তাদেরকে

যারা আছে তাই,

আমি আছি।।

STUDIES ON MORPHO-DYNAMIC BEHAVIOUR OF RIVER DAMODAR DUE TO COMBINED INFLUENCE OF DAM DISCHARGE AND BARRAGE OPERATION

Thesis submitted by

SAYAK NANDY

DOCTOR OF PHILOSOPHY (ENGINEERING)

DEPARTMENT OF CIVIL ENGINEERING

Faculty Council of Engineering & Technology

Jadavpur University

Kolkata-700032, India

2023

INDEX NO: 300/16/E

1. Title of the Thesis:

STUDIES ON MORPHO-DYNAMIC BEHAVIOUR OF RIVER DAMODAR DUE TO COMBINED INFLUENCE OF DAM DISCHARGE AND BARRAGE OPERATION

2. Name, Designation and Institution of the Supervisors:

(1) Prof. (Dr.) Ramendu Bikas Sahu,

Professor, Department of Civil Engineering,

Jadavpur University,

Kolkata-700 032

(2) Dr. Bibhas Chandra Barman,

Deputy Director(Hydraulics), ,

River Research Institute, West Bengal

Irrigation and Waterways Directorate,

Govt of West Bengal

Mohanpur, Nadia

(3) Dr. Manas Kumar Das

Deputy Director (Hydraulic study department),

Kolkata Port Trust, Kolkata 700043

3. List of Publication.

S. Nandy, M. K. Das, B. C. Barman & R.B. Sahu (2023) Morphodynamic modelling of an alluvial river controlled by dam discharge and barrage operation: a study on Durgapur Barrage, India, ISH Journal of Hydraulic Engineering, DOI: 10.1080/09715010.2023.2235704.

Conference presentation leading to book chapter:

- S. Nandy,M. K. Das,B. C. Barman and R. B. Sahu(2020).“Remote sensing based quantitative analysis of annual reduction of barrage reservoir capacity due to sedimentation: A case study of Durgapur Barrage.”.International Conference on Sustainable Water Resources Management under Changed Climate 2020, ICSWRMCC-2020 in Jadavpur University held on 13th to 15th March, 2020.
- “A quantitative assessment of hydrodynamic impacts due to variable discharges on the backwaterdeposits of Durgapur Barrage over River Damodar in India using MIKE 11.” S. Nandy, R. B. Sahu.,B. C. Barman and M. K. Das. Riverflow 2020, Delft University, Netherlands, July 6-9, 2020.

4. List of Patent:

NIL

5. List of Presentations in National/International/Conferences/Workshops:

- S. Nandy,M. K. Das,B. C. Barman and R. B. Sahu(2020).“Remote sensing based quantitative analysis of annual reduction of barrage reservoir capacity due to sedimentation: A case study of Durgapur Barrage.”.International Conference on Sustainable Water Resources Management under Changed Climate 2020, ICSWRMCC-2020 in Jadavpur University held on 13th to 15th March, 2020.
- S. Nandy,M. K. Das,B. C. Barman and R. B. Sahu(2020).“A study on impact of Grain-size (d50) of bed material on sedimentation in alluvial riverusing one-dimensional MIKE 11 Model.”S. Nandy,M. K. Das,B. C. Barman and R. B. Sahu. Conference of American Society of Civil Engineers, challenges of resilient and sustainable infrastructure development in emerging economics, March2-4,2020.
- “A quantitative assessment of hydrodynamic impacts due to variable discharges on the backwaterdeposits of Durgapur Barrage over River Damodar in India using MIKE 11.” S. Nandy, R. B. Sahu.,B. C. Barman and M. K. Das. Riverflow 2020, Delft University, Netherlands, July 6-9, 2020.

STATEMENT OF ORIGINALITY

I, Sayak Nandy registered on 22/08/2016 do hereby declare that this thesis entitled "**STUDIES ON MORPHO-DYNAMIC BEHAVIOUR OF RIVER DAMODAR DUE TO COMBINED INFLUENCE OF DAM DISCHARGE AND BARRAGE OPERATION**" contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work

I also declare that I have checked this thesis as per the "Policy on Anti Plagiari Jadavpur University, 2023" and the level of similarity as checked by iThenticate software is 9%.

Sayak Nandy

Signature of Candidate:

Date: 21/08/2023

Certified by Supervisor(s)

21/08/2023

Dr R. B. Sahu
Professor of Civil Engineering
Jadavpur University
Kolkata 700 032.

1. Prof. (Dr.) Ramendu Bikas Sahu
Civil Engineering Department, J.U.
Kolkata-700032

2. Dr. Bibhas Chandra Barman,
Deputy Director (Hydraulics),
River Research Institute, West Bengal
Irrigation and Waterways Directorate,
Govt of West Bengal

3. Dr. Manas Kumar Das
Deputy Director (Hydraulic study department),
Kolkata Port Trust, Kolkata 700043

CERTFICATE FROM THE SUPERVISORS

This is to certify that the thesis entitled "Studies on morpho-dynamic behaviour of river Damodar due to combined influence of dam discharge and barrage operation" submitted by Shri Sayak Nandy, who got his name registered on 22/08/2016 for the award of Ph. D. (Engg.) degree of Jadavpur University is absolutely based upon his own work under the joint supervision of Prof. (Dr.) Ramendu Bikas Sahu, Dr.Bibhas Chandra Barman and Dr. Manas Kumar Das that neither his thesis nor any part of the thesis has been submitted for any degree/ diploma or any other academic award anywhere before.

21.08.2023

Prof. (Dr.) Ramendu Bikas Sahu
Civil Engineering Department, J.U.
Kolkata-700032

Dr R. B. Sahu
Professor of Civil Engineering
Jadavpur University
Kolkata - 700 032.

Dr. Bibhas Chandra Barman,
Deputy Director (Hydraulics),
River Research Institute, West Bengal
Irrigation and Waterways Directorate,
Govt of West Bengal

Dr. Manas Kumar Das
Deputy Director (Hydraulic study department),
Kolkata Port Trust, Kolkata 700043

ACKNOWLEDGEMENT

It's my pleasure to express my congratulation for the assistances rendered by all those who helped in completing my Ph.D thesis.

At the outset, I would like to thank my supervisors, Prof. Ramendu Bikas Sahu, Department of Civil Engineering, Jadavpur University,Kolkata, Dr. Bibhas Chandra Barman(Deputy Director, Hydraulics), River research Institute, West Bengal, Irrigation and Waterways Directorate, Govt of West Bengal and Dr. Manas Kumar Das, Deputy Director(Hydraulic study department), Kolkata Port Trust, Kolkata 700043, for their constant guidance during the research works. Without their unwavering support, this study would not have been possible.

I am extremely appreciative for the research experience at the Jadavpur University, which would not have been possible without the support from all the faculty members and technical support staff of the Civil Engineering Department.

Also, I express my heartiest gratitude and thanks to my lab mates, Atriyo Chowdhury, Saptarshi Roy, Surajit Biswas and Biplab Ranjan Adhikary, they made this journey a memorable one.

I am thankful to my friend Dr. Partha Dey, Arindam Mukherjee, Sankhadeep Biswas and Ankan Jana for their prompt assistance.

I would like to thank all my family members, with out their constant support and love, this research work would not have been reached a successful conclusion.

Date: 21/08/2023
Place: KOLKATA

Sayak Nandy

ABSTRACT

Reservoirs and barrage pond areas, built across alluvial rivers throughout the world, are losing their storage capacity at an estimated rate of about 0.5 to 1% annually. The pond area of Durgapur Barrage on River Damodar, India, fed by variable discharge from Panchet and Maithon dams and also controlled by barrage-gates is no exception. In spite of its service for more than 60 years through judicious gate-operation schedule, it is found that 52% of initial storage capacity of the Durgapur Barrage Pond has been lost since its inception in 1956. It has been reported that total upland sediment load transported downstream gets deposited in the barrage pond area due to the ponding effect. The present thesis highlights morpho-dynamic behavior of the Damodar River, extending from Maithon and Panchet dams at upstream to Durgapur Barrage in the downstream owing to the fluctuating discharge depending upon the rainfall pattern in the catchment areas of the dams. The analysis has been performed by means of numerical model of MIKE-11 software considering hydrometeorological and fluvial data of Damodar-Barakar River basin. Hydrodynamic and Sediment Transport models of MIKE-11 were simulated to ascertain annual rate of erosion and deposition during the period from the year 1956 to 2066. The river network has been delineated using a software (ArcGIS) from the old maps and relevant data of digital elevation model [DEM of Shuttle Radar Topographic Mission data (SRTM)]. From these maps of different years and SRTM data, a total 128 number of cross sections at 500 m intervals have been reconstructed through ArcGIS. A synthetic hydrograph, in the form of time-series discharge data, was prepared for the entire simulation period 1956 to 2016, by corelating the IMD's public domain gridded rainfall data of Damodar-Barakar basin-catchment and the measured inflow discharge in the receiving dams, Maithon and Panchet for the period 2009 – 2016.

A representative value of measured suspended sediment concentration (SSC) for different discharges throughout the year from various locations of the model domain has been calculated and utilized for sediment transport analysis. Calibration and validation of the model for both hydrodynamic and sediment transport simulation have been done using field data, collected throughout the year from various measuring stations.

Initially, it is observed that the river bed in the upstream portion (chainage 0 to 40 km) gets eroded and a significant part of these eroded material including the susceptible component of suspended load gets deposited in the lower stretch of the river (chainage 40 km to 66 km). And almost 50% of the total deposition, was deposited only within the pond area. Study reveals that about 6 MCM catchment-sediment has entered in the model domain through Dam-discharges during the year 1956 to 2016, a part of which got deposited in the river bed while the remaining 4.9 MCM sediment departed towards downstream through Barrage gates. Though the rate of sediment deposition in the barrage pond area was initially higher during the period 1956-1985 but with the passage of time it has reduced considerably. However, daily deposition increased more or less linearly with the increase in discharge of the river. The present capacity of the pond area has been reduced from 10.273 MCM to 4.843 MCM (about 47% of the initial capacity) as measured in the year 2016.

To get rid of the problem of siltation in the pond area, an alternative solution – ‘sediment removal through flushing’ has been examined in the model experiment and suggested for implementation. Different combination of flushing options (empty flushing and draw down flushing) with 15 days sinusoidal hydrograph and 4 days rectangular hydrograph, yearly once with 4000 Cumecs pick discharge have been tested in the model and the best possible option for capacity augmentation was identified. A comparative statement of the outcome of different options, as envisaged by the model experiment, advocated that a hybrid flushing arrangement with 4-days drawdown flushing (gate opening full) and 1-day pressurized flushing (gate opening at 60m) for 4000 Cumec constant discharge supported with agitation dredging is the best option for giving a respite to the authority. This technique appears to be most effective in controlling sedimentation pattern in the pond area with variable discharge and may help the practicing engineers for proper management of barrage operation.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

1D=One dimensional

ADCP= Acoustic Doppler Current Profiler

ANN=Artificial Neural Network

C/S= Cross-section

CWC= Central Water Commission

DEM=Digital Elevation Model of data (SRTM)]

DHI=Danish Hydraulic Institute

DVC=Damodar Valley Corporation

FVM=Finite volume method

HD=Hydrodynamic

I &WD=Irrigation and Waterways Department

MCM=Million Cubic Meter

RANS= Reynolds-averaged Navier-Stokes

RRI=River Research Institute

SRTM= Shuttle Radar Topographic Mission

SS=Suspended solids

SSC=suspended sediment concentration

ST= Sediment Transport

SWAT= Soil Water Assessment Tool

LIST OF SYMBOLS

Q = Discharge

q = Lateral inflow

h = Stage above datum

A= Flow area

C =The Chezy resistance coefficient

R = The hydraulic radius

α= The momentum distribution coefficient

t= Time

g= Gravitational acceleration

C' = The volumetric concentration

V_P^∞ = The terminal settling velocity of a single particle in still water and

$\in_S$= Turbulent diffusion coefficient

$\boldsymbol{V}$ =Flow Velocity

N = Manning's 'n'

$\boldsymbol{R}$ =Hydraulic Radius

$\boldsymbol{S}$ =Bed Slope of the channel

CHAPTER 1

INTRODUCTION

1.1. GENERAL

Natural River flow is an open-channel flow that is not completely surrounded by rigid boundaries. The open surface is freely deformable, where pressure and shear stress (boundary conditions) are always zero. The river system achieves a state of dynamic equilibrium when it effectively manages the movement of water and sediment, leading to adjustments in factors like the shape and slope of the river channel. These adjustments occur in response to inputs of water discharge and sediment load, maintaining a balanced state. If variations in these inputs transpire owing to the different river control measures along and across the rivers, the system responds immediately by adjusting its morphology. Construction of dams and barrages across a river is an age-old practice throughout the world for storing and supplying water for irrigation, industry and human consumption including flood control, power generation etc. The storage capacity of the dams and barrage reservoirs depends upon the extent of catchment area, intensity and distribution of rainfall. The stored water is released throughout the year as per the demand of the service areas and of course, if the inflow exceeds the threshold level during excessive rainfall.

Damodar-Barakar, one of such river system is flowing across the Indian states of Jharkhand and West Bengal. Earlier known as the Sorrow of Bengal because of its ravaging floods in the plains of West Bengal, the river system has been planned to tame with the construction of several dams at Maithon, Panchet, Tenughat, Konar and Tilaiya. These dams were constructed during 1950s, as a part of Damodar Valley Corporation (DVC) project in line with the Tennessee Valley Project of USA, for accommodating a million cusec of flood water and to keep the monsoonal discharge of the river Damodar within 0.25 million cusecs. Further, to ensure perennial irrigation, supply of water to municipalities and industries Durgapur Barrage was also constructed near Durgapur steel town (Fig. 1.1 and Fig 1.2) over River Damodar.

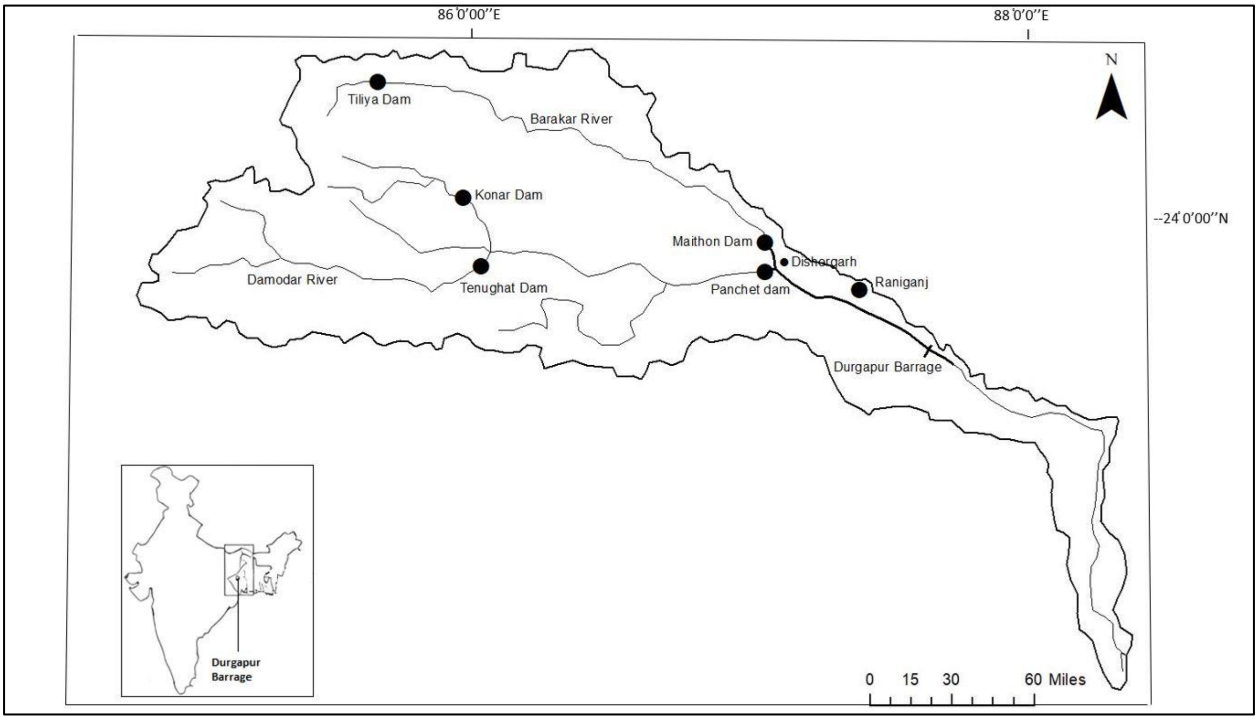


Fig.1.1 Index map of Damodar basin

(a) Pond area

(b) Empty pond area

Fig. 1.2 (a) &(b)Photograph of Durgapur Barrage Pond Area

Construction of these five dams and Durgapur barrage were started in the year 1951 and completed in 1978. The year of commissioning of these barrage and dams and also their storage capacities are given in Table 1.1.

Table 1.1 Year of commissioning and storage capacities in Million Cubic Meter of dams and barrage in DVC area

Name of Dams / Barrage	Year of commissioning	Storage capacity (MCM)
Maithon	1955	90
Panchet	1956	107
Tenughat	1978	1000
Konar	1955	30
Tiliaya	1953	40
Durgapur	1956	10.273

Generally, reservoirs and barrage pond areas, built across alluvial river systems throughout the world, are losing their storage capacity at an estimated rate of about 1% annually and so the life span of a reservoir cannot be longer than a century (Basson 2009; Rutschmannet et al.

2013; Ghosh et. al. 2014; Rahmani et al 2018). Since Damodar Valley Corporation reservoirs are within a tropical climate region and the basin is degraded, the rate of sedimentation in reservoirs is very high (Hoque et. al. 2022). The uncontrolled sand mining, industrialization and rapid growth of agriculture have significant contributions in the river sedimentation leading to the decay of the channels as well as reduction of storage capacities of reservoirs (Barman et. al. 2019). Five reservoirs constructed over the river Damodar and its tributaries have lost their storage capacity between 23% and 43% over a period of about sixty years after their commissioning in 1956 [Rudra 2018], while the capacity of the pond area of Durgapur Barrage has been reduced by about 52% during the period 1956 – 2016 [CWC (2012)].

As concerned as the Barrage-Pond Area, a shallow reservoir in the upstream of the barrage is produced due to the restricted natural flow. Water stored in the reservoir maintaining the designed pond depth over backwater length of the barrage is used to maintain the balance between inflow of river and outflow of canals. Natural flow of the river is being rapidly changed in the reservoir due to the backwater effect caused by control structure leading to the reduction in sediment carrying capacity due to the decrease in energy gradient. Further reduction in velocity along with greater cross-sectional area acts as an efficient sediment trap in the pond area. The eroded soil which is being carried as suspended sediment by flowing water gets deposited in different levels of barrage reservoir and leads to reduction of storage capacity as well as efficiency of barrage (Brandt, 2000).

Things get worse with improper maintenance of barrage gate operation and design pond depth (Sinha et. al. 1986). This accumulation of sediment in the vicinity of barrage is a universal phenomenon and loss of about 1% of storage capacity is equivalent to a loss of about $16 billion per year (Rutschmannet et al. 2013). As reported by CWC (2012) reduction in gross capacity of Durgapur Barrage was at the rate of 0.816 % per annum and at minimum pond level it was at the rate of 1.01% per annum due to incessant sediment discharge from upstream, local catchment and also may be from the erosion in the upper reaches of the river. The researchers working on the complex hydro-geomorphology of this basin unanimously opined that the problem of Damodar is not so much with the disposal of its surplus water but that of surplus sediment (Ghosh and Gucchait 2014). Sinha et al. (1986) advocated that chances of sedimentation increase with longer barrage waterway and greater pond water depth, while Morris (1995) suggested that an integrated sediment management approach is needed for proper sustainable operation of barrages. According to Fan and Jiang (1980), the regulation of sediment load and water flow is the governing task in order to balance the sediment budget across a reservoir.

A recent experimental study on the Yamuna River Barrage showed that flushing of sediment in barrage pond area is highly dependable upon the barrage gate operation and the rate of sediment deposition can be controlled by proper gate operation (Ghosh et al. 2014). In this context it may be noted that several researchers used a numerical model for sediment transport study in the upstream of barrage. Zhang et al (2013) applied a 2-D model to simulate the process of sediment deposition at the upper reaches of Three Gorges Dam Reservoir in Yichang, China. The results were used for prediction of detailed change of bed level in the next 70 years. Abed et al. (2014) conducted a study focusing on numerical modelling of sediment transport near Al-Ghammas Barrage, Iraq to enhance understanding of sediment dynamics in the upstream area, crucial for effective water resource management and river engineering.

Isaac and Eldho (2016) conducted numerical model studies using HEC-RAS for a narrow elongated reservoir on a river in Sikkim-West Bengal, India in connection with a hydropower project and was shown to be highly efficient in predicting the long-term deposition pattern, which finally helped in developing guidelines for future studies**.** Duan et al. (2017) conducted a study using a numerical model to simulate sediment transport in the upstream of a reservoir to investigate sediment dynamics and transport patterns, considering variations in inflow rates and sediment loads and highlighted their effects on river morphology, erosion, deposition processes, ecological habitats, water quality, and hydraulic structures. Daham and Abed (2020) focused on the simulation of sediment transport processes in the upper reach of Al-Gharraf River and also aimed to enhance understanding of sediment dynamics in the river and provide valuable insights for river management and engineering by providing effective sediment control measures, erosion prevention strategies, and maintenance of hydraulic structures.

Some studies were also reported on flushing of reservoirs to enhance their capacity by employing numerical methods supported by laboratory as well as field data. Janssen and Shen (1997) performed flushing tests during drawdown with uniformly sized non-cohesive sediments and no incoming sediment load. They found that the flushing channel widens and incises rapidly when the flow through the reservoir reaches riverine conditions. Ji et al (2011) and Parker et al (2013) employed numerical model for predicting the effectiveness of sediment flushing and made comparison of sediment deposition with and without mechanical dredging to highlight the usefulness of flushing in sediment erosion in Nakdong River Estuary Barrage.

1.2. MOTIVATION

Various literature reviews suggest that the worldwide reservoir and barrage pond areas are losing their storage capacity due to the natural cause as well as anthropogenic activities. This trend has also been observed in different barrage pond areas of West Bengal, India such as Teesta Barrage, Mahananda Barrage, Farrakka Barrage and Durgapur Barrage. The present study emphasized on Durgapur Barrage because of its strategic location, where number of water-dependent industries are situated and demand of Agri-irrigation is more. Apart from these, a complex array of several dam-barrage network coupled with numerous installations of water abstraction structure made this water resources scientifically important and potentially an unexplored research area.

From the institutional point of view, the concerned authority (I&WD, Govt. of WB) observed that over several years of operation, the capacity of the barrage pond was depleted due to siltation. The situation further aggravated after a flash flood in September 2009. The authority is also in search of solution to restore the original capacity of barrage pond area by carrying out de-siltation work.

It is observed from pond capacity survey that Durgapur barrage has lost its greater half of storage capacity in 60 years of operation. As a result of massive erosion in upper catchment there is huge sedimentation in flat terrain of downstream. River morphology has been changed due to extreme siltation resulting in upliftment of river bed level. Due to decreased storage capacity the barrage authority is bound to increase the pond level height, encroaching the afflux and the barrage is now unable to absorb even a moderate flood. Cohesive property of river-bed soil at the upstream bars has increased with time and it seems to be impossible to remove the bar by operating barrage gate only. As such, smooth operation of the Durgapur Barrage and augmentation of its storage capacity were the need of hour and accordingly, a strategy for proper sediment management through scientific study had to be done.

While significant research efforts have been directed towards understanding sedimentation and the removal of sediment from reservoirs formed by dams, there is a notable scarcity of literature focusing on similar investigations for shallow reservoirs such as barrage ponds. [Annandale (1987), Morris and Fan (1997), Brandt (1999), Olsen (1999, 2000) Olesen and Basson (2004), Kantoush et al. (2005, 2006)].

There is hardly any attempt to study on sediment transport models, particularly morphological transformation of a river with variable upstream dam-discharge synchronized with downstream barrage operation, like Damodar. More precisely, morphological study of a river, influenced by combined effect of varying catchment rainfall, scheduled dam-discharge with harmonious barrage operation is still lagging. This has necessitated a study on post barrage behaviour of an alluvial river in order to develop a meaningful correlation amongst different hydraulic parameters. Moreover, work on flushing strategy for removing the shoals as well as reducing the rate of sedimentation, especially those are very close to the barrage structure is lacking. Therefore, conducting a methodical investigation in this direction could prove advantageous for both engineers working in the field and society at large.

The present study, therefore, attempts to evaluate sediment transport mechanism active in Damodar river due to variable dam fed discharges and assess the quantity of erosion and deposition during a period of more than hundred years since its commissioning in 1956 by employing numerical study of morpho-dynamic behavior of the river controlled by discharge of Maithon - Panchet dams as a function of rainfall in the catchment area and scheduled barrage-operation(Annexure-A) at Durgapur. For this purpose, one-dimensional (1D) mathematical model was simulated based on numerical scheme of Danish Hydraulic Institute (DHI), MIKE11 software, for hydrodynamic and sediment transport analysis of Damodar river between Maithon and Panchet dams at upstream to one kilometer downstream of Durgapur Barrage.

1.3. OBJECTIVE

- To study the morphological changes of the river Damodar between Maithon and Panchet dams at upstream and one kilometer downstream of Durgapur Barrage considering variable discharge from the dams.
- To quantify the yearly rate of sedimentation in the model domain with special emphasis on Barrage pond area during the study period from 1956 to 2066.
- To develop a judicious approach for flushing out the deposited sediment from the pond area of the barrage.

1.4. SCOPE OF WORK

The scope of works of the present investigation is as follows:

1. Collection of historical as well as present morphological and hydrological data of Damodar River System.
2. Development of 1-D Mathematical Model of Damodar River system with upper boundary at Maithon-Panchet Dams and lower boundary at one kilometer downstream of Durgapur Barrage using numerical scheme of Danish Hydraulic Institute of Denmark (DHI-MIKE 11).
3. Simulating hydrodynamic (HD) and sediment transport model of the River system for the period from 1956 to 2016.
4. Calibration and validation of the model using collected historical and sediment transport data of different observation sites.
5. Quantification of the morphological parameters and resultant changes thereon occurred in the upstream of barrage within the model domain for the period from 1956 – 2066 including the barrage pond area.
6. To study the various flushing options for augmentation of storage capacity of the barrage pond area.

1.5. ORGANISATION OF THESIS

The work has been organised in such a way that the research objectives are fulfilled. The thesis is divided into total five chapters (Chapter 1 to Chapter 5) as briefly described below:

Chapter 1: Introduction

It is an introductory chapter describing the background and motivation of this research work and also outlines the specific objectives and scope of the study.

Chapter 2:

Here, I have presented a state-of-the art literature review works highlighting the changes in reservoir capacities of dams and barrages all over the world due to sedimentation as a function of various related morphological parameters. Some studies are also reported on flushing methodology for enhancing the capacities of the reservoirs / pond areas.

Chapter 3:

It deals with the methodology highlighting theoretical background of the model used in the present study along with hydrodynamic (HD) and sediment transport (ST) simulation. This chapter also presents calibration and validation of the model based on collected observed field data.

Chapter 4:

This chapter deals with results and discussion with the help of figures and tables to show the spatial and temporal variation of erosion and sedimentation in the model domain along with that in the pond area in front of the barrage. Variation of sedimentation with river discharge and also cumulative deposition in the pond area are also presented. Various flushing options, as considered in the present study, are also presented to highlight their effectiveness in increasing the pond capacity.

Chapter 5:

It brings out the conclusions of the findings and outcomes of the study. Suggestions for future scope of research are also presented at the end.

An abstract of the whole studies has also been included at the beginning and a list of references are given at the end of this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1. GENERAL

Water, being an indispensable component of civilization, has prompted humanity since ancient times to effectively manage its water resources, leading to the emergence of the concept of river engineering. The field of river engineering has traditionally encompassed all hydraulic engineering endeavours aimed at flood mitigation, water diversion, river course modification, and navigation enhancement. River hydraulics involves assessing the flow characteristics and physical behaviour of rivers, offering a comprehensive qualitative and quantitative comprehension of water and sediment movements within natural river systems. The examination of river hydraulics stands as an integral aspect of river projects, with the insights derived from these assessments often playing a pivotal role in the project's inception, design, construction, and ongoing operation.

River training works in India has been initiated from mid-twentieth century. A number of dam and barrages like Narmadasagar Dam across river Narmada, Nijamsagar Dam across river Godavori, Hirakud Dam across river Mahanadi, Farakka barrage across river Ganga, Koshi barrage across river Koshi have been constructed and became an important part of society and GDP aspect/social and economic aspects. All these hydraulic structures experienced morphological problems in the form of sediment deposition and erosion, capacity reduction and shoal formation. A comprehensive understanding of geo-hydro-morphologic processes and sediment transport mechanism is essential for modelling and predicting the riverine parameters to efficient management of water resources, habitat and flood hazards. A detailed investigation based on the above theoretical understanding duly validated by adequate field data is also required to find out a plausible solution for the problems.

In this chapter, hydraulics of channel and stream flow, fluvial morphology, numerical and physical modelling of sediment transport with barrage gate operation are discussed.

2.2. RIVER HYDRAULICS

Rivers are, in general, nearly one-dimensional gravity driven flow down a slope and resisted by bed friction. Though this may appear simple from physical perspective, in fact it is a very complex phenomena depending upon the upstream and downstream boundary conditions, governing the flow velocity and depth as a function of space and time. Upstream flow condition and downstream obstacles modifies the flow characteristics of the channel and alters the bed morphology with the passage of time. River hydraulics deals with the river flow associated with related sedimentation problems, such as, flow in the alluvial channels, sediment settling, incipient motion, critical velocity, erosion, transport and deposition.

2.2.1 Flow through alluvial channels

Free surface flow through alluvial channels may be steady or unsteady, uniform or non-uniform depending upon the boundary conditions, channel geometry in the longitudinal and lateral directions, bed topography and their spatial and temporal variations. A steady flow may transform into an unsteady flow with the changes in input discharge as a result of changes in catchment discharge. A uniform flow become non-uniform with the spatial changes in morphology due to the erosion or sedimentation of river channel as a result of bed load or suspended load transport followed by their deposition along various stretches.

This spatial and temporal variation in flow characteristics induces fluctuation of corresponding bed shear stresses, which is a function of flow depth, bed slope, average flow velocity and related other non-dimensional parameters. Dey (2014) compiled the expressions for bed shear stress proposed by various researchers for different cases particularly for unsteady-uniform flow considering logarithmic law of wall.

2.2.2 Sediment threshold

With the increase in the flow velocity, the bed particles are entrained randomly if the hydrodynamic lift and drag forces exceeds a certain threshold value and overcomes the submerged weight of the particles. This condition is just adequate for initiating motion due to rise in induced bed shear stress giving the threshold of sediment movement. The excess bed shear stress over the threshold value controls the sediment entrainment and ultimately erosion and transport of sediment along with the channel flow. Shields (1936) conducted pioneering research work to show the variation of non-dimensional threshold bed shear stress, which was later popularly known as threshold Shields parameter, with shear Reynolds number corresponding to the threshold of sediment entrainment. The threshold shields parameter was shown to divide the flow into two zones, upper one sediment motion while the lower one no sediment motion corresponding three distinct flow regions, hydraulically smooth flow with R_e(Reynold's number) $\leq$ 2, hydraulically rough turbulent flow with $R_e \geq 500$ and transitional flow between 2 to 500. It was seen that threshold shear velocity can be determined by trial-and-error method. Subsequently, additional efforts were undertaken by different researchers to alter the shield's diagram through conducting supplementary experiments and examining the issue from a theoretical perspective using deterministic and probabilistic methods (Miller et al. (1977), Buffington and Montgomery (1997), Dey (1999), Paphitis (2001), Zanke (2003) and Dey and Papanicolaou (2008) considering both force equilibrium or moment equilibrium of bed particles over horizontal as well as sloping beds.

2.2.3 Sediment transport

Water discharge associated with sediment transport rules the aggradations and / or degradations of channel beds which may lead to their dynamic stability or instability. So their quantification is very much essential in understanding the fluvial processes in a river channel. The total amount of sediment transported comprises of bed load and suspended load in addition to wash load which, sometimes, found to be not insignificant. Bed-load transport is the mechanism through which particles on the riverbed move by sliding, rolling, or making a series of small leaps known as saltation. These particles remain in proximity to the bed and occasionally become temporarily airborne before returning to the bed.The dislodgement of bed particle occurs when the bed shear stress induced by velocity fluctuations exceeds the threshold values followed by transportation.

In Einstein's work (1942, 1950) the transport of sediment particles in a thin layer, about two particle diameters thick, just above the riverbed was described as bed-load transport. This movement involved sliding, rolling, or successive jumping over a distance of a few particle diameters along the direction of the flow. On the other hand, Bagnold in 1956 defined bed-load transport as a process where particles interact sequentially with the riverbed, influenced primarily by gravity. When the excess shear stress over the bed increases, turbulence forms near the bed and moves upwards, causing finer sediment particles to be lifted and suspended in the flow. This upward motion counteracts gravity's pull, allowing these finer particles to remain in the fluid. Meanwhile, coarser particles continue to be transported as bed load. In reality, particles intermittently touch the bed but move in larger jumps, often surrounded by the fluid, depending on the ratio of their settling velocity to shear velocity. In cases where settling velocity is much smaller than shear velocity, bed-load transport typically constitutes about 5-25% of the suspended load in larger, deeper rivers.

Pioneering work on bed load transport rate was by Du Boys (1879) based on the equilibrium of the force exerted by the moving fluid onto the uppermost layer of the sediment bed and the frictional resistance between the sediment layers beneath it and is expressed as the function of difference of threshold bed shear stress and mobilized bed shear stress. Shields (1936), Meyer-Peter and Müller (1948) and other researchers modified the above equation to express it in terms of non-dimensional term, bed-load transport intensity, as a function of the Shields and threshold Shields parameters. Later Bagnold (1956) identified the deficiencies of the abovementioned methods and decomposed bed shear stress into two components, into the shear stress acting on dispersed particles, which arises from the momentum exchange during collisions between moving particles, as well as the shear stress at the fluid-particle interface. Ultimately, this gives rise to the expression for the rate of bed load transport, which is dependent on factors like threshold bed shear velocity, average flow velocity, flow depth, and bed particle size.

This is followed by van Rijn (1984b) and Dey and Debnath (2001), who conducted experiments with various uniform and nonuniform sand sizes to propose volume rate of sediment removal as function of Shields parameter. Van Rijn (1984) and others highlighted saltation mode of movement of particles to propose bed particle velocity as a function Shields parameter as well as bed shear velocity and non-dimensional bed material parameter. All these expressions, in general, indicate that bed load transport rate increases with the increase in bed shear velocity with respect to the threshold values. Though bed load has a significant contribution on sediment movement, in natural channels large amount of sediment is transported as suspended load. Based on advection-diffusion equation Rouse (1937) proposed variation of concentration as a function of reference concentration and non-dimensional Rouse number. This expression was then modified by van Rijn (1984), Ni and Wang (1991), Bose and Dey (2009) and others as a function of flow velocity and particle size in the suspension.

River engineers and practitioners estimate the total load in a river section by directly adding bed load and suspended load components. However, distinction between them sometimes very difficult as they are often observed to be interchangeable. In case of high suspended transport rate bed load is hardly separated from suspended load (Chien and Wan 1999). Einstein (1950) advanced the computation of total load transport by applying some parameter to incorporate sediment type fraction on bed load and suspended load separately to compute total load transport. Bagnold (1966) considered energy balance concept to derive suspended load transport rate by equating work done per unit time for sediment suspension to the net stream power used for the suspended-load transport. This concept was applied by Engelund and Hansen (1967) to obtain the work done per unit time and width to lift the sediment particle as well as to move the particle over bedform thereby giving rise to the expression for total load transport rate.

Meanwhile, Ackers and White (1973) conducted dimensional analysis to represent the total-load transport rate using a newly introduced mobility number along with several other dimensionless parameters. Their assumption was that a fraction of the bed shear stress contributes to the movement of larger sediment particles. In contrast, for finer sediment particles, the primary mechanism is suspended load transport, where the overall bed shear stress propels the motion of these fine particles. Considering the field applicability of these expressions Molinas and Wu (2001) modified the different non-dimensional parameters by using field data collected from large sand-bed rivers.

2.3. SEDIMENTATION IN RESERVOIRS / BARRAGE

As a natural stream flows into a reservoir, certain changes occur due to the altered conditions. The flow depth in the reservoir increases while the flow velocity decreases, resulting in a gentler friction slope. Consequently, the unit stream power decreases within the reservoir, leading to a reduced capacity for sediment transport and the formation of a delta, as illustrated in Figure 2.1. The sediment carried into the reservoir eventually gets deposited, causing the reservoir bed to aggrade and storage capacity to decrease. The deposition process usually starts with delta formation near the reservoir's headwater area. Morris and Fan (1997) classified the sediment deposition into three zones: topset, foreset, and bottomset, with the topset being composed of coarser materials and the bottomset consisting of finer materials.

Upstream channel aggradation may extend over a significant distance above the reservoir. Fan and Morris (1992a) observed several key characteristics of reservoir deltas, such as an abrupt change in slope between the topset and foreset deposits, coarser sediment particles on the topset bed compared to the foreset bed, and the elevation of the transition zone between the topset and foreset beds being dependent on the reservoir's operating rule and pool elevation.

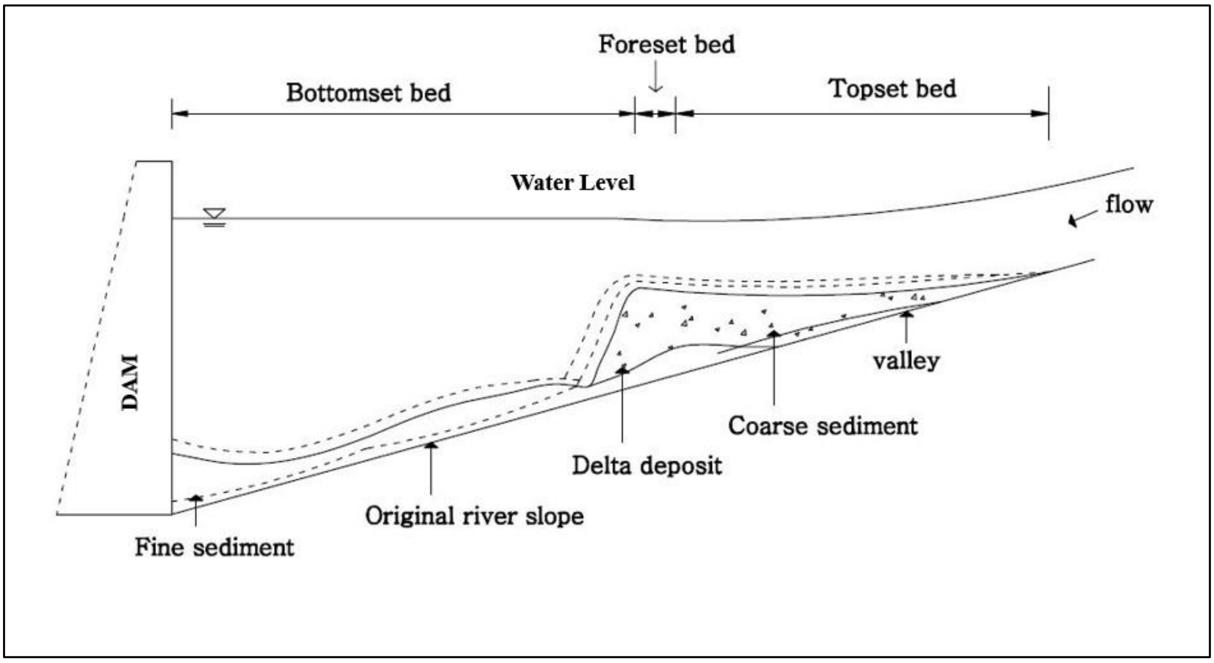


Fig 2.1 Typical formation of delta in a reservoir (Morris and Fan, 1997)

Fan and Morris (1992a, 1997) contributed valuable insights into sediment deposition patterns through field measurements conducted in China. They categorized these patterns into four general longitudinal deposit geometries. The initial category, referred to as the "Delta" type, primarily consists of either coarse sediment influx or a significant proportion of finer sediment, such as silt. In cases where sediment deposition transpires during high sediment-laden flows or within compact reservoirs featuring a substantial influx of fine sediment, the deposition configuration adopts a wedge-like shape. When water is systematically released from a reservoir or barrage gate, the apex of the delta migrates toward the dam, leading to a wedge-shaped deposition pattern. This pattern represents the equilibrium state for certain reservoirs over extended timeframes. The second type, known as "Tapering" deposits, is commonly observed in lengthy reservoirs that exhibit a tendency for fine deposition. Conversely, "Uniform" deposits manifest in narrow reservoirs characterized by frequent water level fluctuations and a relatively modest quantity of fine sediment loading.

2.3.1 Reservoir Sedimentation Control Methods

Three approaches are identified by Fan and Morris (1992b) for controlling reservoir sedimentation. The first involves reducing sediment input from the basin through erosion control or installing upstream traps, which can help reduce long-term sediment deposition. However, this approach may not address the issue of already reduced reservoir storage. The second method, dredging, can restore reservoir storage, but it is impractical due to high costs and environmental implications. The third strategy involves using hydraulic methods to remove sediment through various techniques, as classified by Fan and Morris (1992b) in China:

(1) Reduction of sediment yield;

(2) Sediment excavating; and

(3) Hydraulic regime methods such as sediment routing and flushing

(1) *Reduction of sediment yield:*

Although reducing the sediment yield entering a reservoir cannot completely solve the problem of reservoir sedimentation, it can significantly slow down the rate of sediment accumulation through erosion control and upstream sediment trapping, as suggested by Fan and Morris (1992b). Various management practices are employed globally to mitigate sediment yield. Structural or mechanical measures are utilized for erosion control, which involves decreasing flow velocity, enhancing surface water storage, and managing runoff (Morgan, 1995). Nonstructural controls, such as vegetative and agronomic measures, are also applied to minimize erosion potential. Hydraulic structures, like check dams, debris basins, and sediment detention basins, are implemented to trap sediment at the upstream area. While sediment trapping can be an effective approach to reducing sediment yield, it is not without its weaknesses, including high cost, potential silting issues, limited sustainability, and restricted benefits. Therefore, a more widely adopted strategy for sediment yield reduction involves watershed management in conjunction with erosion control practices.

(2) *Sediment excavating*:

Sediment dredging is a widely employed technique in lakes, reservoirs, and barrages to uphold reservoir capacity and facilitate navigation routes, despite its considerable expenses. The feasibility and strategy for executing dredging operations hinge on diverse factors, including sediment volume, dredging site, particle size, deposit shape, and water levels. Dredging methods can be broadly classified as either hydraulic or mechanical. Hydraulic dredging involves using water to transport sediments, while mechanical dredging involves excavating and lifting sediments to the surface.

Hydraulic dredging, particularly when utilizing a cutterhead, proves exceptionally efficient in managing sediments ranging from fine to coarse sand. For example, at the upstream channel of the Nakdong River Estuary Barrage (NREB), hydraulic suction dredging, employing a cutterhead and a substantial pump, has been continuously implemented for approximately a decade, resulting in an annual dredging of around 0.665 million cubic meters of sediment (Ji et al, 1998).

Siphon dredging represents another hydraulic technique that eliminates the need for a pump and discharge line. It relies on the difference in water levels between the reservoir's surface and the lowest discharge point on the dam to transport sediments downstream. While smaller siphon dredges are often used in Chinese reservoirs, this method is restricted by the variance in head levels and reservoir water elevations.

Cable-suspended dredge pumps are specialized hydraulic dredging systems used for precision dredging with the aid of a submerged video monitor. They create a suction vortex without the employment of a cutterhead. Nevertheless, this approach can be expensive to operate. For instance, a cable-suspended pneumatic pump was utilized to remove 0.55 million cubic meters of silt from the Gibraltar Reservoir at Santa Barbara (Morris and Fan, 1997).

In contrast, mechanical dredging involves extracting sediment using enclosed or open buckets. In comparison to hydraulic dredging, mechanical dredging is better suited for sediments with lower water content, and the excavated quantities tend to be relatively small. This method can be suitable for managing gravel or larger materials found within a reservoir.

(3) *Sediment routing and flushing*

When the floodwater rise, the sediment discharge outflow diminishes compared to the inflow due to reduced flow velocity and the backwater effect (Fan, 1985a). While both sediment routing and flushing techniques aim to manage sediment in reservoirs, they serve different purposes. Sediment routing mainly seeks to minimize sediment deposits and achieve a balance between deposition and scouring during floods. On the other hand, sediment flushing is focused on removing already deposited sediments. The key distinction between sediment routing and sediment flushing lies in their approach to maintaining the natural hydrograph and the time-wise sediment transport pattern. During flood events, the sediment concentration in the water is higher on the rising limb of the hydrograph than the decreasing limb, resulting in lower sediment content after the flood peak (Fan and Morris, 1992b). Hence, delaying impoundment for as long as possible is advisable to reduce the sediment content in the water (Basson, 1997).

Partial drawdown, a sediment routing technique, has been employed below the Three Gorges Project on the Yangtze River to minimize the reservoir's impact on the natural hydrograph (Chen, 1994). Smaller reservoirs or estuary barrages are more effective in sediment routing as they can release significant amounts of water during floods. However, in some cases, sediment routing may require additional methods like flushing and dredging since it may not fully remove accumulated sediment.

Fan (1985a) classified the process of flushing into two distinct categories: free-flow flushing and pressure flushing. Free-flow flushing revolves around emptying the reservoir through the utilization of the natural river flow. This method is put into action when the sluices are free of sediment and typically commences when the water level has already receded to a lower point (Wu, 1989). In certain cases in China, specific irrigation reservoirs are completely drained during the initial phase of the flood season to facilitate flushing, after which they are subsequently refilled later in the flood season. This seasonal drainage can also be adopted when there is limited demand for water during a particular period. For instance, Jing (1956) proposed flushing techniques to eliminate sediment from the Jensanpei Reservoir in Taiwan, which was designed to be operational for just six months annually. Flushing can also be executed during the non-flood season, although this might necessitate a lengthier flushing period due to the reduced discharge.

On the other hand, pressure flushing entails releasing water through the lower outlets after lowering the water level; however, this method only manages to scour a limited area.

2.4. POST BARRAGE EFFECTS ON REGIME RIVERS

Generally, the construction of a barrage on a river can bring about significant changes in both the upstream and downstream areas. These changes can lead to erosion, accretion, bank failures, and floods. The river meandering course may also be altered to a braided one due to changes in erosion and accretion patterns. Furthermore, flood intensities may increase in the upstream area. The process of jacketing rivers can have serious consequences for the morphology of the area. Therefore, barrages are designed with the aim of being able to withstand floods with a return period of 50 to 100 years. However, in practice, the non-judicious operation of barrage gates has been found to cause the formation of shoals both upstream and downstream of the river. Shoal formation near the barrage can lead to flow passage through a narrow channel during high floods, resulting in cross flow, damage to flexible embankments, and deep scour formation around piers. Ultimately, this can shorten the structure's lifespan and cause damage to river training works.

2.4.1 Upstream Problems

According to De (1966) the storage capacity of reservoirs such as Mayurakshi in West Bengal and Damodar in Bihar and West Bengal has been significantly reduced due to increased sediment deposition caused by upland discharge. Specifically, the Mayurakshi reservoir's storage capacity was reduced by 19.5%, and the Damodar reservoir's storage capacity was reduced by 37.5%. According to technical reports from the River Research Institute of West Bengal in 1967 on the Durgapur Barrage Model, several changes occurred in the river channel due to the construction of a barrage. These changes included water spilling over both banks due to siltation, scouring near the upstream nose of the 2nd divide wall, and the formation of a sandbar near the upstream of the barrage.

Sen (1989) observed that in the sub-Himalayan region, the morphology of the river course changed significantly within a short period due to the construction of barrages and bridges over rivers, as well as the deposition of heavy silt loads. Table 2.1 presents sedimentation data (Chitale, 1992) for some selected reservoirs in India.

The table shows that the observed annual rate of siltation in the selected reservoirs is much higher than the predicted values, resulting in a reduction of their storage capacity. A case study of the Kangsabati and Kumari reservoirs (De1994-95) revealed that their storage capacities had been reduced by 11.69% and 6.69%, respectively, between 1966 and 1994. De (1996-97) also observed that siltation problems seriously affected the functioning of the Tilpara Barrage, Bakreswer Weir, and Kopai Barrage over the Mayurakshi River. During the period from 1994 to 1995, the total storage capacities of these structures were reduced by 15.23% of their total capacity. However, suitable measures taken for soil conservation had led to a decreasing trend in siltation in the Mayurakshi River basin for some years.

Table 2.1 Sediment data of selected reservoir (Chitale, 1992)

Sl. No	Reservoir	Year of impounding	Annual rate of Silting in ha/m 100sq m.		Percentage loss of storage capacity up to 1975	
			Predicted	Observed	Total	Annual
1	Bhakra	1959	4.29	6.00	5.6	0.35
2	Maithon	1956	1.62	13.1	10.06	0.5
3	Panchet	1956	2.47	10.0	12.4	0.65
4	Mayurakshi	1955	3.61	16.56	10.24	0.5
5	Kangsabati	1965	3.27	3.76	1.4	0.13
6	Hirakud	1956	2.52	3.57	7.00	0.37
7	Tungabhadra	1953	4.29	6.54	9.9	0.5

2.5. BARRAGE OPERATION PROBLEMS

It is a common occurrence for silts to accumulate in the pond formed upstream of a barrage, which can lead to the formation of shoals. This can create significant problems, particularly during times of high floods, as it affects the regular flow downstream, causing damage and destruction of embankments, flooding of low-lying lands, and the opening of new, shorter paths. A hydraulic engineer's primary responsibility is to manage these significant changes in channel morphology resulting from river training works. The IS Code 7349:1989 specifies several features that should be followed during the operation of barrage gates. These include maintaining the pond level during non-monsoon and post-monsoon periods, positioning non-monsoon flows near the under-sluice bays to feed the canals through head regulators, maintaining a uniform discharge along the width of the barrage, minimizing the risks of deep scour and shoal formation in the vicinity of the barrage, and preparing gate operation schedules to avoid constraints in flow regulation.

The hydraulic performance of a barrage is largely influenced by its looseness factor, which is determined by the ratio of gross waterway to Lacey's regime perimeter. This factor should be considered when designing waterways at the barrage site, taking into account its effect on sediment transport capacity. The obliquity of flow, migration of deep channel, and development of cross flows are among the major factors contributing to shoal formation in the upstream of a barrage, as observed by Sinha et al (1986) in their study of the Dakpatha barrage.

According to Sen (1989), barrages are typically designed to withstand floods with a frequency of 50 to 100 years, which means that there is a low chance of the upstream sediments being flushed out. However, draining the shoals can be successful by implementing the following methods:

- Adjusting gate openings during low floods to pass concentrated flushing discharge across the shoals. The pond level can be slightly lowered during flushing to achieve a better effect.
- Dredging and flushing the dredged material in the deep channel portion.
- Using dozers and dumpers to remove shoals that appear above the surface water during non-monsoon periods.
- Dredging pilot cuts through shoals to provide adequate design depth and width, and then draining out concentrated discharge through these cuts by carefully operating the gates.

2.5.1 Barrage gate operation

The operation and regulation of barrage gates (IS 7349: 1989) depends on the dominant flow conditions throughout the year, which are:

(A) Pre-monsoon period, (B) Monsoon period, and (C) Post-monsoon period.

During the pre-monsoon period, which is a low flow period, the barrage gates should be regulated to prevent water wastage and maintain the pond level. Any excess discharge should be released through under sluice bays and silt excluder tunnels, if available. If there is a flash flood and the suspended silt load exceeds the permissible limit, the canal head regulator should be temporarily closed.

2.6. NUMERICAL MODELS

Numerical modelling is an alternative tool to predict the sediment transport of a barrage and to design a sediment management strategy. Numerical models use computational techniques to solve the governing equations of sediment transport. These models can simulate complex flow conditions and sediment transport processes and are widely used in practical applications. In this literature review, we will discuss recent developments in numerical modelling of sediment transport of barrage.

2.6.1 Sediment transport model of Dams

Saad (2002) performed an evaluation of the alterations in the physical characteristics of the Nile River triggered by the establishment of the Aswan Dam in Egypt. The High Aswan Dam (HAD) project significantly played a role in advancing Egypt's economic and societal progress. During the construction of the High Aswan Dam in 1963, the flow of the Nile River was partially obstructed, and by 1968, once the dam was fully built, the river's flow was completely halted. This comprehensive control over river discharges eliminated instances of high floods, leading to the complete regulation of water flow, which reached a maximum value of around 2800 m3/s.

The surplus flood water has been stored in Lake Nasser, resulting in a 300% reduction in the maximum monthly discharge and a 40% increase in the minimum monthly discharge. The sediment regime downstream of the dam underwent significant changes, affecting the river's hydraulic geometry stability. Due to reduced discharges, the water surface slope in four reaches between Aswan and Delta Barrage decreased by 2% to 7%, resulting in relatively small velocities and sediment transport rates. Sediment concentration measurements showed a substantial reduction from 3000 ppm to 65 ppm at El-Gaafra station after HAD construction. These changes led to the development of the Nile River downstream of HAD, reflecting the water discharge and sediment load conveyed by the river.

Ahn (2011) focuses on predicting sedimentation and flushing in the Xiaolangdi Reservoir on the Yellow River using the GSTARS4 model. The reservoir experiences high sediment concentrations, with common operations ranging from 10 to 100 kg/m3 and flushing operations reaching 100 to 300 kg/m3, with fine materials comprising about 20 to 70% clay. For a 3.5-

year simulation period, both unsteady and quasi-steady simulations were conducted with calibrated coefficients specific to the Xiaolangdi Reservoir. From the comparison of numerical results with the measured data it has been observed that the unsteady simulation demonstrated better agreement with the measured thalweg elevation and channel cross-section compared to the steady flow simulation. During the flushing process, the unsteady simulation outperformed the steady flow simulation in predicting the gradation of sediments flushed from the reservoir.

Moussa (2012) attempted to predict the deposition in the Aswan High Dam Reservoir (AHDR), in Egypt, in order to estimate the effective life span of the reservoir. AHDR in Egypt contains the maximum amount of 162 billion cubic meters of fresh water. Approximately 124 million tons of sediment per year is deposited in the reservoir and the capacity of the reservoir decreased heavily during the period 1964 - 2003. A 150 km long reach was taken as the study area, where the most sediment deposits. A two dimensional hydrodynamic and sediment transport model, CCHE2D, an open source model, was used for modelling the reach. The average flow velocity in different cross-sections were computed and validated with measured data. The bathymetric changes of AHDR were also computed, showing the changes in bed level of cross section and longitudinal profile. Finally, the numerical model CCHE-2D is proved to be a useful tool for future operations and maintenance of the AHDR.

Moussa (2012) strives to forecast the buildup of sediment within the Aswan High Dam Reservoir in Egypt as a means of estimating its operational longevity. To achieve this, a two-dimensional numerical model called CCHE-2D was employed to replicate the sedimentation process along a 150 km segment of the reservoir, which represents the primary area of sediment accumulation. Calibration and validation of the model for flow and sediment deposition were done for the period 2006-2007, showing good agreement between observed and modelled results. Based on the confidence in the obtained outcomes, the model was extended to predict sediment deposition from 2009 to 2014. This study provides valuable insights for understanding and managing sediment dynamics in the reservoir.

Isaac and Eldho (2016) conducted an investigation that combined 1D numerical modeling using HEC-RAS 4.1 (an open-source software) with physical model experiments carried out at the Central Water and Power Research Station (CWPRS) in Pune, India. The purpose of their study was to address sediment-related concerns at the Devsari Hydroelectric Project in Uttarakhand, India. The modeling and experiments specifically focused on the Pinder River, encompassing a stretch from 5.5 km upstream to 0.3 km downstream of the dam axis, as well as a segment of the Kaliganga River spanning 3.5 km upstream from its confluence with the Pindar River.

The numerical simulations, based on the physical model, were employed to predict short-term sediment deposition patterns and velocity profiles within the reservoir. The outcomes from the numerical simulations closely aligned with the results from the physical model tests. Additionally, the physical model studies were employed to forecast sediment removal through drawdown flushing, considering various discharges and durations. The findings revealed that the restoration of reservoir capacity could be achieved by implementing flushing during a peak discharge of 500 cubic meters per second (cumecs) over a duration of 252 hours.

Olsen and Hillebrand (2018) conducted 3D Computational Fluid Dynamics (CFD) modelling of sedimentation with dredging Iffezheim reservoir located in the Rhine River at the border between Germany and France for the period 2000-2011 using the sediment transport formula proposed by van Rijn (1984) and Engelund-Hansen (1967). The results indicated that the predicted values are reasonably close to the measured data for the default values of the parameters chosen in the study and found to be effective in long-term projections of deposition and dredging volumes.

Hanmaiahgari et al (2018) conducted a numerical analysis concerning sediment transportation in the Tenryu River's section between the Hiraoka and Sakuma Dams. The study spanned a distance of 32 km. Their numerical simulations encompassed the manipulation of various factors, including sediment transport functions, roughness coefficients, flow water temperature, fall velocity, and computational increments.

To calibrate their model, they utilized available monthly flow data spanning a 48-year period from 1957 to 2004. Through this calibration process, they established optimal values for computational increments (24 hours) and Manning's roughness coefficient (0.02).

By comparing changes in bathymetry through the use of the HEC-RAS model, they observed that the most appropriate formulas for sediment transport function and fall velocity in the Tenryu River were the Engelund and Hansen formula from 1967 and the van Rijn formula from 1993, respectively. These formulas, when combined with the best-fitting calibrated parameters, yielded the most accurate results in their simulations.

Charafi (2019) studied a water intake initiative within a dam reservoir situated in northern Morocco. The primary objective involves developing a two-dimensional numerical model that can effectively replicate sediment movement within the reservoir. The model comprises two key components: a hydrodynamic module grounded in the Saint-Venant equations and a sediment transport module that relies on the mass-balance equation. The solutions to these modules are obtained using the MacCormack and upwind numerical schemes, respectively.

Through the utilization of this model, an analysis is conducted to anticipate the periods when the drinking water production station might need to be shut down. These shutdown periods are related to the concentration of suspended solids (SS) specifically during intense rainfall events. The study's outcomes offer valuable insights into the natural factors influencing the functionality of the water intake system and contribute to effective management of sediment-related concerns within the reservoir.

2.6.2 Sediment transport model of barrages

Sediment transport modelling of barrages is an important aspect of river engineering, as it helps to predict and manage sediment transport processes, which can have significant environmental, economic, and social impacts. In this literature review, we shall discuss the key concepts and methods used in sediment transport modelling of barrages, as well as the major research findings and applications in this area. Khan and Hossain (2001) assessed aggradation and degradation in the Teesta River caused by a barrage using various methods, including mathematical modelling. The Mike 11 morphological module of DHI was used for predicting sedimentation in the Teesta River, showing a 1-meter rise in bed level over ten years after barrage construction.

Similar findings indicated a 2.5-ft bed level change in the extreme upstream cross-section over the past decade, with greater degradation observed downstream and within a 15-km impact zone of the barrage. It was concluded that the MIKE 11 sediment transport and morphological model can accurately simulate transient bed profiles in a laboratory flume under non-uniform flow using calibrated transport formulae. Schmidt et. al. (2005) investigated the effectiveness of flow guide structure for minimizing sedimentation in the upper weir channel of the Iffezheim barrage at the river Rhine by carrying out hydrodynamic and the morphodynamic simulations by using TELEMAC-2D developed by Electricité de France-Laboratoire National d'Hydraulique. Introduction of guiding structure were shown to increase the flow velocity thereby modifying the flow pattern and increasing the bed load transport efficiency.

Kim and Julien (2008) carried on a study on Sangju weir of Nakdong river, South Korea for estimating the sediment yield in the upstream of the weir and defining trap efficiency.

Consecutive weirs are constructed in Nakdong River that causes geo-morphological changes in the river that leads to changed erosion and sediment pattern along the river. So examining sedimentation pattern was becoming necessary for better operation of the weirs. Field measurements, runoff modelling and regional analysis were done to obtain daily discharge. Suspended sediment measurements were done by collecting samples from local stations and particle size distribution was done using laser diffraction method. Reservoir sedimentation amount were calculated using flow rate and sediment concentration. Trapping efficiency was found to increase with particle size and stage, and decreases with increasing flow rates. Finally, it was found that annual rate of reservoir sedimentation was 332,000t, that is, 0.76% of the total reservoir storage capacity.

Istiaq et al (2011) numerically modelled Ganges Barrage operation. The objective of the proposed Ganges Barrage is to manage water flow to meet the water demand of the Ganges dependent area during dry seasons. The successful operation of the barrage relies on a proper regulation system, which requires the use of mathematical models. A primary gate operation plan has been developed, using the MIKE 11 model for one-dimensional hydrodynamics and the MIKE 21C model for two-dimensional morphological analysis. The study concludes that a Semi open pond system is suitable for the Ganges Barrage operation. The operation plan considers various discharge ranges and emphasizes maintaining flow channels and managing sedimentation.

Majid et al (2014) developed a model to predict the sediment transport behaviour in the upstream reach of the Al-Ghammas Barrage in Iraq. The model was developed using the finite volume method (FVM) and by solving the Reynolds-averaged Navier-Stokes (RANS) equations with the k-epsilon turbulence model. The sediment transport was modelled using the Exner equation and a sediment transport equation based on the sediment transport rate. The simulation results were compared with field measurements of water discharge and sediment concentration, and a good agreement was found. The model was used to investigate the effect of flow discharge and sediment size on the sediment transport pattern in the upstream reach of the Al-Ghammas Barrage. The results showed that increasing the flow discharge increased the sediment transport rate, while increasing the sediment size decreased the sediment transport rate.

Ghosh et al (2014) investigated the effectiveness of gate operation of a barrage gate and other parameters on the sediment flushing efficiency by conducting physical model tests on Yamuna River Barrage with 34 gates and performing analysis using artificial neural network (ANN). The physical experiments were done varying different parameters like pond water level, river discharges, position of shoal with respect to the barrage, gate opening area and different types of gate opening patterns, like, rectangular, arch type and inverted arch type. From the experiments and the analysis using ANN it is observed that for high discharge, pond level does not affect flushing efficiency, otherwise flushing efficiency is inversely proportional to upstream pond level and increases with the increase in discharge and gate opening area showing 'inverted arch' gate opening pattern as the most efficient one. Further, it was highlighted that the results were in line with that reported by Ji et. al. (2011) on Nakdong River Estuary Barrage (NREB).

Khassaf and Abbas (2015) conducted a one-dimensional numerical investigation to simulate sediment transport within the channel of Al-Shamia Barrage, located on the Euphrates River at Al-Diwaniya city in Iraq. They employed the HEC-RAS program version 4.1 for a study segment spanning 6 km. Their approach involved comparing the projected values from their model with field measurements gathered using an Acoustic Doppler Current Profiler (ADCP).

Upon comparing their model's predictions with the actual field measurements, it was evident that the Enguland-Hansen formula employed in their model yielded results closest to the field measurements. This model indicated an average annual sediment transport load of around 209,000 tons using the Enguland-Hansen formula, whereas the average annual sediment transport load measured in the field was approximately 140,965 tons.

2.7. STUDY ON FLUSHING

Sediment flushing is a widely employed technique to restore the storage capacity of reservoirs in order to extend the life expectancy of dams and barrage reservoirs. Historical evidence of flushing practices can be traced back to the 16th century in Spain, as reported by D'Rohan (1911, cited in Talebbeydokhti and Naghshineh, 2004). Another early example of flushing was documented by Jordana (1925) in Peña Reservoir, Spain. Atkinson (1996) also highlighted the effectiveness of flushing and listed various cases as examples. For instance, the Mangahao reservoir in New Zealand experienced a loss of 59% of its original operating storage by 1958, 34 years after the reservoir was first impounded. However, in 1969, through a flushing operation, 75% of the accumulated sediments were successfully removed within a month (Jowett, 1984). Furthermore, numerous other studies have investigated on sediment flushing. In this section, we review recently conducted studies that have utilized flume experiments, physical models, as well as analytical and numerical models.

2.7.1 Flushing with physical model-based studies

Researchers like Hotchkiss and Parker (1988, cited in Hotchkiss and Parker, 1990) conducted flume experiments to study sedimentation and sluicing in reservoirs. They observed the formation of a depositional delta at the upstream area of the sluice gate, and after draining the simulated reservoir, they noticed progressing degradation. However, they cautioned that sluicing in the laboratory model should be performed carefully to avoid unrealistic features not observed in the field. Lai and Shen (1995, 1996) conducted experiments using lightweight walnut shell grits to enhance the understanding of flushing processes. Their findings demonstrated the effects of pressure flushing and revealed that increasing the height of the opening led to retrogressive erosion in the upstream direction, resulting in the flushing of a significant amount of sediment through the reservoir.

Physical models were also utilized to examine flushing operations in various reservoirs. Janssen and Shen (1997) performed flushing tests during drawdown with uniformly sized noncohesive sediments and no incoming sediment load. They found that the flushing channel widens and incises rapidly when the flow through the reservoir reaches riverine conditions. However, when the flow is confined to the flushing channel, the channel incises more slowly into the sediment bed. Several other physical models were conducted for various reservoirs, including the Jensanpei Reservoir in Taiwan, Cowlitz Falls project in the U.S., and reservoirs in China, Austria, and India (Brandt, 1999). Talebbeydokhti and Naghshineh (2004) employed polymer particles in a one-dimensional reservoir flume to investigate flushing operations. Their study revealed that the rate of sediment flushing was influenced by factors such as outflow rate, water surface gradient with the dam section, and the width of the flushing channel.

2.7.2 Numerical Studies

Since the 1980s, numerous numerical studies have been performed to simulate sediment flushing processes. Wang and Locher (1989) utilized a one-dimensional HEC-6 model to develop operational procedures for minimizing sediment accumulation in the Cowlitz Falls reservoir. Morris and Hu (1992) used the same model to analyze the impacts of different gate operations for the Loíza Reservoir during floods. Other studies by Ju (1992) and Shen et al. (1993) involved one-dimensional diffusion models and a two-dimensional mobile-bed model, respectively, to predict sediment transport and bed evolution in reservoirs. Two-dimensional numerical models were also employed to simulate flushing operations in various reservoirs, such as the Rock and Cresta Dams in the U.S., reservoirs on the North Fork Feather River, Abbey-stead Reservoir in the U.K., and Tapu Reservoir in Taiwan. These models facilitated the optimization of operation rule curves, evaluation of flushing flows, and exploration of flushing efficiency under different conditions (Chou et al 2004). Liu et al. (2004) developed a one-dimensional model that predicted the amounts of flushed and deposited sediment, and it was calibrated using field data from Dashidaira and Unazuki reservoirs in Japan.

Olsen (1999) investigated flushing of sediment from a water reservoir with a two-dimensional numerical modelling based on two-dimensional depth average Navier Stokes equations supported by physical model studies on Kali Gandaki Hydropower Reservoir in Nepal. Van Rijn (1987) formula for near bed suspended load concentration, calibrated properly with the physical model tests, was used in the convection-diffusion equation for prediction of suspended sediment concentration. When contrasted with the findings from the physical model experiment, the essential characteristics of the erosion pattern were replicated, and the difference between the estimated and observed scour volume remained minimal, primarily because the simplifications applied in the numerical model were generally justified. The primary disparities between the computed and observed bed level profiles were probably attributed to secondary currents within bends, which could not be adequately simulated using the two-dimensional approach.

Khosronejad and colleagues (2008) constructed a comprehensive three-dimensional model that combines hydrodynamics and sediment transport. This model is based on the Reynolds-averaged Navier-Stokes equations and employs the finite volume method for its implementation. In the hydrodynamic module, equations for mass and momentum conservation were utilized alongside a conventional k–ε turbulence closure model. Concurrently, the sediment transport module relied on the convection/diffusion equation for sediment concentration and the sediment continuity equation to calculate both sediment concentration and variations in bed level within the reservoir, especially during the flushing process.

Both the hydrodynamic and sediment transport models were established within a boundary-fitted curvilinear coordinate system. To validate the hydrodynamic component, the model's outputs were compared against experimental data and results from direct numerical simulations. The model's predictions for sediment concentration also exhibited good agreement with experimental outcomes. Additionally, the model's depiction of bed evolution upstream of a sluice gate corresponded well with results from physical model tests as reported by Salehi Neishabouri et al. (2003).

Ji et al (2011) studied the possibilities of sediment by flushing by proper gate operation as an alternative of mechanical dredging in Nakdong River Estuary Barrage (NREB) in South Korea, that prevents salt-water intrusion but causes sedimentation problems in downstream. In this study sediment flushing curves is considered as a function of river stage and discharge. Flushing curve and flow duration curve has been compared for assessing the feasibility of flushing. A one-dimensional numerical model has been developed, for predicting the effectiveness of sediment flushing and comparison has been made about sediment deposition with and without mechanical dredging. The river bed is considered as impervious and wide and rectangular channel geometry. Equation of Brownlie was used for calculating volumetric sediment discharge, while the model calibration and validation was done using field measurement. Flush sediment volume was calculated by estimating changes of bed level and accordingly, sediment flushing curves were developed, considering that sediment flush volume is a function of time. The study concluded that during the early flood season where discharge lies between 1000 to 2200m^3/s sediment flushing could be done by adjusting gate operation. Sediment flushing was also possible in reasonably short flushing duration, where sediment flushing curve lies below the flow duration curve.

Park et al. (2013) conducted numerical study using 1-D HEC-6 model and 2-D CCHE2D model to evaluate the effectiveness of dredging operation on the sedimentation behaviour in the approach channel at the Nakdong River Estuary Barrage. 1D model showed that the Lower Nakdong River had typical features of aggradation near the estuary barrage due to decreased velocity. 2D analysis showed that simulation with dredging had faster sedimentation rate than that without sedimentation. However, it was shown that natural flushing had a significant role in most of the total sediment erosion.

Rodriguez et al. (2017) demonstrated flushing feasibility of a Mexican reservoir using 2D and 3D numerical models employing Spanish software IBER for 2D analysis and FLOW 3D software for 3D analysis. In order to prove flushing feasibility, the Atkinson method was carried out by using the dam's actual condition and actual field data were used to calibrate both the models. The results indicated that 66% of the reservoir capacity could be recovered with scouring out of 35% of the sediment which ultimately helped in sediment management of the dam reservoir. Chaudhury et al (2018) reported reservoir flushing studies for Dri Limb Etalin hydroelectric project in Arunachal Pradesh, India, by conducting 2D numerical simulations using MIKE21C for two alternative bed profiles and five flushing discharges. It was shown that magnitude of flushing increases with the increase in flushing discharge as well as duration. Further, it was highlighted that annual flushing of 30 hours with flushing discharge of $1000m^3$/sec can remove 40% of the deposited sediment, after the reservoir bed stabilized which appeared to be possible due to higher initial bed slope of the reservoir.

2.8. SUMMARY

The above literature review highlighted that there would be a gradual increase in sedimentation with the passage of time in dam and barrage reservoirs, with an annual reduction in capacity in the order of 0.5 % to 1.0 %. Numerical studies reported were found to more or less in line with field observation for reservoirs with different geometric and morphological parameters. Further, numerical studies for capacity enhancement using various flushing techniques were also studied and it was highlighted that flushing is an effective tool for increasing the reservoir / pond capacity for both dam and barrages. In this context it may be noted that all these studies were performed on dam reservoirs and on barrage ponds built over perennial / estuarine river. There is almost none reported (in the public domain) on a river with upland variable discharges from upstream dams and controlled by judicious gate operation of downstream barrage. Therefore, in the present study an attempt has been made to evaluate bedform characteristics of river Damodar for stretch between two upstream dams (Panchet and Maithon) and Durgapur barrage with special emphasis on restoration of pond capacity by flushing technique.

CHAPTER 3
METHODOLOGY

3.1. GENERAL

An ever-expanding water demand on the densely populated Sub-Himalayan plateau, where the monsoon downpour of basin catchment discharges through Damodar-Barakar River system, has made it a subject of prime concern and accordingly, understanding of the sediment transport processes and the erosion-accretion pattern in the Damodar River has become urgent. A precise numerical model-based prediction of the water balance and sediment fluxes within the river system also improves our competence in management and decision making, building economically efficient flood defenses and executing optimal water abstraction and irrigation strategies.

This section outlines the methodology employed in the research, substantiates the chosen methods by connecting them to the findings from the literature review, and outlines the processes of data collection and analysis. On the basis of primary objectives and scope of works we have developed a mathematical model, customizing one-dimensional numerical scheme MIKE-11 of Danish Hydraulic Institute (DHI) to quantify the hydrological parameters and resultant morphological outcomes of the Damodar River system, which is described in detail below.

3.2. MATHEMATICAL MODELING

In recent times, development of mathematical model has progressed rapidly due to advent of high-speed digital computers, which enable solution of complex hydrodynamics using the equations of fluid flow. The processes of fluid flow and related transport are represented by mathematical equations and are based on the conservation of mass, momentum and energy. These are partial differential equations, nonlinear in nature and difficult to solve analytically

(Abbott, 1979). Based on certain assumptions these equations are simplified and can be solved using digital computers at discrete points in the computational domain. In this thesis, the opportunity of using available numerical computational model as analytical tool has been explored for simulating the hydrodynamics and sediment transport of the Damodar River.

Normally, in a one-dimensional flow model, velocities are averaged over two dimensions (usually width and depth) and is assumed to vary only in one direction (usually longitudinally). Thus, the 1D models are capable of handling very long or complicated river systems with little computational effort. The MIKE 11 model is such type of one-dimensional model that employs the Saint-Venant equations averaged over cross-sectional segments to simulate the development of water levels, discharges, and mean flow velocities. This model is capable of predicting the water depth at specific points across the Damodar River, subject to the given boundary conditions. Cross sections and chainage are used to describe the river, from its upstream to downstream points. The MIKE 11 model has several advantages, such as its ability to compute quickly and its requirement for minimal field data to create the model setup. The model represents rivers and floodplains as a network configuration with interconnected branches, where water level 'h' and discharge 'Q' are calculated at alternating points over time. The MIKE 11 model's simulation engine is the hydrodynamic (HD) module, which uses an implicit, finite difference scheme to calculate unsteady flows in river (Source: MIKE 11 Reference Manual 2014).

One-dimensional mathematical model using MIKE 11 has been setup with river cross section data, variable upland discharge as released from two mighty dams in the upstream (Maithon and Panchet) as upper input boundary and variable water level at the downstream gauge point of Durgapur Barrage [1 km downstream of Barrage] as lower boundary due to the scheduled Barrage gate operation. The model was simulated for sixty hydrological years to get the hydrodynamic and sediment transport behaviour of the river stretch between dams at upstream and barrage at downstream maintaining the present practice of gate operation schedule.

3.2.1 Theoretical Background

MIKE 11 Hydro-Dynamic module (HD) and Sediment Transport module (ST) have been used in the present study. An implicit, finite difference program is used for computing unsteady flow. Change in flow velocity and water depth in different time and space is simulated with input of varying water surface elevation and flow rate with known initial condition and bed morphology. It solves width integrated dynamic continuity equations and conservation of momentum (Saint-Venant equations) as shown in Eq. 1 and 2.

Conservation of mass:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad (3.1)$$

Conservation of momentum:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial \mathrm{x}}\left(\alpha \frac{Q^2}{A}\right) + gA\frac{\partial \mathrm{h}}{\partial \mathrm{x}} + \frac{\mathrm{g}\mathrm{Q}|Q|}{C^2 AR} = 0 \qquad (3.2)$$

Where, $Q, q, h, A, C, R, \alpha\ and\ t$ are discharge, lateral inflow, stage above datum, flow area, the Chezy resistance coefficient, the hydraulic radius and the momentum distribution coefficient and time respectively.

Sediment transport module has been used for simulation of sediment transport for computing morphological changes. The model is based on a one-dimensional equation of mass conservation of suspended or dissolved materials (Advection-dispersion equation) as shown in Eq. 3. Description of sediment settling with different settling velocities (flocculation) is included in the model. Bottom shear stress is calculated considering river bed velocity. Storage capacity of different cross sections in flood plain is computed with elevation curves.

$$(1 - C')^m C' V_P^{\infty} + \in_S \frac{dC}{dy} = 0 \tag{3.3}$$

Where, the C', V_P^{∞} and $\in_S$ are the volumetric concentration, the terminal settling velocity of a single particle in still water and turbulent diffusion coefficient respectively (MIKE 11, 2014).

3.2.2 Model Set up

The software package, MIKE 11 as available in the RRI, GoWB was installed in a high-speed computer. Customization of the module, as per requirement of Damodar River study was also done for hydrodynamic and sediment transport simulation. A brief description of working procedure of the model MIKE 11 is presented below, which includes operation of multiple editors for managing different types of input data.

3.2.2.1. Integrating Editors – the Simulation Editor

MIKE 11 encompasses a variety of distinct editors that allow data to be inserted and modified separately. Due to this structure of isolated editor files, direct connections between these individual editors are absent when accessed individually. The amalgamation and sharing of data among these disparate editors are accomplished through the utilization of the MIKE 11 Simulation Editor. This Simulation Editor serves a dual role:

a. The simulation editor serves as the tool to initiate the simulation process by including parameters for controlling simulation and computation.

b. Simulation editor establishes a connection between the visual representation in the network editor and the rest of the MIKE 11 editors, depicted in Figure 3.1.

After designating the editor file names within the input section, the data from each editor is seamlessly interconnected. This enables us to effortlessly visualize and retrieve all data originating from distinct editors (including cross-sectional data, boundary conditions, and various parameter file details) within the graphical representation of the river network editor.

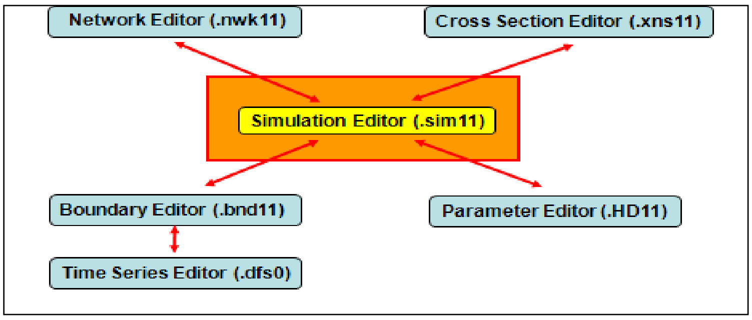


Fig. 3.1 The MIKE 11 Simulation editor

3.2.2.2 Working with the Network Editor

The Network editor holds a pivotal role within the MIKE 11 Graphical User Interface. Through the graphical depiction found in the network editor's plan plot, it becomes feasible to present data from all other data editors within MIKE 11. The core functions of the network editor encompass:

1. Facilitating editing capabilities for data that define the river network, which includes tasks such as point digitization and the linkage of river branches, as well as the specification of hydraulic structures like weirs and culverts.

2. Offering a comprehensive view of all data encompassed within the river model simulation.

The tabular and the graphical view of the Network editor are shown in Fig. 3.2.

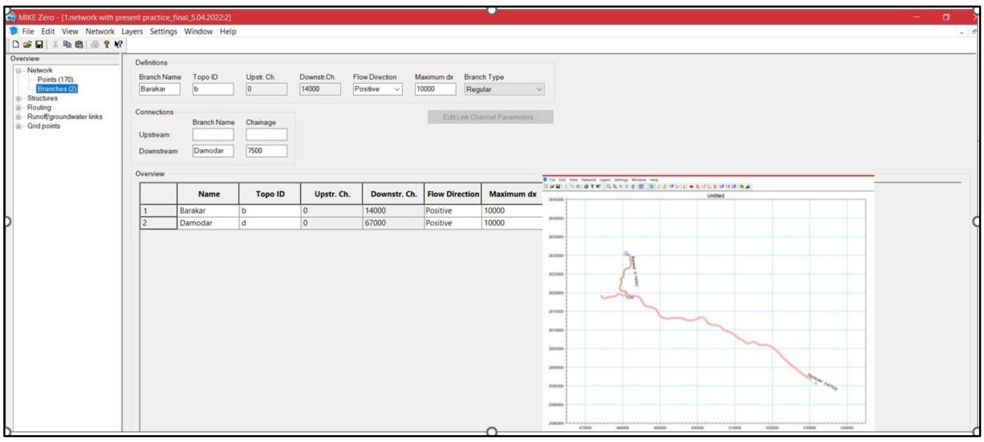


Fig. 3.2 Network editor, Tabular and Graphical view

3.2.2.3 Working with the Cross-section Editor

River cross-section data consists of two distinct sets: raw and processed data. The raw data delineates the actual configuration of a cross-section through (x, z) coordinates, usually derived from the riverbed survey conducted by RRI. The processed data, on the other hand, is computed from the raw data and encompasses correlated values such as the water level, cross-sectional area, flow width, and hydraulic or resistance radius. This processed data table is directly utilized within the computational module (as depicted in Figure 3.3).

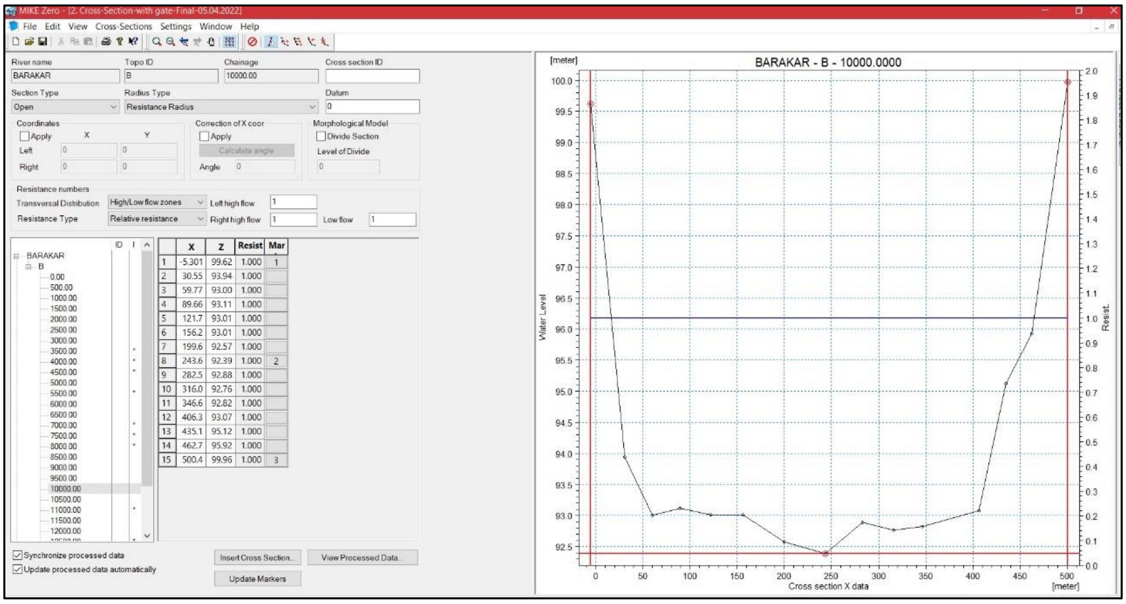


Fig. 3.3 Cross-section, raw data editor

3.2.2.4 Working with the Boundary Editor

In MIKE 11, boundary conditions are established through a dual approach: the utilization of time series data, which is formulated within the Time Series editor, and the delineation of specifics concerning boundary points, boundary types, and related aspects in the Boundary editor (Figure 3.4).).

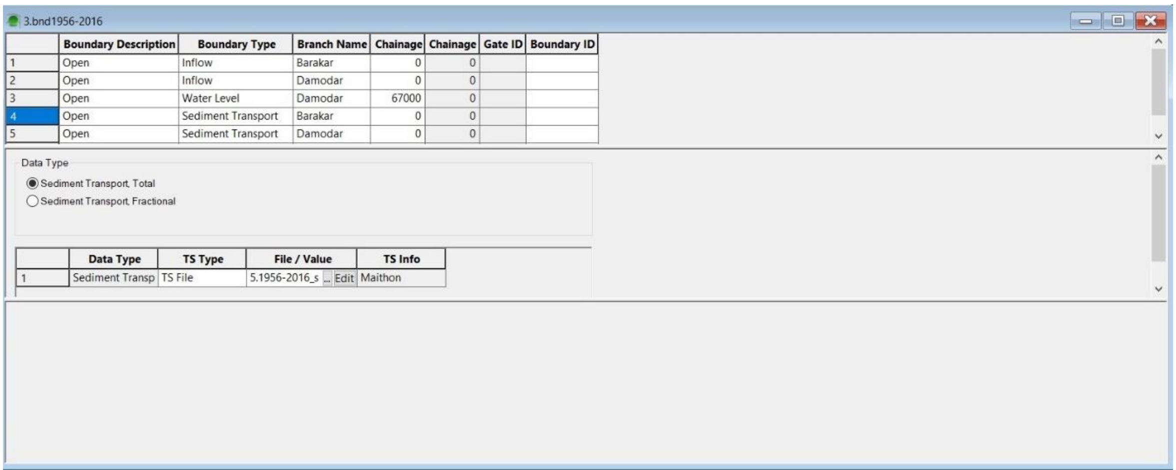


Fig. 3.4 Boundary editor

3.2.2.5 Working with Parameter file Editor

The MIKE 11 parameter file editors consist of three segments: the Hydrodynamic, Advection-Dispersion, and Sediment Transport editors. These Parameter editors house data pertaining to variables associated with the chosen computation type. For instance, within the HD Parameter Editor, information concerning bed resistance, a crucial variable for hydraulic calculations, is stored (Figure 3.5).

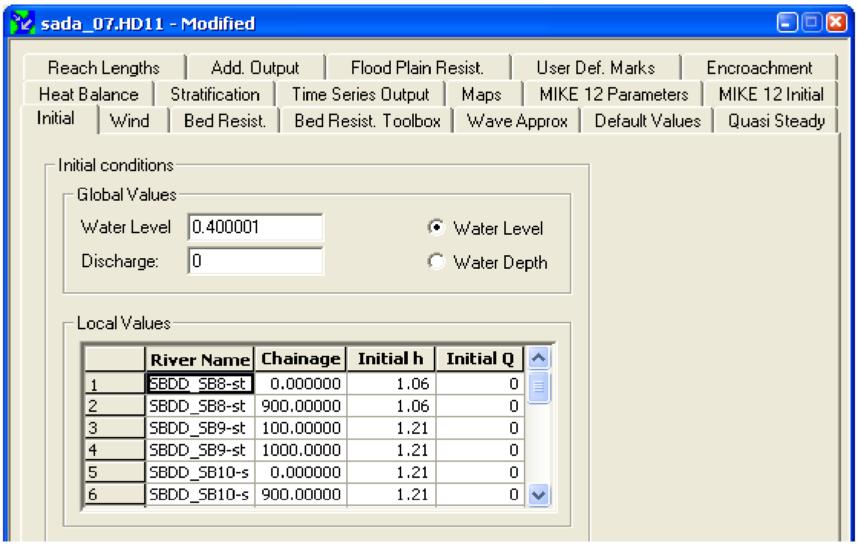


Fig. 3.5 HD Parameter Editor

3.2.2.6 Working with Sediment Transport (ST) Parameter Editor

For conducting a simulation of non-cohesive sediment transport, it is essential to provide details regarding sediment grain size, specifically grain diameters, to ensure accurate computation of transport and resulting morphological alterations.

MIKE 11 enables the calculation of non-cohesive sediment transport capacities and the corresponding rates of accumulated erosion or sedimentation. This is accomplished through various transport and calculation models (Fig. 3.6).

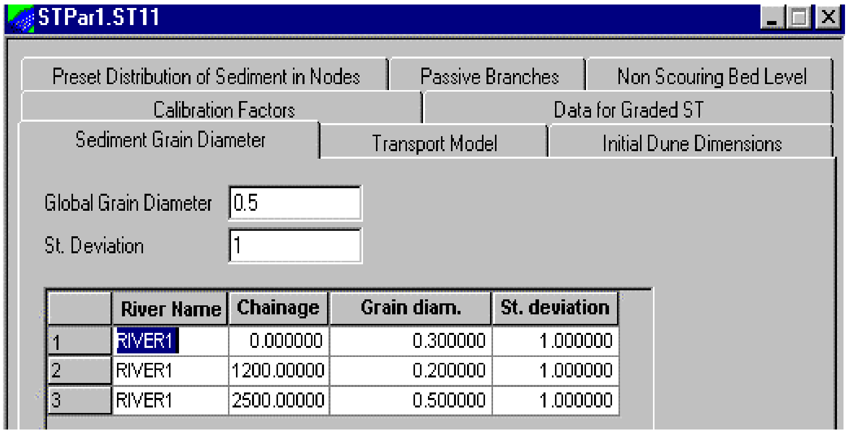


Fig. 3.6 ST Parameter Editor

3.2.3 Model Input

3.2.3.1 River Network

Network data of the Damodar-Barakar River system typically includes reaches, nodes, and cross sections. A reach connects two nodes in the network and has both an upstream and downstream end. To indicate a position along the reach, the distance from the upstream end is measured and referred to as chainage. The shape of the cross section and friction may vary along the length of the river reach. Nodes are points that correspond to reach ends and junctions. Each reach has a node at both ends, while the junction is associated with other branches that meet at a common node.

This river system comprising of (i) the Damodar River (67 Km) originated from Maithon Dam, (ii) Barakar River (14.5 Km) from the Panchet Dam and (iii) the Durgapur Barrage has been modelled numerically in the present study. The domain of this numerical model has extended from the outfall of up-stream Dams (chainage 0 to 66 km) to the 1 Km down-stream of Durgapur Barrage, covering a total longitudinal distance of 67 Km (Fig. 3.7).

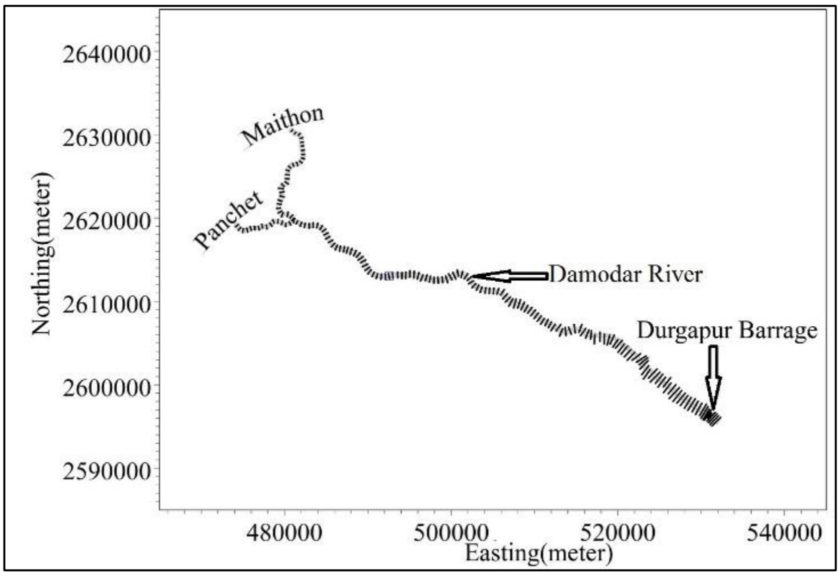


Fig. 3.7 MIKE generated River Network

The river network has been delineated from the maps and digital elevation data, (source: RRI) as 67 Km long Damodar River starting from outfall of Panchet Dam and 14 Km of Barakar River starting from outfall of Maithon Dam and lower boundary at Durgapur Barrage.

3.2.3.2 Cross Section

Cross section is a profile of the river reach that is perpendicular to the direction of flow and represented in two dimensions. It determines the volume of water in the reach for a given water level and regulates the speed and amount of water flow. For accurate simulations, detailed and dependable cross section data is required. The geometry of the cross section determines the reach's width and water volume at a given water level, while the resistance value defines the ease of water flow through the reach.

There are two methods to define the characteristics of a cross section.

1. Raw data
2. Processed data

Raw data consists of a set of (x, z) coordinates that describe the shape of the cross section. The x coordinate indicates the transverse distance from a reference point, usually the left bank, while the z coordinate denotes the corresponding bed elevation. After processing the raw data, tables of processed data are generated, which the flow computation engine utilizes. Processed data presents a simplified representation of cross sections by providing the characteristics of a reach, such as storage width, flow area, resistance number, and hydraulic radius, for multiple water levels in a tabular format. Processed data is automatically calculated from raw data for a given cross section.

In the present study, a total 128 number of cross sections have been prepared from the entire river network with 500 m interval with the help of SRTM data (Shuttle radar topographic mission open source) and surveyed data collected from RRI. A typical cross-section at Chainage 64.5 km is shown in Fig. 3.8.

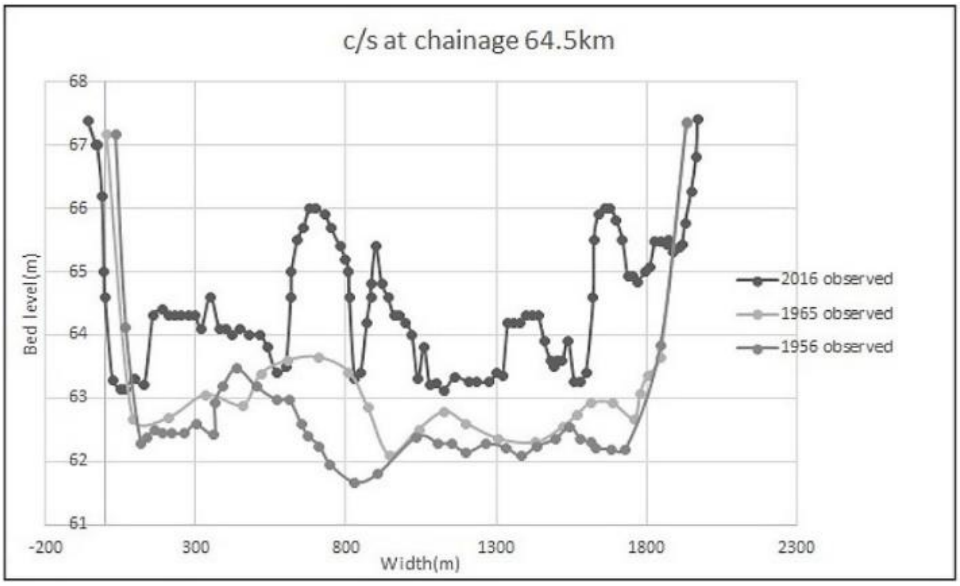


Fig. 3.8 Cross sections data collected from field

3.2.3.3 Hydraulic roughness (Manning's n)

One of the frequently employed equations that governs the flow in open channels is recognized as the Manning's Equation. This equation was formulated by the Irish Engineer Robert Manning in 1889 as a substitute for the Chezy Equation. The Mannings equation is an empirical formula that is applicable to steady flow within uniform open channels. It takes into account variables such as channel velocity, flow area, and channel slope.

The formula developed by Manning can be expressed using the equation provided below

$$\boldsymbol{V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}} \tag{3.4}$$

Where, $\boldsymbol{V}$ is Flow Velocity, (m/s) of the river discharge

$\boldsymbol{N}$ is Manning's 'n' of the river discharge

$\boldsymbol{R}$ is Hydraulic Radius (m)of the river cross section

$\boldsymbol{S}$ is Bed Slope of the river

The equation is utilized to predict the velocity or discharge of water if the width, depth, and slope are given. Manning's 'n' is a measure of the flow resistance, and it is affected by various factors that can impact it directly or indirectly. With the continuous advancements in technology, particularly in computational resources, it has become possible to adjust the value of Manning's 'n' to match the observed water levels with the simulated values. This process of calibrating and validating the value of Manning's 'n' is now feasible due to technological progress.

3.2.3.4 Boundary data

The boundary editor is utilized to define the boundary conditions for a MIKE 11 model. The boundary editor provides information on the type of boundary, such as open, closed, point source, distributed source, and others. The open boundary is usually set at the upstream and downstream free ends of the model domain. When selecting the open boundary option in a boundary description cell, it is necessary to define the branch name and chainage to specify the location of the boundary. Discharge, water level, and rating curve, among others, can be specified at an open boundary. Additionally, the water level boundary can be defined at the downstream of a river boundary, water level control, and other similar locations.

In this study open inflow is given at 0(zero) chainage of Maithon and Panchet Dams. The inflow water and sediment hydrograph are prepared using discharge data and suspended sediment concentration data of Maithon and Panchet Dams, collected from River Research Institute (RRI). The downstream boundary condition is given at chainage 67 km, with specified water level data, collected from RRI (Fig. 3.8).

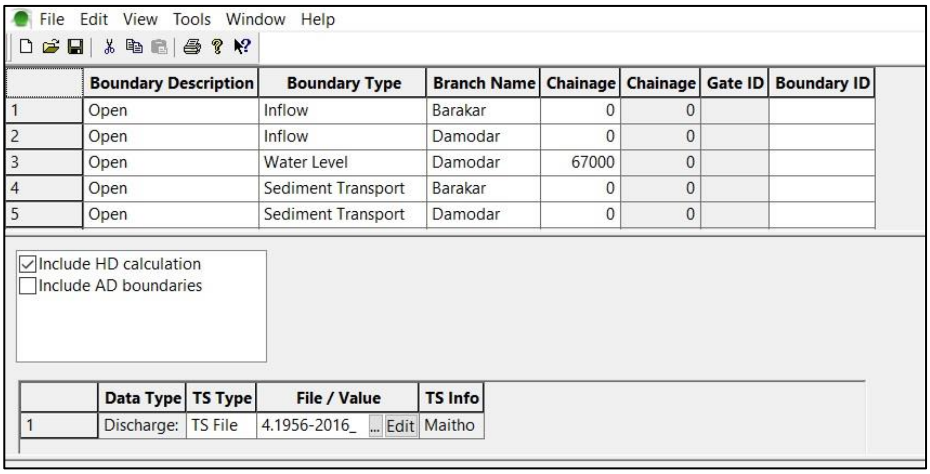


Fig. 3.9 Boundary description in MIKE 11

3.2.3.5. Hydrodynamic simulation

After setting up the model, the upstream and downstream boundaries have been energized with the water force from the dam discharges, which are ultimately a derivative of the rainfall received from basin catchment for hydrodynamic simulation.

The gridded daily rainfall data of Damodar-Barakar River basin for the year 1916 to 2016 was downloaded from the site (https://mausam.imd.gov.in) of Indian Meteorological Department (IMD), Government of India, for calculation of catchment runoff. The rain catchment area of Damodar-Barakar River basin has further divided into two sub-basins and corresponding stream length of Maithon and Panchet Dams (Table 3.1) are calculated with the help of Soil Water Assessment Tool (SWAT) and presented in Fig. 3.10.

The SWAT model is a physically based model that operates on a continuous time scale, divides the basin into sub-basin according to flow network and works on Digital Elevation Model (DEM), land use, soil and weather data.

Table 3.1 Details of the Maithon and Panchet dams

Details	Maithon	Panchet
Area (Sq Km)	6185	10500
Reach length (Km)	234	268.75

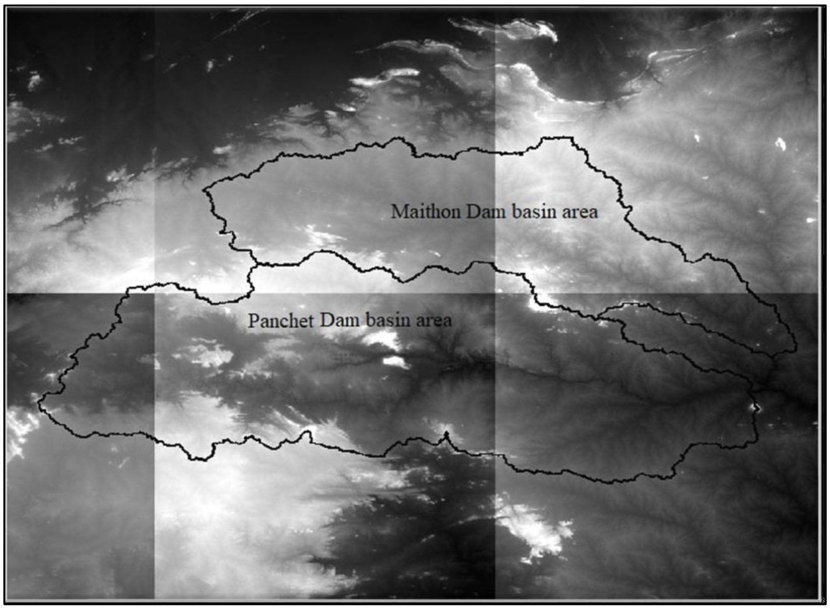


Fig. 3.10 Rain catchment area of Damodar-Barakar River basin delineated as two sub-basins (at Maithon and Panchet dams location) through SWAT model

The rainfall data for a period of last 100 years have been analyzed and it is observed that the monsoon period in the basins starts in the first week of June and continues up to October. The total annual rainfall thus counts for this monsoon period is about 90 days which causes dam discharges for about 60 days from both Maithon and Panchet dams. Monthly average rainfall including Standard Deviation (SD) as observed in the last 100 years (1916 to 2016) have been calculated and presented in Fig. 3.11.

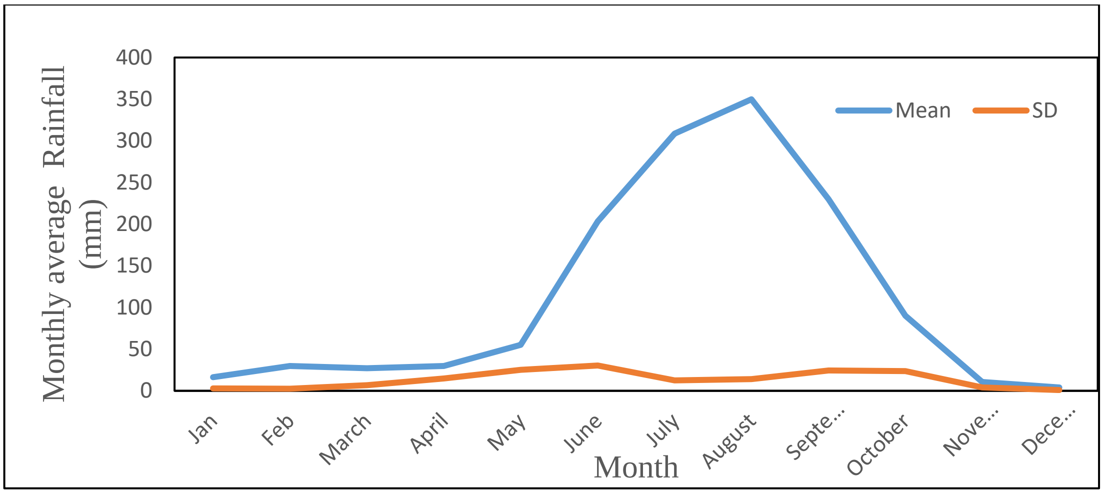


Fig. 3.11 Monthly average rainfall of Damodar-Barakar River basin for last 100 years (1916-2016)

The discharge data of both the dams were available only for the period of 2009-2018 from the corresponding Authority. To prepare a time-series discharge data for the entire period of model simulation, the above available rainfall data and corresponding combined dam discharges have been correlated with standard statistical methods and presented in Fig. 3.12.

In the process, the daily dam discharge data of both the dams and daily rainfall data of both the sub-basins are converted into combined cumulative discharges and cumulative rainfall respectively. From these two cumulative series a correlation has been established which follows an equation (Eq. 3.5)

$$i = 0.498j^{0.9632} \qquad (3.5)$$

with $R^2 = 0.9469$, where, i = cumulative rainfall and j = cumulative discharge. This equation has been used to calculate dam discharges during the entire study period.

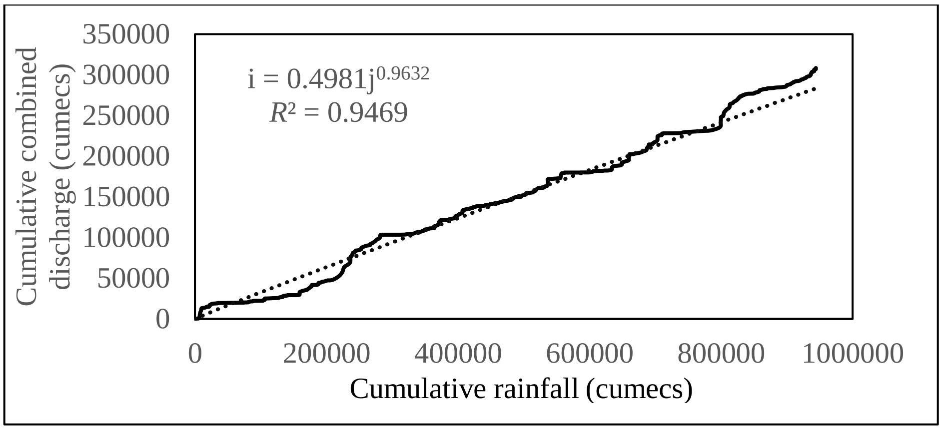


Fig. 3.12 Relation between Cumulative combined discharge and Cumulative rainfall

Combined rainfall and Combined Dam discharge of 10 years have been correlated to generate an equation to combined discharge with available combined rainfall data. The observed rainfall of the 1961, in Maithon and Panchet catchment Basin have been compared and plotted in Fig. 3.13. Typical plots of observed inflow, outflow and water level data of Maithon and Panchet dam during the monsoon period of 2016 are shown in Fig. 3.14 (a) and Fig. 3.14 (b). Now, from the available discharge data it has been observed that the ratio of outflow of Maithon Dam and Panchet Dam is 1:3. So the calculated combined discharge data has been distributed maintaining this ratio. Fig 3.15 represents the graph of Maithon and Panchet outflow monsoon period (June 2016 to October 2016).

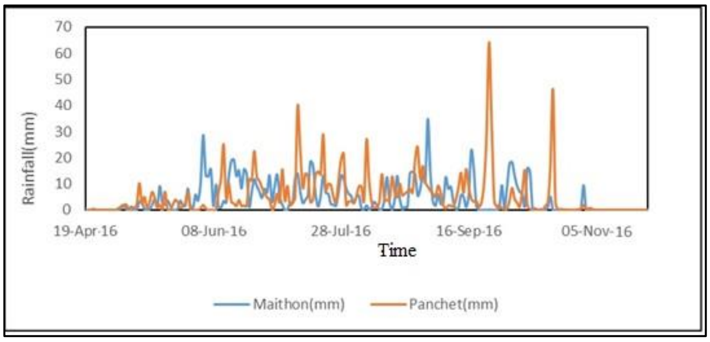
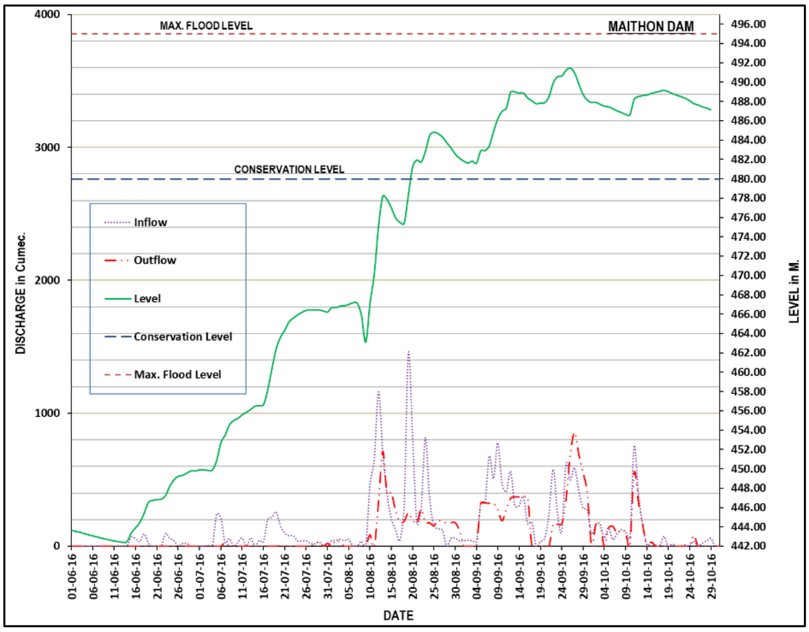
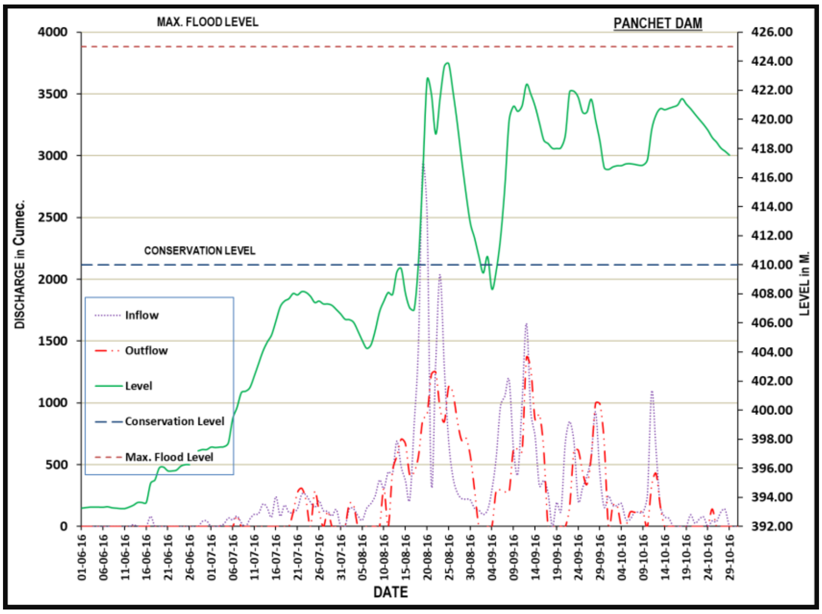


Fig. 3.13 Observed rainfall of Maithon and Panchet Basin



(a) Maithon Dam



(b) Panchet Dam

Fig. 3.14 Hydrograph of Maithan and Panchet dams respectively of the monsoon year 2016

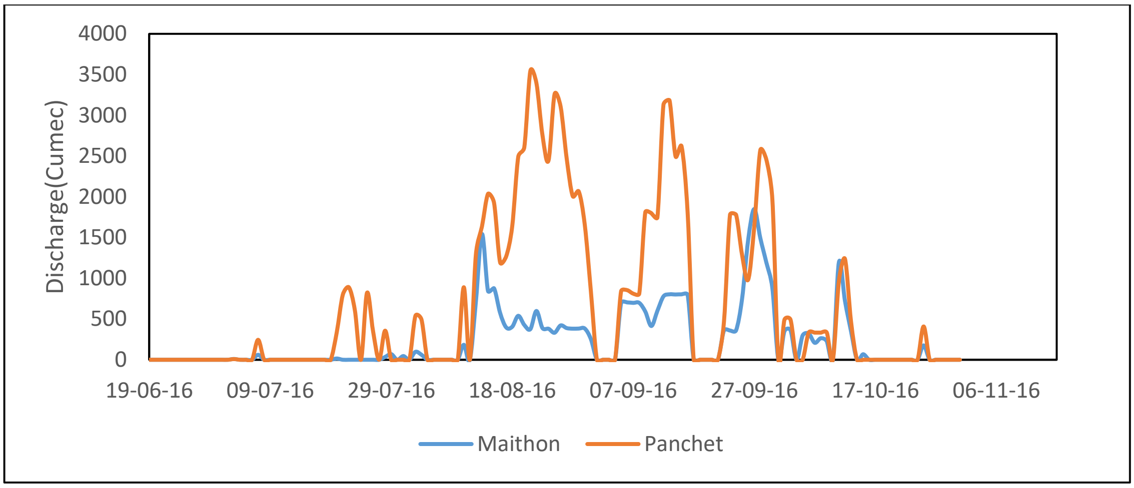


Fig. 3.15 Outflow hydrograph of Maithon and Panchet Dam

3.2.3.6 Sediment transport simulation

The river-bed soil sample and water sample were collected from the Damodar river near Raniganj and in the pond area to ascertain grain size analysis (Fig. 3.16) and suspended sediment concentration (SSC) respectively. The grain size analysis depicts that the average diameter of the bed sediment (d_{50}) is 0.34 mm having d_{10} = 0.12 mm and d_{90} = 0.43 mm respectively.

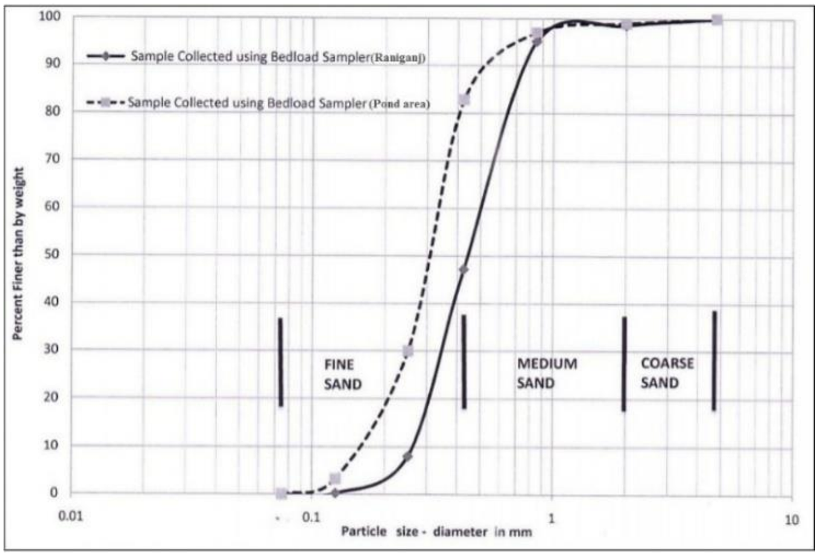


Fig. 3.16 Grain size distribution of river bed sediment (average d_{50}=0.34mm)

The water samples collected from different locations (Bokaro, Dishergarh, Raniganj and Durgapur) of Damodar River, in different season throughout the year were analyzed in the laboratory for determination of suspended sediment concentration (SSC) of river-water. The SSC values have been plotted against the corresponding upstream discharge and presented in Fig. 3.17. From the Fig. 3.17, it is evident that the seasonal SSC, in general, increases linearly with the increase in upstream discharge which was judiciously used in model analysis. Further, from Fig. 3.18, it is also observed that the value of suspended sediment concentration increases during monsoon and reduces during the lean season.

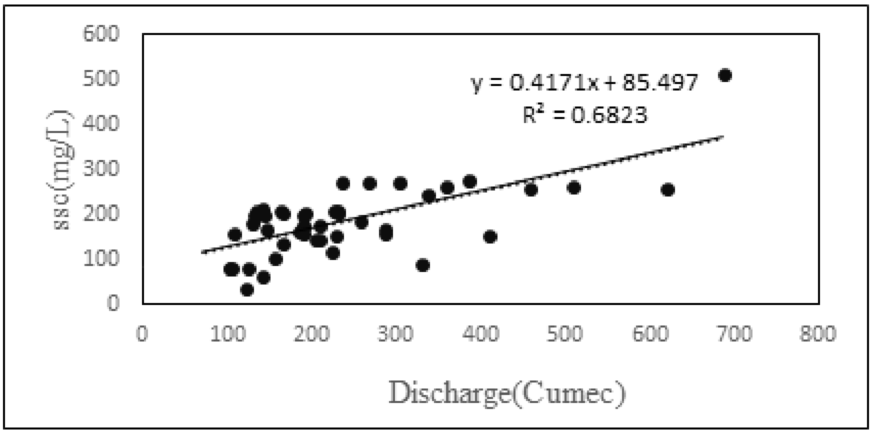


Fig. 3.17 Variation of suspended sediment concentration (SSC) with discharge of the River Damodar measured at Bokaro, Dishergarh, Raniganj and Durgapur

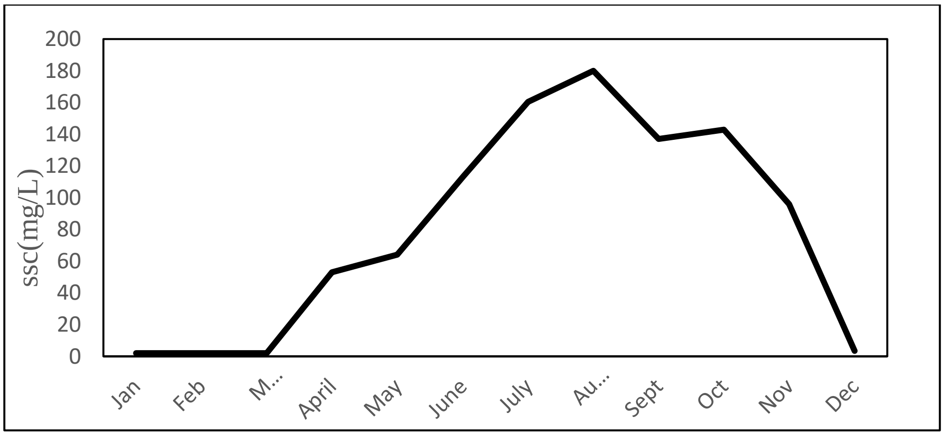


Fig. 3.18 Seasonal suspended sediment concentration (SSC) of Damodar (measured at Bokaro)

3.3. CALIBRATION AND VALIDATION OF MODEL

The hydrodynamic and sediment transport model for morphodynamical analysis was simulated from the year 1956 to 2016. Daily discharge data of the Maithon Dam and the Panchet Dam were used as input in the upstream boundary condition of the model. Similarly, variable water level data, as recorded in the gauge station situated 1 km downstream of Durgapur Barrage, caused by corresponding scheduled gate opening was used in downstream boundary conditions of the model. When any dam releases water, the discharge passes through two notable Gauge Stations. These stations are located at Raniganj town at the river-chainage 42 km and at Left Canal Diversion point at river-chainage 65.5 km in the river Damodar. After providing all boundary data and other constant parameters required for specific empirical equations as mentioned earlier, the model was simulated for the desired period. At this juncture, to evaluate its efficacy and accuracy, the model results were verified and accordingly, calibrations were done as follows:

3.3.1 Hydrodynamic calibration

Manning's coefficient of roughness (n) was used as a model calibration parameter for hydrodynamic calculation. In the initial stage, approximations for the Manning's coefficient of roughness (n) = 0.033 for the river Damodar were taken from available literature (IS Code 2912 1999). However, for the present study 'n' value was varied from 0.0294 to 0.04 during the model calibration. In MIKE 11 software Manning's number, N, is taken as $1/n$. The model was then simulated for different Manning's coefficient (n) and the output as water elevations were extracted from the result files. These extracted values (Model predicted values) and corresponding observed values measured at Chainage 61.5 km (at Pond Area) and at Chainage 42 km (Raniganj gauge station) for three different dates 1st Aug 2016,8th Aug 2016 and 16th Aug 2016 have been compared and provided in Table 3.2 and Table 3.3.

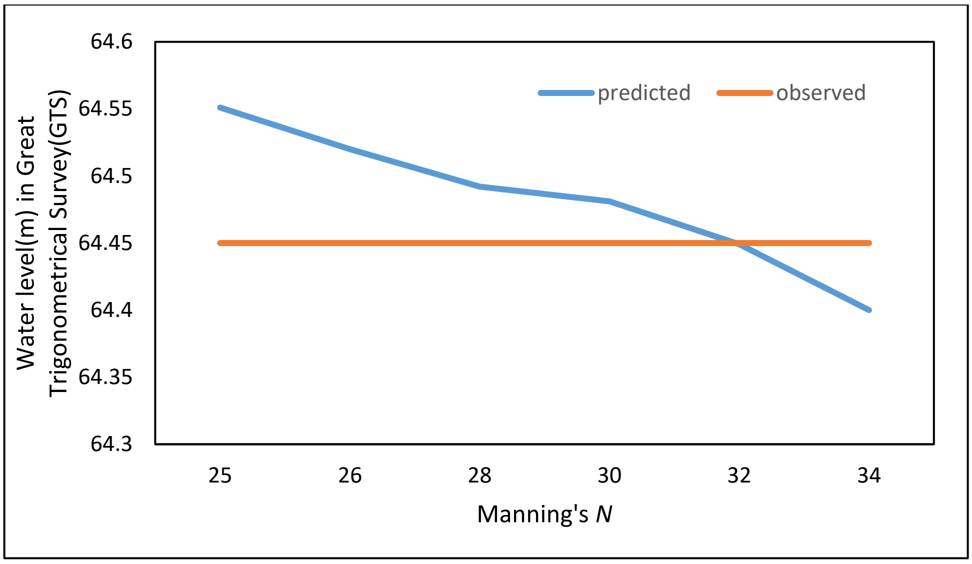
A pictorial graph of the same for Raniganj and Pond Area Gauge stations has also been presented in Fig. 3.18.

Table.3.2. Surface water elevation at Pond Area on different dates(Chainage: 61.5 km)

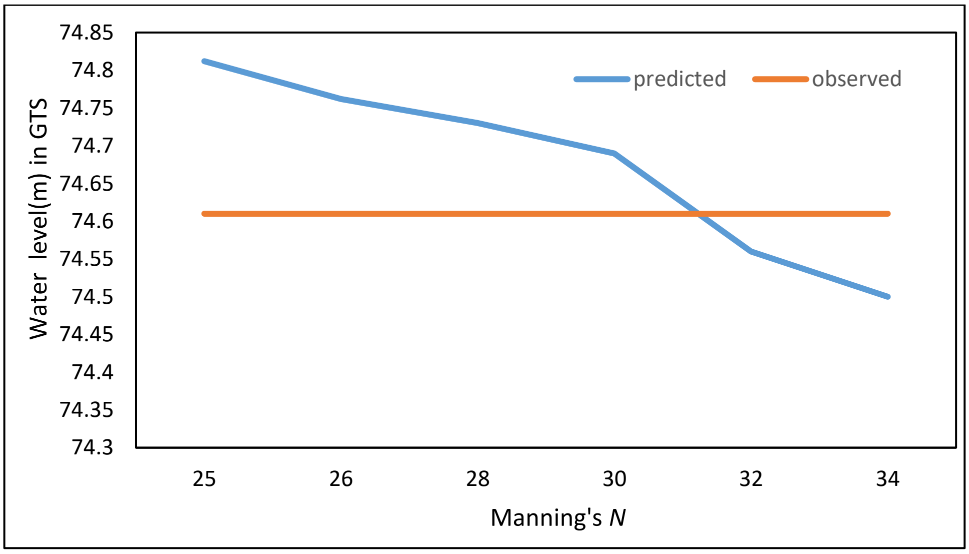
<table>
<tr><th rowspan="2">Date</th><th rowspan="2">Manning’s n</th><th rowspan="2">MIKE used Manning’s (N) =1/n</th><th colspan="2">Surface water elevation in m</th></tr>
<tr><th>Model predicted</th><th>Observed value</th></tr>
<tr><td rowspan="6">01-Aug-2016</td><td>0.0294</td><td>34</td><td>64.42</td><td rowspan="6">64.48</td></tr>
<tr><td>0.03125</td><td>32</td><td>64.472</td></tr>
<tr><td>0.033</td><td>30</td><td>64.496</td></tr>
<tr><td>0.0357</td><td>28</td><td>64.51</td></tr>
<tr><td>0.038</td><td>26</td><td>64.54</td></tr>
<tr><td>0.04</td><td>25</td><td>64.57</td></tr>
<tr><td rowspan="6">08-Aug-2016</td><td>0.0294</td><td>34</td><td>64.4</td><td rowspan="6">64.45</td></tr>
<tr><td>0.03125</td><td>32</td><td>64.449</td></tr>
<tr><td>0.033</td><td>30</td><td>64.481</td></tr>
<tr><td>0.0357</td><td>28</td><td>64.492</td></tr>
<tr><td>0.038</td><td>26</td><td>64.52</td></tr>
<tr><td>0.04</td><td>25</td><td>64.551</td></tr>
<tr><td rowspan="6">16-Aug-2016</td><td>0.0294</td><td>34</td><td>64.41</td><td rowspan="6">64.46</td></tr>
<tr><td>0.03125</td><td>32</td><td>64.44</td></tr>
<tr><td>0.033</td><td>30</td><td>64.521</td></tr>
<tr><td>0.0357</td><td>28</td><td>64.531</td></tr>
<tr><td>0.038</td><td>26</td><td>64.562</td></tr>
<tr><td>0.04</td><td>25</td><td>64.57</td></tr>
</table>

Table.3.3 Surface water elevation at Raniganj Gauge station on different dates (Chainage: 42km)

Date	Manning's n	MIKE used Manning's $(N)=1/n$	Surface water elevation in m	
			Model predicted	Observed value
01-Aug-2016	0.0294	34	74.465	74.55
	0.03125	32	*74.58*	
	0.033	30	74.62	
	0.0357	28	74.67	
	0.038	26	74.78	
	0.04	25	74.8	
08-Aug-2016	0.0294	34	74.5	74.61
	0.03125	32	*74.56*	
	0.033	30	74.69	
	0.0357	28	74.73	
	0.038	26	74.762	
	0.04	25	74.812	
16-Aug-2016	0.0294	34	74.585	74.69
	0.03125	32	*74.63*	
	0.033	30	74.76	
	0.0357	28	74.83	
	0.038	26	74.872	
	0.04	25	74.9	



(a) At cross section 61.5 km



(b) At cross section 42 km

Fig. 3.19: Variation of water level with varying manning's number '*N*' on 08-Aug-2016 (a) At cross section 61.5km (b) At cross section 42km

Finally, by comparing the simulated results with the observed values, Mannings's number *N* (= $1/n$) was fixed at 32 and used for simulation. On the other hand, the activity of the model has also been validated by another set of observed water level data.

3.3.2 Hydrodynamic Validation

The model was validated with the observed water level data of the pond area at chainage 65 km during the period from 25-Aug-2016 to 18-Sept-2016 (25 days). The results as predicted by model and the observed values are plotted in Fig.3.20. Using these data the coefficient of determination(R^2), The Nash–Sutcliffe model efficiency coefficient (NSE) and sum of squares error (SSE) are found to be 0.9172, 0.934 and 0.046 respectively. It may be seen that *R*2 is close to 1, NSE > 0.5 and SSE close to 0 which indicate the model with manning's number 32 would work satisfactorily.

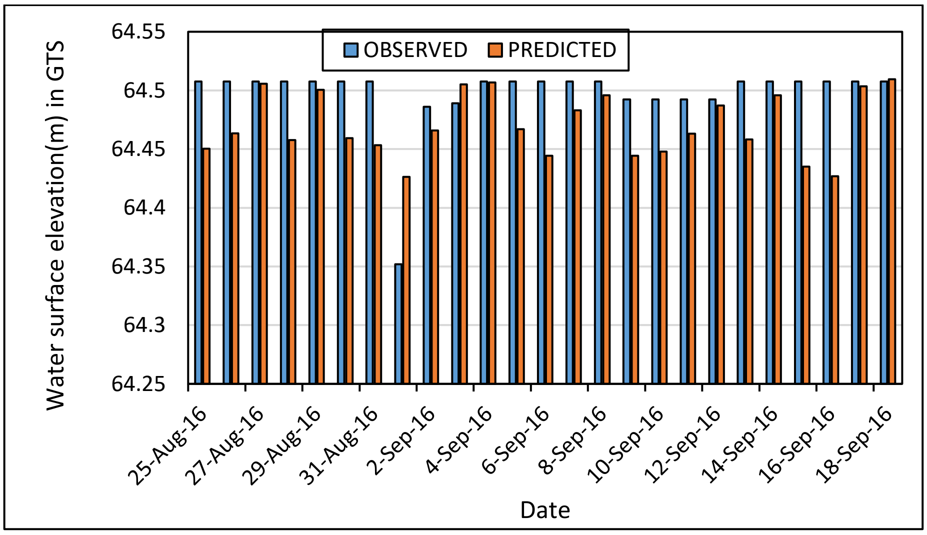


Fig. 3.20 Observed and simulated surface water elevation at Durgapur Barrage Pond

3.3.3 Sediment transport model calibration and validation

In the present study, the sediment transport equation proposed by Ackers and White (1973) was employed for determining the morphological changes of the study domain. For this purpose, a preliminary study was conducted using different sediment transport model, e.g., Ackers and White (1973), Engelund and Hansen (1967) and Van Rijn (1984) to evaluate bed level at Raniganj (Chainage 42 km) with the change in Manning's coefficient '*n*' on 04th Aug 1965. The results obtained are plotted in Fig. 3.21 along with the observed data and it has been found that the predicted values for Manning's '*n'* of 0.0312 using Ackers and White (1973) is close to the observed data and so, it was decided to use this model for sediment transport study in the present analysis.

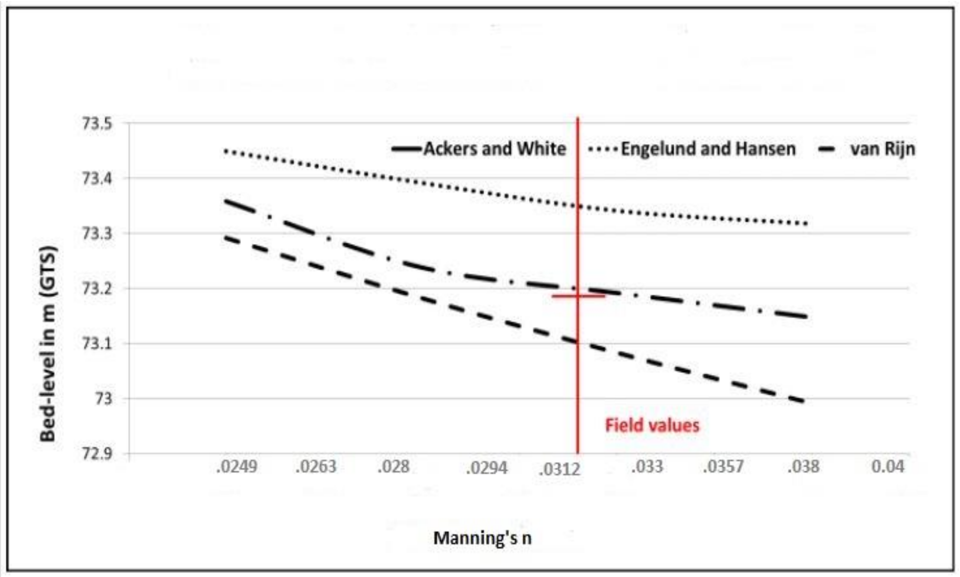


Fig. 3.21 Morphological calibration

The sediment transport model was calibrated with two dependable variables, cross-sectional areas of three different Chainages and volumetric cubic capacity of the Barrage Pond. Variations of cross-sectional area of the model at chainage 61.5 km, 62 km and 63.5 km in the pond area on 4th Aug 1965 have been plotted for different Manning's number (N) along with the observed (surveyed) cross section area (Fig.3.22.) and (Table 3.4). It is found that the cross-sectional areas as predicted by a model with Manning's number, $N = 32$, are in close proximity with the observed data. Corresponding observed and predicted values of cross-sectional areas and pond volume have been shown in Table 3.5 along with corresponding values of R^2, NSE and SSE.

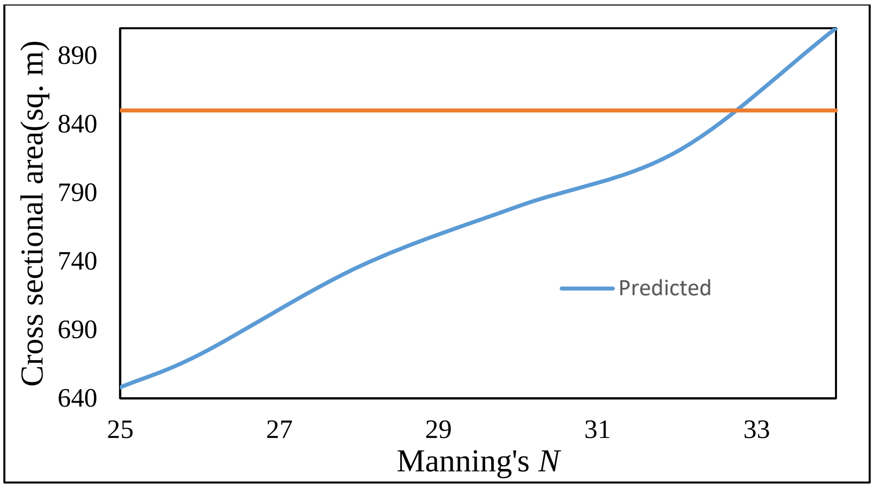


Fig. 3.22 Cross-sectional area with varying manning's number '*N*' at Chainage 61.5 km

Table-3.4. Calibration of sediment transport model

Date	Cross-Sectional Area (sq. m)			Pond Capacity (MCM), year 1965	
4th Aug 1965	Chainage in km	Simulated	Observed	Simulated	Observed
	61.5	850	937	9.45	9.1
	62	1945	1821		
	63	3364	3099		

A model performance has been evaluated through testing of the corresponding values of R^2, NSE and SSE, which are found to be 0.969, 0.942 and 0.02 respectively.

Validation

The above calibrated sediment transport model was validated by another set of observed data. The cross-sectional area at Raniganj gauge station (chainage 42 km) and the Pond capacity of Durgapur Barrage (Chanage 60km to chainage 66km) were observed on 08th Aug 2016.(Table 3.5) These values were compared with the extracted values from model result files on the same date and tabulated.Corresponding magnitude of R^2, NSE and SSE shows a good agreement of 0.98, 0.961 and 0.09 respectively. Thus, the calibrated sediment transport model was simulated for the whole study period to assess morphological changes of the river.

Table3.5. Comparison of validation parameters (Cross-sectional area and Pond capacity) for sediment transport simulation

Date	Cross-Sectional Area (sq.m)			Pond Capacity (Million Cubic Meter) (MCM), year 1965	
	Chainage in km	Simulated	Observed	Simulated	Observed
4thAug1965	42 64 64.5 65	4442 1248 1680 1997	4329 1300 1550 1850	6.32	6.05

3.4. METHODOLOGY OF FLUSHING:

An alternative method of sediment removal was employed through application of Flushing technique. In this method, an extra impetus is applied by the onslaught of large discharge released from Dams to the river bed. A model simulation was conducted to assess the impact of flushing just at the beginning of monsoon for a period of consecutive 15 days depending upon the expected arrival of monsoon, During this period a reasonably higher discharge was passed through the barrage gates corresponding to the hydrograph shown in Fig 3.23 In order to flush-out the deposited sediment from the pond area approximately 4000 Cumec discharge was released for a period of two days with gradually increasing discharge on 8^{th} day, thereafter reducing gradually following an approximate sine curve. To prepare a synthetic hydrograph (Fig.3.23), a number of trials were made with different combination. In present condition it has been observed that 4000 Cumec of discharge is available in most of the flood period during monsoon months as shown in Fig. 3.15. So flushing hydrograph was prepared considering peak flow of 4000 Cumec. Depending upon the capacity of the dam reservoirs one third of the discharge during flushing has been taken from Maithon and rest from Panchet.

Another flushing hydrograph (Fig 3.24) with constant discharge of 4000 Cumec for 4 days for both pressure and empty flushing condition, has been examined to show its performance with respect to that of gradually varying one. Fig 3.25 represents the inflow hydrograph of Durgapur Barrage where no flushing discharge hydrographs have been incorporated. Fig. 3.25 is representing the scenario, when gradually increasing additional discharge for 15 days will be incorporated with the normal discharge of dam. And the Fig. 3.26 represented for additional 4 days constant discharge with existing normal discharge has been incorporated. Further, an attempt was also made to highlight the effectiveness of flushing in the river which has reached regime condition after 60 years of operation with variable discharge. For this purpose, bed profile in the pond area as predicted in 2026 was modified by mechanical dredging and considered to be the initial bed profile in the pond area. The model was then run for the period year 2026 – 2066 incorporating annual flushing with rectangular discharge hydrograph.

During the flushing period barrage gates were opened following the scheduled pattern. The model was then simulated accordingly for the study period 1956-2016. In this context it may be mentioned that both pressure flushing and drawdown flushing were considered. In case of pressure flushing water level in the pond was maintained at design pond level of 64.46m and at 60.00m respectively and for drawdown flushing was with empty pond (sill level 58.865m) condition.

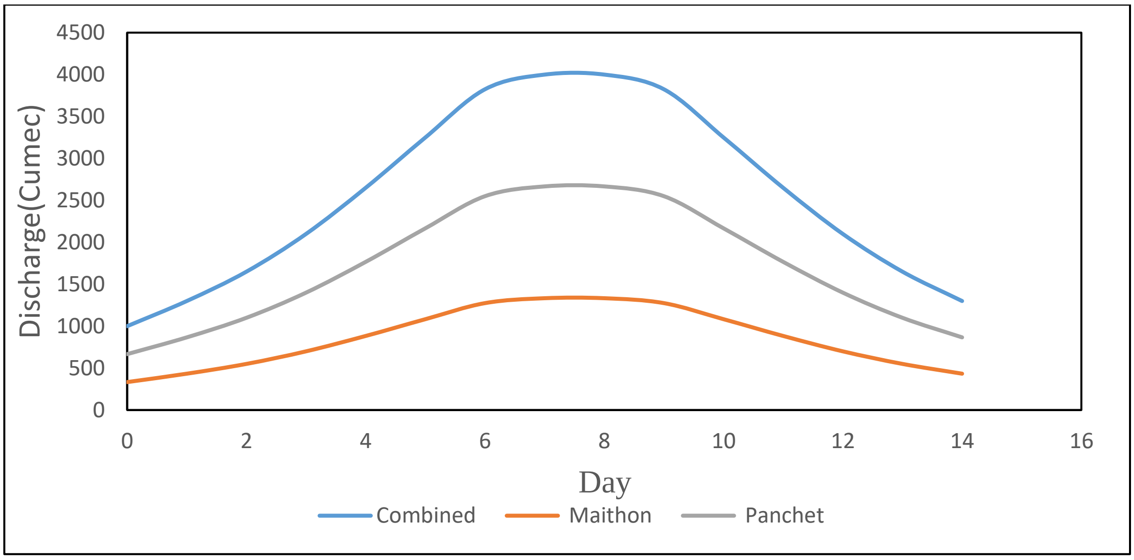


Fig. 3.23 Synthetic Combined discharge hydrograph

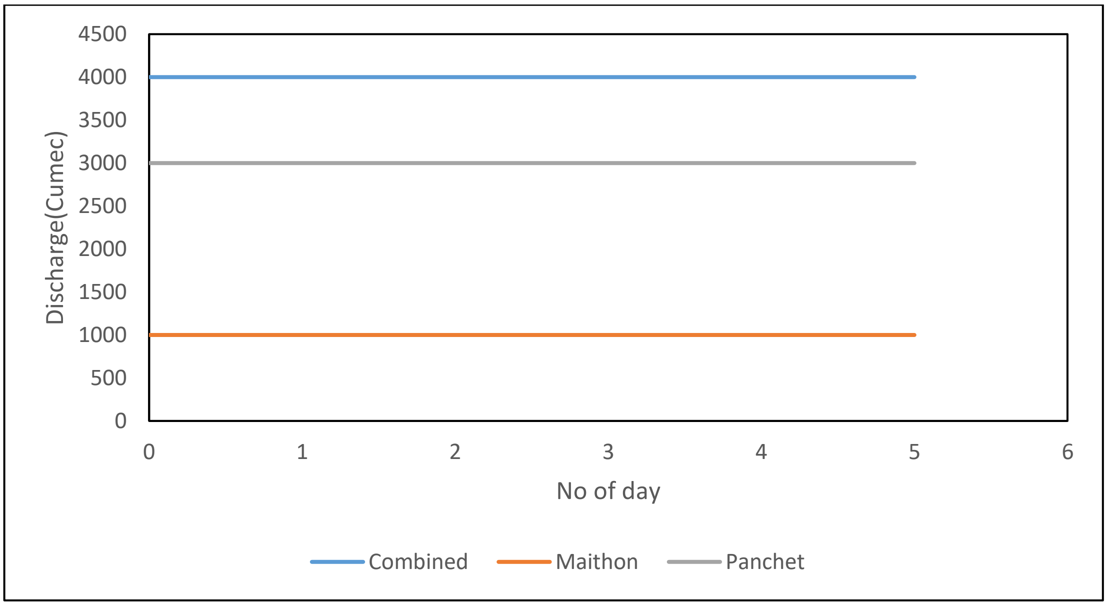


Fig. 3.24 Rectangular hydrograph for 4 days flushing

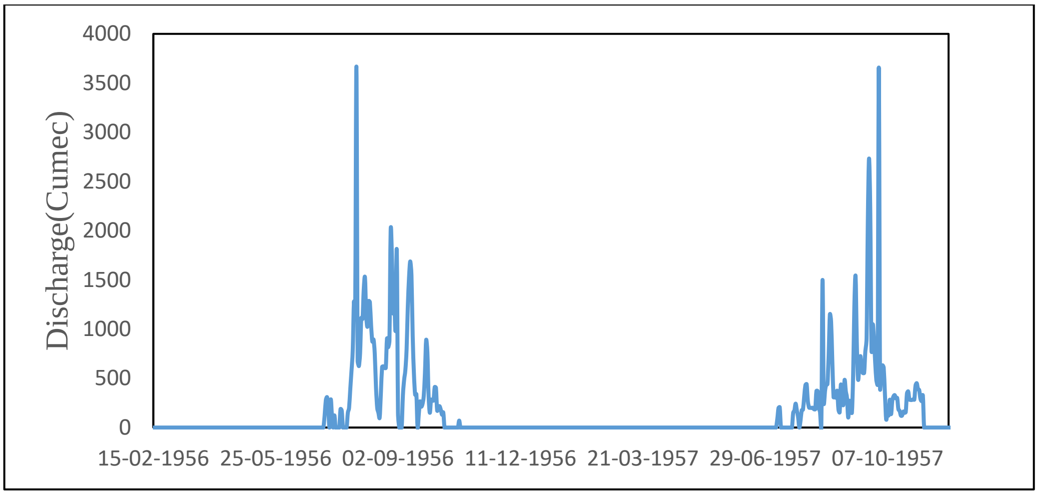


Fig. 3.25 Discharge hydrograph without flushing

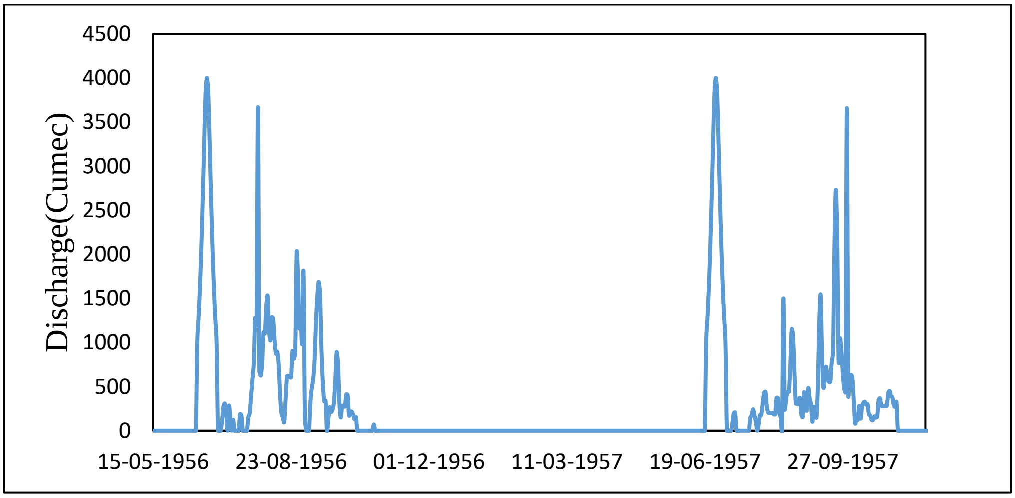


Fig. 3.26 Discharge hydrograph with flushing

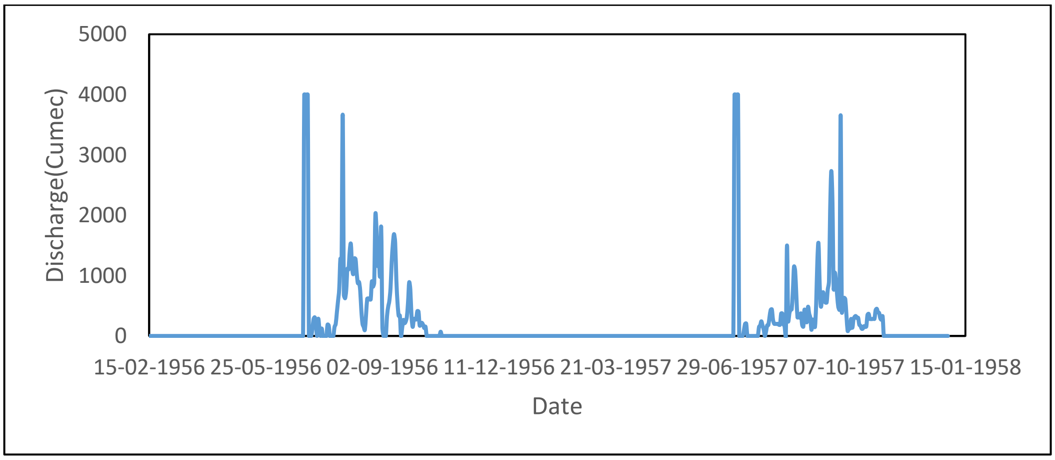


Fig.3.27 Hydrograph with constant flushing

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. GENERAL

The calibrated model, duly validated by field data, was simulated for a period of 60 years since 1956 to 2016. To understand the complex sediment transport mechanism under the combined effect of upland dam discharge and downstream barrage gate operation, outputs of the morphological model have been examined and discussed. The primary focus was to find out the temporal changes in the river-bed profile in the perspective of erosion-deposition and to highlight the depositional behavior of the river due to variable discharge which is a function of upland rainfall of the dams in the model domain during the study period of 1956 – 2056. Further, an attempt has been made to establish relations between discharge and deposition prevailing in the Damodar River system with the progress of time. Finally, some alternative method of flushing has also been indicated to enhance the capacity of the pond volume which will help in increasing the design life of the barrage pond.

4.2. HYDRODYNAMIC MODEL SIMULATION

A holistic exercise for establishing a correlation amongst the riverine parameters prevailing in the Damodar River system was done. An in-depth analytical study has been done from the simulated result files generated in model experiment. The discharge hydrograph of the year 1960 and corresponding longitudinal profile of water surface elevation of Damodar River have been extracted from the simulated result file and presented in Fig. 4.1 and Fig. 4.2. The tendency and behavioral pattern of fluctuating water level in tandem with velocity variation have been studied in synchronous with varying dam discharges. Accordingly, the variation of velocity in the river stretch including the pond area and variation of velocity at different chainages for the year 1960 has been presented in Fig. 4.3. The interpreted information from these figures suggests that there are two distinctive zone within the river stretch as marked as upstream zone and downstream zone divided by the Chainage 64 km. Though the upstream zone is very sensitive to variable discharge, the downstream is almost non-responsive to discharge variation, as beyond Chainage 64 km there is practically no change in water profile with the variation in discharge. In the upstream of 64 km Chainage, water depth (*h*) and velocity (*v*) is directly proportional to discharge (*Q*) and that the ratio between them always stays the same. The maximum velocity as predicted by model was in the order of 1.5 m/sec in the upstream zone, whereas in the downstream (in the pond area), it never exceeds beyond 0.5 m/sec (Fig. 4.4 to Fig. 4.8).

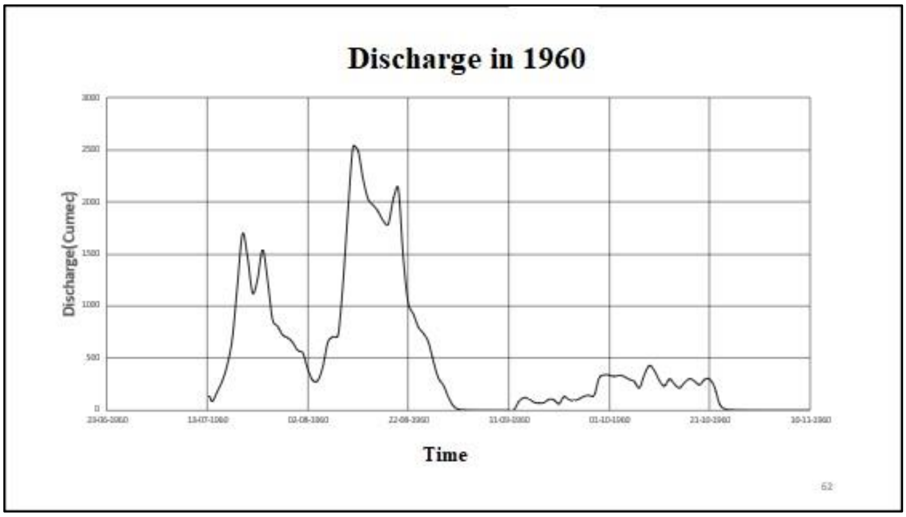


Fig.4.1 Variation of discharge with time for the year 1960

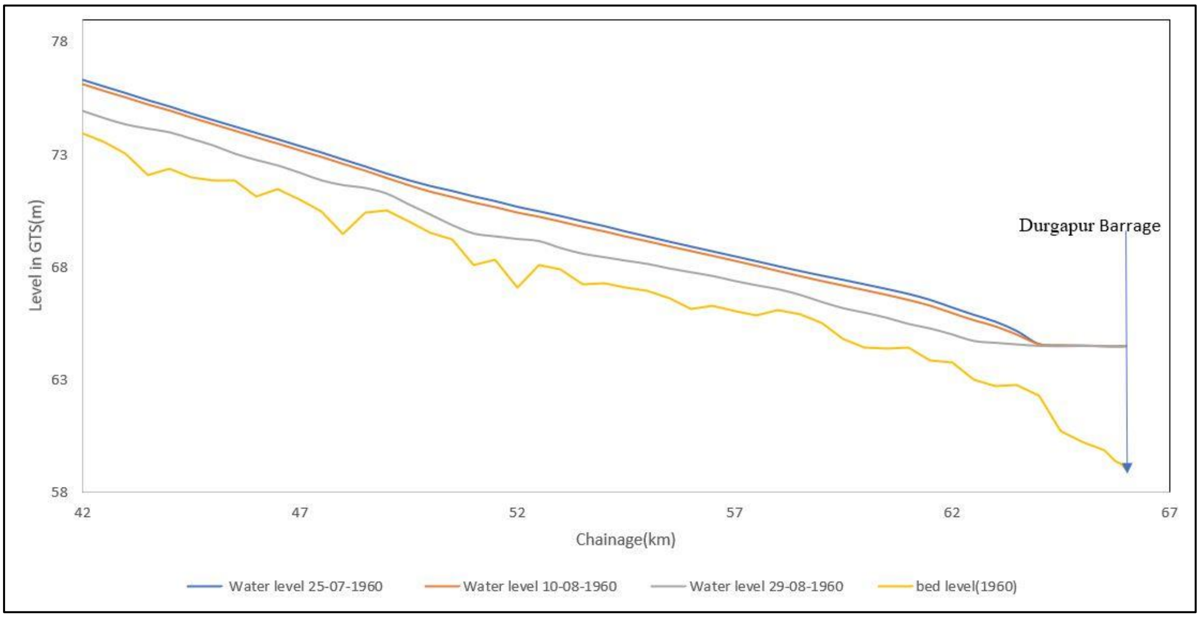


Fig.4.2 Longitudinal profile of water level for different discharge in the year1960

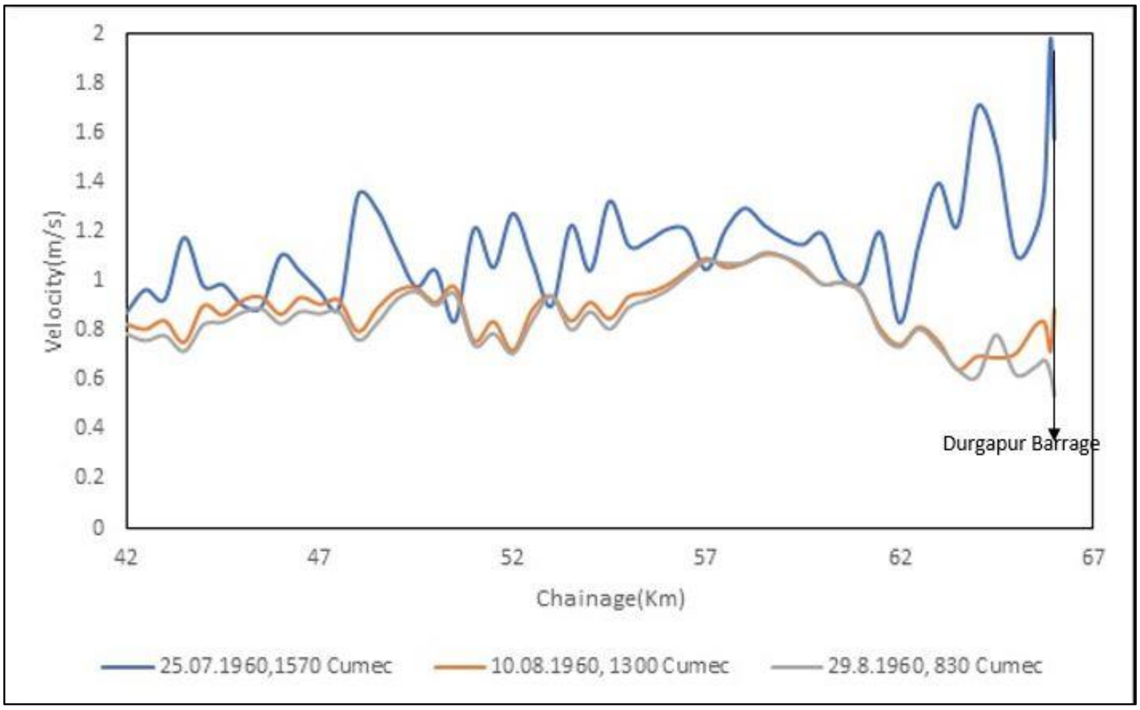


Fig.4.3 Spatial variation of average velocity for different discharge during the year 1960

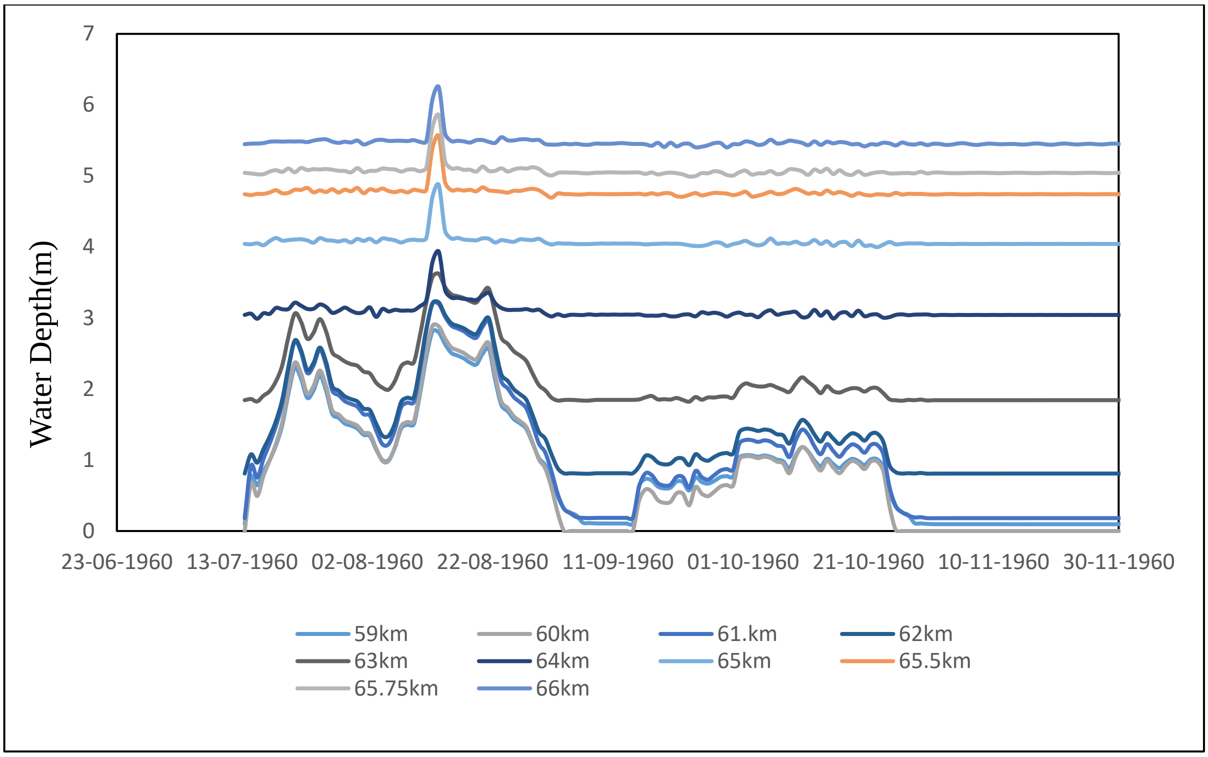


Fig. 4.4 Variation of water depth at different chainages in pond area in the year 1960

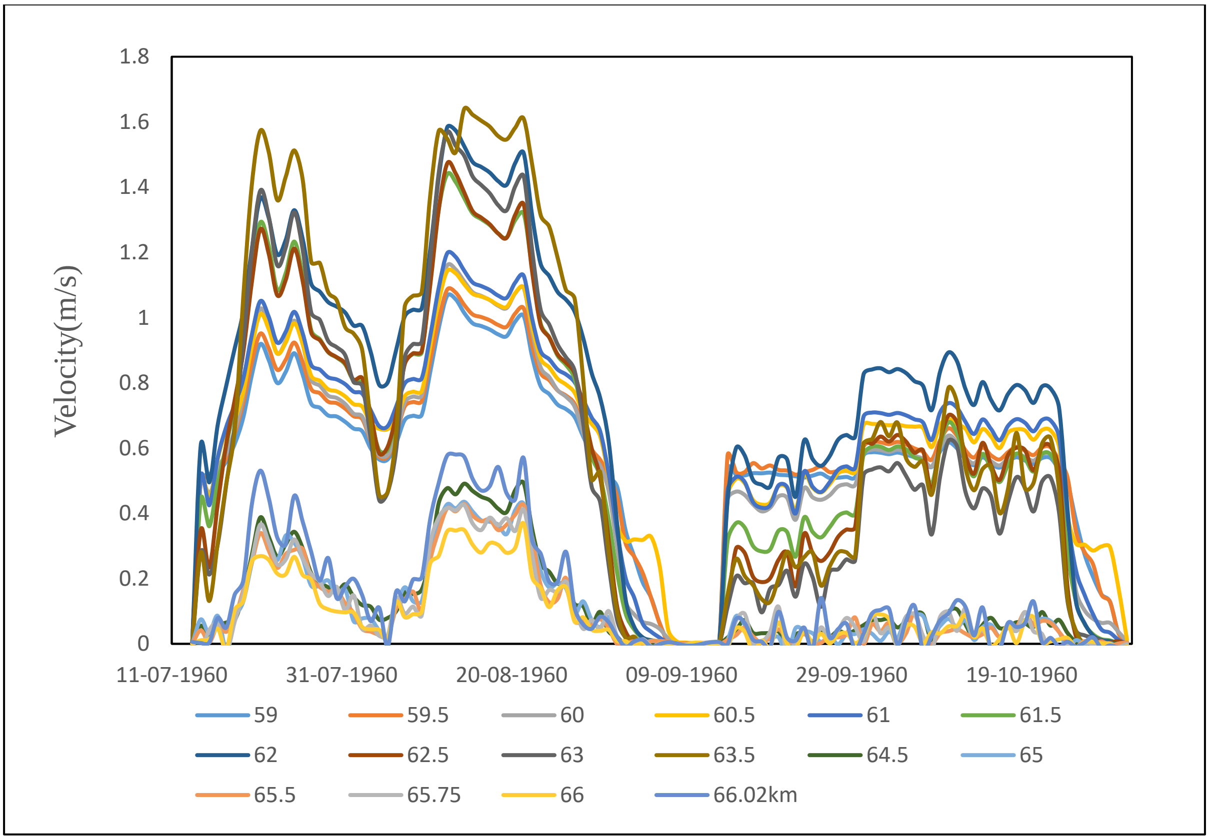


Fig. 4.5 Variation of velocity at different chainages in pond area in the year 1960

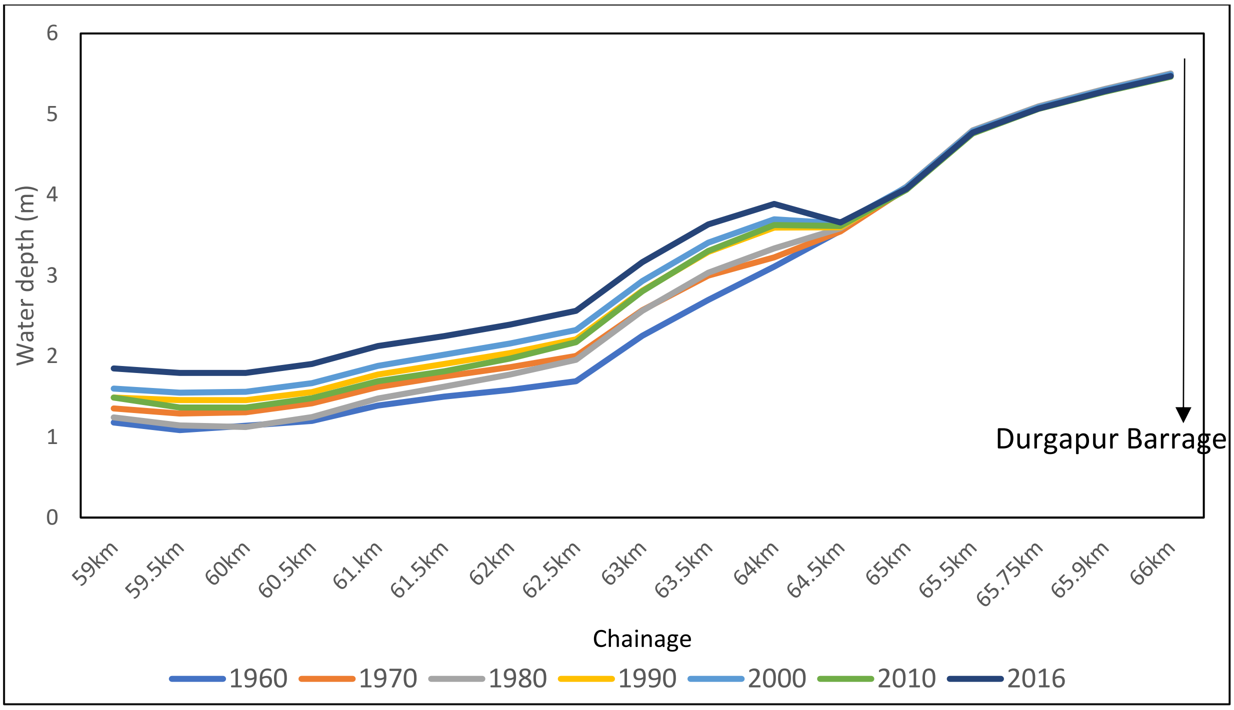


Fig.4.6 Average water depth in pond area

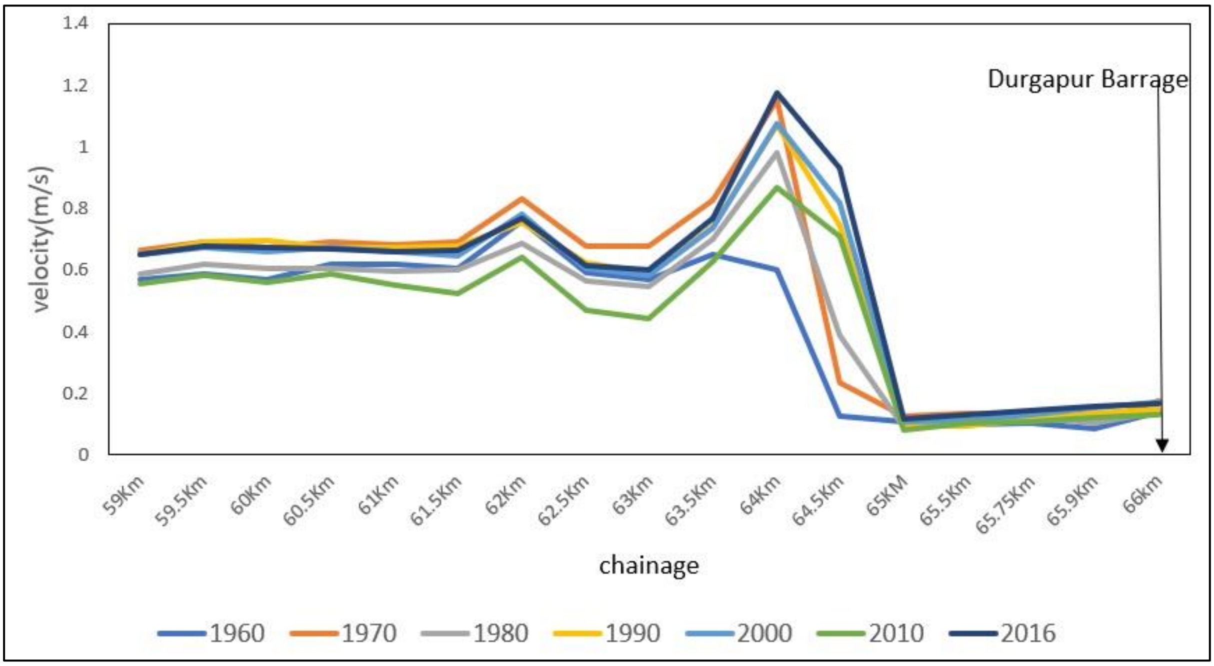


Fig. 4.7 Average velocity profile in pond area

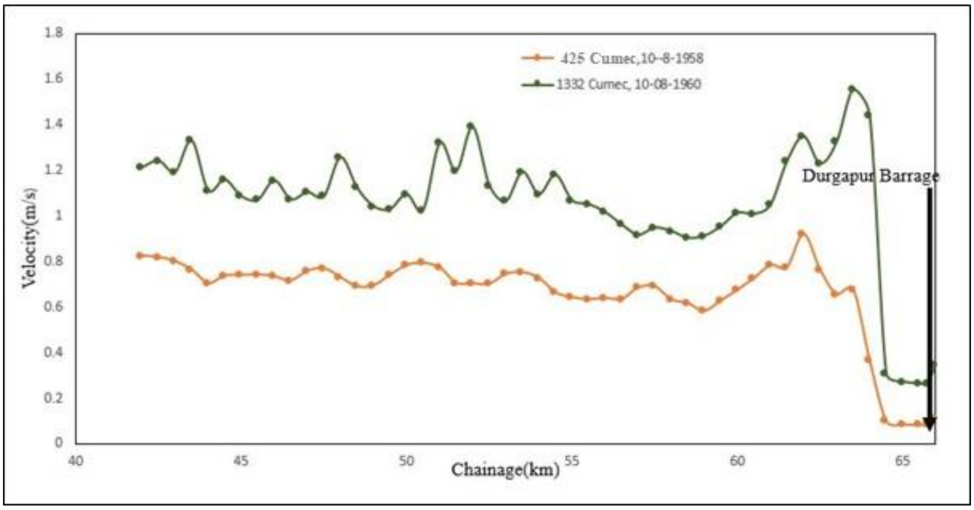
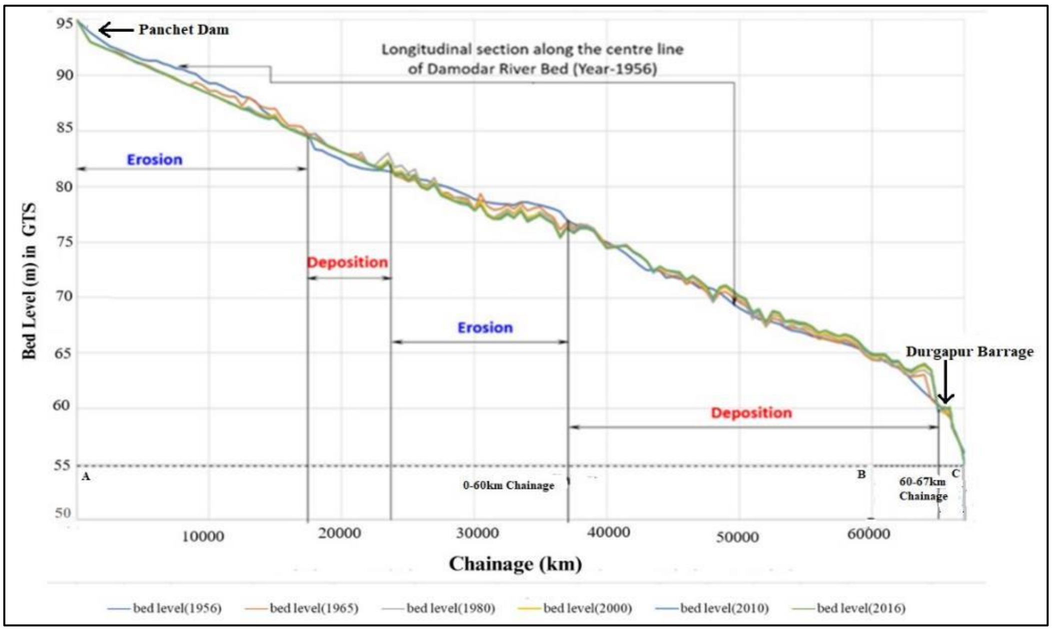


Fig.4.8 Longitudinal profile of velocity with varying discharge

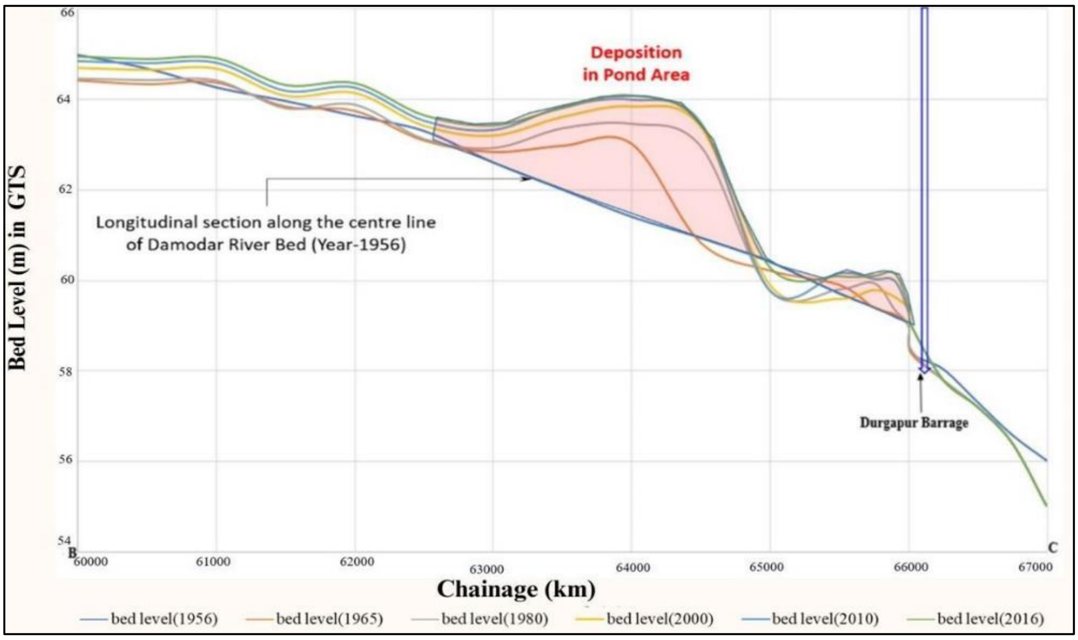
4.3. TEMPORAL CHANGES IN THE RIVER-BED PROFILE

The longitudinal river-bed profile for the years 1965, 1975, 1985, 1995, 2005 and 2016, as predicted by the model, were prepared from the result files and plotted in Fig. 4.9 . It is observed that the erosion has taken place in the upper part of the model domain (chainage-0 to 40 km) due to steep gradient and in the lower part being comparatively flatter in gradient, majority of sediment are deposited, barring a small middle portion. As concerned as the pond area, the rate of sediment deposition is very high which conforms to the global trend as reported in the literature (Fig. 2.1). A time-series sediment erosion-deposition matrix for every 10 km length of the river during every 10-year interval has been presented for better understanding of the morphological process prevailing in the river system (Table 4.1).

A closer look at the tabulated data reveals that the river bathymetry has played a pivotal role in controlling the river dynamics. In the zone of steeper gradient, as the velocity of flow increases due to gravity, bed shear stress increases, resulting in higher rate of erosion. On the contrary, in the lower part of the river stretch being flatter in gradient, deposition is observed where flow velocity has decreased gradually to a level reducing bed load movement as well as settling of suspended particles. In the pond area, bed shear stress changes with the shape of the channel being wide. And finally, stagnation of barrage pond water reduces velocity of flow and carrying capacity of the channel, causing huge deposition in the upstream of the barrage gate.



(a) Chainage from 0 to 67 km



(b) Chainage from 60 to 67 km

Fig.4.9 (a) & (b) Change in bed level (from 1956 to 2016)

Table 4.1 Calculated erosion and deposition

Chainage in km	Year						
	1956-65	1965-75	1975-85	1985-95	1995-05	2005-16	Total
	Deposition (+ve) and erosion(-ve) in (MCM)						
0-10	-1.84	-0.204	-0.018	-0.06	-0.104	-0.284	-2.51
10-20	0.282	-1.152	-0.882	0.106	-0.294	0.0238	-2.328 0.412
20-30	-0.236	0.351	0.29	-0.415	-0.258	-0.372	-1.281 0.641
30-40	-1.16	-0.547	-0.468	-0.124	-0.371	-0.277	-2.947
40-50	0.585	0.387	0.2115	0.187	0.387	0.1745	1.932
50-60	0.8	0.619	0.415	0.173	0.6	0.371	2.978
60-66 (Pond area)	2.37	0.7	0.9	0.6	0.4	0.46	5.43
Total erosion	-3.236	-1.903	-1.368	-0.599	-1.027	-0.933	-9.066
Total deposition	4.037	2.057	1.8165	1.066	1.387	1.0293	11.3928
Total erosion / total deposition	0.8	0.925	0.753	0.562	0.74	0.906	0.796
Total suspended load (input)	1.008	1.034	1.009	1.013	1.02	0.96	6.04
Total suspended load (going out through barrage gates)	0.79	0.84	0.83	0.81	0.85	0.81	4.878* (3.713**)

*as obtained from model

** calculated [erosion(9.066MCM) + input suspended load (6.04MCM)– deposition(11.3928MCM)]=3.713MCM

From the Table 2.1, it may be seen that the upper part of the model domain, below the dams outfall from 0 – 40 km chainage, has experienced erosion of 9.066 million cubic meter (MCM) and the lower part of the model domain, 40 km – 66 km chainage which is upstream of the Durgapur Barrage (Pond area) has conversely undergone deposition of 11.3928 MCM during the year 1956 - 2016. It is important to note that the sediment deposition has started immediately after commissioning of the barrage (1956) in the pond area (60 km – 66 km) due to its typical morphological characteristics, which still continues. The middle part of the river stretches in the vicinity of the Raniganj, due to its typical topographical feature, fluvial hydrodynamics, the bed slope and soil characteristics, sedimentary process in the form of erosion was much active. The above matrix of the volumetric data (Table 4.1), further, depicts that the river is trending towards its regime condition as the rate of sedimentation is reducing gradually with time, yet the saturation is still uncertain.

From erosion and sedimentation data as obtained from the numerical model study, it is observed that out of 60 years of morphological modelling during the first 10 years there was huge erosion in the upper part of the model domain which is compensated by extensive sedimentation in the lower part of the model. In the first 10-year period (1956 – 1965), deposition was about 35% of total deposition occurred during entire study period. Thereafter, rate of deposition reduces considerably and becomes in the order of 9.0% during the last 10-year period. The predicted result of our model is duly corroborated by the Technical Report of RRI, 2016 where it is mentioned that about 30% (RRI, Unpublished Technical Report, 2016) of the Durgapur Barrage Pond capacity was reduced within the first ten years after commissioning. The remaining period of next 50 years upto 2016 the model simulation shows that there is further reduction of 20% at a rate of 0.4% per year.

It is pertinent to mention here that the Damodar River system is primarily dependent on Indian tropical summer monsoon, where rainfall fluctuation and consequent variable dam discharge is dominant and records its footprints in the sediment transport behavior. Though contribution of the suspended sediment component is higher than the bed load component for a normal alluvial river, due to intervention of the barrage operation during monsoon period most of the suspended sediment could not be deposited in the pond model area and are moving out of the system through the opening of barrage gates. This is also clear from the data presented in Table 2.1, where it is seen that sedimentation generated due to transport / movement of eroded bed material in the upper reaches of the river, predominantly from 0 – 40 km chainage, is about 75% - 90% of the deposition in the stretch from 40 – 65 km chainage. The remaining part of the deposition seemed to have been generated from suspended load from the dam and / or from banks of the river. To assess again contribution of eroded bed material an attempt was made to evaluate erosion and deposition in the river without any input of suspended material. The corresponding erosion and deposition in different chainages for each 10 years period from 1956 – 2016 has been presented in Table 4.2. it is seen that contribution of eroded material in pond sedimentation is in the order of 72%. [=(8.22*100)/11.3928].

The upper part of the model domain below the dams outfall, from 0 – 40 km chainage, has experienced erosion of 9.066 MCM and the lower part of the model domain, 40 – 66 km chainage upstream of the Durgapur Barrage (Pond area), has conversely undergone deposition of 11.3928 MCM during 1956 - 2016. The pond area (60 – 66 km) sedimentation during this period was 47% of total deposition. Out of 60 years of morphological modelling during the first 10 years there was huge erosion in the upper part of the model domain which is compensated by extensive sedimentation in the lower part of the model.

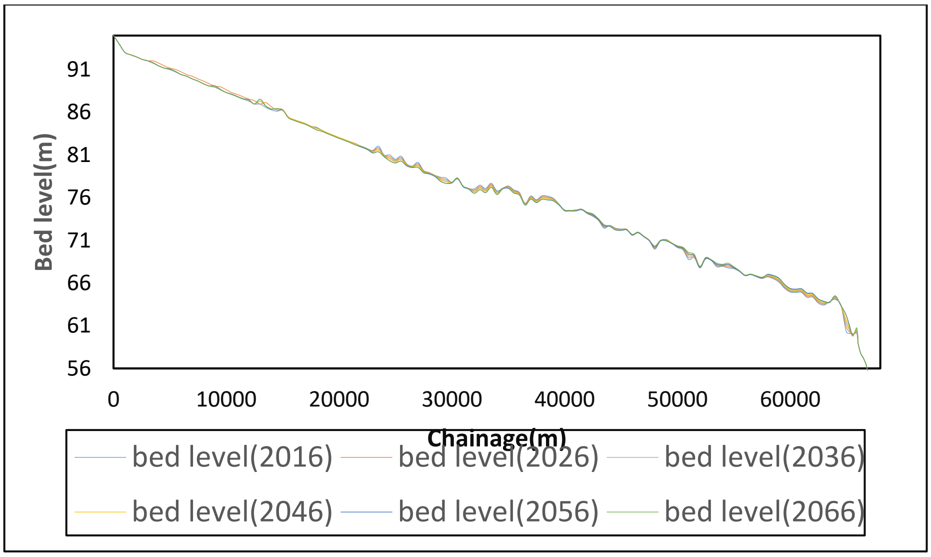
Table 4.2 Calculated erosion and deposition for no input of suspended load

Chainage in km	Year						
	1956-65	1965-75	1975-85	1985-95	1995-05	2005-16	Total
	Deposition (+) and erosion (-) (MCM)						
0-10	-1.84	-0.204	-0.118	-0.16	-0.104	-0.284	-2.71
10-20	0.020	-1.152	-0.882	0.026	-0.294	0.013	-2.269
20-30	-0.236	0.251	0.21	-0.492	-0.258	-0.372	-0.897
30-40	-1.16	-0.547	-0.468	-0.131	-0.371	-0.277	-2.954
40-50	0.405	0.321	0.105	0.062	0.296	0.129	1.319
50-60	0.542	0.453	0.206	0.103	0.264	0.245	1.813
60-66 (Pond area)	2.136	0.679	0.866	0.564	0.402	0.440	5.088
Total erosion	-3.236	-1.903	-1.468	-0.783	-1.027	-0.933	-8.83
Total deposition	3.103	1.705	1.387	0.756	0.962	0.8275	8.22
Total erosion / total deposition	1.042	1.116	1.058	1.035	1.0675	1.1274	1.0742
Total suspended load (input)(MCM)	0						
Total suspended load (going out through barrage gates)	0.139	0.133	0.129	0.141	0.136	0.144	0.82* (0.62**)

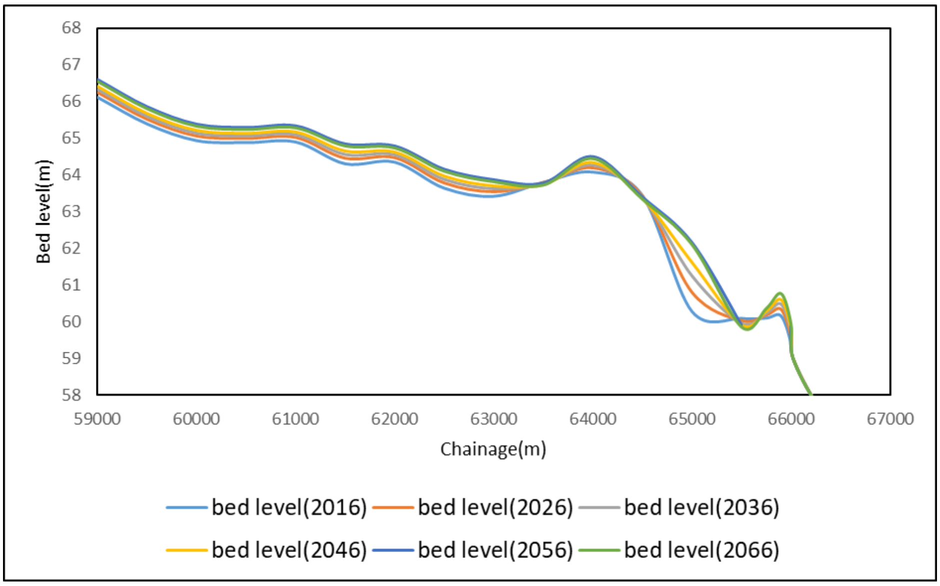
*as obtained from model

** calculated [erosion(8.83MCM) + input suspended load (0MCM)– deposition(8.22MCM)]=0.62MCM

A trend analysis of erosion and deposition for the entire model domain during the period from 2017 upto 2066 has also been done. The corresponding dam discharge has been assumed as a repetition of rainfall pattern similar to year 1967 - 2016. The change in bed level during this period for the model domain are presented in Fig. 4.10. Erosion and deposition for different stretches of the river during 10-years interval from 2016 to 2066 are presented in Table 4.3. Analysis shows that the total erosion or deposition is reducing considerably with time. Rate of deposition in the pond area is found to be 0.24 Million Cubic Meter (MCM) during the year 2046 - 2056 which is about 50% of that during year 2006 - 2016. This indicates that the whole river stretches as well as the pond area is tending towards regime condition as time progresses.



(a)Chainage from 0-67km



(b)Zoom view of Chainage 60-67km

Fig. 4.10 Change of bed level with time for the period 2016 - 2066

Table 4.3 Erosion and deposition for the period 2026-2066

Chainage in km	Year					
	2016-26	2026-36	2036-46	2046-56	2056-66	Total
	Deposition (+) and erosion(-) in Million Cubic Meter (MCM)					
0-10	-0.189	-0.217	-0.08	-0.109	-0.0954	-0.6904
10-20	-0.138	-0.057	-0.282	0.0106	0.009	-0.4574
20-30	-0.12	0.1097	-0.029	-0.141	-0.02	-0.2003
30-40	-0.26	-0.392	-0.246	-0.124	-0.138	-1.16
40-50	0.186	0.1387	0.1415	0.028	0.067	0.5612
50-60	0.32	0.149	0.415	0.103	0.129	1.116
60-66 (Pond area)	0.3219	0.293	0.227	0.24	0.18	1.2619
Total erosion	-0.707	-0.666	-0.637	-0.374	-0.253	-2.5081
Total deposition	0.8279	0.6904	0.783	0.3816	0.385	2.9391
Total erosion / total deposition	0.854	0.965	0.813	0.98	0.657	0.853
Total suspended load (input)(MCM)	1.03	1.047	1.045	0.9803	1.14	5.4431
Total suspended load (going out through barrage gates)(MCM)	0.91	1.0226	0.9	0.9727	1.08	4.8853* (5.0121**)

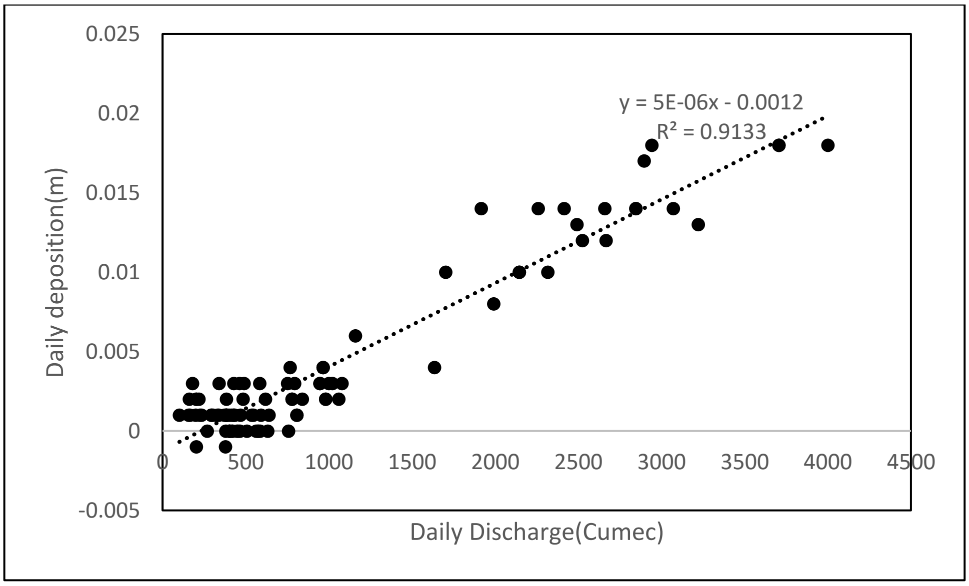
*as obtained from model

** calculated [erosion (2.5081MCM)+input suspended load(5.4431MCM) – deposition(2.9391)=5.0121MCM

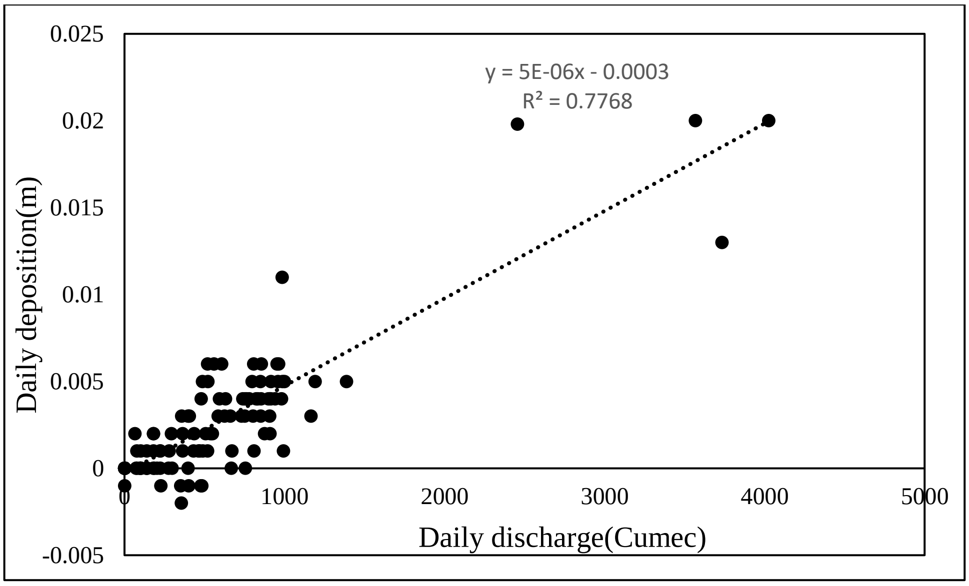
4.4 Discharge - deposition relation

River Damodar being a dam fed river its discharge is very low during dry period and depends upon the water demand of the downstream reservoir. During the monsoon period from June to November, it depends not only on the water demand but also on the upstream rainfall in the catchment area. The monsoon downpour, in general, fluctuates erratically with intensified quantity for a shorter period, resulting in inconsistent sediment transport in the river channel. This causes uneven erosion and sedimentation in the river bed.

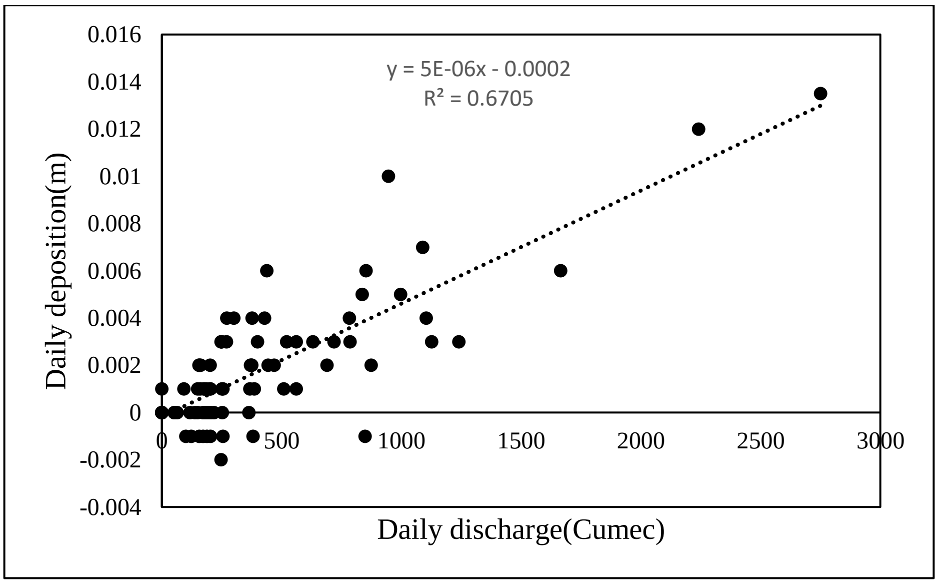
In the present study variation of daily deposition for different years 1965, 1975, 1985, 1995, 2005, 2016, 2026, 2036, 2046, 2056 and 2066 has been plotted against daily discharge in Fig. 17 along with R^2 value ranging from 0.55 to 0.91. The plots, however, shows a more or less linear trend of deposition with the increase in discharge which possibly for higher contribution of eroded bed material moving downstream. The eroded material deposited in the lower reaches of the river including the pond region as a result of reduction in flow velocity (stagnation of water in the barrage pond) as indicated in Fig. 4.11. (a to k)



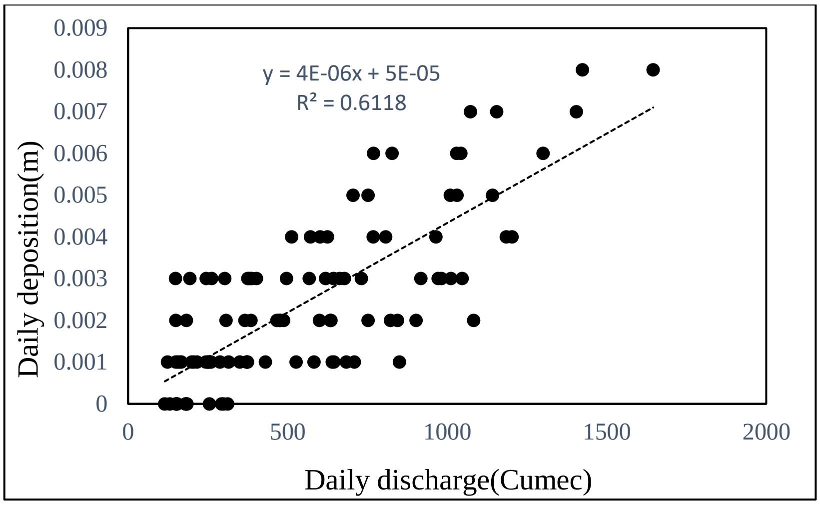
(a) Of the year 1965



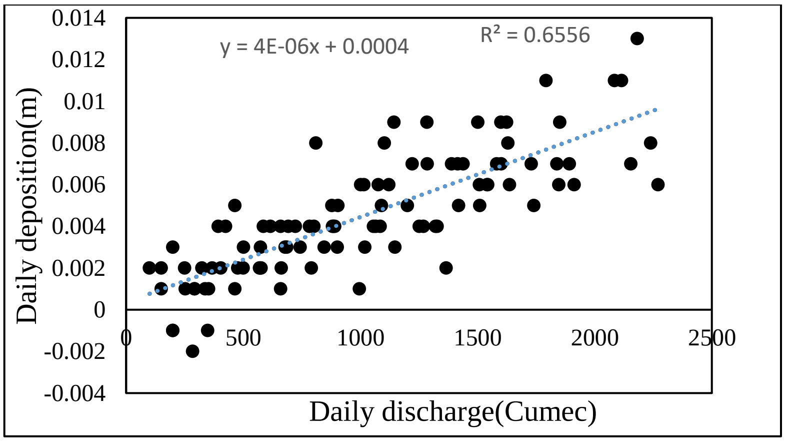
(b) Of the year 1975



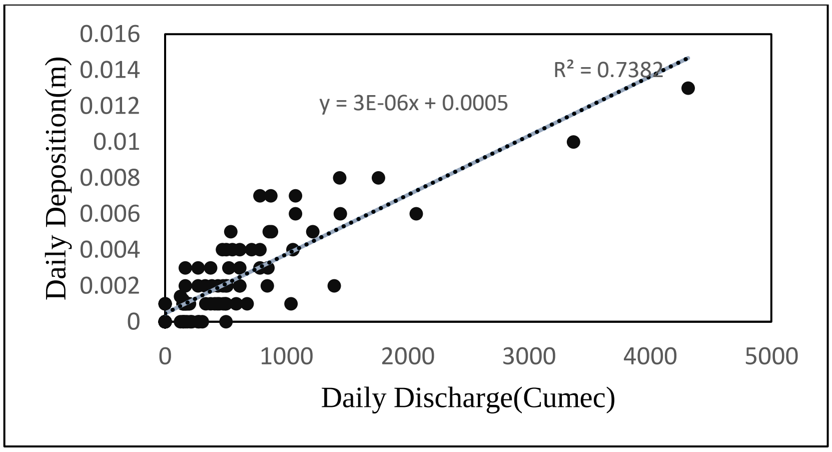
(c) Of the year 1985



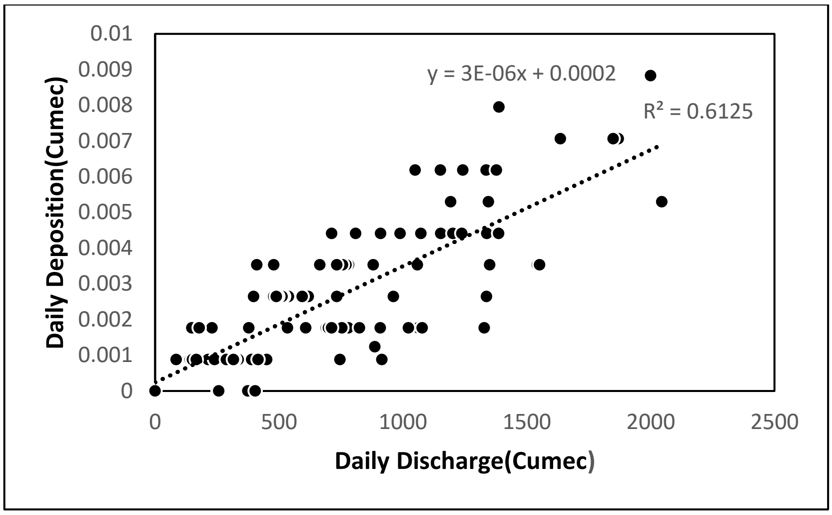
(d) Of the year 1995



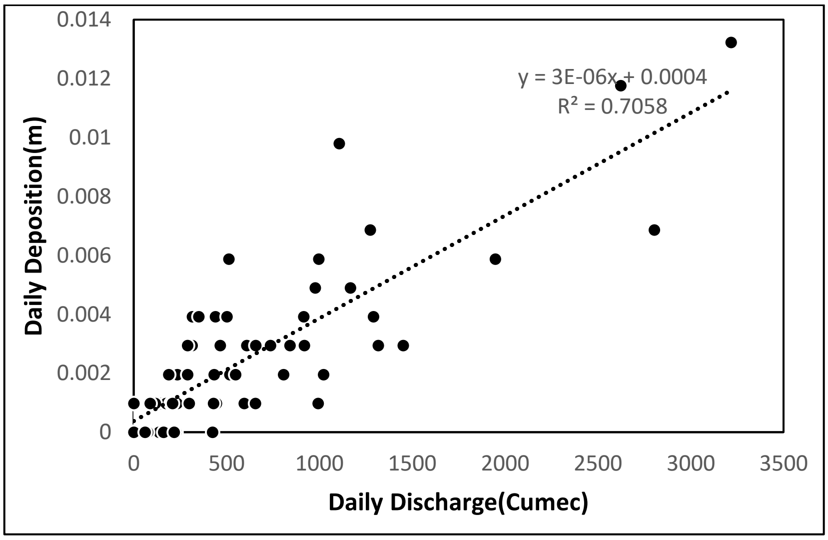
(e) Of the year 2005



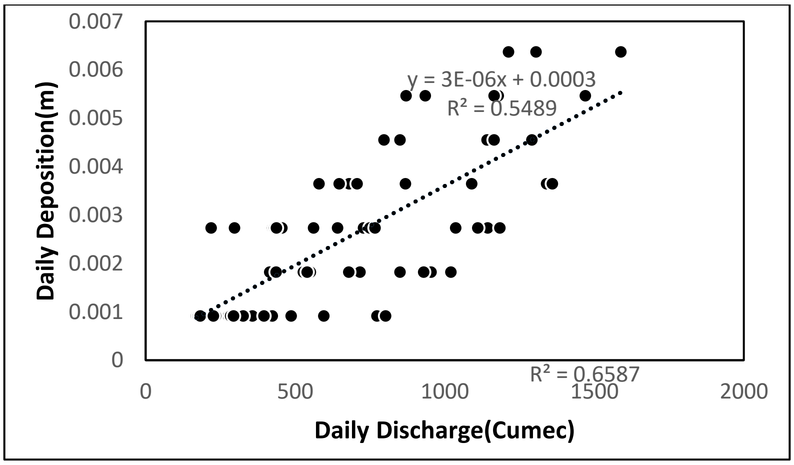
(f) Of the year 2015



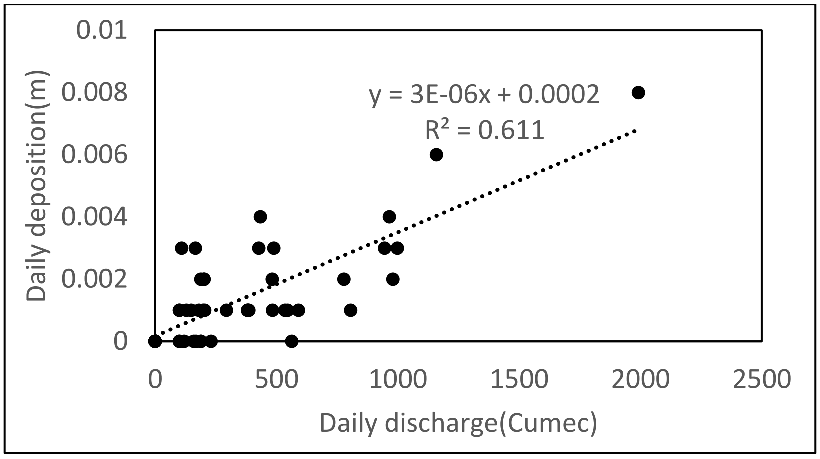
(g) Of the year 2025



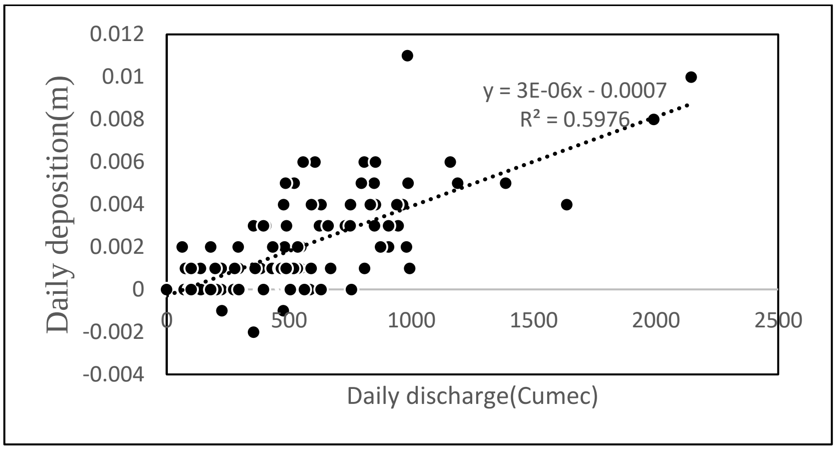
(h) Of the year 2035



(i) Of the year 2045



(j) Of the year 2055



(k) Of the year 2065

Fig. 4.11(a) to (k): Rate of deposition against daily discharge

The variation of cumulative deposition and cumulative discharge in the pond area (chainage 61 – 66 km) has been plotted for the study period and presented in Fig. 4.12. It is observed that maximum sediment filling at the pond area has occurred during the period from 1956 to 1965. The cumulative deposition reduces with cumulative discharge for the next 20 years upto the year 1985 and thereafter the trend line of deposition become flatter till the end of the study period upto the year 2066. This indicates that the deposition rate is becoming gradually slower with the passage of time and marching towards the point of saturation.

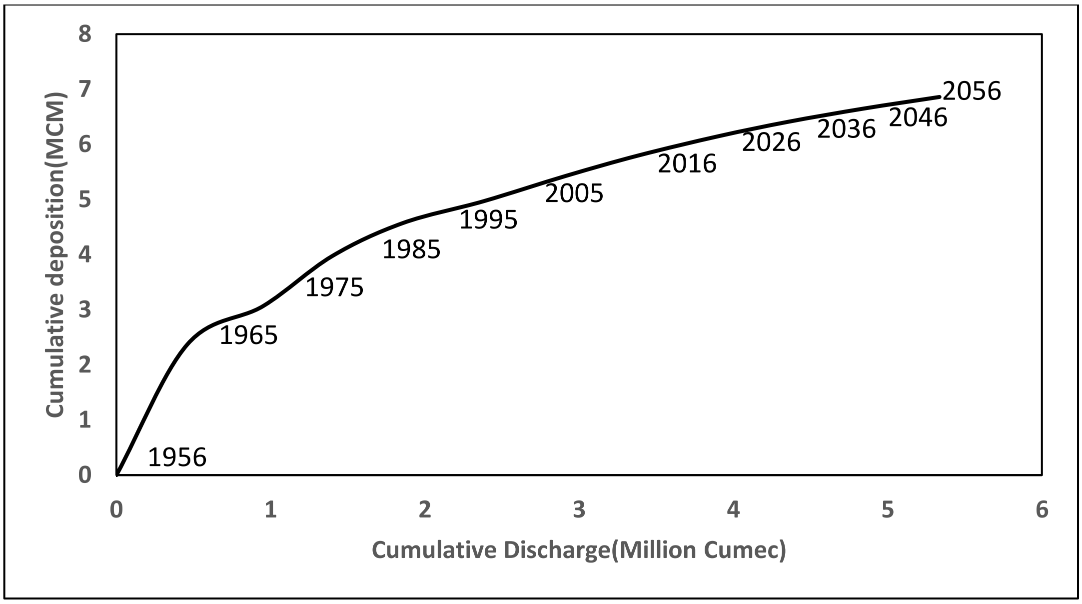


Fig 4.12:Cumulative deposition vs Cumulative discharge in pond area since inception

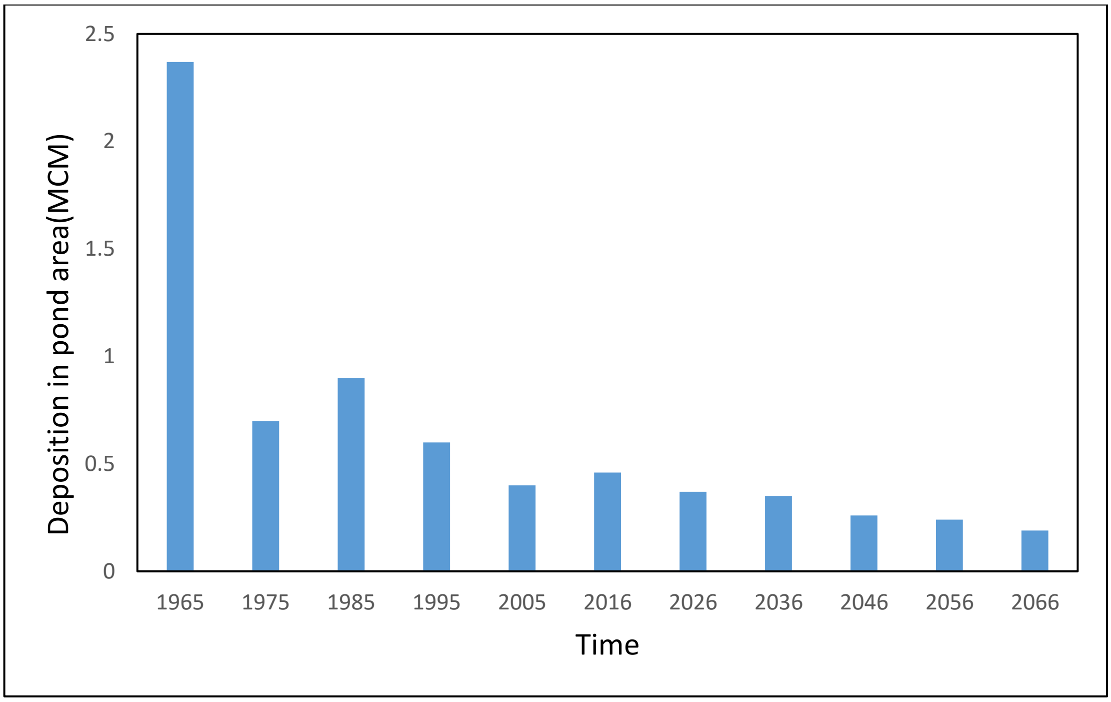


Fig 4.13 Deposition vs discharge in pond area since inception

4.5 . FLUSHING – AN ALTERNATIVE SOLUTION FOR AUGMENTATION OF POND CAPACITY

Various flushing options have been tried to evaluate their impact on sedimentation behavior in the pond area of the barrage. Initially, the Model was simulated with two typical hydrographs: (a) 15 days sinusoidal hydrograph and (b) 4 days rectangular hydrograph with constant discharge of 4000 cumec, once in a year. The flushing experiment also accommodated three different pond-water levels: (i) 64.46 m (design pond level) (ii) 62.00 m (Mid-pond-level) and (iii) 58.865 m (empty pond condition). The resultant cumulative deposition in the pond area with respect to time are plotted for all the scenarios including no-flushing scenario and presented in Fig. 4. 14 (a)-(b).

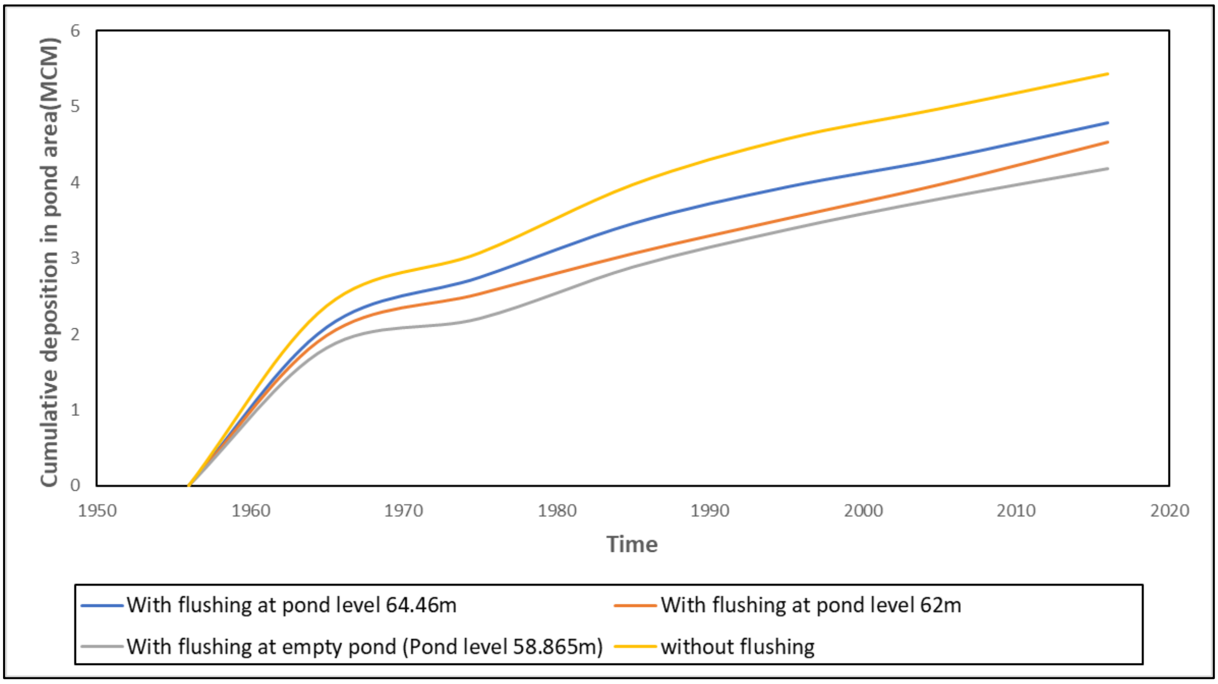


Fig. 4.14 (a) Variation of cumulative deposition in the pond area with time for sinusoidal hydrograph

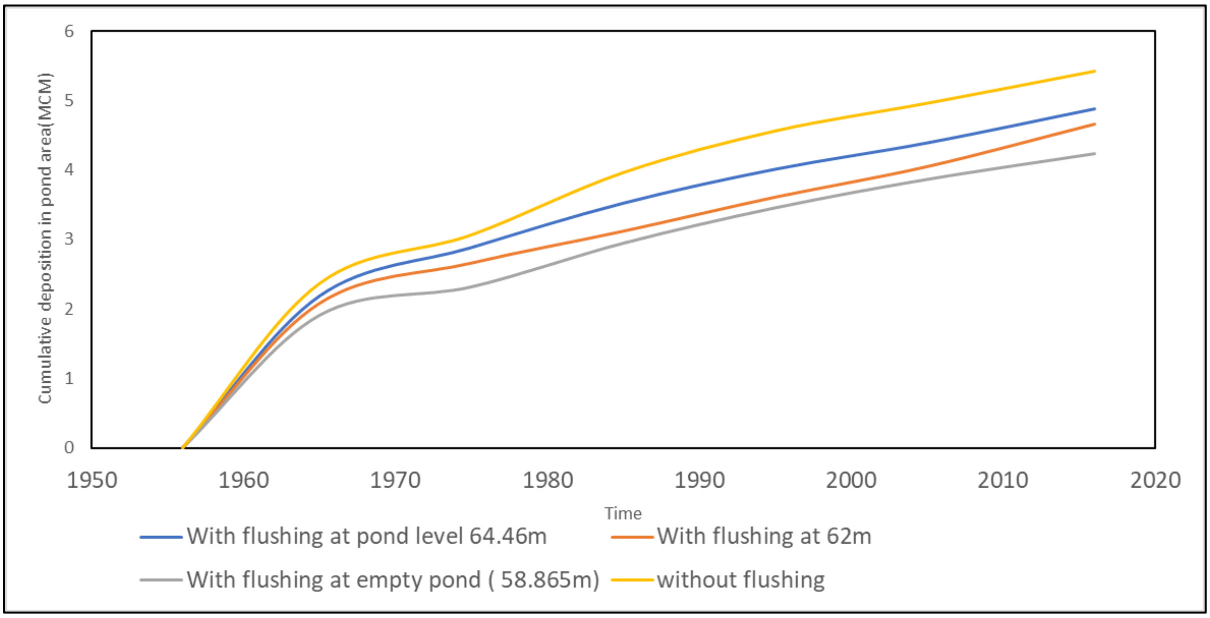


Fig. 4.14. (b) Variation of cumulative deposition in the pond area with time for rectangular hydrograph

The cumulative deposition for different options is also shown in Table 4.4(a)-(b) for sinusoidal and rectangular hydrograph respectively. It is important to note that reduction in deposition due to flushing may be in the order of 10% to 20% for all the options tried.

Table 4. 4(a) Cumulative deposition (MCM) with flushing (sinusoidal hydrograph)

	With flushing at pond level 64.46m	With flushing at pond level 62m	With flushing at empty pond (Pond level 58.865m)	without flushing
1956	0	0	0	0
1965	2.09	1.98	1.82	2.37
1975	2.75	2.53	2.21	3.07
1985	3.46	3.06	2.89	3.97
1995	3.94	3.52	3.38	4.57
2005	4.31	3.97	3.79	4.97
2016	4.79	4.53	4.19	5.43

Table 4. 4(b) Cumulative deposition (MCM) with flushing (rectangular hydrograph)				
	With flushing at pond level 64.46m	With flushing at 62m	With flushing at empty pond (58.865m)	without flushing
1956	0	0	0	0
1965	2.19	2.08	1.91	2.37
1975	2.89	2.66	2.32	3.07
1985	3.53	3.12	2.95	3.97
1995	4.02	3.61	3.46	4.57
2005	4.40	4.05	3.87	4.97
2016	4.89	4.66	4.24	5.43

4.5.1 Flushing coupled with dredging in the pond area

To judge the efficacy of flushing after dredging the pond area, a detailed analysis has been carried out for the period 2026 – 2066 with a modified bed level in the pond area (Fig. 4.14). The model was simulated once in a year with initial bed level and rectangular hydrograph having 4000 cumecs maximum discharge. Additionally, four days empty flushing followed by one-day pressure flushing with pond level at 62 m was also carried out. The corresponding change in bed profile with time have been plotted in Fig. 4.15. Variation of cumulative deposition with time have been plotted in Fig. 4.17 and also in Table 4.5. Analysis depicts that dredging followed by flushing is a lucrative option as it helps distributing the deposited material evenly in the entire pond area (Fig 4.16).

It is pertinent to mention that the depositional rate in the pond area would reduce by about 40% if dredging in the pond area is done before adopting flushing in the barrage. For the case with four days empty flushing followed by one-day pressure flushing reduction in deposition would be in the order of 60%. This is because the river channel is now approaching to the regime state after a period of 60 years.

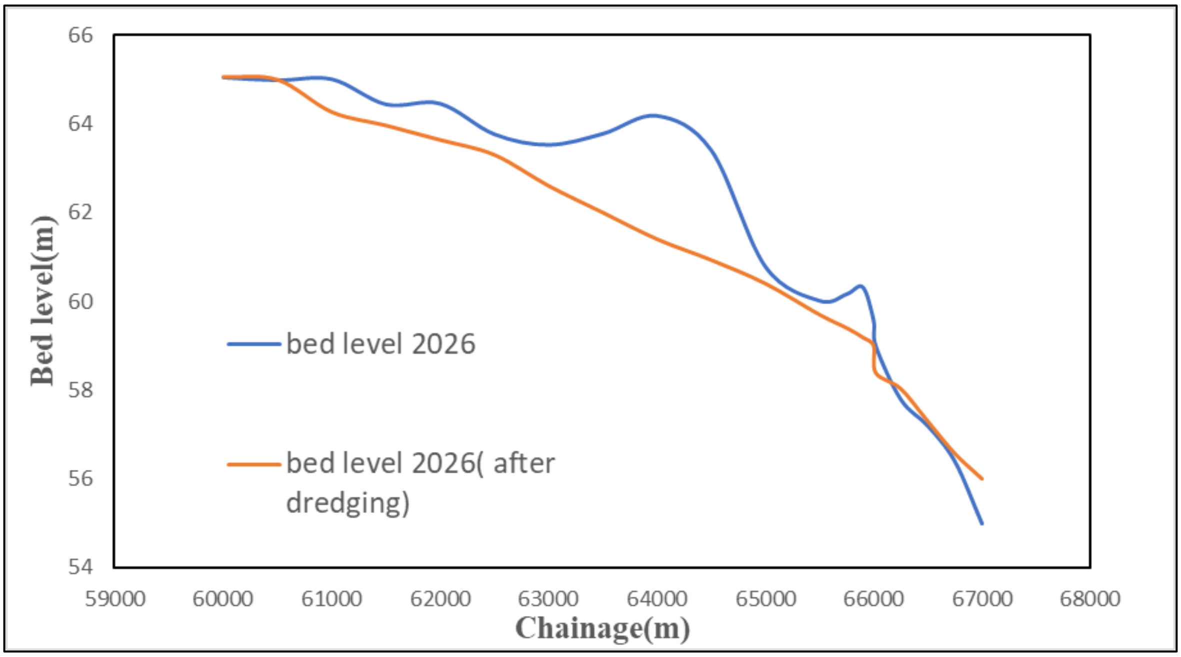


Fig. 4.15 Bed level(2026) before and after dredging

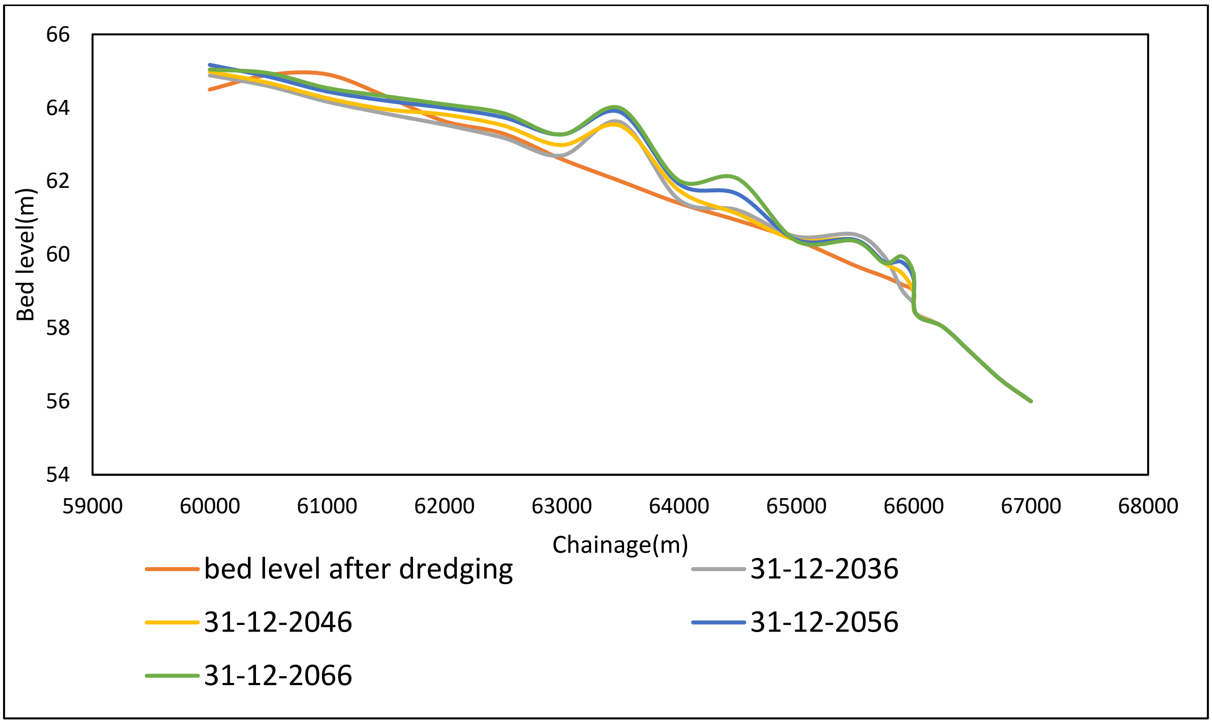


Fig. 4.16 Bed level with dredging and rectangular empty flushing

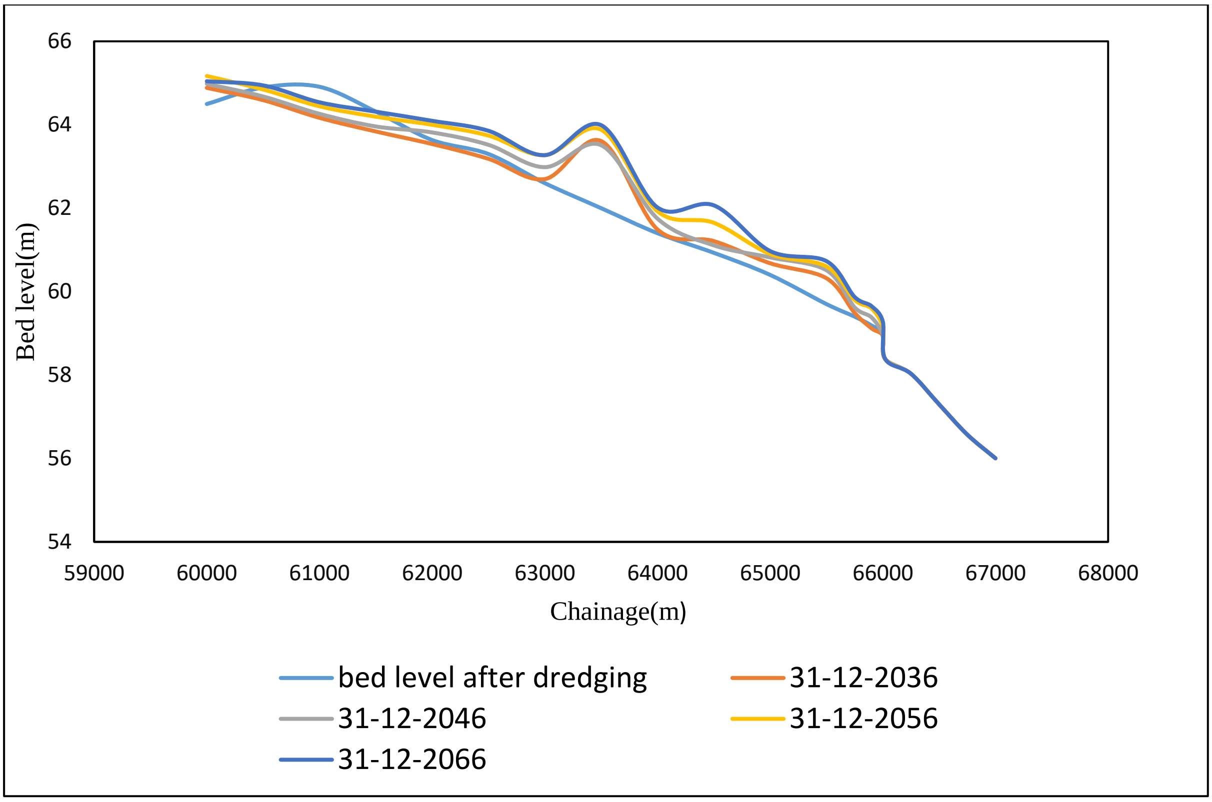


Fig.4.17 Bed level with dredging and rectangular flushing with empty pond and pressurized condition

Year	Table 4.5 Cumulative deposition (Million Cubic Meter) with dredging (Rectangular hydrograph)			
	With flushing at pond level 64.46m – 4 days	With flushing at pond level 62m- 4 days	With flushing at empty pond (Sill level 58.865m) – 4 days	With empty flushing for 4 days followed by one day pressure flushing with pond level at 62m
2026	0	0	0	0
2036	1.4892	1.3312	1.1842	1.053
2046	1.9652	1.7024	1.4384	1.28
2056	2.4004	1.9968	1.829	1.564
2066	2.7336	2.3104	2.1452	1.988

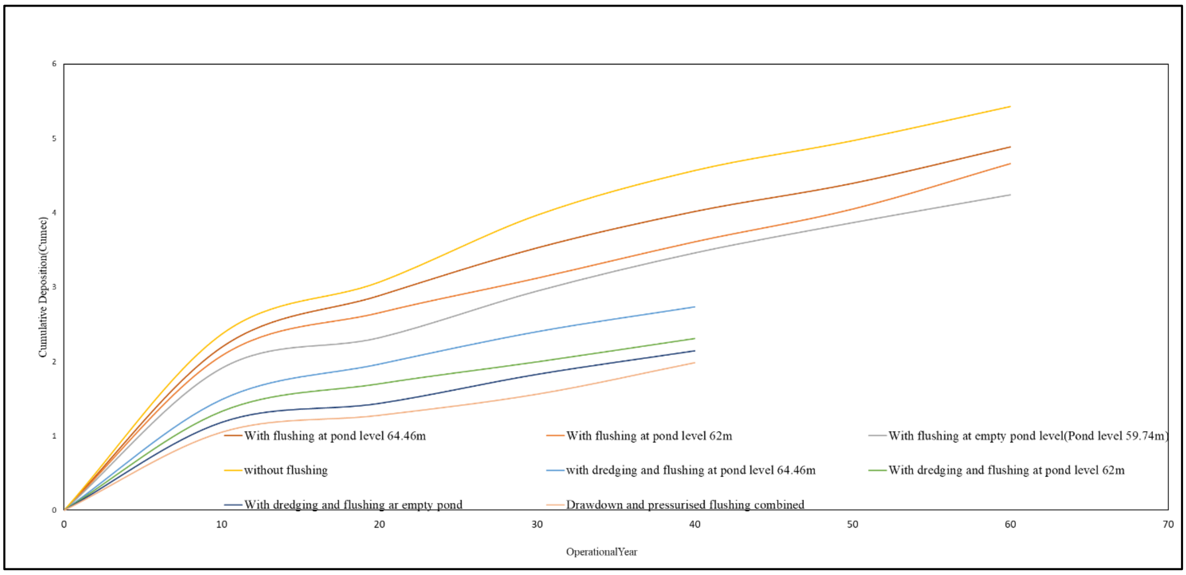


Fig. 4.18 Variation of cumulative deposition without and with dredging

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1. SUMMARY

This research has been carried out in a phased manner for obtaining a spatio-temporal sedimentation picture of Damodar-Barakar River system for a truncated length of 67 km bounded by two mighty dams Maithon and Panchet in the upstream end and a gated Durgapur Barrage at the downstream.

The scientific gamut of the study roamed with a one-dimensional (1D) mathematical model (MIKE 11 of DHI) that was simulated for hydrodynamic and sediment transport analysis of the aforesaid river system. The basic model was suitably customized for an object-oriented, phased-mannered study of Damodar-Barakar River system by integrating seven essential editor: Simulator, River Network, Cross Section, Boundary Condition, HD Parameters, ST Parameters and result viewer. The river network was delineated from the old maps (year 1950, 1956, 1965, 2000 and 2016 collected from RRI) and relevant data of digital elevation model [DEM of Shuttle Radar Topographic mission data (SRTM), a mission launched by NASA having accuracy ±10 m of elevation by a software (ArcGIS). From those maps of different years and SRTM data of the year 2000, a total 128 number of cross sections at 500 m intervals have been reconstructed through ArcGIS.

Hydrodynamic simulation was carried out considering rainfall pattern of the catchment of the River Damodar and Barakar obtained from IMD and correlating this with the reported inflow discharge for a period 2009 – 2016, thereby developing synthetic hydrograph, i.e., time-series discharge data for the entire period of model simulation. Seasonal variation of measured suspended sediment concentration for different discharges throughout the year from various locations of the model domain has been utilised for sediment transport analysis. Both hydrodynamic and sediment transport calibration and validation of the model have been done using observed and measured data during different seasons in different years at various observation stations.

The morphological changes of the river due to variable dam discharges and resulting erosion and deposition during study period from 1956 to 2066 in different chainages has been discussed with the help of tables and figures. Plots are given to highlight the increase in sedimentation with the increase in discharge in the river and cumulative increase in sedimentation in the pond area with time. The model results are found to be in line with the reported observations of different Government authorities.

Various flushing options have been tried to evaluate their impact on sedimentation behaviour in the pond area of the barrage. Initially, the Model was simulated with two typical hydrographs: (a) 15 days sinusoidal hydrograph and (b) 4 days rectangular hydrograph with constant discharge of 4000 cumec, once in a year. The flushing experiment also accommodated three different pond-water levels: (i) 64.46 m (design pond level) (ii) 62.00 m (Mid-pond-level) and (iii) 59.74 m (empty pond condition). The resultant cumulative deposition in the pond area with respect to time are recorded for all the scenarios including no-flushing scenario.

This technique appears to be most effective in controlling sedimentation pattern in the pond area with variable discharge and may help the practicing engineers for proper management of barrage operation. Though the relevant observations, inferences and explanation are provided to the best of our ability and knowledge, considering hydrodynamic uniqueness and complex sedimentary processes of Damodar river system the present study may be construed as 1st level of understanding and accordingly it has been methodically documented for further study to be conducted by the future generation.

5.2. CONCLUSIONS

On the basis of the output of this study following conclusions may be drawn:

- Initial rate of sediment depositions over a period of about first ten years in the barrage pond area is maximum and thereafter it reduces considerably. This is in line with the reported observation during the study period of 1956 – 2016.
- Deposition in model domain during the study period has occurred in the lower stretch (Chainage 40 – 66km) of the river with about 50% in the pond area.
- Contribution of the eroded bed material seems to be in the order of 75 % of the total sedimentation in the model stretch during the study period.
- The rate of deposition is found to increase linearly with the discharge throughout the study period and is found to reduce considerably with time.
- Cumulative deposition in the pond area was considerably very high during 1956 to 1965, after which the rate of deposition gradually decreases. During the period 2026 - 2066 the predicted rate of cumulative deposition is low.
- Flushing preceded by mechanical dredging is found to be most effective for reviving the pond capacity of the barrage. This may help the barrage controlling authority for proper operation of barrage in respect of scheduling of flushing and gate operation.

5.3. SCOPE OF FUTURE WORK

Considering the challenges for operation of barrage pond the following studies may be undertaken for practical implementation.

- Physical model study may be conducted to validate the numerical findings considering different parametric variations.
- 2D numerical analysis may be carried out for getting sediment depositional pattern in the lateral direction.

REFERENCES

Abed, K., Majid, H., Hobi, A., J. Jihad, A. and Hamed, H. (2014). “Numerical Modeling of Sediment Transport Upstream of Al-Ghammas Barrage.” International Journal of Scientific and Engineering Research. 5. 469.

Ackers, P., and White, W.R.(1973). “Sediment transport: New approach and analysis.” J. Hyd. Div. ASCE, 99, no. HY11:2041-60.

Ahn, J.(2011).“Numerical modeling of reservoir sedimentation and flushing processes (Doctoral dissertation, Colorado State University).”

Al-Khafaji, A. H., Khaleel, K. M. and Othman, M. A. (2019). “Numerical modeling of the effect of water level variation on sediment transport upstream of a dam.” Water, 11(11), 2249.

Annandale, G.W.(1987). “Reservoir Sedimentation.” Elsevier Science Publishers, New York.

Atkinson, E.(1996). The Feasibility of Flushing Sediment from Reservoirs. Report OD 137, HR Wallingford, Wallingford.

Bagnold, R. A. (1956). “The flow of cohesionless grains in fluids. Philosophical Transactions of the Royal Society of London.” Series A, Mathematical and Physical Sciences, 249(964), 235-297.

Bagnold, R. A. (1966). “An approach to the sediment transport problem from general physics.” US government printing office.

Barman, B.C., Saha, A., Dalal, D. S. S. and Sinha, B.(2019). “Introspect into reservoir sedimentation in some chotanagpur plateau drainage basins.” Published on 2nd International Conference on Sustainable Water Management organized by Water Resources Department, Govt. of Maharashtra during November 6-8, 2019 at Pune, Maharashtra, India.

Basson, G. A. (1997). “Dealing with reservoir sedimentation.” Water research commission report, 1-4.

Bose, S. K., & Dey, S.(2009).”Reynolds averaged theory of turbulent shear flows over undulating beds and formation of sand waves.” Physical review E, 80(3), 036304.

Bi, S., Zhang, Y., Han, N., and Long, X.(2009). "Numerical Simulation on The Flow Field of Inlet Structure of Dongsong Pumping Station." Advances in Water Resources and Hydraulic Engineering - In Proceedings of 16th IAHR-APD Congress and 3rd Symposium of IAHR-ISHS (2009).

Brandt, S. (2000). "A review of reservoir desiltation." International Journal of Sediment Research. VL – 15, 321-342.

Bui, M.D., and Rutschmann, P. (2013). "Assessment of sedimentation and flushing efficiency for Kajbar hydropower project in the Nile River." Proc. 35th Congress Int. Assoc. Hydraul. Res., Chengdu, China.

Central Water Commission, Government of India, "Final Report Capacity Survey of Durgapur Barrage." Watershed and Reservoir Sedimentation Directorate, Volume-I, May 2012, Pages- 33-40.

Charafi, M. M. (2019). "Two-dimensional numerical modeling of sediment transport in a dam reservoir to analyze the feasibility of a water intake." International Journal of Modern Physics C, 30(01), 1950003.

Chien, N., & Wan, Z. (1999). "Mechanics of sediment transport." American Society of Civil Engineers.

Chitale, M. A. (1992). "Development of India's river basins." International journal of water resources development, 8(1), 30-44.

Chow, V. T., Maidment, D. R., and Larry W. Mays. (1988). "Applied Hydrology. McGraw-Hill series in water resources and environmental engineering, New York." McGraw-Hill.

Chou, F. N., & Wu, C. W. (2011). "Operation Study of Hydraulic Flushing of Shimen Reservoir in Taiwan." In Proceedings of the 34th World Congress of the International Association for Hydro-Environment Research and Engineering: 33rd Hydrology and Water Resources Symposium and 10th Conference on Hydraulics in Water Engineering (pp. 1985-1993). Barton, ACT: Engineers Australia.

Daham M. H.and Abed, B. S. (2020). "Simulation of sediment transport in the upper reach of al-gharraf river" iop conf. Ser.: mater. Sci. Eng. 901 012012 doi 10.1088/1757-899x/901/1/012012.\

Damodar Valley Corporation, Hydraulic Data Division, P.O- Maithon Dam, Dist Dhanbad, Jharkhand, PIN-828207, (2019a) "Sedimentation Survey Report of the Maithon Reservoir under NHP", 79-127.

Damodar Valley Corporation, Hydraulic Data Division, P.O- Maithon Dam, Dist Dhanbad, Jharkhand, PIN-828207, (2019b) "Sedimentation Survey Report of the Panchet Reservoir under NHP", 45 to 154.

Dey, S. (1999). "Sediment threshold." Applied Mathematical Modelling, 23(5), 399-417.

Dey, S., & Debnath, K. (2001). "Sediment pickup on streamwise sloping beds." Journal of irrigation and drainage engineering, 127(1), 39-43.

Dey, S., & Papanicolaou, A. (2008). "Sediment threshold under stream flow: A state-of-the-art review." KSCE Journal of Civil Engineering, 12, 45-60.

Du Boys, M. P. (1879). "The Rhone and streams with movable beds". Annals des Pontes et Chaussees, 18(22).

D'Rohan, W. (1911). "The silting up of reservoirs and canals and some methods for preventing same." Engin. and Contract, 35, 56-58.

Duan, J., Cheng, H., Liu, H., Wang, C., & Wang, H. (2017). "Numerical simulation of sediment transport in the upstream of a reservoir with different inflow conditions." Water, 9(5), 313.

Einstein, H. A. (1942). "Formulas for the transportation of bed load."Transactions of the American Society of Civil Engineers, 107(1), 561-577.

Einstein, H. A. (1950). "The bed-load function for sediment transportation in open channel flows (No. 1026)." US Department of Agriculture.

Engelund, F.,& Hansen, E.(1967). "A Monograph on Sediment Transport to Alluvial Streams." Copenhagen, Teknik Vorlag.

Fan, J.(1985a). "Methods of preserving reservoir capacity. Methods of Computing Sedimentation in Lake and Reservoir." A contribution to the International Hydrological Programme, IHP-II Project A. 2.6.1 Panel, S. Bruk, ed., Unesco, Paris, pp. 65-164.

Fan, J.(1985b). "Methods of preserving reservoir capacity." Lecture Notes of the Training Course on Reservoir Sedimentation. Series of Publication IRTCES, Beijing, pp. II.1-II.96.

Fan, J.& Jiang, R. (1980). "On methods for the desiltation of reservoirs." In International Seminar of Experts on Reservoir Desiltation, Tunis,17.

Fan, J., & Morris, G. L. (1992). Reservoir sedimentation. I: Delta and density current deposits. Journal of Hydraulic Engineering, 118(3), 354-369.

Ghomeshi, M. (1995). “Reservoir Sedimentation Modelling,” Doctoral Thesis, University of Wollongong, Australia.

Ghosh, M., Dutta, S. and Sen, D. (2014). “Sediment Flushout from Pond of River Diversion Barrages by Gate Operation.” Water Resources Management.VOL-28,5335-5356.

Ghosh, S., and Guchhait, S. (2014). “Hydrogeomorphic variability due to dam constructions and emerging problems: A case study of Damodar River, West Bengal, India.” Environment Development and Sustainability. 16. 769-796. 10.1007/s10668-013-9494-5. 37

Gonzalez Rodriguez, L., McCallum, A., Kent, D., Rathnayaka, C., & Fairweather, H. (2023). “A review of sedimentation rates in freshwater reservoirs: recent changes and causative factors.” Aquatic Sciences, 85(2), 60.

Haun, S., and Olsen, N. R. B. (2012). “Three-Dimensional Numerical Modelling of Reservoir Flushing in A Prototype Scale.” International Journal of River Basin Management, 10(4), 341–349.

Haun, S., Kjærås, H., Lovfall, S., and Olsen, N. R. B. (2013). “Three-Dimensional Measurements and Numerical Modelling of Suspended Sediments in A Hydropower Reservoir. Journal of Hydrology.” 479, 180-188.

Hanmaiahgari, P., Gompa, N., Pal, D. & Pu, Jaan H. (2018). Numerical modeling of the Sakuma Dam reservoir sedimentation. Natural Hazards. 91. 10.1007/s11069-018-3168-4.

Hotchkiss, R. H., & Parker, G. (1990). “Laboratory modelling of reservoir sedimentation and sluicing: scale considerations.” In International Conf. on Physical Modelling of Transport and Suspension (p. 14B).

Hoque, M.M., Islam, A. and Ghosh, S.(2022). “Environmental flow in the context of dams and development with special reference to the Damodar Valley Project, India: a review.” Sustain. Water Resour. Manag. 8, 62. https://doi.org/10.1007/s40899-022-00646-9

Isaac, N. and Eldho, T.I. (2016). “Sediment management studies of a run-of-the-river hydroelectric project using numerical and physical model simulations.” International Journal of River Basin Management. Vol-14, 1-11.

IS Code 2912 (1999). “Liquid Flow Measurement in Open Channels- Slope Area Method [WRD 1: Hydrometry]” March -1999; Bureau of Indian Standards, Manak Bhavan, 9 Bahadur Shah Zafar Marg, New Delhi 11002.

Ishtiaq, K. S. (2011). “Development of Operation Rule of Proposed Ganges Barrage Using Mathematical Model.”

Izadpanah, Z., & Salehi Neishabouri, A. (2003). “Investigation of sediment transport in lateral intakes.” *Journal of Agriculture*, *26*, 15-24.

Jensen, Richard & Shen, Qiang. (2005). Shen, Q. “Semantics-preserving dimensionality reduction: rough and fuzzy-rough-based approach. IEEE Trans. Knowl. Data Eng. 16(12)”, 1457-1471. Knowledge and Data Engineering, IEEE Transactions on. 16. 1457- 1471. 10.1109/TKDE.2004.96.

Janssen, R. H., & Shen, H. W. (1997). “The development of equilibrium profiles for flushing channels.” In *Energy and Water: Sustainable Development* (pp. 108-113). ASCE.

Jordana, J. (1925). El pantano de la peña en 1924 (The Peña Reservoir in 1924). *Revista de Obras Pœblicas*, *73*, 39-42.

Jowett, I. (1984). “Sedimentation in New Zealand hydroelectric schemes.” Water international, 9(4), 172-176.

Ji, U, Julien, P. Y., Park, S. K. (2011), “Sediment Flushing at the Nakdong River Estuary Barrage”, Journal of Hydraulic Engineering, ASCE, Issue 11, Vol 137, pp 1521-1529.

Jing, C., 1956. A Report on the Experiment of Sediment Flushing of Jensanpei Reservoir. Taiwan Sugar Company, Taipei.

Ju, J. (1990). “Computational method of headwater erosion and its application” Journal of sediment research, Vol(1),30-39.

Julien, P.Y. (1998). “Erosion and Sedimentation.” Cambridge University Press, Cambridge, UK.

Khan, A. S., & Hossain, M. M. (2001). “Assessment of morphological changes due to construction of a barrage in the Teesta River.” In 45th, Convention of IEB, Khulna (pp. 16-18).

Khassaf, S. I., & jaber Abbas, M.(2015). “Modeling of Sediment Transport Upstream of Al-Shamia Barrage.”

Khosronejad, A., Rennie, C. D., Salehi Neyshabouri, A. A.and Gholami, I. (2008). “Three-Dimensional Numerical Modeling of Reservoir Sediment Release.” Journal of Hydraulic Research, 46(2), 209–223.

Kantoush, S. A., Bollaert, E.F.R., Boillat, J.-L., Schleiss, A.J. and Uijttewaal, W.S.J. (2006). “Sedimentation Processes in Shallow reservoirs with different geometries” Proc. Int. Conf. on Fluvial Hydraulics, Lisboa, Portugal.

Lai, J. S., & Shen, H. W. (1996). “Flushing sediment through reservoirs.” *Journal of Hydraulic Research*, *34*(2), 237-255.

Langbein, W. & Schumm, S. (1958). “Yield of Sediment in Relation to Mean Annual Precipitation.” Transactions, American Geophysical Union. 39. 10.1029/TR039i006p01076.

Liu, J., Minami, S., Otsuki, H., Liu, B., & Ashida, K. (2004). “Prediction of concerted sediment flushing.” *Journal of Hydraulic Engineering*, *130*(11), 1089-1096.

Mahata, H.K. and Maity, R. (2019). “Evolution of Damodar Fan Delta in the Western Bengal Basin, West Bengal.” J Geol Soc India 93, 645–656. https://doi.org/10.1007/s12594-019-1243-4.

Meyer-Peter, E., & Müller, R. (1948). “Formulas for bed-load transport.” In IAHSR 2nd meeting, Stockholm, appendix 2. IAHR.

Miller, M. C., McCave, I. N., & Komar, P. (1977). “Threshold of sediment motion under unidirectional currents.” Sedimentology, 24(4), 507-527.

MIKE 11.(2014). “MIKE 11 reference manual, Danish Hydraulic Institute”, Denmark.

Morris, G. and Fan. J. (1998). Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs and Watersheds for Sustainable Use. McGraw-Hill Book Co, New York, USA.

Mohamed, M. A. M. (2018). “Effect of sediment deposition upstream of the New Ibrahimia Head Regulator on its flow characteristics,” Water Science, 32:2, 241-258, DOI: 10.1016/j.wsj.2018.09.002.

Molinas, A., & Wu, B. (2001). “Transport of sediment in large sand-bed rivers.” Journal of hydraulic research, 39(2), 135-146.

Montgomery, D. R., & Buffington, J. M. (1997). “Channel-reach morphology in mountain drainage basins.” Geological Society of America Bulletin, 109(5), 596-611.

Morris, G. L., & Hu, G. (1992, August). “HEC-6 modeling of sediment management in Loíza Reservoir, Puerto Rico. In *Hydraulic Engineering: Saving a Threatened Resource—In Search of Solutions* (pp. 630-635).” ASCE.

Morris, G. L. (1995). “Reservoir sedimentation and sustainable development in India.” In: Proc. 6th Int. Symp. On River Sedimentation (New Delhi), 57–61.

Morris, G.L. and Fan, J.(1997). “Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoir, and Watersheds for Sustainable Use”. McGraw Hill, New York.

Morgan, R.P.C. (1995). “Soil Erosion and Conservation, 2nd ed.” Longman Group, Essex, UK.

Morris, S. C. (1997). “Experimental investigation of an aerodynamic shroud for cooling fan applications. Michigan State University.”

Moussa, A. M. A. (2013). “Predicting the deposition in the Aswan High Dam Reservoir using a 2-D model.” Ain Shams Engineering Journal, 4(2), 143-153.

Olsen,N.R.B., Jiminez, O., Lovoll, A. and Abrahamsen, L. (1994). “Calculation of water and sediment flow in hydropower reservoirs”. International conference on Modelling, Testing and Monitoring for Hydropower Plants, Hungary, 1994. 38

Olsen, Nils R.B. (1999). “Two-Dimensional Numerical Modelling of Flushing Processes in Water Reservoirs Réservoir.” Journal of Hydraulic Research, 37(1), 3–16.’

Olesen, K. W., & Basson, G. (2004). “1D and 2D modeling of sedimentation and flushing in shallow reservoirs. In Conference proceeding of Hydraulic of Dams and River Structures.”

Olsen, N. R. B., & Hillebrand, G. (2018). “Long-time 3D CFD modeling of sedimentation with dredging in a hydropower reservoir.” Journal of Soils and Sediments, 18, 3031-3040.

Park, S.B.(1998). “Basic water quality of the mid to lower part of Nakdong River and the influences of the early rainfall during monsoon on the water quality.” M.S. thesis, Pusan National University, Busan, South Korea.

Park, S. K., Ji, U., Yeo, W., & Kim, D. (2013). “Analysis for the effectiveness of sediment dredging in the approach channel at the Nakdong River estuary barrage.” *KSCE Journal of Civil Engineering*, *17*, 1489-1495.

Park, SK., Ji, U., Yeo, W. *(2013).* Analysis for the effectiveness of sediment dredging in the approach channel at the Nakdong River estuary barrage. *KSCE J Civ Eng* **17**, 1489–1495. https://doi.org/10.1007/s12205-013-1134-y.

Parker, G., C. Paola, and S. Leclair (2000). "Probabilistic form of Exner equation of sediment continuity for mixtures with no active layer.", J. Hydraul. Eng., 126(11), 818–826.

Pal, Swades. (2017). "Impact of Tilpara barrage on backwater reach of Kushkarni River: a tributary of Mayurakshi River." Environment, Development and Sustainability. 19. 10.1007/s10668-016-9833-4.

Paphitis, D. (2001). "Sediment movement under unidirectional flows: an assessment of empirical threshold curves.'' Coastal engineering, 43(3-4), 227-245.

Pu, J. H., Tait, S., Guo, Y., Huang, Y., & Hanmaiahgari, P. R. (2018). "Dominant features in three-dimensional turbulence structure: comparison of non-uniform accelerating and decelerating flows." Environmental Fluid Mechanics, 18, 395-416.

Rudra, K. (2014). "Changing river courses in the western part of the Ganga–Brahmaputra delta. " Geomorphology. 227. 87–100. 10.1016/j.geomorph.2014.05.013.

Rahaman, M. M., Joshi, N., Kalra, A., Lamichhane, G., and Ahmad, S. (2019). "Application of HEC-RAS to Study the Sediment Transport Characteristics of Maumee River in Ohio." 10.1061/9780784482353.024.

River Research Institute, (2016). "An Interim Report on the Observations of the Status of Bed Load and Suspended Load of the Damodar Upstream of the Durgapur Barrage." Haringhata, West Bengal.

Rouse, H. (1937). "Modern conceptions of the mechanics of fluid turbulence." Transactions of the American Society of Civil Engineers, 102(1), 463-505.

Rudra, K. (2018). "Rivers of the Ganga-Brahmaputra-Meghna Delta." Springer International Publishing, Cham, Switzerland.

Ryan & Blackwood, Adam. (2018). "Examining Storage Capacity Loss and Sedimentation Rate of Large Reservoirs in the Central U.S. Great Plains."Water. 10. 10.3390/w10020190.

Saad, M. B. A. (2002)." Nile River morphology changes due to the construction of high Aswan dam in Egypt. Ministry of Water Resources and irrigation, 14."

Schmidt, A., Brudy-Zippelius, T., Kopmann, R., & Imiela, M. (2005). “Investigations to reduce sedimentation upstream of a barrage on the river Rhine.” WIT Transactions on Ecology and the Environment, 80.

Shields, A. (1936). “Application of similarity principles and turbulence research to bed-load movement.”

Sinha CP., Sharma N., and Mohanty N C (1986). “Study of looseness factor for barrages.” 53rd Annual R&D Session, CBIP, Technical session 1 paper no. 10, India.

TALEB, B. N., & Naghshineh, A. (2004). “Flushing sediment through reservoirs.”

van Rijn, L. C. (1984a). “SEDIMENT TRANSPORT, PART I: Bed Load Transport.” Journal ofHydraulic Engineering - ASCE, 110(10), 1431–1456.

van Rijn, L. C. (1984b). “SEDIMENT TRANSPORT, PART II: Suspended Load Transport.” Journal of Hydraulic Engineering, 110(11), 1613–1641.

Wang, G. Q., & Ni, J. R. (1991). “The kinetic theory for dilute solid/liquid two-phase flow.” International journal of multiphase flow, 17(2), 273-281.

Wang, j.,& locher, f. A.(1989). “Sediment study for ralston afterbay reservoir operation for sediment pass-through and reduction of sediment deposition.”

Wen Shen, H. (1999). “Flushing sediment through reservoirs.” Journal of Hydraulic Research, 37(6), 743-757.

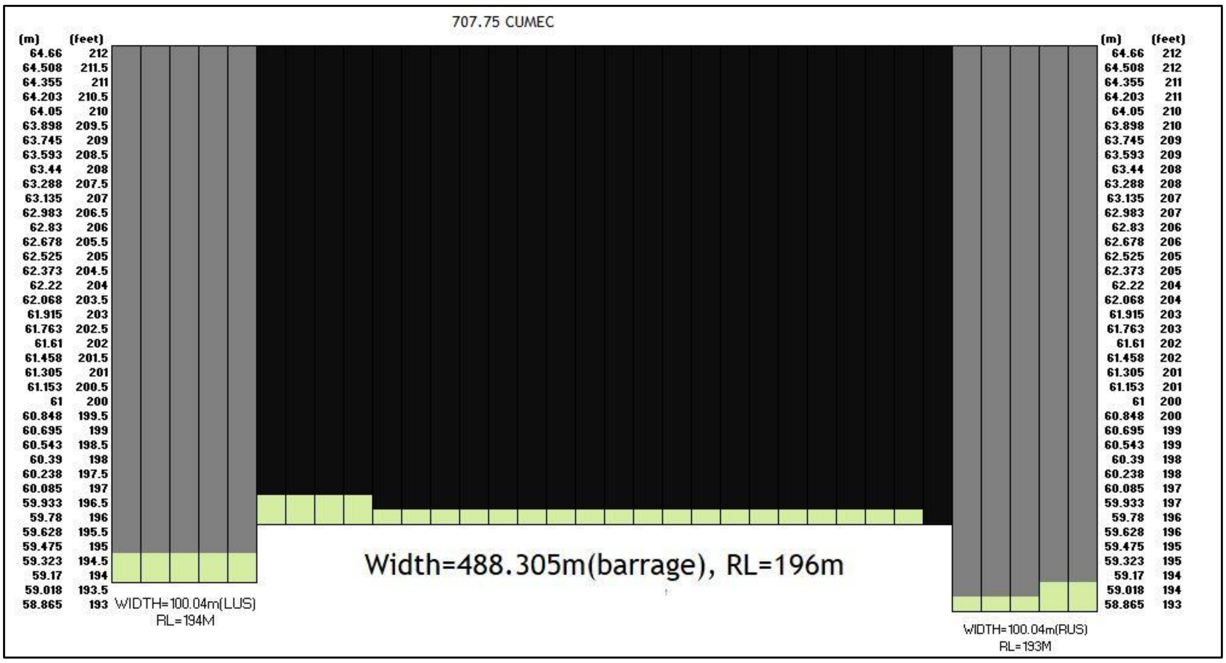
Wu, C.M. (1989). “Hydraulic properties of reservoir desilting.” Proceedings of XXIII 137 Congress of the IAHR, Hydraulics and the Environment, Technical Session B: Fluvial Hydraulics, Ottawa 1989, pp. B587-B593.

Zanke, U. C. E. (2003). “On the influence of turbulence on the initiation of sediment motion.”International Journal of Sediment Research, 18(1), 17-31.

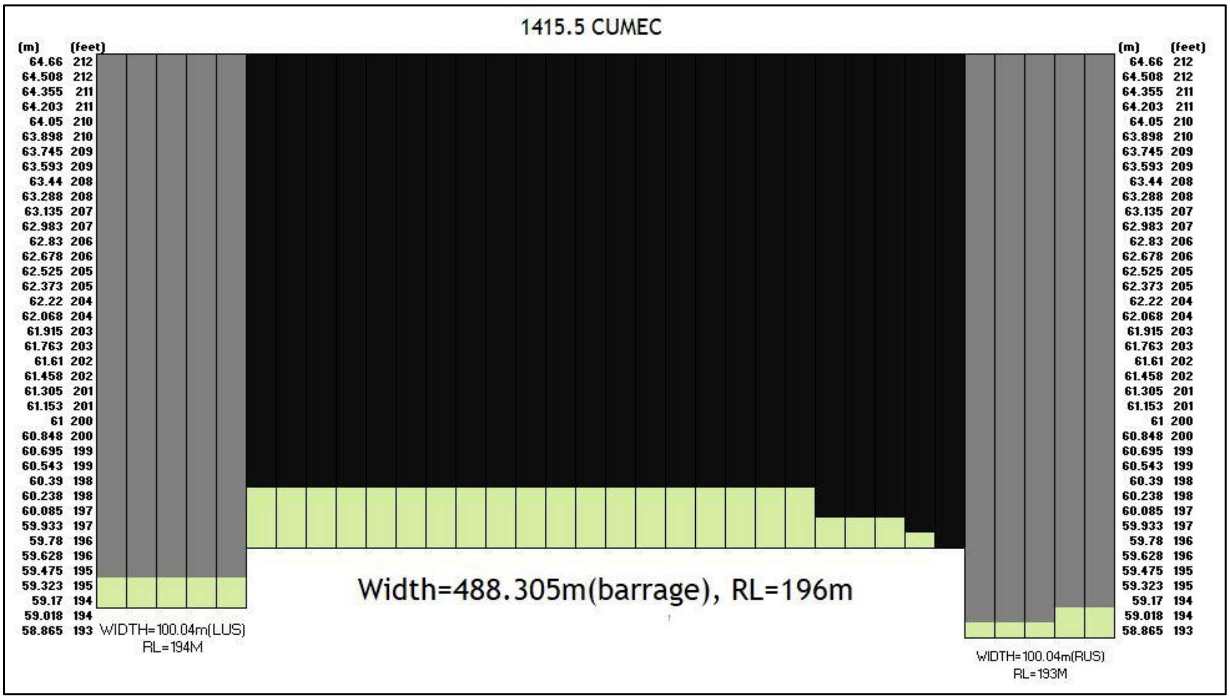
Zhang, Y., Hu2, C., and Wang, Y. (2005). “1 - D Mathematical Model for Heavily Sediment–Laden Rivers and its Applications.”Us-China Workshop On Advanced Computational Modelling In Hydroscience and Engineering, 1–11. Oxford, Mississippi, USA, (2005).

Zhang, Q., Singh, V.P., Xu, C.Y., Chen, X. (2013). “Abrupt behaviours of streamflow and sediment load variations of the Yangtze River basin, China.” Hydrol. Processes 2013, 27, 444–452.

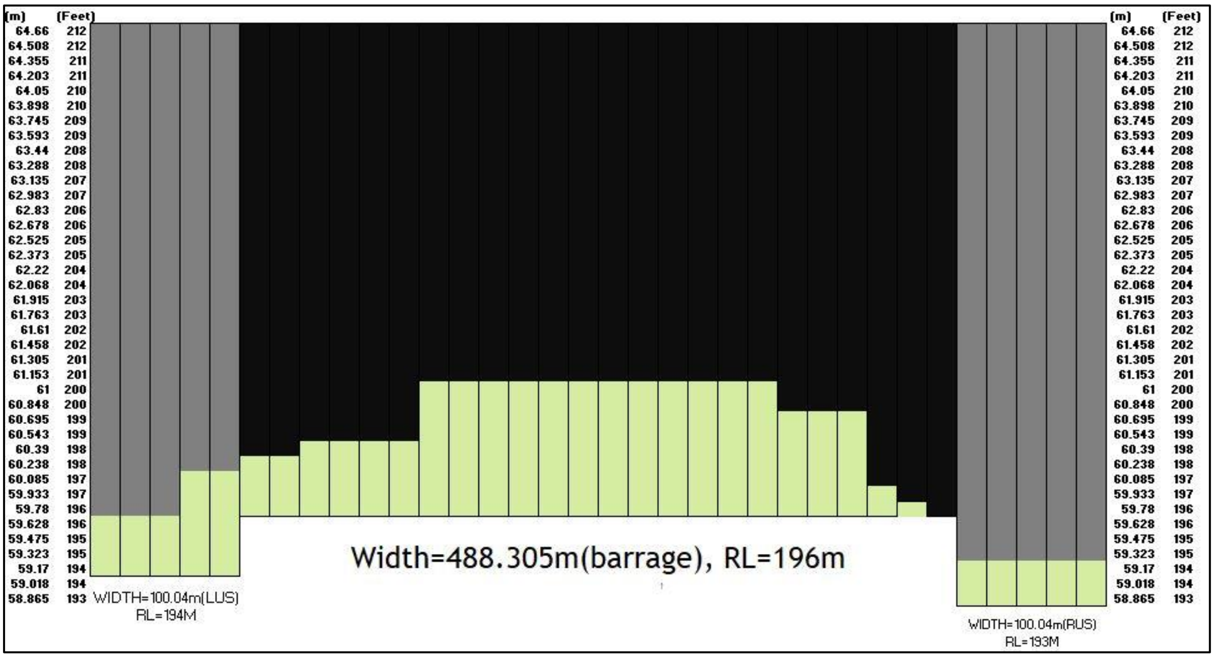
ANNEXURE



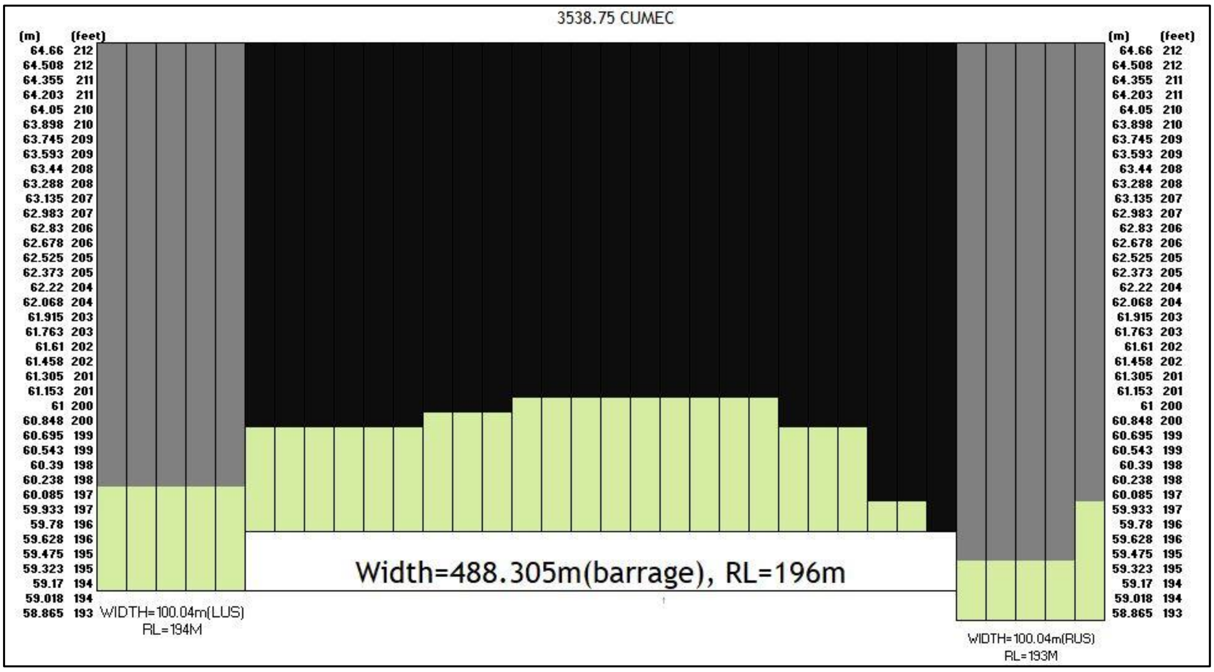
(a) Gate opening pattern for 707.75 Cumec



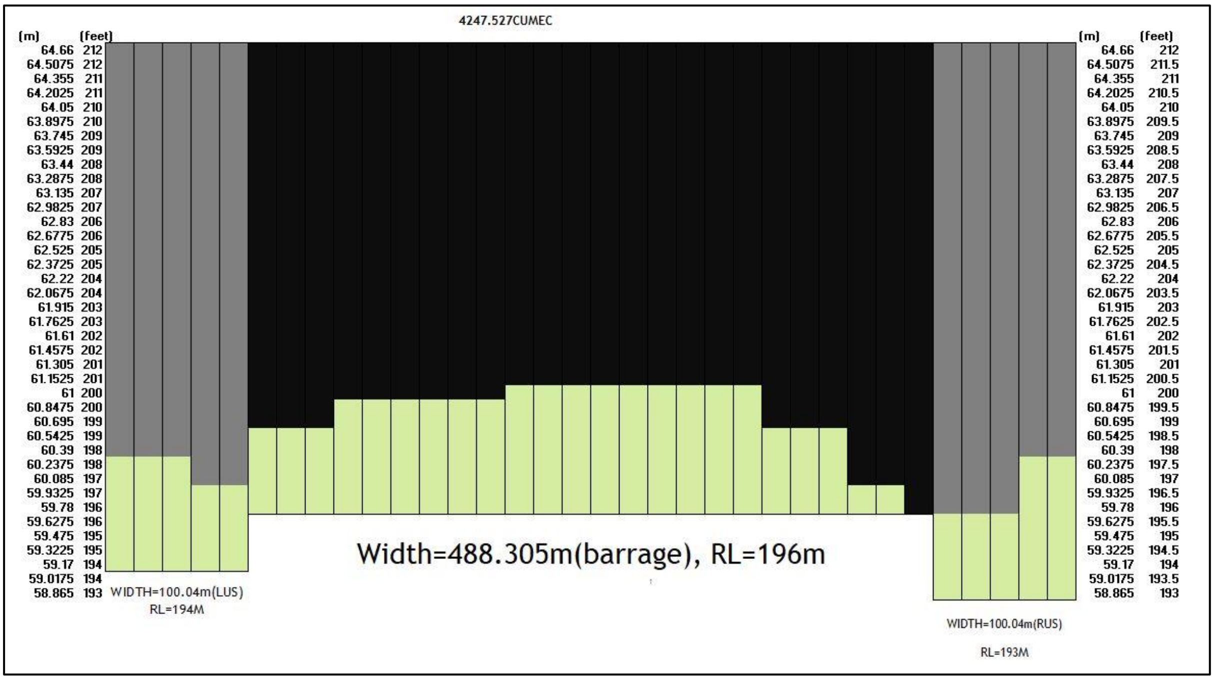
(b) Gate opening pattern for 1415.5 Cumec



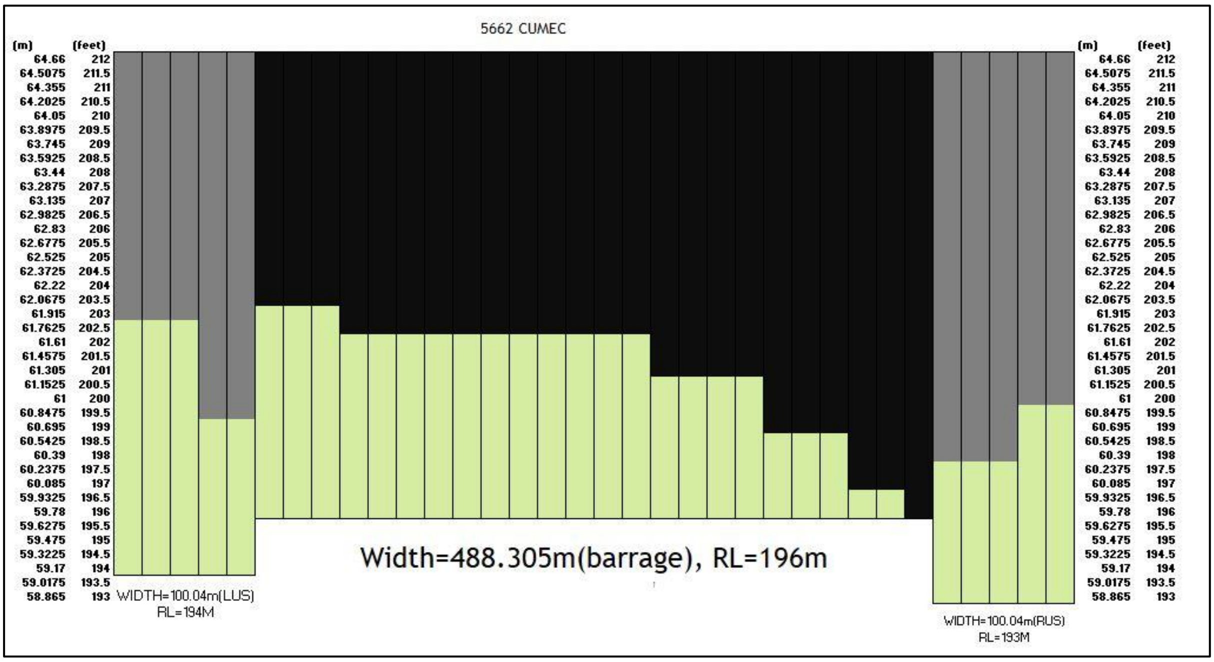
(c) Gate opening pattern for 2100 Cumec discharge



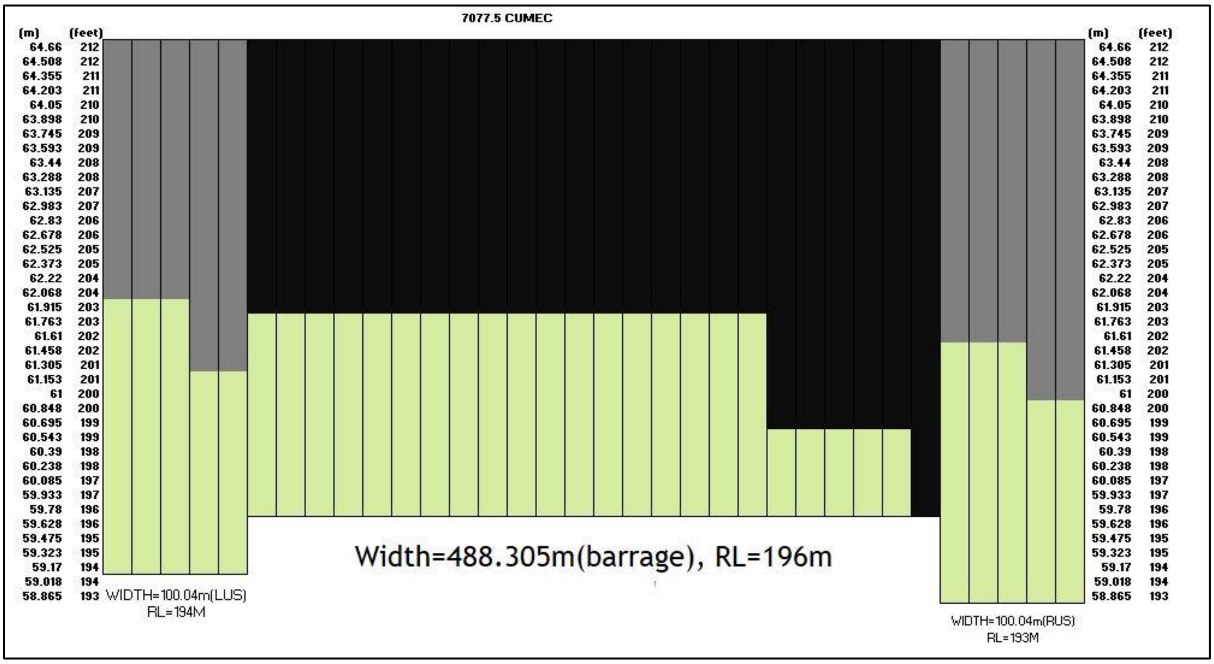
(d) Gate opening pattern for 3538.75Cumec



(e) Gate opening pattern for 4247 Cumec



(f) Gate opening pattern for 5662 Cumec



(g) Gate opening pattern for 7077 Cumec

Remote sensing based quantitative analysis of annual reduction of barrage reservoir capacity due to sedimentation: A case study of Durgapur Barrage

Sayak Nandy[1],Manas Kumar Das[2], Bibhas Chandra Barman[3]and RamenduBikas Sahu[4]

[1]*Department of Civil Engineering, Jadavpur University, Kolkata 700032, West Bengal, India*

E-mail: nandi.sayak88@gmail.com

[2]*Hydraulic Study Department, KolkataPort Trust, Kolkata 700043,West Bengal, India*

E-mail: mydearmanas@gmail.com

[3]*River Research Institute, Govt of West Bengal, Haringhata 743195, Nadia, West Bengal, India*

E-mail: bcbrri@gmail.com

[4]*Department of Civil Engineering, Jadavpur University, West Bengal, Kolkata 700032, India*

E-mail: rbsahu1963@yahoo.co.in

Abstract

Barrage across a river restricts natural flow and the suspended sediment settles down causing reduction of live storage capacity of reservoir. The matter of reduction of storage capacity of barrage reservoir is a matter of concern and needs to be assessed properly as it reduces service life and efficiency of a barrage resulting in unwanted flooding, bank erosion etc. Other than conventional methods this paper tries to develop a more cost and time effective method for quantifying the live storage capacity of a reservoir. Annual rate of storage capacity loss of Durgapur barrage reservoir has been assessed in this study using Remote Sensing and Digital Hydrography. Water spread area and char area in the reservoir is identified from the year of1965 to 2016, with an interval of 10 years using satellite images. Bed level of the reservoir has been assessed with hydrographic survey. Digital Elevation Model (DEM) of the reservoir area is developed combining remote sensing and survey data using ArcGIS. Cubic capacity of the reservoir on a specific time period is calculated using conventional method and thereby, the loss of storage capacity is also estimated. Present study concludes that Durgapur Barrage is losing its live storage capacity with a rate of .72% annually. Flushing with proper gate operation can be an effective tool for de-siltation of this reservoir.

Introduction

Construction of Dams or Barrages across the River is an age-old practice throughout the World. These interventions architected by the society aiming towards reduction of heterogeneity of available water in nature. They are built for the purpose of power generation, irrigation, discharge regulation and flood control. Sedimentation in Dams and Barrages is an inherent problem and Scientific understanding of riverine parameters in the vicinity of the barrages are prerequisite for better management of associated watershed. Barrage obstructs natural flow of water through diversion structures resulting in changed flow phenomenon in the upstream and downstream of the hydraulic structures. Restricted flow causes afflux with backwater effects in the upstream

AIC2020-29-744

A STUDY ON IMPACT OF VARIOUS FACTORS ON SEDIMENTATION IN ALLUVIAL RIVER USING MIKE 11 1D MODEL

S. Nandy[a], R. B. Sahu[b], M.K. Das[c] and B. C. Barman[d]
[a]Civil Engineering Department, Jadavpur University, 188 Raja S.C. Mallick Road, Kolkata, India,
nandi.sayak88@gmail.com
[b]Civil Engineering Department, Jadavpur University, 188 Raja S.C. Mallick Road, Kolkata, India,
sramendu@gmail.com
[c]Kolkata Port Trust, Govt. of India, 15, Strand Road, Kolkata, India
mydearmanas@gmail.com
[d]River Research Institute, Haringhata, Mohonpur,Nadia, India,
bcbrri@gmail.com

Sedimentation in rivers and channels is a natural phenomenon which occurs either naturally or by human enhanced process leading to deposition of suspended particulate matters originated elsewhere in the land surface or water bodies in the upstream. In general sediment is a natural product of erosion enhanced by unvegetated catchment areas, uncovered stream banks etc. The magnitude of sedimentation depends upon the size of suspended particles, discharge point in the stream, bed slope and water discharge in the stream. It has been reported widely that for alluvial rivers with flatter slope are subjected to increase in bed level due to sedimentation. This reduces discharge capacity and ultimately led to flooding; bank erosion etc. There is a need for quantitative assessment of impact of various factors on the depositional pattern of the rivers. In the present investigation a parametric study has been carried out using MIKE11 by varying the size of suspended material, concentration of suspended load and water discharge. In order to assess their impact on sediment transportation pattern of a river which has been investigated by quantifying rise of river bed level with time. Results have been documented in the paper which may help the engineers to develop sustainable water resource management scheme.

River Flow 2020 – Uijttewaal et al (eds)
© 2020 Taylor & Francis Group, London, ISBN 978-0-367-62773-7

A quantitative assessment of hydrodynamic impacts due to variable discharges on the backwater deposits of Durgapur Barrage over River Damodar in India using MIKE 11

Sayak Nandy & Ramendu Bikas Sahu
Civil Engineering Department, Jadavpur University, Kolkata, West Bengal, India

Manas Kumar Das
Kolkata Port Trust, Govt of India, West Bengal, India

Bibhas Chandra Barman
River Research Institute, Nadia, Govt. of West Bengal, India

ABSTRACT: Reservoirs behind barrages have a finite functional lifetime. Worldwide average lifespan of reservoir is about 22 years. Durgapur Barrage, India, built in 1955 across a high sediment laden straight River, Damodar (in the order of 300 mg/lit), still is working satisfactorily under the perpetual threat of capacity loss and sediment accumulation. 50% capacity of the reservoir has been reduced within 60 years from the design capacity 10.27 million cubic meter with an annual filling rate of 0.7% which is less the world average of 1% annually.. To minimize the stress of the existing procedure, through this paper, an additional methodology has been suggested under the surveillance of mathematical modeling, wherein a stretch of 66 km of the River Damodar and 14 Km long Barakar river have been modeled using MIKE-11. With the help of present analysis, the capacity, average velocity, water level and effect of dam discharges has been quantified.

1 INTRODUCTION

Water resource development is measured in terms of augmentation of the base flow in rivers and worldwide it is achieved economically and reliably by storage reservoirs. The aggregate storage capacity of reservoirs in the world is around 6000 km^2 (about 16 percent of the total annual runoff) and these reservoirs are responsible for supplementing the global base flow by roughly 20 percent (Basson, 2000). The reservoirs have been created by construction of Dam/Barrages on large and small rivers for various purposes. Though the earliest recorded Dam is believed to have been built across the river Nile about 2900 BC to supply water to Memphic, the capital of King Menes and the history of construction of Dams in India goes back to pre-Harappan period, the history of modern Dams in operation as old as Lake Homs water supply dam (1300 BC) in Syria (Olsen, 1994).

The 20th century witnessed a surge in construction of large dam who were the most significant and visible tools for the management of water resources. During this period there were over 45000 large dams in over 140 countries and have served an important purpose for agricultural production, flood control, domestic use and energy generation. Current estimates suggest that some 30– 40% of irrigated land worldwide now relies on dams and that dams generate 19 % of world electricity (Bui and Rutschmann, 2013).

Soil erosion in the form of clastic sediment is a part of the drainage process. In the perspective of Barrage reservoirs, these sediments, a product of geologic erosion, often accentuated by anthropogenic interferences.

ISH JOURNAL OF HYDRAULIC ENGINEERING
https://doi.org/10.1080/09715010.2023.2235704

Taylor & Francis
Taylor & Francis Group

Check for updates

Morphodynamic modelling of an alluvial river controlled by dam discharge and barrage operation: a study on Durgapur Barrage, India

S. Nandy[a], M. K. Das[b], B. C. Barman[c] and R.B. Sahu[d]

[a]Research Scholar, Department of Civil Engineering, Jadavpur University, Kolkata, India; [b]Deputy Director, Hydraulic Study Department, Kolkata, West Bengal, India; [c]Deputy Director (Hydraulics), River Research Institute, Mohonpur, Nadia, West Bengal, India; [d]Department of Civil Engineering, Jadavpur University, Kolkata, West Bengal, India

ABSTRACT

Reservoirs and barrages , built across alluvial rivers throughout the world, are losing their storage capacity at an estimated rate of about 1% annually. The pond area of Durgapur Barrage on River Damodar, India, controlled by barrage-gates is no exception. In spite of its service for more than 60 years through judicious gate-operation schedule, it is found that 52% of initial storage capacity Pond has been lost since its inception in 1956. A morphodynamic study of the alluvial Damodar River, extending from Maithon and Panchet dams at upstream to Durgapur Barrage in the downstream, has been done using a numerical model of MIKE-11. Hydrometeorological data of Damodar-Barakar River basin were used to simulate hydrodynamic and sediment transport models for ascertaining annual rate of erosion and deposition during the period 1956–2016. Study shows that about 6 million M^3 sediment were transported from catchment through Dam-discharge, a part of which got deposited in the river bed while the remaining 4.9 million M^3 washed away downstream through Barrage gates. Although the rate of deposition in the pond area was initially higher during the period 1956–1985, which has subsequently reduced . However, daily deposition increased more or less linearly with the increase in discharge of the river.

ARTICLE HISTORY
Received 11 February 2023
Accepted 9 July 2023

KEYWORDS
MIKE11; Durgapur Barrage; hydrodynamic; sediment transport; and erosion and deposition

1. Introduction

Damodar River originating from Palamou hills (about 600 m above MSL) travelled eastward for about 200 km to join main tributary Barakar at Disergarh, then moved south-eastward before joining river Hooghly at Garchumuk in the Howrah district about 50 km below Kolkata. Tectonic and depositional history of the region revealed that the western part of Bengal Basin is characterized by numbers of north-south trending normal faults, shifting river courses and repeated marine transgression and regression phases. After collecting a huge amount of sediment from Chhotanagpur plateau, this River system, along with its tributaries covering a total drainage area of 22,000 sq. km., deposits its sediment in the subaerial and subaqueous environment throughout the geological period. The morpho-dynamical process due to sedimentation had been started in late Cretaceous and still it is continuing in a sub aerial environment (Mahata and Maity 2019). In the past, the Damodar river system used to cause immense flood damages in the then Bihar and West Bengal, so much so that the river came to be associated with sorrow and sufferings. To tame the vehemence of the torrential flood of this alluvial river system five dams at Maithon, Panchet, Tenughat, Konar and Tilaiya were constructed, in line with the Tennessee Valley Project of USA, for accommodating a million cusec of flood water and to keep the monsoonal discharge of the River Damodar within 0.25 million cusecs. Further, to ensure perennial irrigation, supply of water to municipalities and industries Durgapur Barrage was constructed near Durgapur steel town (Figure 1).

Reservoirs and Barrage-Pond-Areas, built across alluvial river systems throughout the world, are losing their storage capacity at an estimated rate of about 1% annually, and so the life-span of a reservoir cannot be longer than a century (Ghosh et al. 2014). Since the Damodar Valley Corporation reservoirs are within a tropical climate region and the basin is degraded, the rate of sedimentation in reservoirs is very high (Hoque et al. 2022). The uncontrolled sand mining, industrialization and rapid growth of agriculture have significant contributions in the river sedimentation, leading to the decay of the channels as well as reduction of storage capacities of reservoirs (Barman et al. 2019). Five reservoirs constructed over Damodar and its tributaries have lost their storage capacity between 23% and 43% over a period of about 60 years ([Rudra 2018; Damodar Valley Corporation2019a 2019a; Damodar Valley Corporation2019b 2019b]) while the capacity of the pond area of Durgapur Barrage has been reduced by about 52% during the period 1956–2016 ([CWC2012 2012]).

As concerned as the Barrage-Pond Area, a shallow reservoir in the upstream of the barrage is produced due to the restricted natural flow. Water stored in the reservoir maintaining the designed pond depth over backwater length of the barrage is used to maintain the balance between inflow of river and outflow of canals. Natural flow of the river is being rapidly changed in the reservoir due to the backwater effect caused by control structure, leading to the reduction in sediment carrying capacity due to the decrease in energy gradient (Jana et al. 2022). Further reduction in velocity along with greater cross-sectional area acts as an efficient sediment trap in the pond area. The eroded soil which is being

CONTACT S. Nandy nandi.sayak88@gmail.com Research Scholar, Department of Civil Engineering, Jadavpur University, Kolkata, India
© 2023 Indian Society for Hydraulics