TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS
DEPARTMENT OF CIVIL ENGINEERING

FINAL YEAR PROJECT REPORT
ON
SEDIMENT DEPOSITION ANALYSIS OF NAUMURE RESERVOIR

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APRIL 2023

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ON

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IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF BACHELOR DEGREE IN CIVIL ENGINEERING
(Course Code: CE755)

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CERTIFICATE

This is to certify that this project work entitled "sedimentation deposition Analysis of Naumure reservoir" has been examined and declared successful for the fulfilment of academic requirement towards the completion of Bachelor's Degree in Civil Engineering.

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ABSTRACT

The proposed Naumure Multipurpose project is located near Bhalubang of western Nepal. The project's benefits include hydropower production, irrigation, flood control and navigation. The proposed dam height of the Naumure reservoir is 165 m. Sedimentation deposition in reservoirs leads to the loss of the capacity of reservoirs, damaging the reservoirs and dam infrastructures thus, by sediment analysis such problems can be mitigated by making the policy. Therefore, this study aims to assess the sustainability of the Naumure multipurpose project with respect to the probable sedimentation in it.

HEC-RAS 1D is used as the numerical modelling tool for the simulation of sediment transport. Rating curve calculator using HEC-RAS is used for obtaining sediment rating curve at Chernata station and Bagasotigaon station. The submergence is extended in the main and two tributaries, so sufficient length i.e. 2.21 km for main West Rapti, 25.46 km and 18.58 km for Mari and Jhimruk River respectively from Confluence point with Main West Rapti are considered for modelling.

The Correlation coefficient obtained using observed and simulated sediment load at Bagasotigaon station for calibration of the model for three years (1985-1988) is 65.1% and the correlation coefficient using computed and simulated sediment load for Validation of model at Bagasotigaon station for three years (1990-1993) is 86.27%. Delta propagation deposition pattern is seen in the reservoirs. The percentage loss in the storage of Naumure reservoir for 10, 20, 30, 40 and 50 years are 0.61%, 1.46%, 2.39%, 3.37% and 7.4% respectively. The most influential and important five parameters: computational increment, transport function, maximum scour depth, sorting method and fall velocity method are selected for the sensitivity analysis. Among this transport function is the most sensitive parameter.

TABLE OF CONTENTS

LIST OF TABLES

ANNEX TABLE

LIST OF FIGURES

LIST OF ABBREVIATIONS

1D	: One-Dimensional
2D	: Two-Dimensional
3D	: Three-dimensional
BCR	: Benefit cost ratio
CFRD	: Concrete Face Rock Fill Dam
DHM	: Department of Hydrology and Metrology
DEM	: Digital Elevation Model
DoED	: Department of Electricity Development
DoI	: Department of irrigation
DPR	: Detailed Project Report
Et al	: and others (from Latin et alia)
FRL	: Full Reservoir Level
FSL	: Full Supply Level
GDP	: Gross Domestic Product
GIS	: Geographic Information System
GoN	: Government of Nepal
GWh	: Gigawatt hours
HEC	: Hydrological Engineering Center
HEC-RAS	: Hydrologic Engineering Centre River Analysis System
i.e.	: that is (from the Latin id Est)
IoE	: Institute of Engineering
JV	: Joint Venture
LOB	: Left Over Bank
LULC	: Land use land cover
m^3	: Cubic meter
masl	: Meters above sea level
mm	: Millimeter
m^3/s	: Cubic meter per second
MCM	: Million Cubic Meters
MDDL	: Maximum Draw Down Level

MPM	: Meyer Peter Muller
MW	: Mega Watt
NEA	: Nepal Electricity Authority
NMP	: Naumure Multipurpose Project
OLS	: Ordinary Least Square
PMF	: Probable Maximum Flood
PPM	: Parts per million
PRoR	: Peaking run of the river
PVC	: Polyvinyl Chloride
ROB	: Right Over Bank
ROR	: Runoff River
SRTM	: Shuttle Rader Topographic Mission
US	: United States
USACE	: United States Army Corps of Engineer
WECS	: Water and Energy Commission Secretariat
WSE	: Water Surface Elevation

Chapter 1: INTRODUCTION

1.1 General Background

A dam is a structure or barrier built across a river, stream, or other body of water to restrict and then regulate the passage of water. So, stopping the passage of water and forming a reservoir constitute a barrier. Dams come in a variety of sizes, from modest earth embankments used frequently for farming to tall, massive concrete structures typically used for irrigation, hydropower, and water provision. In addition to its benefits, the growth of such a structure leads to imbalances in natural systems. It causes imbalance of ecosystem and disturbance in sediment transport equilibrium (Raja & Bilal, 2012). The local, or site-specific, alterations caused by dams, especially very large dams, have been studied extensively over the last few decades. Storage of water and capture of sediment by dams cause profound downstream changes in the natural patterns of hydrologic variation and sediment transport. In natural alluvial streams, the flow discharges along with sediment are in equilibrium state and produce no any objectionable scour or deposition. When the governing factor such as flow and sediment discharge, geometry of channel, properties of water and sediment are unchanged, alluvial rivers reach to the state of dynamic equilibrium (Audusse, et al., 2012). However, if this delicate balance is disturbed by changing any of these properties through natural or man-made factors, e.g., the construction of weirs, barrages, dams, sudden change in sediment supply rate due to heavy erosion or landslide in the river basin, narrowing of river for navigation, river dredging, bend cutting, lowering of the channel bottom, etc., the river would achieve another state of equilibrium. The process of gaining an equilibrium state is accompanied by aggradation and/or degradation along the riverbed (Spreafico & Lehman, 2009).

Nepal is blessed with extraordinary water endowments in the form of snow cover, rivers, springs, lakes, and groundwater. However, its most important water resources are the over 6,000 rivers and rivulets across the country. They not only provide a reliable source of water for different purposes but, together with the steep topography of the country, also offer significant opportunities for hydropower generation. The total annual average run-off from Nepal's 6000 rivers is over 225 billion cubic meters. As surface sources, there are four main rivers—the Koshi, Gandaki, Karnali, and Mahakali;

seven medium-sized rivers, and numerous small rivers making use of the water coming from the Himalayas is the focal point of Nepal's growth plan to boost its GDP. The technical and economically feasible hydropower potential of Nepal has been estimated at 83,000 and 42,000 megawatts (MW), respectively. At present altogether 114 projects having 45,610 MW capacity has been identified economically feasible. According to Nepal Electricity Authority (NEA), the installed hydropower capacity of Nepal reached 2190 MW as of 2021. This is still far from the government’s stated aim of creating 10,000 MW of installed capacity by 2026. The Nepal Electricity Authority hopes to now achieve this by 2030, through power purchase agreements for 4,839 MW with private companies and producing 4,341 MW itself. Under Nepal’s Electricity Development decade 2016/2026, 11 storage projects with installed capacity 5373 MW has been proposed. In additional, four major storage projects are proposed and these are the Karnali Chisapani (10,800 MW) the Pancheswor (6700 MW), the Budhi Gandaki (1200 MW) and the Sapta Koshi high dam (3,600 MW) which in total, would provide 22,200 MW installed capacity (WECS, 2003). The only storage project of Nepal is Kulekhani. Its storage capacity when constructed was 85.3 million m^3. But during its 22 years of operation (1982- 2004) it had lost more than 21 million m^3 of its capacity due to the sedimentation (Sangroula, 2007).

In the Himalayas of Nepal, the high concentrations of sediments in the rivers are largely related to climatic, tectonic and geological factors. Himalayan rivers provide some of the greatest challenges in water resources development. Any river project in the Himalayas must evolve within the context of land use practices and natural phenomena like monsoon hydrology, the complex geology and the severe sediment transport (Andermann, et al., 2012). Nepal is a Himalayan country with great hydropower potential. However, sedimentation is one of the major challenges for hydropower development. Nepalese rivers have the highest sediment load compared to the rivers of other countries. The main reason for the high sediment yield is that the mountains have been uplifted rapidly and the rocks have fractured and weathered more than most geological zones in other mountains. Despite adequate availability of surface water and hence, the opportunity of development of hydropower in the Himalayas, sedimentation is one of the major challenges for the sustainable development of hydropower. There is always risk of monsoon storms in the Himalayas which sometimes creates unusual events and produces unexpected sediment loads. The sustainability of hydropower projects in the Himalayas mostly depends on proper sediment management (Regmi, 2021).

The Naumure multi-purpose hydropower project is a proposed project located on the West Rapti River in Nepal. The project is designed to generate electricity, provide irrigation water, and control floods in the region. The proposed project site is located in the Nawalparasi district in western Nepal. The project is being developed by the Nepal Electricity Authority (NEA) and is expected to have a total capacity of 220 MW. The project will include a dam, a reservoir, a power station, and transmission lines. The dam will be located near the village of Naumure, and the reservoir will be spread over an area of approximately 17 square kilometers. The project is expected to have significant benefits for the region, including providing electricity to local communities and industries, reducing the risk of floods, and increasing agricultural productivity through irrigation. However, there are also concerns about the potential environmental and social impacts of the project, including the displacement of local communities and the loss of biodiversity. The project is currently in the planning and development stage, and the NEA is conducting feasibility studies and consultations with stakeholders. The project is expected to take several years to complete, and construction is not expected to begin until all necessary approvals and permits have been obtained.

1.2 Problem Statement

Development of a country can be evaluated by the amount of energy it consumes. Energy is very important medium for the overall development of a nation. Hydropower is one of the most prominent resources for future economic development of country. Nepal has to import most of the types of fuel, paying large amount though being extremely rich in water resources. So, the proper utilization of water resources is required for the development of the country (Raja & Bilal, 2012). Though Nepal has huge hydropower potential and water resource, it has faced energy crisis for several years because most of the hydropower projects in Nepal are based on the river run-off schemes except Kulekhani-I & II (92 MW). The ROR type hydropower projects do not able to meet the power crises especially during dry season of years. So, Storage schemes are quite essential to meet the Peak demand and power crisis. But sedimentation in the reservoir is the major issue in this type of project (DoED, 2019). Some previous studies showed that over 40,000 dams exist in the world, the total estimated storage capacity of these reservoirs as a volume worldwide is about 7000 km^3 that is operated for different purposes (Palmieri A. , et al., 2003). It is estimated that approximately 0.5 percent to 1 percent of storage volume of the water is lost annually because of sedimentation. Reservoir sedimentation causes the loss of live storage of the reservoir storage capacity, reducing the useful life of dams. Thus, to ensure that sediment accumulation will not impair the functioning of the reservoir during the useful operational economic life of the project, sufficient sediment storage capacity should be provided for the reservoir design stage (Imanshoar, et al., 2014). Thus, this study helps in gaining an insight into the prospective behavior of sediment transport, estimation of which provides a background for policy making. Some of benefits of such studies may include estimation of possible expenditure in coming years to remove deposited sediments and approximation of the dam life to serve its intended purposes.

1.3 Objectives of the Study

The main objective of this study is to assess reservoir sustainability with respect to sedimentation of the proposed Naumure Multipurpose Project.

The specific objectives to fulfill the main objectives are:

i. To assess sediment deposition pattern in the Naumure Multipurpose Project reservoir.
ii. To determine storage loss due to sedimentation in the Naumure Multipurpose Project reservoir during its useful life.
iii. To perform sensitivity analysis of the sediment transport model parameters for the study area.

1.4 Scope of the Study

This study is mainly focused on the sedimentation study of the proposed NMP Reservoir whose dam is located near Bhalubang of the West Rapti River. Sediment transport model is set up using quasi unsteady sediment transport in HECRAS.

The study covers the following scope of works.

i. Collection of Climate, water discharge and stage, sediment discharge data and Digital Elevation Model (DEM) of the study area.
ii. To calibrate and validate the developed model based on results comparing with measured data.
iii. To assess sediment deposition in the reservoir of the proposed NMP.

iv. To determine storage loss due to sedimentation in the NMP reservoir during its useful life.
v. Perform sensitivity analysis of different model parameters used for calibration in the sediment model.

1.5 Limitations

The study of sediment is a complex phenomenon in which lots of parameters have to consider which may not be possible. So, Limitations of study are listed below:

i. Numerical modelling is performed using HEC RAS 1D, which means that it can only model the sediment transport along the length of river and it does not consider change in velocity along the depth or width of the river.
ii. Sufficient data were not available for the Manning's roughness calibration.
iii. Data for the bed gradient and flux gradient were not available.
iv. Transversal movement of water, meandering, point bar formation etc. are ignored in 1D Model.
v. The long-term sediment data is not available. The sediment data available for Jhimruk (station no. 339.5) is from 2010 – 2014 and 2017; West Rapti (station no. 350) is from 1985-1990 and 2016 – 2020.
vi. The temperature of water is taken 18°C throughout the year.
vii. Digital Elevation Model (DEM) of 30m resolution is used for extraction of geometric data which could not properly represent the actual topography of the study area.

1.6 Organization of the Report

There are six chapters in this project report briefed below in order.

Chapter 1 incorporates introduction with general Background, statement of problem, objective of Study, significance of study and limitations of the study.

Chapter 2 provides the summary of literature reviewed during the course of this thesis.

Chapter 3 provides description of study area selected for this study.

Chapter 4 contains methodology of research which includes analysis of field data, model setup, sensitivity analysis, calibration and validation and reservoir sedimentation.

Chapter 5 includes the results obtained and their discussion, recommendations and limitation of analysis.

Chapter 6 includes the conclusion of the study showing how the research objectives were fulfilled by this study and recommendations for the overcoming of limitations for future.

Copyright, Acknowledgement, Approval Page, Abstract and abbreviations, List of Figures, List of Table, List of Annexes and Table of Content are given in preface section. References and Annexes are attached at the beginning of this report.

Chapter 2: LITERATURE REVIEW

2.1 Project Studies on Main Rapti River Course

The first departmental study for a storage dam on West Rapti was centered to a location that will generate sufficient flow for the fulfillment of year-round irrigation water requirement to available agricultural lands in Nepal. The site was identified in the upstream of East-West highway bridge over Rapti at Baglung. After the investigation of site, commandable irrigation areas were determined through appointment of an international consultant, Lahmeyer International of Germany on November 26, 1974.

The study report was produced in June, 1976 titled “West Rapti Multipurpose Project: Prefeasibility Study”. The report shows irrigation area between 40,350 ha to 111,065 ha with hydropower production from 92 MW to 135 MW in terms of installed capacity and 400 GWH/yr to 996 GWh/yr in terms of average energy production. After that WECS (Water and Energy Commissioned Secretariat) conveyed a team for the reconnaissance level survey through walkover to inspect the possibility to shift the dam site upstream. The site was identified at Naumure at about 200m downstream of the confluence of the Jhimruk and Mari khola by the team. The further survey and investigations were then undertaken by the Nepal Electricity Authority, NEA. After examining the various alternative dam sites in the vicinity of WECS dam site, the final dam and headwork site were decided to be located 1.5 km downstream of the confluence of Mari khola and Jhimruk Khola. The final report of the Naumure Multipurpose Project was produced in July 1988 (Shrestha, 2016).

The NEA then upgraded its study to prefeasibility level in 1990, the dam height was reduced to 190m (maximum), this made reduction in gross storage, installed capacity and annual energy to 1021 x 10^6 m^3, 245 MW and 932 GWh respectively. But irrigation components were not included in the study.

The review study further undertaken in 2001 reduced dam height to 169m, hence, reducing gross storage, installed capacity and annual energy to 810 x 10^6, 207MW and 844.5 GWh. In both studies conducted by NEA the BCR was close to unity i.e. 0.995 in 1990 study and 1.03 in 2001 study (Shrestha, 2016).

The Department of Irrigation (DoI) commissioned an independent new study in May, 2003 by employing a Joint Venture (JV) of local consultants comprising an East consultant, Hydropower Engineering Services and Nepal Consult. The project was entitled as “Preliminary Study of West Rapti Multipurpose Project”. Its final report was submitted in March, 2004. The study gives higher priority for irrigation water supply to Kapilvastu sub-project as no other dependable alternate source than West Rapti river source.

On the other hand, nationwide master plan study was conducted by Japan International Cooperation Agency (JICA) and Ministry of Energy (MoE), Government of Nepal with the NEA as counterpart agency. Its final report submitted on March 20, 2014 recommended the Naumure (245MW) storage hydropower project commissioning in the fiscal year 2030/2031 BS (Shrestha, 2016).

Now the Department of Electricity Development (DOED) is intending to take the EIA and feasibility studies of Naumure site under new project name as Naumure Multipurpose Project in the assistance of foreign consultants in association with local consulting firms (Shrestha, 2016).

But the hope of speeding up the construction work of Naumure Multipurpose Project is turning into hopelessness. During the visit to India of then Prime Minister Puspha Kamal Dahal, India promised to build the project as a gift but in August 2014 AD the government decided not to supply water to India and build the project on its own. A budget of Rs 128 billion has been estimated for this. The fate of Naumure Multipurpose Project is hanging in the balance as no progress has been made to prepare its Detailed Project Report (DPR) (Bhandari, 2018).

2.2 Reservoir Sedimentation

Sedimentation can be defined as the process in which soil particles are eroded and transported by flowing water or other transporting media that gets deposited in water bodies like reservoirs and rivers as layers. It is a complex process that changes with sediment yield, rate of transportation and mode of deposition. The construction of the dam in a river affects its physical and hydraulic characteristics, by reason of the reduction of flow velocity and also turbulences. The passive pool behind the dam will create favorable conditions for the sediment settling which results in loss of important storage. The reservoir siltation may affect dam safety and reduces reservoir lifespan. A study conducted on world’s 145 major river rivers with consistency long terms records shows that about 50% of the rivers have statistically a significantly downward flow trend due to sedimentation (Walling & Fang, 2003). The global reservoir storage capacity is about 6000 km^3 and reservoir annual sedimentation is about 31 km^3 (0.52%) which means at this rate, the global reservoir capacity will be reduced to 50% by 2100 (Sumi & Hirose, 2009). About 0.5% to 1% of the total reservoir volume of water stored in reservoirs in the world is annually lost due to sedimentation (Morris, Annadale, & Hotchkiss, 2008).

Due to this reason sedimentation has become a hot topic and numerous researchers have developed numerical models for computing sedimentation rate in the rivers. However, the behavior of the sediment has not been explored completely that’s makes it a challenging issue. So, over the years various numerical and physical methods have been developed to predict reservoir sedimentation (Merritt, Letcher, & Jakeman, 2003).

As the water gets impounded after the construction of the dam, it will form a reservoir upstream and change the flow regime of the river due to back water effect. The flow velocity and rivers ability to transport sediment will get decreased due to increase of the flow cross sectional area of the river before entering the reservoir. Finer sediment enters the reservoir and may also travel to the vicinity of the dam site. The dam will prevent the flow of most sediment downstream and will get passed out through runoff on the spillway and the bottom outlet (Grade & Raju, 1985). The sediments may be suspended or bed load entering the reservoir. Coarse materials are transported as bed load along the topset delta deposits whereas the fines are transported deeper into the reservoir either by stratified or non-stratified flow. The pattern of deposition is affected by various factors such as nature and properties of sediment, discharge of water, shape and operation mode of reservoir, quantity and size of sediment entering the reservoir (USBR, 1987).

The sediment deposits within the reservoir is divided into three zones. They are topset beds, foreset beds and the bottomset beds which is shown in Figure 2-1. The topset beds is the delta deposits which are composed of coarse sediment with trace amount of fine particles. It extends from the point where the backwater curve ends to downstream limit of the bed material transport in the reservoir. Foreset deposit are the advancing part of delta deposit towards the dam in the reservoir. They differ from the topset beds by an increase of slope and decrease in the grain size. The bottomsets beds are fine sediments deposited beyond delta close to the dam by non-stratified flow or turbidity current (Fan & Morris, 1998).

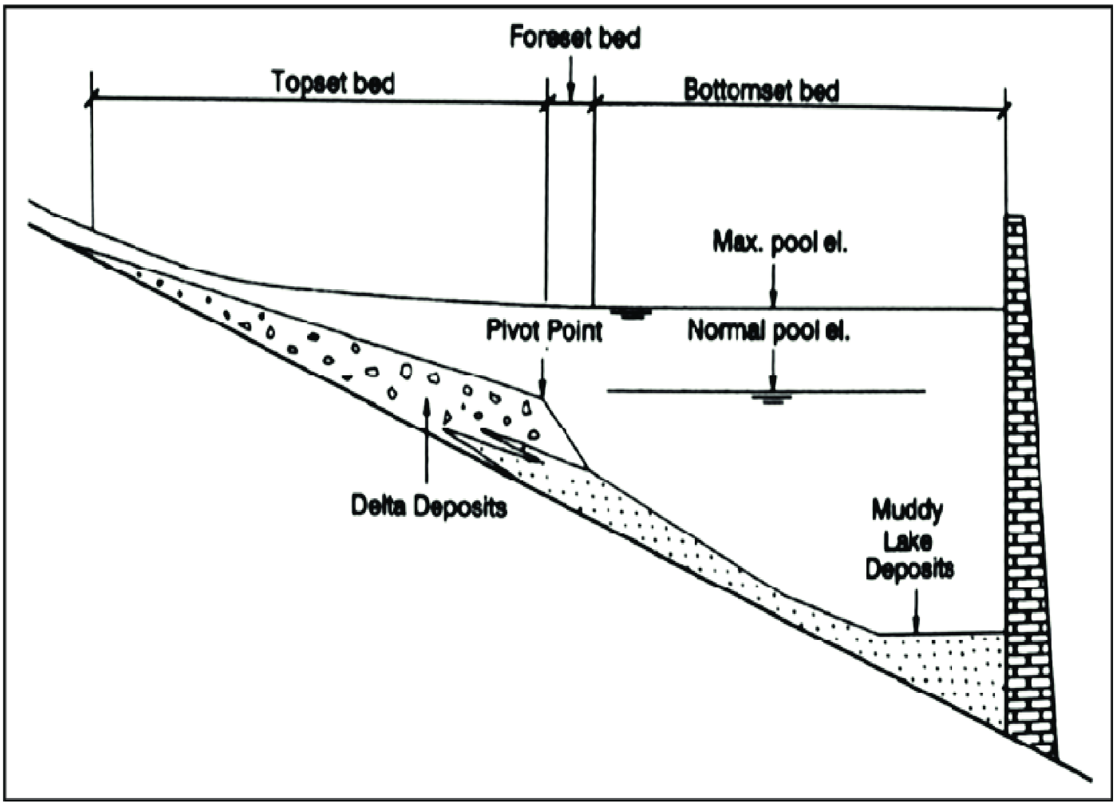


Figure 2-1 Sediment deposit zones in reservoir *(Fan & Morris, 1998)*

2.3 Reservoir Trap Efficiency

The amount of sediment deposited within a reservoir depends on the trap efficiency.

In general, the amount of sediment accumulated in a reservoir is expressed as the percentage of the inflow sediment quantity, known as sediment Trap Efficiency (TE).

$$TE=\frac{Amount\ of\ sediment\ deposits}{Amount\ of\ sediment\ inflow} \tag{2.1}$$

The trap efficiency is dependent on several parameters, like sediment size distribution; the time rate of water inflow to the reservoir; the reservoir size and shape; the location of the outlet structure and water discharge schedules; the reservoir detention time; the reservoir capacity inflow ratio (Campos, Three-Dimensional Reservior Sedimentation Model, 2001), (Fan & Morris, 1998).

(Campos, Three-Dimensional Reservior Sedimentation Model, 2001) noted out the main variables on which TE depends.

These are:

i. The inflowing sediment size distribution
ii. The reservoir operation
iii. The reservoir detention time, Td
iv. The reservoir capacity inflow ratio, C/I

The sediment size distribution has influence on TE because a sediment load composed of coarser particles will be trapped in a bigger amount compared with another composed of finer sediments. This happens since the fall velocity of the bigger particles is higher. Then the consequence is the deposition of the coarser particles in a shorter time avoiding their release. The manner in which reservoir is operated during different times of a year has direct impact on TE. Maintaining low water level during floods will increase the flow velocity and consequently the turbulence. The increased turbulence will reduce the TE by discharging the sediment load over the dam. If a dam is equipped with sluice gates, these must have maintained open during floods to permit the sediments to be flushed. (Campos, Three-Dimensional Reservior Sedimentation Model, 2001) cited (Brune, 1953) who observed that if a reservoir is flushing water at the same time as the occurrence of density currents, the flushing of sediments can be multiplied by three of four. The reservoir detention time T_d is the average time that the water remains in a reservoir. It is the ratio of the reservoir capacity and annual average affluent flow as given in equation 2.2.

$$T_d = C/Q \qquad (2.2.)$$

T_d is the detention time, C is the reservoir capacity and Q is the reservoir annual average affluent flow. A long T_d indicates that the inflowing water remains in the reservoir for longer time thereby enabling the bigger part of the sediment load to be deposited.

The ratio of reservoir capacity to the annual inflow C/I is a very popular variable used in trap efficiency computations and quite often related in literatures. C/I is a dimensionless variable and do not have any theoretical basis but, reviewing the literatures, it seems that C/I gives the best relationship between TE and the reservoir characteristics.

Many empirical studies showing the relation between reservoir storage capacities, water inflow, trapping efficiency are reported in the literature. Most of the methods define relationship of TE with the capacity and average annual inflow parameters of the reservoir, generally through curves. Researchers like (Churchill, 1948) and (Brune, 1953) have devised methods to estimate the TE. (Campos, Three-Dimensional Reservior Sedimentation Model, 2001) cited (Gill, 1979) saying that the first estimating method to be published was the pioneer work by Brown in 1934.

(Brune, 1953) developed rating curve relating TE to capacity (V) to annual average inflow (I) ratio presented in Figure 2-2, which is extracted from (Morris & Fan, 1998). Brune's curve is widely used for estimation of sedimentation in reservoir.

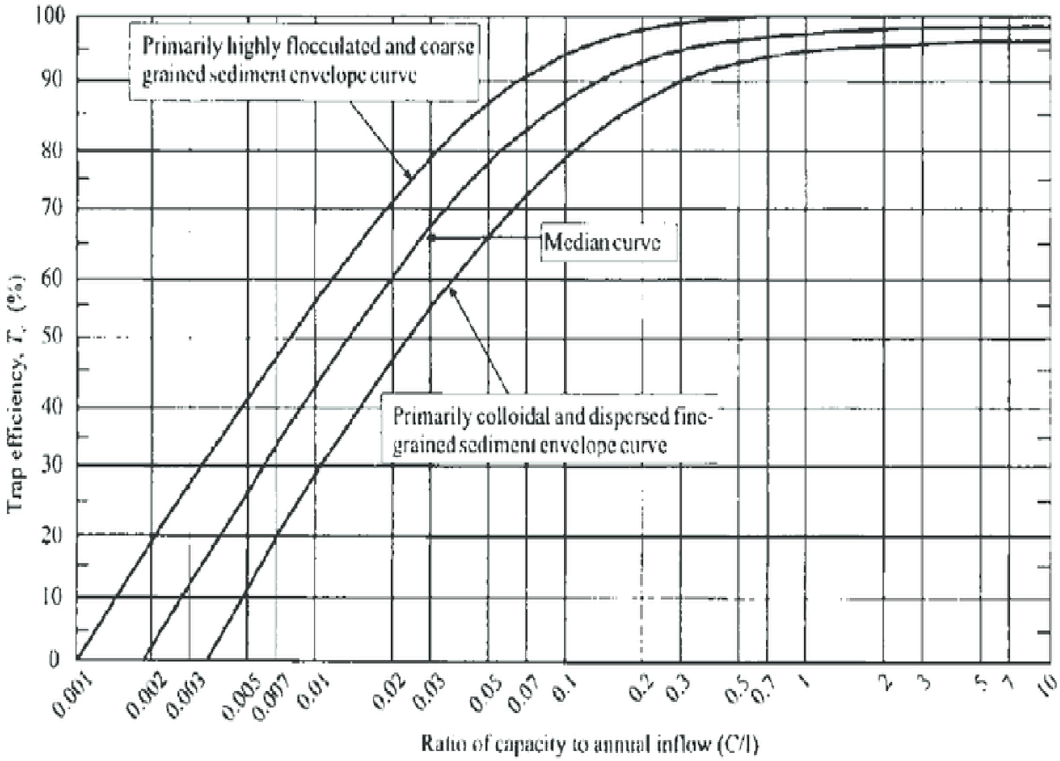


Figure 2-2 Brune Curve (Brune, 1953)

The curve can be presented as:

TE = $100 \times 0.97^{0.19^{Log(V/I)}}$ (2.3)

Where,

TE= trap efficiency

V = reservoir capacity

I= annual average inflow

(Brune, 1953) has considered only 2 parameters in his formulation V and I and many other parameters affecting reservoir sedimentation has not been represented in his method. In addition, (Brune, 1953) has used only normally ponded reservoir in deriving his empirical relationship. However, this method is not so accurate as the sediment trapped in the reservoir will be very much influenced by sediment inflow rate.

Further, (Siyam, 2000) shows (Brune, 1953) as a special case of a more general trap efficiency function given by equation 2.4.

$$\text{TE}= 100\ e^{\beta(\frac{V}{I})} \tag{2.4}$$

Where β is sedimentation parameter which reflects the reduction in the reservoir storage capacity due to sedimentation.

(Churchill, 1948) developed a graphical relationship between Release Efficiency (RE) and sedimentation Index (SI) as shown in Figure 2-3 below which is extracted from (Morris & Fan, 1998).

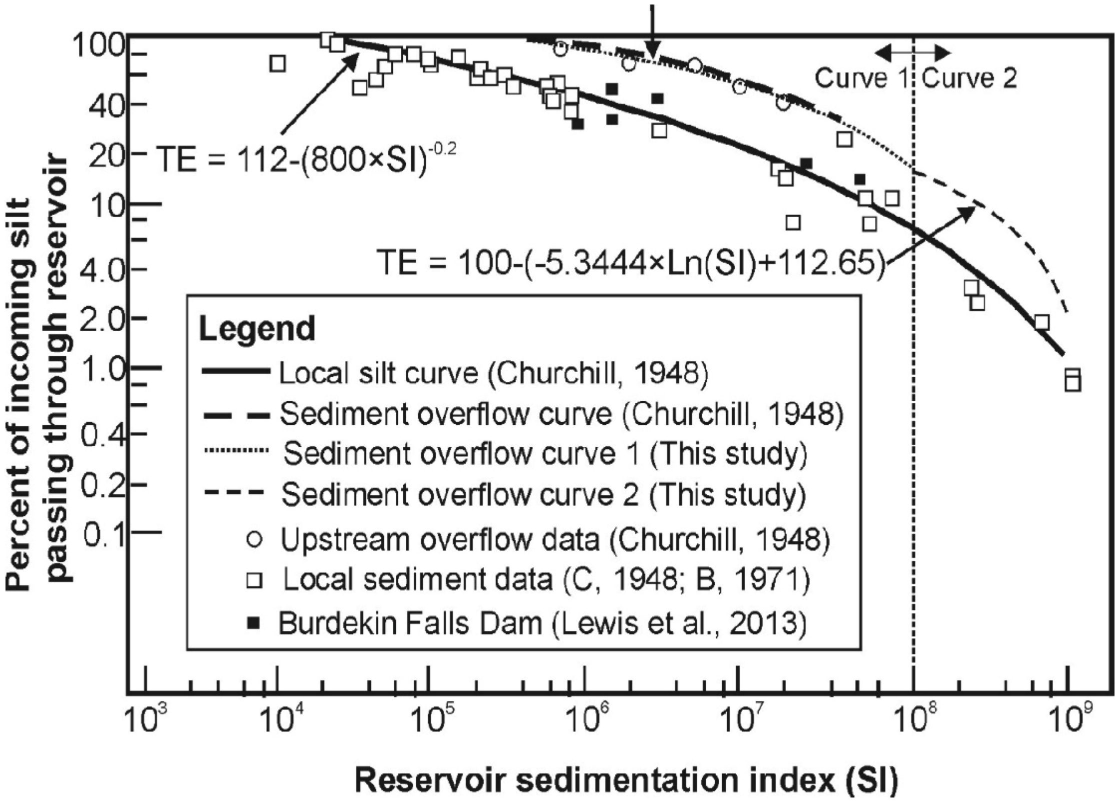


Figure 2-3 Churchill curve (Churchill, 1948)

Sedimentation index can be defined as follows:

$$\text{SI} = \frac{Detention\ time}{Mean\ velocity} \tag{2.5}$$

$$\text{SI}= \frac{g\ x\ (Reservior\ capacity)^2}{Reservior\ length\ x\ (Reservior\ inflow)^2} \tag{2.6}$$

Churchill has only considered a limited parameter like detention time and mean velocity while omitting other parameters that affects reservoir sedimentation. But (Trimble & Carey, 1990) concluded that (Churchill, 1948) produces more realistic estimate of sediment yield than from (Brune, 1953), for reservoir receiving sediment from upstream reservoir.

(Verstraeten & Poesen, 2000) also stated (Churchill, 1948) method although being more accurate than (Brune, 1953), it is very complex to obtain data for calculating SI for (Churchill, 1948). This may be the reason for using (Brune, 1953) extensively than (Churchill, 1948).

2.4 Sediment Control and Management

When Sediment load moves down a reservoir in vicinity of dam, the velocity and turbulence are considerably reduced. The largest particle which moves along the bed load, gets deposited in the upper reservoir. While suspended load may travel some distance and gets accumulated near reservoir. If this process of deposition continues longer, a stage reaches when whole reservoir will get silted up and this reduces the storage capacity of reservoir. Following measures should be adopted to control sediment deposition in reservoir:

i. Methods that reduce sediment yield from the watershed,
ii. Methods that minimize sediment deposition, and
iii. Methods that increase or recover the reservoir volume

Sediment Management methods that can be adopted to get long term benefits from reservoir can be categorized into four measures:

i. Reduce sediment concentration moving down reservoir which is also called watershed management techniques,
ii. Route sediment particles away or through reservoir, to reduce sediment deposition within reservoir
iii. Removal of sediment particles already deposited in reservoir by empty flushing, dredging,
iv. Adopt suitable strategies to manage sediment laden flood flow towards reservoir.

2.5 Sediment Prediction Using Numerical Method

Numerical models for prediction of sediment flow within the river is nowadays improved by the use of computer resources. According to (Yang & Simoes, 2000) the advances have occurred particularly in the fields of water quality, sediment transport, and multidimensional fluid flow and turbulence. Modelling can be simulated by the advancement of river analysis tools like GIS, HEC-RAS. Models can be 1D, 2D, or 3D. 1D models are preferred because of requirement of less computation times and data.

2.5.1 One-Dimensional Models

1D numerical models is used to developed for simulation of sediment behavior in rivers and reservoirs, such as HEC-6, FLUVIAL12, CONCEPTS, GSTARS series, EFDC1D, CCHE1D, etc.

HEC-6 It considers the sediment transportation from flow of bed, upstream sources and suspended loads, and consequences of an armored surface layer. This model can be used to predict the transport of sediment sizes of larger sizes as 2,048 mm. (U.S Army, 1991).

FLUVIAL-12 This model predicted width of channel, inter-related changes in bed profile and topography of bed affected by curvature of channel. It is a model developed for sediment routing in river channels.

GSTARS is a model developed for sedimentation studies in reservoir and river. GSTARS first version was launched in 1986 and GSTARS 2.0 was developed in 1998 with use of FORTAN IV/77. GSTARS 2.1 developed with improved Graphical User Interface (GUI) which assists for the calculation of channel geometry with mobile channel width and cross-section.

CCHE1D This model is used for channel networks which calculates the unsteady flow in channels of combined cross-sections. Graphical interface facilitates the user to simulate networks of channel based on layers of GIS for example: aerial photographs, satellite imagery, aerial photographs.

HEC-RAS is an integrated system of software, designed for interactive use in multitasking, multi-user network environment. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities.

HEC-RAS system contains four one-dimensional river analysis components for: (1) steady flow water surface profile computation; (2) Unsteady flow simulation; (3) Movable boundary sediment transport computation; and (4) Water quality analysis. A key element is that all four components use a common geometric and hydraulic computation routine. In addition to the four river analysis components, the system contents several hydraulic design features that can be invoked once the basic water surface profile and computed.

2.5.2 Two-Dimensional Models

The more detailed information on sediment transport processes and the impact of sedimentation on coastal ecosystem or river can be obtained from 2D sediment models than 1D models. But, more computational resources and complex processes is required to simulate the sediment models.

Velocity profiles, flow rates, water levels and sediment data such as the particle size distribution, settling velocity and concentration are the input data for the 2D models.

2.5.3 Three-Dimensional Models

Three-dimensional (3D) models for sediment analysis are numerical models that simulate sediment transport and deposition in three dimensions, accounting for the lateral and vertical variations in the flow and sediment transport patterns. These models are more advanced than both 1D and 2D models, as they can provide more detailed information on the sediment transport processes, including the spatial distribution of sediment concentration and deposition rates.

The development of 3D sediment models involves defining the geometry of the river or coastal environment, including the bathymetry and hydraulic characteristics such as flow rates, water levels, and velocity profiles. The model parameters, such as sediment transport equations, erosion rates, settling velocities, and bed shear stresses, are also selected. The input data for the model includes hydraulic data, such as flow rates, water levels, and velocity profiles, and sediment data, such as the particle size distribution, concentration, and settling velocity.

The numerical model simulates sediment transport and deposition in the river or coastal environment, accounting for factors such as sediment transport capacity, sediment deposition, and sediment erosion, in three dimensions. The model output can include sediment concentration and deposition rates in all three dimensions, providing a more detailed understanding of sediment transport processes and the impact of sedimentation on river or coastal ecosystems.

The accuracy of the 3D sediment model is validated by comparing the predicted sediment concentration and deposition rates with field observations or data from previous studies. If the model's accuracy is found to be insufficient, model parameters may be adjusted, and the simulation may be rerun to improve the accuracy.

2.6 Sediment Modeling Using HEC-RAS

Hydrologic Engineering Centre-River Analysis System (HEC-RAS) is software, which is designed to perform steady flow water surface profile computations through natural rivers and full networks of natural and engineered channels, unsteady flow simulations, and movable boundary sediment transport computations. Furthermore, HEC-RAS is also capable to perform water quality analysis. A key element is that all three components will use a common geometric data representation and hydraulic computation routines (Brunner, HEC-RAS River Analysis System, 2010).

HEC-RAS has the ability to make the calculations of water surface profiles for steady and gradually varied flow as well as subcritical, super critical, and mixed flow regime water surface profiles. In addition to that, HEC-RAS is capable to do modelling for sediment transport, which is notoriously difficult. Therefore, modelling sediment transport is based on assumptions and empirical theory that is sensitive to several physical variables (Brunner, HEC-RAS River Analysis System, 2010).

2.6.1 Steady Flow

HEC-RAS is capable of calculating 1D steady flow water surface profile in river channels for sub critical, super critical and mix flow regime. 1D steady flow model solve energy equation for calculating the water surface profile with an iterative procedure called the standard step method. The Energy equation is written as follows:

$$Y2 + \frac{V2^2}{2g} + z2 = Y1 + \frac{V1^2}{2g} + z1 + he \qquad (2.7)$$

Where,

P2, P1 = Pressure in section 2 and 1

V2, V1 = Velocity in section 2 and 1

Z1, Z2 = Datum head in section 2 and 1

h_e = head loss between section 2 and 1.

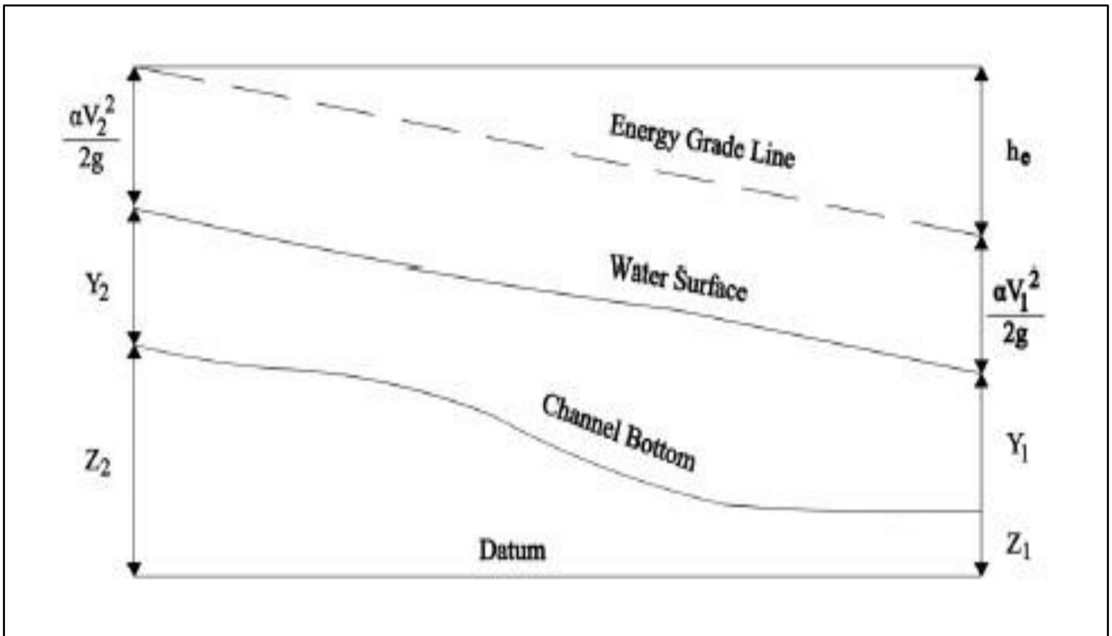


Figure 2-4 Graphical representation of energy equation

The head loss (he) is expressed as

$$he = LS_f + C(\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}) \tag{2.8}$$

Where,

L = discharge weightage reach length

S_f = representative friction slope between two sections

C = expansion or contraction loss coefficient

When flow regime changes from sub critical to super critical, the energy equation is no longer validated. The energy equation is only applicable to gradually varied flow situations, and the transition from subcritical to supercritical or supercritical to subcritical is a rapidly varying flow situation. While modelling the rapidly varying flow, the momentum equation is derived from Newton's second law of motion is used, which is written as follows.

$$\sum F_x = ma\ (rate\ of\ change\ of\ momentum) \tag{2.9}$$

Where,

F_x = force along x direction
m = mass of the body
a = acceleration of the body

Applying Newton's second law of motion to a body of water enclosed sections at locations 1 and 2 momentum over a unit time can be written:

$$P1 - P2 + Wx - Ff = Q\rho\Delta Vx \tag{2.10}$$

Where,

P1, P2 = Hydraulic pressure force at locations 1 and 2.

W_x = Force due to the weight of water in X direction.

F_f = Force due to external friction losses from 2 and 1.
Q = Discharge ρ = density of water
ΔV_x = Change on velocity from 2 to 1, in the X direction.

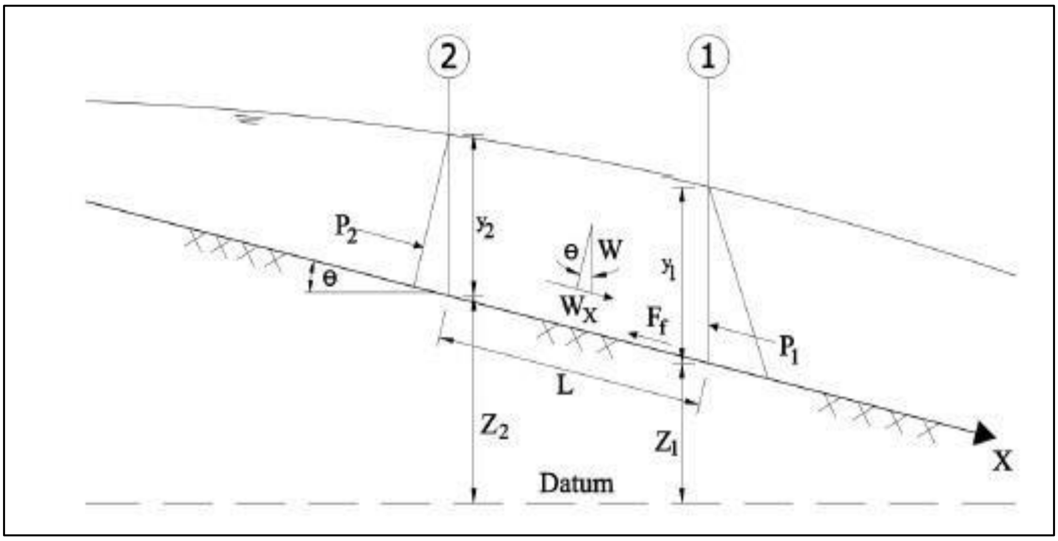


Figure 2-5 Application of momentum principle

$$\frac{Q_2^2\beta_2}{gA_2} + A_2Y_2 + \left(\frac{A_1+A_2}{2}\right)LS_0 - \left(\frac{A_1+A_2}{2}\right)L\overline{S_f} = \frac{Q_1^2\beta_1}{gA_1} + A_1Y_1 \tag{2.11}$$

Where,

γ = unit weight of water.

A_i = Wetted area of the cross section at locations 1 and 2.

Y_i = Depth measured from water surface to the centroid of the cross-sectional area at locations 1and 2.

Q_i = Discharge measured through the cross-sectional area at locations 1and 2.

L = Distance between sections 1 and 2 along the X axis.

S_o = Slope of the channel, based on mean bed elevations.

Z_i = Mean bed elevation at locations 1 and 2.

S_f = Slope of the energy grade line (friction slope).

β = momentum coefficient that accounts for a varying velocity distribution in irregular channels.

This momentum equation is basic for HEC-RAS calculation. All the momentum equation used in HEC-RAS is derived form of this equation.

2.6.2 Unsteady Flow

It is unusual for a natural river channel to flow in steady flow condition; rather river channel flow is unsteady. The discharge in river channel actually varies with time and velocity, depth is function of time and location.

1D unsteady flow routing solves the Saint-Venant equations. Barre de Saint-Venant developed the Saint-Venant equations, also called the shallow water equations, in the late 1800's. The Saint-Venant equations were developed from Conservation of Mass (2.12) and Conservation of Momentum (2.13) applied to a small control volume of fluid (Brunner, HEC-RAS River Analysis System, 2016).

$$\frac{\mathrm{dAT}}{dt} + \frac{\mathrm{dQ}}{dx} - \mathrm{q} = 0 \qquad (2.12)$$

$$\frac{dQ}{dt} + \frac{dQV}{dx} + gA\left(\frac{dz}{dx} + S f\right) = 0 \qquad (2.13)$$

Where,

A is the area of cross-section,

t is a time,

Q is the flow,

X is the distance along channel,

q is a source or sink term,

V is a velocity of flow

g is the gravity acceleration,

S_f is the friction slope and

dz/dx is the water surface slope.

2.6.3 Sediment Transport Simulations

Sediment transport simulations within HEC-RAS are based on calculations of one-dimensional movable material from the river bed causing scour or deposition over a certain modelling period of time, typically years. Furthermore, modelling of a single flood event is also an option available.

Generally, sediment transport through rivers, streams and channels occurs through two modes which depend on parameters such as particle size, water velocity, and bed slope. Bed load and suspended load are the two modes. Computing sediment capacity associated with each cross section as a control volume and for all grain sizes in that particular case is the basic principle of evaluating sediment transport capacity in HEC-RAS.

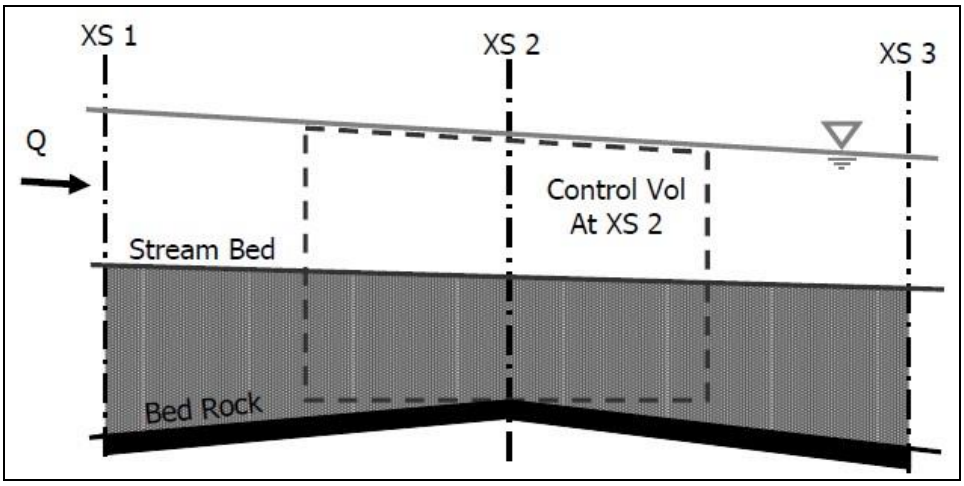


Figure 2-6 Control Volume used in Sediment Calculation in HEC-RAS

In HEC-RAS, sediment routing routines are based on the concept of mass conservation of through the sediment continuity equation, which is also known as the Exner equation written as:

$$(1 - \lambda_p)B \frac{\partial \eta}{\partial t} = -\frac{\partial Q_s}{\partial x} \qquad (2.14)$$

Where:

λ_p = porosity of active layer

B = width of channel

η = channel elevation

Q_s = transported sediment load

x = distance

t = time

The continuity equation used in HEC-RAS mentioned above states that the aggradation or degradation for a particular control volume, which is the change in the bed level, equals the difference between the inflow and outflow of sediment for that particular control volume.

For performing sediment transport capacity analysis, steady or unsteady flow simulations have to be run first. Then HEC-RAS will automatically take the required hydraulic parameters from the steady or unsteady outputs to be used in sediment transport analysis.

2.7 Quasi-Unsteady Flow

The quasi-unsteady flow model simplifies hydrodynamics, representing a continuous hydrograph with a series of discrete steady flow profiles. Computing transport over flow record duration, HEC-RAS keeps flow constant for each flow record. The steady flow profiles are more stable than the unsteady Saint-Venant equations, but approximating a hydrograph with a series of steady flows does not conserve flow or explicitly account for volume.

The quasi-unsteady flow model divides time into three-time step. HEC-RAS divides each discrete steady flow profile (Flow Duration), over which HEC-RAS holds flow constant, into Computational Increments. Computational Increments are the hydraulic and sediment transport time step. HEC-RAS updates the hydraulics and cross sections every Computational Increment, but further subdivides this time step into Bed Mixing Time Steps. This bed mixing time steps update bed gradation accounting for each bed layer several times each Computational Increment.

2.8 Sediment Modelling Parameters

2.8.1 Computation Increment

The primary step of the quasi-unsteady hydraulic and sediment time computation is Increment Computation. The Computation Increment subdivides the durations as it can be equal to the duration but not longer than the duration. HECRAS updates bed geometry and hydrodynamics once a computation increment of the flow rate has been made, while flows are continuous over the duration of the flow.

Model stability can be hampered by the computation increment, as HEC-RAS presumes that bed geometry and hydraulics are constant. When the bed changes rapidly, huge computation increments decouple feedback between the sediment and hydraulic processes directing unreasonable erosion or decomposition causing the model to fail.

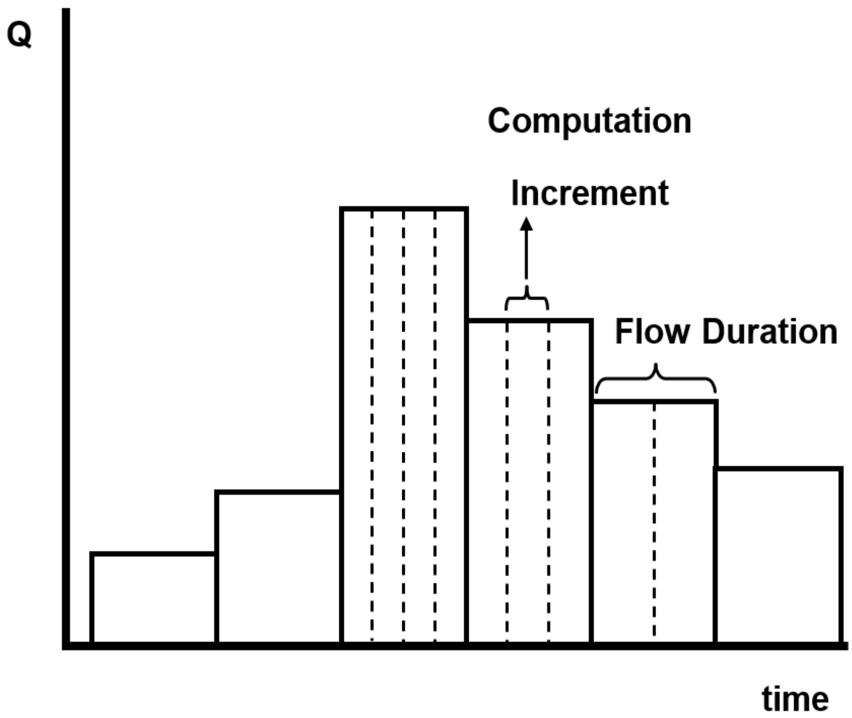


Figure 2-7 A Quasi-Unsteady Flow Series with time step

2.8.2 Transport Functions

The transport function in HEC-RAS works by solving the sediment continuity equation, which accounts for the amount of sediment being transported and deposited at different locations within the river system. In HEC-RAS, various sediment transport functions are available. The following six transport functions have been used in this study:

Ackers-White:

Ackers-White is a total load sediment transport function that was developed for non-cohesive soils of grain size ranging from 0.04mm to 7mm. This function is also not valid for the upper phase transport with Froude numbers in excess of 0.8. Particle size, mobility, and transport are the basic terms for the development of this transport function. However, the transport of coarse sediments is associated with net grain shear with mean velocity (Ackers & White, 1973).

Engelund-Hansen:

Engelund-Hansen's transport function is a total load predictor which estimates total load of sandy rivers with a significant amount of suspended load. This function was developed on flume data with sediment sizes between 0.19mm and 0.93mm. It has been extensively tested, and found to be fairly consistent with field data (Englund & Hansen, 1967).

Laursen:

The total load function derived from a combination of qualitative analysis, original experiments, and supplementary data is Larsen for the prediction of sediment transport. This function is based on sediment characteristics of gradation and fall velocity and the hydraulic characteristics of mean channel velocity, depth of flow, and energy gradient. It is applicable for grain sizes from 0.011mm to 29mm (Laursen, 1958).

Meyer-Peter Muller:

Based on experimental data and used in rivers with relatively low sediment content, the Meyer-Peter Muller (MPM) load transport function is based on experimental data. The difference in mean share stress acting on grains and critical shear stress is proportional to the rate of sediment transport. MPM tends to predict the transport of the finer materials in the running stream. This function is applicable for sediment particles ranging from 0.4mm to 29mm, with a specific gravity of 1.24 to 4 (Meyer-Peter & R.Muller, 1948).

Toffaleti:

The Toffaleti method is a modification of Einstein's complete load function, breaking the distribution of suspended loads to vertical zones and constituting 2D sediment movement. This function presumes that the stream has a sediment load of four vertical different zones, upper zone, middle zone, lower zone, and bed zone. For each zone and summed to arrive at the total transport of sediment, the transport of sediment is calculated on its own. Using flume information for sediment with a diameter ranging from 0.3 to 0.93mm, this method has been developed and it is successfully used on particles of size 0.095 mm. (Brunner, Version 4.1, 2010).

2.8.3 Sorting Method

The sorting method also called the bed sorting method which keeps track of the bed gradation which uses to compute grain-class specific transport capacities and can also simulate armoring processes which regulate supply. In this method, sediment is sorted based on size which different grain sizes are tracked in HEC-RAS and also simulates armoring processes that regulate sediment supply.

Thomas (Exner 5):

In HEC-RAS, Thomas method (formerly Exner 5) which was expanded by Tony Thomas is the default and armoring method. Thomas's method is a three-layer bed mixing algorithm, which was designed to account for the effects of static armoring. Active layer is divided into a cover layer and a subsurface layer, allowing a thin cover layer to reduce and suppress erosion while retaining the more general graded active layer. Based on the gradation of the active layer, HEC-RAS evaluates transport capacity. Sediment deposits into and erodes from a cover layer. As long as it is available under the layer of cover, HECRAS may break down a grain class.

Active Layer:

Thomas and Copeland's methods are sophisticated, multi-layer approaches to bed mixing and armoring. As HEC-RAS evaluates transport capacity for each grain class independently, these methods limit erosion while computing transport that mirrors the subsurface gradation so they are complicated and provide results that can be difficult to interpret. Less vertical resolution and no explicit armoring factors are the disadvantages of a simple active layer approach. This method is more natural and transparent, which can give rise to a smooth or fine inactive layer with an adequate exchange rate increment, it may be preferable in some cases for the modeling of vehicle armor systems. (Gibson and Piper, 2007).

Copeland (Exner 7)

The Thomas method was initially developed for the snake river and later generalized for another river morphology. This method tends to over predict armoring, and under predict erosion on finer systems (USACE, 1993, Thomas, 2010). The Thomas method has been adapted by Copeland in order to be used more widely on sand beds. It allows gradation of the former to control erosion from the later. A “bed source” layer is added but is still almost a three-layer method which is similar to Thomas method. The Copeland method differs from some equations and assumptions, allowing for more extensive scours to be performed on large sand bed rivers.

2.8.4 Fall Velocity

The fall velocity of sediment is a crucial factor that impacts the transportation of sediment in flowing water and determines how particles are deposited on the riverbed. When the fall velocity decreases, the sediment remains in suspension for longer periods in the water. The settling velocity of sediment is influenced by several factors, including particle size, flow velocity, fluid viscosity, and shape factor.

Ruby:

To get a simple, statistical function on fall velocity, Ruby uses the Reynolds number. Toffaleti has developed a series of empirical, decline velocity curves based on experimental data that is directly read and interpolated by HECRAS.

Van Rijn:

Ruby, as an initial guess is used by Van Rijn then the Reynolds number computed from the initial guess, is the base for the calculation of new fall velocity from experimental curves.

Chapter 3: STUDY AREA

3.1 Overview

The study area is a West Rapti Basin which lies in Lumbini Province of Nepal. The proposed Naumure hydropower project is a storage type project. The project is located in the West Rapti River approximately in the latitude of 27°55′2″and longitude of 83°10′ which is about 2 km downstream from the confluence of its two main tributaries namely Jhimruk and Mari khola.

The study area includes the Naumure dam and reservoir site, the Re-regulating reservoir, the Lamatal Reservoir, the Surainaka Powerhouse site, water conveyance routes, and the water distributed through the project will irrigate 83,302 hectares of land in Deukhuri, Banke, and Kapilvastu. Irrigation facilities will be provided to 10,800 hectares of land in Deukhuri, 42,766 hectares in Banke, and 29,736 hectares in Kapilvastu district.

The study area and the river networks of the West Rapti basin are shown above in Figure *3-1* and Figure *3-2*.

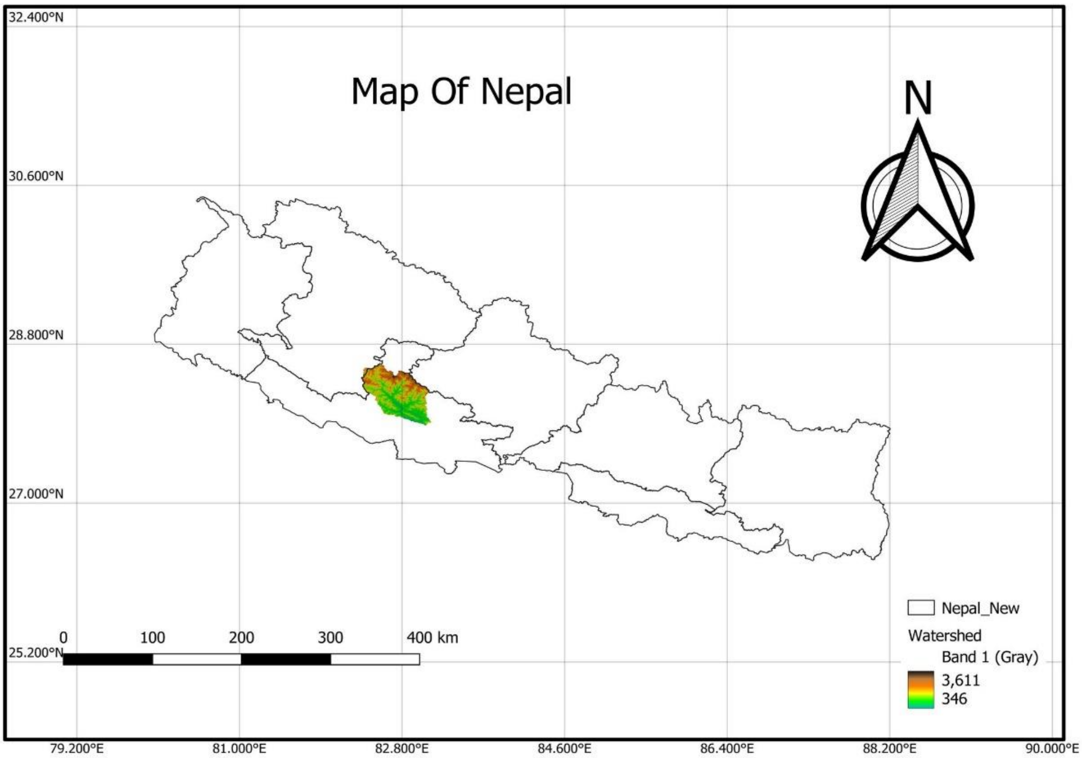


Figure 3-1 Map of study area

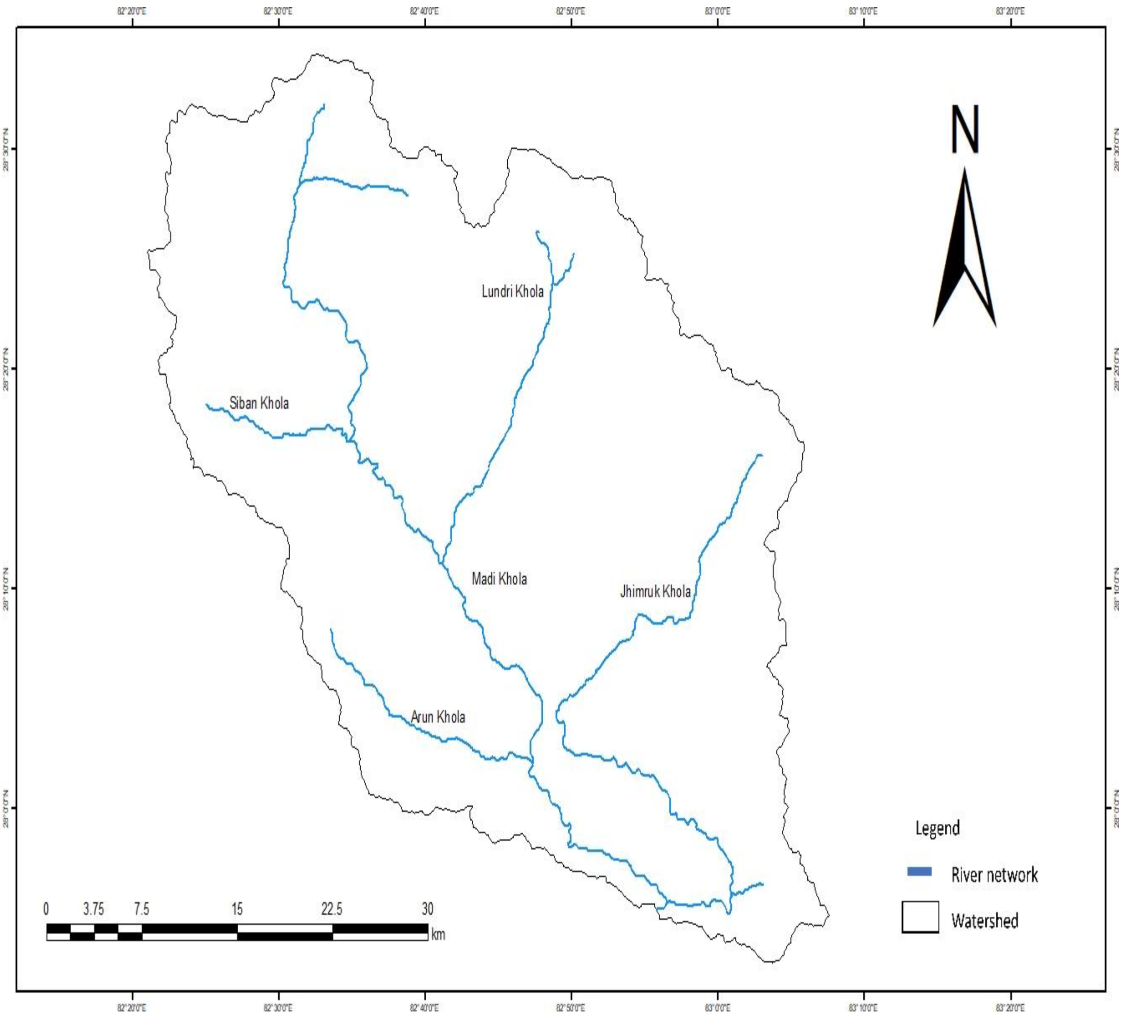


Figure 3-2 Map showing river networks and hydrological area

The Naumure Multipurpose Project is situated in the Pyuthan district for which a 165 m high Concrete Face Rock Fill Dam (CFRD) has been proposed after careful analysis of topography, geology, availability of construction materials, and total cost between various dam types. It consists of an underground type powerhouse with three units of Francis turbines designed to have an installed capacity of 220 MW with a total design discharge of 154.68 m^3/s and a net head of 159.08 m. The project area lies in the Siwaliks and Midland group separated by Main Boundary Thrust (DoED, 2019).

3.2 Climatology

In general, two types of climatic condition prevail in the river basins of Nepal, Sub-tropical and temperate. In the lower part of the West Rapti Basin, it is hot and humid during the rainy season and relatively warm during the winter. The middle and upper part of the basin have a temperate climate; the summers are warm and the winters are cold. Mean monthly rainfall of the catchment area is determined by using Thissen polygon method in **Error! Reference source not found.**. Rainfall data from 1985 to 2 021 is taken for determining mean monthly rainfall. Most of the rainfall in the Naumure's catchment area is found to be concentrated in the May to July period. The highest rainfall in the area is on July month is 364.4 mm. The annual rainfall of the area is 1371.37mm.

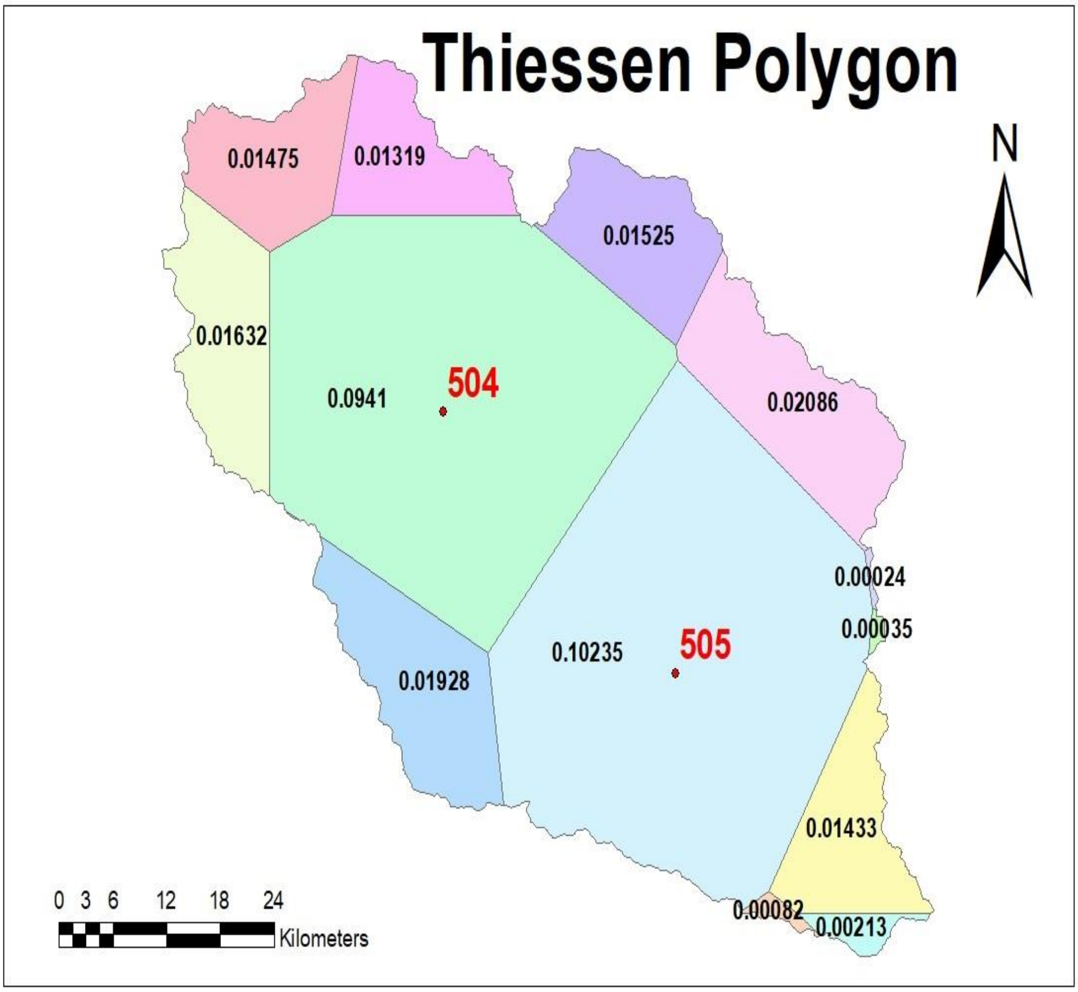


Figure 3-3 Thissen polygon analysis of catchment

The average temperature at Bijuwatar from 2009 to 2021 is shown in **Error! Reference s ource not found.**. The average temperature obtained from the graph was 20.89°C. The maximum average temperature is observed in June with the average value of 26.39°C and the minimum temperature is observed in January with the average value of 13.11°C.

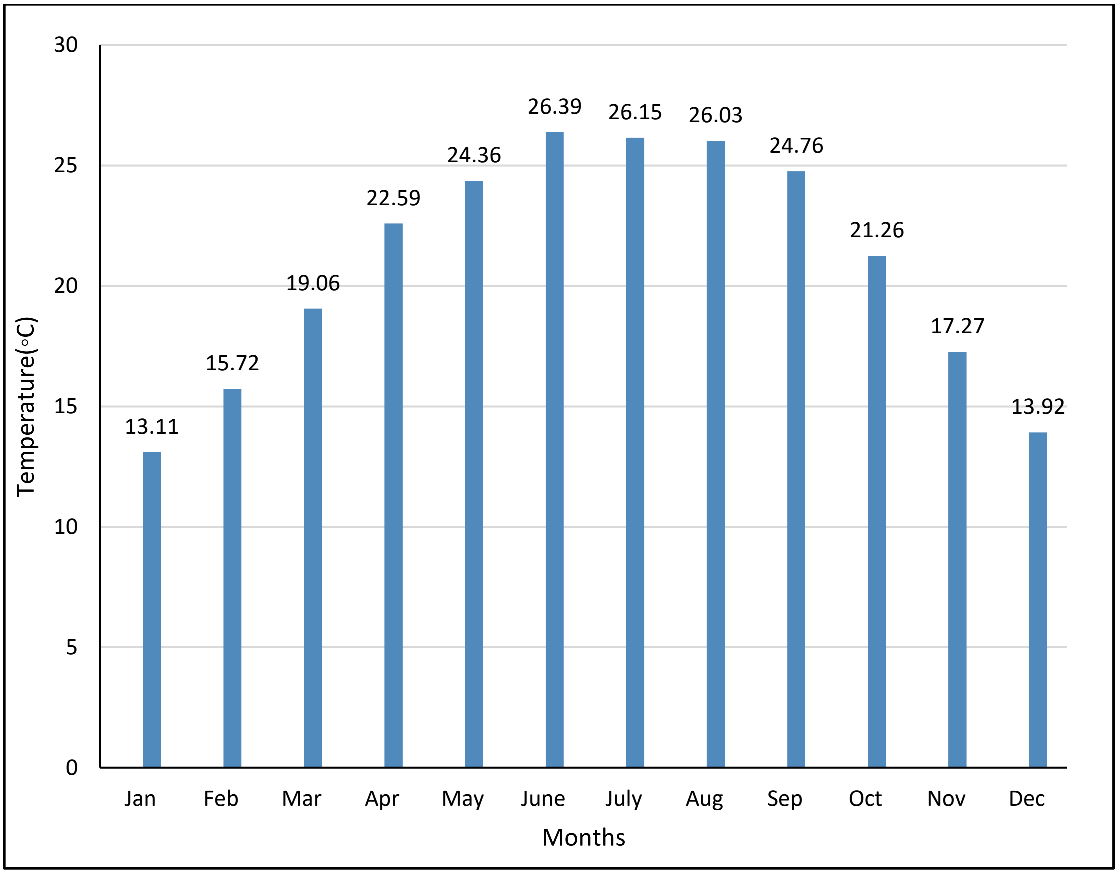


Figure 3-4 Average Temperature at Bijuwatar 2009-2021

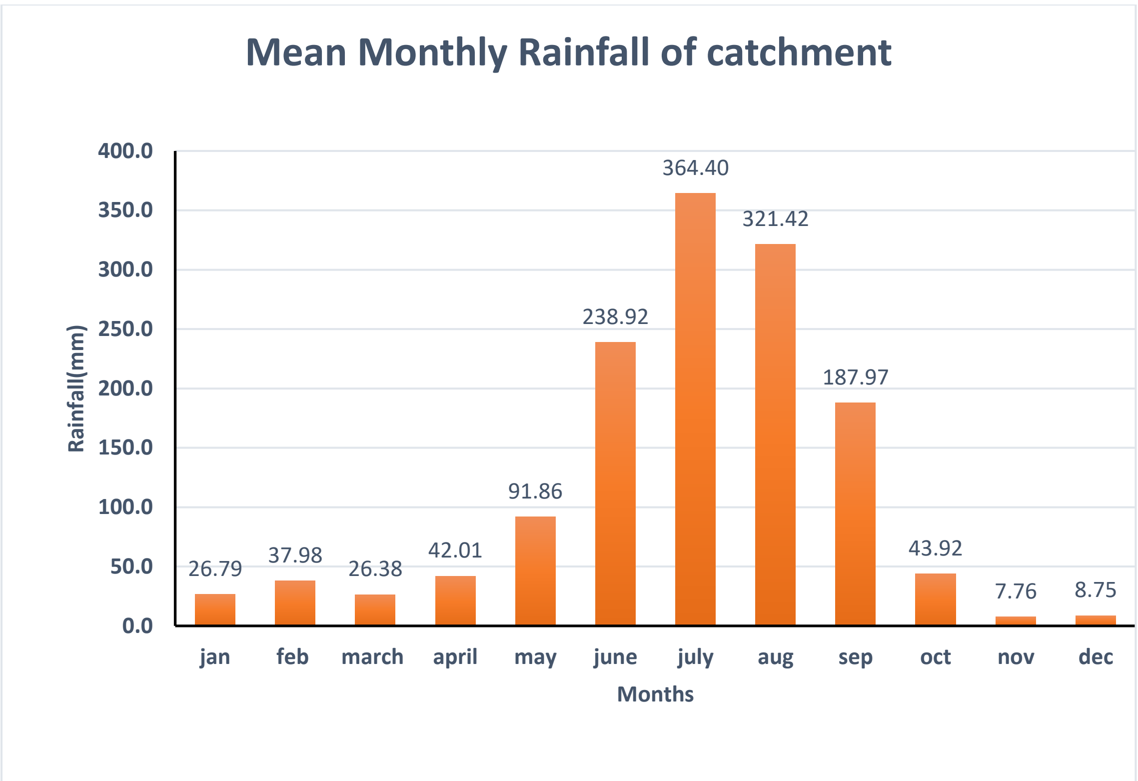


Figure 3-5 Mean Monthly Rainfall of Catchment from 1985-2021

3.3 Hydrological Analysis

Long-term monthly flow is the average flow of water in a river or stream over a long period of time, typically several decades or more. The data were collected from four hydrological stations namely 350, 340, 339.5 and 330. The maximum flow was observed in August with the flow of 381.04 m^3/sec in hydrological station 350 (West Rapti river) and the average flow of this station was observed to be 107.40 m^3/sec. Other stations also gave the maximum flow in August with the flow of 215.47 m^3/sec, 90.33 m^3/sec, and 63.85 m^3/sec in hydrological stations 330 (Mari river), 339.5 (Jhimruk river) and 340 (Jhimruk river) respectively. Similarly, the average flow given by the respective stations were 61.08 m^3/sec, 26.97 m^3/sec and 20.25 m^3/sec. The minimum flow was observed in April with the flow of 15.24 m^3/sec, 10.7 m^3/sec, 3.74 m^3/sec and 3.42 m^3/sec in hydrological stations 350, 330, 339.5 and 340 respectively.

The long term mean monthly flow for the various hydrological stations is shown in Figure 3-6.

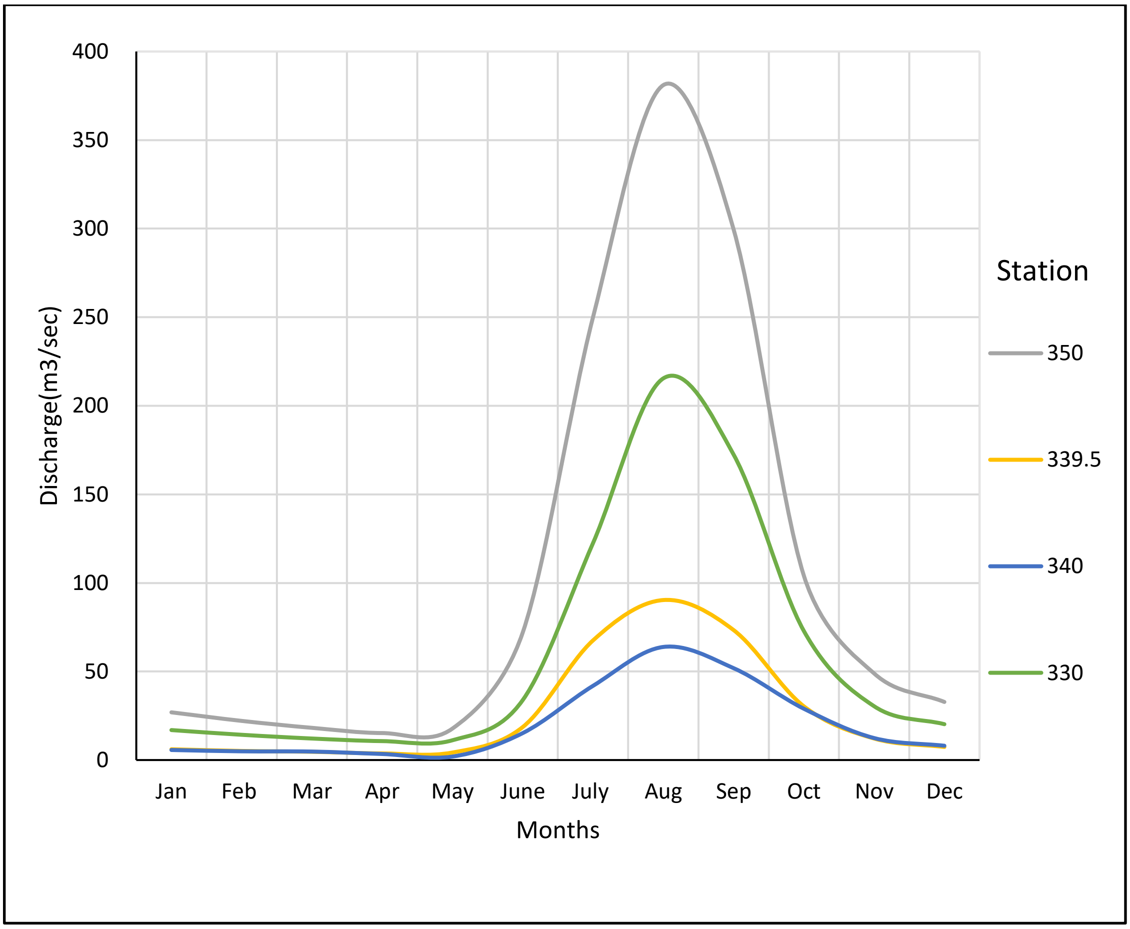


Figure 3-6 Long term mean Monthly Flow for various hydrological station

Table 3-1 Mean Monthly Flow at different station

Months	330 (Mari)	339.5 (Jhimruk)	340 (Jhimruk)	350 (West Rapti)
January	16.93	6.09	5.67	26.93
February	14.25	5.14	4.92	22.10
March	12.16	4.67	4.79	18.19
April	10.70	3.74	3.42	15.24
May	11.18	4.24	1.97	17.80
June	33.87	18.64	15.22	72.04
July	122.50	67.55	41.90	250.05
August	215.47	90.33	63.85	381.04
September	172.50	73.40	51.88	299.66
October	72.87	30.33	28.97	104.09
November	30.38	12.16	12.41	48.90
December	20.23	7.40	8.07	32.79

3.4 Catchment Characteristics

The DEM (SRTM 30 m) for the Catchment area of the study area is shown in **Error! Reference source not found.** and salient features of the basin obtained by processing the SRTM DEM is given in **Error! Reference source not found.**.

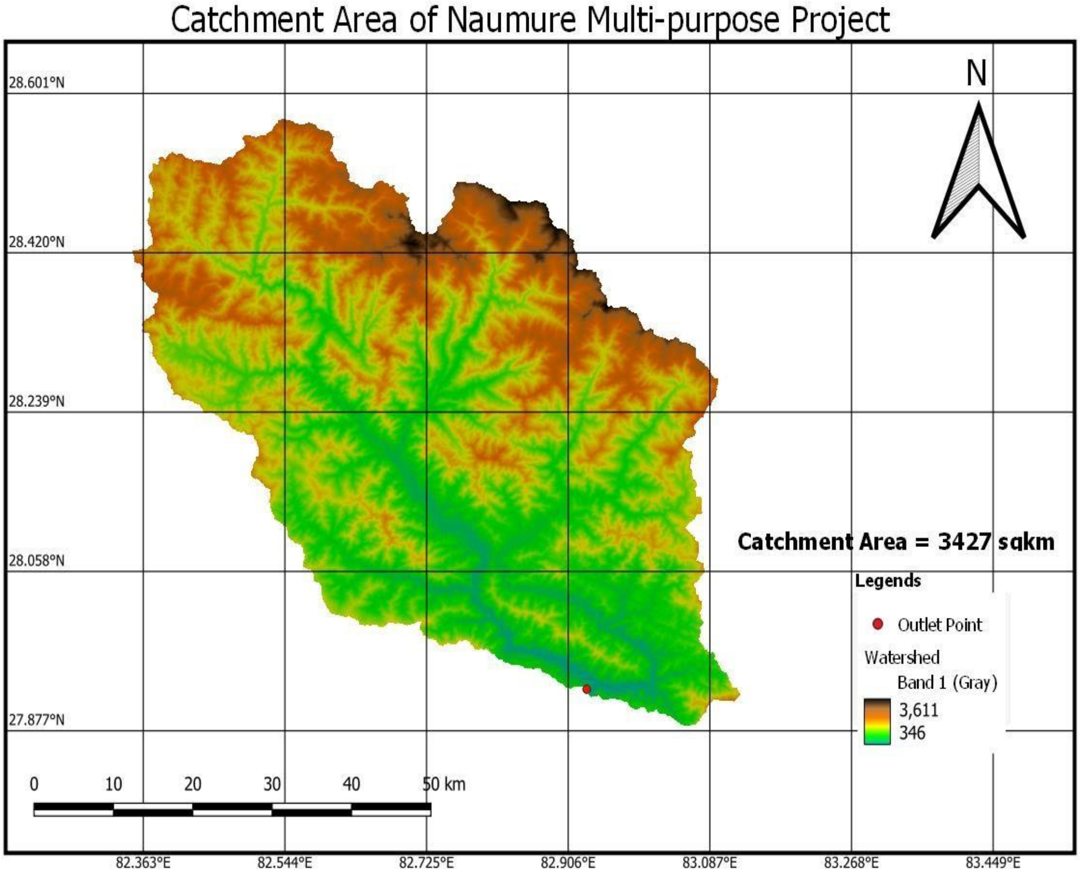


Figure 3-7 Dem file with Elevation Symbology

Table 3-2 Salient features of the catchment area

Basin area at Naumure	3427	km^2
Basin perimeter	296	km
Max. elevation	3611	m
Min. elevation	346	m
Mean elevation	1622	m
Length of the longest flow path	115	km
The slope of the longest flow path	0.022	
The centroidal longest flow path	57	km
Centroidal elevation	1392	m
Centroid	(82820.9,3130550)	

Average basin slope	0.5	
Time of concentration	15	hours

3.5 Characteristics of Naumure Dam

CFRD is a rock-fill dam with a concrete face slab on its upstream face, which will act as water tight barrier made by a system of reinforced concrete slabs, connected to the plinth on the rock foundation. The connecting joints are protected with copper and PVC seals in the perimeter joints & the area of tensional stress. To minimize deformation of the concrete face, the body of the dam is to be designed and built with alluvial materials looking for the minimum deformation. This design provides safety to the structures without concern for uplift pressure. According to the DOED report, the design flood (PMF) is about 12140 m^3/s and has to be passed safely across the dam downstream in the Rapti River.

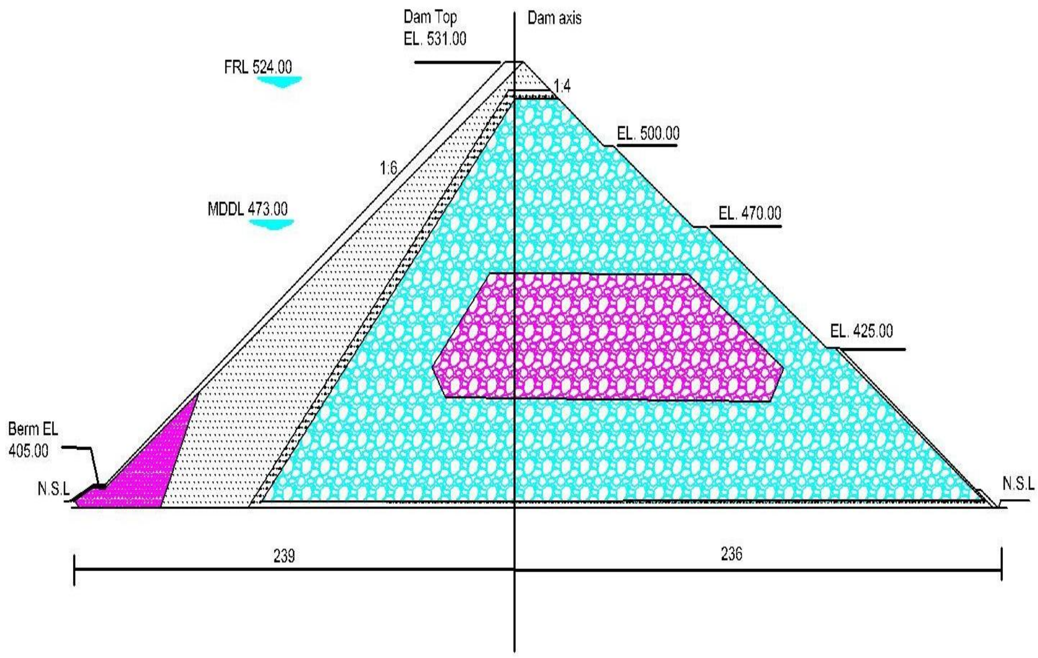


Figure 3-8 Cross-section of Naumure Dam

Source: Dam breach analysis of NMP by Biswas Nepal

Table 3-3 Salient features of Naumure CFRD Dam (DoED, 2021)

S.N.	Particulars	
1	Length of the dam at Top	690.00 m (90 m Chute spillway blocks + 600 m Rock fill Dam)
2	Top of the Dam	531.00 m
3	Maximum Water level (MWL)	524.00 m
4	Full reservoir level (FRL)	524.00 m
5	Minimum draw Down Level (MDDL)	473.00 m
6	New Zero Elevation of Reservoir	459.50 m
7	The top width of the Dam	12.00 m
8	Upstream & Downstream slopes	1.6H: 1V & 1.4H: 1
9	Upstream integrated Coffer Dams	2.5H: 1V
10	D/stream integrated Coffer Dams	2.0H: V1
11	Approach channel length & width	Approx. 350.00 m & 83.00 m
12	No. & Size of Chute Spillway gates	5 Nos & 11 m x 16.5 m
13	Chute Spillway crest level	493.00 m
14	Chute Spillway D/S channel length & width	Approx. 255.00 m & 83.00 m
15	Chute Spillway Discharging capacity	12270.63 > 12140 m^3/s, Ok
16	Energy Dissipation	A Trajectory flip bucket along with a pre-formed plunge pool

Chapter 4: METHODOLOGY

The general methodology for the numerical modeling defines the steps for the preprocessing data and computational domain preparation. The post processing of collected data by running the model and their visualization are important for concluding the result of simulation. The methodology adopted for different objectives in this study is represented by the flowchart shown in Figure 4-1.

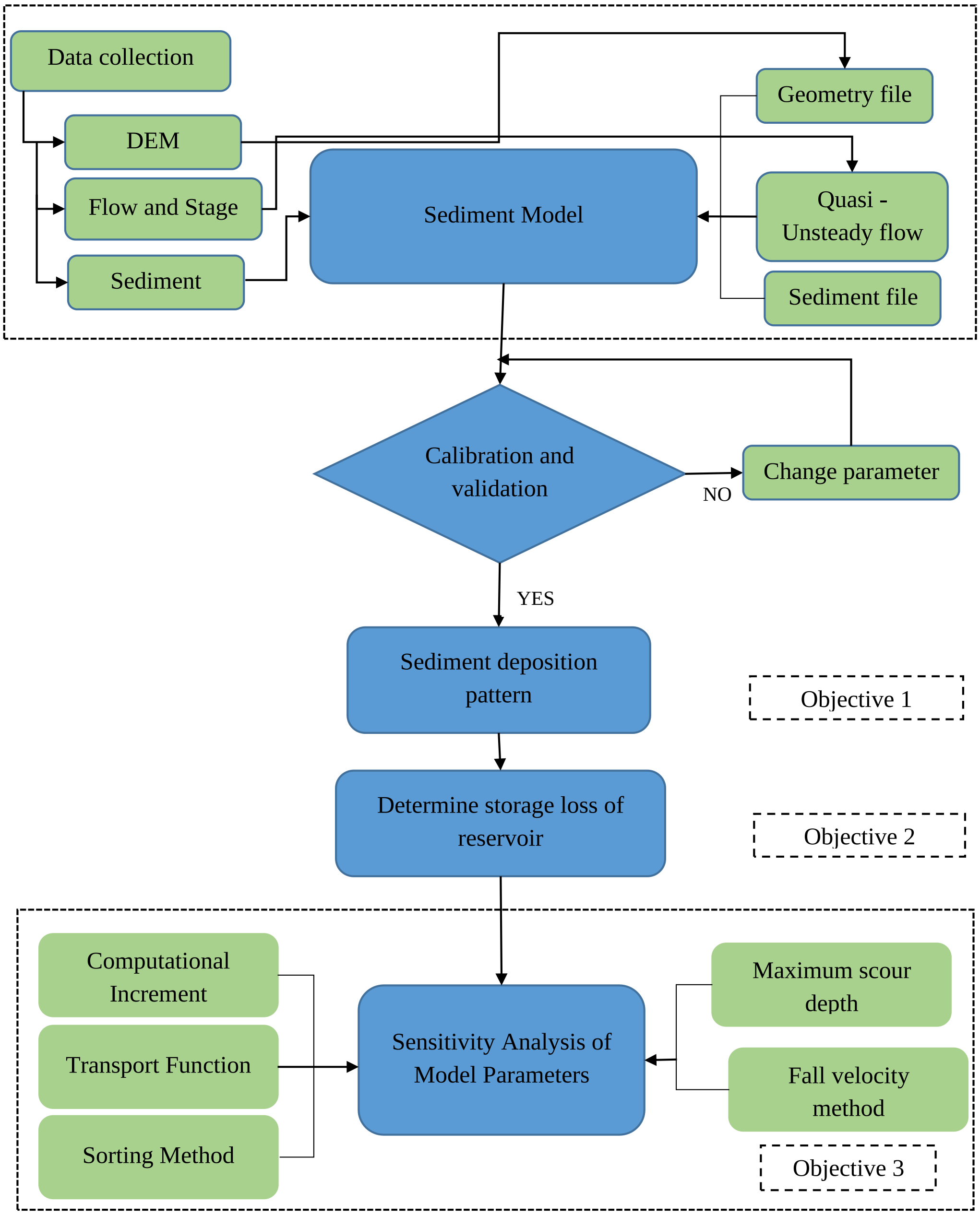


Figure 4-1 Methodological Chart

4.1 Data Analysis

4.1.1 Data Collection

The Digital Elevation Model of 30m resolution is obtained from USGS Shuttle Radar Topography Mission. Daily River discharge for the hydrological Nayagaon stations 330 (Mari), Chernata station 339.5 (Jhimruk), Kalimatighat station 340 (Jhimruk) and Bagasotigaon station 350 (West Rapti) obtained for the year 1965 to 2015 from Department of Hydrology and Metrology. Similarly, the instantaneous discharge along with stage is obtained from DHM as per availability for those above four stations. The suspended sediment discharge for West Rapti (station number 350) was obtained for 1985 to 1990 and similarly for Jhimruk (station number 339.5); it is obtained for 2016 to 2020.

From the obtained sediment data at these two stations, sediment rating curve is generated and also the sediment concentration for required years are forecasted for calibration and validation.

Table 4-1 Data collection and their sources

S. N	Data	Source	Remarks
1	Digital Elevation Model	USGS SRTM	30 m resolution
2	Daily River Discharge	DHM	1965 to 2015
3	Daily Water level (stage) data	DHM	2010 to 2015
4	Sediment Data	DHM	1985 to 2017

4.1.2 Manning's Roughness Coefficient

From the instantaneous discharge and the corresponding stage rating curve is developed for two hydrological stations. The discharge rating curve is:

$$Q = C_r(G - a)^b \qquad (4.1)$$

Where,

Q= Discharge

G= Gauge Height

C_r, a and b are the constants to be determined. These values of constant are determined using Least Square Technique. The HEC-RAS model is run for those discharge using different Manning's roughness values and the rating curve from the model is obtained.

According to (Chow, 2009), for an irregular and rough natural stream with top widths at flood stage greater than 30m, the range of n value is 0.03 to 0.04. As the reach of the west Rapti River taken here is in mountainous terrain with a rough bed, a 'n' value greater than 0.03 is logical for the channel. The overbanks are rougher than the main channel, and hence the 'n' value is higher than in the main channel. However, during the low flow period, the flow occurs only in the main channel and there is no significance of the 'n' value of the banks.

4.1.3 Sediment Rating Curve

Sediment rating curve is the relation between suspended sediment concentration and stream flow. It can be obtained from the various methods. HEC-RAS rating calculator method has been adopted for the generation of the sediment rating. Data screening of the poor-quality data to has been done by visualization manually.

Various methods like Schoklistch method, Shield method and Meyer-Peter and Muller method are applied for bed load calculation. But the result is full of deviation, so an assumption is made for the Bed load consideration. Bed load contribution of 20 percent is assumed for a mountainous basin like West Rapti River to arrive to total load.

4.2 HEC-RAS Modelling

There are very less sediment data measuring stations in West Rapti River. The reservoir is very long as compared to its width.

HEC-RAS is one of the broadly used modelling tools by water resource engineer. Its advantage is that it is freely available and has user friendly environment. Hence 1D HEC-RAS model has been preferred in this study.

4.2.1 Extraction of Geometry Data

RAS Mapper is used for extraction of the geometry for the study area. The river is divided into five reaches West Rapti reach, Jhimruk reach, Mari downstream, Mari upstream, and Arun reach. The River center line, Bank lines, Flow paths and cross sections are created using tools available in the RAS-Mapper. The properties of

Geometric representation are shown in Table 4-2 and Figure 4-2. The details for every cross section are presented in Annex Table A- 1 of annex.

Table 4-2 Geometric data

Rivers	Reach	Reach Length (Km)	No. of C/S
West Rapti River	West Rapti reach	2.21	5
Jhimruk River	Jhimruk reach	38.5	37
Mari Khola	Mari downstream	28.87	26
Mari khola	Mari upstream	27.96	17
Arun khola	Arun reach	14.72	15

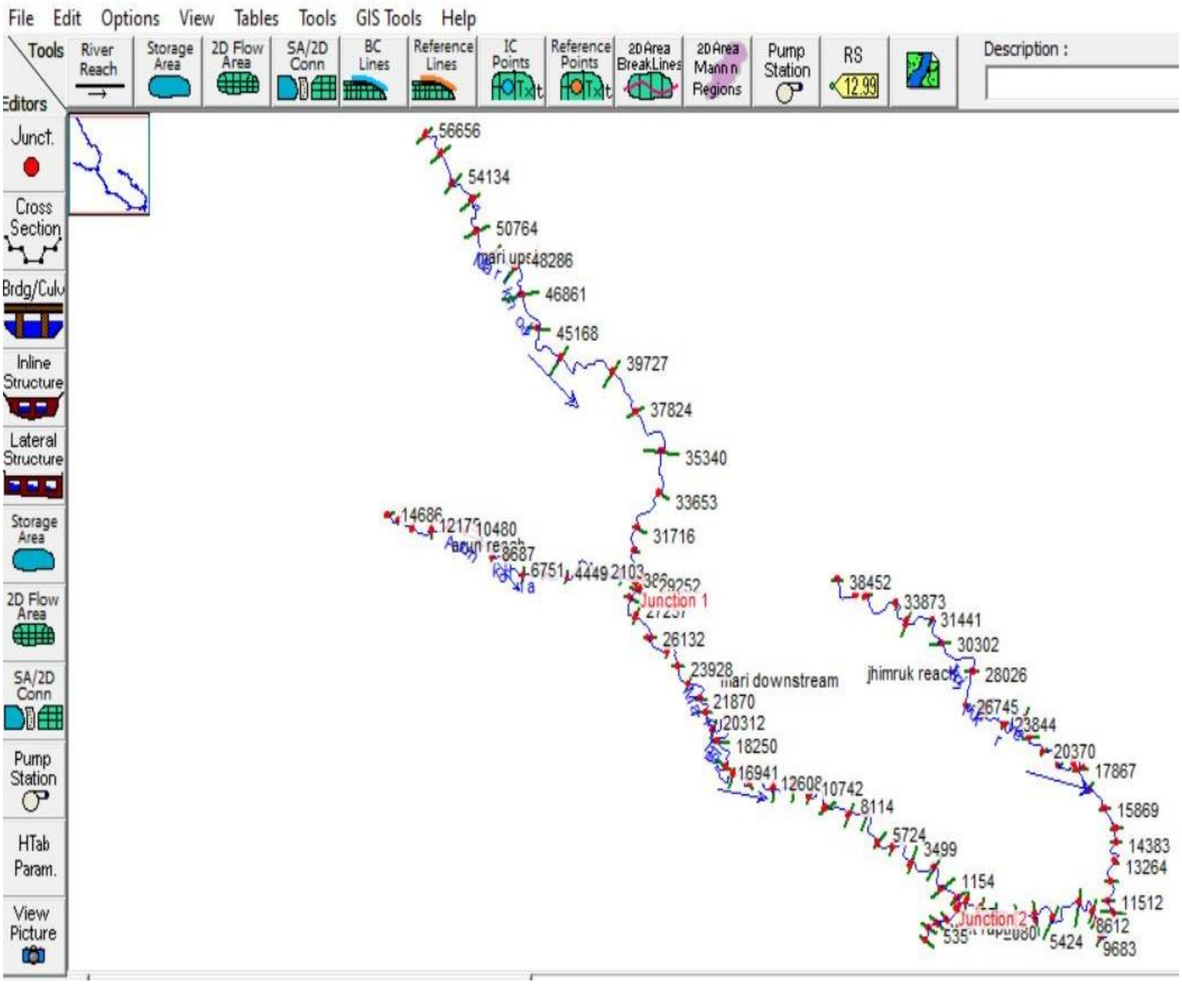


Figure 4-2 Geometric representation

4.2.2 Quasi-Unsteady Flow File

Daily Discharge data obtained from DHM is used as Quasi-unsteady flow data. The temperature of the water is unavailable so 18°C is used throughout the year. Different value of Computation time increment is provided for different discharge.

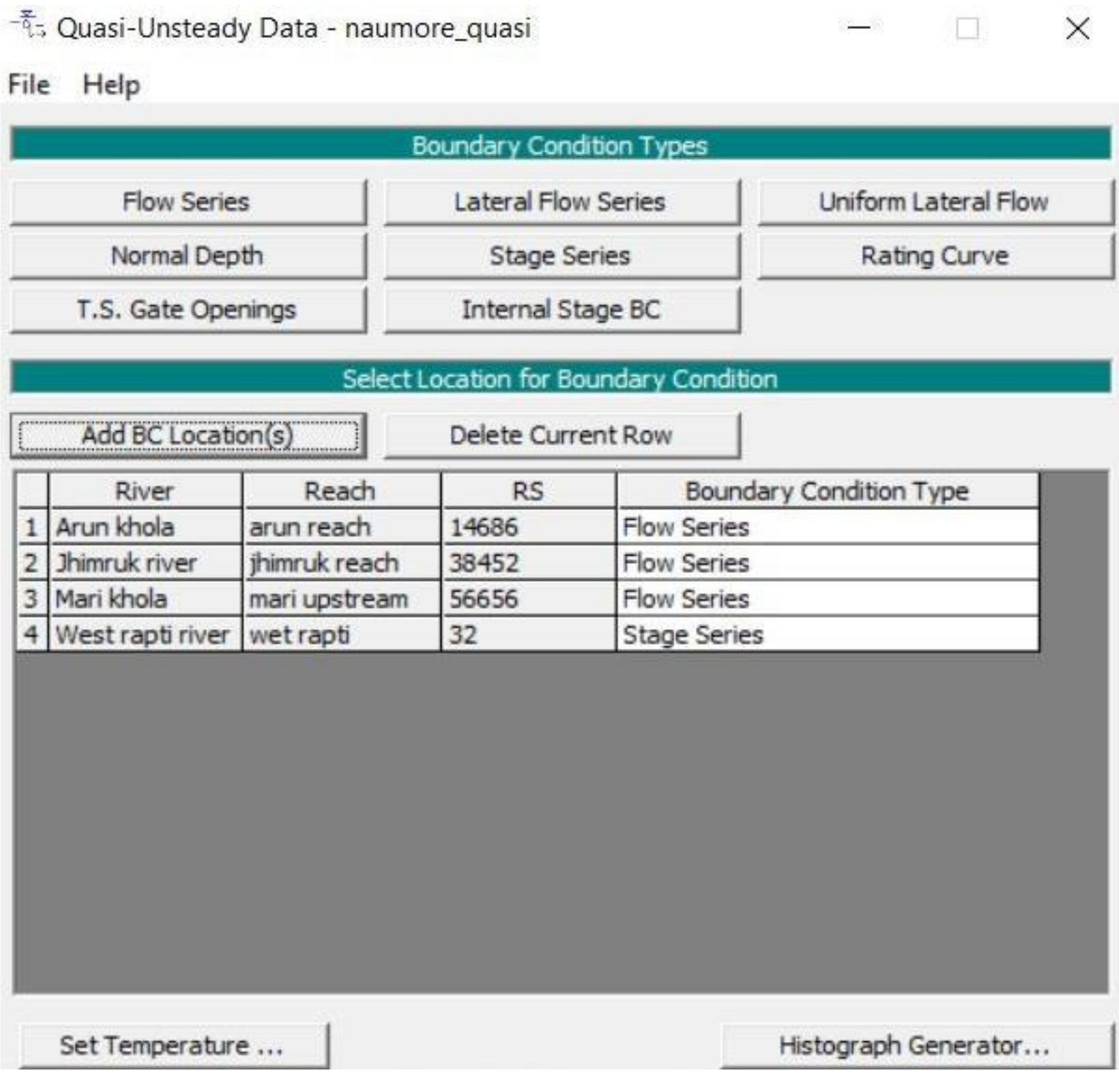
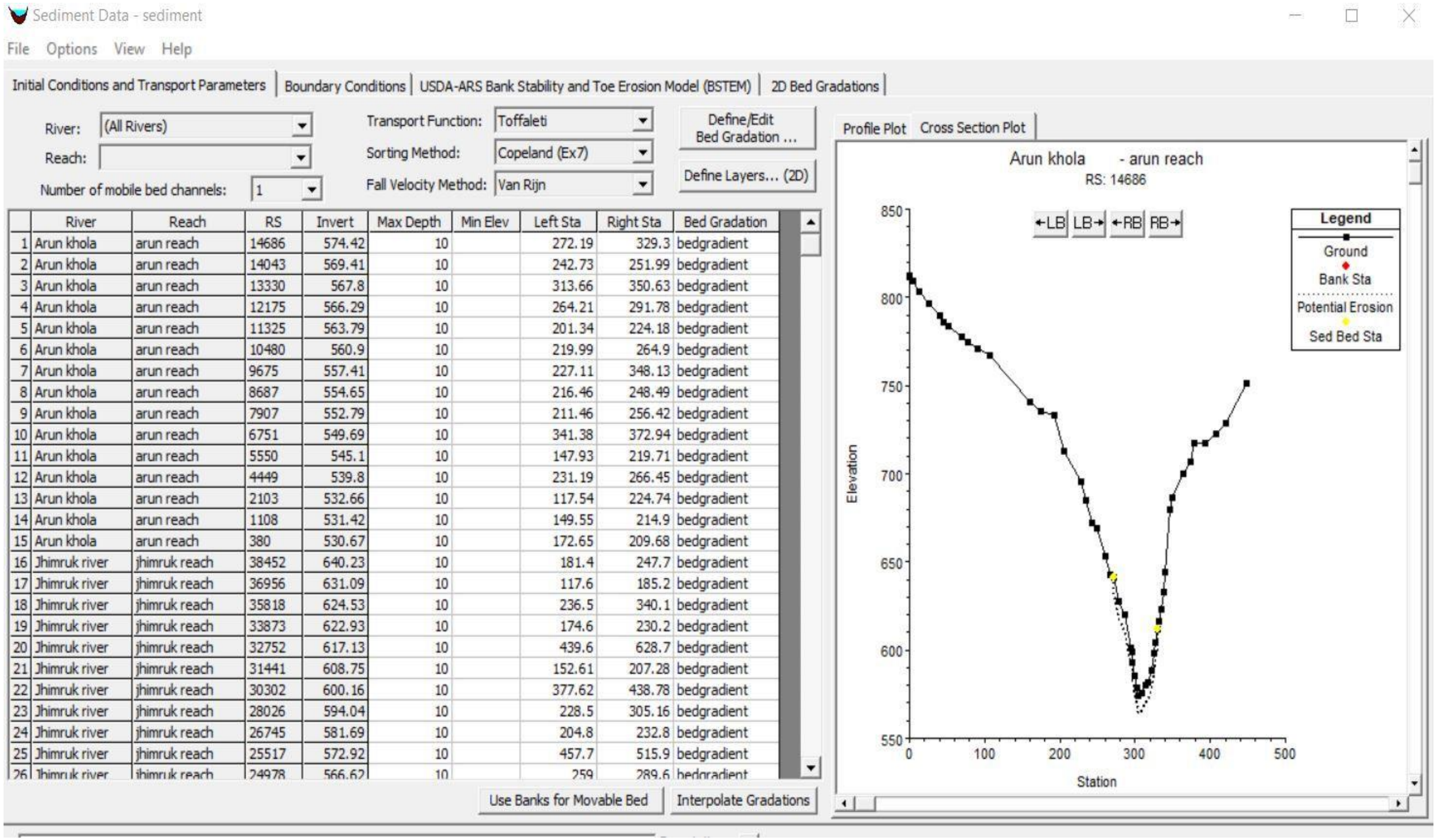


Figure 4-3 Flow Boundary Condition

4.2.3 Sediment File

The Initial Conditions and Transport Parameters is the first tab in the Sediment Data Editor and open by default when the editor launches. The transport function, sorting method, fall velocity method for the entire model is specified here. Sediment control volume and Bed Gradation is also specified for each cross section. From the Define/Edit Bed Gradation tab, the bed gradation sample is created.

From the second tab Boundary Condition, Rating curve is given as upstream sediment boundary condition.



	River	Reach	RS	Invert	Max Depth	Min Elev	Left Sta	Right Sta	Bed Gradation
1	Arun khola	arun reach	14686	574.42	10		272.19	329.3	bedgradient
2	Arun khola	arun reach	14043	569.41	10		242.73	251.99	bedgradient
3	Arun khola	arun reach	13330	567.8	10		313.66	350.63	bedgradient
4	Arun khola	arun reach	12175	566.29	10		264.21	291.78	bedgradient
5	Arun khola	arun reach	11325	563.79	10		201.34	224.18	bedgradient
6	Arun khola	arun reach	10480	560.9	10		219.99	264.9	bedgradient
7	Arun khola	arun reach	9675	557.41	10		227.11	348.13	bedgradient
8	Arun khola	arun reach	8687	554.65	10		216.46	248.49	bedgradient
9	Arun khola	arun reach	7907	552.79	10		211.46	256.42	bedgradient
10	Arun khola	arun reach	6751	549.69	10		341.38	372.94	bedgradient
11	Arun khola	arun reach	5550	545.1	10		147.93	219.71	bedgradient
12	Arun khola	arun reach	4449	539.8	10		231.19	266.45	bedgradient
13	Arun khola	arun reach	2103	532.66	10		117.54	224.74	bedgradient
14	Arun khola	arun reach	1108	531.42	10		149.55	214.9	bedgradient
15	Arun khola	arun reach	380	530.67	10		172.65	209.68	bedgradient
16	Jhimruk river	jhimruk reach	38452	640.23	10		181.4	247.7	bedgradient
17	Jhimruk river	jhimruk reach	36956	631.09	10		117.6	185.2	bedgradient
18	Jhimruk river	jhimruk reach	35818	624.53	10		236.5	340.1	bedgradient
19	Jhimruk river	jhimruk reach	33873	622.93	10		174.6	230.2	bedgradient
20	Jhimruk river	jhimruk reach	32752	617.13	10		439.6	628.7	bedgradient
21	Jhimruk river	jhimruk reach	31441	608.75	10		152.61	207.28	bedgradient
22	Jhimruk river	jhimruk reach	30302	600.16	10		377.62	438.78	bedgradient
23	Jhimruk river	jhimruk reach	28026	594.04	10		228.5	305.16	bedgradient
24	Jhimruk river	jhimruk reach	26745	581.69	10		204.8	232.8	bedgradient
25	Jhimruk river	jhimruk reach	25517	572.92	10		457.7	515.9	bedgradient
26	Jhimruk river	jhimruk reach	24978	566.62	10		259	289.6	bedgradient

Figure 4-4 Sediment Data Editor

4.3 Sensitivity Analysis

Sensitivity analysis is the most important part of any model task for understanding the accuracy and uncertainty of the model. Sensitivity analysis is done for the most influential and important five parameters; computational increment, transport function, sorting method, fall velocity method, and maximum scour depth. This analysis is done for the all above five parameters for finding the percentage change in mass out cumulative at the dam axis. The simulation is performed for five years from 1965 to 1970.

The computational increment is provided higher for lower flow and lower for higher flow.

Table 4-3 Scenarios for computational increment

Flow (m^3/s)	T1(hours)	T2(hours)	T3(hours)
0-100	24	12	6
100-1000	6	3	1.5
1000-10000	1	0.5	0.25

For calculation of general scour depth for Mari river,

Design flood discharge (Q)= 6865.28 m^3/s

Average bed width(b)= 105m

Specific discharge (q)=65.38 $m^3/s/m$

Cohesion (c)= 0.2 kg/cm^2

Taking F=2 for $\phi<5°$

Clay silt factor (K_{sfc})= F (1+ $\sqrt{c}$) = 2.89

Mean Scour depth from high flood level= $1.34(q^2/ K_{sfc})^{1/3}$ = 14.89m

HFL from rating curve= 8.45m

Mean scour depth from bed = 14.89-8.45= 6.44m

Take maximum scour depth of 10m

Table 4-4 Model Parameters and their scenarios to perform sensitivity analysis

S. N	Parameters	Sta ndard Values	Scenarios
1.	Computational Increment	T2	T1
			T2
			T3
2.	Transport Function	Toffaleti	Achers-White
			Engelund Hansen
			Laursen (Copeland)
			Meyer Peter Muller
			Toffaleti
3.	Sorting Method	Copeland (Ex 7)	Thomas (Exner 5)
			Active Layer
			Copeland (Exner 7)
4.	Fall Velocity Method	Van Rijn	Ruby
			Van Rijn
			Wu & Wang
5.	Maximum Scour Depth	10m	5 m
			10 m
			15 m

4.4 Sediment Deposition Pattern

4.4.1 Calibration and Validation

Calibration and Validation are performed by using Correlation Analysis. It is statistical tool to compute the data variance between the observed and simulated sediment concentration obtained at the Bagasutigaon station (station no 350).

$$r = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2 \Sigma(y_i - \bar{y})^2}} \qquad (4.2)$$

In Calibration, various trials have been made to obtain a better correlation between the simulated and observed values. Three years of data are calibrated and the parameters are set accordingly and the same data parameters validation is done for three years. Calibration and validation are done for the flow data from 1985-1988 and 1990-1993 respectively.

4.4.2 Reservoir Sedimentation

A model is set up for evaluation following calibration and validation of the model. The flow data from 1965 to 2015 set as the boundary condition at upstream of Mari Khola, Jhimruk Khola, and Arun Khola. The downstream of West Rapti River is set up for the initial stage boundary to obtain the reservoir water level.

4.5 Storage Loss of the Reservoir

Storage loss in the reservoir is obtained by calculation of the sediment volume deposit in every reach from the HEC-RAS simulation result. The total volume of sediment deposited in the reservoir is determined and finally, the storage loss for the year 10 year, 20 years, 30 years, 40 years and 50 years is calculated for 1965 to 2015. The calculation is done using equation 4.2.

$$Storage\ loss = \frac{cumulative\ volume\ in - cumulative\ volume\ out}{total\ storage\ volume} \times 100\% \quad (4.3)$$

Here, the loss of live storage volume is used for the calculation of loss in energy.

Chapter 5: RESULTS AND DISCUSSION

5.1 HEC-RAS Model Output

5.1.1 Sediment Rating Curve

Sediment rating curve for Chernata station (339.5) and Bagasotigaon station (350) are obtained from the observed data using rating curve calculator from HEC-RAS. HEC-RAS uses least-squares regression technique which biases logarithmic rating curves. Log-transform regressions compute the geometric mean instead of the arithmetic mean, which underestimates loads. There are several approaches to computing representative values from log-normally distributed data. USACE studies (Copeland, 2011) apply (Ferguson, 1984) estimator most often. This unbiased estimator is based on the standard error of the regression. It is a multiplicative corrector in the flow-load or flow concentration power function such that:

$C=\exp(s^2/2) \times aQ^b$

Where C is concentration, Q is flow, a and b are the biased coefficients of the log transformed least squares regression, and $\exp(s^2/2)$ is the correction factor,

where:

$$S^2 = \sum_{i=1}^{n} \frac{(\ln(C_i\ (obs) - \ln(C_i\ (measurd))^2}{N-k} = \sum_{i=1}^{n} \frac{\ln\left(C_i\ (obs) - \ln\left(aQ_i^b\ \right)\right)^2}{N-k} \tag{5.1}$$

The sediment rating curve obtained is $Q_s = 0.00236\ Q^{1.2868}$ with R^2 value of 0.655 for Jhimruk station and $Q_s = 0.0306\ Q^{1.2507}$ with R^2 value of 0.807 for West Rapti station. At both station, screening of many high concentration data is done to make the rating curve representative. This result very low estimation of sediment concentration.

The rating curves are presented in Figure 5-1 and Figure 5-2 for Jhimruk and West Rapti station respectively.

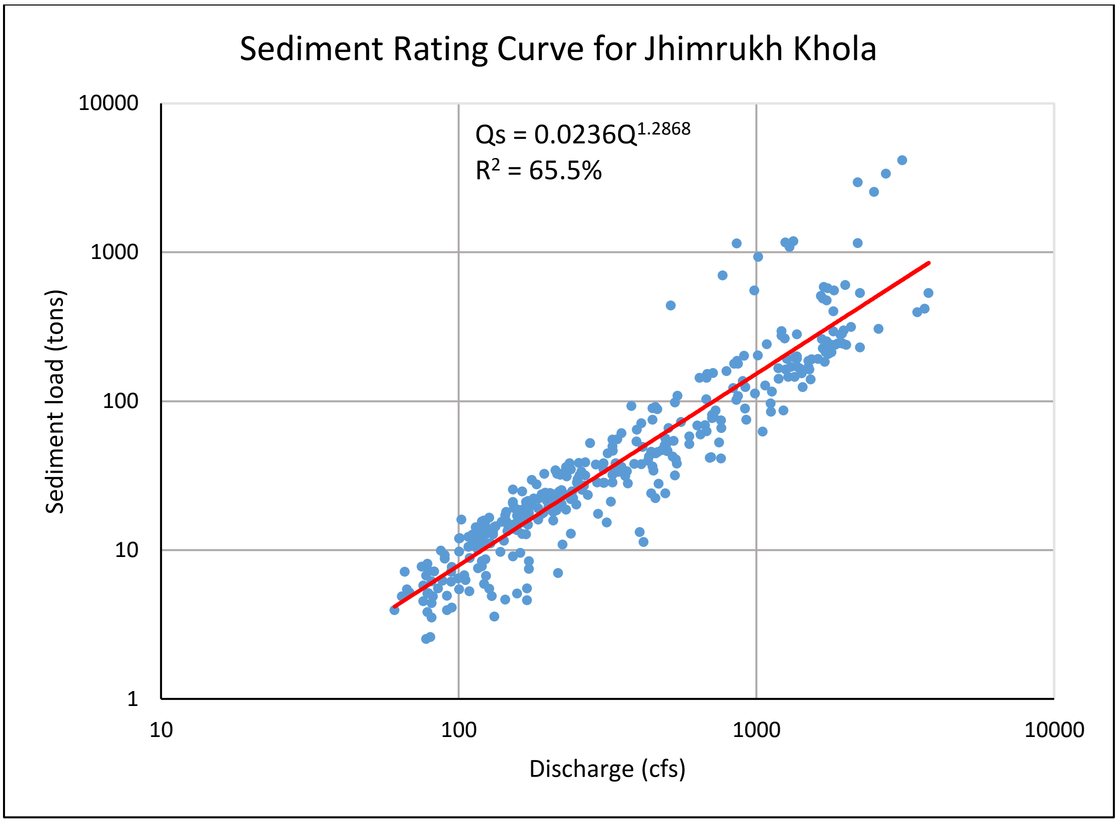


Figure 5-1 Sediment Rating curve of Jhimruk Station

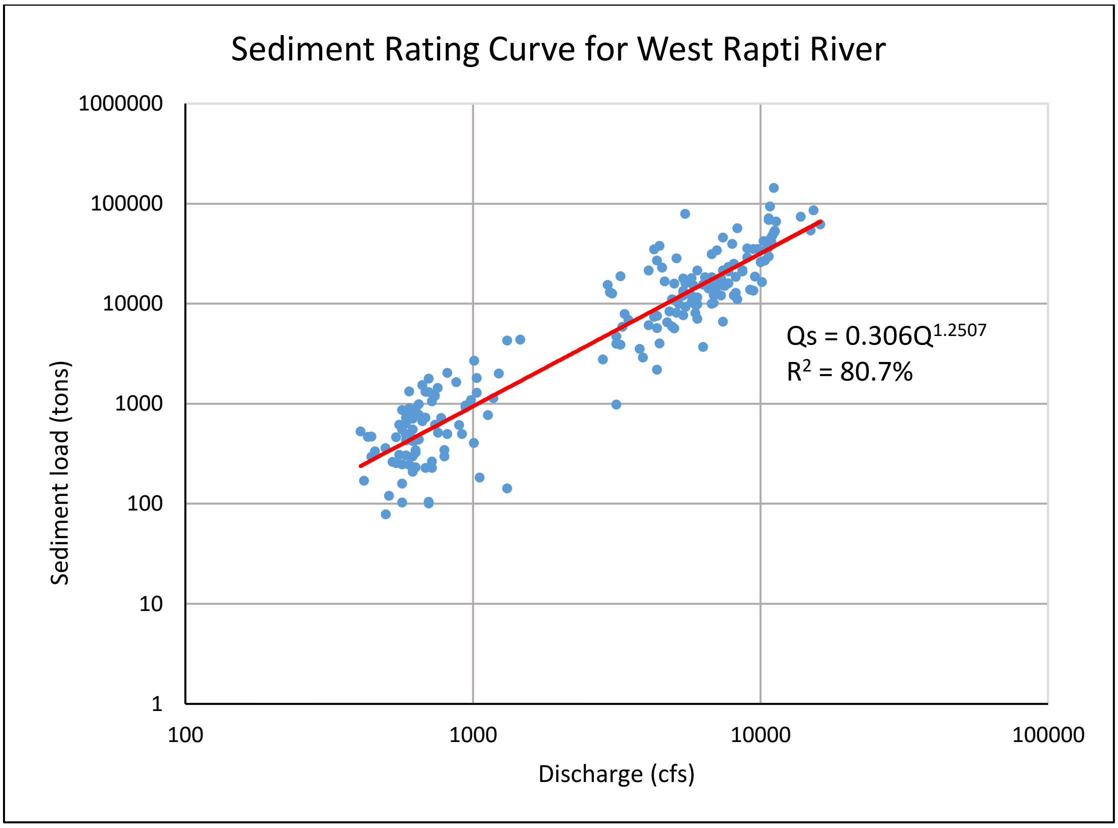


Figure 5-2 Sediment Rating Curve at West Rapti Station

5.1.2 Manning's Roughness Coefficient

The Manning's n value selected in HEC-RAS model from which the results are best related is presented here in Table 5-1. It is assumed that bed material and land cover of study area are constant throughout the catchment. So same manning's coefficient is used for all the reaches.

Table 5-1 Selection of Manning's n for different River Reach

River	Reaches	Manning's n		
		LOB	Channel	ROB
West Rapti	Reach 1	0.04	0.03	0.04
Mari	Reach 2	0.04	0.03	0.04
Jhimruk	Reach 3	0.04	0.03	0.04
Arun	Reach 4	0.04	0.03	0.04

5.1.3 Submergence Area and its Extent

To identify the extent of the river, reach to be taken for HEC-RAS model set up, submerged area due to the dam at Bhalubang is assessed using the surface analysis in GIS. The total submergence area is 19.512 km^2 and total volume is 1259.832 Mm^3. The map showing the maximum submerged area due to the dam is shown in Figure 5-3. The impact length obtained from submergence analysis is as follows:

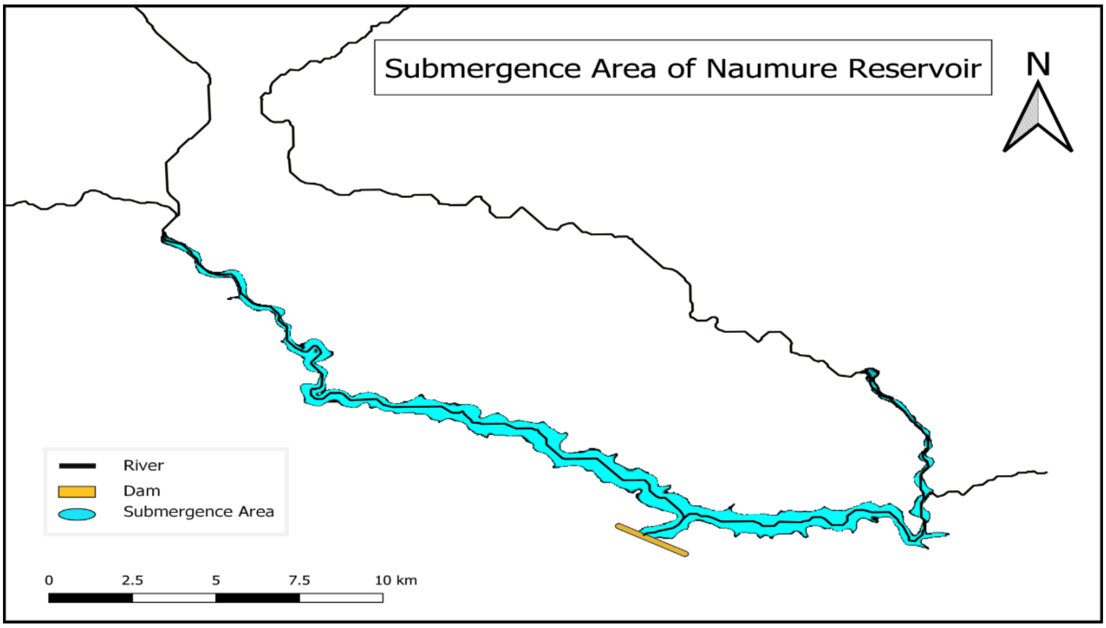


Figure 5-3 Submergence area for NMP reservoir

Table 5-2 Submergence Length for River reaches

SN	Rivers	Length (km)	Remarks
1	West Rapti	2.26	From Dam site
2	Mari	25.46	From Confluence with West Rapti main
3	Jhimruk	18.58	From Confluence with West Rapti main

5.2 Calibration and Validation

Comparison plot for Sediment load calculated from the observed data and simulated data obtained from HEC-RAS model from year 1985 to 1988 and 1990 to 1993 are presented in Figure 5-4 and Figure 5-5 as calibration and validation respectively.

The correlation coefficient obtained for Calibration is 65.1% and for Validation is 86.27%.

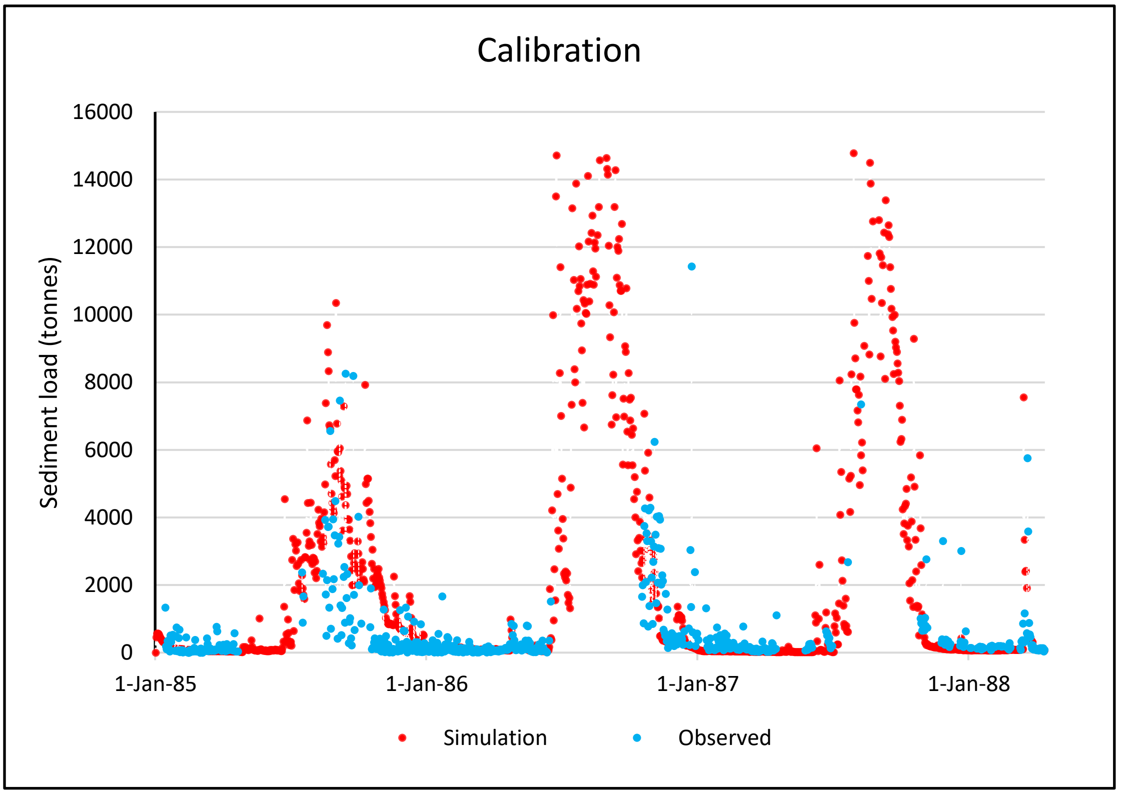


Figure 5-4 Calibration of sediment load at Bagasotigaon station 350

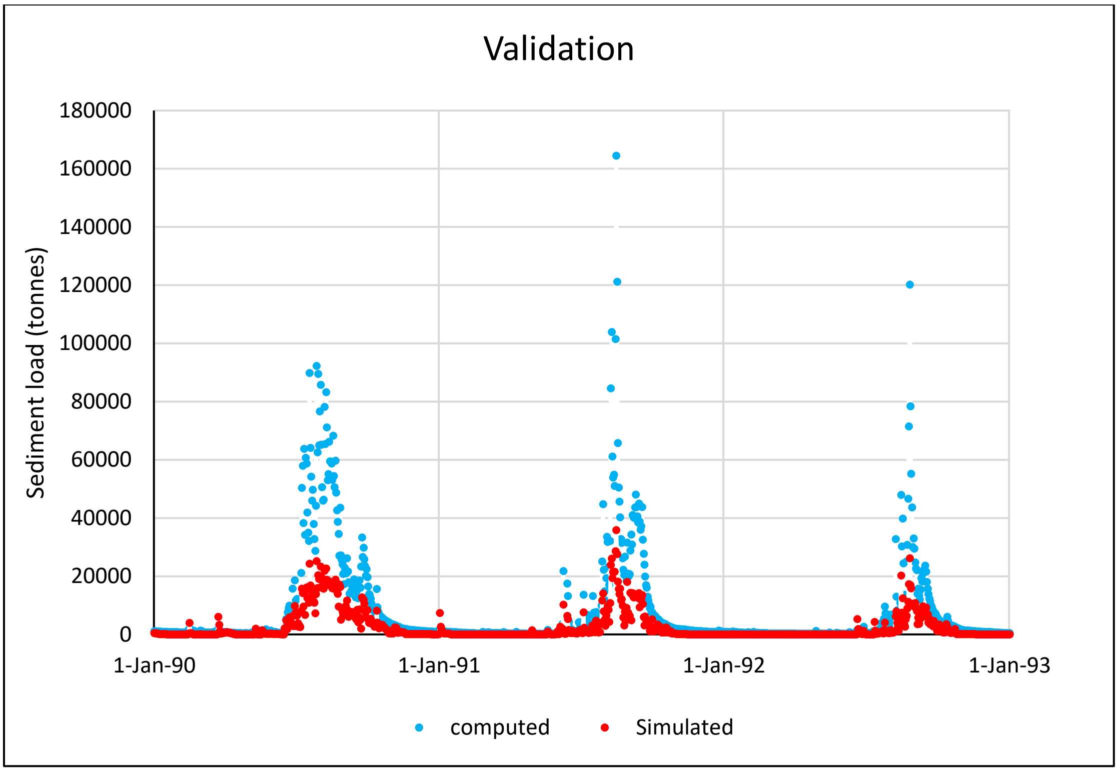


Figure 5-5 Validation of sediment load at Bagasotigaon station 350

5.3 Sediment Deposition in NMP Reservoir

The change in bed level due to the sediment transport for 10, 20, 30, 40, and 50 years' simulation period is shown in Figure 5-6, Figure 5-7 and Figure 5-8 for West Rapti and Mari khola, Arun Khola and Jhimruk Khola respectively. As expected over time, the delta in the reservoir propagates in the upstream and downstream direction, due to the deposition of sediments. The typical cross sections for every river reaches at the pivot point of delta is shown in Figure 5-9, Figure 5-10, Figure 5-11, Figure 5-12, Figure 5-13, Figure 5-14, Figure 5-15 and Figure 5-16. Also, the velocity obtained from HEC-RAS shows that the velocity is reduced to almost zero from the upstream end of reservoir, due to which the sediment starts to deposit more there. This is shown in Figure 5-17 and Figure 5-18.

The delta propagation for Mari river starts 21 km to 29 km upstream from confluence point with West Rapti. The delta profile for Jhimruk begins from 17 km to 23 km upstream from confluence point with West Rapti. Arun is a small tributary and the delta profile is seen just above confluence point with Mari khola. The detail deposition length and place for all the tributaries is presented in Table 5-3.

Table 5-3 Sediment deposition in the river reaches

SN	River	Confluence at distance from Dam site	Sediment deposition				
			10 years	20 years	30 years	40 years	50 years
1	Jhimruk	2.21km	17 to 22 km	17 to 21.5 km	17 to 21.7 km	17 to 22 km	0 to 23.4 km
2	Mari	2.21km	14.2 to 23.7 km	22.1 to 57.9 km	24.8 to 57.9 km	23.6 to 57.9 km	22.1 to 57.9 km
3	Arun	31.08km	0 to 8.3 km	0.7 to 4.7 km	1.7 to 10.1 km	0 to 1.72 km	0 to 1.72 km

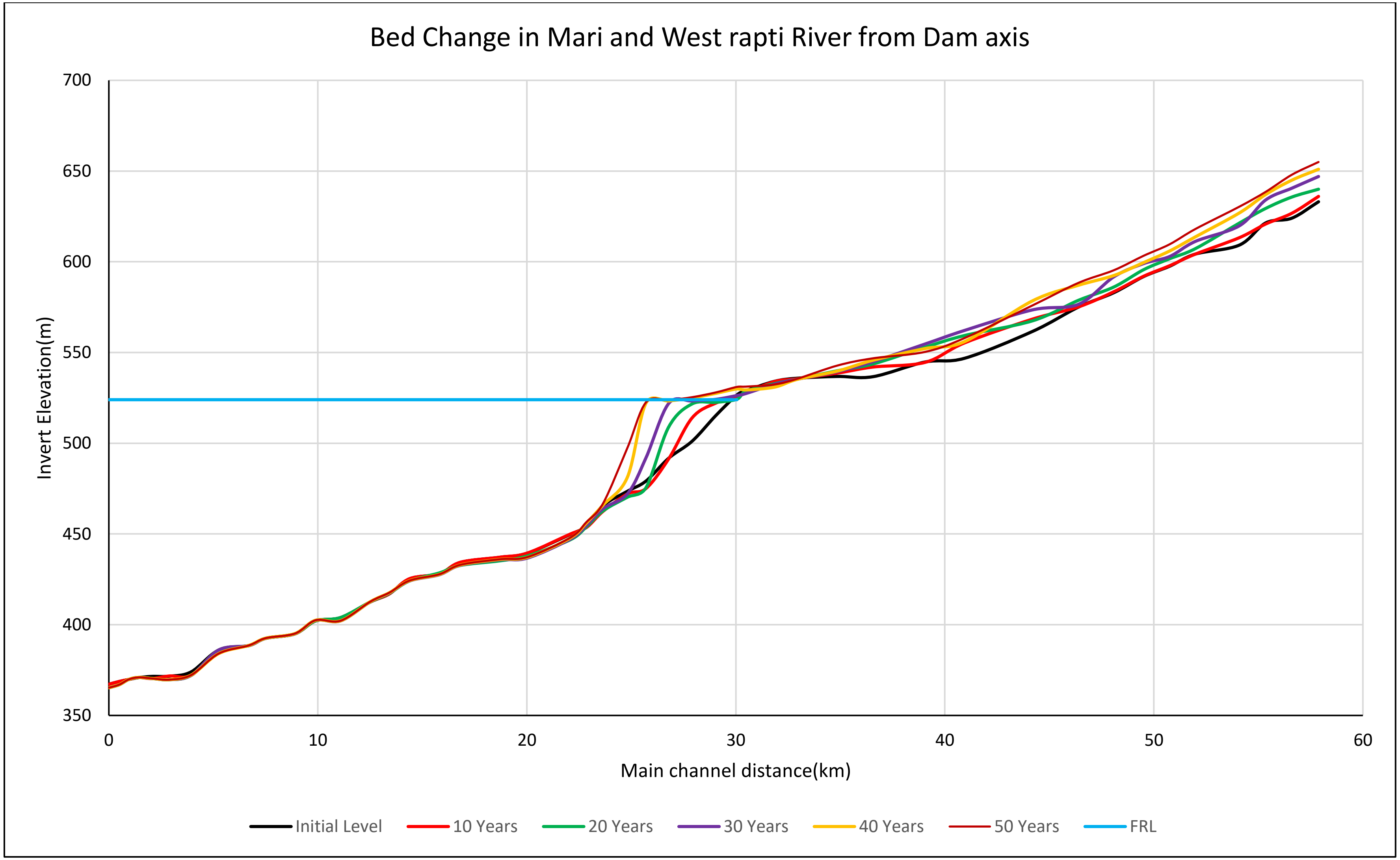


Figure 5-6 Sediment Deposition in Mari Reach and West Rapti Reach

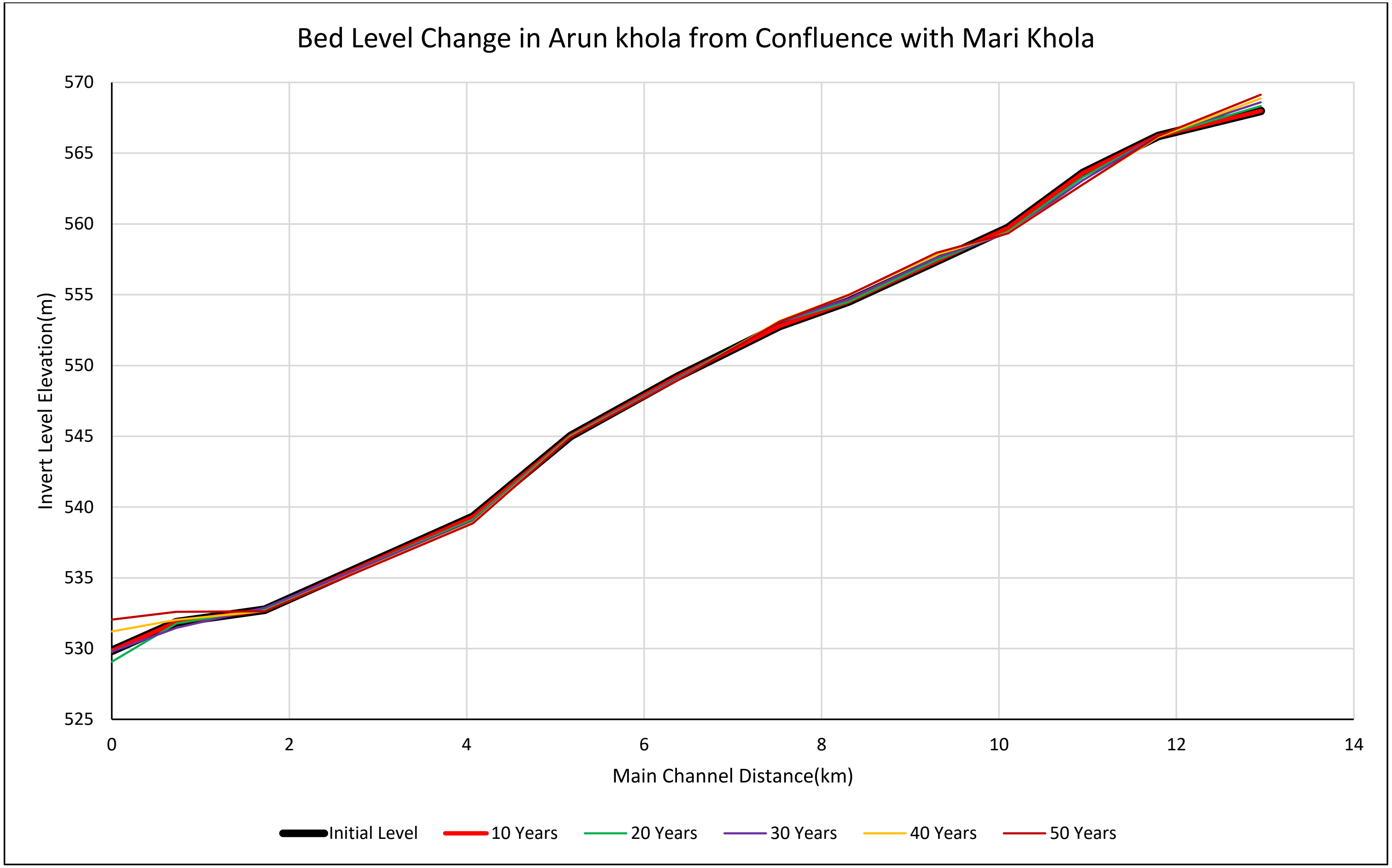


Figure 5-7 Sediment Deposition in Arun Reach

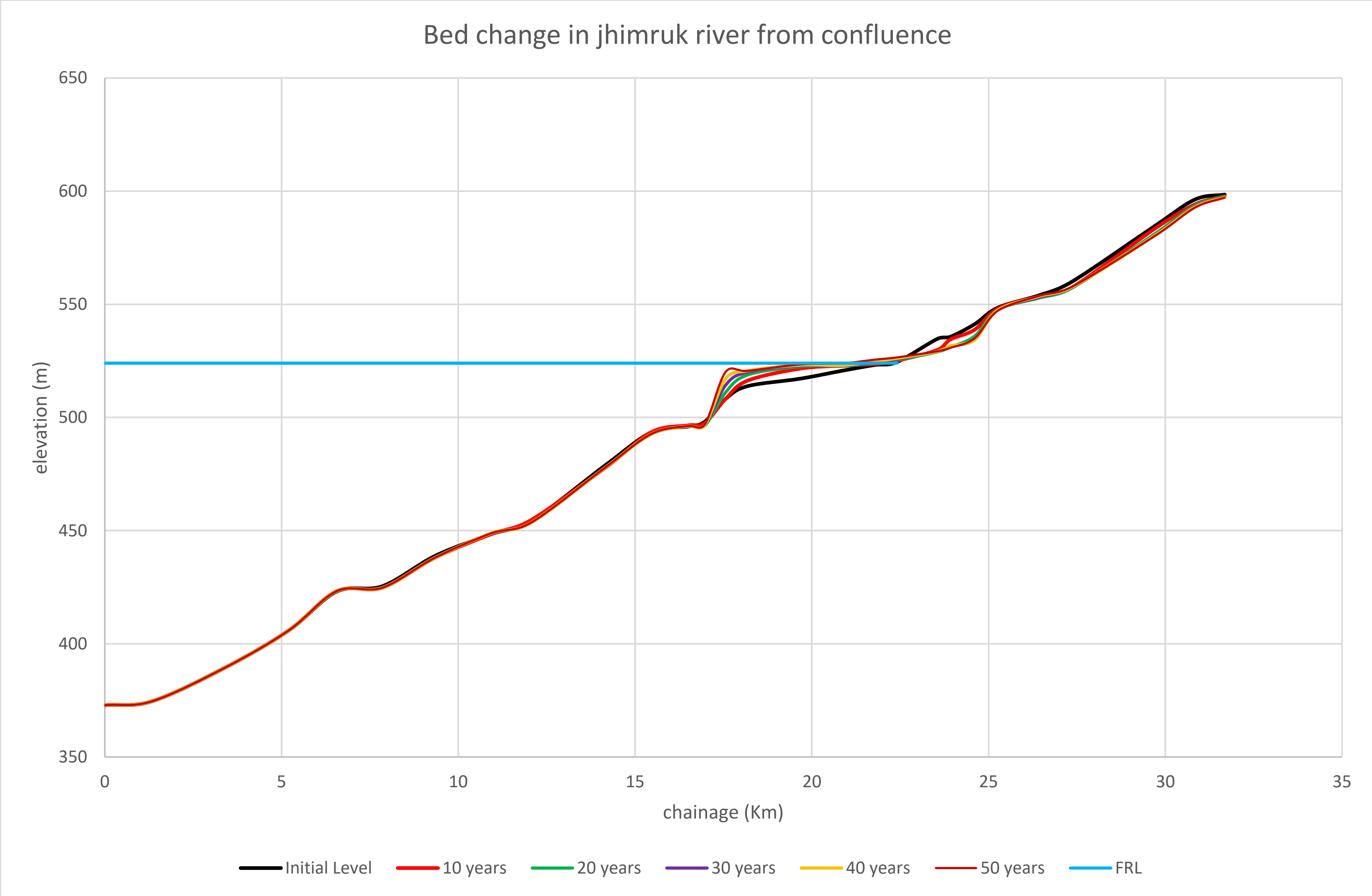


Figure 5-8 Sediment Deposition in Jhimruk Reach

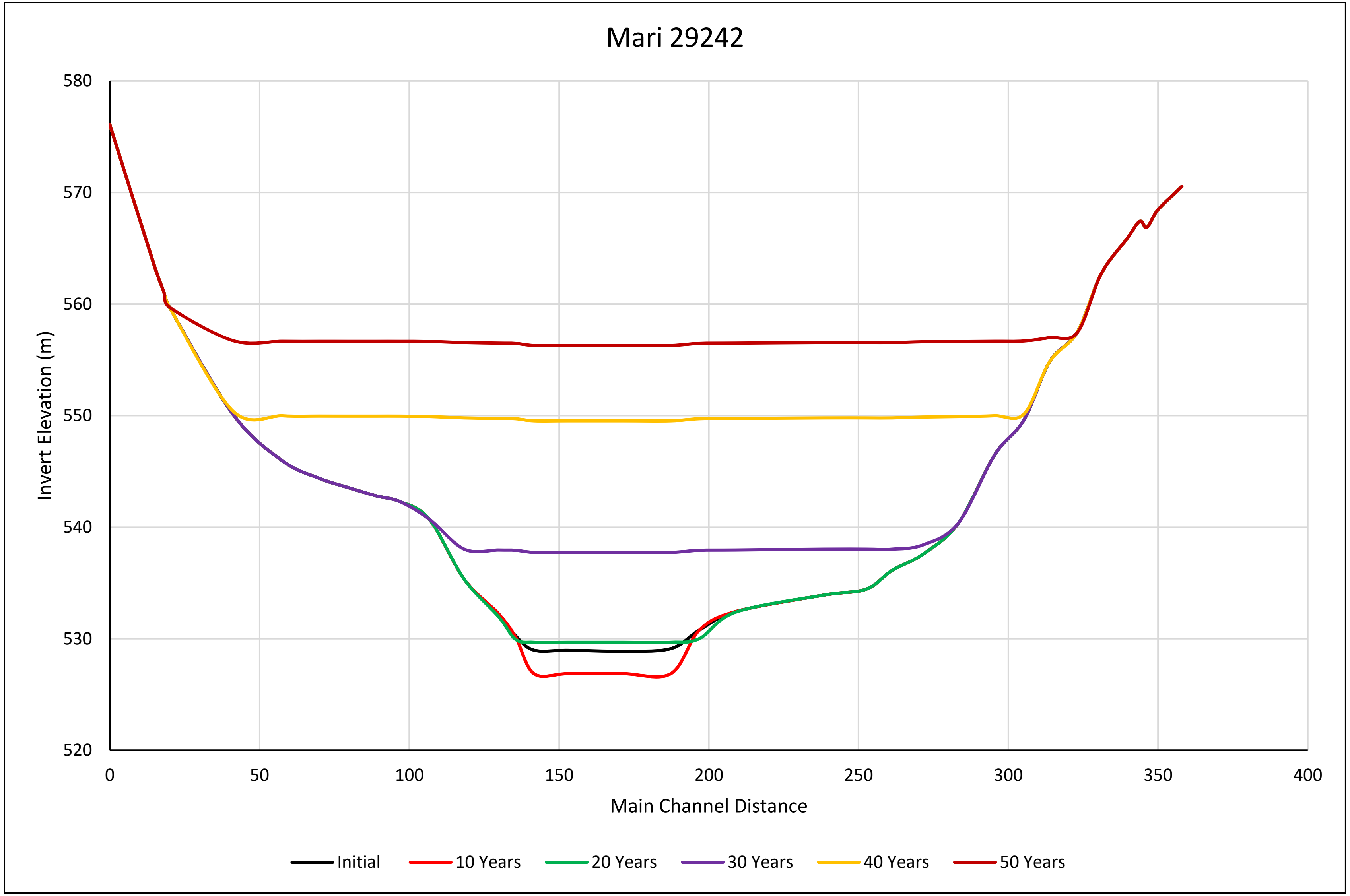


Figure 5-9 Cross section at Mari 29242

Figure 5-10 Cross section at Mari 28697

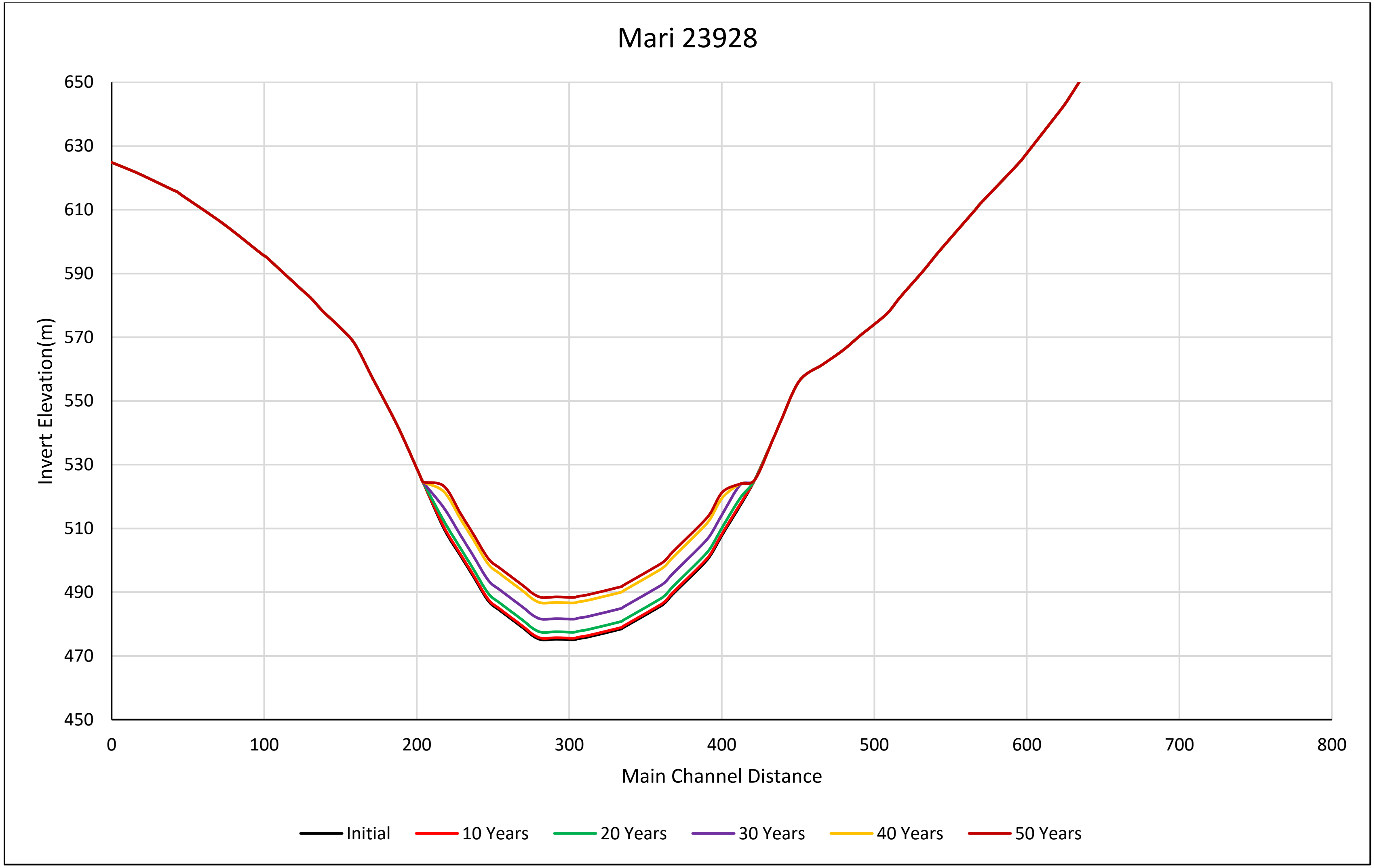


Figure 5-11 Cross Section at Mari 23928

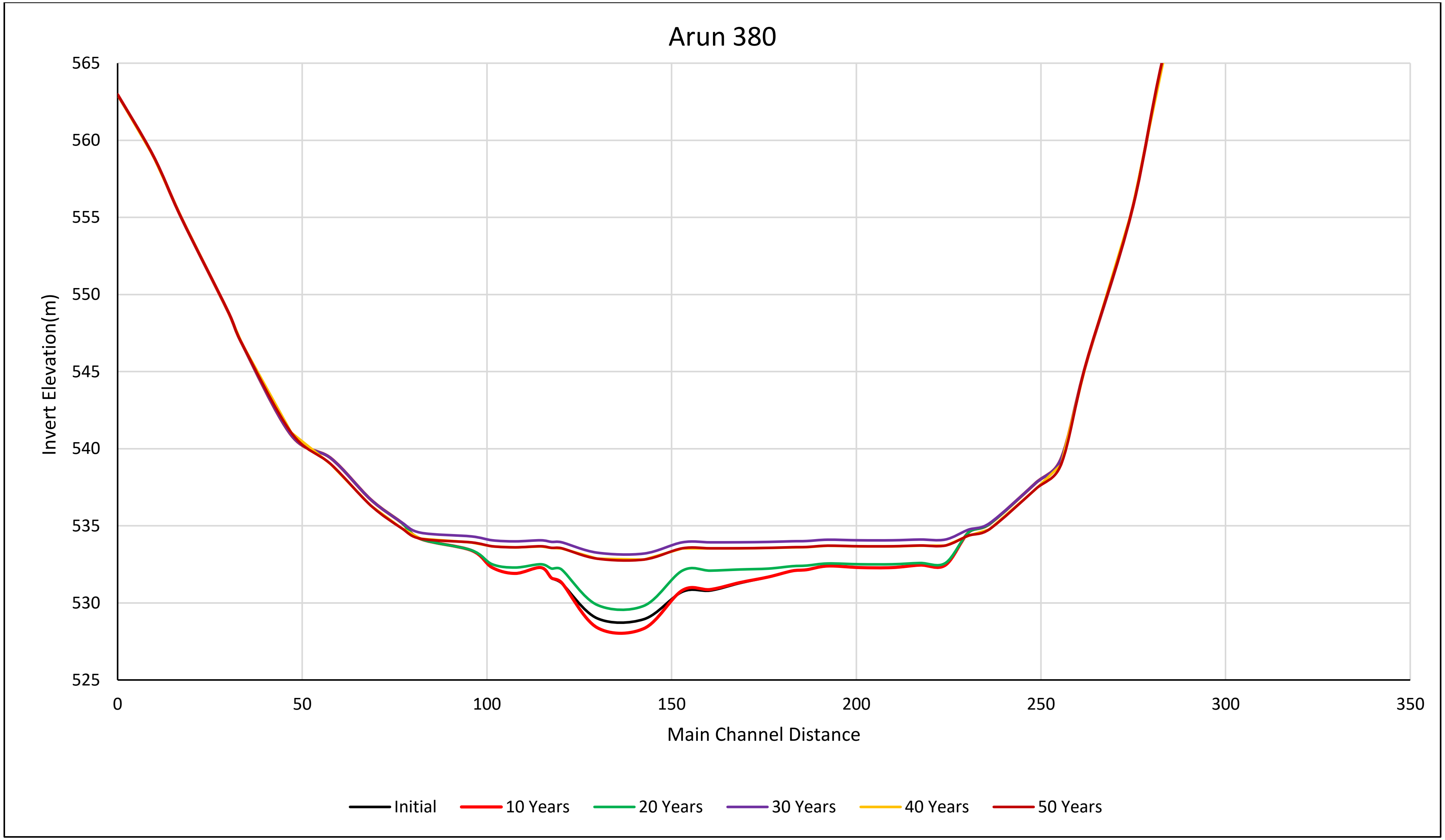


Figure 5-12 Cross Section at Arun 380

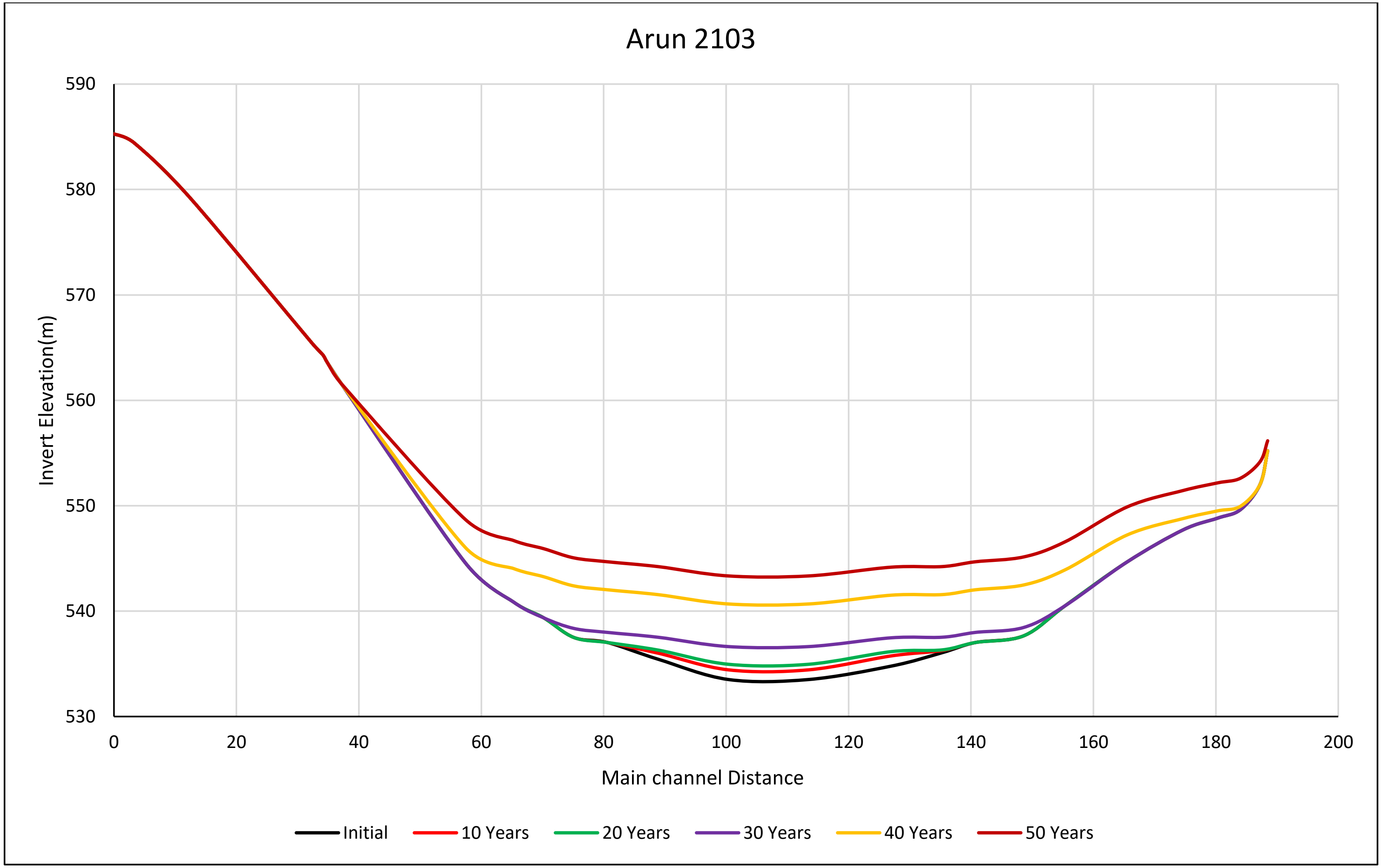


Figure 5-13 Cross Section at Arun 2103

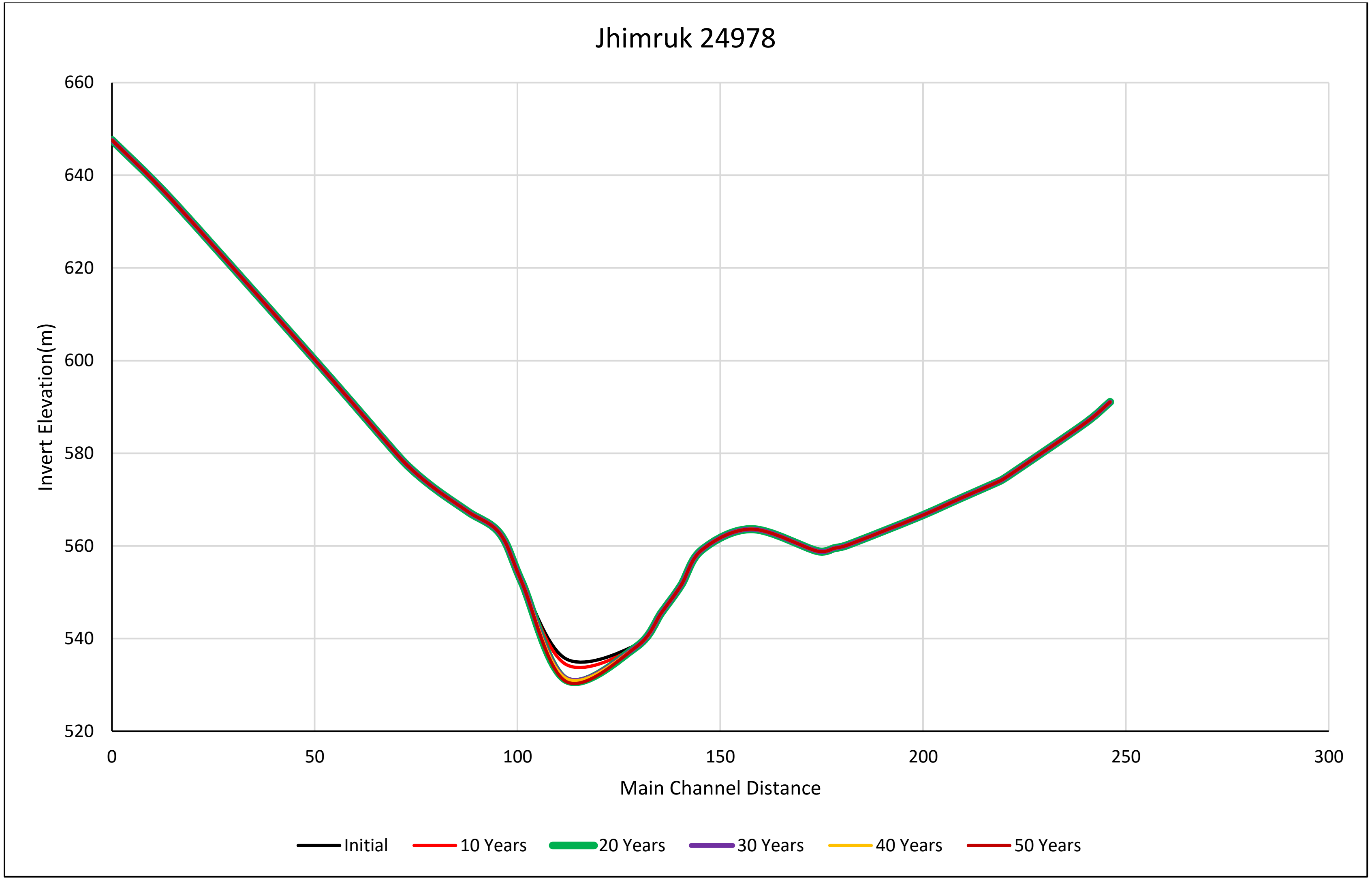


Figure 5-14 Cross Section at Jhimruk 24978

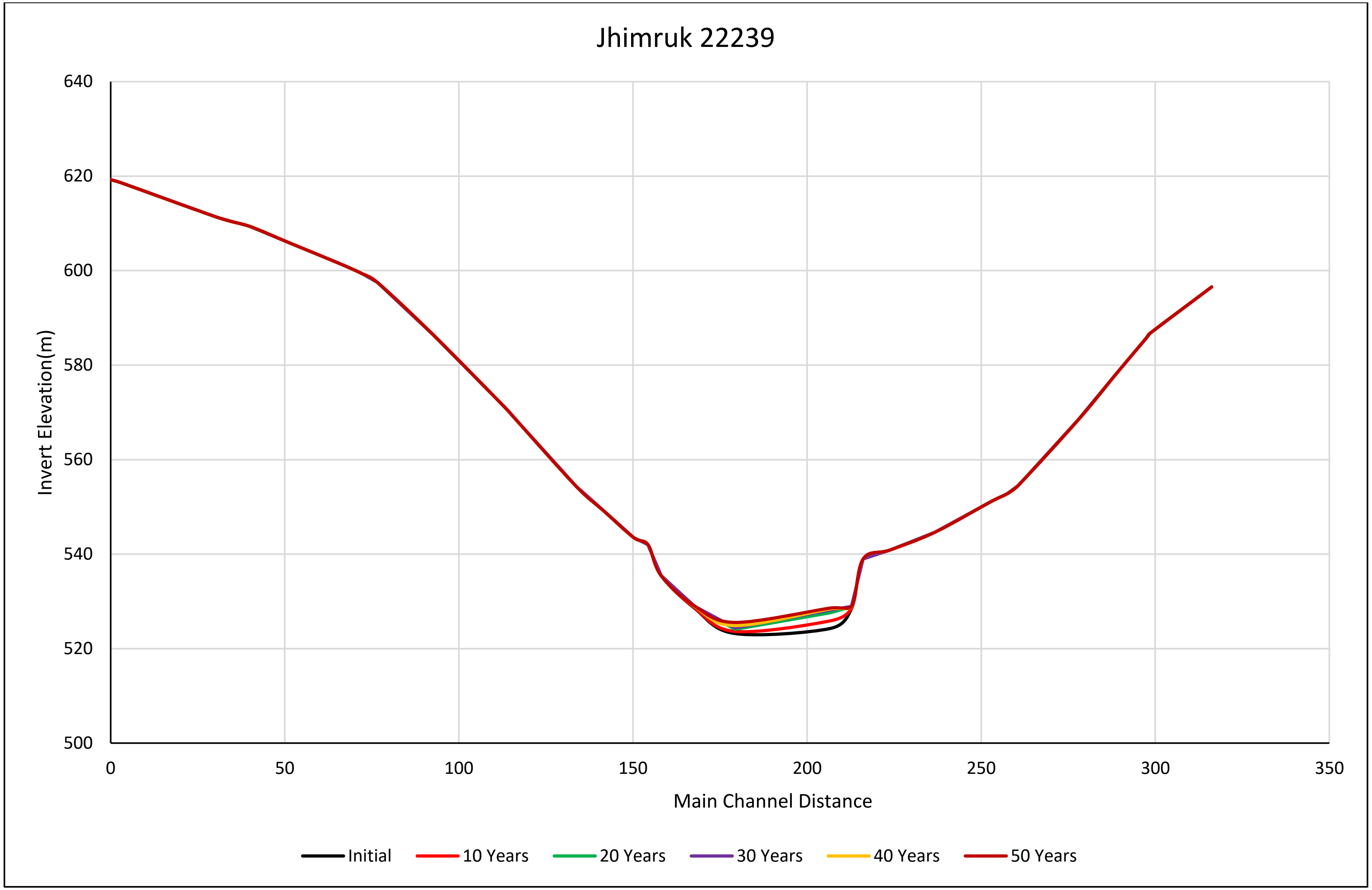


Figure 5-15 Cross section at Jhimruk 22239

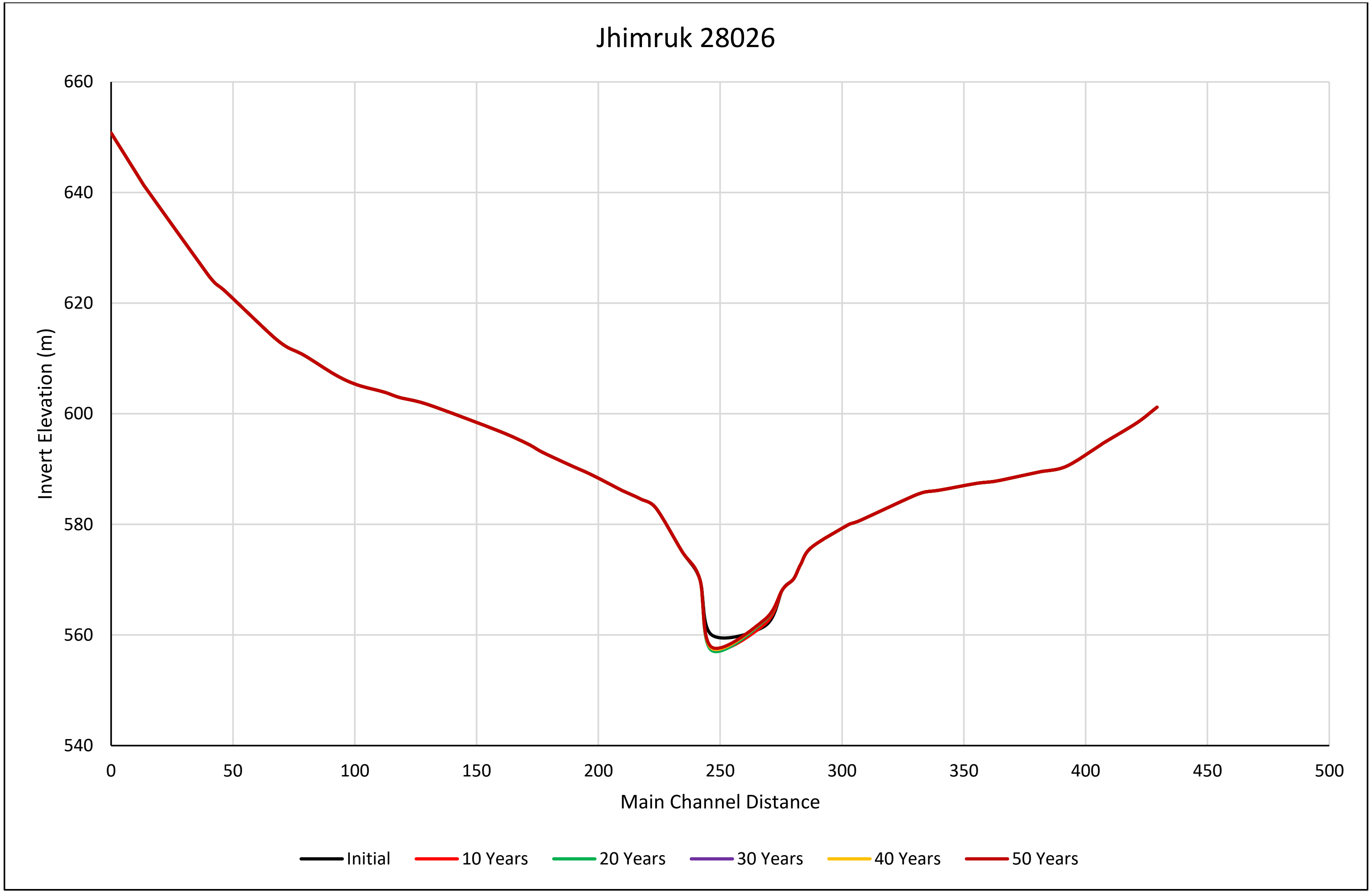
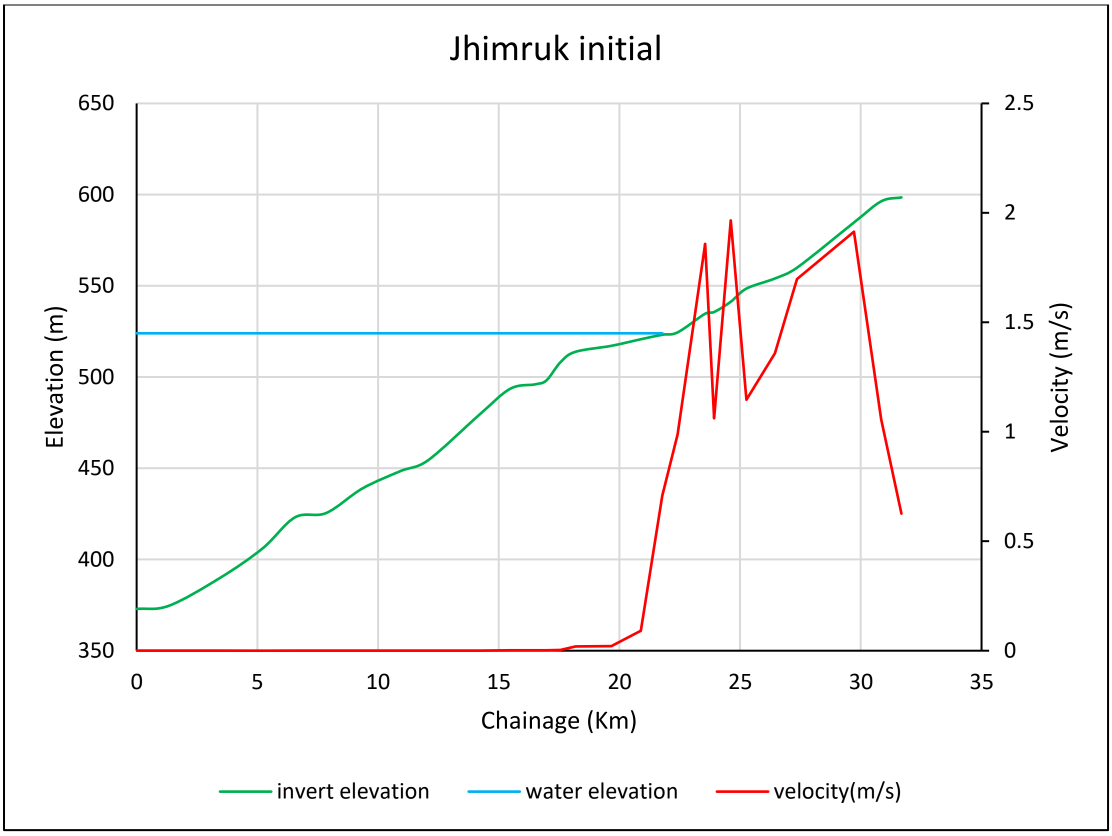


Figure 5-16 Cross Section at Jhimruk 28026



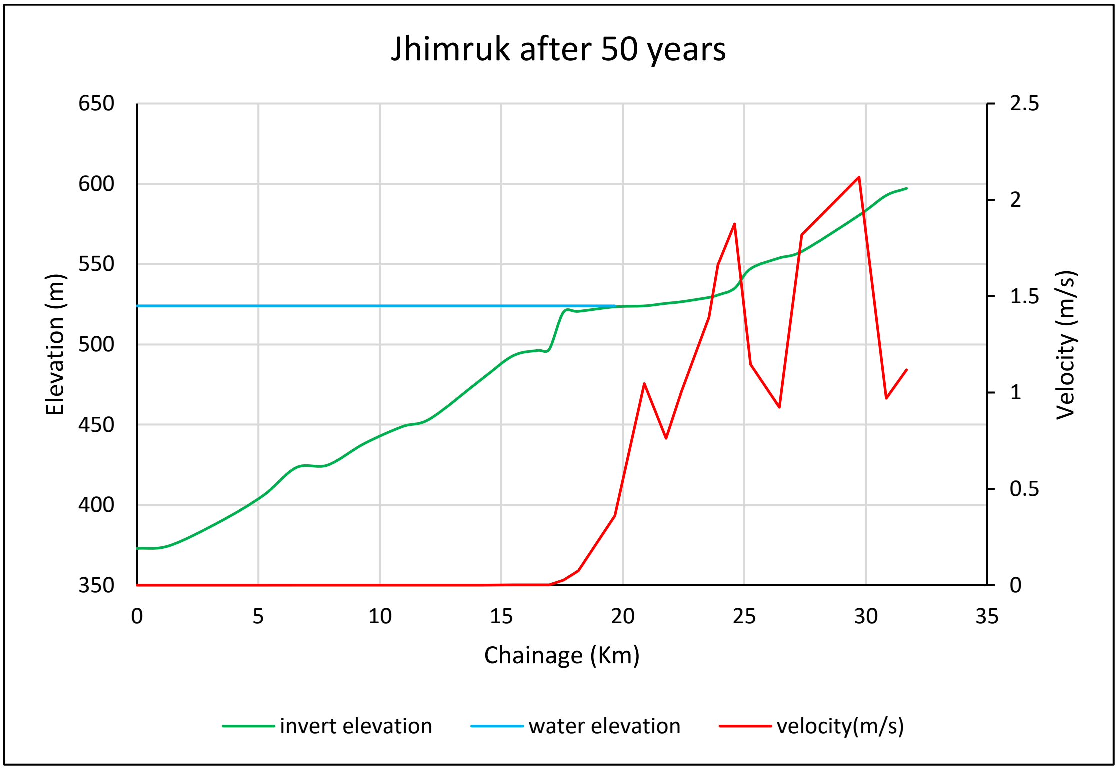
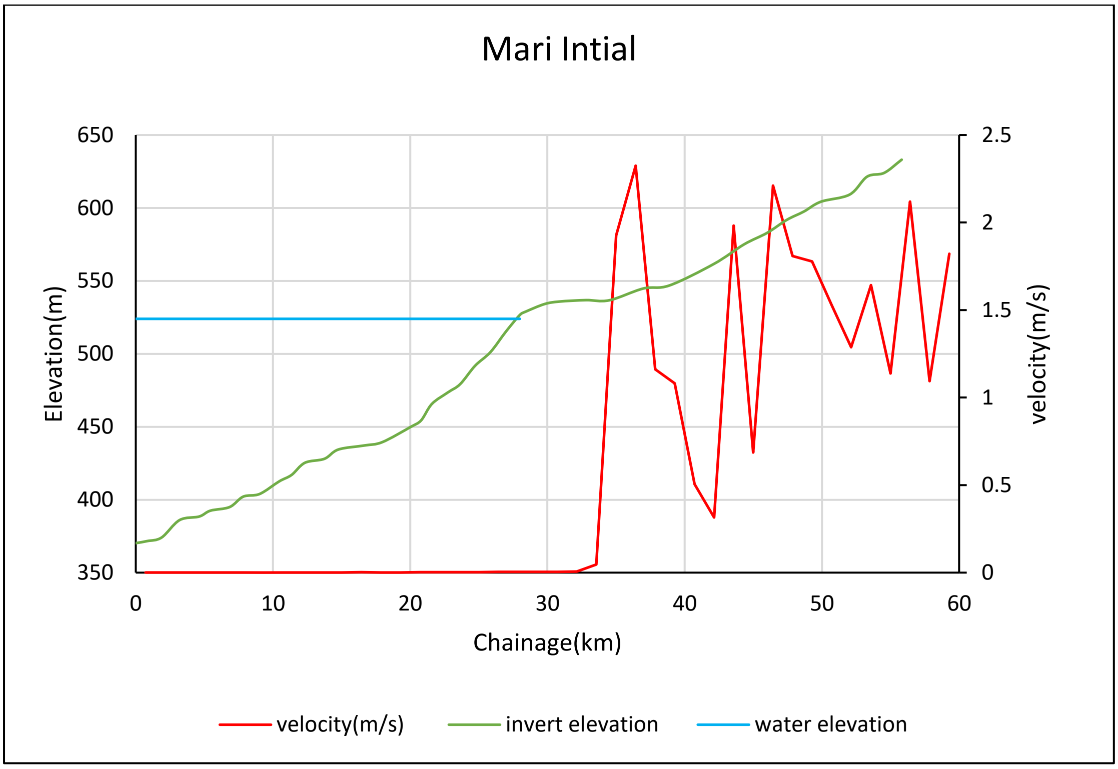


Figure 5-17 Profile Plot for Velocity, Invert Elevation and WSE for Mari Reach at Initial and 50 Years' Time Period



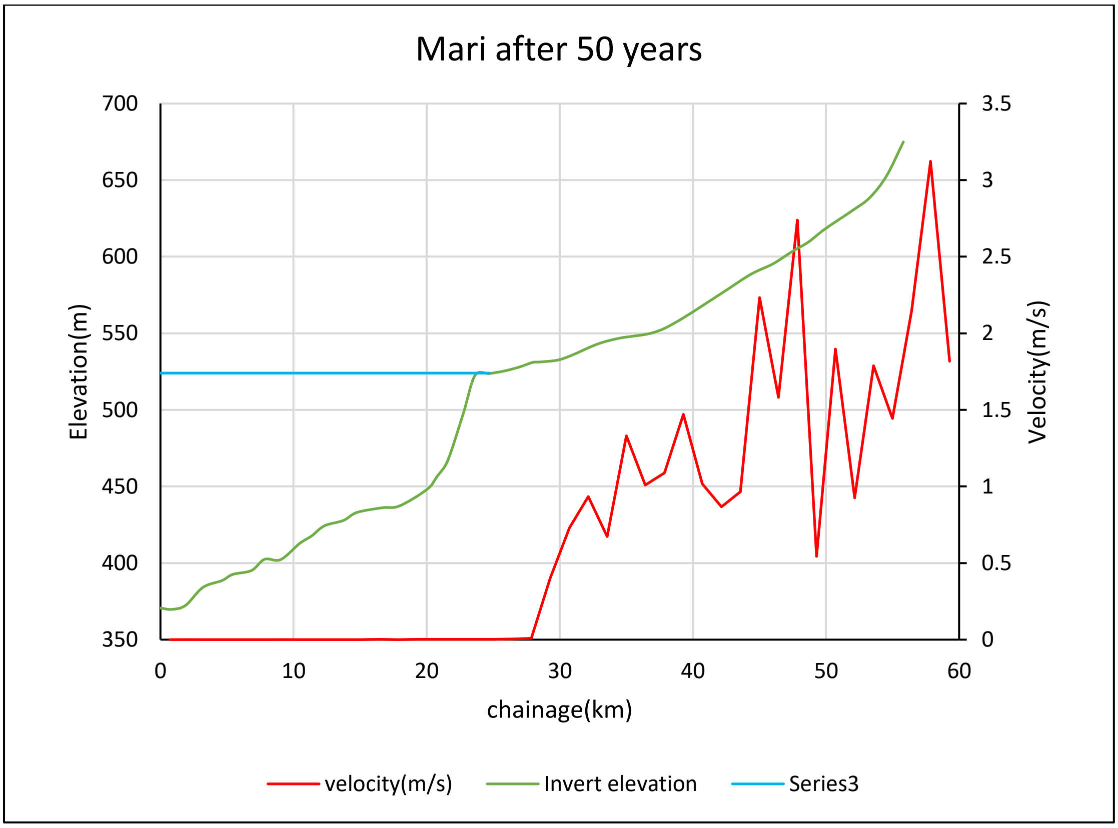


Figure 5-18 Profile Plot for Velocity, Invert Elevation and WSE for Mari Reach at Initial and 50 Years' Time Period

5.4 Storage and Energy loss due to Sediment deposition

Table 5-4 Volume of storage sediment deposition and storage loss when simulated from 1965-2015.

years	Sediment Deposited in reaches (10^7 m^3)			Total deposited sediment reaches (10^7 m^3)	% loss in storage
	Mari	West	Jhimruk		
10	0.474	0.002	0.059	0.535	0.607
20	1.166	0.001	0.125	1.291	1.464
30	1.929	0.003	0.174	2.106	2.388
40	2.747	0.004	0.220	2.972	3.370
50	3.151	0.005	3.376	6.531	7.406

The total sediment deposition in all three reaches and the percentage loss in the storage volume from year 1965 to 2015 is presented in Table 5-4.

For obtaining the results, the discharge data from 1965 to 2015 for the three hydrological station Mari station, Jhimruk station and West Rapti station have been used. As presented in table, the percentage lost in storage volume are found to be 0.607, 1.464, 2.388, 3.370 and 7.406 for 10 years, 20 years, 30 years, 40 years and 50 years respectively.

5.5 Sensitivity analysis of model parameters

The result obtained from the sensitivity analysis of 5 different parameters of quasi unsteady sediment transport model is shown in Table 5-5. Here dam axis is taken as the pivot point for sensitivity analysis.

Table 5-5 Sensitivity Analysis of model parameters

S. N	Parameters	Standard Value	Scenarios	% change in cumulative mass out (time series)
1	Computational increment	T2	T1	0.61
			T2	0
			T3	0.18
2	Transport function	Toffaleti	Toffaleti	0
			Achers-White	6.56
			Engelund Hansen	2.02
			Laursen (Copeland)	6.97
			Meyer Peter Muller	-3.25
3	Sorting Method	Coplend (Exner 7)	Coplend(Ex 7)	0
			Active Layer	-0.27
			Thomas (Ex5)	0.16
4	Fall velocity method	Van Rijn	Van Rijn	0
			Ruby	-0.14
			Wu and Wang	-0.14
5	Maximum scour depth	10 meters	10 meters	0
			5 meters	-0.098
			15 meters	-0.51

5.5.1 Sensitivity of Computational Increment

Figure 5-19 represents time series plot for total cumulative mass out at pivot point at the end of the simulation of 5 years for the different scenarios of computational time.

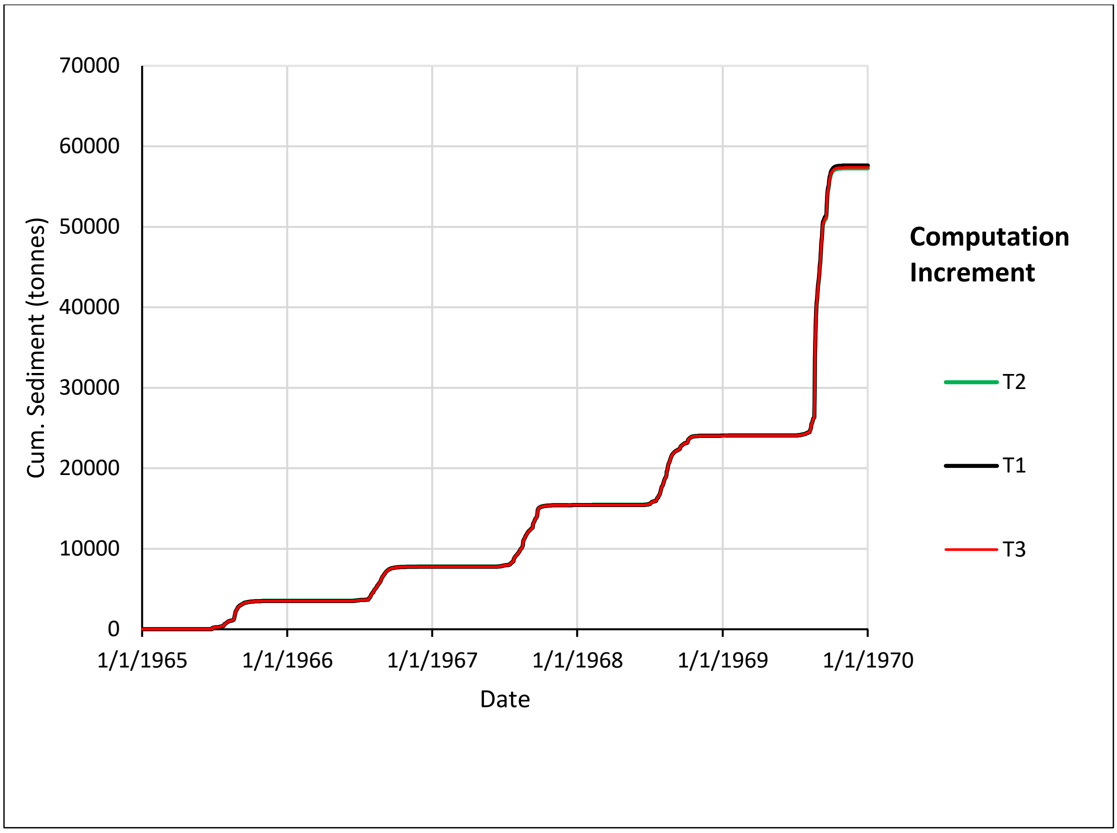


Figure 5-19 Time Series Plot of total Cumulative Mass Out for Computational Increment

The result obtained from the three scenarios of computational increment T1, T2 and T3 shows there is slight significant change in percentage change in cumulative mass out. So, Computation Increment is found to be moderately sensitive parameter in the study area.

5.5.2 Sensitivity of Transport Function

Figure 5-20 represents time series plot for total cumulative mass out at pivot point at the end of the simulation of 5 years for the different scenarios of Transport functions.

There is high significant change in the percentage change in cumulative mass out for different transport functions. The maximum percentage change and minimum percentage change for the total cumulative mass out at the end of 5-year simulation at pivot point is 6.97% and -3.25% for Laursen Copeland and Meyer Peter Muller respectively. So, it is highly sensitive parameter.

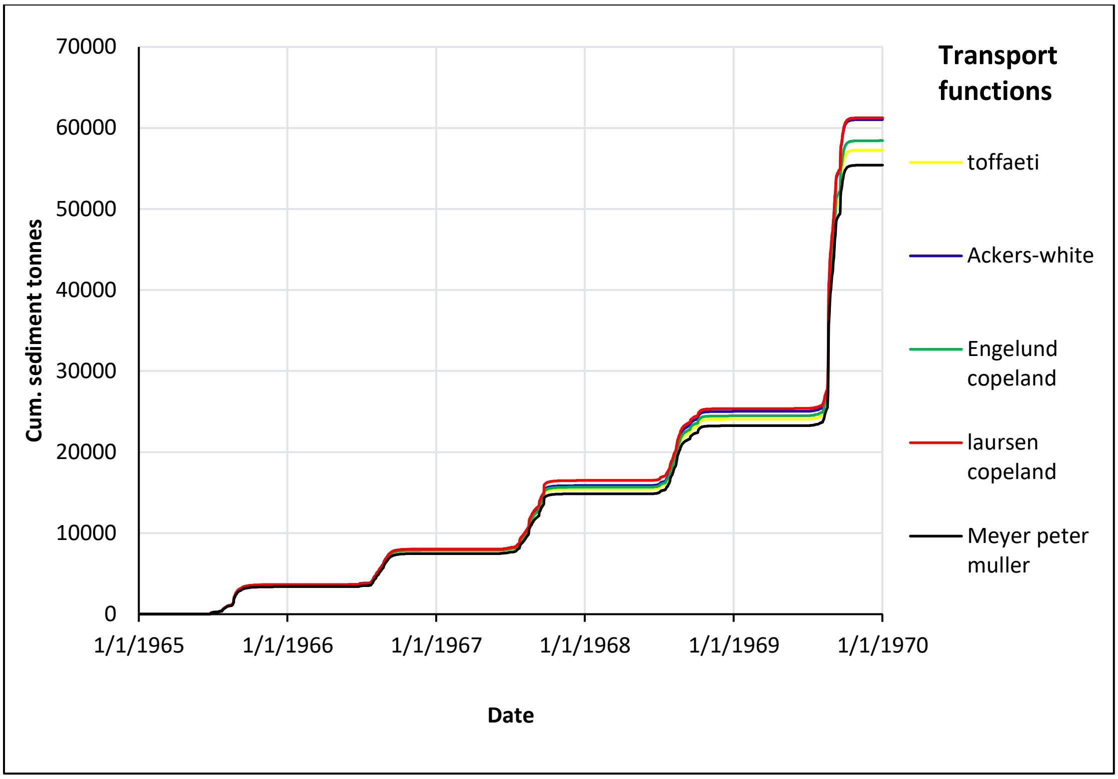


Figure 5-20 Time Series Plot of total Cumulative Mass Out for Transport function

5.5.3 Sensitivity of Sorting Method

Figure 5-21 represents time series plot for total cumulative mass out at pivot point at the end of the simulation of 5 years for the different scenarios of Sorting Method.

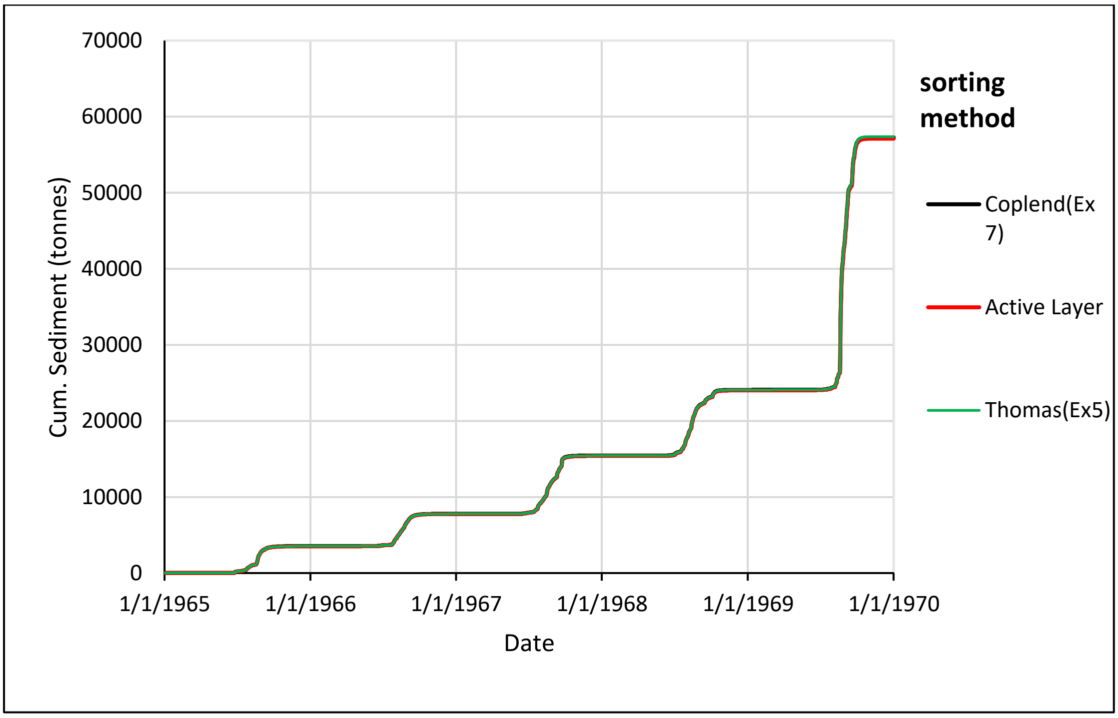


Figure 5-21 Time Series Plot of total Cumulative Mass Out for Sorting Method

The percentage change in cumulative mass out using Active Layer and Thomas (Exner 5) is - 0.27 and 0.16 respectively with respect to Copeland (Exner 7). This is slight significant change in percentage change in cumulative mass out in the result. So, sorting method is found to be moderately sensitive parameter in the study area.

5.5.4 Sensitivity of Fall Velocity Method

Figure 5-22 represents time series plot for total cumulative mass out at pivot point at the end of the simulation of 5 years for the different scenarios of fall velocity method.

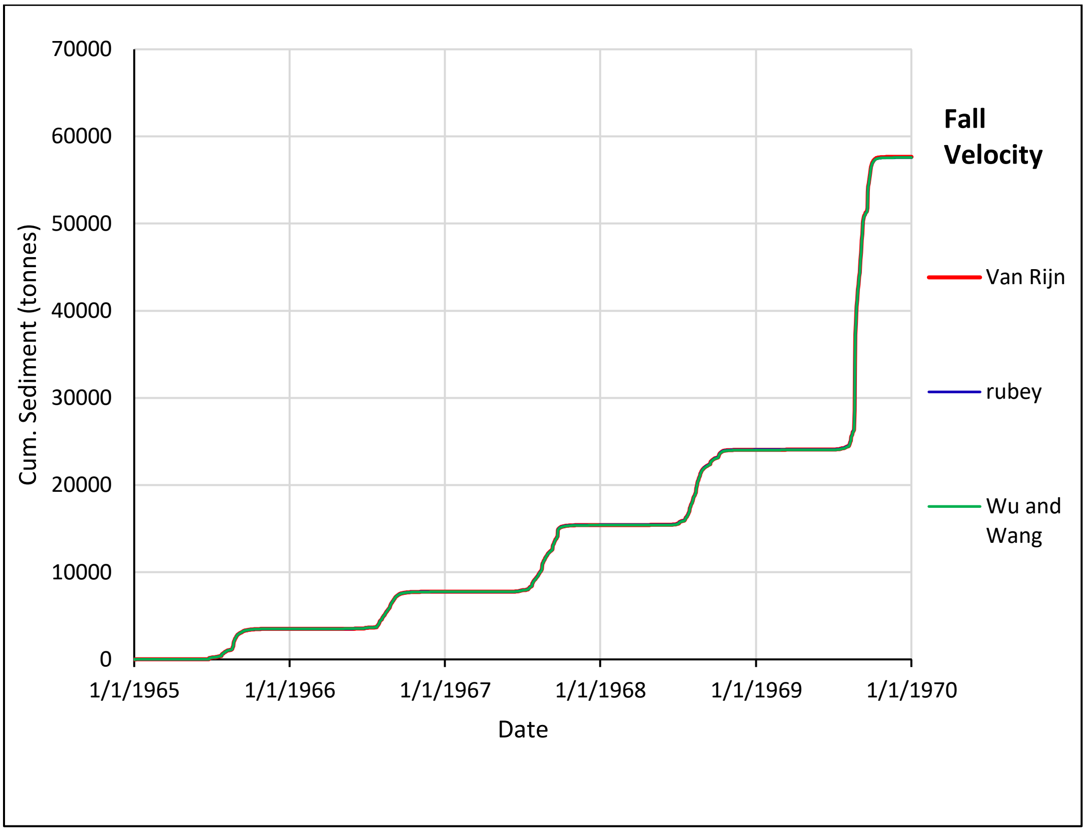


Figure 5-22 Time Series Plot of total Cumulative Mass Out for Fall Velocity Method

There is less change in percentage change in cumulative mass out which can be seen in result. so, fall velocity method is found to be less sensitive parameter in the study.

5.5.5 Sensitivity of Maximum Scour Depth

Figure 5-23 represents time series plot for total cumulative mass out at pivot point at the end of the simulation of 5 years for the different scenarios of scour depth.

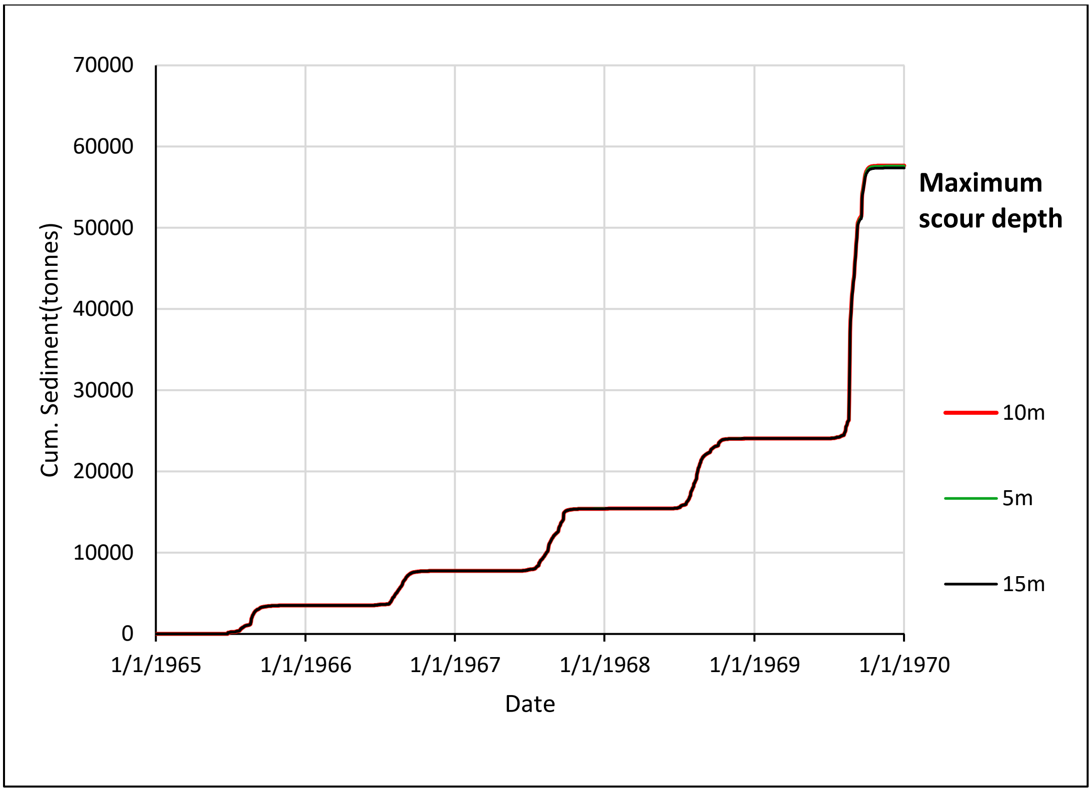


Figure 5-23 Time Series Plot of total Cumulative Mass Out for Scour Depth

For the scour depth of 5 m and 10 m, there is no significant change in the result.

Chapter 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The study is done for the evaluation of sustainability of the proposed Naumure Hydropower Project with respect to sedimentation using HECRAS as the numerical modelling tool. The simulation is performed for 10 years, 20 years, 30 years, 40 years and 50 years to assess the deposition pattern and loss of the storage due to sediment deposition into the reservoir. There are four specific objectives to fulfill the main objective.

The following conclusions can be drawn with respect to the specific objectives of the study:

i. The delta propagation for Mari river starts 21 km to 29 km upstream from confluence point with West Rapti. The delta profile for Jhimruk begins from 17 km to 23 km upstream from confluence point with West Rapti. Arun is a small tributary and the delta profile is seen just above confluence point with Mari khola.

ii. The percentage loss in the storage of Naumure reservoir for 10, 20, 30, 40 and 50 years are 0.61%, 1.46%, 2.39%, 3.37% and 7.4%. respectively.

iii. Transport Function are the most influencing and highly sensitive model parameters. Sorting method and Computational Increment Method are moderately sensitive parameters. Fall Velocity Method and Maximum Scour Depth are less sensitive model parameters.

6.2 Recommendations

Based on the results, discussions and conclusion following recommendations are made:

i. Calibration of Manning's roughness coefficient is strongly recommended using long term instantaneous flow and stage data as it is very sensitive model parameter.

ii. Climate change study is important to project the future flow of all the river stations necessary for the study.

iii. Suspended sediment data of few years is not adequate for long term estimate of sediment yield and reservoir life. Continuous data measurement with regular monitoring of the hydro meteorological network is recommended to enhance the project area database for the future data analysis work.

iv. Sediment measurement is only carried out Jhimruk and West Rapti stations. It is recommended to establish additional stations for sediment flow measurement in the river and its tributaries

v. The empirical methods like Schoklistch method, Shield method and Meyer Peter and Muller method do not provide accurate percent of bed load. So, measurement of bed load should be carried out at field.

vi. It is also recommended to carry out cross section survey along the channel reach time to time and so that it would provide data for better calibration and validation of the model.

vii. The sediments that transported to reservoir will decrease water storage capacity and the useful life of reservoir. A complete hydrographic survey provides accurate reservoir topography, capacity, and sediment accumulation. Therefore, it is recommended to conduct reservoir bathymetric survey during the project operation phase to maintain operations, and take necessary precautions to prolong the useful life of dam.

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ANNEXES

Annex Table A- 1 Details of Cross Section in every reach

Details of Cross Section in every reach

S. N	River	Reach	River Station	LOB	Length Channel	ROB
1	Arun khola	Arun reach	14686	574.5	642.6	662.5
2	Arun khola	Arun reach	14043	673.7	712.8	740.1
3	Arun khola	Arun reach	13330	1017.7	1154.6	1089.2
4	Arun khola	Arun reach	12175	808.5	849.9	835.6
5	Arun khola	Arun reach	11325	858.9	845.5	801.7
6	Arun khola	Arun reach	10480	768.5	805.2	769
7	Arun khola	Arun reach	9675	958.7	987.5	843.8
8	Arun khola	Arun reach	8687	775.3	780.2	640.8
9	Arun khola	Arun reach	7907	1112.3	1155.6	1142.4
10	Arun khola	Arun reach	6751	1218.4	1201.1	1092.8
11	Arun khola	Arun reach	5550	1049.1	1101.5	1149.4
12	Arun khola	Arun reach	4449	2314.9	2346.2	2278.1
13	Arun khola	Arun reach	2103	982.8	995.7	977.3
14	Arun khola	Arun reach	1108	737.1	727.6	714.1
16	Jhimruk river	Jhimruk reach	38452	1129.9	1495	1701.6
17	Jhimruk river	Jhimruk reach	36956	1401.4	1138.3	885.5
18	Jhimruk river	Jhimruk reach	35818	1795.3	1945.1	2003.6
19	Jhimruk river	Jhimruk reach	33873	1082.1	1121	994.9
20	Jhimruk river	Jhimruk reach	32752	1276.2	1311.8	1339.8
21	Jhimruk river	Jhimruk reach	31441	1261.8	1139.6	1006.6
22	Jhimruk river	Jhimruk reach	30302	2274.8	2276	2244.6
23	Jhimruk river	Jhimruk reach	28026	1214.8	1281.6	1296.2
24	Jhimruk river	Jhimruk reach	26745	1130.1	1227.8	1259.4
25	Jhimruk river	Jhimruk reach	25517	525.9	538.6	497.1

S. N	River	Reach	River Station	LOB	Length Channel	ROB
26	Jhimruk river	Jhimruk reach	24978	1177.8	1133.9	1083
27	Jhimruk river	Jhimruk reach	23844	1400.2	1605.5	1509.1
28	Jhimruk river	Jhimruk reach	22239	1135.1	924.8	833.8
29	Jhimruk river	Jhimruk reach	21314	806.6	944.2	951.2
30	Jhimruk river	Jhimruk reach	20370	1043.8	1111.1	1091.8
31	Jhimruk river	Jhimruk reach	19260	568.4	814.7	885
32	Jhimruk river	Jhimruk reach	18445	922.4	578.3	438
33	Jhimruk river	Jhimruk reach	17867	755.8	918.2	965.1
34	Jhimruk river	Jhimruk reach	16949	1160.7	1079.2	1001
35	Jhimruk river	Jhimruk reach	15869	910.4	906.1	888.7
36	Jhimruk river	Jhimruk reach	14963	604.8	579.9	483
37	Jhimruk river	Jhimruk reach	14383	1099.3	1118.8	1074.3
38	Jhimruk river	Jhimruk reach	13264	872.5	928.6	969.8
39	Jhimruk river	Jhimruk reach	12335	801.1	822.9	801.4
40	Jhimruk river	Jhimruk reach	11512	510.1	520.8	479
41	Jhimruk river	Jhimruk reach	10991	1423.7	1308.8	1180.6
42	Jhimruk river	Jhimruk reach	9683	610.4	623.5	583.2
43	Jhimruk river	Jhimruk reach	9059	422.5	447	513.1
44	Jhimruk river	Jhimruk reach	8612	1234.8	1335.4	1252.8
45	Jhimruk river	Jhimruk reach	7257	1849.3	1802.3	1756.4
46	Jhimruk river	Jhimruk reach	5424	1087.2	1182.6	1185
47	Jhimruk river	Jhimruk reach	4179	1005.1	995.6	943.9
48	Jhimruk river	Jhimruk reach	3183	1055.4	1103.3	1075.9
49	Jhimruk river	Jhimruk reach	2080	894	944.8	821.5
50	Jhimruk river	Jhimruk reach	1135	682.3	707.8	723.6
52	Mari khola	Mari upstream	56656	1031	1272.7	1008.3
53	Mari khola	Mari upstream	55383	1212.6	1249.1	1253.1
54	Mari khola	Mari upstream	54134	1140.9	1265.3	1149.3
55	Mari khola	Mari upstream	52869	1689.9	2104.7	1136.2

S. N	River	Reach	River Station	LOB	Length Channel	ROB
56	Mari khola	Mari upstream	50764	1181.5	1237.5	1270
57	Mari khola	Mari upstream	49526	1198	1240.1	1196.7
58	Mari khola	Mari upstream	48286	1260.9	1425.4	1222.3
59	Mari khola	Mari upstream	46861	1649.1	1692.7	1521.7
60	Mari khola	Mari upstream	45168	2006.6	2193.2	2135.7
61	Mari khola	Mari upstream	42975	2750.1	3247.5	2960.2
62	Mari khola	Mari upstream	39727	1894.5	1902.4	1744.6
63	Mari khola	Mari upstream	37824	2409.8	2484.3	2117
64	Mari khola	Mari upstream	35340	1641.1	1687.7	1504.1
65	Mari khola	Mari upstream	33653	1833.7	1936.2	1888
66	Mari khola	Mari upstream	31716	995.7	1089.4	1061.7
67	Mari khola	Mari upstream	30627	1233.3	1375.2	1231.3
69	Mari khola	Mari downstream	28697	420.5	424.8	410.4
70	Mari khola	Mari downstream	28272	796.7	1015.7	1161.8
71	Mari khola	Mari downstream	27257	1227.1	1124.6	975.1
72	Mari khola	Mari downstream	26132	996.8	1122.3	1177.3
73	Mari khola	Mari downstream	25010	1151.7	1082.3	926.3
74	Mari khola	Mari downstream	23928	773.8	888.2	990.7
75	Mari khola	Mari downstream	23039	1195.3	1168.3	1027.6
76	Mari khola	Mari downstream	21870	756.7	798.1	737.2
77	Mari khola	Mari downstream	21072	663.9	760.1	871
78	Mari khola	Mari downstream	20312	2086.4	2062.2	1826.8
79	Mari khola	Mari downstream	18250	1301.8	1309.3	1209
80	Mari khola	Mari downstream	16941	1620.5	1892.2	2003.9
81	Mari khola	Mari downstream	15048	926.6	1014.1	1081.2
82	Mari khola	Mari downstream	14034	1426.7	1425.7	1297.8
83	Mari khola	Mari downstream	12608	951.1	967.8	949.2
84	Mari khola	Mari downstream	11640	918.9	898.7	846.4
85	Mari khola	Mari downstream	10742	1499.5	1425.9	1333.7

S. N	River	Reach	River Station	LOB	Length Channel	ROB
86	Mari khola	Mari downstream	9316	1206.3	1201.4	1215.7
87	Mari khola	Mari downstream	8114	833.5	986.7	884.8
88	Mari khola	Mari downstream	7130	1458.3	1403.6	1237
89	Mari khola	Mari downstream	5724	801	815.5	801.4
90	Mari khola	Mari downstream	4909	1250.6	1432.3	1336.1
91	Mari khola	Mari downstream	3499	1215	1304.3	1243.2
92	Mari khola	Mari downstream	2195	1073.5	1040.7	934.1
93	Mari khola	Mari downstream	1154	820.9	846.2	877.1
95	West Rapti river	west Rapti	2096	655.4	630	603.1
96	West Rapti river	west Rapti	1466	459.1	476.1	468.4
97	West Rapti river	west Rapti	990	433.1	454.9	449.4
98	West Rapti river	west Rapti	535	489	502.7	466.9

Annex Table A- 2 Thissen polygon

rainfall station no.	Thissen polygon coefficient
512	0.0163
501	0.0132
725	0.00035
505	0.1024
722	0.00024
514	0.0147
721	0.00082
515	0.0193
615	0.0209
730	0.00213
502	0.01525
504	0.0941
715	0.0143

Annex Table A- 3 Rainfall of the catchment area by Thissen Polygon method

year	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1995	29.429	47.713	44.407	3.133	57.858	361.895	299.838	430.636	164.268	2.492	73.962	1.910
1996	50.124	140.464	8.380	36.998	13.457	346.523	414.814	433.912	218.824	111.958	1.027	0.000
1997	37.430	5.082	25.528	120.458	88.216	195.429	626.544	364.778	185.411	62.186	38.316	83.069
1998	1.010	19.526	74.044	63.750	132.519	327.387	554.087	479.571	195.237	93.330	41.396	0.009
1999	10.982	1.568	15.369	5.757	101.902	360.403	353.151	455.187	316.728	60.198	1.423	6.684
2000	23.914	43.730	26.450	62.585	117.324	463.661	342.570	533.618	406.965	6.987	2.266	0.101
2001	3.370	16.998	17.211	42.630	139.796	375.272	391.869	450.485	220.470	28.685	1.691	0.047
2002	62.588	135.583	27.940	51.676	105.966	162.811	189.569	320.168	151.965	28.518	5.218	3.991
2003	35.569	59.406	22.990	21.904	52.359	299.065	446.445	386.462	311.890	31.415	2.055	11.919
2004	47.007	3.973	2.266	44.824	87.828	117.768	448.550	183.793	118.584	80.340	14.128	10.900
2005	52.461	42.809	34.961	33.226	32.499	173.855	434.364	335.715	210.873	97.081	2.156	2.455
2006	0.000	7.257	49.226	67.949	129.552	203.763	402.248	222.734	66.275	12.503	9.373	14.288
2007	3.327	85.003	56.813	41.870	81.397	208.973	402.493	270.064	201.728	16.455	1.029	1.609
2008	23.340	13.099	7.675	48.116	95.387	389.385	302.746	245.883	251.348	24.619	3.257	4.933
2009	4.315	10.159	14.502	7.674	180.321	155.971	192.690	162.508	83.606	64.828	8.119	0.585
2010	10.033	38.619	7.122	9.394	73.812	176.244	157.941	155.432	166.343	33.806	1.649	2.798
2011	6.882	18.460	18.221	34.897	128.491	236.142	302.355	220.291	229.485	7.192	0.000	1.092
2012	39.273	34.830	8.448	32.018	27.945	159.199	376.557	214.481	130.802	5.328	0.288	0.875

year	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
2013	18.262	62.839	5.102	63.103	59.769	309.654	388.841	321.810	142.815	74.747	0.000	0.000
2014	43.331	20.582	17.953	3.056	77.962	134.458	309.501	288.974	93.793	72.481	0.000	25.256
2015	49.560	21.148	62.650	85.065	14.937	186.811	222.465	313.673	107.396	17.196	1.140	0.002
2016	26.022	17.270	14.219	7.890	140.849	160.058	608.275	217.073	187.230	71.173	0.000	0.047
2017	27.230	8.332	35.587	24.734	109.418	160.824	401.878	287.599	136.604	5.198	0.023	0.231
2018	4.443	11.875	20.809	90.615	63.173	101.560	331.339	364.139	83.392	3.084	0.000	0.270
2019	56.294	115.308	15.337	33.139	36.721	109.648	314.750	235.438	269.171	10.380	0.653	24.438
2020	56.985	36.899	71.480	54.789	114.647	198.190	280.618	327.015	171.293	0.000	0.416	0.000
2021	0.157	6.884	7.657	42.990	216.107	375.858	342.200	456.784	252.809	163.730	0.000	38.746
Average	26.79	37.98	26.38	42.01	91.86	238.92	364.40	321.42	187.97	43.92	7.76	8.75