using the same channel dimensions throughout the simulation and the second is to activate channel degradation and allow channel dimensions to change and updated us a result of down cutting and widening.

When channel down cutting and widening is simulated, channel dimensions are allowed to change during simulation period. Three channel dimensions are allowed to vary in channel down cutting and widening simulations: bank full depth, channel width and channel slope. Channel dimensions are updated when the volume of water in the reach exceeds 10m (Neitsch et al., 2011). In this study the former option was adopted in channel routing since the latter option is still in the testing phase.

3.11.4 Landscape contribution to sub-basin routing reach

Tracking the distribution of degraded sediments' particle sizes from the landscape component, SWAT directs the materials through surface waterbodies such as ponds and channels. Before entering the stream channel, the sediment production from the landscape is routed and delayed through vegetative filter strips, ponds, and grassed waterways. According to Neitsch et al. (2011), the total sediment output determined by MUSLE less the lag, as well as the silt trapped in grassed waterways, vegetative filter strips, and/or ponds, add up to the total sediment yield that reaches the stream channel. The watershed did not include small ponds.

3.11.5 Sediment routing in stream channels

Peak river discharge rate and mean daily flow determine sediment routing. Each of the minor sub-basins created by the delineation of the watershed has at least one primary routing reach. As a result, these reaches get the sediment from upland sub-basins, which is subsequently contributed to downstream reaches. The greatest amount of sediment that may be transported from a reach segment is a function of the peak channel velocity, and SWAT employs the simplified version of the Bagnold equation (Bagnold, 1977) to do this (Neitsch et al., 2011).

3.12 Sensitivity Analysis, Calibration and Validation

After obtaining the satisfactory SWAT model parameters for the sub-basins, implementing the parameters sensitivity analysis procedures, followed by model calibration and validation on the catchment were carried out. From the selected parameters, sensitive variables that are sufficient for the model to generate satisfactory predictions are identified using sensitivity analysis. In order to arrive at a satisfactory NSE and R^2 values, the model has to be calibrated by comparing the expected output of ET with the generated Terra Climate ET data.

To ensure the accuracy of the SWAT model, the SUFI2 (Sequential Uncertainty Fitting Version 2) program is used in conjunction with SWAT_CUP for model calibration and validation. To improve the accuracy of the SWAT model, it is recommended to edit the parameters using SUFI2 or other similar programs after each iteration. This process involved updating the SWAT model with a new set of parameters and running it to obtain a new set of outputs. The newly generated SWAT outputs were then be used for the next iteration, and the process was repeated until the desired level of accuracy was achieved.

The overall structure of the SWAT_CUP program is illustrated in Fig. 3.6 which provides a clear overview of the iterative process involved in optimizing the

SWAT model parameters. In the process of improving the SWAT model, the parameters using SUFI2 or other similar programs after each iteration have to be

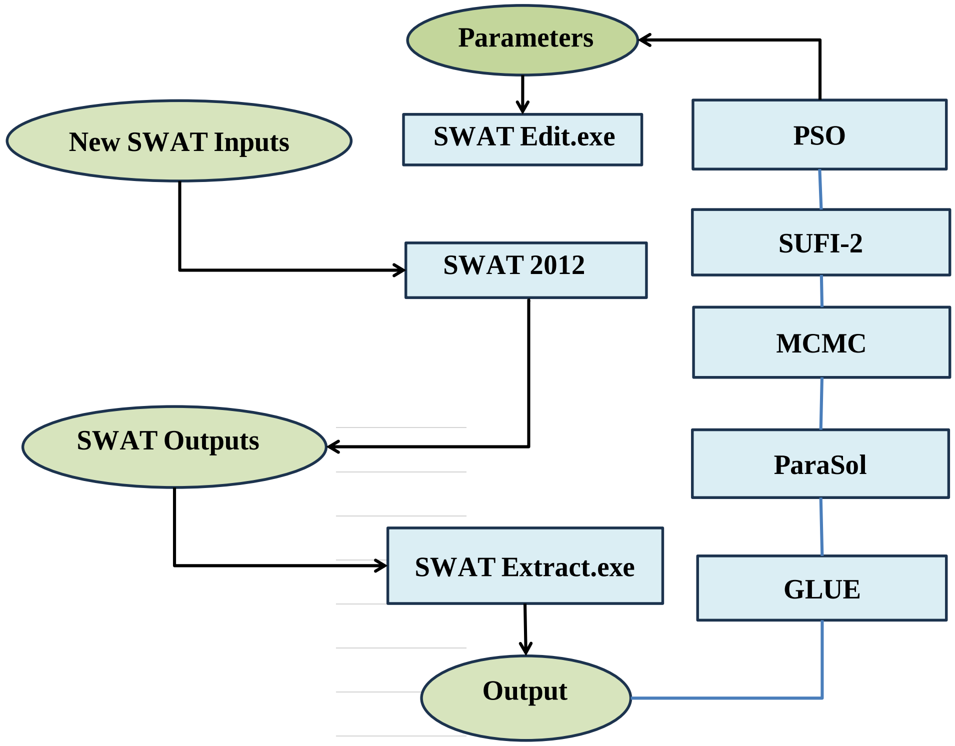


Fig. 3.6 Overall program structure of SWAT_CUP

3.12.1 Model efficiency criteria

One way to gain insight into the behaviour of a model is by comparing simulated flow and observed flow on a single coordinate system. This allows to determine if the model has over or under predicted. However, for more accurate evaluation of the model, mathematical measures of performance are necessary. These measures can provide a quantitative assessment of the model's performance and help identify areas where improvements can be made. By combining both subjective and objective evaluations, an overall understanding of the behaviour of the model can be arrived at to make decisions about future improvements.

3.12.2 Reasons to evaluate model performance

To offer a quantitative assessment of the capacity of the model to replicate past and projected watershed behaviours, as suggest by (Krause et al., 2005).

i. To establish a framework for appraising enhancements to the modelling methodology, achieved by modifying model parameters, making structural refinements, incorporating additional observational data and capturing vital spatial and temporal watershed attributes.
ii. To make comparisons between ongoing modelling endeavours and outcomes from prior studies.
iii. The performance of the model during both the calibration and validation phases is done by two statistical metrics viz. the coefficient of determination (R^2) and the Nash-Sutcliffe efficiency coefficient (NSE).

3.12.3 Coefficient of determination (R^2)

The coefficient of determination (R^2) measures the fraction of the variation in the measured data that is replicated in the simulated model results and is given by the Eqn. (3.11).

$$R^2 = \left\{\frac{\sum_{i=1}^{n}(O_i - O_{avg}) * (S_i - S_{avg})}{(\sum_{i=1}^{n}(O_i - O_{avg})^2 * \sum_{i=1}^{n}(S_i - S_{avg})^2)\hat{}0.5}\right\}^2 \qquad (3.11)$$

where n: number of data's; O_i: observed stream flow; O_{avg}: mean of observed stream flow, Si: simulated stream flow and S_{avg}: mean of simulated stream flow. While evaluating a model's performance, the value of R^2 lies within the range of 0 to 1.

3.12.4 Nash-Sutcliffe Efficiency coefficient (NSE)

The NSE is calculated using the following Eqn. (3.12).

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - S_i)\hat{}2}{\sum_{i}^{n}(O_i - O_{avg})\hat{}2}\right] \qquad (3.12)$$

where n: number of data's; O_i: observed stream flow; O_{avg}: mean of observed stream flow, Si: simulated stream flow and S_{avg}: mean of simulated stream flow. This coefficient measures the predictive power of the model and the value of NSE falls within the range of around 1.0.

3.13 Rainfall Analysis

The Wyra watershed's rainfall distribution was examined using 28 years' precipitation data (1991 to 2019). Fig. 3.7 illustrates that 2013 saw the most annual rainfall, whereas 2011 saw the lowest.

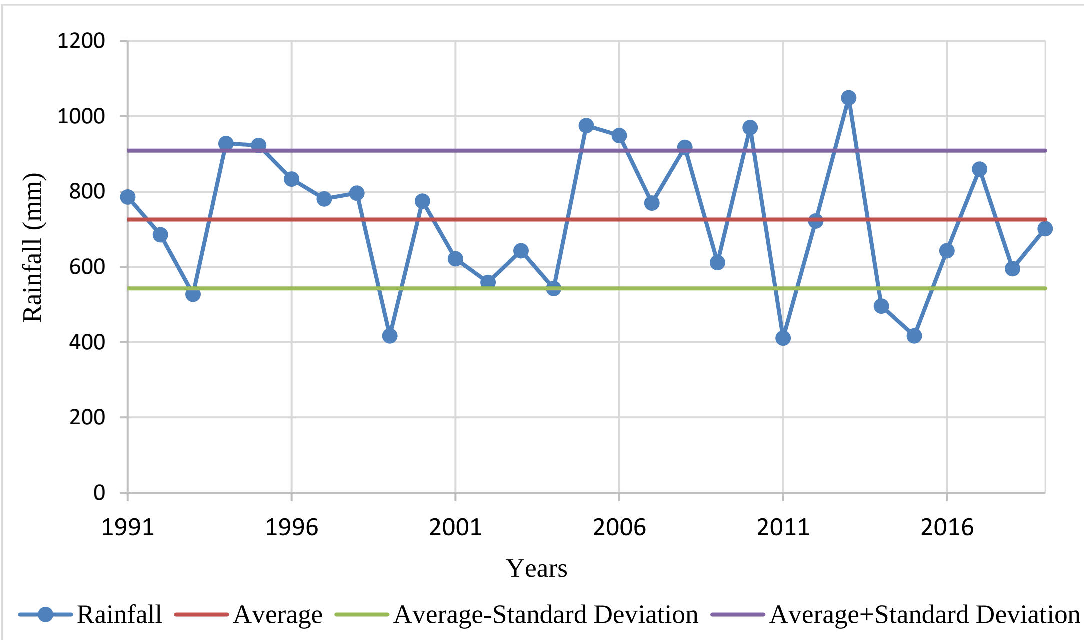


Fig. 3.7 Average annual rainfall in the study area from 1991 to 2019

It is found that, in comparison to normal and dry rainfall years, sedimentation is higher in the rainy years. The following is how dry and wet years are regarded in this study:

(i) **Dry year**: when the values of rainfall are below the line (average – standard deviation).

(ii) **Wet years**: when the values of rainfall are above the line (average – standard deviation).

(iii) **Normal years**: when the values of rainfall are between the lines (average+standard deviation) and (average – standard deviation).

3.14 Flow Chart of the Methodology Adopted

The complete flow chart of the methodology is shown in the Fig. 3.8. This chart consists of three models viz. i) The practical model, ii) The empirical model and iii) The SWAT model.

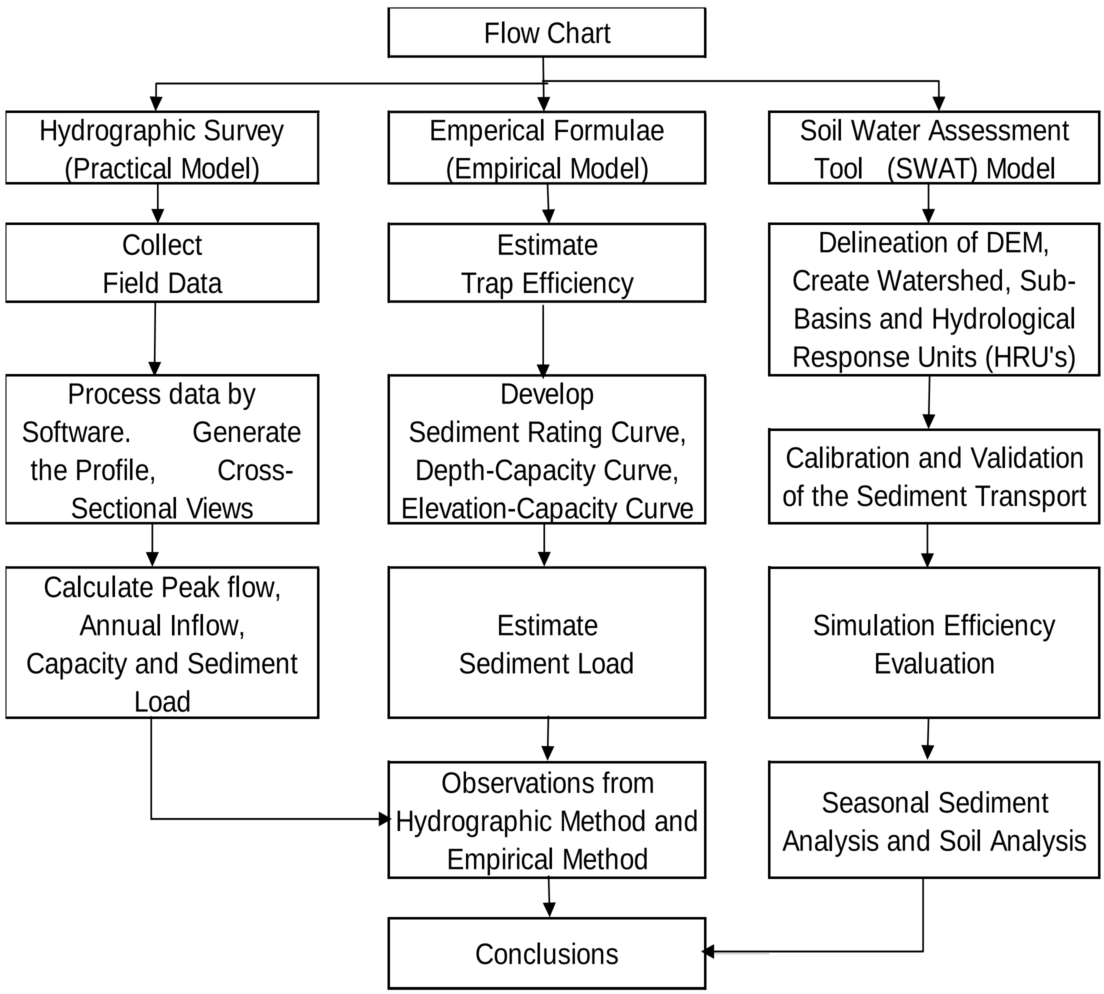


Fig. 3.8 Flow Chart of the Methodology Adopted

In the first model, field data is collected by conducting hydrographic survey and the data is processed by the Navisoft and Surfer software to generate profile, cross-sectional views as well as peak discharge/flow and annual inflow including sediment load. Then in the second model empirical formulae were used to calculate Te, to draw graphs of sediment and to evaluate sediment load. Finally in the third model SWAT is used to calibrate and validate the model including performing seasonal sediment analysis.

3.15 Summary

This chapter outlined the steps involved in sediment analysis including hydrographic survey, T_e determination, SWAT model utilization, hydro-meteorological data acquisition, as well as the processes of sensitive analysis, calibration and validation. The applicability and adaptability of the model in various conditions has been discussed. A combination of ArcGIS and SWAT approach is used for studying the sedimentation along river.

CHAPTER 4
APPLICATION OF METHODOLOGY

4.1 Overview

This chapter explains the application of the developed methodology to the study area and the details of the results obtained along with their analysis. The application of SWAT model along with the generated output files is also described in the chapter.

4.2 Hydrographic Surveys during 1980, 2002 and 2018

This chapter describes the hydrographic surveys carried out in the years 1980, 2002 and 2018 on the Wyra reservoir to find out the capacity of the reservoir at that period. The survey involves the use of echo-sounder to take soundings on the pre-established range lines, by recording the water depths, at each location with reference points on the starting and end points and then using the contour map as well as the Prismoidal formula, the reservoir's capacity is calculated.

The Wyra reservoir was built in 1929 with an initial capacity of 70.07 Mm^3 at full reservoir level (F.R.L.) +95.77 metres. The results of first hydrographic survey done in 1980 showed that the gross capacity at FRL was 62.20 Mm^3 and the loss in storage volume was 7.87 Mm^3 and the rate of siltation was 3.566 ha-m/100 km^2/year and the loss in the capacity was 11.23%.

As per the second survey in 2002, the gross capacity at FRL stood at 55.76 Mm^3, while the capacity loss was 14.31 Mm^3, the rate of siltation was 4.535 ha-m/100 km^2/year, and the loss in the capacity was 20.44%.

4.3 Reservoir capacity as per hydrographic survey 2018

The capacity of Wyra reservoir was calculated using the Prismoidal formula given by Eqn. (3.2) and results of the same are presented in the Table 4.1.

A1 is the area of contour at 88m = 0.228 Mm^3

A2 is the area of contour at 87m = 0.112 Mm^3

The volume or capacity of the reservoir is calculated by substituting the values of A1 and A2 in Eqn. (3.2) with the following values:

$$V = \frac{(88 - 87)}{3} \text{ x } (0.112 + 0.228 + \frac{\sqrt{0.112 \text{ x } 0.228}}{1}) \quad = 0.166 \text{ Mm}^3$$

Table 4.1 Capacity calculations of Wyra reservoir

Sl. No	Contour m	Area in m^2	Area in Mm^2	Volume in Mm^3	Cumulative Volume in Mm^3
1	85.00	7335	0.007	-	-
2	86.00	55404	0.055	0.028	-
3	87.00	112028	0.112	0.082	0.11
4	88.00	227620	0.228	0.166	0.28
5	89.00	1037688	1.038	0.584	0.86
6	90.00	2313085	2.313	1.633	2.49
7	90.28	2686874	2.687	0.699	3.19
8	91.00	3613631	3.614	2.260	5.45
9	92.00	5065134	5.065	4.319	9.77
10	93.00	6635920	6.636	5.833	15.60
11	93.55	8638995	8.639	4.189	19.79
12	94.11	9160716	9.161	4.983	24.78
13	95.66	11942986	11.943	16.308	41.08
14	95.77	12140000	12.140	1.325	42.41

The latest hydrographic survey in 2018 showed that the gross capacity loss was 27.66 Mm^3 (70.07 Mm^3 – 42.41 Mm^3) over a period of 89 years since the beginning of the Wyra project while the total percentage loss in the original capacity was 39.47% and the annual loss in gross capacity is about 0.311 Mm^3/ Year. As against the 3.405 ha.m/100 km2/year that was estimated during the project's planning phase, the rate of sedimentation was obtained as 6.857 ha.m/100 km2/year.

The data and the analyses show that the overall capacity of the reservoir has been decreased significantly over time, from 70.07 Mm^3 in 1929 to 42.41 Mm^3 in

2018 which is 39.47%, 45% and 70% of the original gross, live and dead storage capacities respectively. The live capacity had decreased at a faster rate than the dead storage capacity, with a loss of 20.18 Mm^3 in the live capacity compared to 7.48 Mm^3 in the dead storage capacity in 2018 respectively. The loss in capacity as a percentage of the original capacity had also increased steadily over time, from 11.23% in 1980 to 39.47% in 2018. As observed, the calculated sedimentation rate was 2.014 times to that of the value adopted during the construction of the project. The average percentage annual loss in capacity of the reservoir has been steadily increasing since the commencement of the project i.e., 0.22% in 1980 (in a span of 51 years), 0.28% in 2002 (in a span of 72 years), and 0.44% in 2018 (in a span of 89 years) which shows that the loss in the capacity during the years from 2002 to 2018 was higher than that during the years 1980 to 2002. The results of the surveys are presented in the Table 4.2. The calculations of loss in original capacity are given as under:

Table 4.2 Computation of sediment deposition in the reservoir

Sl. no.	Description		Original Survey	Hydrographic Survey		
			1929	1980	2002	2018
1	Capacity (Mm^3)	Gross	70.07	62.2	55.76	42.41
		Live	59.4	-	52	39.22
		Dead	10.67	-	3.75	3.19
2	Loss in Capacity (Mm^3)	Gross	-	7.87	14.32	27.66
		Live	-	-	7.4	20.18
		Dead	-	-	6.92	7.48
3	Loss in capacity (%)	Gross	-	11.23	20.44	39.47
		Live	-	-	12.46	33.97
		Dead	-	-	64.85	70.1
4	Sedimentation Rate (Ha-m/ 100 km^2/year)	Gross	-	3.405	4.328	6.857
		Live		-	2.236	5.003
		Dead		-	2.091	1.854

Original capacity in 1929 = 70.07 Mm^3

Capacity as per 2018 HS = 42.41 Mm^3

Loss in capacity $= (70.07 - 42.41) = 27.66\ Mm^3$

% Loss in capacity w.r.t. 1929 $= \frac{(70.07 - 42.41)100}{70.07} = 39.47\%$

% Average annual loss $= \frac{39.47}{(2018 - 1929)} = \frac{39.47}{89} = 0.44\%$

This trend showed that Wyra basin is facing significant environmental challenges, which are mostly related to human activities. The erosion increased due to deforestation and other land use changes in the basin.

The Table 4.3 shows the average annual loss in capacity over a span of 16 recent years, that is from 2002 to 2018 as 0.785 Mm^3, which indicates a steady decline in the capacity.

Table 4.3 Average annual loss in capacity

Sl.No.	Year of Hydrographic Survey	Loss in Capacity Mm^3
1	2002	14.32
2	2018	27.66
	Average annual loss in capacity	0.785

4.4 Trap Efficiency Curve

The T_e curve in Fig. 4.1 illustrates the relationship between the capacity to inflow (C/I) ratio to the incoming sediment and the percentage of sediment that is trapped within the reservoir. The curve is similar to the average or medium-grained sediment curve. This suggests that the nature and quality of the incoming sediment is medium grained sediments, thus effectively trapping sediment within the reservoir. Based on the available field data, values were plotted with (C/I) as the independent variable and T_e as the dependent variable. The regression line was fitted using the logarithmic function provided by Eqn. (4.1). According to Brune's method for the median curve, T_e = 100% for C/I > 0.70 and T_e can be represented by the Brune (Modified) equation for values of C/I ratio less than 0.70.

$$T_e = 5.9563 \ln(C/I) + 101.33 \quad (4.1)$$

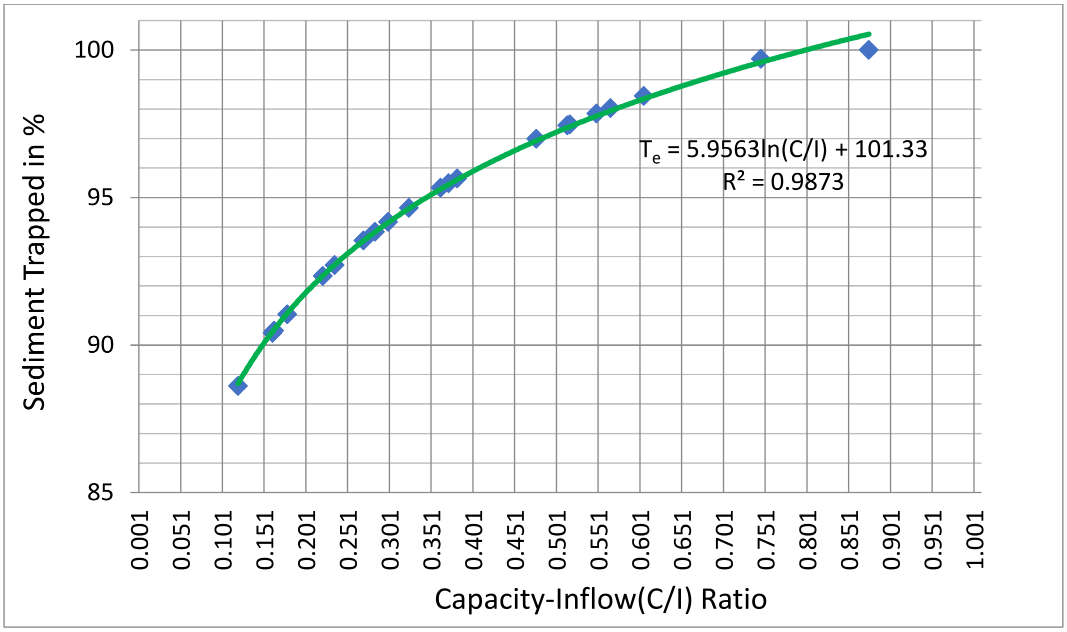


Fig. 4.1 Trap Efficiency Curve of Wyra Reservoir

From the Fig. 4.1, it can be observed that more than 50% of the capacity to inflow ratio (C/I) values are below 0.40, and sediment trapped percentage was up to 95.52%. In between the C/I ratio of 0.40 to 0.70, the sediment trapped percentage ranged from 95.50 to 99.13%. The curve demonstrated that the system is highly effective under a wide range of conditions and the sediment does not impact downstream ecosystem. The effectiveness of the system is further supported by the R^2 value of 0.98.

The T_e values shown in Fig. 4.2 as dotted points are plotted on the original Brune's T_e curve for coarse, medium and fine grain sediments. From the plot, it can be observed that dotted points closely followed the median curve of Brune's method. Table 4.4 shows a comparison of the T_e values obtained in the present work by Brune's method against the C/I ratios for the years from 2005 to 2019 with those calculated by other empirical methods viz. Brown (1943), Dendi (1974), Gill (1979), Heinemann (1981), Garg, & Jothiprakash (2008a,b). It can also be seen that the average T_e value obtained in the present work is 93.10. The values derived from the other empirical methods range from 87.40 to 94.05.

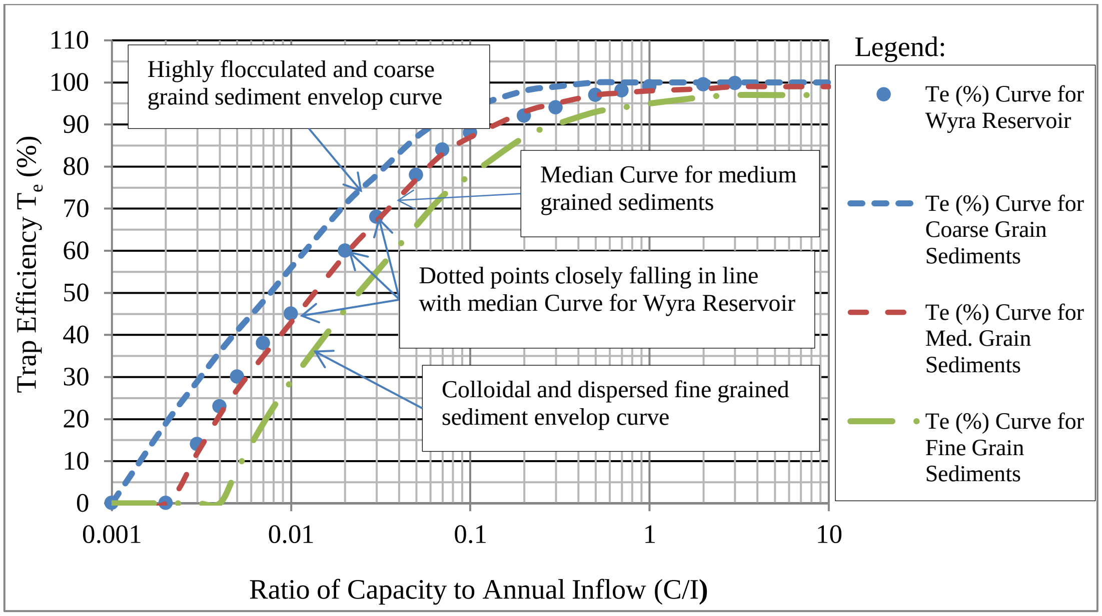


Fig. 4.2 Brune's Trap Efficiency Curve

Table 4.4 T_e values for C/I ratios (from 2005 to 2019)

Year	C/I Ratio	T_e in % as per the empirical method					
		Present Work (Brune)	Brown	Dendi	Gill	Heineman	Garg & Jothi-prakash
2005	0.14	89.68	94.56	88.26	91.21	79.07	90.51
2006	0.18	90.95	94.48	89.85	92.75	84.77	91.87
2007	0.24	92.74	94.39	91.75	94.49	90.30	93.40
2008	0.13	89.13	94.30	87.51	90.46	76.08	89.84
2009	0.69	100.00	94.22	96.10	97.96	97.07	96.40
2010	0.09	87.29	94.12	84.64	87.52	63.87	87.21
2011	0.41	95.96	94.03	94.34	96.66	95.27	95.28
2012	0.29	93.88	93.93	92.77	95.38	92.63	94.17
2013	0.13	89.06	93.83	87.41	90.36	75.67	89.75
2014	0.45	96.53	93.72	94.70	96.94	95.74	95.53
2015	0.38	95.52	93.62	94.03	96.42	94.84	95.07
2016	0.19	91.31	93.50	90.26	93.14	86.11	92.21
2017	0.41	96.00	93.39	94.36	96.67	95.30	95.30
2018	0.43	96.36	93.27	94.59	96.86	95.60	95.45
2019	0.21	92.13	93.14	91.14	93.94	88.70	92.92
Average T_e in %		93.10	93.90	91.45	94.05	87.40	92.99

4.4.1 Annual sediment rating curve

The sediment load values in tonnes which are derived by the various methods viz. Present work, Brown, Dendi, Gill, Heinmann, Garg & Jothiprakash as dependant variable and the same have been plotted against the year of sediment accumulation as independent variable in Fig. 4.3. The results obtained from this graph show that the curves almost merge or bundle together with each other, and the values of sediment load fall very close to that of the present work. This proves that all the methodologies employed in the present project are quite relevant and suitable. The graph provides a clear picture of the annual sediment rate, and it is evident that there is hardly any difference in the sediment load values obtained from the other methods. The graph serves as a validation of the employed methodologies and provides a basis for future studies in sedimentology.

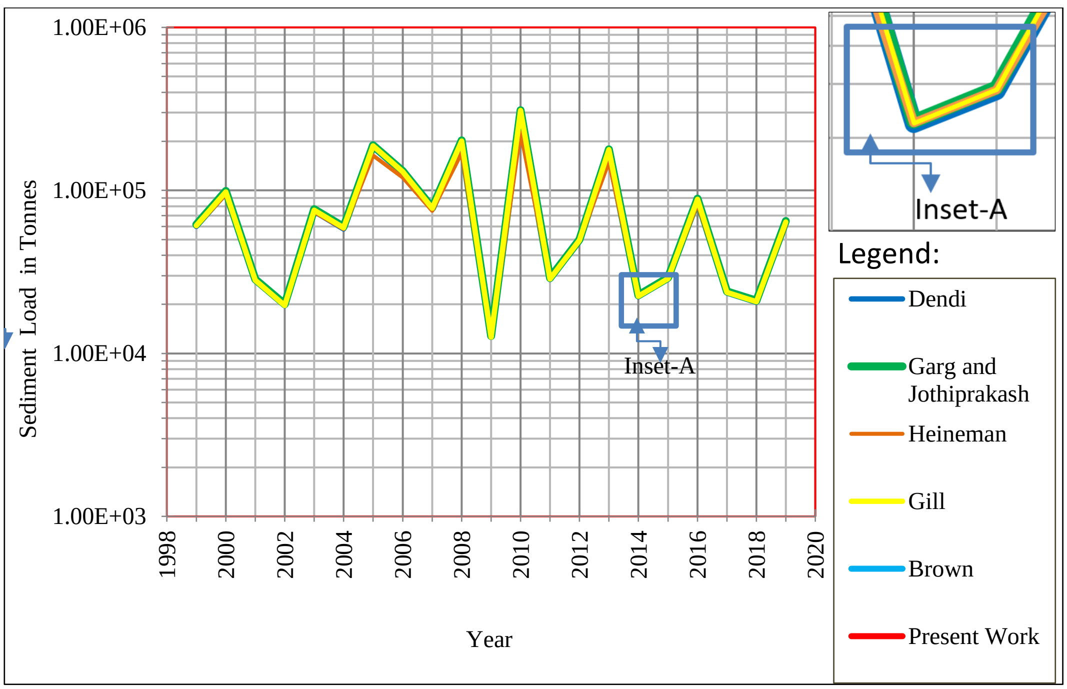


Fig. 4.3 Annual Sediment Rate Curve by Different Approaches

Table 4.5 shows a comparison of the sediment load or yield values in tonnes per km^2 for the period from 2005 to 2019 obtained in the present work with those calculated by other empirical methods viz. Brown (1943), Dendi (1974), Gill (1979), Heinemann (1981), Garg, & Jothiprakash (2008b). It can also be seen that the average sediment load or yield value in tonnes per km^2 is 138 or 1.38 tonnes/ha. The average values derived from the other empirical methods range from 141 to 121 tonnes/km^2 or 1.41 to 1.21 tonnes/ha. This demonstrates how appropriate and pertinent each methodology used in the current project is. The table clearly illustrates that there is marginal difference in the amount of sediment load or yield acquired from the other approaches which supports the methods used and a ground for further research. It is also observed that during the years 2009, 2011, 2012, 2014, 2015, 2017, 2018 and 2019, when the runoff is below 400mm, the sediment yield calculations have shown no significant difference from which it can be understood that the empirical methods produced results with much less difference especially when the runoff is below 400mm and it can be concluded that the erosion rate is also very less during that particular rainfall season.

Table 4.5 Sediment Yield (Tonnes per km^2) (from 2005 to 2019)

Year	Sediment Load or Yield (Tonnes per km^2)					
	Present Work (Brune)	Brown	Dendi	Gill	Heineman	Garg & Jyothi-prakash
2005	314	293	301	263	303	298
2006	214	203	208	192	210	206
2007	126	122	124	120	126	123
2008	338	313	322	272	324	319
2009	21	20	20	20	20	21
2010	497	536	482	496	363	498
2011	46	45	45	46	46	47
2012	79	79	78	79	78	80
2013	283	298	277	285	240	287
2014	36	35	36	36	36	36
2015	46	45	46	46	46	47
2016	140	144	139	142	132	143
2017	38	37	38	38	38	38
2018	34	32	33	33	33	34
2019	102	103	101	103	98	104
Av.	138	141	135	133	121	138
Average of all the methods						134

4.4.2 Sediment rating curve

The measured sediment concentration data of Wyra river was analysed to prepare the sediment rating curve. The sediment rating curve is an essential tool for estimating the amount of sediment that is being transported by a river or a stream. Plotting the values from the observed field data yields this curve. The independent variable is the annual inflow Q in m3/sec, and the dependent variable is the sediment load Q_s in tonnes per km2. which can be represented by the Eqn. (4.2), through the mathematical analysis, the equation for the regression line is obtained as the power function, with $R^2 = 0.876$, which indicates that the regression line is a good fit for the observed data.

$$Q_s = 0.265\, Q^{1.6131} \qquad (4.2)$$

where the value of the constant k_2 is obtained as 0.265 and the value of the constant is obtained as 1.6131 and the sediment rating curve or graph is being shown in the Fig. 4.4.

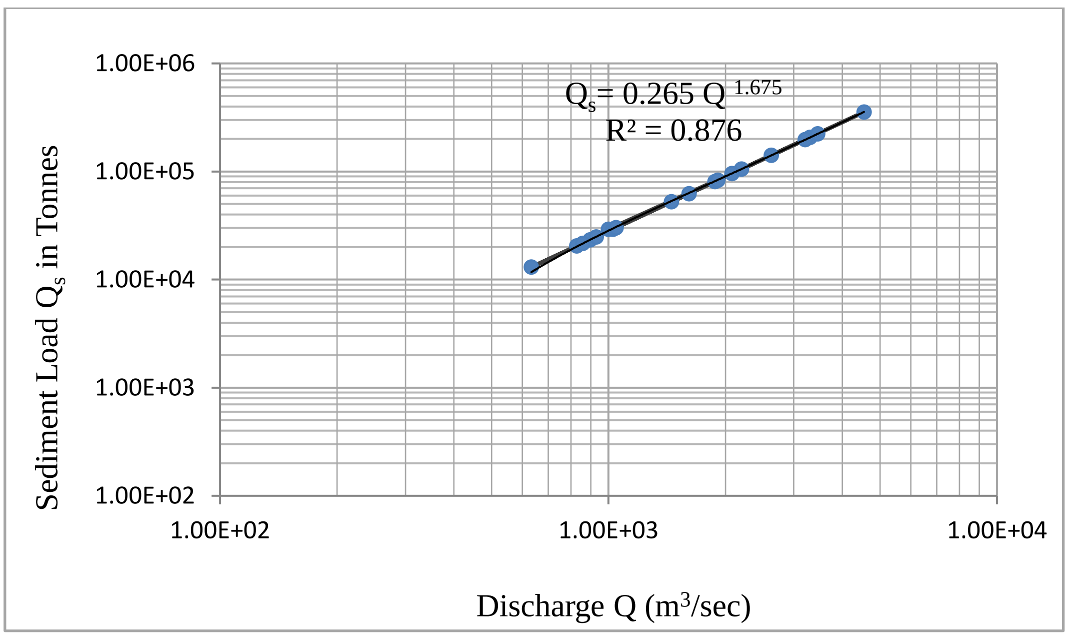


Fig. 4.4 Sediment Rating Curve for Wyra

The equation can also be used to calculate the sediment load of a river or a stream under different flow conditions. In addition, this equation can be used to study the long-term trends in sediment transport, which can provide valuable insights into the dynamics of river systems and their response to changes in the environment.

The above obtained regression equations for the study are quite appropriate and conveniently be used for other projects of medium irrigation with similar hydrological features, including the methodology adopted with minimal modifications if any required.

4.4.3 Depth vs capacity curve

The depth vs capacity curve was plotted taking the capacity in Mm^3 of the reservoir as an independent variable and the depth in m, as a dependent variable, through the mathematical analysis, a regression equation was fitted as a power function, as given by the Eqn. (4.3) with R^2 value as 0.9798.

$$D = 3.6604\, C^{0.2953} \qquad (4.3)$$

where D is the depth of reservoir in meters (m), and C is the capacity of the reservoir in Mm^3 and the inverse or reciprocal of the slope of the line is obtained as 2.75, which fits into Type-II Standard Classification, which shows that the watershed area belongs to the Flood Plain-Foothill category as per Borland & Miller classification and the same is presented in the Fig. 4.5.

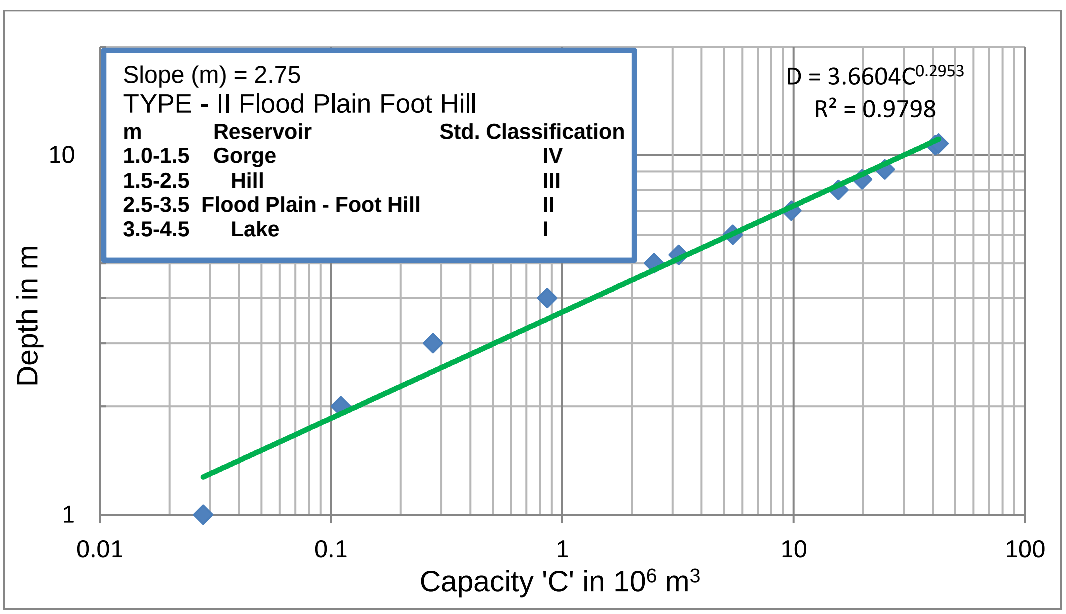


Fig.4.5 Depth Vs Capacity Curve

4.4.4 Elevation vs capacity curve

The elevation vs capacity curve as shown in the Fig. 4.6 is being plotted by taking the capacity of the reservoir in Mm^3 as independent variable and elevation in meters (m) as dependent variable and from the curve it can be understood that how the original capacity of the Wyra reservoir has been reduced continuously over the period of time from the commencement of the project to till date.

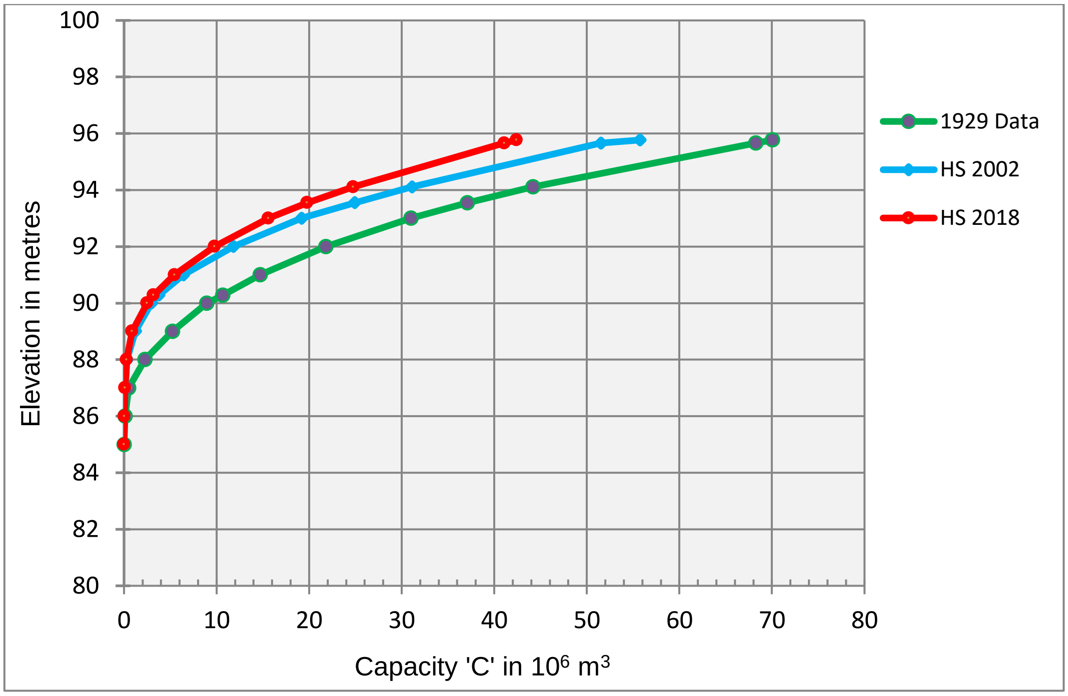


Fig. 4.6 Elevation vs Capacity

4.4.5 Elevation vs water-spread area curve

The elevation vs water-spread area curve or graph is obtained by taking the water-spread area in Mm^2 as independent variable and elevation in meters (m) as dependent variable and the curve shows how the water-spread area of the reservoir has been reduced in the extent of area on a continuous basis over the period of time since 1929 to till date and the same has been presented in the Fig. 4.7.

4.5 Swat Model Structure, Setup and Watershed Delineation

The Arc-SWAT interface user's manual was followed to apply the SWAT model to the study area. The four steps involved in setting up the SWAT model are:

(i) delineating the watershed; (ii) defining the HRU; (iii) defining the custom meteorological data; and (iv) creating the input tables.

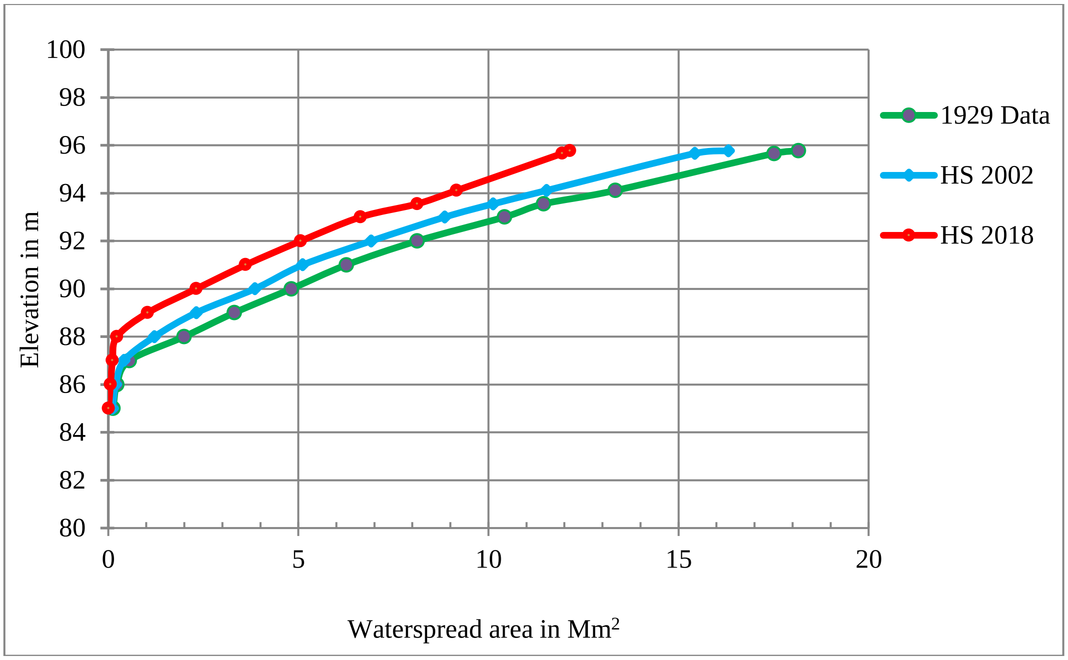


Fig. 4.7 Elevation vs Water-spread Area

Before being imported into the interface, the DEM was clipped to a size that was just marginally bigger than the watershed. To match the known stream position to the defined streams as precisely as feasible, an adjustment was made using a map of the known stream location.

From the stream network developed the digital elevation map (DEM) of Wyra watershed area, the highest elevation was found to be 279.00m, the difference in the highest and lowest elevations was 186.00m (279.00m – 93.00m = 186.00m), the length of the watershed area is about 45km and width of the same is about 25km. These are shown in the Fig. 4.8.

4.5.1 Determination of HRUs

HRUs are determined by combining different thresholds with soil, slopes, and land cover. Despite the fact that the watershed is separated into distinct HRUs, the model allows each sub-basin to have two or more HRUs. For each sub-basin, SWAT identifies a single HRU based on the predominant land cover and soil types. The user must determine a threshold percentage value of land cover and soil type for each HRU in order to have several HRUs in a sub-basin. Therefore, the threshold value for every HRU is based on slope, soil type, and land cover. The following parameter values are applied to multiple HRU's in the simulation: Soil class percentage (%) over land-cover area and land-cover percentage (%) over sub-basin area are taken as 10% each. Percentage (%) of slope class over soil area is taken as 10%.

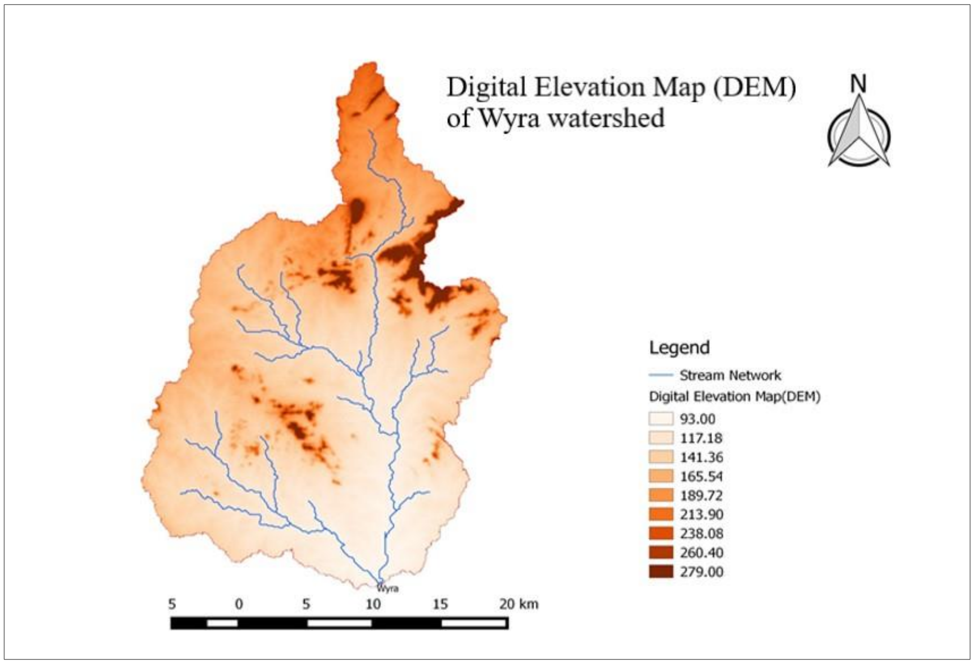
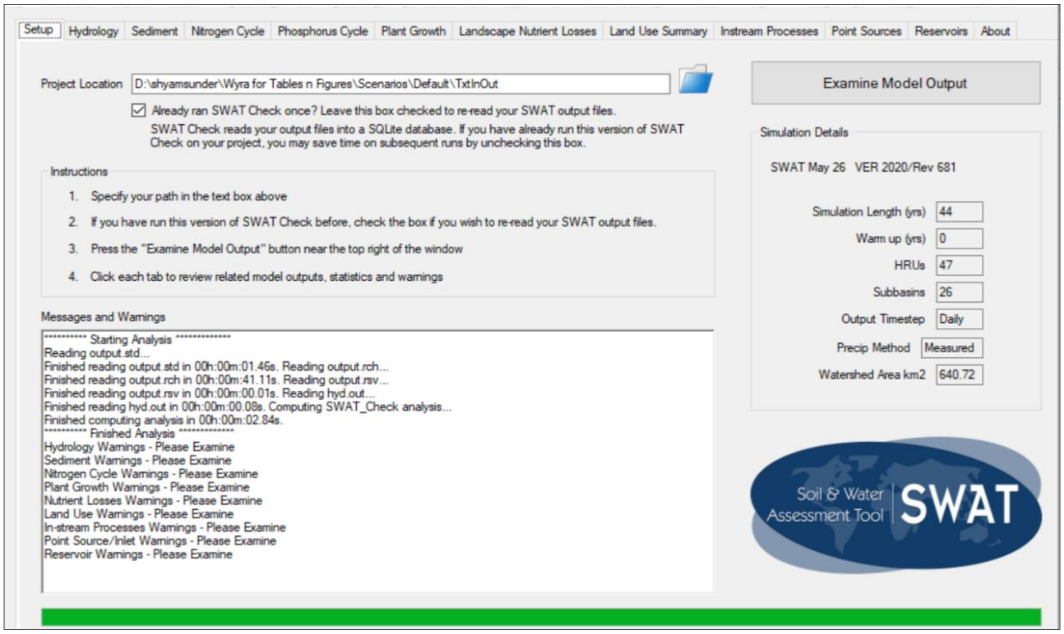


Fig. 4.8 Digital Elevation Map (DEM) of Wyra Watershed

4.5.2 Delineation of watershed area

SWAT May 26 VER 2020 Rev 681 model is used for the present study and the SWAT model output files are generated for Wyra project viz. the watershed showing sub-basins with stream network along with the setup file, the hydrology cycle map, the precipitation map, the sediment yield map, the LULC map. The Fig. 4.9 shows Wyra watershed with stream network which consists of sub-basins or sub-watersheds of 26 nos., HRUs of 47 nos., and 640.72 km^2 of watershed area and other details such as the length of period of simulation shown as '44 years', the output timestep taken as 'daily' and other hydrological details of the Wyra watershed.



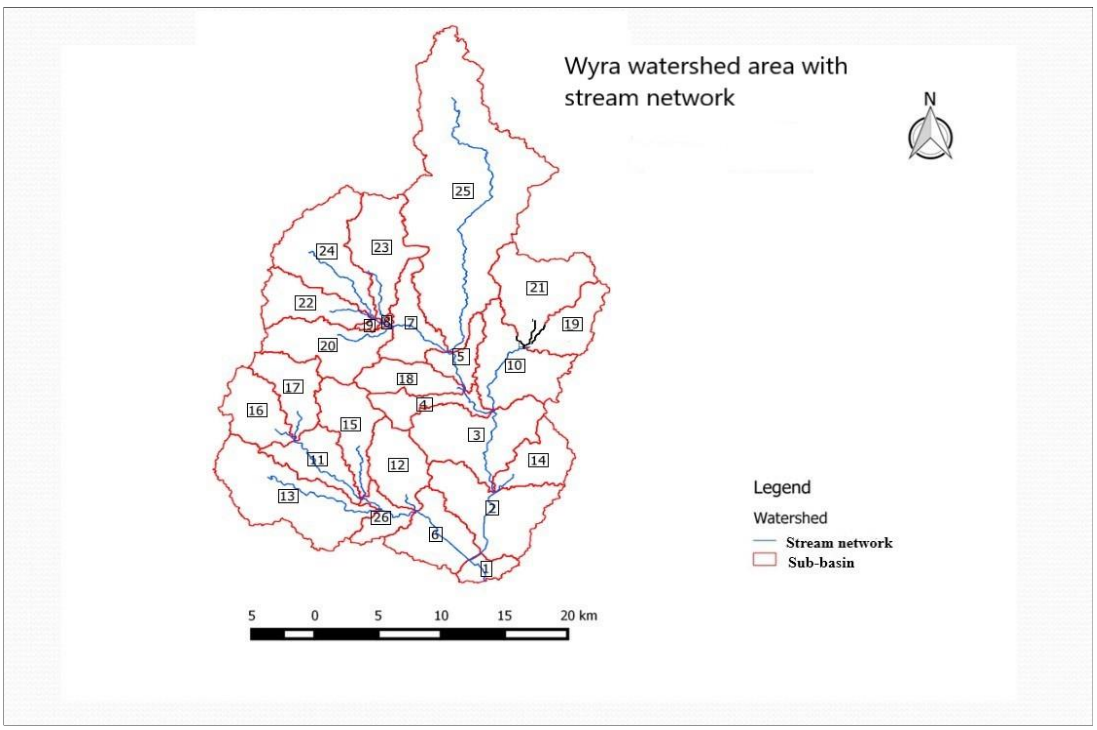


Fig. 4.9 Wyra Watershed with Stream Network

Therefore, in a SWAT model, the sequence or order of the sub-basins is obtained by the characteristics viz., topographic and flow patterns of the watershed. The numbering of the sub-basins need not be arranged in a definite sequential manner, as long as they exactly represent the hydrological processes happening within the watershed. The sub-basins 1, 6, 2, 14, 3, 10, 4, 18, 5 and 25 are adjacent to the main river course, while all the other sub-basins are adjacent to the tributaries joining the main river, from which it can be understood that the sub-basin numbering is not in a sequential order but the order follows the SWAT model's representation of the hydrological processes occurring within the watershed region based on the geographical features.

4.5.3 Hydrology cycle map

Based on the SWAT model analysis, it is found that the value of the average actual evapotranspiration (AET) was 341.9mm while the average precipitation value was recorded as 1057mm, and the average curve number was found to be 80.84. Along with that, the average surface runoff was calculated to be 325.77mm, whereas the recharge to deep aquifer was computed as 19.29mm, lateral flow was recorded as 8.37mm, percolation to shallow aquifer was 385.74mm, evaporation from shallow

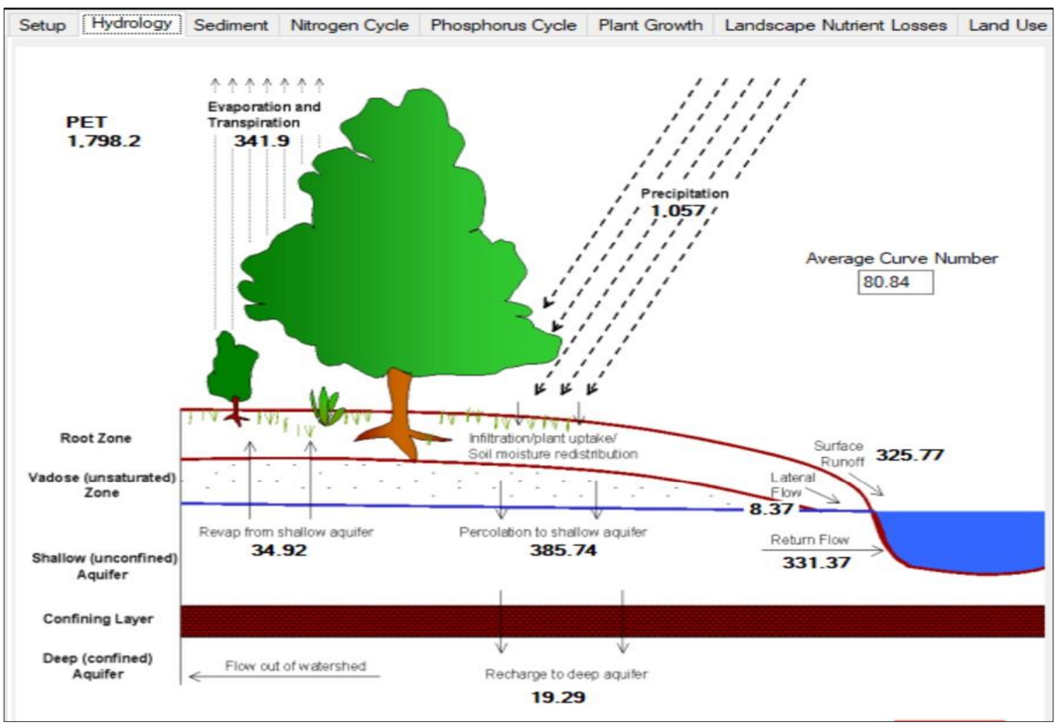


Fig. 4.10 Hydrology Cycle of Wyra Watershed

aquifer was 34.92 mm while return flow is recorded as 331.37mm. The detailed analysis and results are presented in the Fig. 4.10, which provides a comprehensive understanding of these values for the watershed area.

4.5.4 Precipitation map

The sub-basins of the Wyra are categorized both spatially and temporally, into five different groups in terms of average precipitation over the entire watershed and denoted by five different colours as shown in the Fig. 4.11, for a period of 28 years data (from 1991 to 2019). Out of the 26 sub-basins, the sub-basins 2 and 21 are having the maximum and minimum average precipitation range between 1080mm to 1100mm and 1000mm to 1020mm respectively, whereas the sub-basins 4, 15, 18 and 9 are having the average precipitation range between 1020mm to 1040mm, the sub-basins 1, 3, 5, 10, 11, 12, 13, 14 and 26 are having the average precipitation range between 1040mm to 1060mm and the rest of the sub-basins are having the average precipitation range between 1060mm to 1080mm.

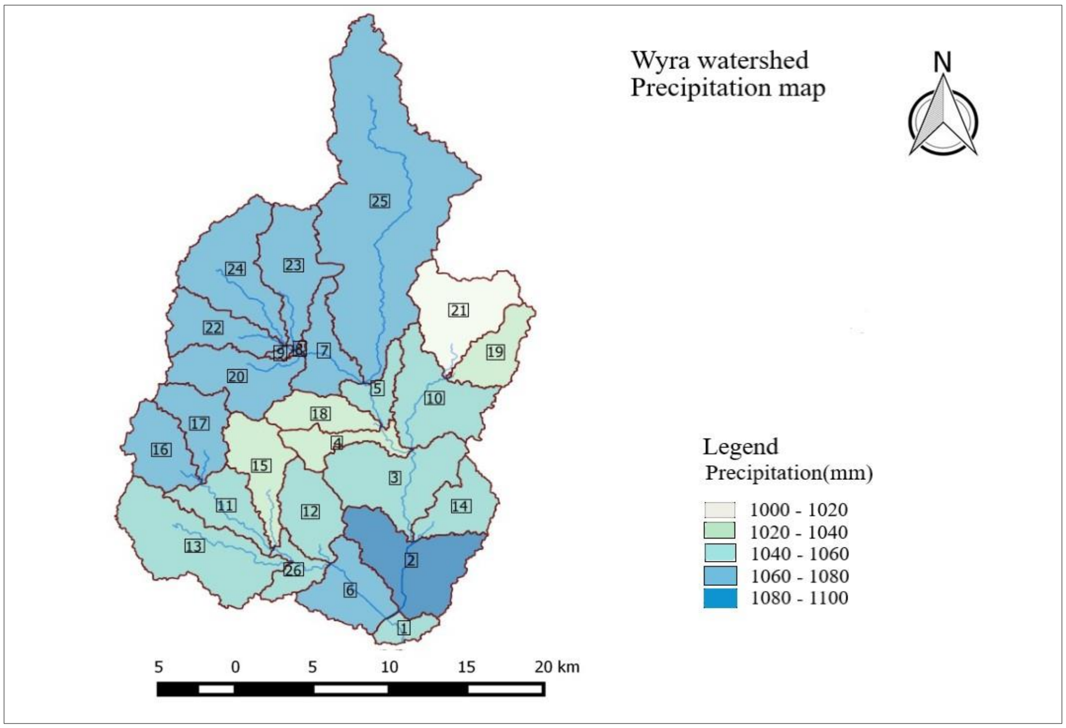


Fig. 4.11 Precipitation Map of Wyra Watershed

4.5.5 Sediment yield map

In the Fig. 4.12, schematic representation of the sediment yield of Wyra watershed area is shown which gives the essential details such as maximum upland sediment yield of 686.06 Mg/ha, average upland sediment yield of 58.24 Mg/ha, surface runoff of 325.77mm and other related details. The SWAT model analysis and results presented in the Figure provides a comprehensive understanding of these values.

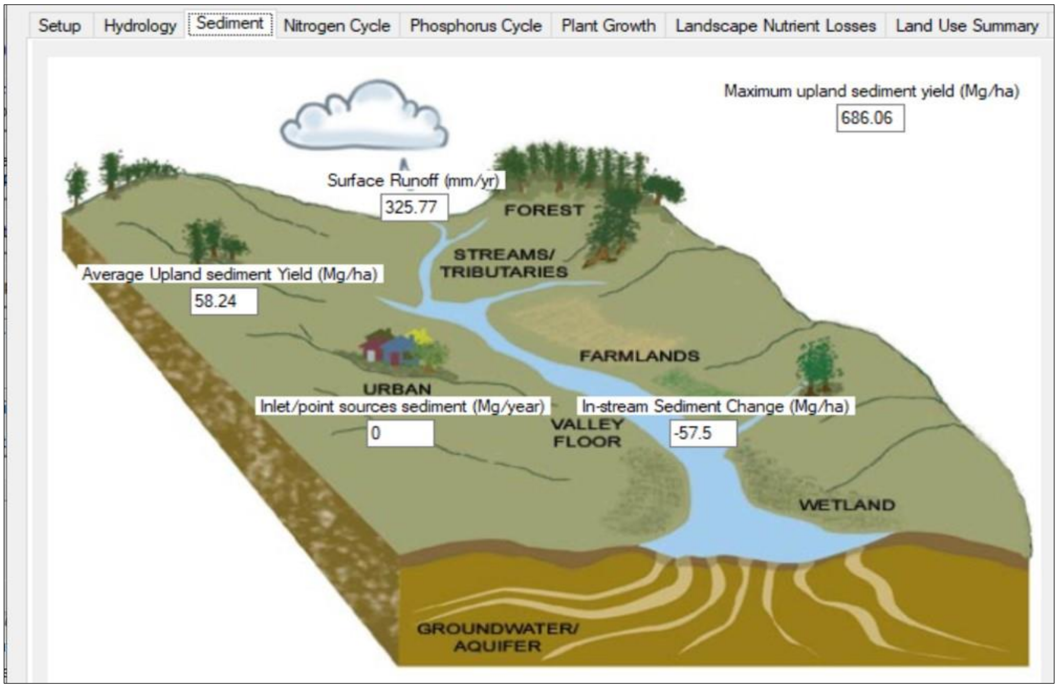


Fig. 4.12 Sediment Yield map of Wyra Watershed

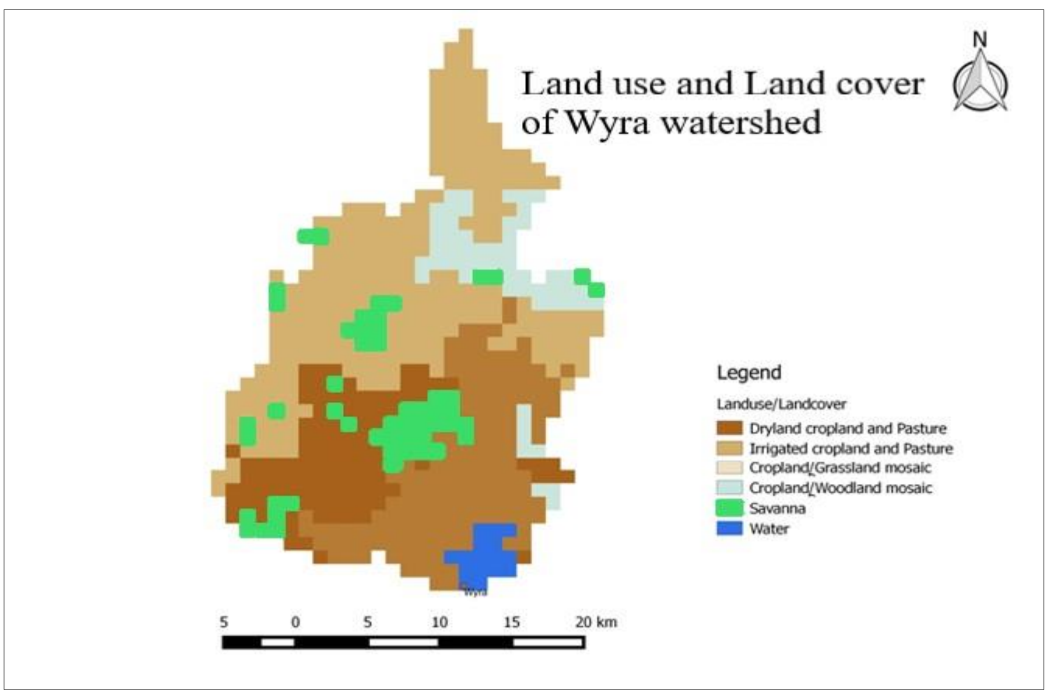


Fig. 4.13 LULC Map of Wyra Watershed

4.6 LULC map of Wyra Watershed

The LULC of Wyra watershed area was divided into six categories viz. Dryland Cropland and Pasture (CRDR), Irrigated Cropland and Pasture (CRIR), Cropland/Grassland mosaic (CRGL), and Cropland/Woodland mosaic (CRWL), Savanna and Waterbodies. Based on DEM, the soil type and he land use type are classified. The red soils completely cover the catchment region. farmland, comprising irrigated farmland (23.65%) and grassland (43.6%), makes up the majority of the watershed. Savanna (10.81%), farmland/woods (0.15%), and dryland cropland (19.17%) make up the remaining portion of the land. The remaining catchment area is covered by the water bodies. The above details are presented in the Fig. 4.13.

4.6.1 Sediment Yield Distribution Over the Wyra Watershed

Sediment yield or production of the Wyra watershed were calculated for the 26 sub-basins. Furthermore, it is examined for each one of the 47 HRUs that the SWAT model delimits within the sub-basin. River sediment yield was primarily estimated by using MUSLE. Each sub-basin's features are incredibly diverse. due to the existence of the HRUs in the basin.

It can be seen from the Fig. 4.14 that the sub-basins 5, 12, 23, and 9 were possessing a high rate of erosion which is in the range of 2000 to 1000 tonnes per km^2, (i.e., 20.00 to 10.00 tonnes per hectare) followed by the sub-basins 13, 3, 2 and 25 with an erosion rate in the range of 1000 to 500 tonnes per km^2 (i.e., 10.00 to 5.00 tonnes per hectare). Further the sub-basins 10, 4, 22 and 11 were in the intermediate level of erosion, in the range of 500 to 300 tonnes/ km^2 (i.e., 5.00 to 3.00 tonnes per hectare) followed by the sub-basins 6, 8, 17, and 7, which were having the erosion rate in the range of 300 to 200 tonnes per km^2 (i.e., 3.00 to 2.00 tonnes per hectare). The remaining sub-basins showed lower erosion, in the range of 200 to 100 tonnes per km^2 (i.e., 2.00 to 1.00 tonnes per hectare). Sub-basin wise erosion rates can be seen in the Fig. 4.14. These findings should be viewed cautiously, though the average values displayed are not consistent over each sub-basin's entire extent.

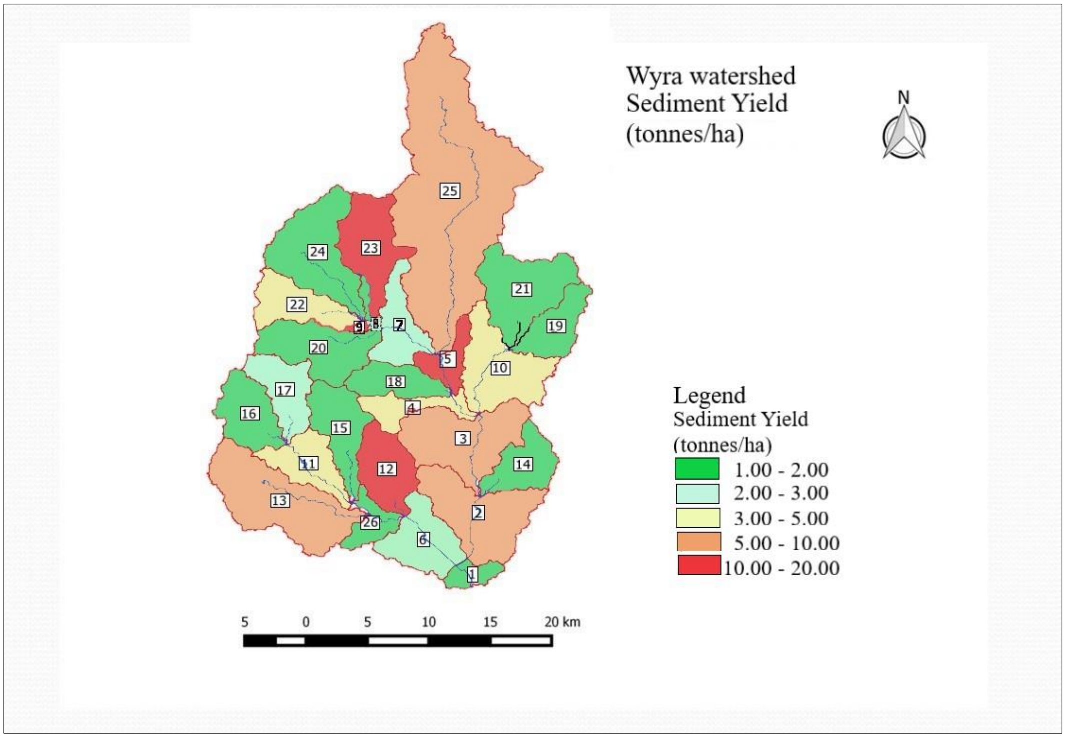


Fig. 4.14 Sediment Yield or Production in the Wyra Watershed

The sub-basins of the Wyra watershed are being categorised into five different groups in terms of sediment production in the basin and denoted by five different colours as shown in the Fig. 4.14. Out of the 26 sub-basins, there are 10 sub-basins which are producing below 200 tonnes per km^2 (i.e., 2.00 tonnes per hectare), the sub-basins which produce 200 to 300 tonnes per km^2 (i.e., 2.00 to 3.00 tonnes per hectare), 300 to 500 tonnes per km^2 (i.e., 3.00 to 5.00 tonnes per hectare), 500 to 1000 tonnes per km^2 (i.e., 5.00 to 10.00 tonnes per hectare) and 1000 to 2000 tonnes per km^2 (i.e., 10.00 to 20.00 tonnes per hectare) are four each.

4.7 Sediment Rate vs Area of each Sub-basin Analysis

It can be observed that the sub-basin 5 which is contributing the highest percentage of production of sediment (18.88%) whereas the sub-basin 24 is contributing the lowest percentage of production of sediment (1.05%). Each sub-basin's total region does not yield the average sediment volume; nevertheless, some locations experience concentrated erosion because of the unique features of that sub-basin. To look into the greater details of the erosion rate analysis, the HRUs of the model are being used and the results are presented in the Fig. 4.15

Details of comparison between the area of the sub-basin and the production of the sediment are presented in the Fig. 4.16, from which it can be observed that area wise, the sub-basins 25 and 8 are having highest and lowest values respectively.

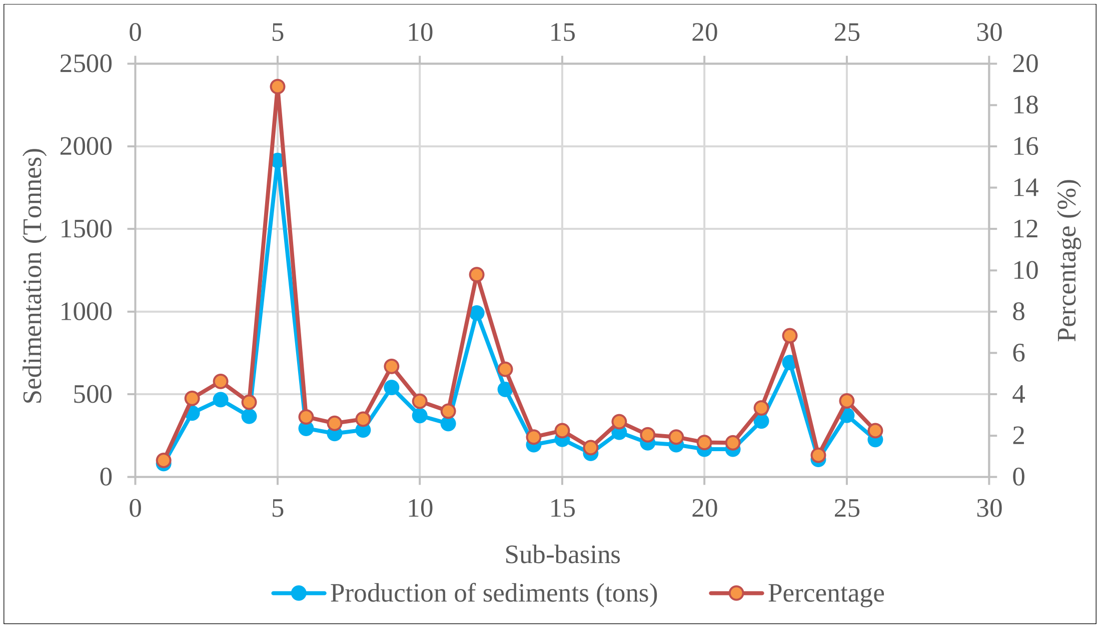


Fig. 4.15 Sediment Rate Generated by Each Sub-Basin

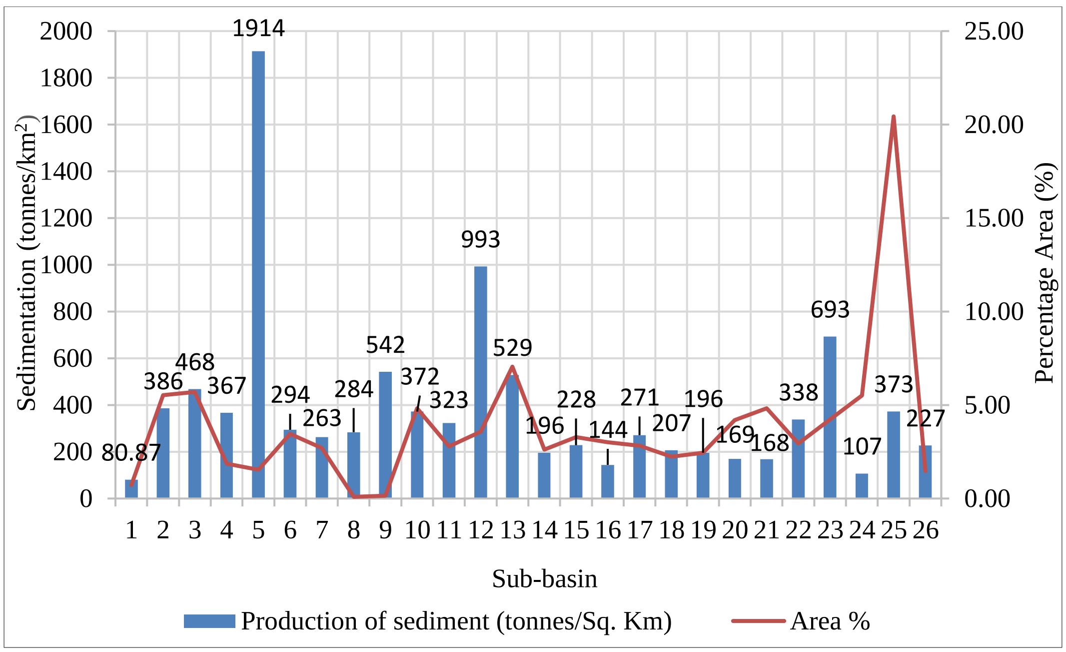


Fig. 4.16 Sediment Yield or Production vs % Area of the Sub-basin

But in terms of the sediment production, the sub-basins 5 and 1 are exhibiting the highest and lowest values respectively.

Further, it can be viewed that the sub-basins 8 and 9 are having less area but the sediment production is more. Interestingly, the sub-basin 12 which is second largest sediment producing is having an area of 3.58 km^2, but in terms of the sediment production, it is showing 993 tonnes per km^2. The sub-basins 13, 3 and 2 also follow the same pattern as that of the sub-basin 12.

4.8 Rainfall Analysis of Wyra Watershed

Data on precipitation for 21 years (from 1999 to 2019) have been used to study the distribution of rainfall in the Wyra watershed. Fig 4.17 shows that the year 2010 had the most annual rainfall of 1455 mm, while the year 2009 had the lowest annual rainfall of 700 mm. According to the literature, there was more sedimentation during the rainy years than during the regular and dry rainfall years. For this study, dry and wet years are considered as follows:

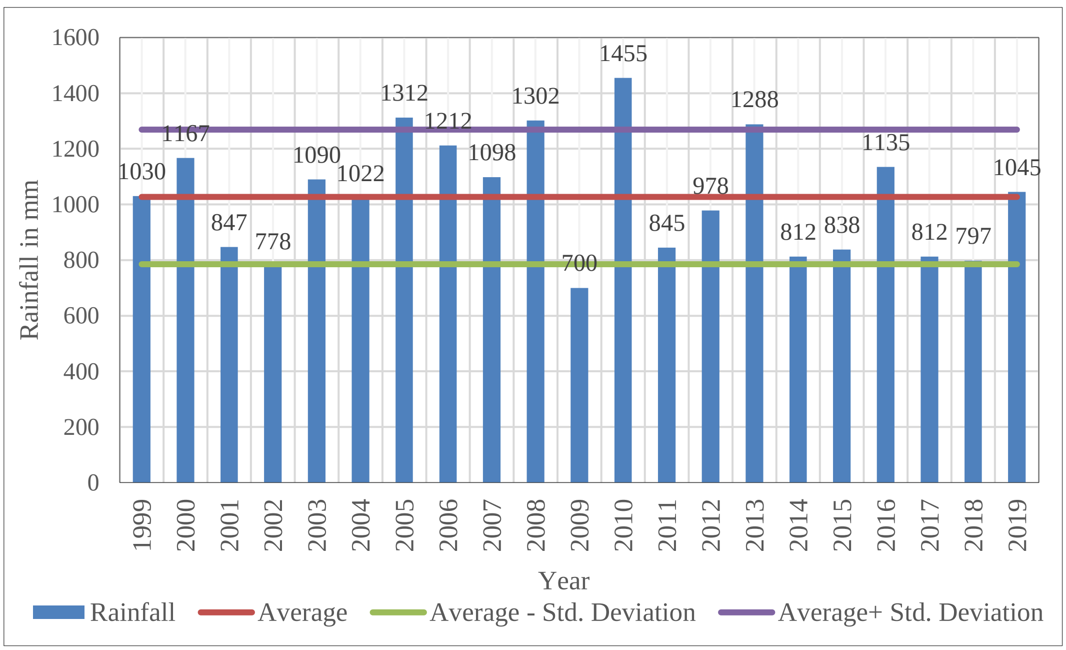


Fig. 4.17 Rainfall Analysis of Wyra Watershed

Dry years: when the rainfall values are falling below the “average – standard deviation” line.

Wet years: when the rainfall values are falling above the “average + standard deviation” line.

Normal years: when the rainfall values are falling between “average+standard deviation” and “average – standard deviation” lines.

Wet, dry, and normal years are segragated and used to ascertain how sedimentation was occurring during wet, dry, and normal years using the rainfall data displayed in Fig. 4.17. Both "the average plus standard devation line" and "the average standard devation line" were plotted in the rainfall study. Based on the yearly rainfall occurring in the watershed and its spatial and temporal distribution, these figures were taken into consideration. 1993, 1999, 2014, and 2015 were regarded as dry years, whilst the years 1994, 1995, 2005, 2006, 2008, 2010, and 2013 were regarded as wet years. The years that remain are regarded as typical years. Instead of computing for all the seasonal months, only the two wet seasons—August and September—and the two dry seasons—March and April—were taken into consideration for the examination of seasonal sediment change.

4.9 Calibration and Validation of the SWAT Model

4.9.1 The runoff or river flow model

The data pertaining to the years 2009 through 2013 were used to calibrate the SWAT model. Grain size, soil parameters, and the Shields' parameter were adjusted until the simulated and observed sediment graphs reasonably matched. The monthly total sediment load was calculated for calibration using the numbers from the daily simulation.

The monthly runoff values observed and simulated as a result of the model simulation using the pre-calibrated model are compared in Fig. 4.18 and Fig. 4.19. During the calibration and validation phases, significant disparities between the simulated and observed data may be noted, underlining the need for model calibration to achieve adequate forecast accuracy.

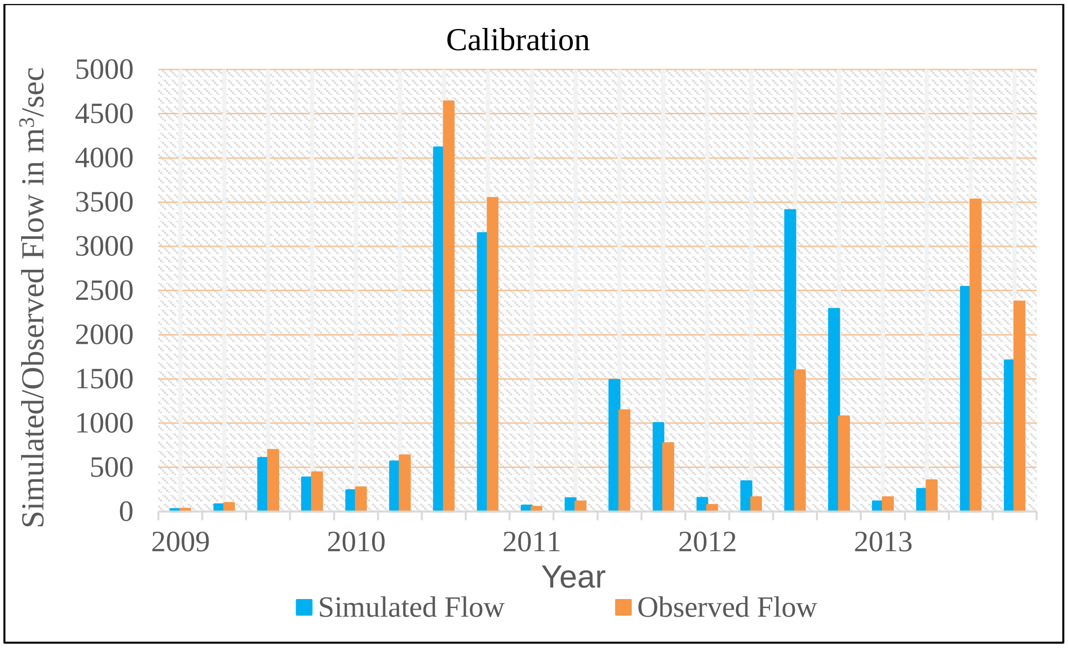


Fig. 4.18 Observed Flow and Simulated Flow During Calibration Period

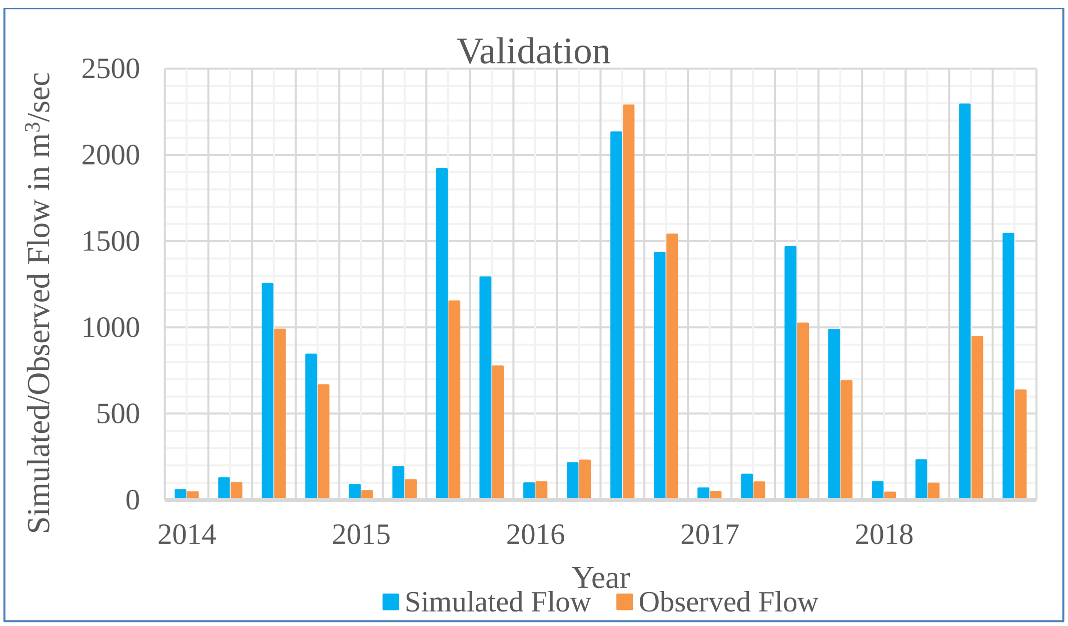


Fig. 4.19 Observed Flow and Simulated Flow During Validation Period

4.9.2 The sediment transport model

The Fig. 4.20 and Fig. 4.21 illustrates the simulated and observed sediment graph for validation. During the calibration and validation phases, there are discernible disparities between the simulated and observed data, highlighting the need for model calibration to achieve high prediction accuracy.

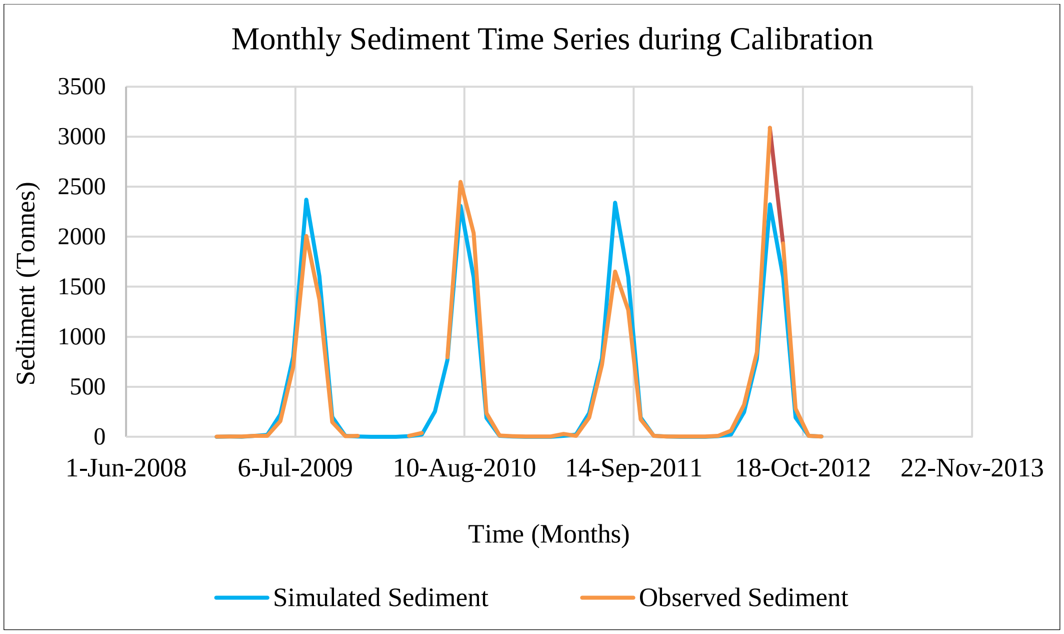


Fig. 4.20 Simulated Sediment and Observed Sediment Load during Calibration

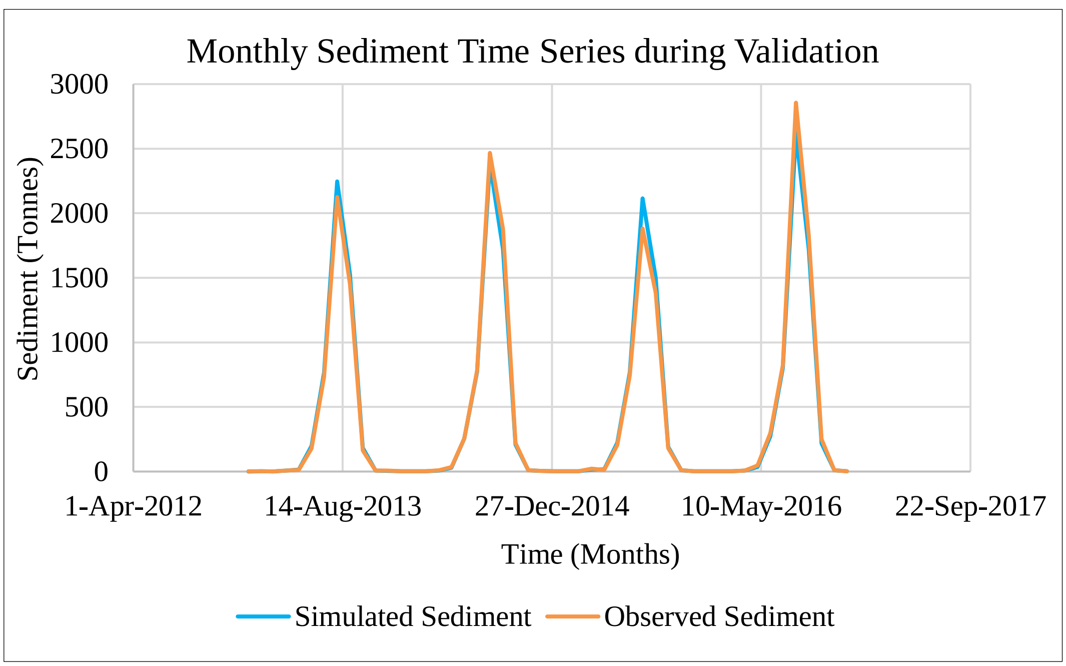


Fig. 4.21 Simulated Sediment and Observed Sediment Load during Validation

4.9.3 Model parameter determination

The data for monthly runoff and sedimentation of Wyra reservoir from 2009 to 2018 were considered for the calibration and validation of the model. The model was calibrated using monthly runoff and sedimentation data from the Konijerla hydrometric station between 2009 and 2013, and it was validated using data from the same station between 2013 and 2018. The values of final parameters after both automatic and human modifications are displayed in Table 4.6.

Table 4.6 Most sensitive parameters with calibrated values

Sl. No.	Parameter name	Physical meaning	Range	Calibrated Values
1	V_CN2	Initial SCS runoff curve number	-0.2 to 0.2	0.007
2	V_ALPHA_BF	α factor of base flow/day	0.0 to 1.0	0.313
3	R_SOL_AWC	Saturated water content of soil/(mm/mm)	-0.2 to 0.2	0.184
4	V_GWQMN	Depth threshold for regressive flow in shallow water layer/mm	0 to 5000	677.38
5	V_ESCO	Soil Evaporation Compensation Factor	0 to 1	0.1945
6	V_GW_DELAY	Groundwater delay time (days)	0 to 500	42.61

The above table contains six parameters that are used in a SWAT model. The first parameter (an empirical one), V_CN2 is the initial SCS runoff curve number, used to estimate the amount of runoff that will occur from a particular area, the value ranges from -0.2 to 0.2, and the calibrated value is 0.007. The second one, V_ALPHA_BF, represents the α factor of base flow per day used to estimate the amount of water that will flow into a stream from water sources, the value ranges from 0.0 to 1.0, and the calibrated value is 0.313. The third one, R_SOL_AWC, represents the saturated water content of soil in units of mm/mm used to estimate the amount of water that will be stored in the soil, the value ranges from -0.2 to 0.2, and the calibrated value is 0.184. The fourth one, V_GWQMN, represents the depth threshold for regressive flow in the shallow water layer in units of mm, used to estimate the amount of water that will flow out of the shallow water layer into the stream, the value ranges from 0 to 5000, and the calibrated value is 677.38mm. The fifth one, V_ESCO, represents the soil evaporation compensation factor, used to account for the amount of water that is lost due to evaporation from the soil surface, the value ranges from 0 to 1, and the calibrated value is 0.1945. The sixth parameter, V_GW_DELAY, represents the groundwater delay time in days, used to estimate the amount of time it takes for water to flow from the groundwater sources to the stream, the value ranges from 0 to 500, and the calibrated value is 42.61.

4.9.4 Evaluation of simulation efficiency

The selected two criteria for model calibration are the Nash–Sutcliffe coefficient (NSE) and Coefficient of Determination (R^2) which are being evaluated using the equations Eqn. (3.11) and Eqn. (3.12). These criteria are evaluated using the simulated and observed streamflow.

In general, the model must have an NSE value greater than 0.50 and an R2 value greater than 0.60 in order to be deemed satisfactory. Specifically, average monthly flow data from 2009 to 2013 were utilised for model calibration, while data from 2014 to 2018 were used for validation. Table 4.7 displays the assessment indices of the monthly runoff simulation effect for both the calibration and validation periods. The NSE and R^2 values for calibration and validation periods were within the acceptable and satisfactory limits.

Table 4.7 Evaluation indices of monthly runoff simulation (at Konijerla hydrometric station)

Simulation period	R^2	NSE
Calibration Period (2009-2013)	0.84	0.83
Validated period (2014-2018)	0.77	0.78

For the SWAT modelling, the data from the years 2009 to 2016 were used to calibration and the data spanning from 2013 to 2016 for sediment transport was used to validation. For both the calibration and validation processes, the same parameters were used. The model's performance metrics during calibration and validation are shown in Table 4.8. These figures demonstrate that the model's performance is very satisfactory. The amount of sediment tends to be overestimated during the validation phase.

Table 4.8 Performance measures of the model during calibration and validation for Sediment Load

Performance measure	Calibration period	Validation period
NSE	0.73	0.51
R^2	0.86	0.80

4.10 Seasonal Sediment Analysis

Two dry months, April and May, and two rainy months, August and September, were taken into consideration for the analysis in order to comprehend the season-wise distribution of sedimentation. Sub-basins 3, 4, 5, 8, 9, 12, 13, and 23 were the only ones taken into account for this analysis since, as shown in Fig. 4.9, they only accounted for 20% of the basin's erosion area, but they produced more than 57% of the watershed's total sediment output (see Fig. 4.14).

Different methods were used for the analysis of seasonal sedimentation in rainy, dry, and normal years. According to the analysis, flood years benefited more from the sediment contributed by rainy years than from normal or dry years. However, because of increased deforestation in the Wyra watershed, considerable sedimentation was also occurring during the dry season.

Fig. 4.22 displays the average sedimentation yield for each of the three periods for the chosen sub-basins and months. Flood-prone months saw production peaks, whilst during the dry season, sediment production hovers around 1 tonne per hectare.

Fig. 4.22 illustrates the variation in sedimentation between wet and dry years in comparison to typical years. It has been noted that the average sedimentation in March increases by 51% in the wet years while decreasing by 95% in the dry ones. It has been shown that August, the month that produces the most sedimentation, increases by 12% in rainy years and decreases by 28% in dry years. The seasonal analysis showed that due to the climate changes, the precipitation was being influenced and leading to the decrease and increase in the sedimentation.

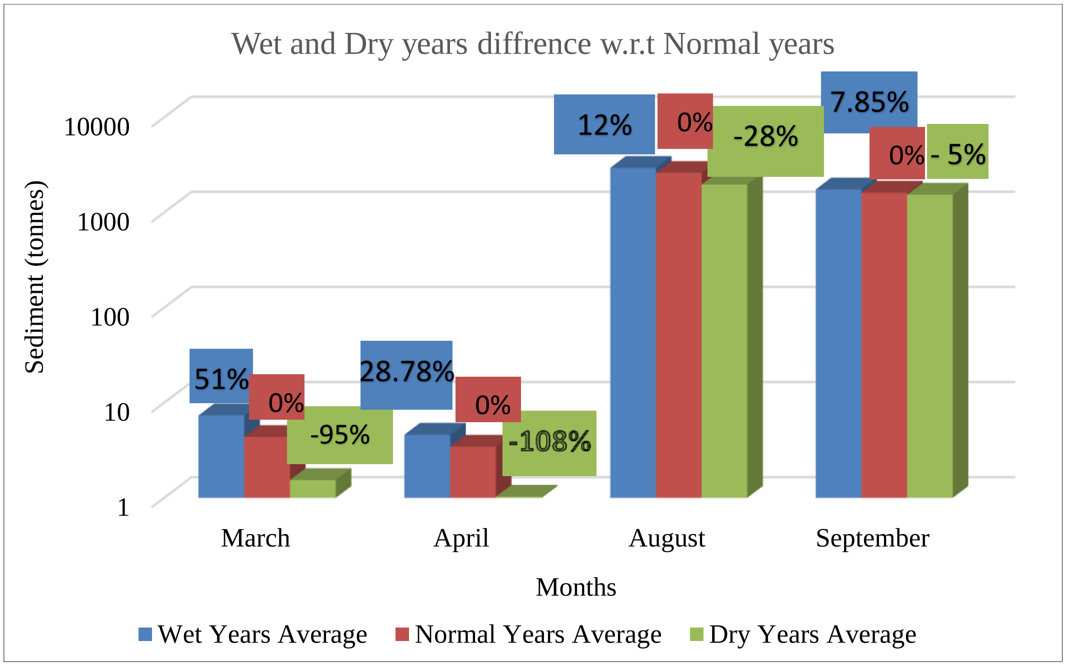


Fig. 4.22 Average Wet, Dry and Normal Years Sedimentation and Percentage Difference of Wet and Dry Years with Respect to Normal Years

4.10.1 Soil Analysis

It is evident by examining the sediments generated by each sub-basin that the kind of soil has a significant impact. Soils of the Wyra watershed can be downloaded using the NASA data-access viewer at https://power.larc.nasa.gov. Red clayey soils are seen in sub-basins 5, 7, 13, and 17, which is consistent with the main sediments produced. Nonetheless, because of its distinct qualities and the consistency of the strata that comprise it, it exhibits excellent resistance to rain erosion.

On the other hand, it can be seen that the predominant soil type is red loamy, calcareous soils and red gravelly clayey soils in the sub-basins 3, 5, 6, 8, 9 and 10 and part of sub-basins 4 and 7. The erosive capacity of this type of soil in particular is medium and yet, a high level of erosion was generated, with steep slopes and medium to intense rainfall.

It can also be seen that erosion was concentrated in this soil type with steep slopes. The use of the soil and the vegetative cover influence enormously the areas without vegetation or with poor quality grasslands, which amplify the production of sediments. Particularly the sub-basins 23, 5, 14,18 and 20 present a medium level of erosion despite the predominant type of soil, which is largely made up of red loamy, and registering less intensity in rainfall. The slopes are moderate, which leaves land use as the most determining erosive factor.

The location of crops and higher quality grasslands, are in the sub-basins 7, 8, 9, 10, 19, 20, 21. 22, 23, 24 and part of 25. Agriculture and livestock (sheep, goats and cattle) are concentrated in this area, due to the grasslands and loamy soils. The present agricultural production is mainly Rice. In this area rainfall also starts from June and the first harvest is carried out in the first days of November. The harvest date occurs when the rains are still present, causing more production of sediments.

The areas attached to the river and watercourses have a low level of erosion and eventually contain sandbanks that settle in the curves of the same watercourses. Very high quality grasslands can be found in the higher altitude locations adjacent to the water network flow, which the soil's impermeable capacity.

4.11 Summary

This chapter outlined the steps involved in sediment analysis including hydrographic survey, T_e determination, SWAT model, hydro-meteorological data acquisition, as well as the processes of sensitive analysis, calibration and validation. The applicability, ease of application, adaptability of the model in various conditions have been discussed. To study sedimentation along the Wyra river, the study used a combination of ArcGIS and SWAT approach. This approach has proven to be effective in analysing sedimentation patterns and identifying potential areas of concern. By this approach, a better understanding of the sedimentation process was gained to develop effective strategies to manage the sedimentation in Wyra reservoir.

CHAPTER 5
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

The primary goal of this thesis work is to develop a predictive model for estimating the soil erosion and the sediment yield or load from the Wyra watershed including the evaluation of the spatial variability of the sediment yield and to identify sub-watersheds which are most vulnerable to the soil erosion and sediment yield within the watershed.

While soil erosion is a very well-known problem, it is quite important to have substantial quantitative data at the micro watershed level to develop effective watershed management strategies and make well informed decisions.

The simulation of the streamflow network is considered to be another important factor to develop the effective as well as sustainable plan of action for flood forecasting, hydraulic structure design, and reservoir management. To achieve all these objectives, various models and tools are available and out of those, the SWAT model is one of the most widely used for the analysis of watershed. SWAT is particularly useful for predicting stream flow and sediment yield or load and assessing the impact of changes in the land use and the climate on a simulated watershed area.

The object of the research was to simulate and compute sediment load entering into the reservoir of Wyra, in order to evaluate the useful life span of the reservoir based on the available current data. The inflows and the sediment yield of the Wyra watershed area were simulated using the SWAT model, which was then calibrated using the data of 4 years from 2011 to 2016 and validated using the data of 3 years from 2017 to 2019. The set of 6 parameters were calibrated by automatic calibration technique available in the SWAT modelling.

The sediment yield was assessed using graphical and statistical methods, and the results were compared using the coefficient of determination (R^2) and Nash-Sutcliffe model efficiencies (NSE) during both the calibration and validation periods. R^2 and NSE had values of 0.83 and 0.84 for calibration and 0.78 and 0.77 for validation respectively. These results indicated a good match between measured and simulated sediment yield, meeting the acceptable limit of the statistical model evaluation criteria. The good performance of the model during both the calibration and validation periods, indicated that the fitted parameters during the calibration and validation periods could be used conveniently as a representative set of parameters for the study of the Wyra watershed.

The conclusions drawn from the study of sedimentation rate and T_e in the Wyra reservoir have significant implications for the management and utilization of water resources in the region. The study highlights the need for periodic hydrographic surveys to assess the capacity and rate of sedimentation in the reservoir, which can aid in effective planning and management of water resources.

The study provides basic insights into the T_e of the reservoir, indicating that the system is effective in trapping sediment within the reservoir. The T_e values obtained from the study are compared with that of the values calculated by other empirical methods. The sediment rating curve obtained from the measured sediment concentration data of the Wyra river is a good fit for the observed data, indicating good correlation with that of the measured values. The conclusions derived from the thesis on SWAT model and T_e are presented separately points wise as detailed below.

5.2 Conclusions from the Trap Efficiency Empirical Model

The hydrographic surveys conducted in 1980, 2002, and 2018 have provided valuable information about the reservoir's capacity and siltation rate. The Prismoidal formula has been used to calculate the reservoir's capacity based on the data obtained by the hydrographic survey. The following conclusions are arrived:

- The overall capacity of the reservoir in the Wyra basin has significantly decreased over time, with a loss of 39.47% of the original gross capacity in 2018.
- The live storage capacity decreased at a faster rate than the dead storage capacity, indicating a higher rate of sedimentation.
- The average annual loss in capacity had also steadily increased since the commencement of the project, with a higher loss rate observed in the years from 2002 to 2018.
- The depth vs capacity curve shows a strong correlation between the depth of the reservoir and its capacity, with a regression equation fitted as a power function.
- The T_e curve demonstrates that the system is highly effective in trapping sediment within the reservoir, with sediment trapped percentage ranging from 95.50% to 99.13% for C/I ratio values between 0.40 to 0.70.
- The T_e values obtained from the present work by Brune's method are comparable to those calculated by other empirical methods, with an average Te value of 93.10 %.
- The watershed area belongs to the Flood Plain-Foothill category as per Borland and Miller classification, with an inverse or reciprocal slope of 2.75, fitting into Type-II Standard Classification.
- The effectiveness of the system is further supported by the R^2 value of 0.98, indicating a strong correlation between the C/I ratio and the percentage of sediment trapped within the reservoir.
- The sediment rating curve obtained from the measured sediment concentration data of Wyra river is a good fit for the observed data, with an R^2 value of 0.876.
- The study's findings indicate that the sedimentation rate is greater than the reservoir's accepted figure at the planning stage. Periodic hydrographic surveys must be carried out as soon as the reservoir experiences substantial rainfall in order to evaluate the pace and capacity of sedimentation and prepare for efficient water use and watershed sediment control.

- The median curve for medium-grained sediments was closely followed by the recorded Te values of the Wyra reservoir. The investigation demonstrated that the empirical equations were yielding T_e values that were largely constant. The regression equations developed in this work can be easily used to any medium-sized irrigation project, regardless of the approach chosen, provided that any necessary small adjustments are made.

The methodologies employed in the present project can serve as a basis for future studies in sedimentology, and can provide valuable insights into the dynamics of river systems and their response to changes in the environment.

5.3 Conclusions from the Application of SWAT Model

- Of the 26 sub-basins, it has been determined that sub-basins 5 and 8 account for approximately 18.88% of the sedimentation.
- According to seasonal sediment studies, there was a 12% rise in sediment erosion in August. Overall, there was a 10.59% increase in sediment erosion during wet years and an 18.78% decrease during dry years. This suggested that the only factors affecting sediment erosion are changes in the climate and deforestation.
- The average sedimentation in March increased by 51% during the wet year while decreasing by 95% during the dry season. Dry periods also contribute sedimentation due to deforestation around Wyra watershed.
- The majority of the soils found in the research region are red clay soils with gravel. Red clayey soils can be found in sub-basins 5, 7, 13, and 17, and these soils match the main sediments produced.
- Results from the SWAT model showed that sub-basins 3, 4, 5, 8, 9, 12, 13 and 23 are having more than 20% of area from the total the basin area but contributing more than 57% of the sedimentation of the entire watershed area.
- The sediment production in each sub-basin is not directly proportional to its area. Sub-basin 5 has the highest sedimentation production, while sub-basin 1

has the lowest. Sub-basins 8 and 9 have less area but higher sediment production.

- Climate changes influence the precipitation, leading to a decrease or increase in sedimentation, affect the magnitude and frequency of extreme events which will cause more intense degradation of soil, the ecological and hydrological atmosphere in general. One of the measures to mitigate the sediment erosion changes is through the treatment of watersheds restoring the natural behavior in the river basin.
- Advanced modelling tools such as the HEC-RAS model are used to understand the complex interactions between water and sediment in river systems. The study also emphasizes the need for sustainable land use practices.
- GIS and remote sensing techniques are employed for monitoring the sedimentation process in lakes, other water bodies and developing appropriate management strategies to mitigate sedimentation problems.

5.4 The Recommendations from the Study

The findings of this research have the potential to assist various stakeholders in planning and executing effective strategies for Wyra watershed. The calibrated model can be used to further analyse the impact of climate and land use changes, as well as to investigate the effects of different management scenarios on stream-flows and sediment yields in the watershed. To prevent severe erosion and conserve the environment, it is recommended to plant vegetation in the mountainous and hilly areas and control further degradation of erosion. Some important recommended points are given below.

- Treatment strategies for watershed areas must be implemented in order to lessen sedimentation from continuous, non-point sources. Building a number of check dams or retention structures over streams, rivulets and tributaries is advised as part of watershed treatment plans.
- To improve the stability and slope of the soil, planting must be done. To filter the sediment flowing towards the reservoir, gravel basins can also be placed

near the mouth of the reservoir and at the base of the hill slopes in the watershed area. Additionally, reservoir dredging could be done.

- Plantation is required to improve the stability and slope of the soil. It is also possible to place gravel basins to filter the sediment flowing towards the reservoir at the mouth of the reservoir and at the base of the hill slopes in the watershed area. Another option is to engage in reservoir dredging.
- Reducing overgrazing, minimising mining operations, and using appropriate tillage techniques can all help to minimise sedimentation.
- In order to mitigate the consequences of severe sedimentation and increase the sustainability and viability of the irrigation project, the authorities must decide on the issue of implementation of the watershed treatment plans.

5.5 The Scope for the Future Work

- Conduct further research on the sources of sediment in the Wyra watershed, including natural erosion and anthropogenic activities, such as agriculture, mining, and construction.
- Investigate the impact of sediment on aquatic ecosystems in the Wyra watershed, including effects on water quality, aquatic biodiversity, and aquatic habitats.
- Investigate the impacts of land use change on sediment yield in the Wyra watershed, including urbanization and deforestation, and assess the potential for land use planning and zoning to reduce sediment erosion.
- Investigate the influence of soil characteristics, such as texture, structure, and organic matter content, on soil erosion and sediment yield in the Wyra watershed.
- Conduct a cost-benefit analysis of different sediment reduction strategies in the Wyra watershed, including assessments of the economic, social, and environmental impacts of these strategies.

- Investigate the impact of sediment on aquatic ecosystems in the Wyra watershed, including effects on water quality, aquatic biodiversity, and aquatic habitats.
- AI applications including advance mathematical tools may also be explored in the analysis of sedimentation analysis.

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ABSTRACT

Sediment deposition is an inherent phenomenon of any reservoir which causes considerable storage loss thereby disturbing the economy of the community for which the reservoir is intended to serve. Failure to take adequate remedial measures to control sedimentation would result in huge loss in storage capacity. Present paper provides the analysis of the field studies using the hydrographic surveys which were conducted on the Wyra Project, a medium irrigation reservoir built across Wyra, a tributary of river Krishna. The surveys were conducted during the period when the reservoir receives good rains. The principal objectives of the study are to assess sedimentation status, annual sedimentation rate in the reservoir and to estimate the trap efficiency (T_e) of the reservoir. The 'T_e' is useful for predicting the remaining useful life span of the reservoir and the pattern of sediment deposition in the reservoir. T_e is also useful in regulating the

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Modelling Runoff and Sedimentation Yield Using Soil and Water Assessment Tool for Wyra River Basin

Shyamsunder Pindi [1], Jayakumar KV [1]
Hide details
[1] National Institute of Technology, Warangal, India

CORRESPONDING AUTHOR
Shyamsunder Pindi
National Institute of Technology, Warangal, India

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RESERVOIR SEDIMENTATION ANALYSIS THROUGH FIELD STUDIES AND HYDROGRAPHIC SURVEY

PINDI SHYAMSUNDER(1), G.SURYA KIRAN(2), ERVA VENKATA RATHNAM(3) & K.V. JAYAKUMAR(4)

[1]*Research Scholar, National Institute of Technology, Warangal, India; email: shyamsunderpindi@gmail.com*
[2]*Graduate Student, National Institute of Technology, Warangal, India; email: suryakirangoud@gmail.com*
[3]*Professor, National Institute of Technology, Warangal, India: email: evr@nitw.ac.in*
[4]*Professor, National Institute of Technology, Warangal, India; email: kvj@nitw.ac.in*

ABSTRACT

The objective of the research is to analyse the field data obtained from hydrographic survey and estimate the rate of sedimentation and storage capacity of the reservoirs. In this study, two major reservoirs, namely Srisailam reservoir and Sriramsagar reservoir, in South India are considered. On the Srisailam reservoir, the soundings were recorded at an interval of 5m and on the Sriramsaga reservoir, the soundings were recorded at an interval of 2m along the predetermined ranges. Average speed of the boat for accurate data collection is usually 3.5 to 4.5 knots. The collection of data during the survey and data editing is done using Navisoft Survey software. The hydrographic surveys were conducted to the extent of maximum water level (MWL), the balance from MWL to FRL (full reservoir level) is supplemented by remote sensing techniques. The capacity of the reservoir are estimated using Prismoidal formula. From the field data, it can be stated that there is loss in the storage capacity with this sedimentation process and is about 2612Mm^3 and 850Mm^3 respectively for Srisailam and Sriramsagar reservoirs. It is estimated that rate of sedimentation is about 12.367ha.m/100km^2/year at Srisailam and 30.1ha.m/100km^2/year at Sriramsagar reservoir. It is observed that rate of sedimentation in the Sriramsagar reservoir is very high and hence authorities have to take precautionary measures.