RESERVOIR SEDIMENTATION AND CAPACITY RESTORATION: A CASE STUDY OF BAJOLI HOLI AND TEHRI RESERVOIRS

A DISSERTATION

Submitted in Partial Fulfilment of the Requirements for the Award of the Degree

of

MASTER OF TECHNOLOGY

in

IRRIGATION WATER MANAGEMENT

by

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Enrolment Number: 1754 7006

Batch: 2017-19

DEPARTMENT OF WATER RESOURCES DEVELOPMENT & MANAGEMENT

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

ROORKEE 247 667 (UTTARAKHAND – INDIA)

JUNE, 2019

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE, ROORKEE 247 667

CANDIDATE'S DECLARATION

I, **Dwoki Justin Sam** hereby affirm that this dissertation report entitled; **RESERVOIR SEDIMENTATION AND CAPACITY RESTORATION: A CASE STUDY OF BAJOLI HOLI AND TEHRI RESERVOIRS**, submitted in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in the Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee 247 667 (Uttarakhand – India), is truthfully the hard work of my hands carried out during the period from July, 2018 to June, 2019, under the co-guidance and supervision of **Dr. M. L. Kansal**, Professor and Head of Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee 247 667 (Uttarakhand – India), and **Mr. A. C. Pandey**, Retired Research Officer, Irrigation Research Institute.

The content contained in here is my original work which neither I nor any other person have presented before aimed at receiving the honour of any other certificate.

Candidate's Signature

Date: …………………

CERTIFICATION BY SUPERVISORS

We, hereby ratify the affirmation by Dwoki Justin Sam is accurate and true to the best of our understanding.

Signature: ………………… **Signature…………….……..**

Dr. M. L. Kansal **Mr. A.C. Pandey**

Date: ………………………. **Date: …...………………..…..**

ABSTRACT

Reservoir sedimentation is a very complex and important phenomenon resulting from the obstruction of the natural river flow by construction of a dam across the river. Reservoirs located in the Himalayan region where sediment production is very high because of the young and fragile nature of the rocks, suffer a lot from this sedimentation disaster. The sedimentation in the Himalayan region is worst in RoR schemes since they have very small storage capacities. For this, it is imperative for dam owners, managers, operators or planners to predict and practice sediment management of different forms not only for RoR projects but for other type of reservoirs as well for sustainable use of these water resources schemes.

In this study two reservoirs (Bajoli Holi and Tehri) both located in the Himalayan region but more importantly having different parameters and purposes were respectively modeled for sedimentation and capacity restoration (for Bajoli Holi only) through depleting flushing using HEC-RAS 5.0.5 software.

In the first model (Bajoli Holi), the simulation was performed on the basis of proto data (sediment inflow and gradation), 3-D physical modeling data (Manning's n values), hydrographic survey (river cross sections), an arbitrary flow hydrograph and observed flow hydrograph obtained from 3-D modeling site. For this project, the model was simulated for sedimentation for 8, 12, and 20 months correspondingly by maintaining MDDL and FRL during monsoon and non-monsoon season respectively following a flow and sediment hydrograph. Also seeing the less storage capacity of the project and as a customary practice the model was further simulated for depleting flushing during monsoon season only by fully opening all gates for 72, 96 and 120 hours in each of the sedimentation periods in order to assess the best flushing results for the sustainability of this reservoir.

The simulation results indicated that out of the three conditions tested on the model, worst sedimentation occurred after 20 months of sedimentation, when only about 1.28 MCM, corresponding to 42 % out of about 3.03 MCM was left. Whereas, 64 % (1.94 MCM) and 72 % (2.19 MCM) were left after 12 months and 8 months' sedimentation respectively. Depleting flushing results showed that maximum capacity of about 93 % (about 2.81 MCM) was restored after 8 months' sedimentation and 5 days depleting flushing. Unlike depleting flushing for the same period when

only 87 % (2.63 MCM) and 67 % (2.02 MCM) capacities were respectively restored after 12 and 20 months' operation.

In the second model (Tehri), the mathematical model was completed in two different runs using two different sets of sediment data.

Firstly, the simulation was performed for 25 years using sediment corresponding to actually observed loss of capacity by previously conducted hydrographic survey and actually observed discharge. From the analysis of both rivers it was seen that sediment mostly deposited in between chainage 22 km and 37 km in R. Bhagirathi and 7 km and 25 km in R. Bhilangna, due to the gradual drop in the river flow velocity from u/s towards the dam in both rivers. In 25 years the loss of capacity was found to be 149.51 MCM or 5.98 MCM per year, resulting to 0.17 % loss of capacity per year in Tehri reservoir. A 5.98 MCM loss per year means that MDDL capacity (925 MCM) is expected to be lost in 155 years.

In the second run, for 25 years also, average sediment observed along with average flow actually observed was used. Which resulted in 216.88 MCM loss of capacity (8.68 MCM/yr.). Hence, a 0.25 % per year loss of capacity. This loss (8.68 MCM/yr.) translates to a projected loss in MDDL capacity (925 MCM) after 107 years.

KEY WORDS: Reservoir Sedimentation, Capacity Restoration, Depleting Flushing, Mathematical Model, HEC-RAS 5.0.5 Software, Hydrographic Survey, 3-D Physical Modeling, RoR Schemes, Sediment Management, Sustainability, Bajoli Holi Model, and Tehri Model.

ACKNOWLEDGEMENT

First and foremost, I would like to take this opportunity to thank our **Almighty God** for the gift of life, good health, strength and courage in doing this work and above all the opportunity to be able to study in one of the best Institutions, Indian Institute of Technology Roorkee.

Secondly, from the bottom of my heart I would like to express my sincere heartfelt appreciation to my supervisors and mentors, Dr. M. L. Kansal and Mr. A. C. Pandey, who always opened their doors and gave me generous, satisfactory, unconditional guidance and a wonderful opportunity to do my dissertation on “Reservoir Sedimentation and Capacity Restoration: Case Study of Bajoli Holi and Tehri Reservoirs,” which also helped me to learn and interact with some professionals in the field of hydraulics, learn some Indian culture to mention but a few. For this, May the Almighty God bless them and their lovely families abundantly?

My sincere acknowledgment also goes to various authorities of the institute and at department level for their support during this struggle. Notably, I would like to thank Prof. Ajit Kumar Chaturvedi, Director, IIT Roorkee, Prof. S. K. Mishra, Prof. Deepak Khare, Dr. Ashish Pandey, Dr. T. R. Chelliah, Er. S. K Shukla, Prof. Raj Deva Singh, All Non-Teaching Staff, My Batch Mates, PhD Scholars, Department of WRD&M, for all the courage, support, contributions of all kinds towards this report.

My special thanks also goes to the owners of both projects as well as IRI for the kind acceptance for me to use their data, without which this work would have been very difficult.

Further gratitude goes to Madam Rekha Pandey for the love and care she always showed to me whenever I come to her house for discussion with Mr. Pandey, made me feel welcomed, loved and above all member of the family/ or community.

With great appreciation and joyfulness, I am humbled to further recognise the love and support rendered to me by my former supervisors, Madam Laura Nistri and Mr. Chandan Nayak, at the International Organisation for Migration (IOM), Juba – South Sudan Office. You gave me an opportunity to pursue my undergraduate degree while “working and learning” from you. Through your exemplary leadership skills, I was lucky to learn among other things how to work; as a team, as a team leader and individually with minimal supervision when it mattered.

I also want to recognise every one of the instructors I gained from since my childhood, I would not have been here without their guidance, blessing and backing.

My statement of acknowledgement will be inadequate without the exceptional notice of individuals who mean world to me. I can't envision an existence without them. Much obliged to you my parents (Mr. Duku Samson Jansuk Wori Lomeje and Late Mum Mrs. Mary Muja Samson), my siblings, my paternal and maternal uncles and aunts, my paternal and maternal grandparents, my cousin siblings, cherished childhood pals and all elders to me in the family. Much appreciative to you Mum and Dad for showing faith in me and giving me freedom to pick what I wanted. I view myself as the most fortunate on the planet to have such a strong family, standing ideal behind me in long periods of bliss and trouble with your affection and backing.

Finally, last but by no means least, I am greatly indebted to the University of Juba, Juba – South Sudan for appointing me as a teaching assistant and the Ministry of Foreign Affairs Government of India through ITEC Program for accepting me for this sponsorship in IIT Roorkee.

Thank You All for Your Support!

(Dwoki Justin Sam)

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% / %age:	per cent / percentage
1000 t/ km^2/ yr:	Thousand tons per square kilometer per year
10^6 t/yr:	Million tons per year
1-D and 3-D:	One Dimensional and Three Dimensional
ArcGIS:	Aeronautical Reconnaissance Coverage Geographic Information System
BC:	Boundary Condition(s)
c/i:	Capacity - inflow ratio
CH.:	Channel
cm:	Centimeter
DSS	Data Storage and Management
E:	East
EL:	Elevation
Fig.:	Figure
FRL:	Full Reservoir Level
G.O:	Gate Opening
GD:	Gage Discharge
Ha and ha-m:	Hectare and Hectare metre
HEC-RAS:	Hydrologic Engineering Center - River Analysis System
HEP:	Hydroelectric Project
IIT:	Indian Institute of Technology
IRI	Irrigation Research Institute
ITEC:	Indian Technical and Economic Cooperation
Km and km^3:	Kilometer and Cubic kilometer.
m / km:	Metre per kilometer
M and m a.s.l:	Metre and Metre Above Sea Level
Million t/ yr:	Million tons per year

MCM:	Million Cubic Metre
MDDL:	Minimum Drawdown Level
MHACM:	Million Hectare Centimeter
MM:	Millimeter
Mr.:	Mister
MW:	Megawatt
NHPC:	National Hydropower Corporation
N:	North
PMF:	Probable Maximum Flood
Q:	Discharge
R:	River
Res. El.:	Reservoir Elevation
RS:	Remote Sensing
SA	South Africa
SCAAP:	Special Commonwealth African Assistance Plan
sq. km:	Square kilometer
T.S:	Time Series
$t/km^2/yr$:	Tons per square kilometer per year
Tab.:	Table
THDC:	Tehri Hydro Development Cooperation
U.S:	United States
u/s or U/S and d/s:	upstream and downstream
UK:	United Kingdom
UP:	Uttar Pradesh
WRD&M:	Water Resources Development and Management
WSP	Water Surface Profile

CHAPTER ONE: GENERAL INTRODUCTION

1.1 GENERAL BACKGROUND OF THE STUDY

Water resource is; a basic human right, annually renewable, scare, finite, and received on the earth's surface as precipitation (either in the form of rain or snow). Its demand is ever increasing to satisfy and save mankind, like but not limited to the following:

a) Drinking purpose,
b) Agricultural use,
c) Industrial use,
d) Municipal use,
e) Recreational activities, and Power generation among others.

In order to meet these ever increasing demands, storage reservoirs need to be constructed. These storage reservoirs may be created in river valleys by building of a barrage across the river to block the natural flow of water such that it can reserve sufficient water behind them to supplement the various demands during periods of paucity. The construction of a dam however, does not only store sufficient water behind them but also alters the natural equilibrium of sediment flow in a river due to the extra ponding created upstream.

The quantity and quality of sediment in a flowing stream depends upon several factors. The stream may be in an unsaturated condition if its capacity to pick up particles is more than the available particles at its bed or banks. In such cases the stream picks up particles at the first available opportunity and exhibit the scouring property. If the capacity of the stream to carry a particular load of sediments equal the available sediment load in the stream then it is said to be in the 'regime' condition, that is non-scouring and non-silting. But, if the capacity of a stream to pick up particles is less than the quantum of sediment particles carried by it, then the stream is in super saturated condition and it will shed (deposit) the particles on its bed or banks and exhibit a silting property.

Therefore, when this stream (sediment laden) flow enters a reservoir, its flow velocity drops due to increase in cross sectional area and so is the collapse in the transport capacity. As a consequence, the silt content carried in the flowing stream will start to shed right at the entrance of the reservoir to form the delta (coarse particles) and it (deposit) advance towards the dam as time passes on. These sediments will continue to deposit in the reservoir until a new equilibrium (when sediment in equals to sediment out) is reached, depending upon certain factors such as; the sediment trap efficiency of the dam, sediment size, reservoir operation, length of the reservoir, viscosity (water temperature), age of the reservoir, type of the reservoir and so on.

These deposits endanger the optimal use of water resources projects in many river basins all over the world, which India is not an exception especially in its Himalayan regions with steep slopes, undeveloped and flimsy rocks. As time goes on the deposited portion of the sediment will start reducing the useful storage capacity resulting in the drop in useful life and the socio-economic benefits of the reservoir. The accumulation of sediment in a reservoir can cause both serious short and long term hazards such as but not limited to the following;

i. wearing of turbine blades by quartz rich sediment, if sediment gets entry into power channel,
ii. reduction in power generation,
iii. damage to agricultural land resources from over wash of infertile material,
iv. loss of useful reservoir life,
v. changes to river morphology,
vi. aggradation and loss of navigable depths upstream,
vii. the river channel and aquatic habitat d/s gets degraded, and lessening of planktons sources for fish in rivers d/s of dams due to limited supply of silt,
viii. impairment of natural drainage,
ix. increased unnecessary load on the dam which may lead to early dam failure and so on.

As a continuous normal depositional process, reservoir sedimentation can stay beneath the water and far out for a noteworthy segment of the store life, however, the absence of visual proof does not lessen the potential effect. Evaluation of the pattern and rigorousness of sedimentation can act as a starting point for any analysis. Based on (Gregory et al 1998), "this appraisal tries to portray the physical procedure of reservoir siltation and the past and plausible upcoming rate, area, and characteristics of deposited silt." Performing mathematical modeling and geomorphic analysis and analysing latest hydrographic survey to conclude the past form and rate of deposition can be a good assessment. Attention during the evaluation has to be paid to land use trends, upstream reservoirs because they are potential factors contributing to future rates of silt delivery.

1.1.1 Sediment Yield from Watershed

Sediment yield is the end product of gross soil erosion, mostly by water from the watershed above the reservoir. Erosion, however, is a post weathering process. Gregory et al. (1998), defined weathering as " a gradual chemical and mechanical activity in the watershed which change rock formation, weakening it (rock) and finally disintegrate into soil." While erosion is "the removal of weathered and disintegrated material from one place to another, by agents such as; glaciers, water streams, and wind," Asthana et al. (2007). When erosion involves the removal and transport of particles from a highland due to rain splash, it is termed as sheet erosion. And gullies and channel erosion are slow or massive in bed and sides of the gullies and channels. It should however be noted that not all materials eroded and transported by agents of erosion are successfully deposited in reservoirs. Sediment yield is therefore the amount of sediment that successfully make its way to a gauging site or any point of interest in water resources projects, such as reservoirs. This shows that erosion rate is greater than sediment yield and the ratio between the sediment yield and the erosion rate is the sediment delivery ratio. Erosion may be affected by several factors such as; climatic factors (for example rainfall, which depend on its intensity, duration and frequency), physical factors (like; size and length of the catchment area, slope steepness and its length, drainage density, soil type, soil cover and land use), and geological factors (say rock type for example). It should also be noted that sediment yield varies in space and time.

1.1.1.1 Spatial Sediment Yield Variation

"The summation of wash load, suspended load, and bed load equals to the total silt load in rivers," (Annandale et al. 2016). Bed load is located on a river bed as it contains the coarsest part of the sediment carried by a river. This bed load is dragged along the river bed by flowing water by rolling, sliding, and saltating. Annandale et al. (2016) also stated that "based on the transport ability of the river, the amount of bed material can either increase or decrease, for example; there shall come a point when the bed solid that hoops may wind up in the water segment," and will become "suspended load." Also according to them, "it is important to note that, 100 per cent of bed material is normally trapped by reservoirs". The turbulence in the water is capable enough to keep the suspended load in suspension because it mostly consists of finer sediment particles that are lighter. However, if the silt transport capability of the streaming water further decreases, due to change in velocity of flowing water, decrease in slope of the terrain or sudden increase in water depth and thus diminishing the water uproar, part of the suspended constituent may deposit to become bed load for a second time. This therefore, means some of the suspended load may be deposited in the reservoir and the rest shall be carried by the river flow further downstream depending on the river hydraulic characteristics, particle size, reservoir operation, among others. Wash load usually is of no importance to a water and hydraulic engineer or water resource planner.

Gregory et al. (1998) however stated that "universal changeability in silt yield cannot be explained by only one constraint or a grouping of constraints."

"The large variability in precise sediment yield worldwide was summarised on the Tab. 1.1 below by Jansson (1988), analysing suspended silt data from 1358 gauging locations with tributary watersheds between 350 and 1,000 square kilometer, and totaling 16 million square kilometer of land," as reported by Gregory et al. (1998).

Table 1. 1: Worldwide Sediment Yield Variation

Yield class, t/sq. km/yr.	Number of gage stations	%age of gaged land area	%age of total gaged load
0-10	230	21.3	0.3
11-50	285	25.6	1.8
51-100	172	11.9	2.1
101-500	426	25.6	14.7
501-1000	145	6.9	21.0
>1000	179	8.8	60.1

(**Source:** Jansson (1988) as reported by Gregory et al. (1998))

A summary of sediment discharge from the world's largest rivers is shown on Tab. 1.2 below. "Yellow River in China drains extremely erosive loess soils, and the Ganges/ Brahmaputra drains the tectonically active and glaciated Himalayas, and human disturbance is also important in both basins," Gregory et al. (1998).

Table 1. 2: Positioning of the Sediment Load Deposited in the Ocean by Rivers in the World

River	Country	Average silt discharge, 10^6 t/yr.
Ganges/ Brahmaputra	India	1670
Yellow	China	1080
Amazon	Brazil	900
Yangtze	China	478
Irrawaddy	Burma	285
Magdalena	Colombia	220
Mississippi	United States	210
Orinoco	Venezuela	210
Hungho (Red)	Vietnam	160
Mekong	Thailand	160

Estimates made of sediment yield on continental basis are given in the Tab 1.3 below according to (Mahmood 1987).

Table 1. 3: Worldwide Distribution of Runoff and Sediment Load

Area	Precipitation			Runoff		Measured Sediment		Yield
	mm	km^3	%	km^3	%	M t/ yr.	%	t/ km^2/ yr
N. America	756	15.8	15.4	6.6	17.1	1.46	10.9	84
Asia	740	25.7	25.0	10.8	28.0	6.35	47.4	380
Africa	740	19.7	19.2	4.2	10.9	0.53	3.9	35
S. America	1600	27.0	26.2	11.8	30.5	1.79	13.3	97
Europe	790	7.5	7.3	2.7	7.0	0.23	1.7	50
Australia	791	7.1	6.9	2.5	6.5	0.60	0.4	28
Oceania						3.00	22.4	1000
Total		**102.8**	**100**	**38.6**	**100**	**13.42**	**100**	**1674**

(**Source:** Mahmood 1987)

From the Tab 1.3 above, it can be seen that sediment yield from basins in Asia is greater than twice of the world average and contributes about 50 per cent of the total world sediment.

"Another estimate cited by Jolly (1982) as reported by (Asthana 2007), puts this figure to about 80 per cent. The maximum sediment yield (1000 tons per sq. km year) occurs in basins in Oceania which include catchments in New Zealand, New Guinea, Taiwan and so on. The lowest rate of sediment yield occurs in Australia (28 t/km^2/ yr). This is attributed to aridity in the region. Due to low sediment yield the reservoirs in Australia do not face severe problem of sedimentation as well as those in Europe," Asthana et al. (2007).

1.1.1.2 Temporal Sediment Yield Variation

Temporal sediment yield variation may be due to the following natural and artificial factors: Continuing changes in sediment yield due to geomorphic factors, long-term changes due human disturbances, changes due to seasonal variability, changes due to inter-annual variability, and within-storm variation in suspended load and so on.

And the life of the reservoir depends on the rate at which sediments are being deposited. The life of a given reservoir reduces as its useful storage is filled by silt.

1.1.2 Life of a Reservoir

A reservoir's life depends upon so many factors as defined below:

- **Useful life.** The duration in which the space taken by the deposited sediment does not interfere with the normal functioning of the reservoir.
- **Economic life.** This is reached when the benefits realised from using the reservoir become equal to or less than the cost of running the reservoir.
- **Design life.** This is the expected economic life based on the practices through which benefits are compared with cost. It is generally taken as 50 or 100 years depending on the agency owning the project.
- **Usable life**. After expiry of its economic life, the reservoir can even keep on filling a portion of the needs to a restricted extend separately or in conjunction with additional facilities created for the purpose.
- **Full life**. When the gross capacity of the reservoir is fully filled by sediment.

1.1.3 Reservoir Silting Rate

"All reservoirs, big or small, created by constructing a dam across a river are subject to silting naturally which results in reduction of storage capacity," (Asthana et al. 2007). The Fig.1.1 below shows the rate of silting in some selected locations. Soil erosion which is responsible for the generation of silt in catchment areas is accelerated by; uncontrolled deforestation, cutting and burning of bush lands, overgrazing of grass lands, improper methods of ploughing, and reckless land use practices, causing a great escalation of sediment influx into watercourses.

Asthana (2007) stated that "sediment in the inflow and the capacity inflow ratio are the two most important factors inducing the rate of silting in any reservoir, whereas, supplementary dynamics which upset the loss in storage capacity in the long run are: The trap efficiency, Sediment characteristics, and The reservoir operation adopted.

The above factors are closely related in that if the capacity is small then the reservoir shall be filled up by silt very fast as compared to big reservoir with large capacity-inflow ratio (c/i). Also, a reservoir having large c/i ratio will trap large amount of sediment entering the reservoir and it will have high trap efficiency". Reservoirs as silt traps will as expected do so for all the inflowing coarse sediment until the reservoir reach its sediment storage capacity. However, not all inflowing silt are trapped by the reservoir as some quota of clay and silt-size sediments can still be transported through the reservoir, principally throughout eras of high influxes. Therefore, this quota of incoming sediment dumped in the reservoir is known as the sediment trap efficiency (the ratio of the retained silt to the total silt inflow).

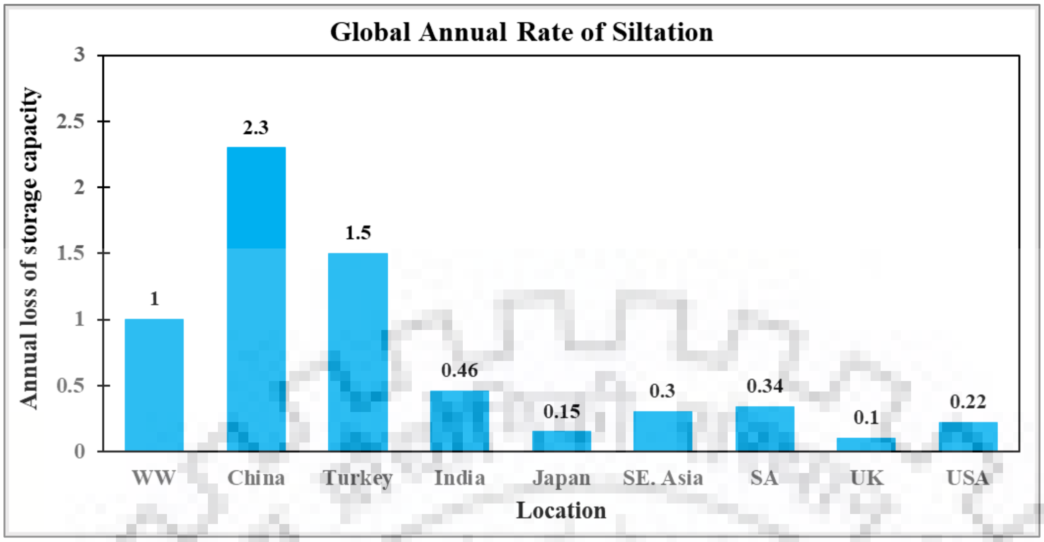

Figure 1. 1: Rate of Siltation Globally

NOTE: WW: Worldwide, SE. Asia: South east Asia, SA: South Africa, UK: United Kingdom, USA: United States of America

1.1.4 Generalised Deposition Patterns

It was generally perceived or assumed initially that sediment gets deposited in the dead storage and so sufficient space should be provided in the reservoir as dead storage to accommodate the sediment entering the reservoir during its life time. However, with the onset of capacity surveys of reservoirs (like bathymetric survey), this assumption was found to be untrue because the surveys revealed that sediment get deposited everywhere in the reservoir and starts even reducing the live storage from the first year of its operation.

So, when an inflowing river enters an impounded reach, its flow velocity gets reduced due to increase in cross-sectional area and thus the silt starts to deposit. The coarse fraction of the sediment with high settling rates get deposited straightaway creating topset bed. Finer silts have lesser falling speeds which makes them to travel further downstream towards the dam by stratified and non-stratified flow. These deposits are called bottomset bed while the transition between topset bed and bottomset bed is the foreset bed.

The Fig. 1.2 below represents a generalised longitudinal deposition profile of the main three zones of deposition in a reservoir.

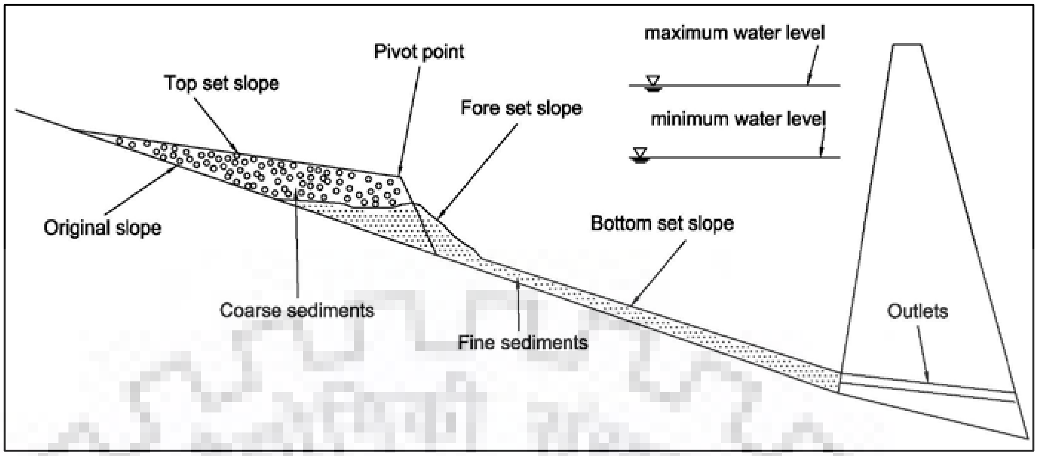

Figure 1. 2: Typical Deposition Pattern in a Reservoir

(Source: George W. Annandale, Gregory L. Morris, and Pravin Karki as cited by (Pande et al. 2015))

There are anyway four basic types of deposition patterns depending upon various factors as mentioned above. These shapes are shown in the Fig. 1.3 below.

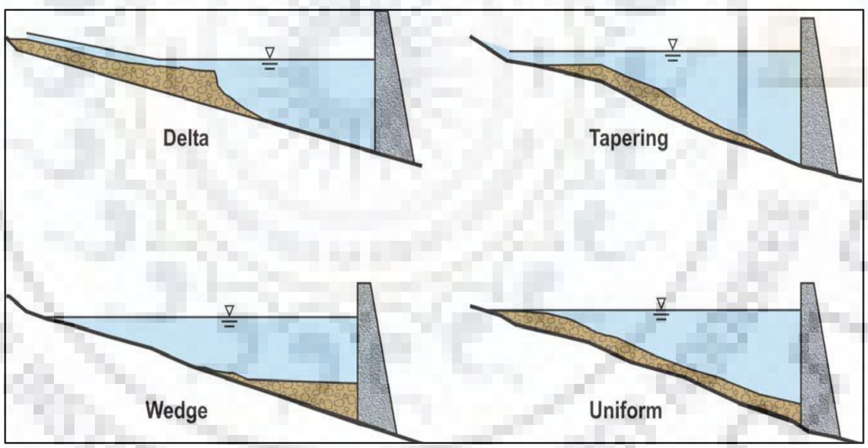

Figure 1. 3: Morris et al. (1997). Four Basic Patterns of Reservoir Sediment Deposition

The above four basic longitudinal patterns of reservoir sedimentation are described below:

1. **Delta deposits**: Are the coarsest part of the silt that get placed first in the mouth of the reservoir. Depending upon the retention time, delta deposits can be entirely composed of coarse sediment (if the holding time of water is not long) or it may as well comprise a substantial segment of fine sediment if the retention time is long.

2. **Wedge shaped deposits**: Usually thinner in upstream and thickest at the dam, mainly occurring due to movement of fine silt towards the dam by turbidity currents.
3. **Tapering deposits**: These become gradually thinner towards the dam, especially in long reservoirs habitually operated at a high level and echoes advanced shedding of fine sediments in d/s course.
4. **Uniform deposits**: Though regarded unfamiliar they do transpire in tapered pools with recurrent water level variation and small fine sediment load may lead to the formation of almost linear deposition depths.

Dam designers are therefore confronted with the task of knowing how much sediment (sediment yield) is being transported and deposited in reservoirs, the rate at which the reservoir capacity is consumed and the shapes or pattern formed by the deposited sediment.

1.1.5 Study Area

1.1.5.1 Bajoli Holi Hydroelectric Project

Bajoli Holi is a run of river project which has salient features as shown in the Tab. 1.4 below.

Table 1. 4: Salient Features of Bajoli Holi Hydroelectric Project

Name of Project	Bajoli Holi HEP
Country/ State/ District/ Village	India/ Himachal Pradesh/ Chamba/ Holi
Coordinates	Lat: 32° 16’ 49’’ N, Long: 76° 40’ 36’’ E
Start of Construction	2013
Commissioning	2019 (proposed)
Purpose	Hydropower generation
Storage type	Run of River
Dam Spillway	
Top of Dam (m)	2020
Stream Bed Level (m)	1975
Dam Foundation Level (Lowest) (m)	1954
Dam Height from Foundation Level (m)	66
Dam Length (m)	178
Spillway Crest Elevation (m a.s.l)	1985
Pier thickness (m)	7 each

Continued on the next page

Intake Crest Elevation (m)	2000
Power Discharge (cumec)	83.1
Power House	
Location	Lat: 32° 20’ 52’’ N, Long: 76° 31’ 58’’ E
Type	Surface power house
Installed capacity (MW)	180 (3 * 60)
Hydrology	
Basin	Ravi/ Indus
Catchment area (sq. km)	902
Area under snow (km^2)	296
PMF (cumec)	7419
Reservoir	
FRL (m)	2018.25
Area of Reservoir at FRL (ha)	16.5
Length of Reservoir at FRL (km)	2.42
MDL (m)	2012
Gross Storage Capacity (MCM)	3 (about)
Dead Storage (MCM)	2 (about)
Live Storage Capacity (MCM)	1 (about)

1.1.5.1.1 Description of Bajoli Holi Project Area

Himachal Pradesh is circumscribed by Jammu and Kashmir in the north, Tibet (China) in the east, Uttarakhand in the south-east and Punjab and Haryana in the south.

The state is characterised by snow and glaciers in many of its areas in the north and east. Sutlej, Beas, Parbati and Ravi are the noticeable rivers rising from these upland glacial zones, all of these rivers flow either South or southwest.

The present run-of-river project (has an installed capacity of 3 * 60 MW). The project is one such scheme in the state located just upstream of Kutehr (240 MW) in Chamba district Fig. 1.4, developed in Ravi river basin. Among the five major tributaries of Kalihan, Budhil, Tundah and Suil and Ravi.

This project does not have scope of irrigation due to the mountainous nature (with altitudes ranging from 559 m to 6,200 m) of most parts of the state. For this, the scope of the project is to harness the hydro electrical potential of Ravi river in its upper reaches. Besides supplying power within the state, the project also supplies power to other northern states of Jammu and Kashmir, Uttarakhand, UP, Union Territory of Chandigarh, Punjab, Haryana, and Delhi through the Northern Regional Grid System.

The project site is about 190 km from Pathankot and roughly 80 km from Chamba, which is the district headquarter of Chamba district. The nearest Broad Gauge railhead, as well as the nearest airport, is at Pathankot.

In Himachal Pradesh state the climate varies from sub-tropical in lower reaches of the valley to sub-arctic conditions in the upper northern areas. Chamba district in Ravi valley covers an area of 6528 km^2.

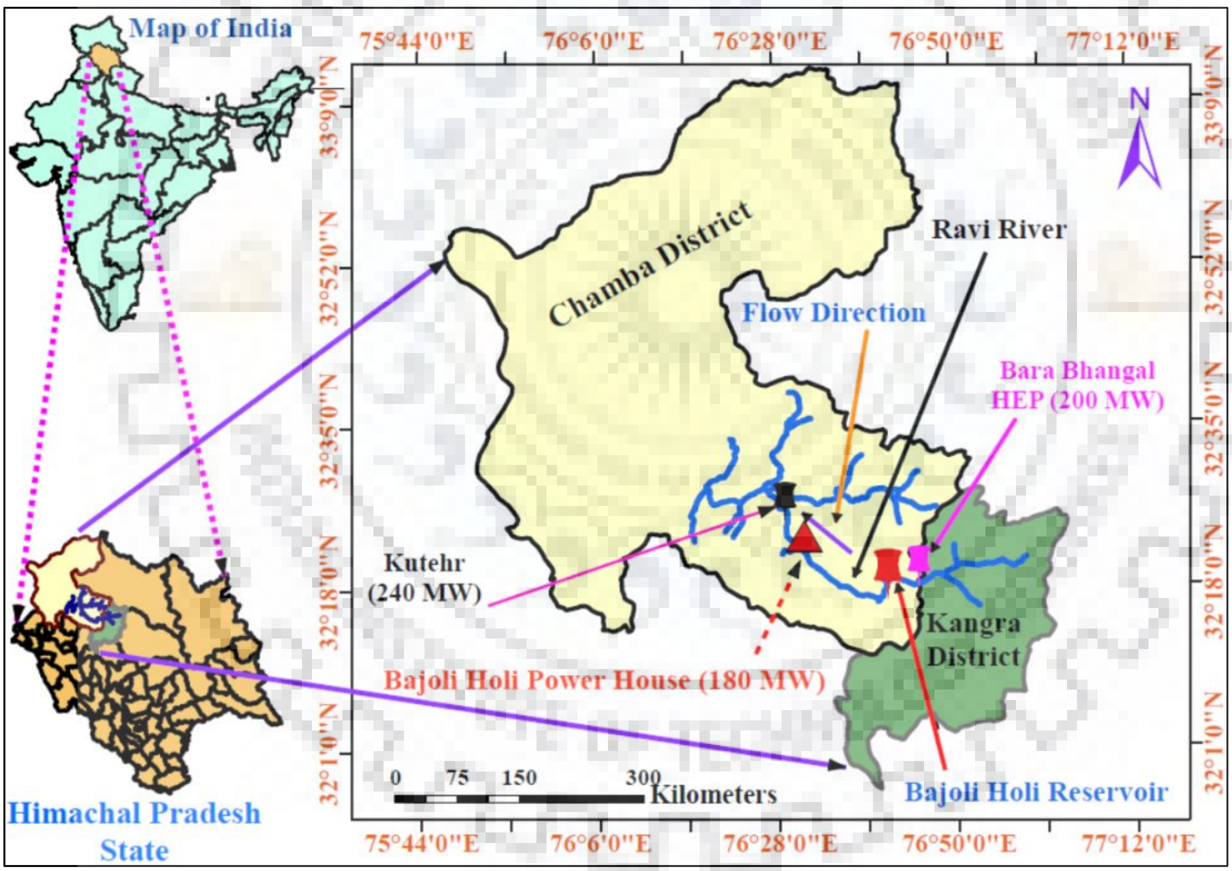

Figure 1. 4: Map Showing the Location of Bajoli Holi HEP

1.1.5.2 Description of Tehri Dam and Reservoir

Tehri dam project is the first major storage scheme in Bhagirathi valley which evolves construction of a 260.50 metres high clay core earth and rock- fill dam across the river Bhagirathi about 15000 metres downstream of the convergence of river Bhagirathi and Bhilangna river, a major tributary of River Bhagirathi figure 1.5**.** This multipurpose river valley project has salient features as given on table 1.5 below.

Table 1. 5: Salient Features of Tehri Project

Project Name	Tehri Multi-Purpose Project
Country/State/ Village	India/Uttarakhand/ Tehri Garhwal
Impounding River(s)	Bhilangna and Bhagirathi
Coordinates	30° 22' 40'' N, 78° 28' 50'' E
Start of construction	1978
Commissioned	2006; 1st stage, the rest is still under construction
Dam	
Type	Earth and rock fill
Height (m)	260.5
Top level (m)	839.5
Top width (m)	25.5
Length at top (m)	595.25
Reservoir	
Maximum flood level (m)	835
Reservoir length (km)	About 42 along Bhagirathi and 25 along Bhilangna
Surface area at FRL (sq. km)	42
FRL (m)	830
MDDL (m)	740
Total storage (MCM)	3,540
Live storage (MCM)	2,615
Dead storage (MCM)	925
Catchment area (sq. km)	7,511
Crest level (m)	815 / 830.2
Maximum discharge (cumec)	13,040
Power House	
Type	Underground
Planned capacity (MW)	2,400 (3 stages) (1000 + 400 + 1000)
Installed capacity (MW)	1,000 (Stage – I) + (400 Koteshwar)
Conventional / Reversible units (No. * MW)	4 * 250
Gross head (m)	231.5
Minimum head (m)	127.5

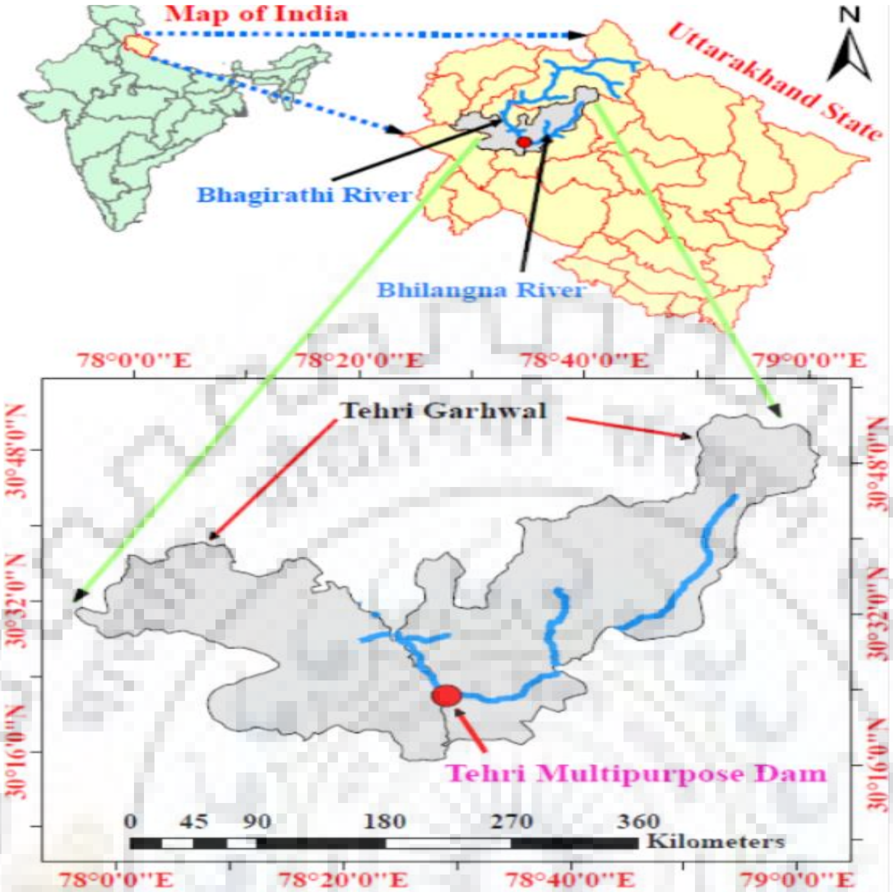

Figure 1. 5: **Location of Tehri Multi-Purpose Dam**

1.1.5.3 Catchment Area for Tehri Reservoir

The catchment area of Tehri dam (Fig. 1.6) is about 7511 sq. km. and is spread over a length of 187 km. Out of the total catchment area about 31 per cent is snow bound, 32 per cent is reserve forest land and remaining 37 per cent comprises of cattle grazing and private agriculture land. The snow bound catchment contributes run off only in lean periods due to melting of snow. The balance 69 per cent of the catchment suffers about 100 to 263 cm average annual precipitation, 80 per cent of which is received during monsoon period only. The valley receives heavy torrential rains causing floods in the river. Both valleys (Bhagirathi and Bhilangna) have steep side slopes and are quite narrow. The bed slopes are quite high varying from 10 m / km at mid distance to 5 m / km near the dam site. The valley at certain places is prone to land slide and has deep deposits of debris, hillside wastes and colluvial talus. Furthermore, the rocks are susceptible to considerable weathering and erosion. Due to weaker rocks, steep bed slopes and similar valley characteristics, river Bhagirathi carries sizable amount of suspended sediment and bed load.

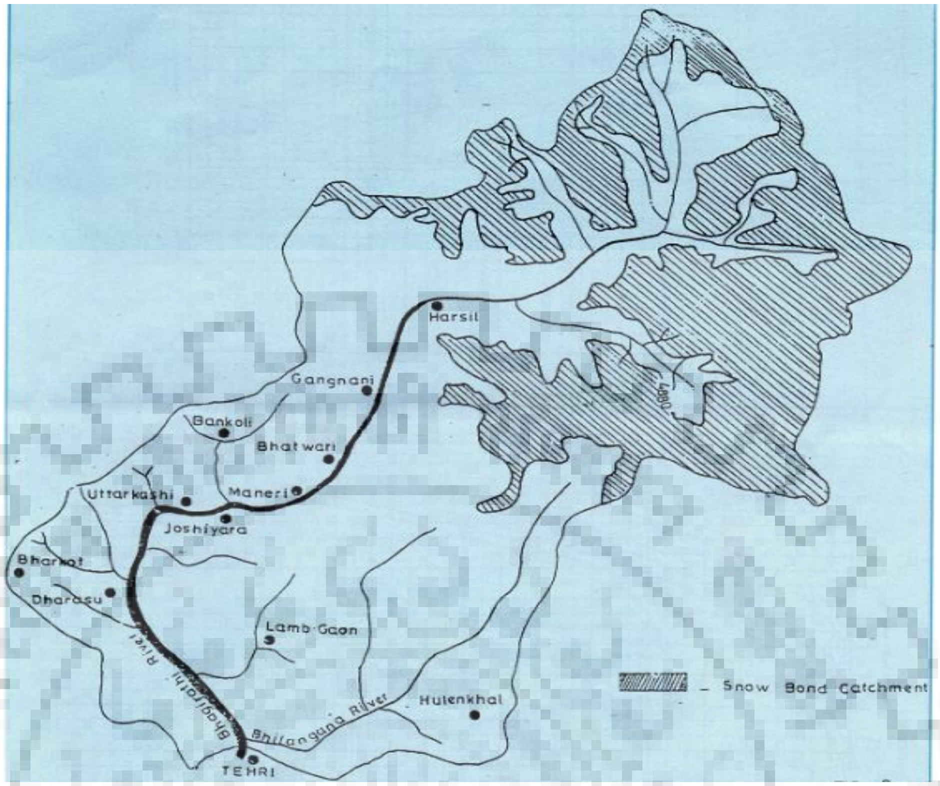

Figure 1. 6: Tehri Catchment Area

1.1.6 Research Gaps

The amount of annual damage of storage capacity in the world is estimated at about 0.5 to 1 %, resulting to a total of approximately 11.8 % storage capacities which have already been lost. In India, it is at about 0.5 % per annum.

Many Indian reservoirs are situated on waterways with high silt concentrations especially in monsoon, particularly in the Himalayan regions (Indus, Ganga and Brahmaputra), where the slopes are very steep and rocks are young and fragile. Also, thousands of RoR schemes are coming up in India. Yet siltation and its management in these schemes such as Bajoli Holi having small storage capacity is still a problem. Such schemes call for an effective and efficient sediment removal methodology to make the project servicing for a long time. This requires a good assessment of sediment deposition pattern and optimum frequency of silt flushing. In the case of project under consideration (Bajoli Holi), where the live storage capacity is only about 1 MCM, the reservoir capacity is expected to be filled up very fast.

And most of the multi-purpose hydroelectric schemes such as Tehri, located in mountainous regions too face a major problem of high silt deposition which goes on progressively until the reservoir is filled up partially or fully. When a reservoir is filled up to a certain limit or upto the crest of intake then these deposits will start to interfere with the primary purpose(s) for which the project was built for. In this case the project's full life is said to have been reached and it may then lead to the closure of the project by retiring else it becomes a run of river.

1.1.7 Study Objectives

The primary objectives of this study were to;

a) Estimate the quality and quantity of sediment deposited, its distribution pattern formed and establish a silt removal technique for Bajoli Holi run of river project,
b) To approximate the quality and quantity of sediment deposited, find its distribution pattern and rate of deposition in Tehri reservoir, and
c) Assess the life of Tehri reservoir.

To achieve the above objectives an HEC-RAS 5.0.5 mathematical model was used in both projects.

1.1.8 Organisation of Dissertation

Chapter 1: In this section, the General Background of the Study including rate and pattern of reservoir sedimentation, description of the Study areas, Research gaps, and Objectives of the Study are presented.

Chapter 2: The main objective of this chapter (Literature Review) is to bring forward what some of the previous studies related to the main topic of this particular study have been about.

Chapter 3: This chapter describes all the various data used, the philosophy adopted for simulating reservoir sedimentation in both the study areas, and it also discusses briefly the capabilities of HEC-RAS 5.0.5 software.

Chapter 4: The running and results of the model studies are being scrutinised and discussed into detail in this part of this book.

Chapter 5: Finally, the overall conclusions derived from the analysis of using HEC-RAS 5.0.5 mathematical model, recommendation(s), and the scope for further studies are presented in this last chapter.

CHAPTER TWO: LITERATURE REVIEW

2.1 INTRODUCTION

There are lots of literature on reservoir sedimentation. Various methods have been employed to assess reservoir sedimentation such as numerical modeling, use of ArcGIS and RS, mathematical modeling using various software like HEC-RAS, MIKE Zero and so on. But, the main objective of this chapter is to only highlight some previous studies related to the main topic of this particular study, as shown below.

2.2 SOURCES OF SEDIMENT

According to (Asthana 2007), " most sediment which are deposited in reservoirs originate from the catchment area of the river above the reservoir." Sediment that enter waterways are products of erosion which is a post weathering process. Apart from destruction to rain fed agricultural and forestry ecosystems, the effects of erosion reach also into surrounding environments like river systems.

2.2.1 Sediment Transport in a River

The river during its course to the reservoir, picks up sizeable amount of sediment and carries it along either as suspended load or bed load (Fig 2.1 below) and when it enters a reservoir, these sediments sink down and it keeps on doing so as time passes on. On this account of continued deposition, the useful storage capacity of the reservoir is progressively lost and hence its reliability goes on reducing with time.

"Sediment transport in a river may be conceived as bed material or suspended material, depending on the forms and rules of movement or it may be categorised as bed load and wash load according to their particle size, its source and effect in fluvial methods," (Gregory et al. 1998, Xiaoqing et al. 2003 and Asthana 2007). Bed load is usually characterised by sliding or rolling and saltating or jumping particles along the bottom of the river. Whereas, the suspended load is lifted from the bed load when shear stress exceeds critical tractive force needed for initiation of motion and these particles are sustained in suspension by water turbulence. Lastly, the wash load is carried by the river flow and remains in suspension even in still water. This load is usually not of interest to hydraulic and water engineers. “Volume and weight are the main ways of expressing the concentration of suspended sediment,” Asthana (2007).

Xiaoqing et al. (2003) in their report also agrees with (Gregory et al. 1998 and Asthana et al. 2007), in the classification of sediment transport loads in a river.

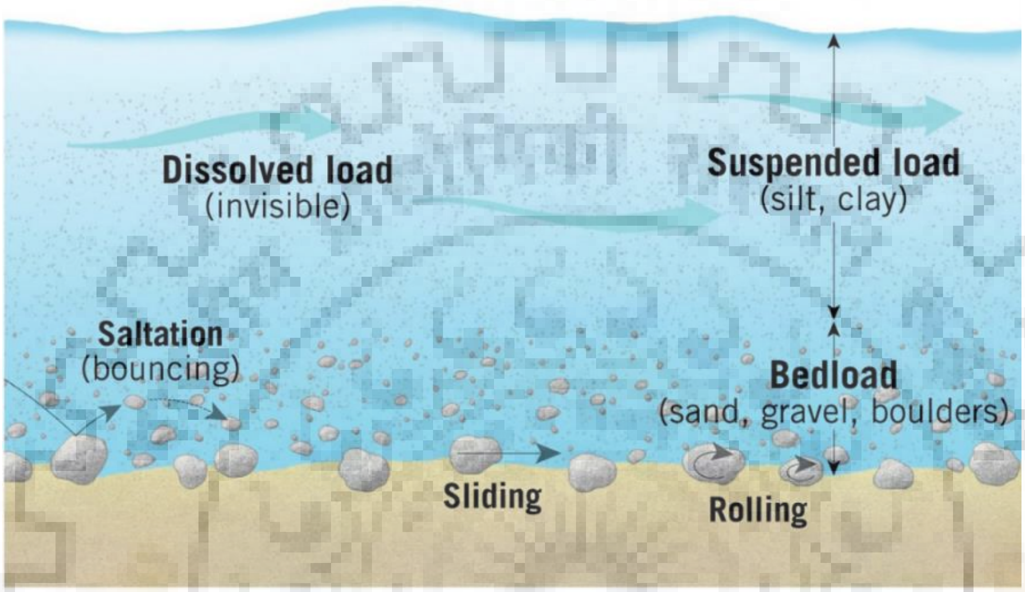

Figure 2. 1: Modes of Sediment Transport in a River, Lutgens et al. (2015) as cited by (Weedman et al. 2017)

2.2.2 Sediment Transport in a Reservoir

Annandale et al. (2016) stated that “in a reservoir sediment transport may be characterised as density/ or turbidity currents and conventional sediment transport.” Density or turbidity currents occur due to difference in densities between the incoming sediment laden water and the still and clean reservoir water. As such the heavy sediment laden water may therefore travel a long distance beside the reservoir’s bed in the direction of the dam. In case of conventional sediment transport, it is defined by uproar in water running through a reservoir, where coarse silt particles are carried along the bed while the suspended load is distributed in the entire water column as opposed to turbidity current transport where sediment is transported along the bed only.

“When sediment finally enters a reservoir it eventually gets deposited due either increased sediment supply or decreasing water velocity as a result of increased cross sectional area,” (Weedman et al. 2017).

2.3 SEDIMENT MANAGEMENT TECHNIQUES

(Annandale et al. 2016), classified 4 groups of sediment management techniques; approaches to diminish silt production in the u/s, passing (routing) of sediment laden water through or around a reservoir to lessen its deposition, removal of deposited sediment, and adapting to sediment. To cut sediment generation from upstream, measures like soil and channel erosion at its source need to be diminished and eroded sediment need to be trapped before reaching a reservoir. "Sediment routing may involve any method to either manipulate reservoir hydraulics or geometry, or even both, to pass sediment through or around the reservoir while minimising intolerable deposition," (Gregory and Jiahua 1998). Whereas, sediment bypass involves on-channel storage, off-channel storage and subsurface storage. Sediment flushing and sluicing (routing) are two terms that need not to be confused. The former is the removal of settled sediments (usually coarser fractions) yet the latter is moving silts (usually finer fractions) through or around the reservoir in periods of high flows. Flushing depends upon many parameters including but not limited to area of the deep sluices, quantity of water released through deep sluices, the sluices size, the geometry of the reservoir, the size and the kind of the deposited sediments in the reservoir. Finally, deposited sediment can be removed through mechanical excavation (dry excavation or dredging) and hydraulic scour and so on. Hydraulic scour usually requires depleting the reservoir by opening all the sluice gates and is mostly done during monsoon season when there is enough discharge.

Maximum usable life of a reservoir can be realised through some of the many methods that have been evolved and are in use worldwide to sustain reservoir life. Some of the methods are watershed management, mechanical dredging and flushing through deep sluices. Fruchard & Camenen (2012) and Kondolf et al. (2014) studied reservoir operation and sediment management for various dam projects. They widely concluded that of all the measures being used to control the sedimentation effects, the deep sluicing and deplete flushing are most effective and are being used in most of the Asian countries. And that is why despite lots of research and field experience in sediment management, no unique solution is yet available to the problem.

A study on sediment management of a run-of-river HEP in the Himalayan region of Kotlibhel in Uttarakhand, India, using an HEC-RAS model was carried out by Isaac and Eldho (2017). The study concluded that reservoir depleting flushing after regular intervals is quite efficient in restoring the reservoir capacity. A discharge of 500 cumec or more for 12 hours is sufficient for flushing the deposited sediment during monsoon season.

Reservoir flushing has proven very successful in some of the world reservoirs (as shown in the Tab. 2.1 below) while in some cases it (flushing) has shown little or no success.

According to a working paper written by (White 2012), after a worldwide study of 50 reservoirs which were being or have been flushed, stated some of the following conditions for a successful sediment flushing: Hydraulic conditions required for efficient flushing, The hydrology (like annual rainfall amount) and sedimentology of the catchment, The storage capacity of the reservoir (site specific), The sediment deposition potential, The shape of the reservoir basin (site specific), The deployment of full or half emptying, The deep sluice facilities provided, Operational limitations (purpose for which the reservoir was built), The scope for enhancements to flushing, and Downstream impacts.

Table 2. 1: Some Successfully Flushed Reservoirs in the World

Reservoir	Country	Reference
Baira	India	Jaggi and Kashyap (1984)
Gebidem	Switzerland	Dawans et al (1982)
Gmund	Austria	Rienossl and schnelle (1982)
Hengshan	China	IRTCES (1985)
Honglingjin	China	IRTCES (1985)
Mangahao	New Zealand	Jowett (1984)
Naodehai	China	IRTCES (1985)
Palagneda	Switzerland	Swiss Nat. Committee on Large Dams (1982)
Santo Domingo	Venezuela	Krumdiek and Chamot (1979)

(**Source:** Atkinson 1996).

2.4 INTRODUCTION TO HEC-RAS

The mathematical model namely HEC-RAS is being used for Hydraulic investigations and river morphological modeling. "This model is developed by the United States Army Corps of Engineers and it permits to execute 1-D steady, unsteady flow hydraulics, **sediment transport or mobile bed** computations for quantifying the effects of new structures and their operation in the river," Brunner (2016). The framework consists of a graphical user interface (GUIC), distinct hydraulic investigation modules, DSS abilities, graphs and reporting abilities. **The sediment transport potential** is calculated by grain size fraction, thus permitting the simulation of hydraulic sorting and armoring, if the case be. The model is planned to simulate long-term changes of scour and deposition in a river that might result from adjusting the regularity and period of the water discharge and stage, or altering the river geometry.

2.4.1 Previous Studies using HEC-RAS

(Mohammad et al. 2016) successfully applied an HEC-RAS model using Ackers-White transport function and Exner equation to simulate silt loads, identifying the geometry of the main path of the river and reservoir, using different cross sections along the Mosul dam reservoir on Tigris river in northern Iraq. The model was calibrated to simulate the flow in Mosul reservoir by determining the degree of agreement between the observed and simulated reservoir levels at different times of the simulation period from 1986 to 2011.

Tiwari and Sharma (2012) applied an HEC-RAS model for the study of reservoir sedimentation in Wangchu (Bhutan). A fourteen year (1994-2008) sediment discharge data was used and Yang transport function was applied based on its suitability to the conditions of the study area. And using a 2 years' data, contour map and cross sections imported from Arc-GIS, the HEC-RAS model was calibrated.

Ochiere et al. (2015), also carried out a "performed a simulation of mobile bed inside the underground canal in Southwest Kano Irrigation Scheme boundaries using HEC-RAS model." Because of its ability to predict sediment sizes deposited at specific sections of the canal at different flow rates, the authors used Ackers-White sediment transport equation in their HEC-RAS model. Specific locations of sediment deposition within the canal can easily be identified and removed through a sediment management strategy.

An HEC-RAS model was further applied by Shelley et al. (2017) to Tuttle Creek Lake, a multipurpose reservoir in Kansas River basin, for calculating the technical likelihood and efficiency of fluctuating the reservoir operations to reduce sediment trapping efficiency. They also stated that "to build or calibrate a model, a baseline survey is needed for building a model geometry and a final survey to compare the model output."

Another flushing event using HEC-RAS model was applied by (Gibson et al. 2018) to Spencer dam on Niobrara river which is one of the only reservoirs in the United States which consistently operates for sediment sustainability objectives. This flushing event was monitored, measured, and modeled with HEC-RAS 5.0, an unsteady one dimensional, mobile bed sediment model. It was found out that when the reservoir was not flushed in the spring of 2014, leaving one full year of sediment accumulation in the reservoir, the reservoir was nearly filled up. This experience clearly shows that timely sediment flushing is very essential.

CHAPTER THREE: METHODOLOGY ADOPTED

3.1 INTRODUCTION

In this chapter, all the data used (some shown on Tab. 3.1 below) and the philosophy adopted for simulating reservoir sedimentation in both the study areas is being discussed into detail.

Table 3. 1: Some of the Data used during the Simulation

Project	Data used	Source	Application
Bajoli Holi	Cross sections	IRI	To build the model geometry.
Tehri			
Bajoli Holi	Discharge	Arbitrary	U/S BC for simulating steady and quasi unsteady flow.
Tehri		THDC Published	
Bajoli Holi	Manning's n value(s)	IRI	For model validation
Tehri			
Bajoli Holi	Sediment input and gradation	IRI	To execute the sediment transport simulation.
Tehri			

To perform any simulation with HEC-RAS, it is first required to perform the following mandatory steps (also shown on the Fig. 3.1 below);

1) create a new project,

2) define the geometry of river reach, enter the necessary geometric data including an inline structure (dam) as in this study,

3) enter test flow data and define boundary conditions for both u/s and d/s,

4) fix test hydraulic conditions like sediment load and particle size, pond level(s),

5) perform the test hydraulic calculations (steady and quasi unsteady simulations, and sediment simulations), as maybe required, and

6) review of output and results.

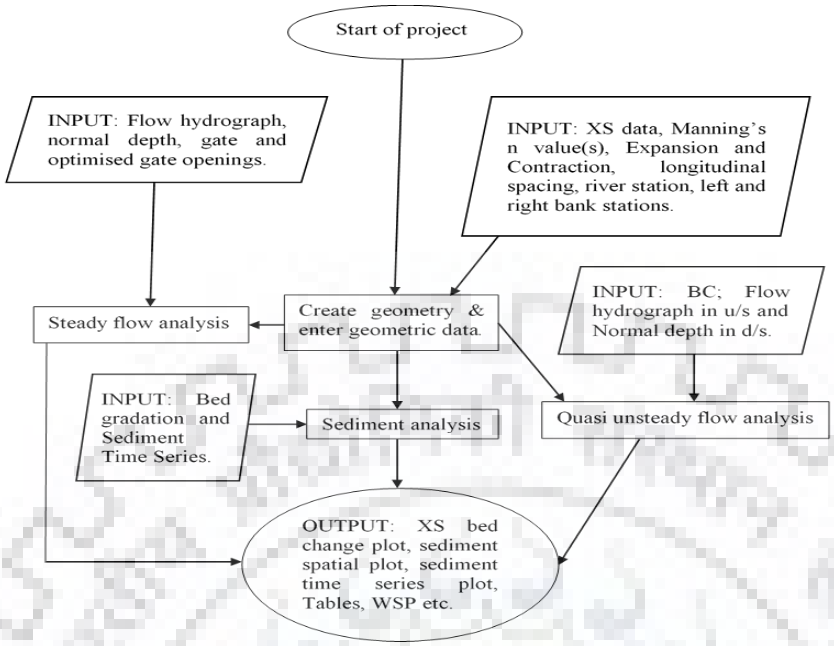

Figure 3. 1: Shows the Flowchart of HEC-RAS Simulation Steps

***NOTE: XS** – Cross Section, **BC** – Boundary Condition, **WSP** – Water Surface Profile*

3.2 PREPARATION OF BAJOLI HOLI MATHEMATICAL MODEL

In order to simulate the Bajoli Holi mathematical model for sediment deposition and depleting flushing, the following data were required; channel cross section geometry, Manning's n values (for cross sections), normal depth (slope), an arbitrary flow and sediment hydrographs, river bank locations and distances between the cross sections.

3.2.1 Creating the Model

The model geometry was set up by providing as inputs surveyed river cross section data to all 18 cross sections of Ravi reach (1.8 km) starting from 0.7 km d/s of the dam axis to 1.1 km u/s of the dam at the longitudinal spacing of about 0.1 km for all cross sections from d/s to u/s. The dam axis is located just above cross section 8. The cross sections were laid (Fig. 3.2 below) as obtained from Irrigation Research Institute (IRI), 3-D physical modeling site in Bahadrabad. During the simulation, Manning's n values of 0.035 on both left and right banks and 0.03 in the middle of the channel were used for Ravi river in the reach simulated in the model.

Two .geo (geometry) files were created for the present study under virgin conditions to be used for hydraulic analysis of the river including validation of the river under virgin conditions. Geometry file with simulations of dam as inline structure to be used for sedimentation and flushing studies post construction of the dam.

HEC-RAS has got an advantage in that once the geometry has been created and its data entered, it can then be used for any hydraulic computations depending on the user's requirements.

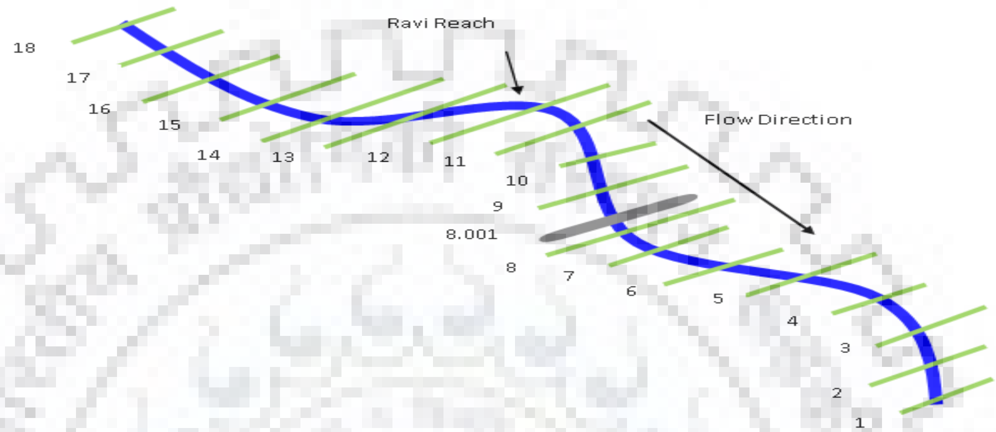

Figure 3. 2: The 18 Cross Sections as Provided by Irrigation Research Institute – Bahadrabad

3.2.2 HEC-RAS Flow Simulation Setup

HEC-RAS allows the calculation of water surface profiles (using energy conservation, momentum, and Manning's equations) in situations where flow is subcritical, supercritical or mixed. For this after creating .geo files, flow data is to be provided to HEC-RAS. For validation of river a simple arbitrary hydrograph of flow profiles (discharge) varying from minimum to maximum of the discharge may be used. An arbitrary flow hydrograph was therefore created (as shown on Fig. 3.3 below) corresponding to the twelve months of the year to enable the steady flow calculations.

The file also requires u/s and d/s BC although natural depth (general slope) is used as BC. Still rating curves at u/s and d/s cross section if available can be used to define boundaries.

HEC-RAS can be used for simulation of operational structures also. For better management of sediment and as per practice in regard to run-of-river projects similar to Bajoli Holi scheme, all the reservoirs are maintained at MDDL during monsoon to rout the incoming sediment to downstream. As such the spillway of Bajoli Holi was operated in the study to maintain the reservoir level at MDDL

(EL. 2012 m) during monsoon months June to September. While during non-monsoon the reservoir level is maintained at FRL (EL. 2018.25 m), as inflows are generally less.

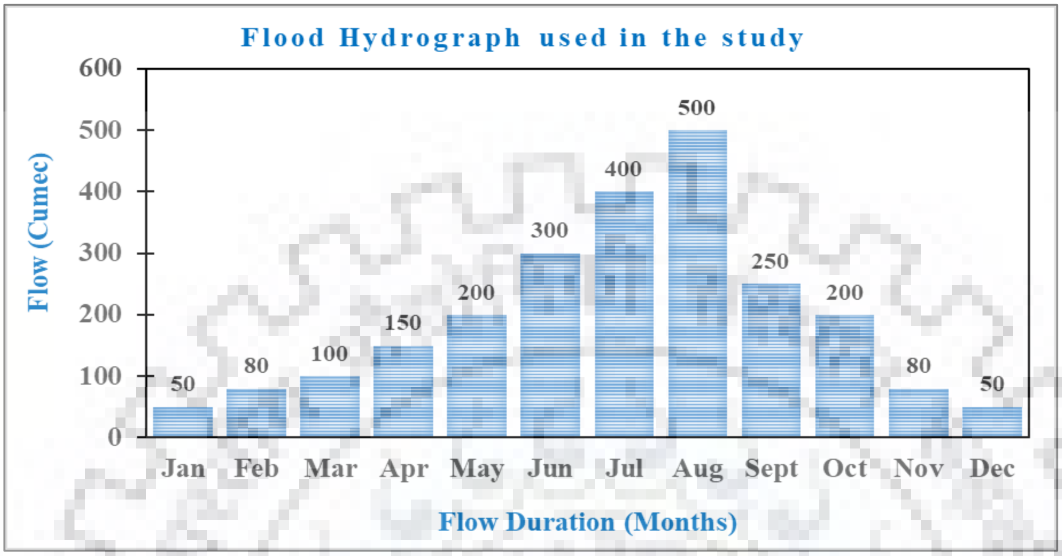

Figure 3. 3: Showing Bajoli Holi Arbitrary Flood Hydrograph

3.2.3 Quasi Unsteady Flow Simulation for Sediment Analysis

The quasi-unsteady flow file is used to define a flow or flood hydrograph (Fig. 3.3 above) as u/s boundary, starting flow conditions, and d/s BC, for running an HEC-RAS sediment transport model. To run this file, it requires geometric data (as created earlier on), flow hydrograph, and normal depth (as d/s BC). The flows are entered as a flow series for a specified duration and are the upstream model BC. The computational increment is specified as part of the flow series, which determines the time interval at which calculations are performed. The model is extremely sensitive to this parameter. Long increments can result in model instability, while very short increments may result in more stable models but require very long run times.

According to Stokes Law, water temperature has a direct effect on the settling rate of silt in a reservoir water column (Sullivan et al. 2007). Thus, a daily time series of water temperature was generated by assuming average temperatures for calculating sediment particle fall velocities.

T.S gate openings for all gate group (a gate group represents all the gates having similar geometry and invert) were also specified for simulating the inline control structure as shown in Fig. 3.4 below. Gate group 1, which has 4 bays of 10 m width separated by 7 m wide piers is used for the safe passage of flood at an El. 1985 m, whereas gate group 2 at El. 2014.25 m is for passing floating debris and logs.

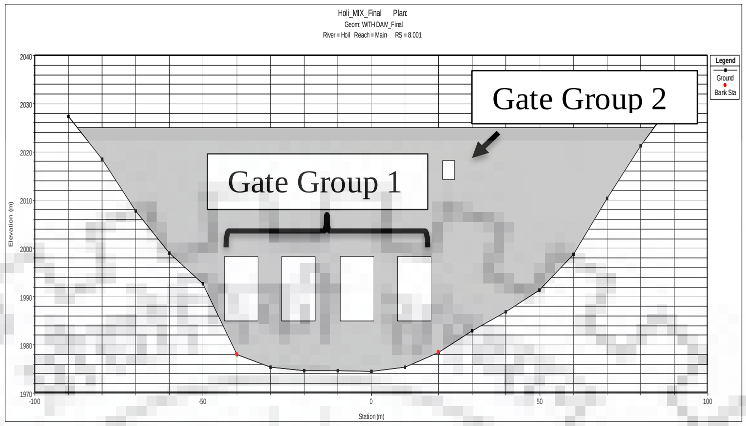

Figure 3. 4: Inline Control Structure Showing Gate Groups

3.2.4 Sediment Data Preparation

This sediment data in HEC-RAS model is provided in a separate file called sediment file. In the file, BC for each reach and flow data needed for execution of the sediment transport simulations was also specified. This sediment file contains the characteristics of both bed material and incoming sediment loads for each cross section. In this study, the natural sediment series and sediment augmentation load were expressed in tons per day.

An arbitrary sediment load in terms of ppm and also in terms of metric tons per month was prepared for using in mathematical model as shown on Tab. 3.2 and plotted on Fig. 3.5 and Fig. 3.6 below.

Table 3. 2: Silt Load, ppm and Discharge used during the Sedimentation Studies

Month	Silt Load (T)	ppm	Q (cumec)	Month	Silt Load (T)	ppm	Q (cumec)
Jan	13392	100	50	Jul	642816	600	400
Feb	23224	120	80	Aug	1071360	800	500
Mar	53568	200	100	Sep	388800	600	250
Apr	116640	300	150	Oct	267840	500	200
May	214272	400	200	Nov	51840	250	80
Jun	388800	500	300	Dec	20088	150	50

HEC-RAS 5.0.5 provide many options for sediment transport equations such as Ackers-White, Engelund-Hassen, and so on. While the sorting methods are; Thomas Exner5, Active Layer, and Copeland Exner7. And finally, the fall velocity has the options; Ruby, Toffaleti, Van Rijn, Report 12 and Dietrich.

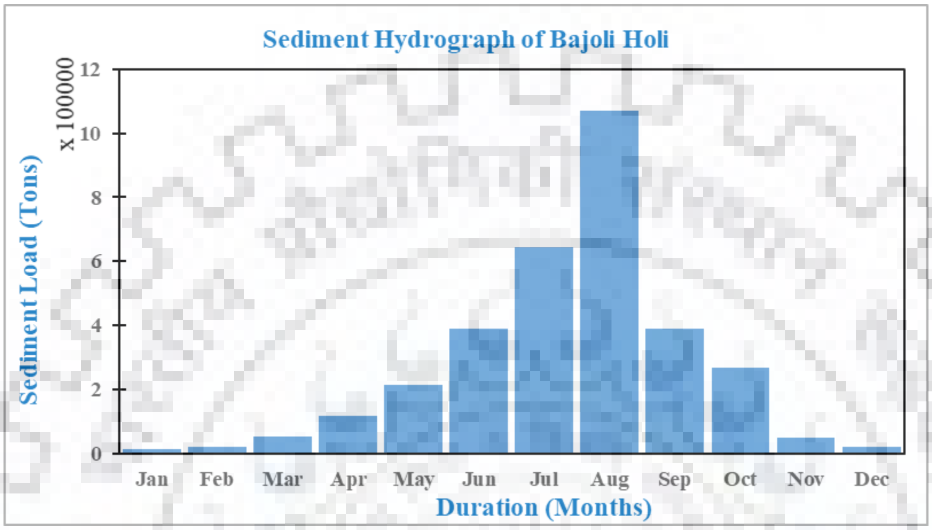

Figure 3. 5: Sediment Hydrograph used in Sedimentation Studies (the Cycle was Repeated up to 20 Months)

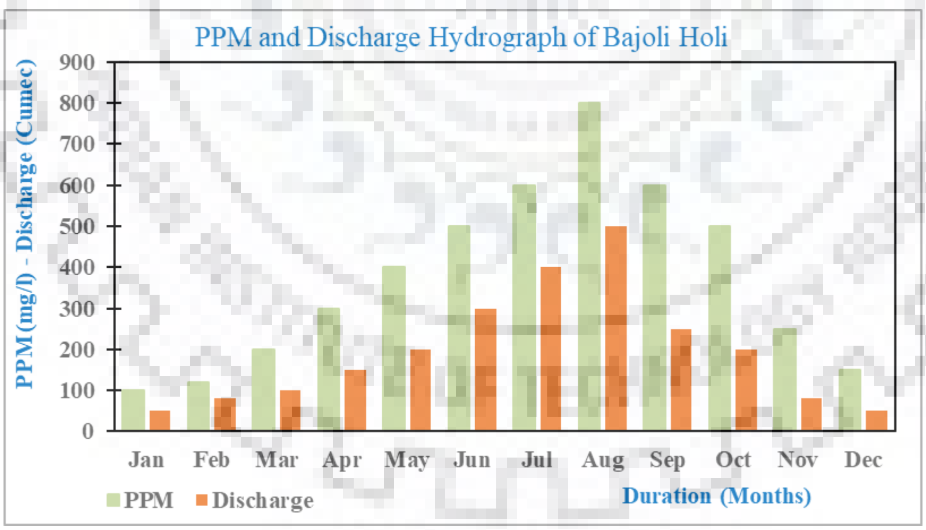

Figure 3. 6: PPM and Discharge of Bajoli Holi used in Sedimentation Studies (the Cycle was Repeated for 20 Months)

In this model, Ackers-White sediment transport function was applied based on its suitability to the conditions of the study area and its ability to guess the grain sizes deposited at particular sections of the reach under varied flow conditions. Because the Thomas Exner5 sorting method is effective in predicting armoring of the bed material and therefore reducing further erosion of bed material, it was chosen. Finally, the Ruby fall velocity method is suitable for silt, sand, and gravel sizes, thus, it was selected. Gradation curve for suspended load is as shown on the Fig. 3.7 below. And the d_{50} and d_{90} respectively are about 0.09 and 0.41 mm.

Therefore, to assess the worst sedimentation condition so as to suggest a sediment management strategy for Bajoli Holi run of river project, the sediment transport simulation was performed for 8 months, 12 months and 20 months separately. For 8 months run, the flood hydrograph was from 1st, January, to 31st, August. In 12 months run, the simulation started from 1st, January to 31st, December. While for 20 months the flood hydrograph was repeated in the same order from 1st, January to 31st, August, of the next year.

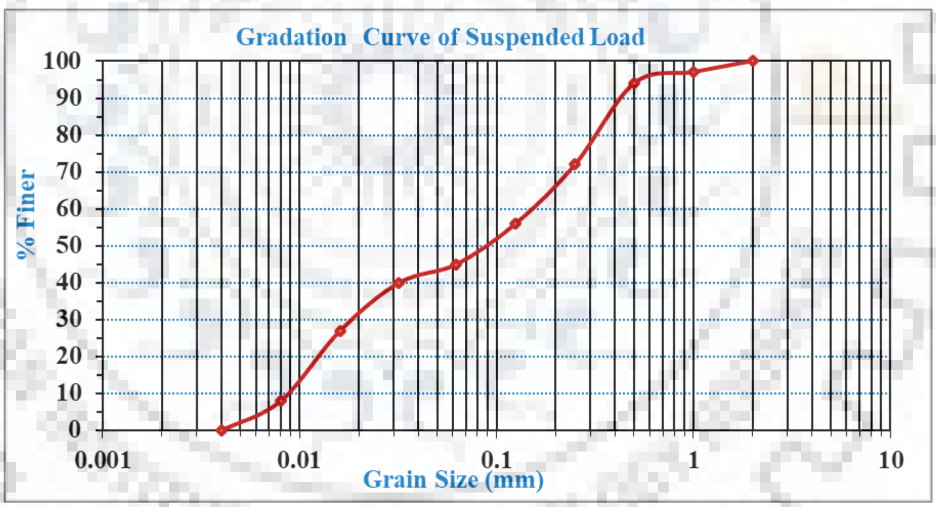

Figure 3. 7: Gradation Curve of Suspended Load for Bajoli Holi Model

3.2.4.1 Preparation of the Model for Sediment Flushing

In all the small size reservoirs, such Bajoli Holi where it is expected to be filled up soon, it is a practice to flush out the reservoir sediment at regular intervals by depleting the reservoir to the lowest level. Flushing Bajoli Holi reservoir has been considered during monsoon, right from the first 8 months of the reservoir operation as per normal practice in reservoir operation of NHPC, for small size reservoirs. Thus, this study was not only run for sediment deposition but also for sediment management, hydraulic flushing in this case. A 300 cumec with a corresponding 200 ppm was used during depleting flushing for 3, 4, and 5 days, in each case.

3.3 PREPARATION OF TEHRI MATHEMATICAL MODEL

The HEC-RAS mathematical model for Tehri project was set up by providing, as inputs, the cross sectional geometric data at the longitudinal spacing of about 1 km starting with 42 km u/s in Bhagirathi and 25 km in Bhilangna valley to -4 km d/s of the dam (Fig. 3.8 below). The cross sections were laid as provided by THDCIL post 2013 survey. 0.045 Manning's (n) value was uniformly used in the mathematical modeling of both rivers in the reach simulated in the model. In place of all the control structures, only Chute spillway (Fig. 3.9 below) was simulated in the model to control the reservoir levels and discharges.

3.3.1 Discharge Data

The discharge data were created in two files namely steady flow data and quasi unsteady flow data. Actual discharge data was used to run the model. Tehri multi-purpose project was designed to run for 100 years. But, in this model it was only run for 25 years (January 2014 to December 2038) and the yearly average of the discharge and reservoir levels were computed and repeated in same cycle upto 25 years. The gate openings were optimised for different reservoir levels against respective discharges. The quasi unsteady flow file requires u/s boundary for main river and tributary (if any), d/s BC, flow change condition (if any) and T.S. gate opening for any inline control structure. The u/s BC for Bhagirathi and Bhilangna rivers were defined at their u/s most cross sections simulated in the model.

The u/s boundaries were defined as flow series providing flow and flow duration (in hours) for each of the twenty-five profiles to be run. Since the model is to run for 25 years the duration of run for each profile was defined as 8760 hours (1 year) and discharge in both rivers were given as per Appendix, Tab. 2. The computational interval for updating the results is also set as 8760 hours. The d/s boundary was defined at the d/s most end of the model and was generally opted as normal depth. At inline structure (Spillway in this case), the gate opening for every discharge was provided with flow duration as 8760 hours.

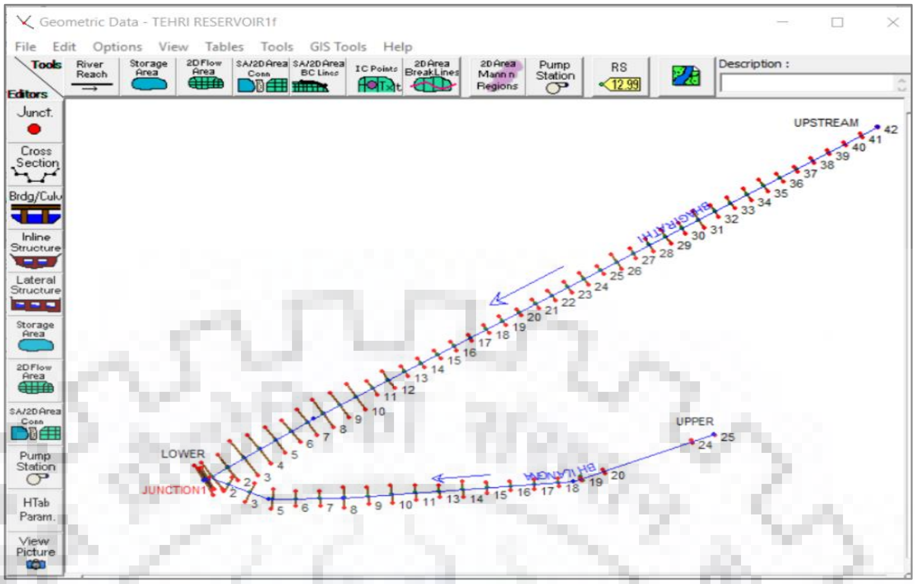

Figure 3. 8: Tehri Geometric Data

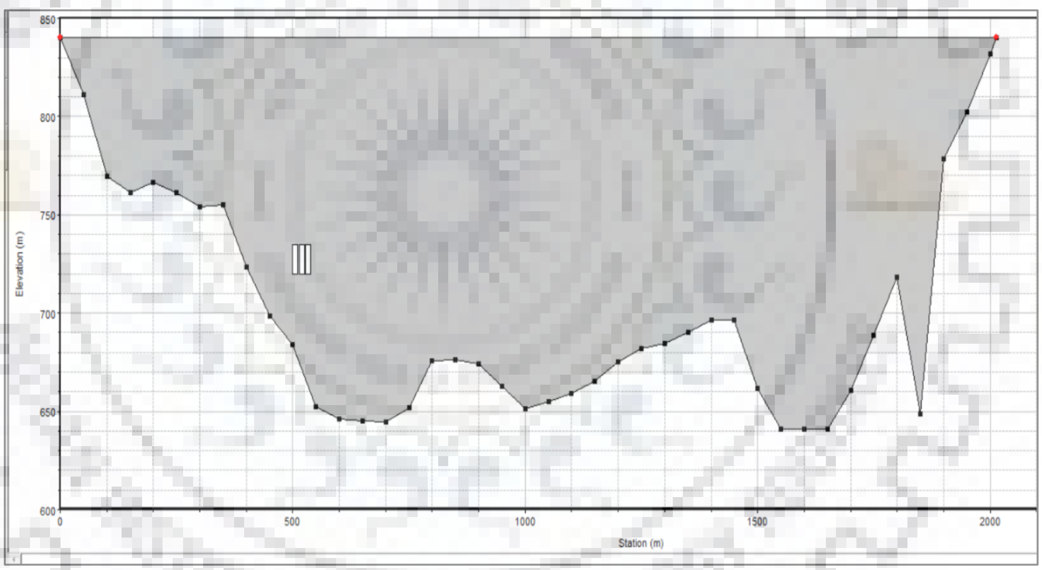

Figure 3. 9: Tehri Chute spillway

3.3.2 With Sediment Corresponding to Actually Observed Loss of Capacity at Tehri

Actual discharge data provided (Appendix – Tab. 2) was used to run the model. The yearly average of the discharge and reservoir levels (Appendix – Tab. 2) were computed and repeated in same cycle upto 25 years. The gate openings were optimised for different reservoir levels against respective discharge given in Appendix – Tab. 2. Sediment corresponding to actually observed loss of capacity by hydrographic survey (**9.46 Million Tons /year**) was fed in R. Bhagirathi and in Bhilangna river, where it (the sediment) was reduced or increased proportional to discharge ratio.

3.3.3 With Average Sediment Data Actually Observed

The sediment data was defined in sediment file which required sediment gradation and quantity of sediment for every profile of flow along with flow and sediment duration. The sediment gradation was provided as per gradation shown in Fig. 3.10 below.

Sediment (**13.37 million tons/ year**) as actually observed at steel girder bridge _ Tehri from 1973 to 1993 (Appendix – Tab. 1) was used in R. Bhagirathi and in Bhilangna river where the sediment was reduced or increased proportional to discharge ratio.

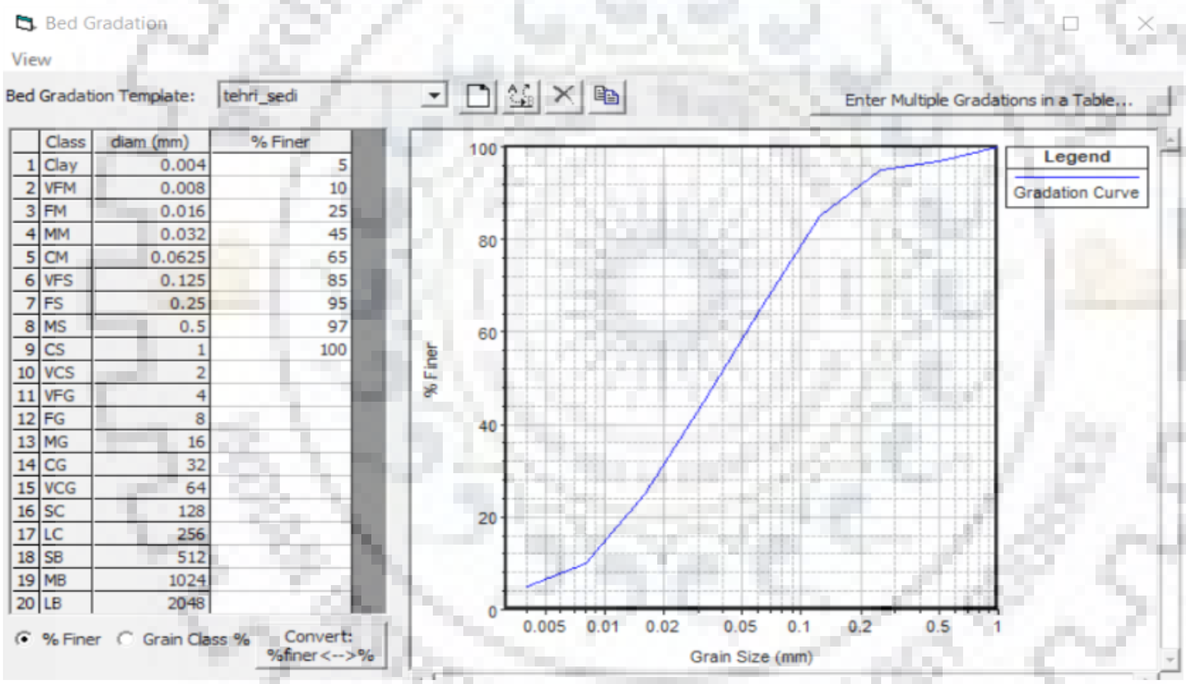

Figure 3. 10: Tehri Sediment Gradation Curve

CHAPTER FOUR: MODEL RUNNING, RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

This chapter presents running of the model(s) for validation, sedimentation and flushing (wherever required) for both models. The chapter also deals with analysis of the findings of the HEC-RAS 5.0.5 mathematical modeling of the two projects, as per the objectives of the study outlined in Chapter One above.

4.2 MODEL VALIDATION

Before proceeding for conclusive studies, the mathematical model needs to be validated. For this purpose, both models were initially validated.

4.2.1 Validation of Bajoli Holi Model

Discharges ranging from 250 cumec to 7419 cumec (PMF) were run on HEC-RAS over a geometry file of the river under virgin conditions (without dam). Out of three possible conditions of flow, that is subcritical, supercritical and mixed, mixed was used for validation purposes. After running the model rating curves at different cross sections were obtained. These rating curves were compared with the rating curves obtained by 3-D physical modeling as shown on Fig. 4.1 to Fig. 4.3 below. The comparison indicated that the rating curves from HEC-RAS fairly tally with rating curves from 3-D physical modeling. Therefore, the HEC-RAS model of river Ravi was taken to be validated.

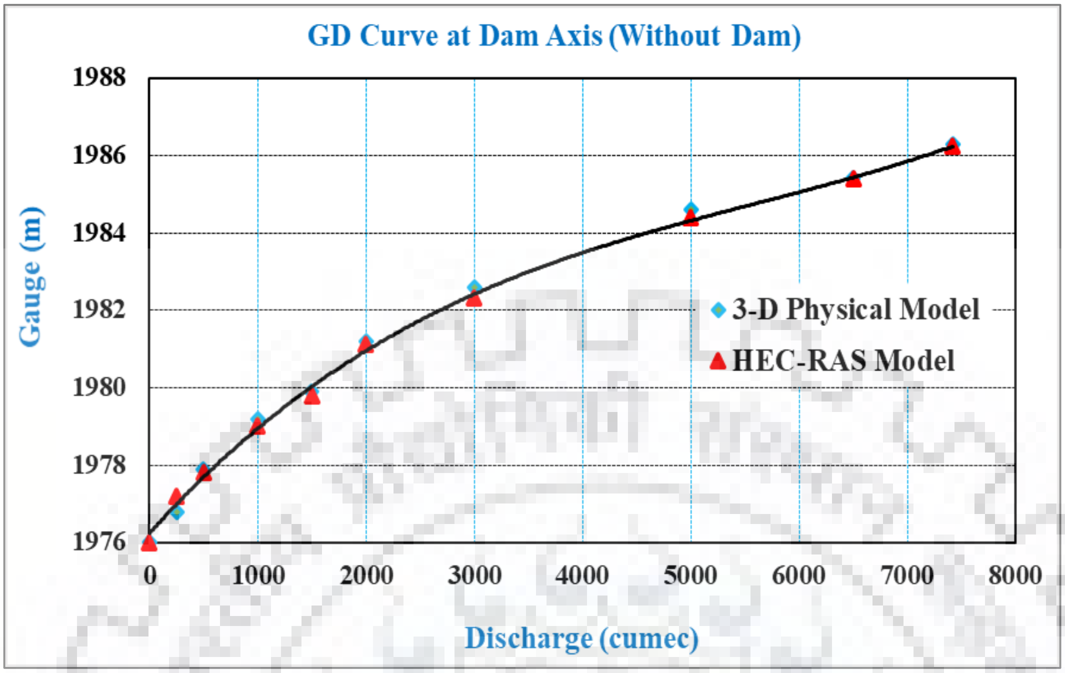

Figure 4. 1: GD Curves at Dam Axis of 3-D Physical Model and HEC-RAS Model

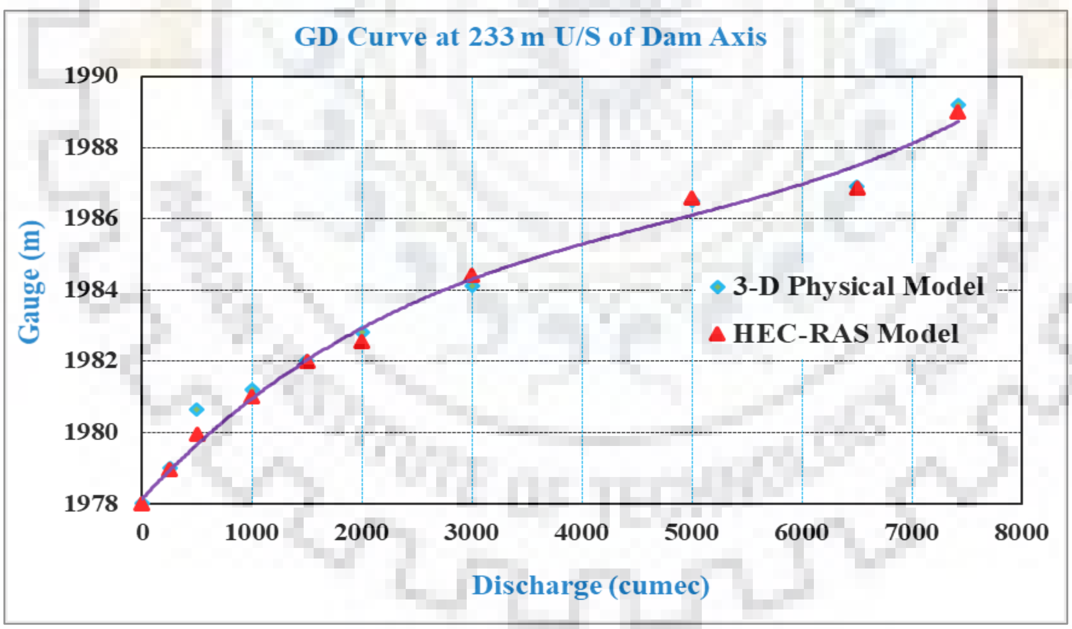

Figure 4. 2: GD Curves at 233 m U/S of Dam Axis of

3-D Physical and HEC-RAS Model

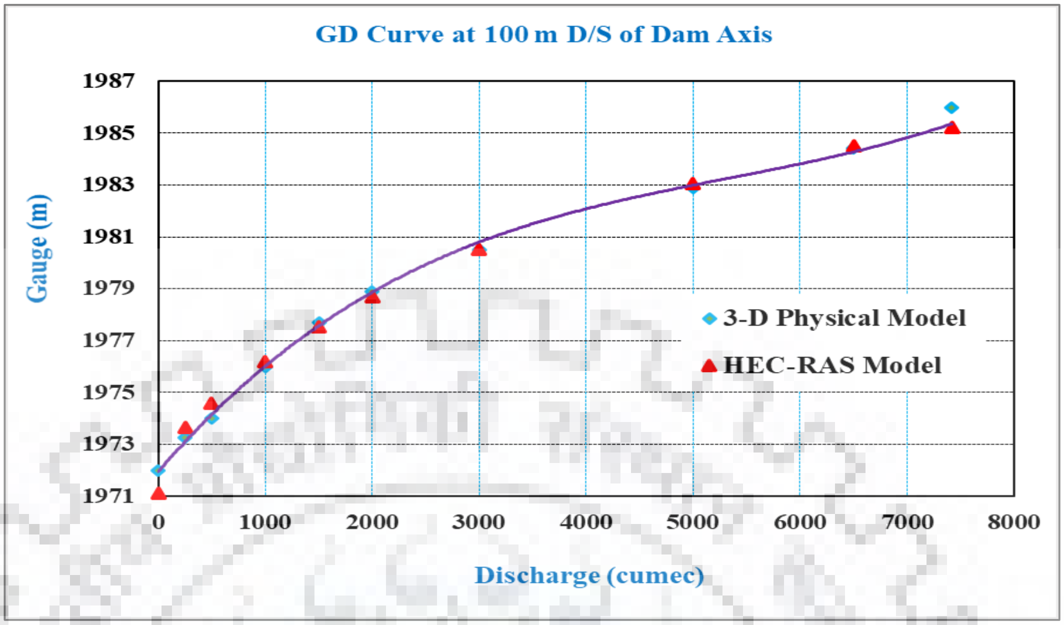

Figure 4. 3: GD Curves at 100 m D/S of Dam Axis of 3-D Physical and HEC-RAS Model

4.2.2 Validation of Tehri Model

In order to validate the model, a geometry file with post 2008 survey was prepared and average discharge data actually observed at site was run for 5 years with sediment corresponding to actually observed loss of capacity by hydrographic survey. Actually observed average reservoir level was also maintained. **After running the model for 5 years a total loss in capacity of 25.33 MCM was observed giving an average of 5.07 MCM / year. The result fairly tallies with yearly rate of sedimentation (5.33 MCM / year) observed by hydrographic survey.**

In the second run the same data was used but sediment rate was used as **13.37 million tons/year** in River Bhagirathi (as actually observed at steel girder bridge Tehri from 1973 to 1993- Appendix – Tab. 1) and corresponding sediment load in R. Bhilangna. **After running the model for also 5 years a total loss in capacity of 50.5 MCM was observed giving an average of 10.1 MCM / year. The result is in close conformity with yearly rate of sedimentation (9.33 MCM / year) calculated theoretically. Therefore, Tehri mathematical model is taken to be calibrated.**

4.3 SEDIMENTATION AND DEPLETING FLUSHING STUDIES FOR BAJOLI HOLI HEP

For sedimentation studies, Bajoli Holi RoR model was simulated by feeding **2.52×10^6 T**, **3.25×10^6 T** and **5.78×10^6 T** of sediment against arbitrary discharges as discussed in chapter 3 above respectively for 8, 12 and 20 months by maintaining MDDL and FRL during monsoon and non-monsoon season to get the worst sedimentation situation. After each run the pattern of sedimentation both quantitative and qualitative was extracted and residual beds after 8, 12 and 20 months respectively were obtained. These results were analysed and it was found from the expected invert changes (Tab. 4.1) and plotted on Fig.4.4 below, that the worst sedimentation reaches after 20 months of running without flushing, when the reservoir was highly silted beyond the power intake (2000 m) starting from a distance of about 200 m u/s onwards of the dam axis. While during the 12 months' sedimentation, the results showed that at a distance of nearly 400 m u/s of the dam axis onwards, the silt load was well above the 2000 m power intake elevation. This siltation scenario may have no disturbance on power discharges as it occurs fairly far away from the dam axis. Within the 8 months' sedimentation, only some few cross sections further away from the dam axis got silted upto the power intake crest.

During 8 months running of project (January to August), out of the **2.52 million tons of sediment** fed about **1.33 million tons** were trapped in the reservoir, corresponding to about **0.84 MCM** loss of capacity due to the sediment.

As it is customary to flush RoR projects or generally small reservoirs once every monsoon season especially those located in catchments with very high sediment yields, it was therefore decided that for the sustainability of this reservoir, the model be run for sediment management (depleting flushing in this case) too. So, after the sedimentation studies for the above mentioned durations, the model was simulated for depleting flushing for 3, 4, and 5 days individually for each of the post sedimentation scenarios. Depleting the reservoir water level was performed by opening all gates full which increase the flow velocity so as to deduce the best flushing period to regain the lost capacity. The flushing was performed utilising the residual bed after 8, 12 and 20 months respectively and with inflow discharge of 300 cumec associated with 200 ppm of sediment load. This corresponds to **15,552 tons for 3 days**, **20,736 tons for 4 days** and **25,920 tons for 5 days**.

The respective longitudinal bed changes after the respective sedimentation and depleting flushing periods are shown from Fig. 4.5 to Fig.4.7 below. Bed changes in some randomly selected cross sections are also presented in Fig. 4.8 to Fig. 4.19, depicting in every case the sediment cross sectional change after every respective sedimentation period and the corresponding depleting flushing days.

Table 4. 1: Projected Invert Change at Different Chainages after Different Time Intervals

River cross section	Chainage (m) from dam	Bed change (m) after 8 months	Bed change (m) after 12 months	Bed change (m) after 20 months
18	1100	12.30	22.80	24.98
17	1000	18.57	21.16	15.70
16	900	16.70	19.77	11.51
15	800	16.22	21.12	22.89
14	700	18.56	21.80	18.81
13	565	25.94	27.97	23.50
12	450	20.24	30.30	26.95
11	330	3.20	6.54	30.14
10	233	2.62	3.74	31.30
9	100	2.00	2.78	7.24
8	0	0.00	0.00	0.00

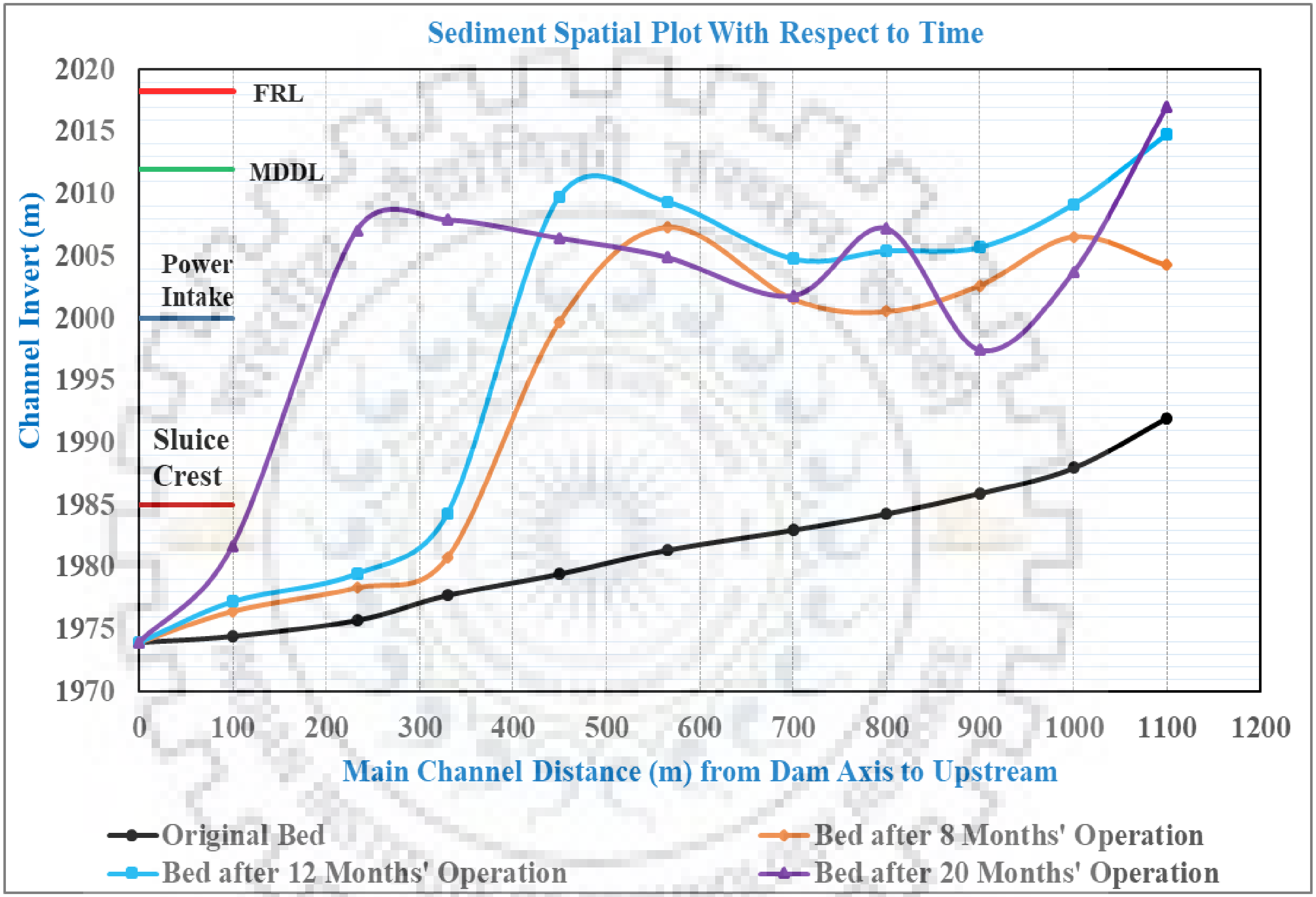

Figure 4. 4: Longitudinal Bed Changes Upstream of Dam Axis after Different Months of Operation

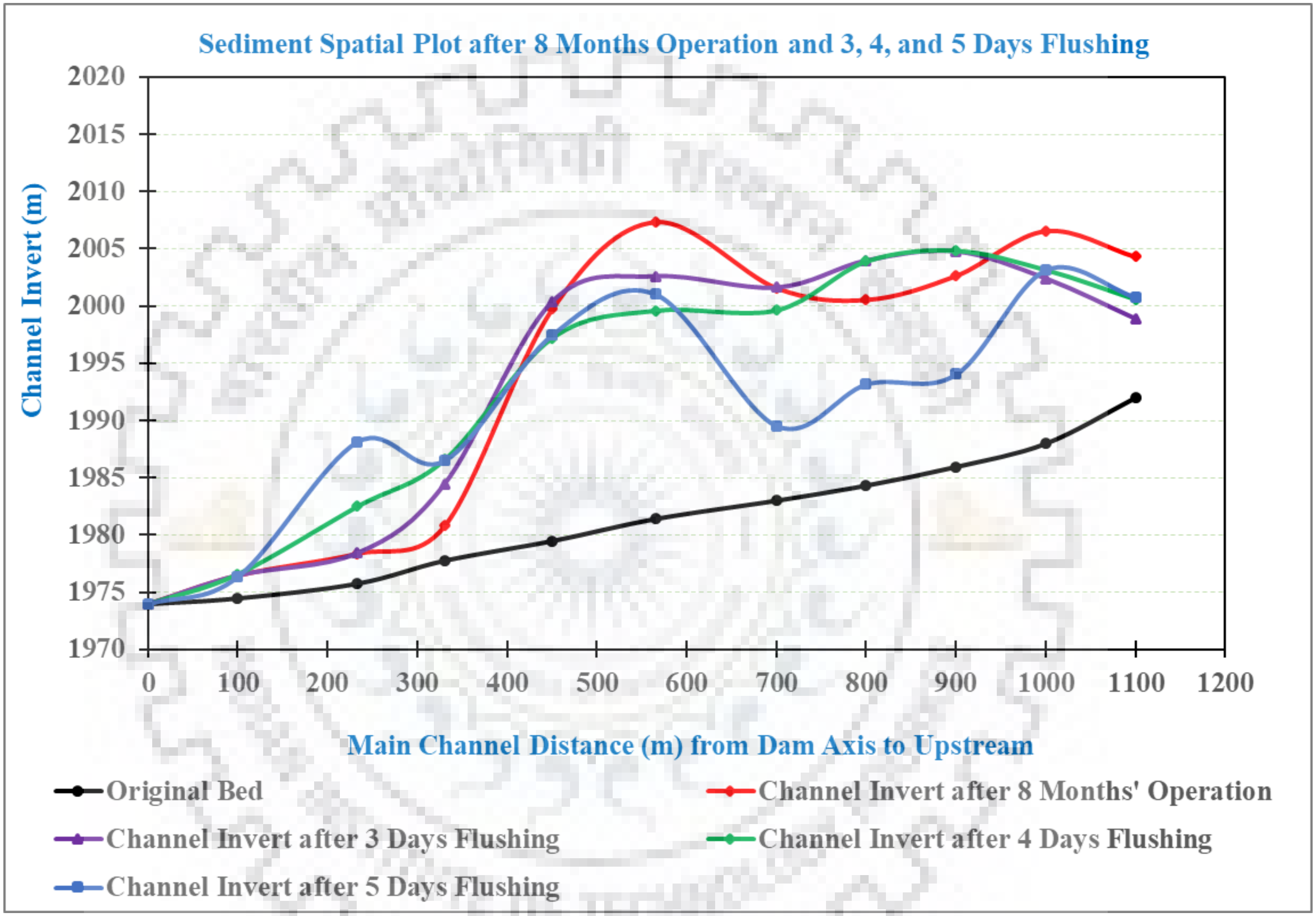

Figure 4. 5: Longitudinal Bed Changes Upstream of Dam Axis after 8 Months' Operation and Different Days of Flushing

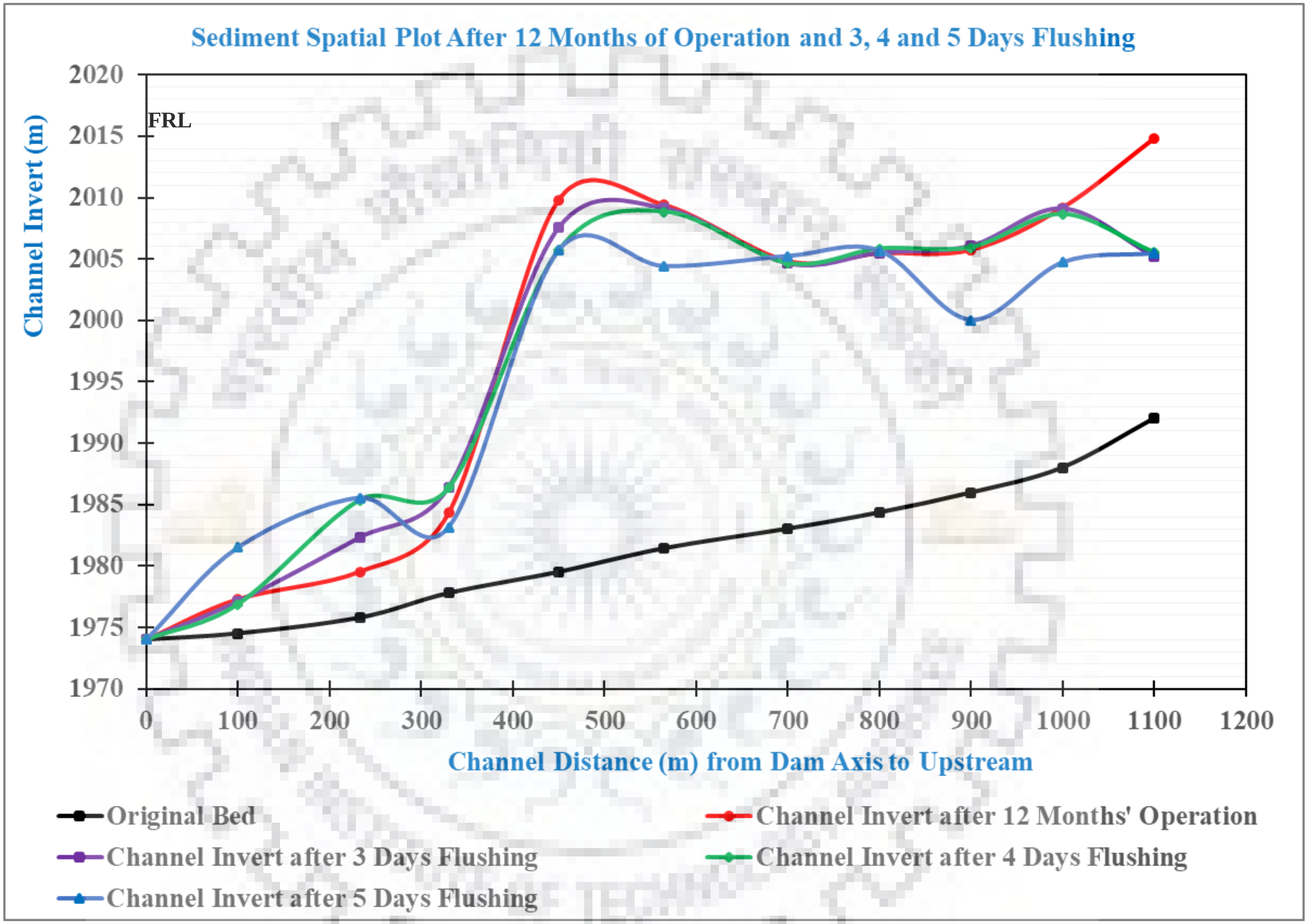

Figure 4. 6: Longitudinal Bed Changes Upstream of Dam Axis after 12 Months' Operation and Different Days of Flushing

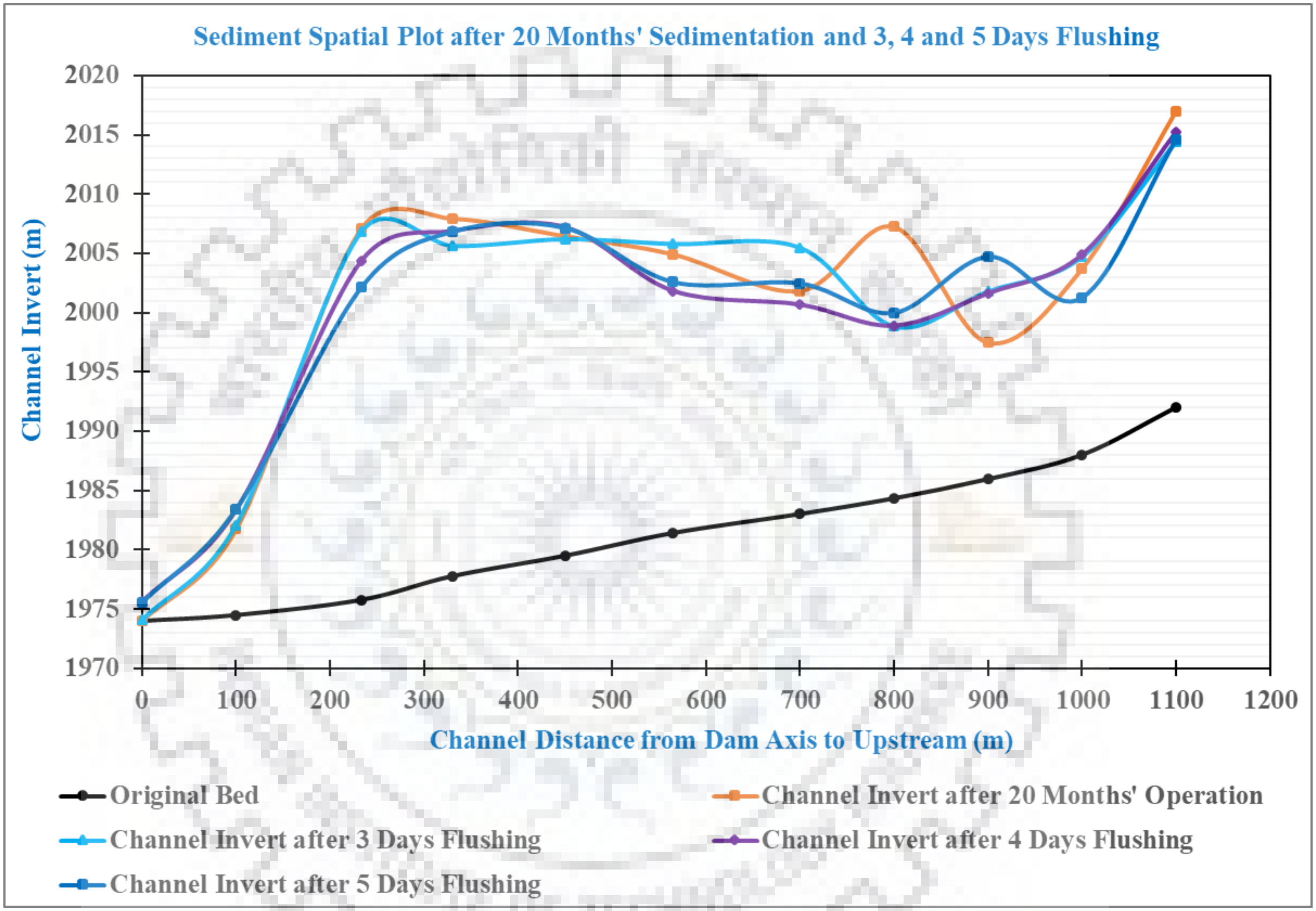

Figure 4. 7: Longitudinal Bed Changes Upstream of Dam Axis after 20 Months' Operation and Different Days of Flushing

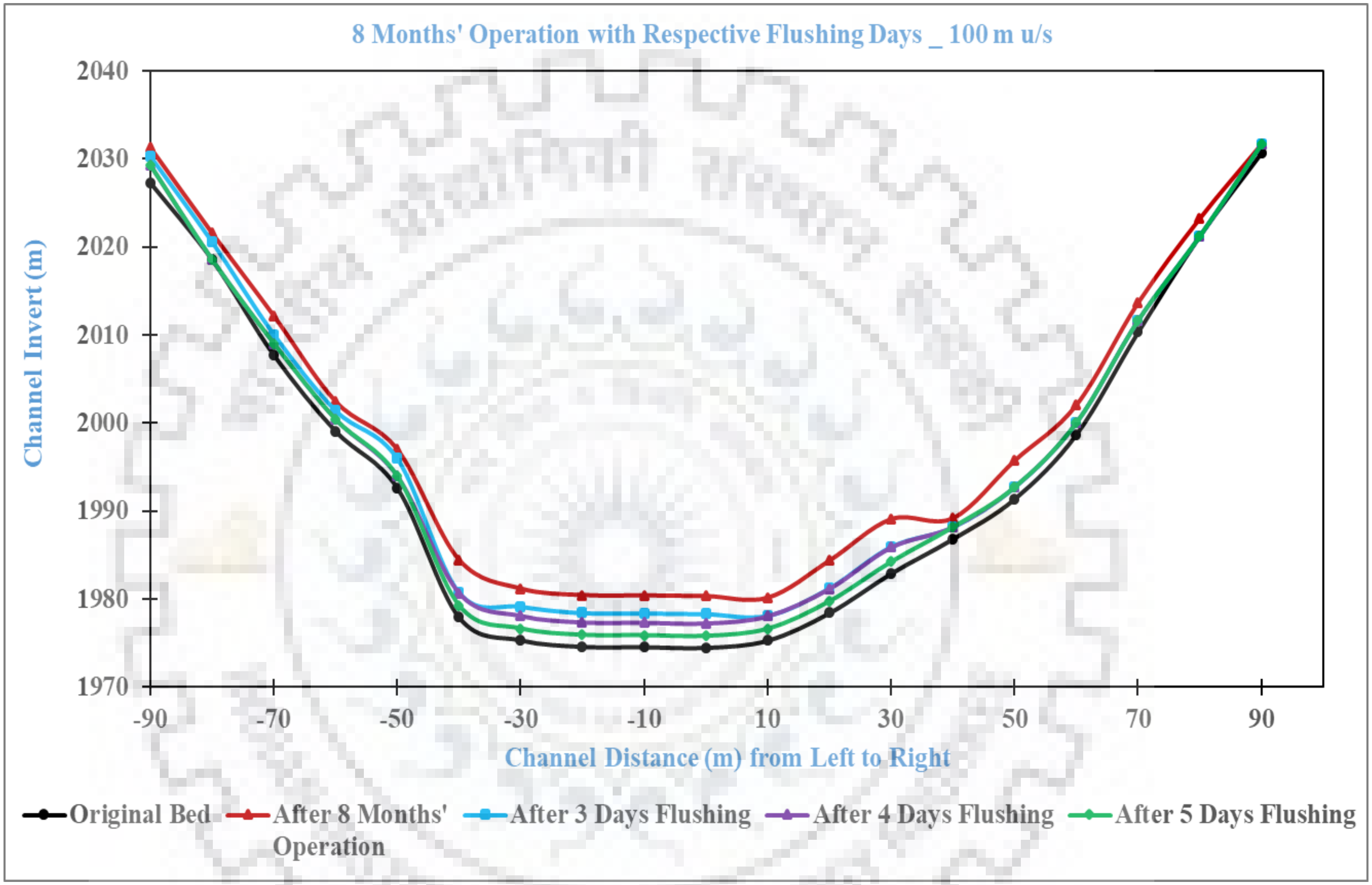

Figure 4. 8: Sediment Cross Section Change 100 m Upstream

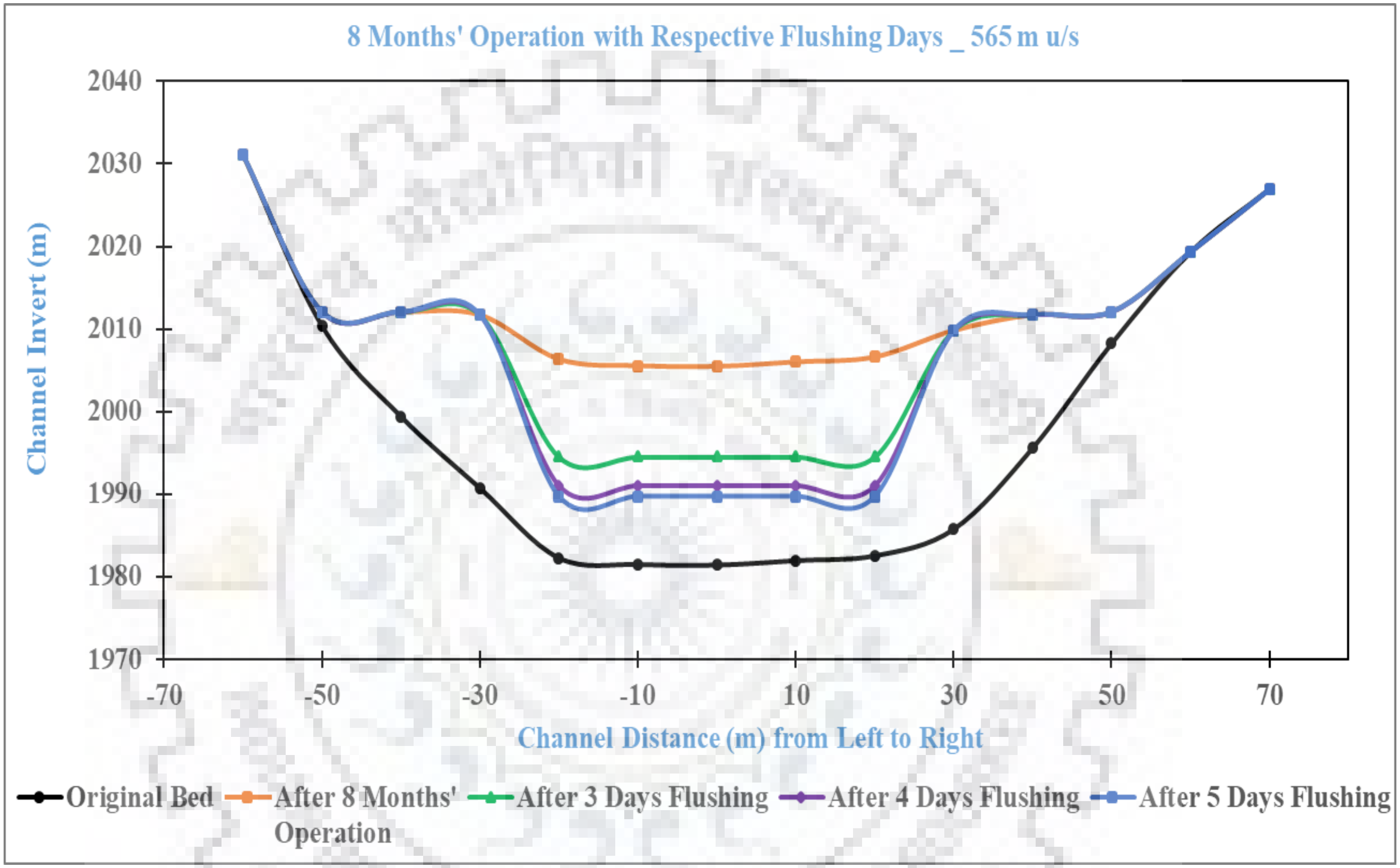

Figure 4. 9: Sediment Cross Section Change 565 m Upstream

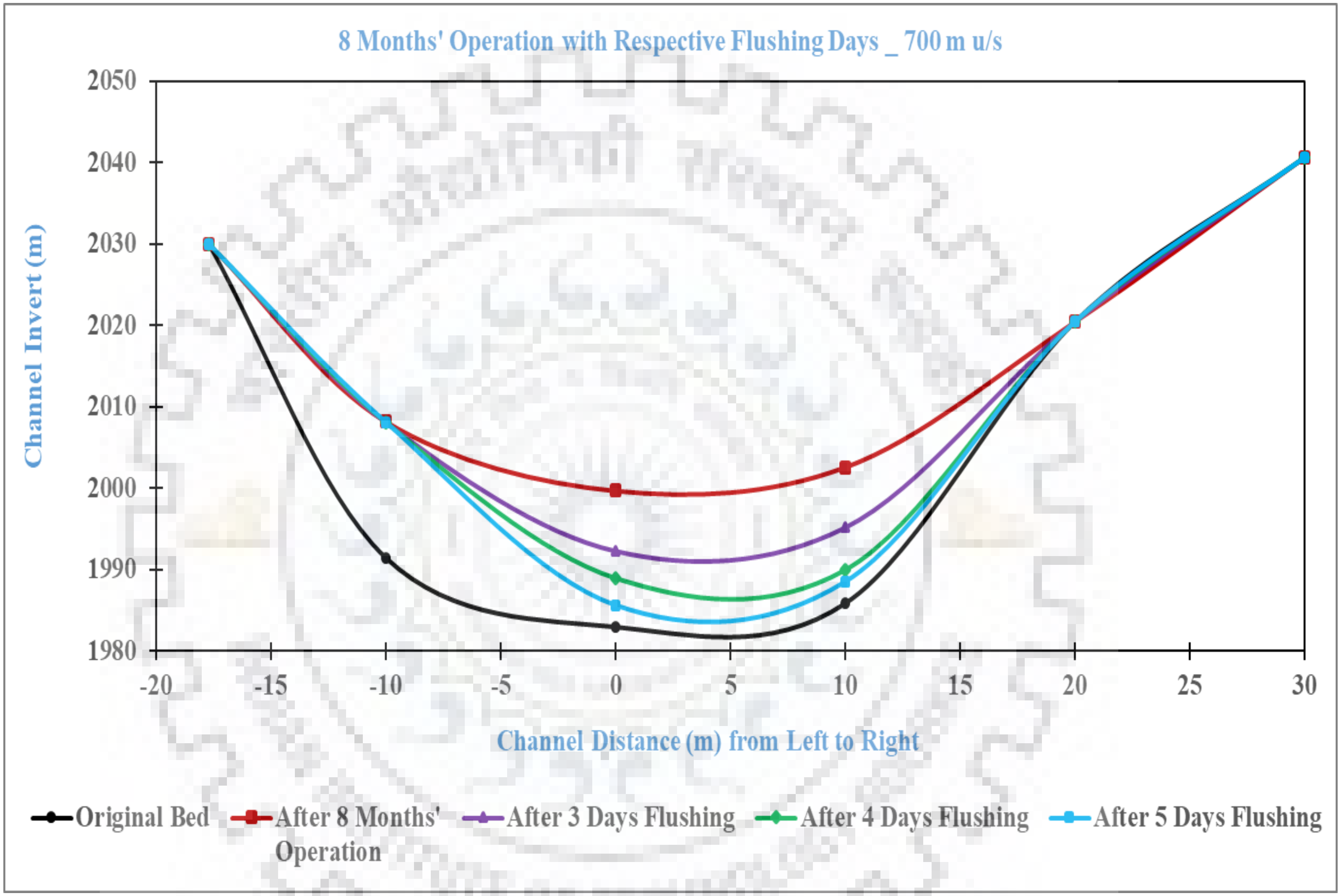

Figure 4. 10: Sediment Cross Section Change 700 m Upstream

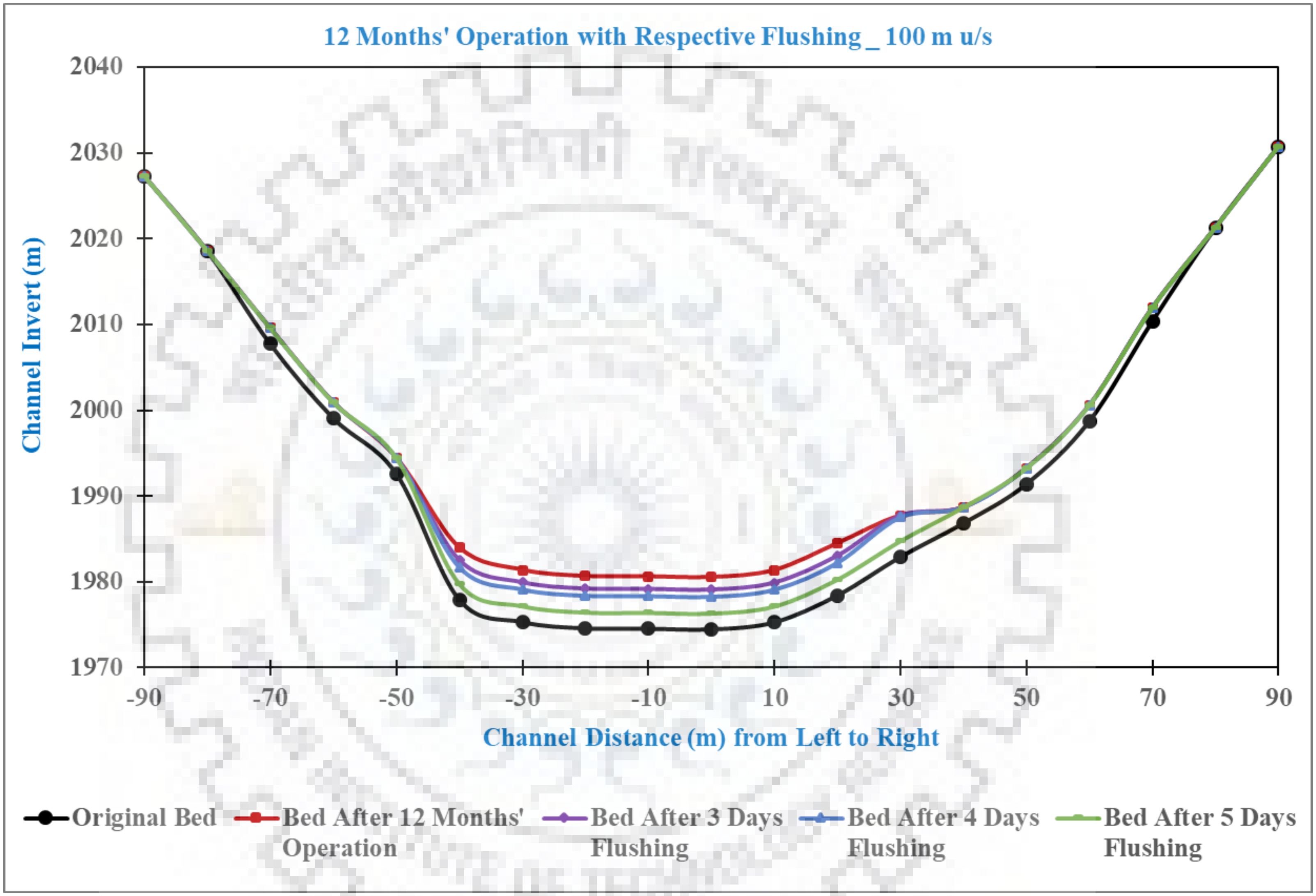

Figure 4. 11: Sediment Cross Section Change 100 m Upstream

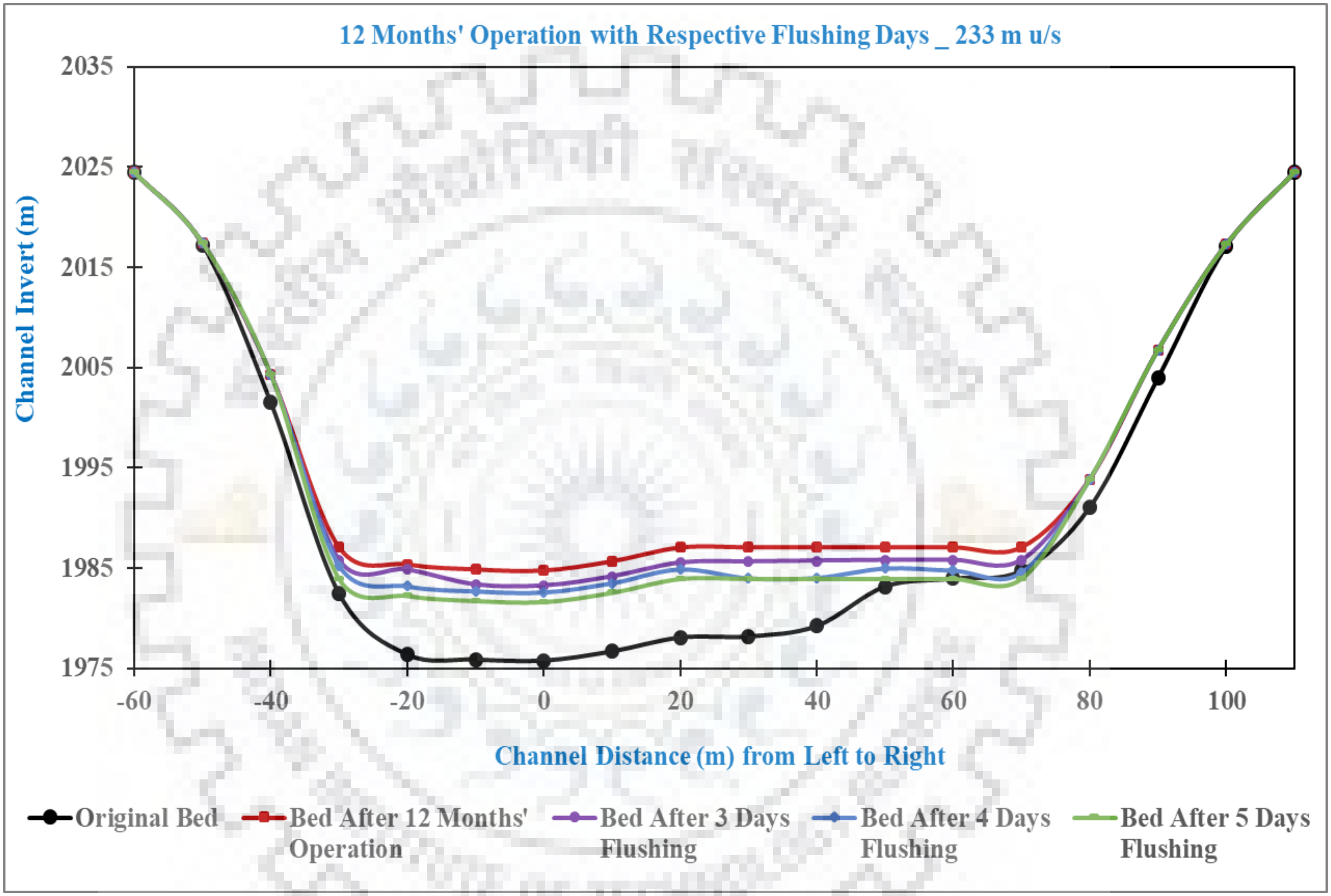

Figure 4. 12: Sediment Cross Section Change 233 m Upstream

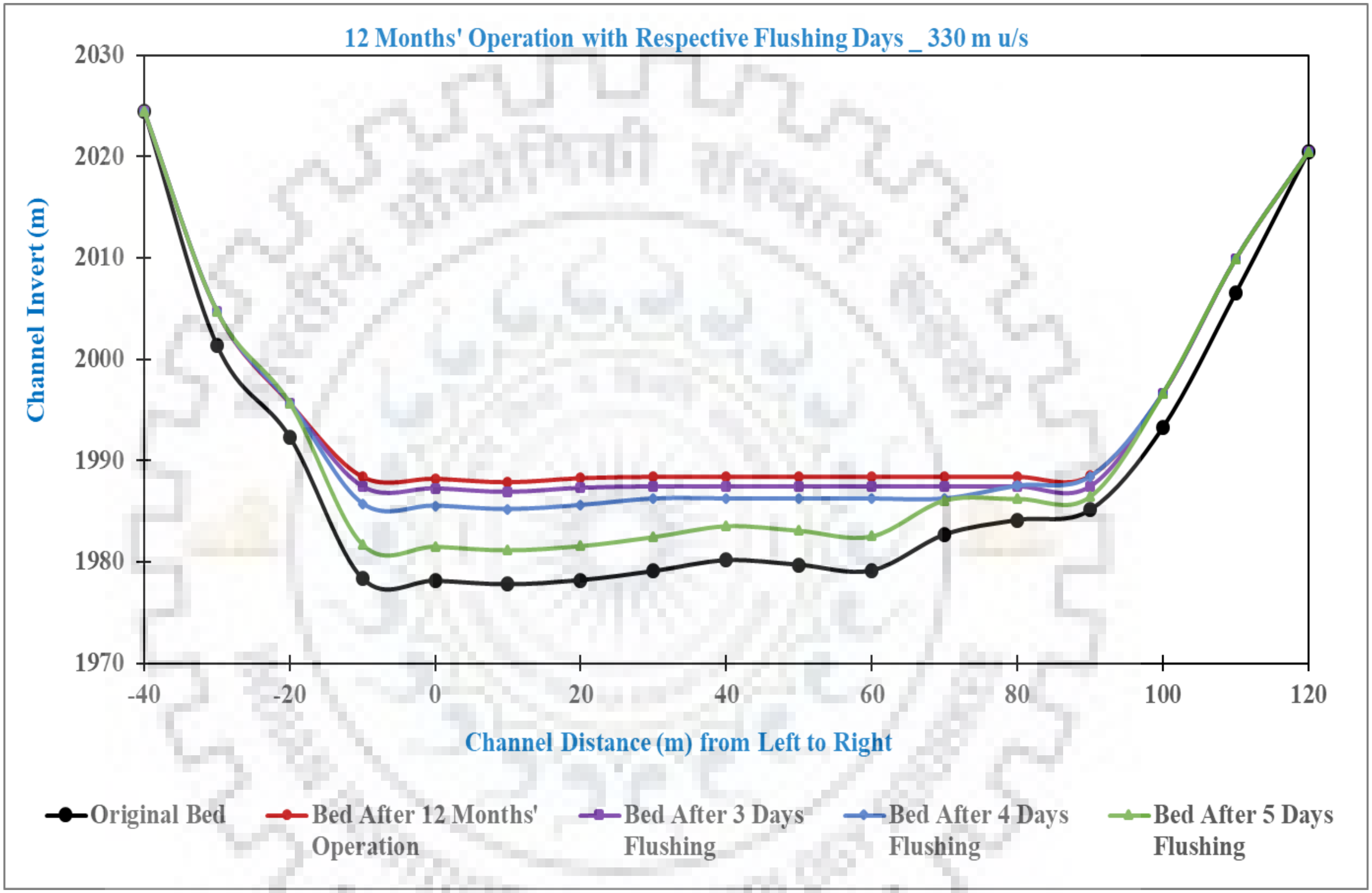

Figure 4. 13: Sediment Cross Section Change 330 m Upstream

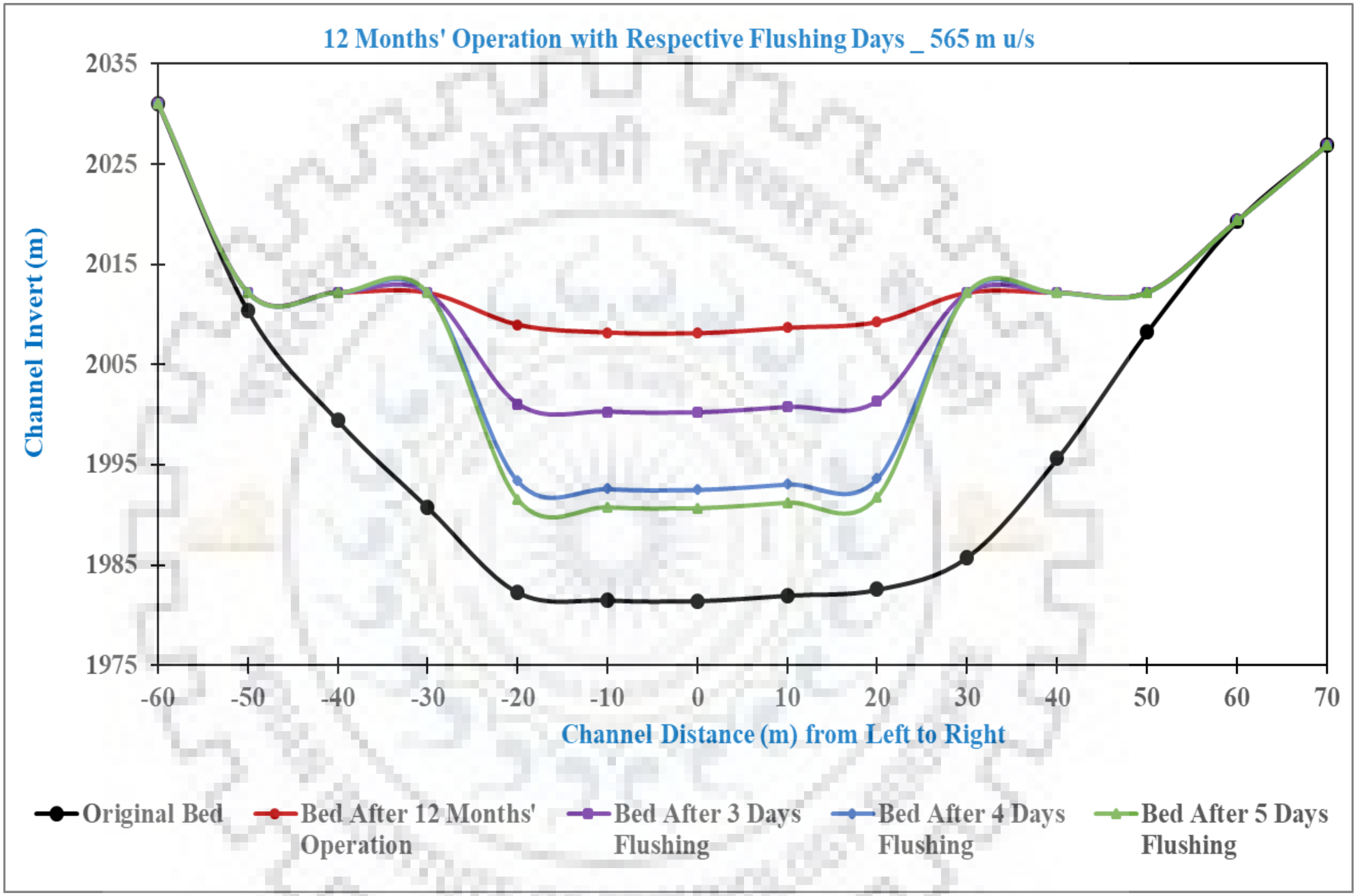

Figure 4. 14: Sediment Cross Section Change 565 m Upstream

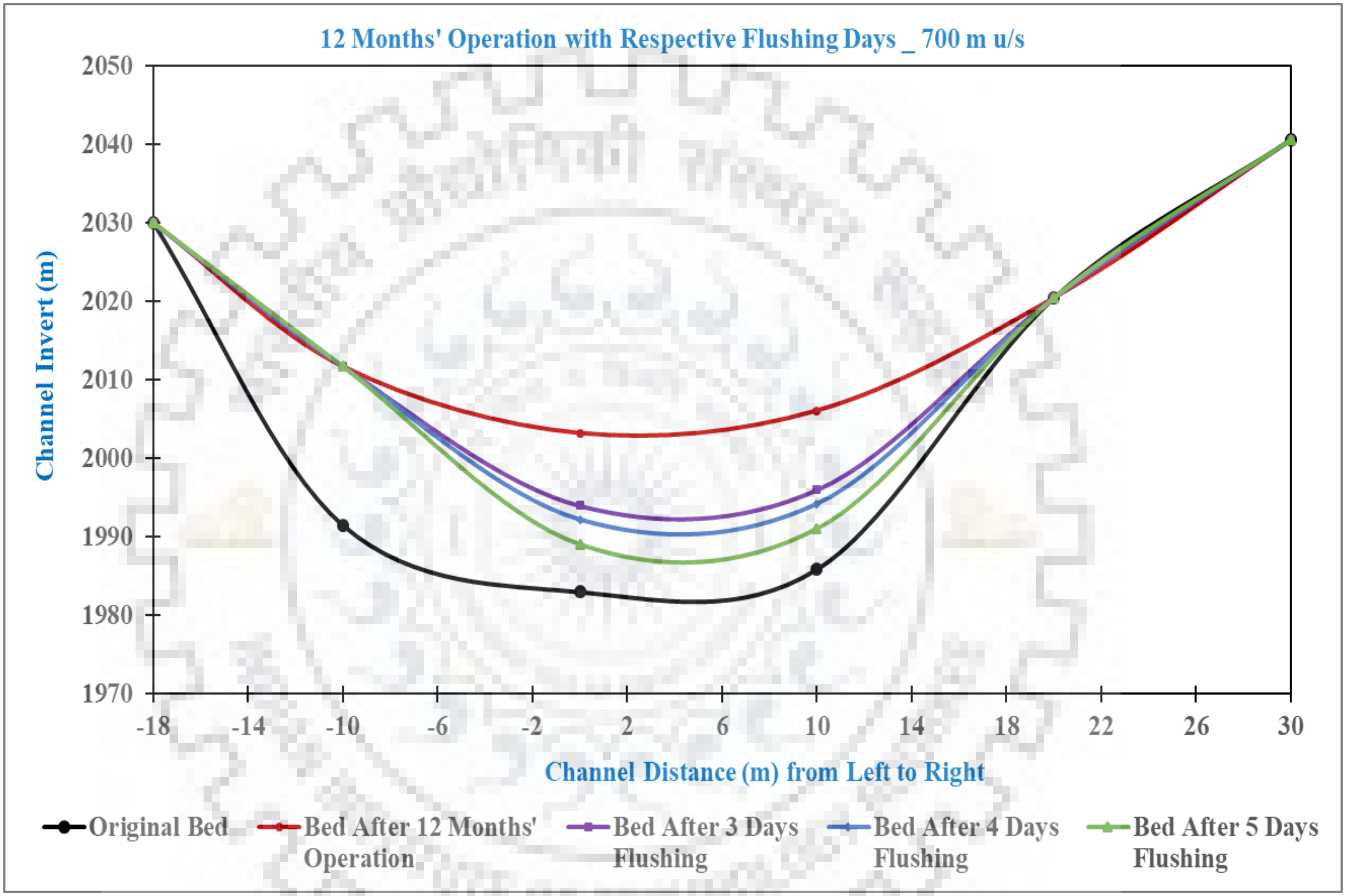

Figure 4. 15: Sediment Cross Section Change 700 m Upstream

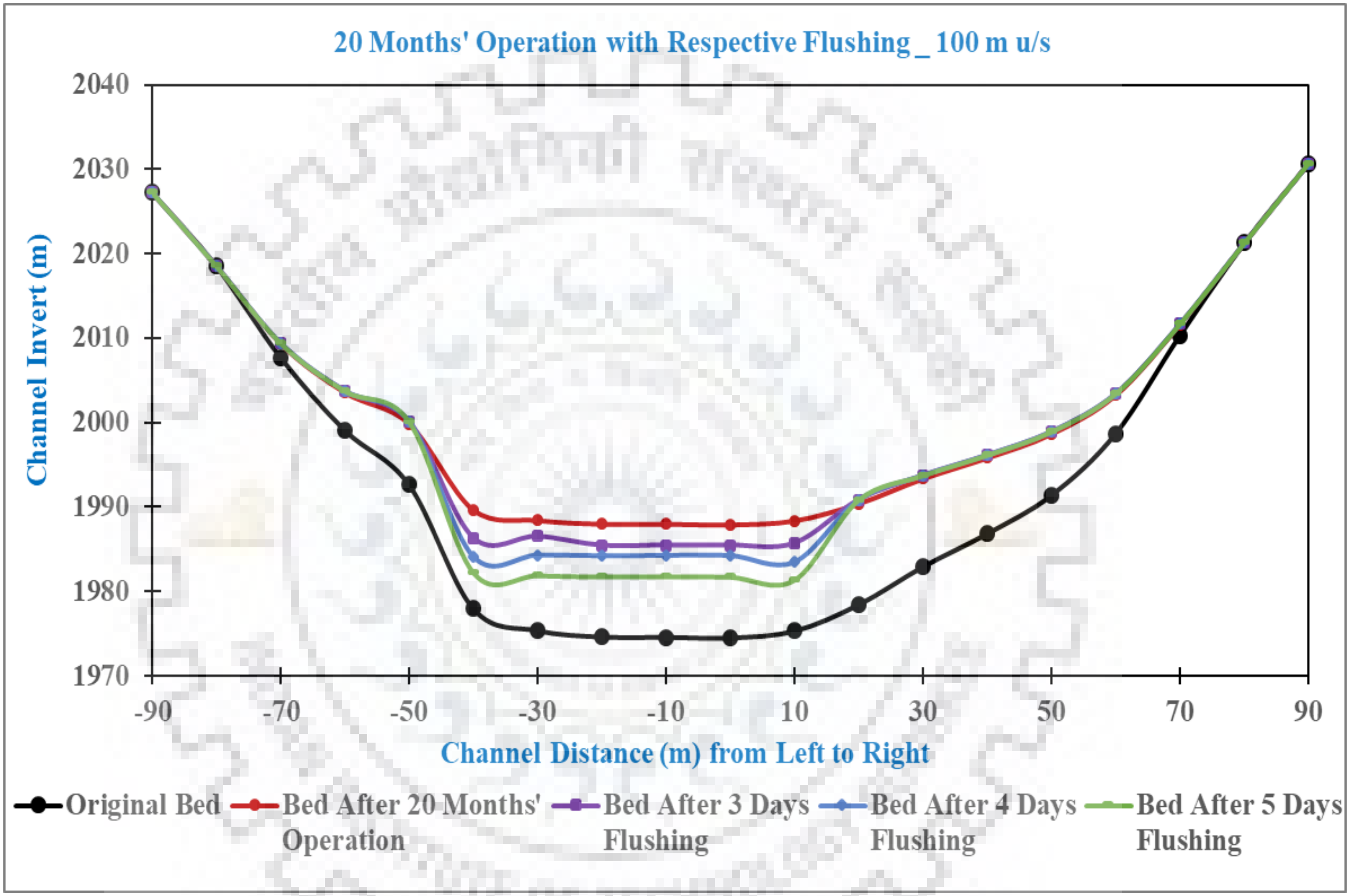

Figure 4. 16: Sediment Cross Section Change 100 m Upstream

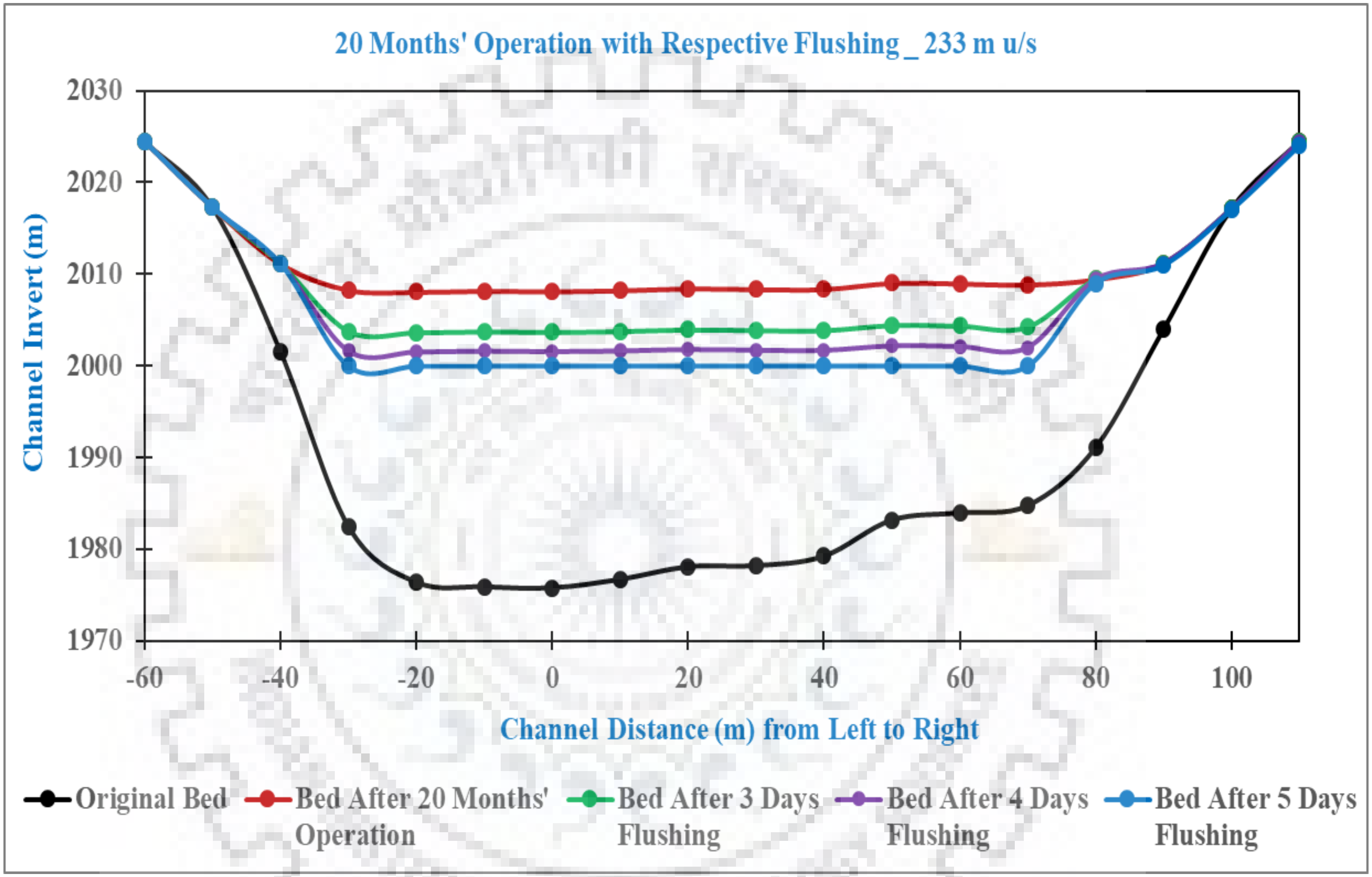

Figure 4. 17: Sediment Cross Section Change 233 m Upstream

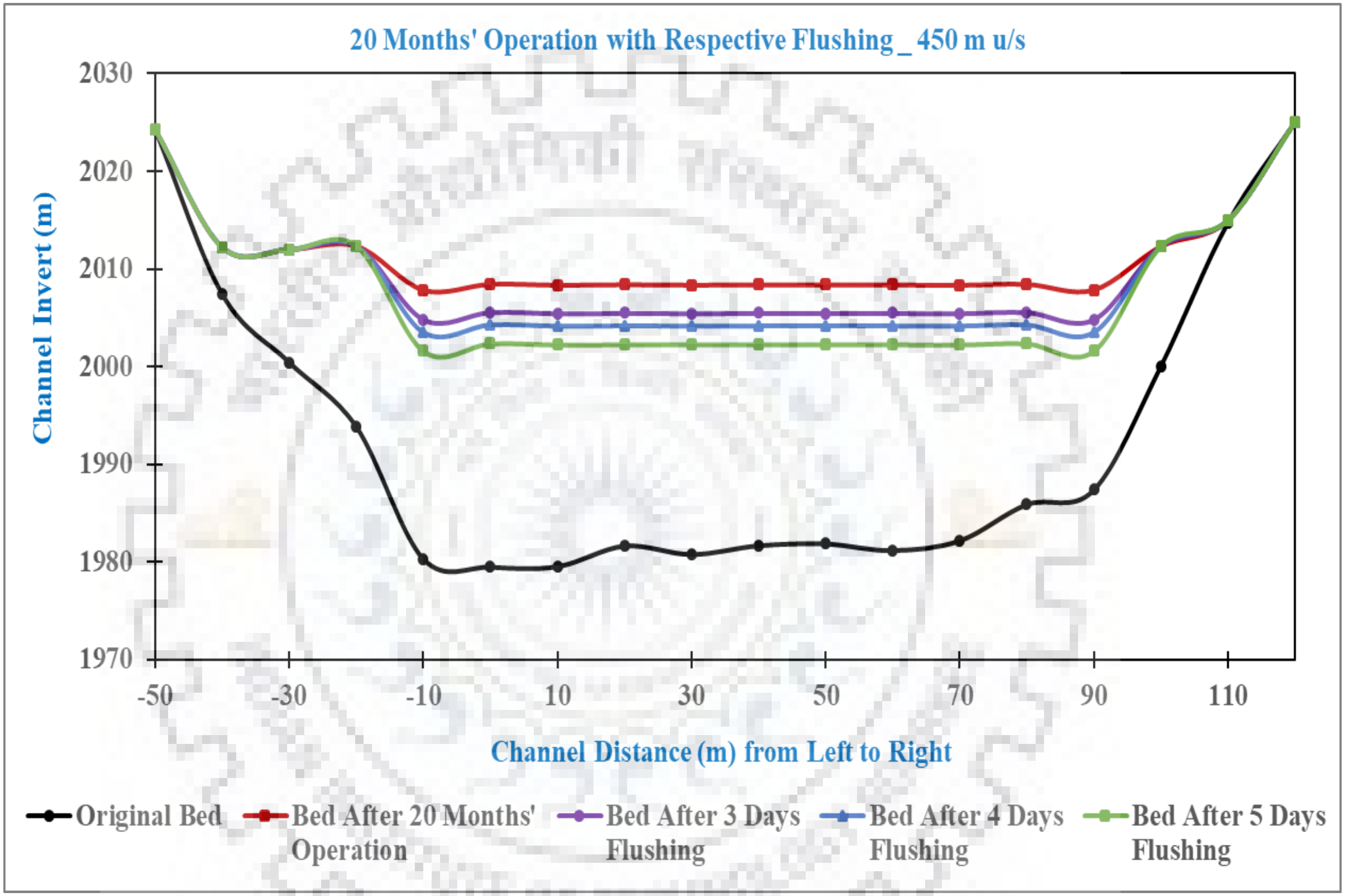

Figure 4. 18: Sediment Cross Section Change 450 m Upstream

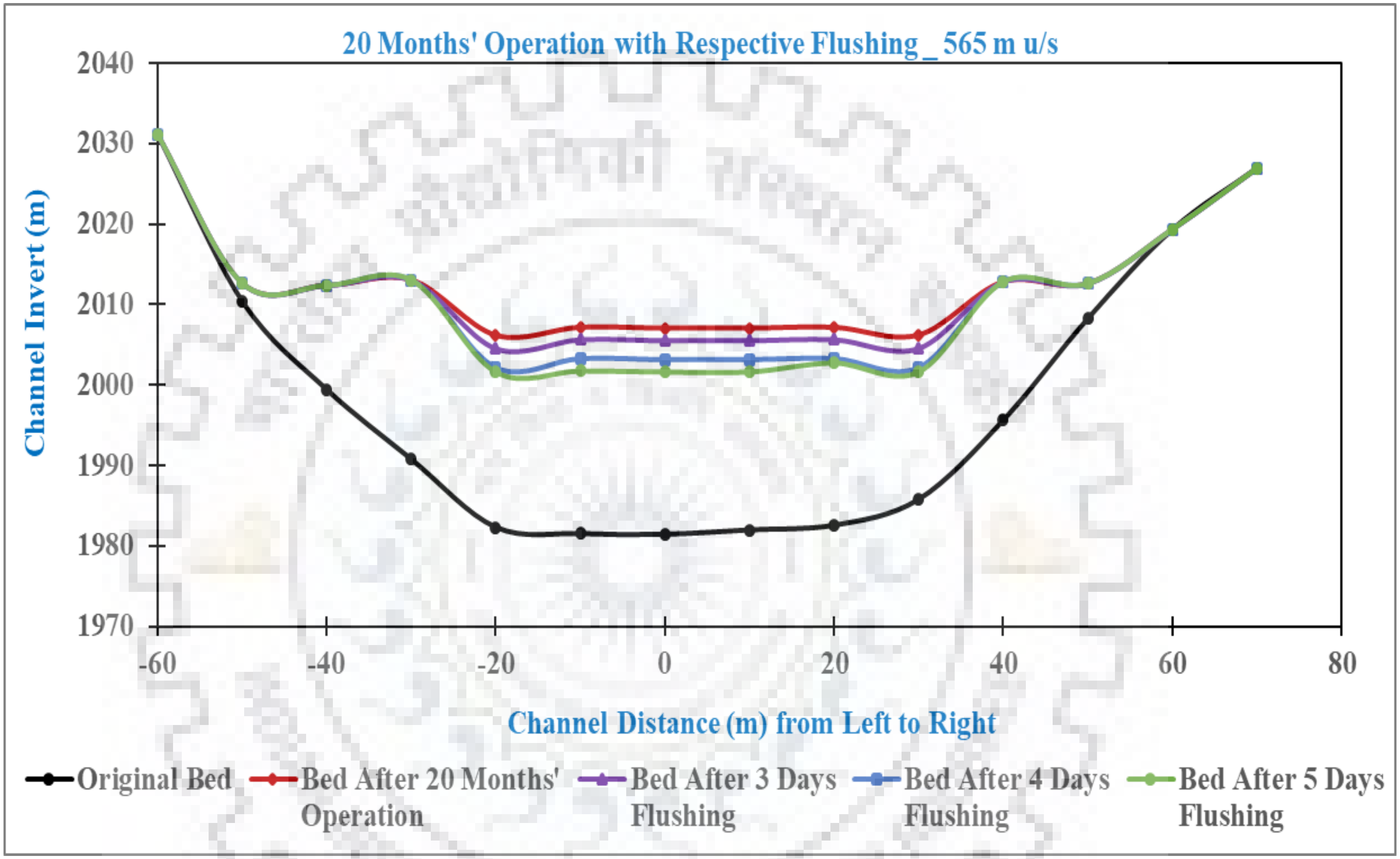

Figure 4. 19: Sediment Cross Section Change 565 m Upstream

4.3.1 Bajoli Holi Results' Discussion

After 8 months of sedimentation, it was seen that the gross capacity of Bajoli Holi reservoir (about 3.03 MCM) was reduced in the first monsoon season by about 28 % (or 72 % capacity remaining), corresponding to about 0.84 MCM of sediment deposited, as illustrated on Fig. 4.20 below. However, after an attempted recovery of the lost capacity through depleting flushing for 3, 4, and 5 days (or 72, 96, and 120 hours), about 89, 91, and 93 % of the original capacity was regained respectively as may be seen on Fig. 4.21 below.

Allowing the HEC-RAS model to run for 12 months was seen to reduce the reservoir gross capacity to 1.94 MCM (or about 36 % capacity lost), equivalent to say 1.09 MCM of sediment accumulated, as illustrated on Fig. 4.20. Also, after depleting the reservoir water level for 3, 4, and 5 days, about 85, 86, and 87 % capacity of the original gross was recouped, in that order (Fig. 4.22 below).

While, for 20 months' sedimentation, the original gross capacity was reduced to nearly 1.28 MCM (Fig. 4.20 below) by almost 1.75 MCM of sediment, thereby reducing the reservoir capacity by approximately 58 %. Again, after depleting flushing for 72, 96, and 120 hours, the reservoir storage capacity (Fig. 4.23 below) was virtually salvaged by 63, 65, and 67 %, respectively.

A separate run was carried out to flush the reservoir for 6 days in each of the sedimentation months, but, the results showed a very insignificant gain in capacity as may be seen that the gain in capacity between the 4th and 5th day of flushing in each of the above cases is not so much.

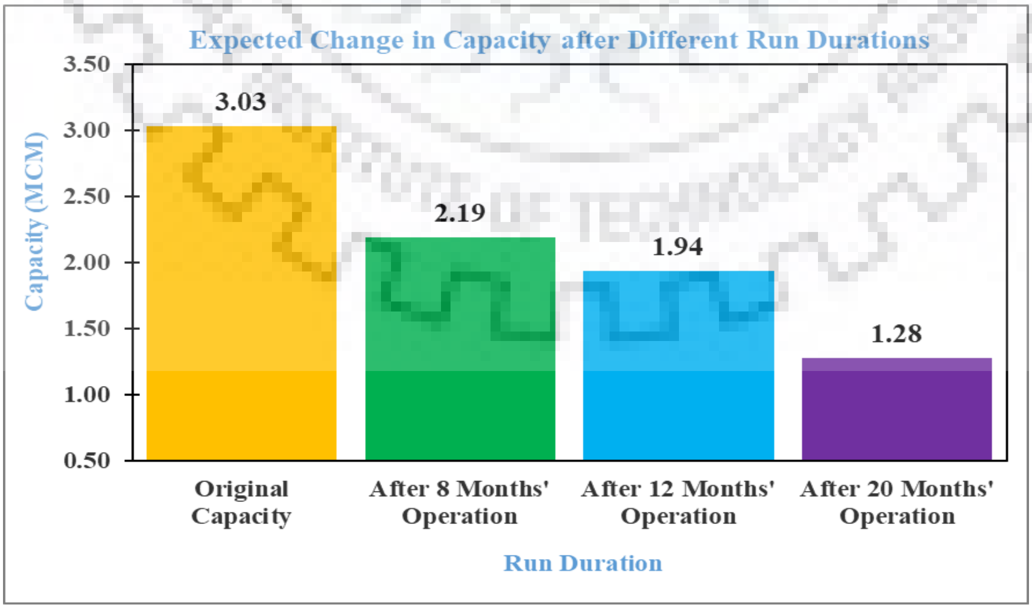

Figure 4. 20: Variation of Bajoli Holi Storage Capacity with Time

The results also showed that a maximum capacity (about 2.81 MCM) was restored after 120 hours of depleting flushing (post monsoon) after 8 months' sedimentation, as compared to the same flushing time after 12 and 20 months' sedimentation respectively, as summarised on Tab. 4.2 and Fig. 4.24 below.

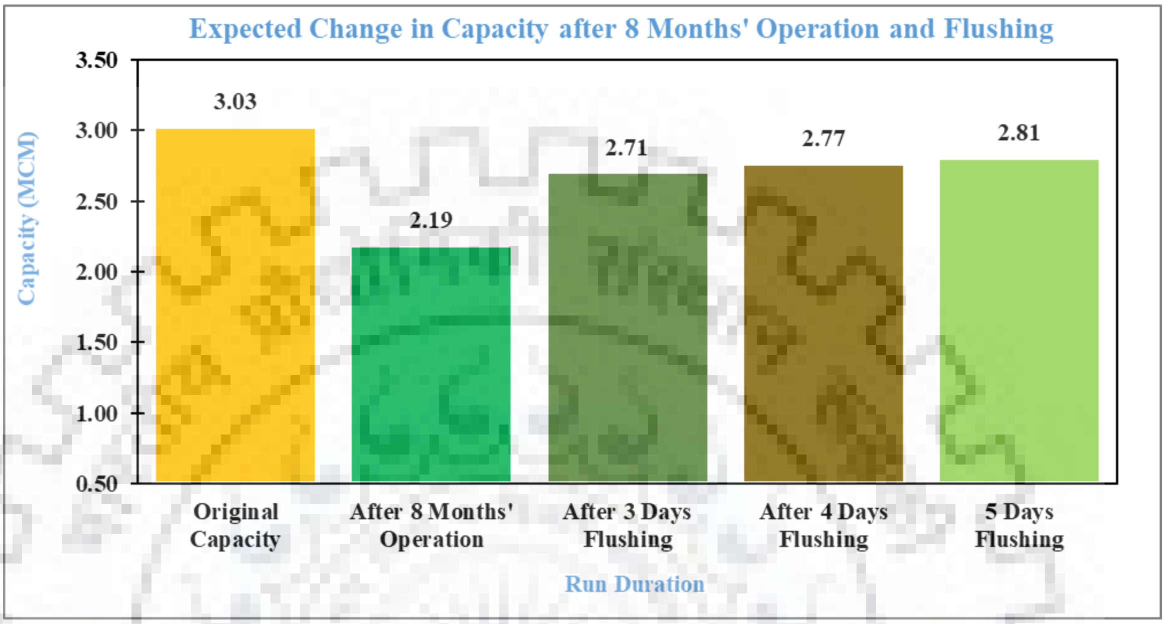

Figure 4. 21: Change in Bajoli Holi Capacity after 8 months' Operation and Flushing Respectively for 72, 96, and 120 Hours.

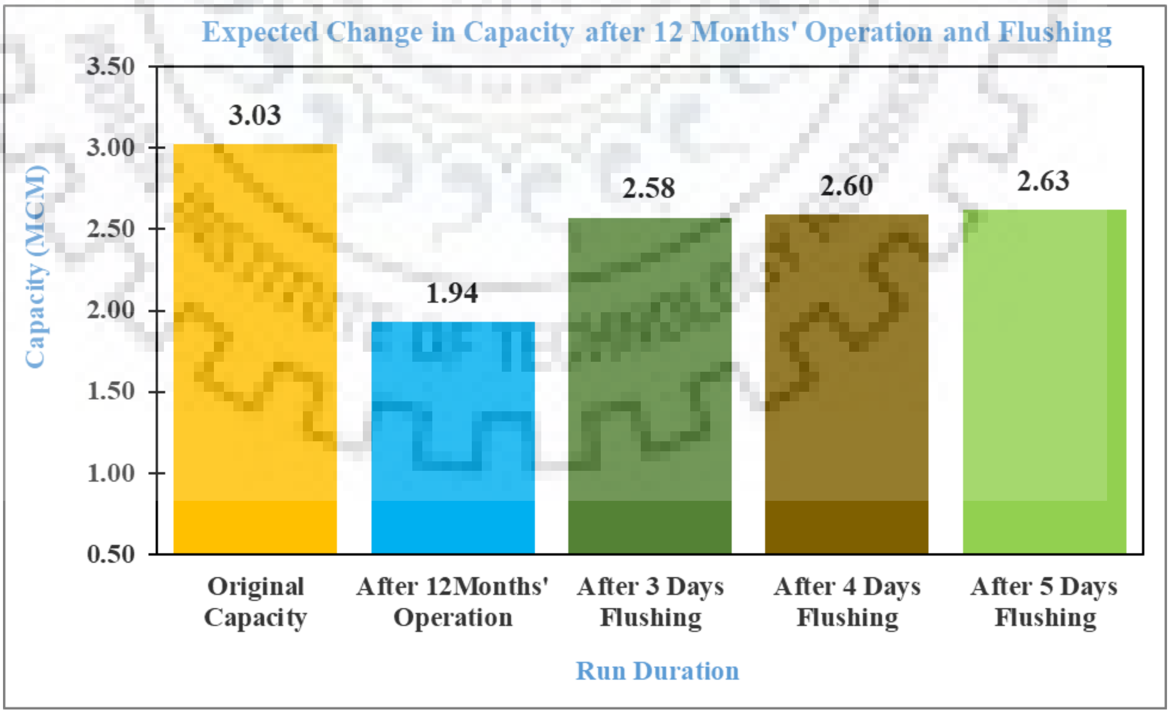

Figure 4. 22: Change in Bajoli Holi Gross Capacity after 12 months' Operation and Flushing respectively for 72, 96, and 120 Hours.

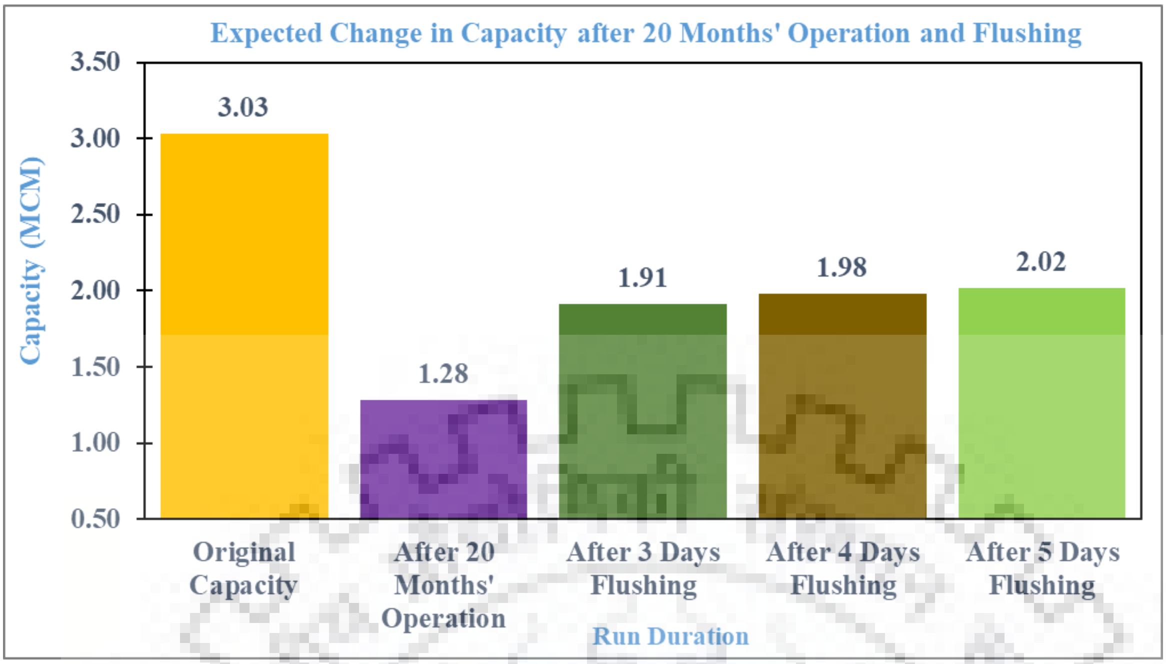

Figure 4. 23: Change in Bajoli Holi Gross Capacity after 20 months' Operation and Flushing respectively for 72, 96, and 120 Hours.

Table 4. 2: Expected Loss of Capacity

Capacity (MCM)	Sediment (MCM)	%age loss of Design Capacity	Remaining %age of Design Capacity	Duration
3.03	**0.00**	**0.00**	**0.00**	**Original/ Designed**
2.19	0.84	28	72	8 months' operation
2.71	0.32	11	89	3 days flushing
2.77	0.26	9	91	4 days flushing
2.81	0.22	7	93	5 days flushing
1.94	1.09	36	64	12months' operation
2.58	0.45	15	85	3 days flushing
2.60	0.43	14	86	4 days flushing
2.63	0.40	13	87	5 days flushing
1.28	1.75	58	42	20months' operation
1.91	1.12	37	63	3 days flushing
1.98	1.05	35	65	4 days flushing
2.02	1.01	33	67	5 days flushing

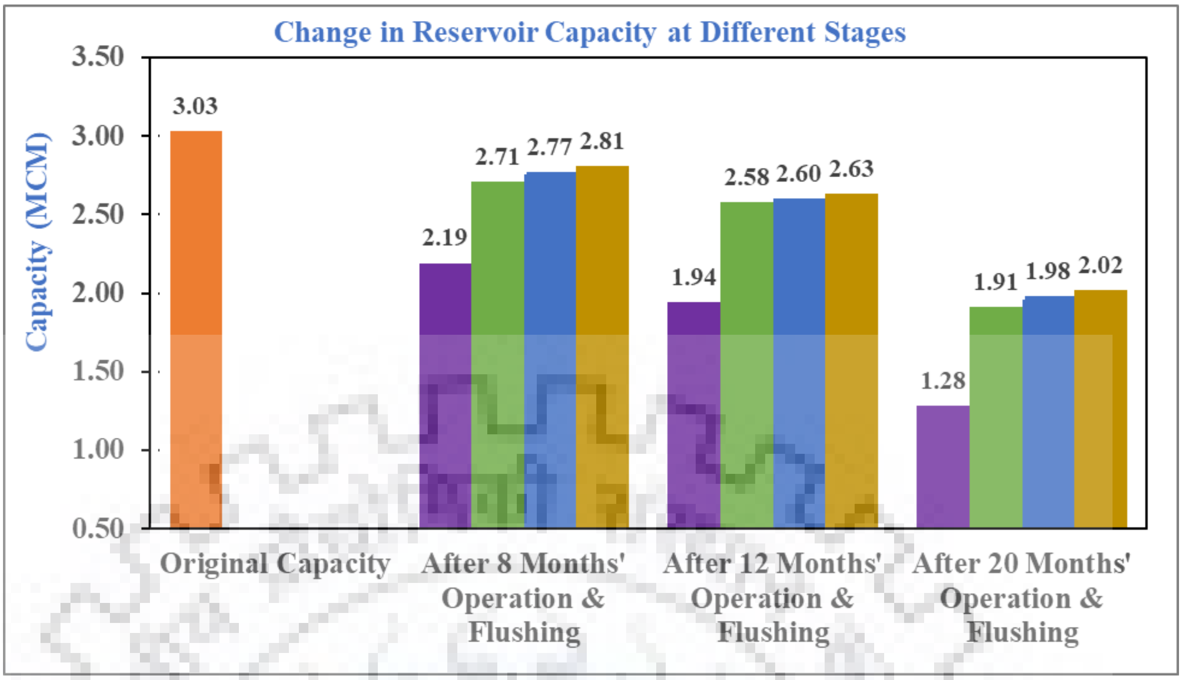

Figure 4. 24: Changes in Capacity due to Sedimentation and Days of Flushing

Legend

Initial Capacity.

Remaining Capacity after 8, 12, and 20 Months' Operation.

Capacity Restoration after 3 Days Flushing.

Capacity Restoration after 4 Days Flushing.

Capacity Restoration after 5 Days Flushing.

4.4 SEDIMENTATION STUDIES FOR TEHRI RESERVOIR

4.4.1 With Sediment Corresponding to Actually Observed Loss of Capacity

Results obtained for both rivers after running the model have been tabulated in Tab. 4.3 to Tab. 4.9 and plotted for every 5 years in Fig. 4.25 to Fig. 4.37, except Tab 4.8 and Tab. 4.9. It may be seen that after suffering some retrogression in the upstream reaches sediment mainly deposits in between 22 km to 37 km reach in Bhagirathi river (Fig. 4.30 to Fig. 4.33) while in Bhilangna river the main deposition is in between 7 km to 25 km as is clear from changes in cross sections in (figure 4.34 to figure 4.37). Figure 4.28 and figure 4.29, show total mass changes in tons at each chainage in R. Bhagirathi and Bhilangna river respectively. It is clear from the figures that chainage 26 km. of Bhagirathi and chainage 20 km. of Bhilangna has maximum mass bed change after 25 years of sedimentation which is also supported by Tab. 4.6 and Tab. 4.7 which show total mass bed changes at each cross section in tons. Longitudinal bed changes at every point starting from the start of the reservoir (taken as zero) is tabulated for both rivers in Tab. 4.6 and Tab. 4.7 and is plotted in Fig. 4.28 and Fig. 4.29. Total outcome in R. Bhagirathi valley is 1.52 X 10^8 tons and in R. Bhilangna is 0.64 X 10^8 tons after 25 years. Mean effective channel invert and change of the bed for both rivers have been tabulated in Tab. 4.8 and Tab. 4.9 for every 5 years upto the year 2038.

After perusal of results it was found that velocity in the reservoir decrease at 37 km of R. Bhagirathi and attains quite low value at 22 km. causing maximum deposition in the vicinity. The same phenomenon is observed in R. Bhilangna between 25 km and 7 km causing maximum deposition within this range. The total bed mass change (Tab. 4.6) was found to be **1.52 X 10^8 tons** in R. Bhagirathi and **0.64 X 10^8 tons** in R. Bhilangna (Tab. 4.7). This shows that deposited sediment load is **1.52 X 10^8 + 0.64 X 10^8 = 2.16 X 10^8 tons in 25 years**. Taking average density of 1.4 tons / cubic meter for submerged sand in Tehri reservoir, the deposition of **2.16 X 10^8 tons** corresponds to **154.29 MCM** deposition in the reservoir in 25 years. The total deposition after every five years and corresponding loss in the capacity is given in Tab. 4.3 and Fig. 4.25 below. The Tab. includes loss of capacity from 2014 to 2038 (25 years) as predicted by mathematical modeling. It may be seen from Tab. 4.3 that total loss of capacity in 25 years is **149.51 MCM** or an average rate of capacity loss of **5.98 MCM/year.** From this, the total loss of MDDL capacity (925 MCM) shall be after **155 years.** So, the loss of **5.98 MCM/ year** is equivalent to **0.17 % per year,** taking the original capacity of 3540 MCM.

Table 4. 3: Expected Loss of Capacity from 2014 to 2038

Total Time (Years)	Year	Capacity (MCM)	Loss/ Sediment (MCM)	%age loss of Capacity
0	2009	3540.00	0.00	0.00
5	2013	3517.61	22.39	0.63
10	2018	3487.27	52.73	1.49
15	2023	3453.74	86.26	2.44
20	2028	3404.81	135.19	3.82
25	2033	3390.49	149.51	4.22
Average Rate of Capacity Loss per Year (MCM) in 25 Years = 5.98				

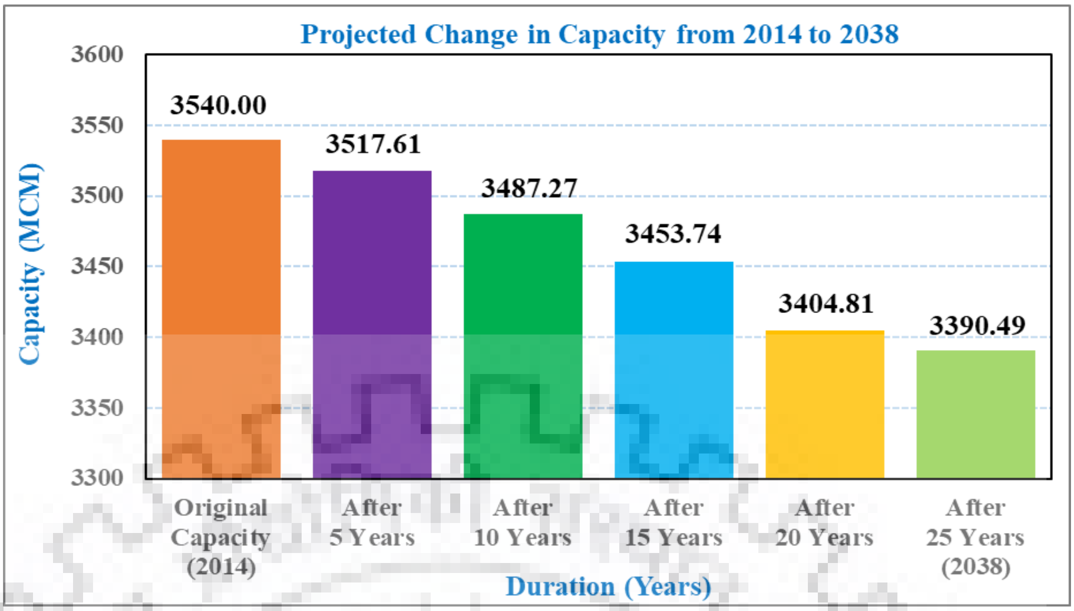

Figure 4. 25: Expected Change in Tehri Reservoir Capacity due to Sedimentation within 25 Years

Table 4. 4: Expected Longitudinal Bed Changes (m) in R. Bhagirathi in 25 Years

Channel Distance (m).	Original Bed.	Expected Bed After 5 Years.	Expected Bed After 10 Years.	Expected Bed After 15 Years.	Expected Bed After 20 Years.	Expected Bed After 25 Years.
42000	827.20	827.48	827.48	827.48	827.48	827.48
41000	821.98	821.98	822.22	822.41	822.62	822.70
40000	815.01	815.37	815.37	815.37	815.37	815.37
39000	808.63	808.63	808.99	808.99	808.99	808.99
38000	802.20	802.43	803.71	803.69	804.92	805.82
37000	795.60	796.22	796.51	797.32	799.14	799.87
36000	790.73	793.01	794.41	794.57	797.86	799.40
35000	782.98	790.69	790.19	789.03	791.69	791.77
34000	776.56	780.61	785.40	790.90	788.56	792.01
33000	768.75	772.32	780.85	788.13	787.16	785.61
32000	762.58	763.66	764.27	765.60	767.85	770.78
31000	758.87	762.83	765.28	765.39	768.55	770.38
30000	752.49	754.55	756.72	759.03	761.23	761.39
29000	747.03	749.03	750.82	751.18	757.97	747.03
28000	741.33	742.78	746.14	746.53	746.55	761.03
27000	733.80	736.87	744.47	751.79	753.69	750.55
26000	727.06	738.29	745.21	747.37	742.06	761.82
25000	721.32	735.85	737.88	748.75	737.99	740.26

Continued on the next page

24000	717.13	724.30	739.58	747.26	753.45	743.15
23000	711.32	725.06	738.36	742.85	742.94	744.84
22000	705.77	710.27	715.94	722.57	730.95	738.68
21000	700.28	704.10	711.12	728.26	749.38	746.51
20000	694.54	700.16	707.94	716.84	719.17	719.66
19000	691.39	694.40	698.29	701.76	706.45	712.90
18000	685.90	689.78	694.54	698.99	703.54	708.81
17000	679.98	683.65	688.47	692.17	696.01	699.99
16000	674.87	678.55	682.10	684.80	687.36	689.92
15000	671.23	674.07	677.81	680.59	683.37	686.08
14000	667.19	671.09	675.62	678.43	680.96	683.54
13000	663.44	665.82	669.57	673.21	676.97	679.74
12000	660.37	661.27	662.84	664.62	666.10	666.99
11000	655.18	656.21	657.68	659.05	660.64	661.83
10000	651.69	652.21	652.92	653.60	655.53	658.21
9000	649.36	649.64	650.01	650.37	650.98	651.66
8000	646.45	646.68	646.98	647.26	647.69	648.15
7000	648.37	648.72	649.18	649.60	650.23	650.93
6000	646.28	646.54	646.87	647.17	647.56	647.98
5000	645.71	645.98	646.31	646.60	646.98	647.37
4000	640.58	640.86	641.19	641.49	641.87	642.26
3000	636.98	637.18	637.43	637.65	637.92	638.19
2000	637.49	637.65	637.83	638.00	638.20	638.40
1000	641.17	641.30	641.46	641.60	641.76	641.92
100	641.17	642.44	643.14	644.15	644.84	646.13
100	641.17	641.17	641.17	641.18	641.18	641.18

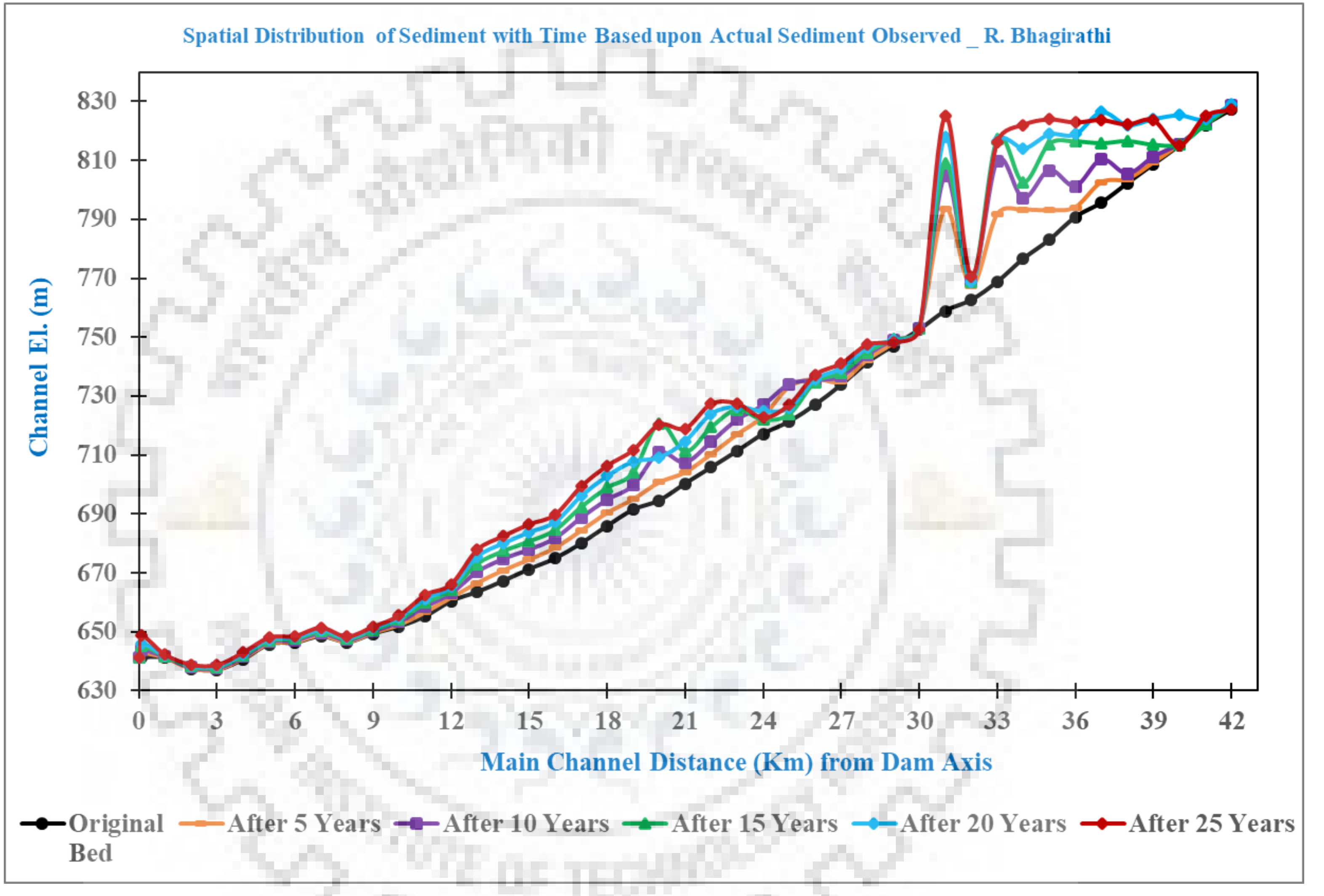

Figure 4. 26: Spatial Sediment Distribution in Tehri Reservoir with Time based upon Actually Observed Loss of Capacity

Table 4. 5: Expected Longitudinal Bed Changes (m) in R. Bhilangna in 25 Years

Channel Distance (m)	Original Bed	Expected Bed After 5 Years	Expected Bed After 10 Years	Expected Bed After 15 Years	Expected Bed After 20 Years	Expected Bed After 25 Years
24000	831.09	832.42	832.66	832.75	834.94	838.16
23000	823.93	823.95	824.03	824.02	824.97	825.13
19000	787.47	788.01	794.30	809.75	823.24	837.67
18000	780.65	817.79	829.16	830.56	834.04	812.15
17000	775.72	776.04	776.06	776.07	776.07	776.21
16000	764.22	767.40	764.53	765.23	764.62	764.68
15000	749.02	750.31	749.20	749.40	749.29	749.88
14000	735.68	738.02	735.79	736.25	736.60	739.33
13000	726.70	729.42	729.41	728.21	727.05	728.51
12000	712.79	716.60	718.77	720.46	721.29	728.12
10000	692.92	694.39	695.24	696.30	696.88	698.02
9000	686.26	687.42	688.19	689.54	690.24	691.55
8000	681.12	682.96	683.83	684.89	685.42	686.40
7000	659.41	660.65	661.23	661.98	662.36	663.23
6000	665.89	670.51	674.27	679.50	682.68	687.82
5000	661.25	663.65	665.29	667.47	668.89	670.93
4000	656.85	658.68	659.91	661.76	662.75	664.56
2000	650.44	653.34	654.77	656.92	658.30	661.00
0	650.44	651.84	652.98	654.30	655.29	657.12

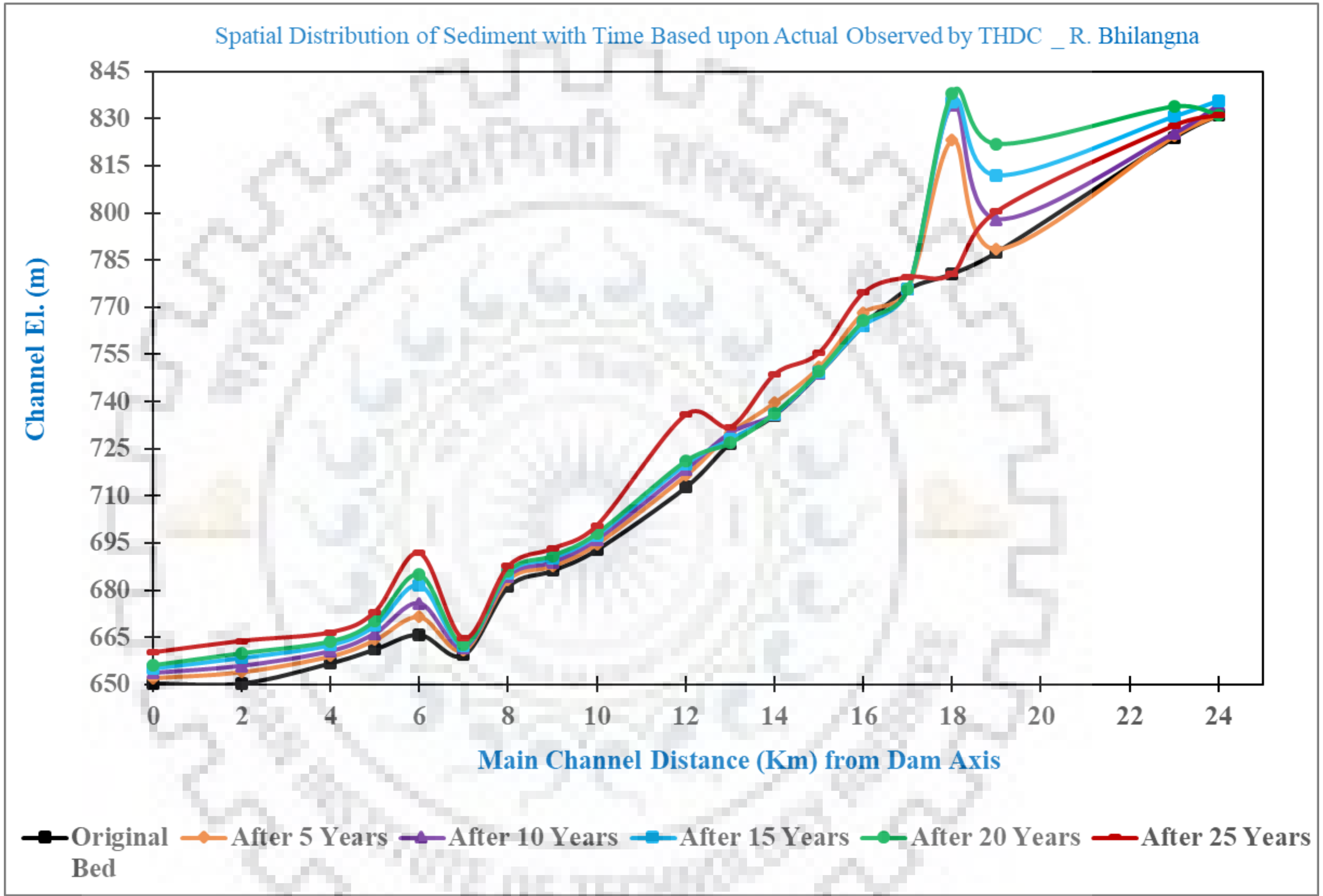

Figure 4. 27: Spatial Sediment Distribution in Tehri Reservoir with Time based upon Actually Observed Loss of Capacity

Table 4. 6: Expected Mass Bed Change Cumulative (Tons) in R. Bhagirathi in 25 Years

Chainage (m)	Original Bed	After 5 Years	After 10 Years	After 15 Years	After 20 Years	After 25 Years
42000	0	6.17E+03	6.17E+03	6.17E+03	6.17E+03	6.17E+03
41000	0	0.00E+00	-5.45E+04	-3.61E+04	-1.80E+04	-6.11E+03
40000	0	2.34E+04	2.34E+04	2.34E+04	2.34E+04	2.34E+04
39000	0	0.00E+00	4.92E+04	4.92E+04	4.92E+04	4.92E+04
38000	0	8.07E+04	6.89E+05	7.29E+05	1.33E+06	1.83E+06
37000	0	7.23E+05	1.06E+06	1.39E+06	1.94E+06	2.41E+06
36000	0	6.97E+05	9.66E+05	1.73E+06	3.11E+06	3.47E+06
35000	0	3.41E+06	3.65E+06	4.32E+06	4.92E+06	5.29E+06
34000	0	1.45E+06	2.99E+06	4.81E+06	4.88E+06	6.13E+06
33000	0	5.49E+05	2.34E+06	3.98E+06	4.37E+06	4.91E+06
32000	0	4.71E+05	1.14E+06	2.66E+06	4.15E+06	6.04E+06
31000	0	1.04E+06	1.88E+06	2.88E+06	3.73E+06	4.89E+06
30000	0	1.11E+06	2.18E+06	3.22E+06	3.83E+06	4.35E+06
29000	0	9.61E+05	3.10E+06	4.79E+06	7.11E+06	7.76E+06
28000	0	1.07E+06	2.21E+06	2.93E+06	4.34E+06	6.43E+06
27000	0	1.73E+06	3.01E+06	4.28E+06	5.87E+06	7.23E+06
26000	0	2.24E+06	4.03E+06	5.21E+06	6.67E+06	**1.06E+07**
25000	0	1.78E+06	2.99E+06	4.40E+06	5.17E+06	6.13E+06
24000	0	9.43E+05	3.03E+06	4.29E+06	5.26E+06	5.31E+06
23000	0	2.09E+06	4.74E+06	6.41E+06	7.13E+06	8.60E+06
22000	0	8.83E+05	2.02E+06	3.61E+06	5.54E+06	7.32E+06
21000	0	6.80E+05	1.80E+06	4.13E+06	7.83E+06	8.20E+06
20000	0	7.66E+05	1.75E+06	2.89E+06	3.28E+06	3.46E+06
19000	0	6.20E+05	1.40E+06	2.13E+06	3.02E+06	4.23E+06
18000	0	5.86E+05	1.30E+06	1.98E+06	2.64E+06	3.39E+06
17000	0	4.95E+05	1.14E+06	1.65E+06	2.16E+06	2.69E+06
16000	0	6.28E+05	1.26E+06	1.75E+06	2.21E+06	2.67E+06
15000	0	4.11E+05	9.54E+05	1.38E+06	1.79E+06	2.19E+06

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14000	0	5.75E+05	1.30E+06	1.77E+06	2.19E+06	2.63E+06
13000	0	3.91E+05	1.01E+06	1.65E+06	2.27E+06	2.75E+06
12000	0	4.60E+05	1.23E+06	2.12E+06	2.88E+06	3.35E+06
11000	0	3.09E+05	7.41E+05	1.16E+06	1.63E+06	1.99E+06
10000	0	3.05E+05	7.19E+05	1.12E+06	2.19E+06	3.69E+06
9000	0	2.80E+05	6.61E+05	1.03E+06	1.66E+06	2.35E+06
8000	0	2.45E+05	5.69E+05	8.78E+05	1.34E+06	1.85E+06
7000	0	2.49E+05	5.76E+05	8.79E+05	1.30E+06	1.78E+06
6000	0	2.01E+05	4.62E+05	6.96E+05	1.01E+06	1.34E+06
5000	0	2.06E+05	4.69E+05	7.03E+05	1.00E+06	1.31E+06
4000	0	1.91E+05	4.33E+05	6.49E+05	9.11E+05	1.18E+06
3000	0	1.80E+05	4.05E+05	6.09E+05	8.43E+05	1.08E+06
2000	0	1.51E+05	3.40E+05	5.10E+05	7.04E+05	9.04E+05
1000	0	5.88E+04	1.32E+05	1.98E+05	2.70E+05	3.44E+05
100	0	7.11E+04	1.10E+05	1.68E+05	2.06E+05	2.79E+05
100	0	2.84E+02	4.81E+02	7.67E+02	9.52E+02	1.31E+03
TOTAL		**0.29E+08**	**0.61E+08**	**0.92E+08**	**1.23E+08**	**1.52E+08**

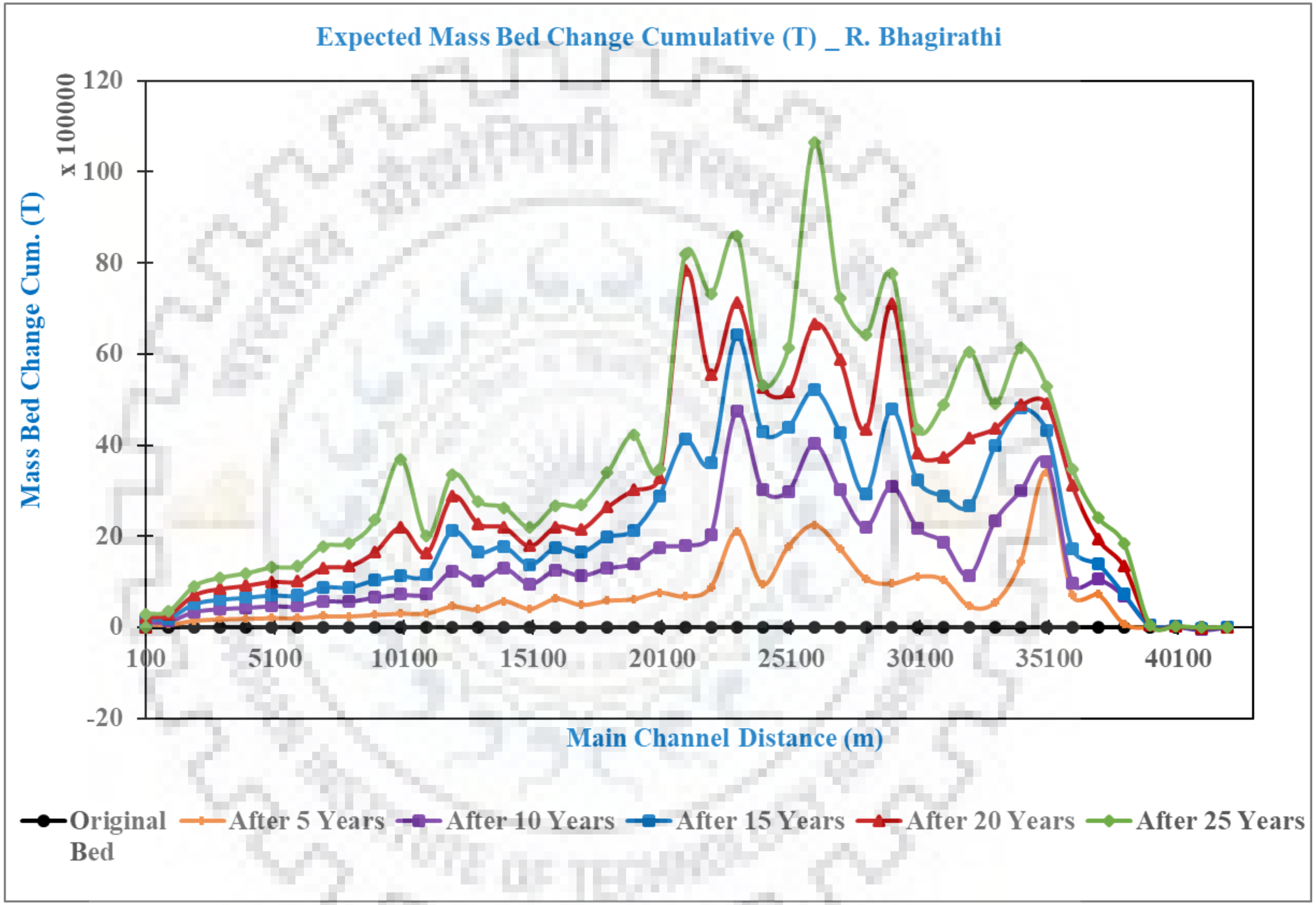

Figure 4. 28: Expected Mass Bed Change Cumulative (T) in 25 Years at each Cross Section in R. Bhagirathi

Table 4. 7: Expected Mass Bed Change Cumulative (Tons) in R. Bhilangna in 25 Years

Chainage (m)	Original Bed	After 5 Years	After 10 Years	After 15 Years	After 20 Years	After 25 Years
24000	0	6.94E+03	1.37E+04	2.10E+04	8.18E+04	1.86E+05
23000	0	3.97E+03	1.84E+04	6.80E+04	4.71E+05	5.48E+05
19000	0	2.16E+05	2.93E+06	1.00E+07	1.57E+07	**2.19E+07**
18000	0	2.65E+06	4.35E+06	4.36E+06	4.61E+06	1.70E+06
17000	0	3.14E+05	3.29E+05	3.31E+05	3.32E+05	5.14E+05
16000	0	1.49E+06	2.47E+06	3.48E+06	3.84E+06	5.58E+06
15000	0	7.66E+05	1.18E+06	1.66E+06	1.85E+06	2.40E+06
14000	0	6.33E+05	9.81E+05	1.37E+06	1.57E+06	2.31E+06
13000	0	1.08E+06	1.40E+06	1.75E+06	1.92E+06	2.69E+06
12000	0	6.22E+05	1.02E+06	1.41E+06	1.61E+06	2.48E+06
10000	0	3.43E+05	5.51E+05	8.14E+05	9.57E+05	1.23E+06
9000	0	3.48E+05	6.00E+05	1.05E+06	1.28E+06	1.70E+06
8000	0	6.52E+05	9.63E+05	1.33E+06	1.52E+06	1.86E+06
7000	0	4.73E+05	6.99E+05	9.90E+05	1.14E+06	1.48E+06
6000	0	1.30E+06	2.39E+06	3.89E+06	4.86E+06	6.35E+06
5000	0	7.67E+05	1.32E+06	2.06E+06	2.55E+06	3.24E+06
4000	0	8.49E+05	1.44E+06	2.32E+06	2.80E+06	3.66E+06
2000	0	8.31E+05	1.26E+06	1.95E+06	2.36E+06	3.19E+06
0	0	1.99E+05	3.57E+05	5.58E+05	6.99E+05	9.56E+05
TOTAL		**0.14E+08**	**0.24E+08**	**0.4E+08**	**0.50E+08**	**0.64E+08**

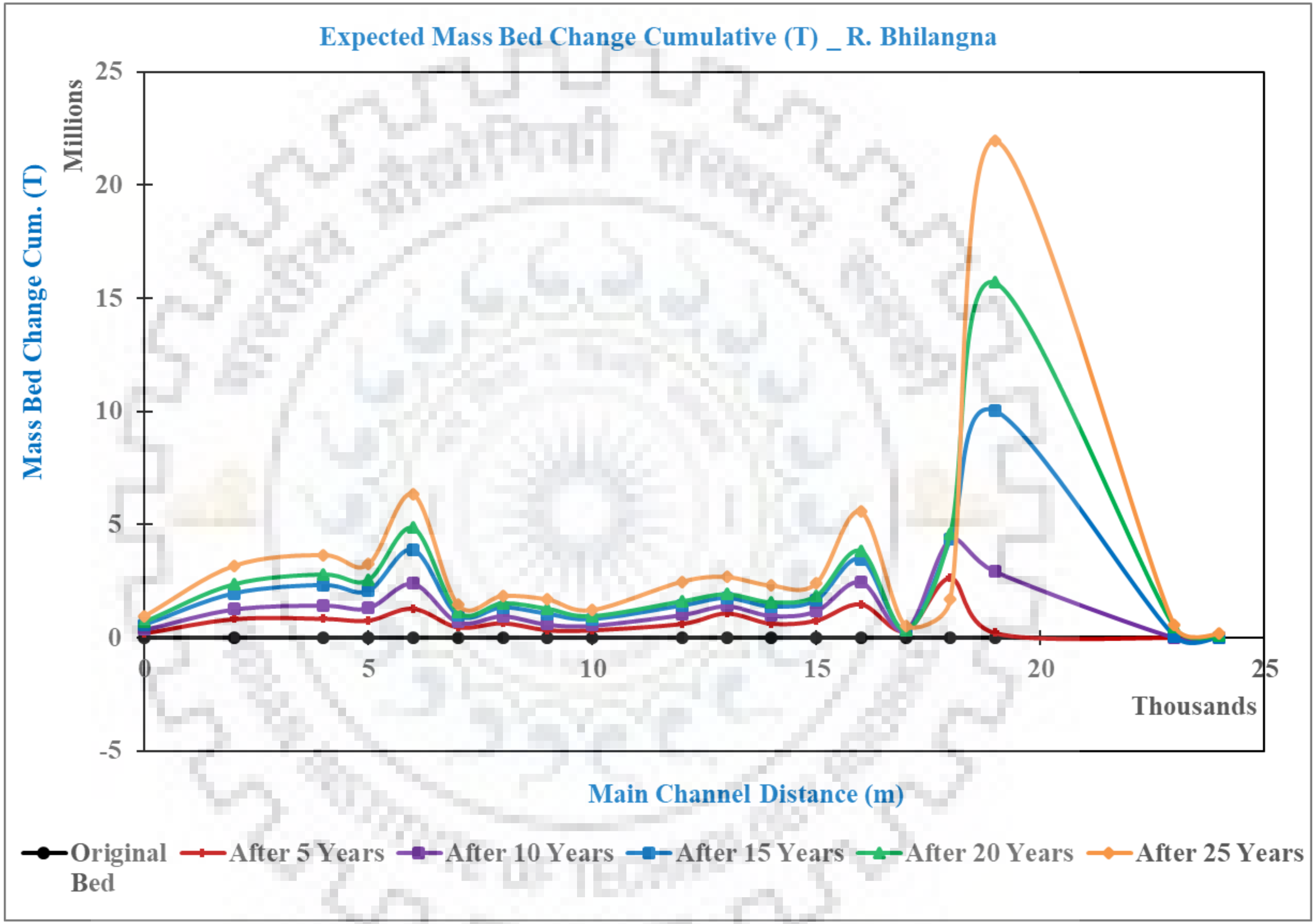

Figure 4. 29: Expected Mass Bed Change Cumulative (T) in 25 Years at each Cross Section in R. Bhilangna

Table 4. 8: Projected Mean Effective Channel Invert and Change (m) in 25 Years in R. Bhagirathi

Chainage (km)	Original Bed Invert	Invert After 5 Years	Invert Change in 5 Years	Invert After 10 Years	Invert Change in 10 Years	Invert After 15 Years	Invert Change in 15 Years	Invert After 20 Years	Invert Change in 20 Years	Invert After 25 Years	Invert Change in 25 Years
42	830.942	830.942	0.000	830.942	0.000	830.942	0.000	830.942	0.000	830.942	0.000
41	827.343	827.343	0.000	827.343	0.000	827.343	0.000	827.343	0.000	827.344	0.001
40	821.981	821.981	0.000	821.981	0.000	821.981	0.000	821.981	0.000	821.981	0.000
39	816.455	816.613	0.158	816.395	-0.060	816.429	-0.026	816.497	0.041	816.457	0.002
38	814.029	814.029	0.000	815.498	1.470	815.498	1.470	816.396	2.367	817.078	3.049
37	810.291	810.515	0.225	812.070	1.780	812.040	1.749	813.493	3.203	816.279	5.988
36	806.912	808.576	1.665	808.727	1.816	809.152	2.240	809.638	2.726	814.795	7.883
35	801.323	802.161	0.838	802.429	1.106	805.725	4.401	808.718	7.395	810.700	9.376
34	802.873	804.431	1.558	803.933	1.060	807.467	4.594	811.012	8.138	817.463	14.589
33	803.910	804.712	0.802	805.815	1.905	809.211	5.300	810.521	6.611	811.897	7.987
32	780.711	784.111	3.399	793.756	13.045	802.410	21.698	808.419	27.708	811.306	30.595
31	792.818	795.008	2.191	803.185	10.367	806.732	13.914	808.081	15.264	810.189	17.371
30	773.747	775.419	1.672	775.916	2.169	775.681	1.934	776.693	2.947	778.943	5.197
29	773.427	785.022	11.595	792.447	19.020	799.538	26.111	809.375	35.948	813.710	40.283
28	771.361	774.049	2.688	774.091	2.731	772.938	1.577	772.408	1.047	772.451	1.090
27	766.031	767.563	1.532	769.451	3.420	770.269	4.239	772.033	6.003	774.101	8.071
26	779.880	785.915	6.035	782.681	2.801	783.130	3.251	781.444	1.564	782.028	2.148
25	773.234	774.649	1.415	775.619	2.385	776.908	3.674	778.329	5.095	779.907	6.673
24	777.372	779.213	1.841	780.990	3.618	782.431	5.058	783.819	6.447	784.873	7.501
23	762.062	763.839	1.777	765.836	3.774	766.869	4.807	767.902	5.840	768.790	6.728
22	755.026	756.290	1.264	757.861	2.835	758.579	3.553	759.764	4.738	760.662	5.636
21	766.029	766.967	0.938	768.071	2.043	768.697	2.669	769.472	3.443	769.906	3.877
20	747.239	748.037	0.799	748.867	1.628	750.005	2.767	750.613	3.374	750.892	3.654
19	742.169	743.862	1.693	745.826	3.657	747.612	5.443	749.401	7.232	750.343	8.174
18	745.998	747.347	1.350	749.027	3.029	750.736	4.738	752.295	6.297	754.137	8.139
17	735.752	737.093	1.341	738.700	2.949	740.254	4.503	742.026	6.274	743.927	8.175
16	727.768	728.654	0.886	729.693	1.925	730.751	2.983	731.803	4.035	732.880	5.112
15	731.363	732.601	1.238	734.257	2.894	735.453	4.090	736.604	5.241	737.718	6.356
14	725.454	726.528	1.074	727.956	2.502	729.015	3.561	730.036	4.582	731.013	5.559
13	721.062	722.089	1.027	723.520	2.458	724.611	3.549	725.692	4.630	726.712	5.651
12	702.330	702.770	0.440	703.349	1.019	703.816	1.486	704.265	1.935	704.686	2.356
11	707.665	708.233	0.569	708.938	1.273	709.514	1.849	710.099	2.435	710.629	2.964
10	696.173	697.197	1.023	698.081	1.907	698.798	2.625	699.670	3.497	700.283	4.110
9	675.583	675.994	0.411	676.379	0.796	676.683	1.100	677.072	1.490	677.344	1.761
8	675.318	675.626	0.308	675.939	0.621	676.187	0.868	676.521	1.203	676.773	1.454
7	699.033	699.398	0.365	699.789	0.756	700.097	1.064	700.524	1.491	700.858	1.825
6	678.081	678.380	0.299	678.721	0.640	678.996	0.915	679.353	1.273	679.659	1.578
5	687.010	687.262	0.252	687.557	0.547	687.797	0.787	688.097	1.087	688.361	1.350
4	691.968	692.205	0.237	692.485	0.517	692.718	0.749	693.003	1.034	693.257	1.288
3	686.474	686.651	0.177	686.862	0.389	687.042	0.568	687.253	0.780	687.447	0.973
2	663.111	663.272	0.162	663.466	0.355	663.634	0.524	663.826	0.715	664.006	0.896

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1	673.514	673.637	0.123	673.785	0.271	673.916	0.402	674.058	0.544	674.196	0.682
0.1	676.811	677.430	0.619	678.064	1.253	678.900	2.089	679.432	2.621	680.227	3.416
0.1	672.921	672.922	0.001	672.923	0.003	672.925	0.005	672.926	0.006	672.928	0.007

Table 4. 9: Projected Mean Effective Channel Invert and Change (m) in 25 Years in R. Bhilangna

Chainage (km)	Original Bed Invert	Invert After 5 Years	Invert Change in 5 Years	Invert After 10 Years	Invert Change in 10 Years	Invert After 15 Years	Invert Change in 15 Years	Invert After 20 Years	Invert Change in 20 Years	Invert After 25 Years	Invert Change in 25 Years
24	838.873	840.580	1.707	840.580	1.707	840.580	1.707	840.580	838.873	840.580	1.707
23	828.320	829.524	1.204	829.442	1.121	829.352	1.032	829.324	828.320	829.189	0.868
19	837.986	840.978	2.992	840.958	2.972	841.387	3.400	841.387	837.986	841.329	3.343
18	815.726	815.733	0.006	815.734	0.007	815.755	0.029	815.767	815.726	815.789	0.063
17	786.051	786.174	0.122	786.534	0.482	786.598	0.547	787.053	786.051	787.514	1.463
16	785.601	787.601	2.000	788.887	3.286	792.227	6.625	792.555	785.601	793.612	8.011
15	776.772	778.107	1.335	778.344	1.572	779.705	2.933	780.160	776.772	781.490	4.718
14	764.241	764.977	0.736	765.230	0.989	766.022	1.781	766.428	764.241	766.963	2.722
13	749.811	750.194	0.383	750.590	0.779	751.239	1.428	751.412	749.811	752.050	2.239
12	751.721	752.197	0.476	752.508	0.787	753.017	1.296	753.324	751.721	754.107	2.387
10	732.913	733.267	0.354	733.428	0.515	733.840	0.927	734.016	732.913	734.460	1.547
9	733.191	733.626	0.435	734.141	0.951	734.798	1.608	735.234	733.191	735.831	2.640
8	721.984	722.344	0.360	722.673	0.689	723.163	1.179	723.429	721.984	723.876	1.892
7	714.681	715.104	0.423	715.722	1.041	716.324	1.643	716.899	714.681	717.671	2.990
6	720.441	724.120	3.679	726.608	6.167	731.344	10.903	733.869	720.441	737.390	16.948
5	707.340	708.590	1.250	709.561	2.221	711.077	3.736	711.984	707.340	713.112	5.772
4	698.185	698.893	0.708	699.467	1.281	700.413	2.228	700.930	698.185	701.736	3.550
2	704.624	705.414	0.789	706.053	1.429	707.076	2.452	707.616	704.624	708.573	3.949
0	699.160	699.792	0.631	700.322	1.162	701.077	1.917	701.552	699.160	702.270	3.110

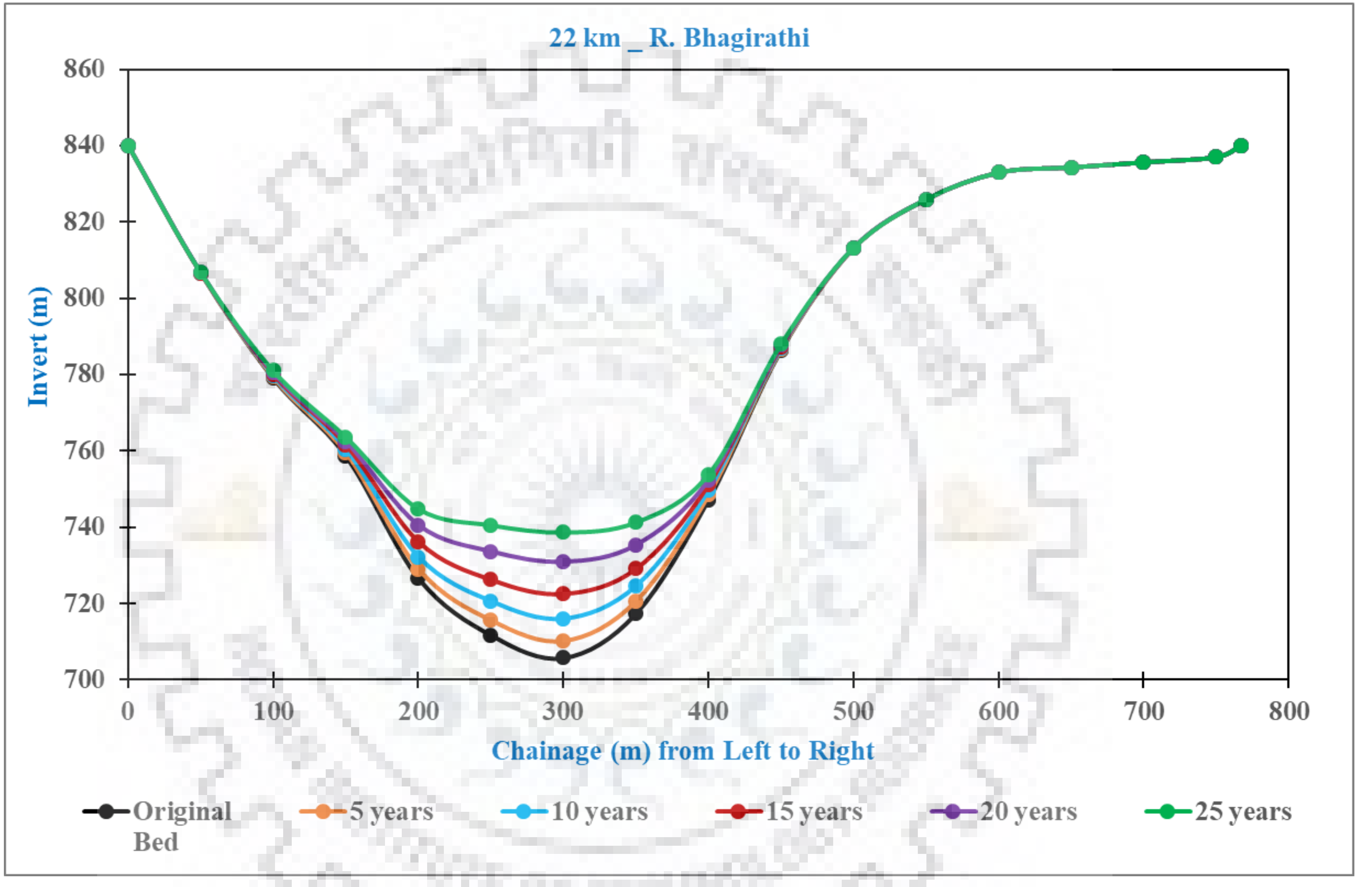

Figure 4. 30: Cross Section Change Upstream of R. Bhagirathi

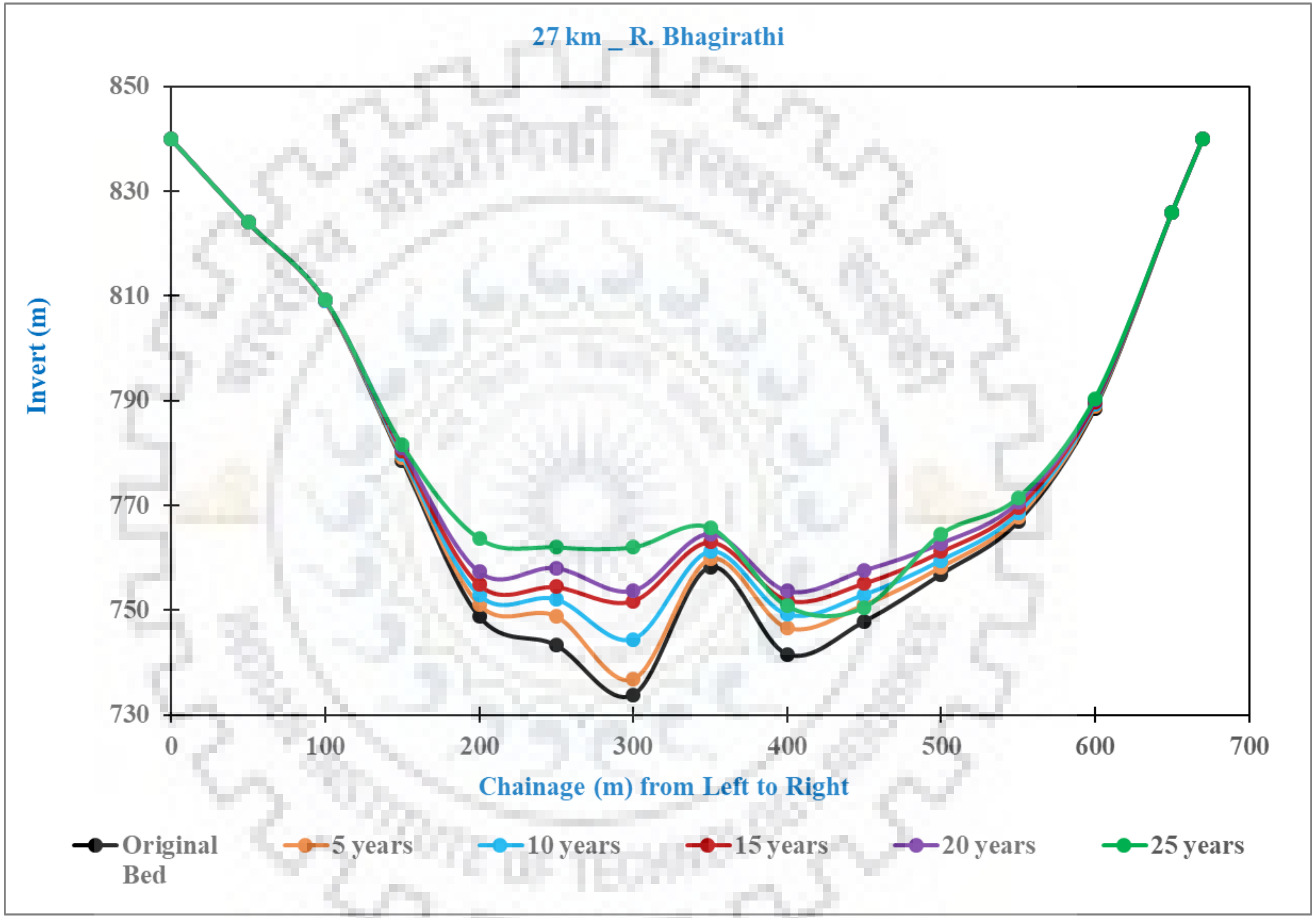

Figure 4. 31: Cross Section Change Upstream of R. Bhagirathi

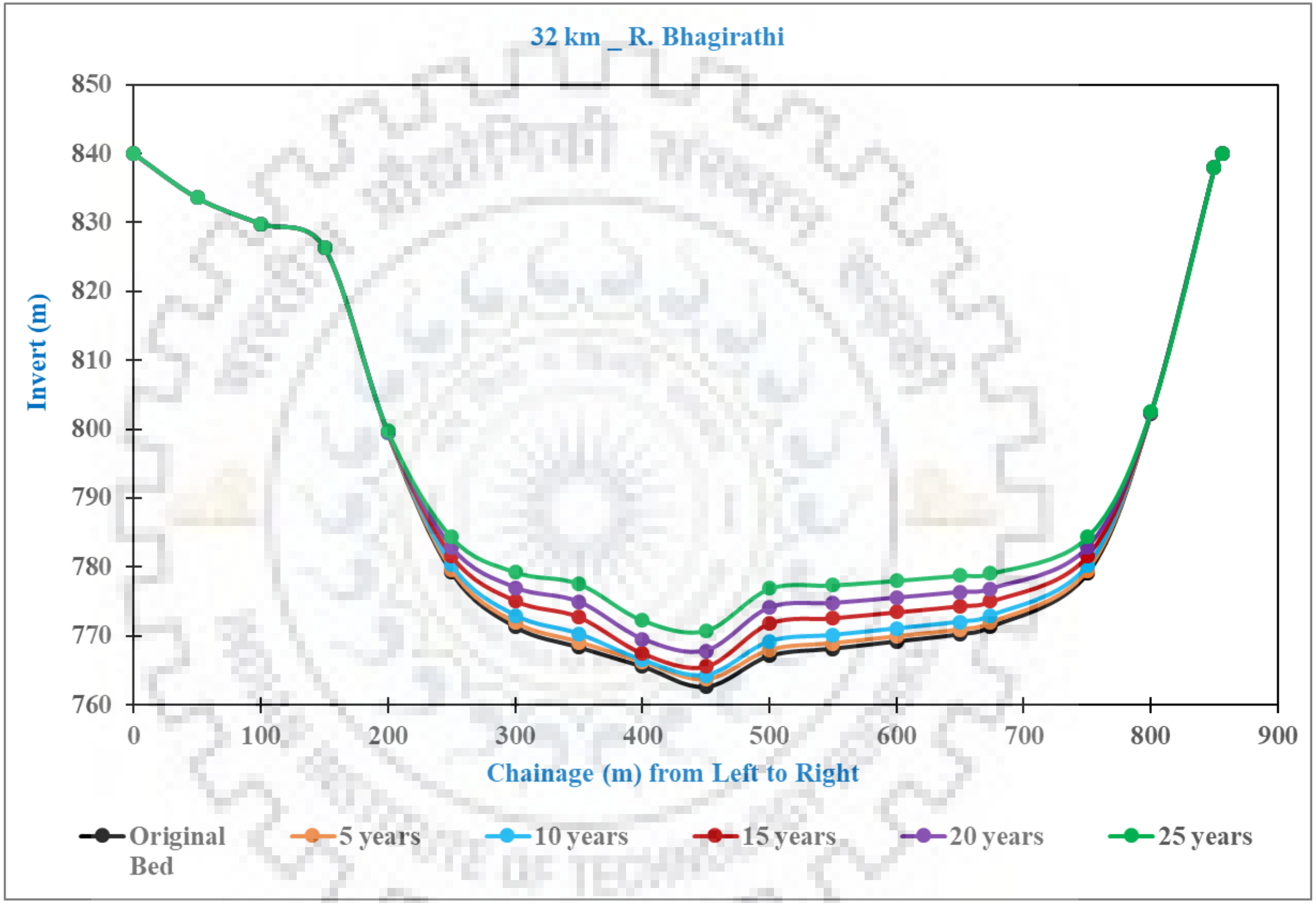

Figure 4. 32: Cross Section Change Upstream of R. Bhagirathi

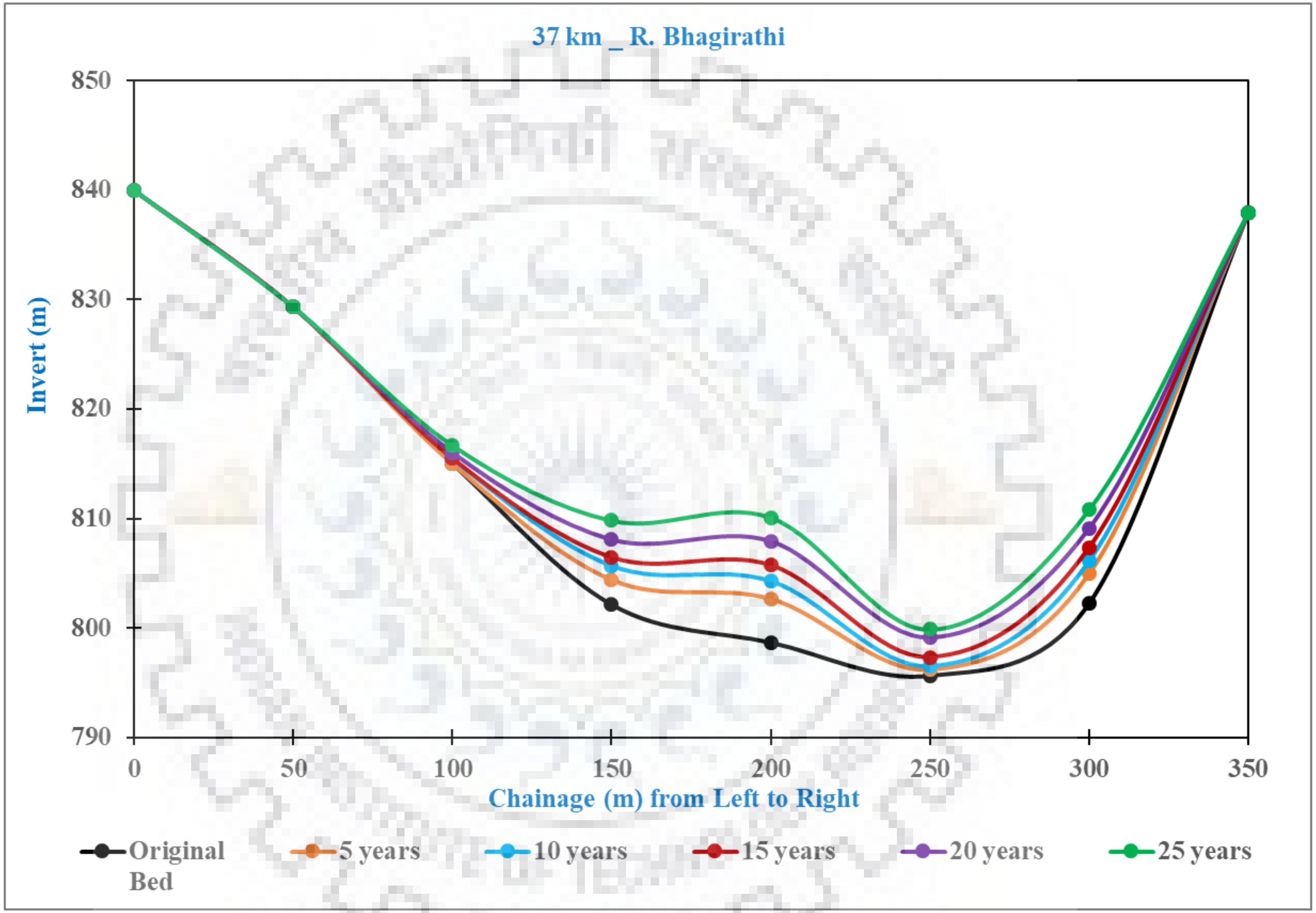

Figure 4. 33: Cross Section Change Upstream of R. Bhagirathi

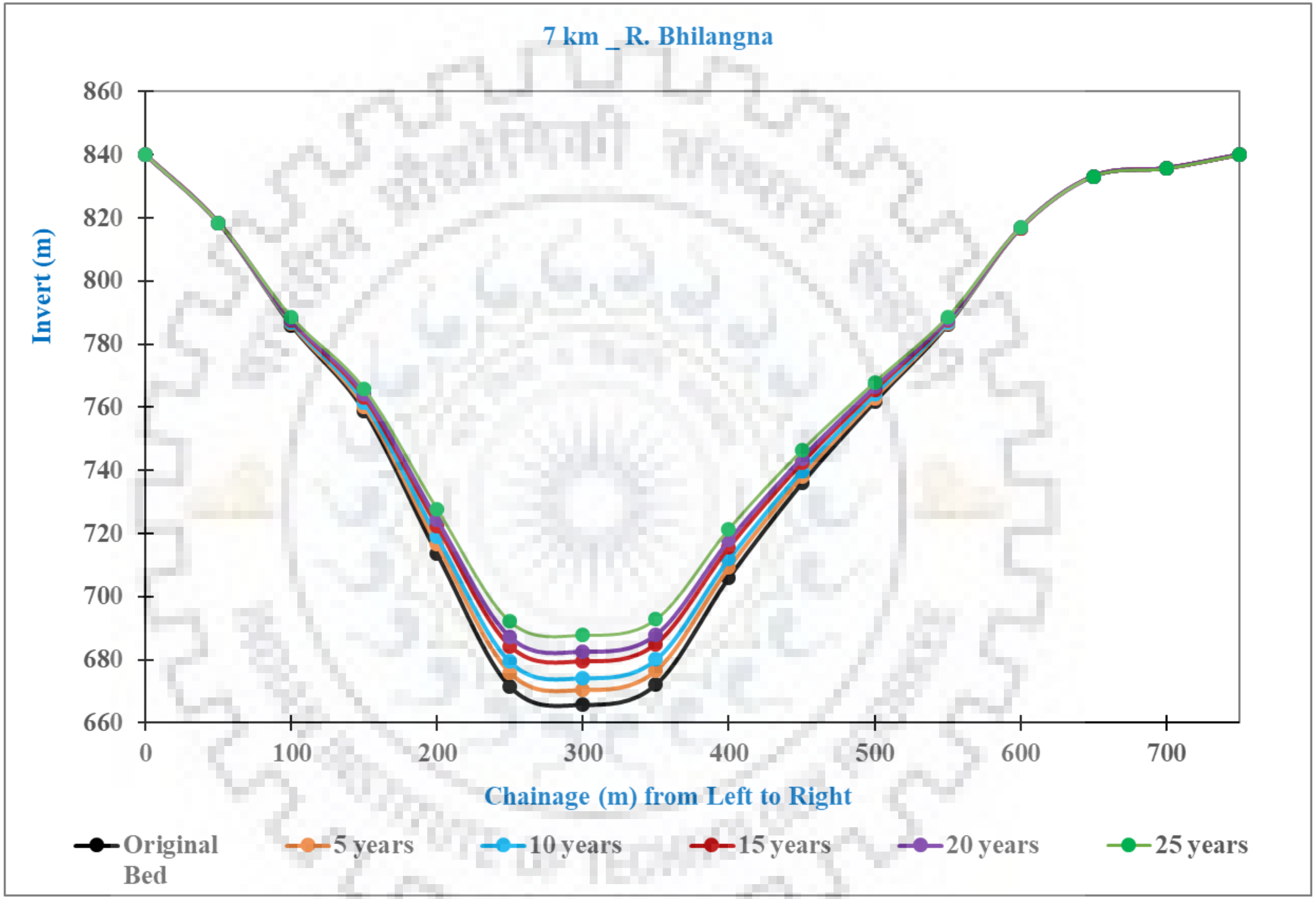

Figure 4. 34: Cross Section Change Upstream of R. Bhilangna

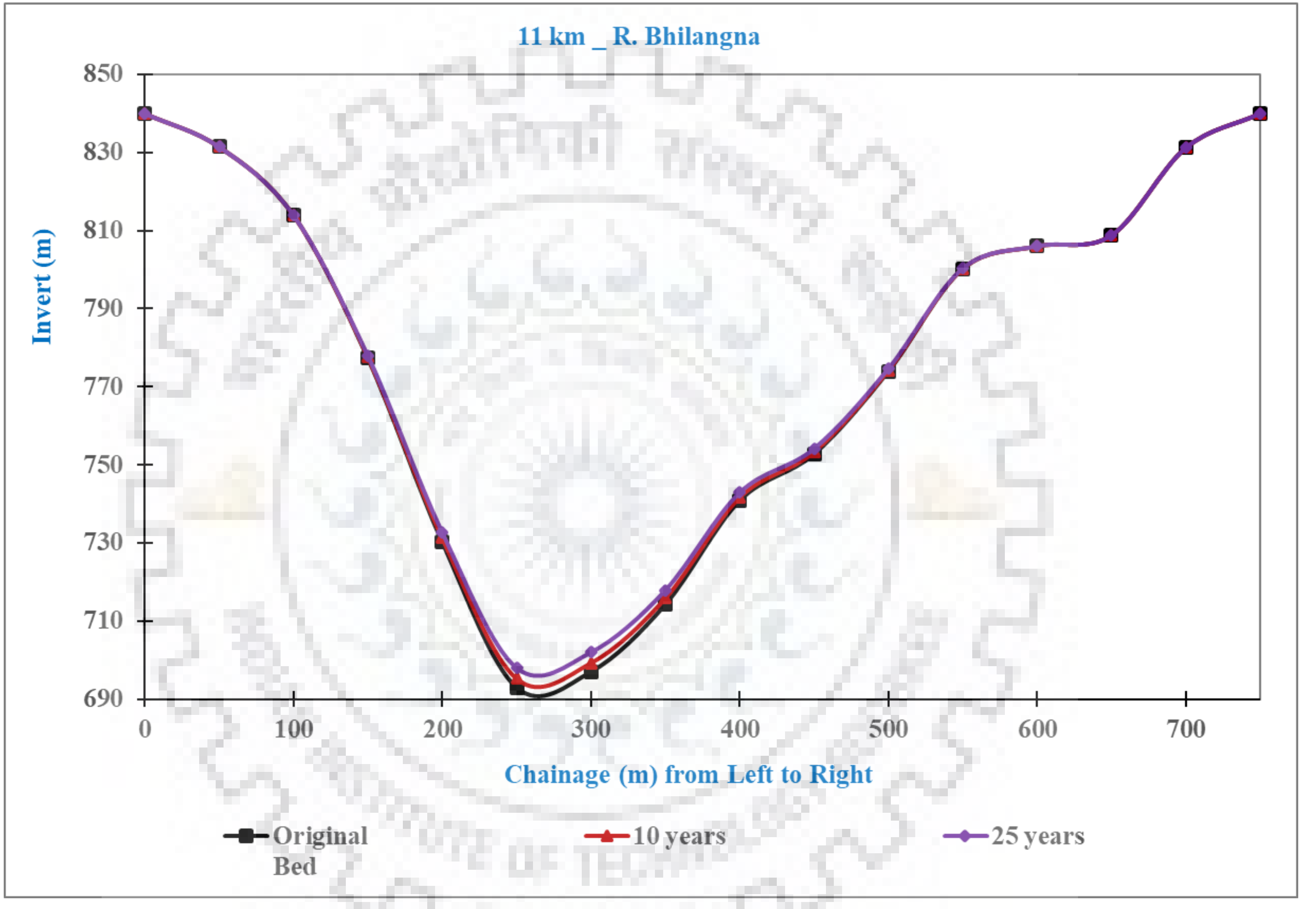

Figure 4. 35: Cross Section Change Upstream of R. Bhilangna

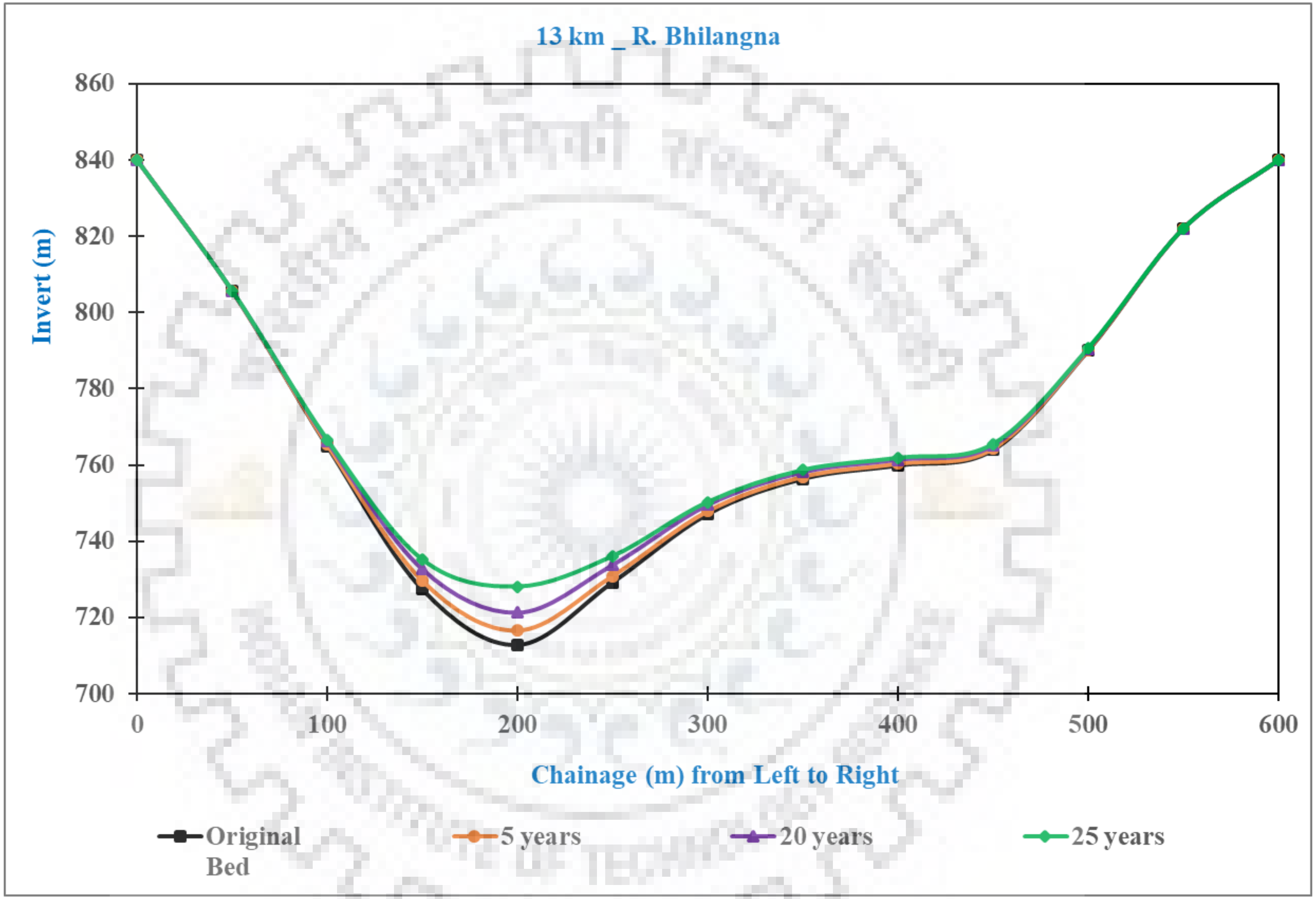

Figure 4. 36: Cross Section Change Upstream of R. Bhilangna

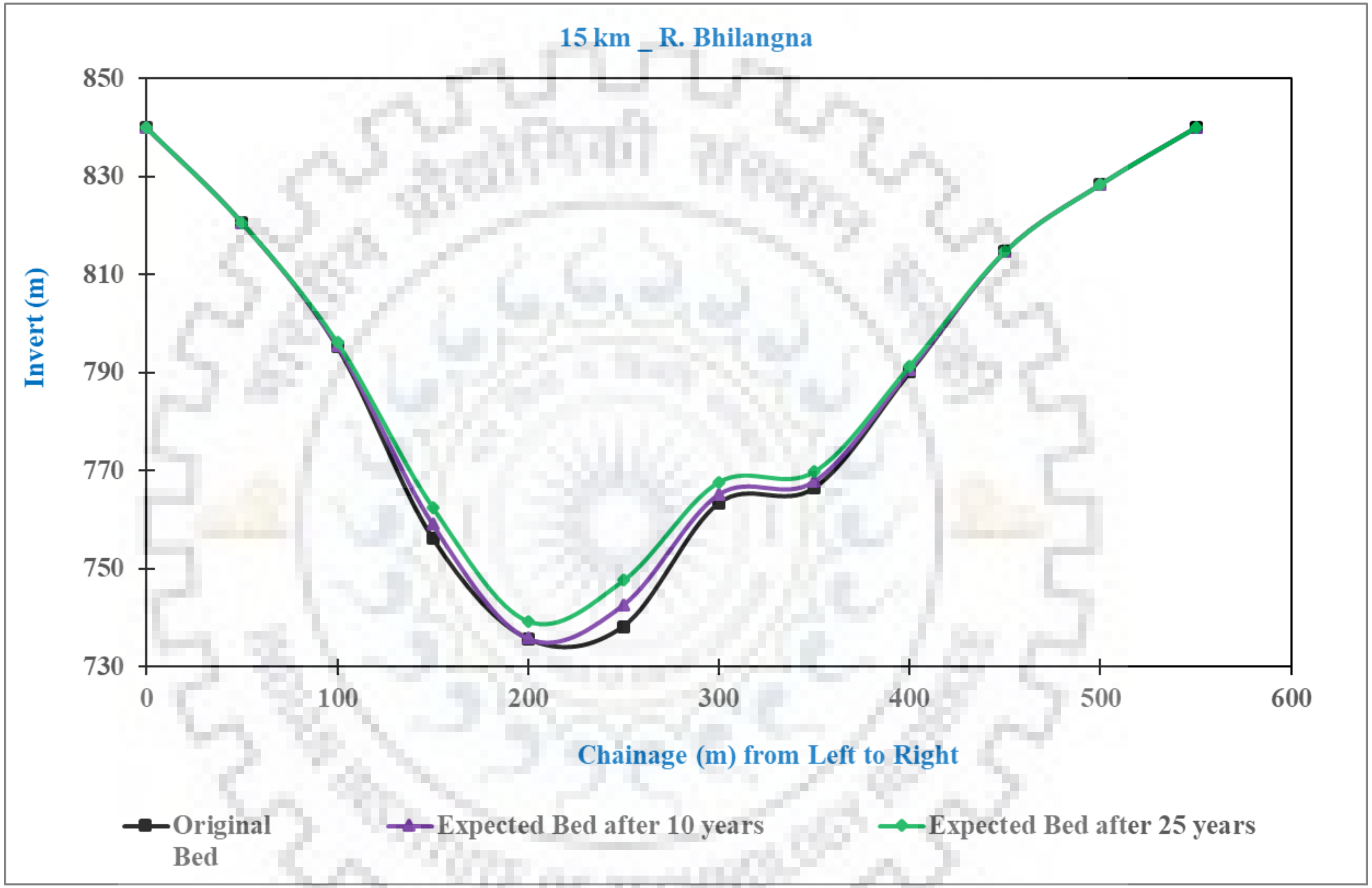

Figure 4. 37: Cross Section Change Upstream of R. Bhilangna

4.4.2 With Average Sediment Actually Observed

Results obtained after the run of the model for 25 years have been tabulated in Tab. 4.10 to Tab. 4.14 and plotted in Fig. 4.38 to Fig. 4.42. The invert changes along the longitudinal section of R. Bhagirathi and R. Bhilangna are tabulated in Tab. 4.11 and Tab. 4.12 and are plotted in Fig. 4.39 and Fig. 4.40 for every five years. It may be seen that after suffering some retrogression in the upstream reaches sediment mainly deposits in between 22 km to 37 km reach in Bhagirathi river while in Bhilangna river the main deposition reaches is in between 7 km to 25 km as is clear from changes in cross section in figure 4.43 to figure 4.47 and figure 4.48 to figure 4.51 in R. Bhagirathi and R. Bhilangna respectively. Fig. 4.41 and Fig. 4.42 show total mass bed changes in tons at each chainage in R. Bhagirathi and R. Bhilangna in that order. It is also clear from the figures that chainage 31 km. of Bhagirathi and chainage 20 km of Bhilangna has maximum mass bed change which is also supported by Tab. 4.13 and Tab. 4.14, which shows total mass bed change at each cross section in tons in R. Bhagirathi and Bhilangna river respectively. Longitudinal mass change in tons at every point starting from the start of the reservoir (taken as zero) is tabulated for both rivers in Tab. 4.13 and Tab. 4.14 and are plotted in Fig. 4.41 and Fig. 4.42 in Bhagirathi river and R. Bhilangna respectively. Total outcome in River Bhagirathi valley is 2.28 X 10^8 tons and in River Bhilangna the outcome is 0.78 X 10^8 tons. Mean effective channel invert and change of the bed for river Bhagirathi and river Bhilangna have been tabulated in Tab. 4.15 and 4.16 for every 5 years upto 2038.

The total mass bed change (Tab. 4.13 and Tab. 4.14) is found to be **2.28 X 10^8 tons in R. Bhagirathi** and **0.78 X 10^8 tons in River Bhilangna**. This shows that deposited sediment load is **2.28 X 10^8 + 0.78 X 10^8 = 3.06 X 10^8 tons in 25 years**. Taking average density of 1.4 tons / cubic meter of the submerged sand in Tehri reservoir, the deposition of **3.06 X 10^8 tons** corresponds to **218.57 MCM** deposition in the reservoir in 25 years. The total projected deposition after every 5 years and corresponding loss in the capacity is given in Tab. 4.10. The table includes loss of capacity from 2014 to 2038 (25 years) as predicted by mathematical modeling. It may be seen from Table 4.10 also that total loss of capacity in 25 years is 216.88 MCM (8.68 MCM per year) which gives the total loss of MDDL capacity (925 MCM) to be **107 years.** This loss (8.68 MCM) out of 3540 MCM gives a yearly loss of **0.25 %.**

Table 4. 10: Expected Loss of Capacity from 2014 to 2038

Total Time (Years)	Year	Capacity (MCM)	Sediment (MCM)	Percentage loss of Capacity
0	2009	3540.00	0.00	0.00
5	2013	3498.67	41.33	1.17
10	2018	3454.00	86.00	2.43
15	2023	3409.93	130.07	3.67
20	2028	3355.48	184.52	5.21
25	2033	3323.12	216.88	6.13
Average Rate of Capacity Loss per Year (MCM) in 25 Years = 8.68.				

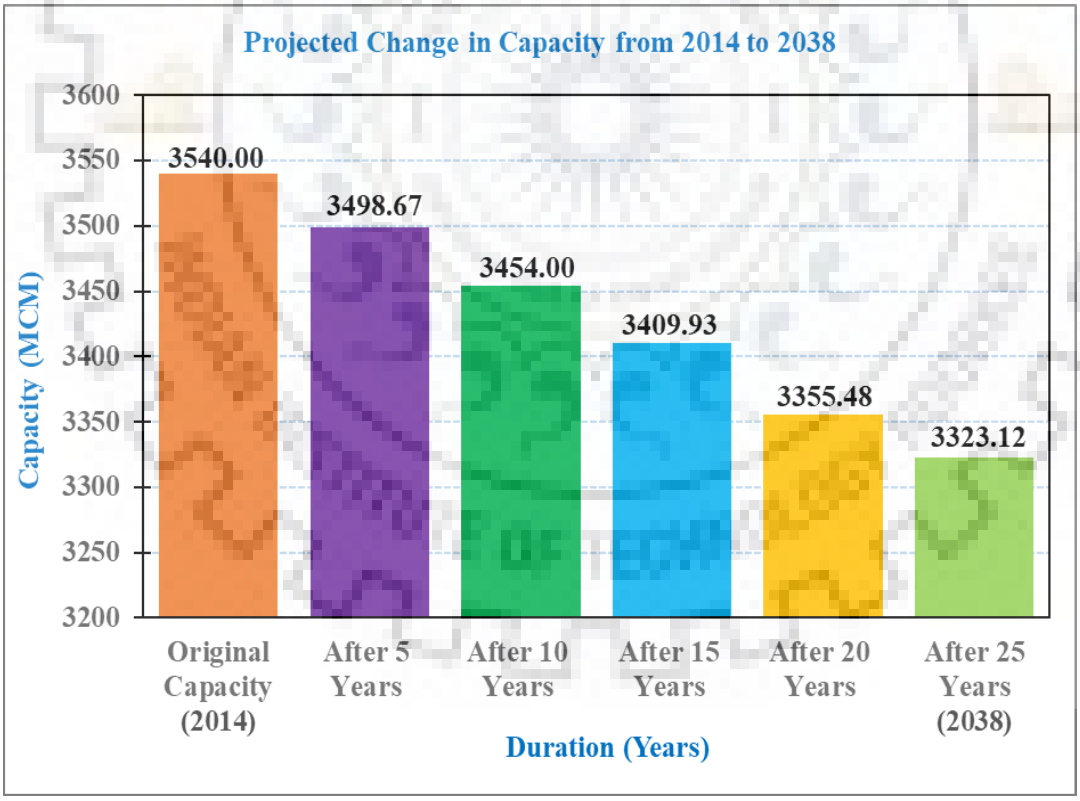

Figure 4. 38: Expected Change in Tehri Reservoir Capacity due to Sedimentation within 25 Years

Table 4. 11: Expected Longitudinal Bed Changes (m) in R. Bhagirathi in 25 Years.

Chainage (m).	Original Bed	Expected Bed After 5 Years.	Expected Bed After 10 Years.	Expected Bed After 15 Years.	Expected Bed After 20 Years.	Expected Bed After 25 Years.
42000	827.200	828.194	828.535	828.690	829.138	827.197
41000	821.980	822.123	822.123	822.123	823.942	824.992
40000	815.010	815.285	815.531	815.491	825.345	815.007
39000	808.630	809.151	811.107	815.314	824.053	823.616
38000	802.200	803.605	805.409	816.533	822.060	822.168
37000	795.600	802.473	810.231	815.816	826.441	823.678
36000	790.730	794.037	801.189	816.416	818.853	822.869
35000	782.980	793.018	806.591	815.607	818.873	823.896
34000	776.560	793.123	797.159	802.593	813.949	822.028
33000	768.750	791.634	809.795	817.190	816.409	816.299
32000	762.580	767.267	769.033	768.793	768.768	770.654
31000	758.870	793.409	804.704	808.888	818.076	824.964
30000	752.490	752.964	752.971	752.873	752.607	752.549
29000	747.030	747.825	749.144	749.379	749.077	748.387
28000	741.330	742.304	743.884	744.862	746.567	747.429
27000	733.800	734.950	736.678	737.928	739.457	741.080
26000	727.060	735.857	735.372	734.786	735.706	737.195
25000	721.320	733.125	734.073	723.895	726.102	727.054
24000	717.130	723.076	726.968	722.017	724.857	722.693
23000	711.320	717.021	722.037	725.475	726.497	727.500
22000	705.770	710.284	714.480	719.462	724.005	727.309
21000	700.280	704.138	707.532	711.215	714.719	719.018
20000	694.540	700.729	710.834	720.811	709.225	720.270
19000	691.390	694.995	699.718	704.114	707.818	711.647
18000	685.900	690.373	694.895	698.936	702.882	706.381
17000	679.980	684.335	688.771	692.414	696.121	699.318
16000	674.870	678.554	681.840	684.583	687.330	689.772
15000	671.230	674.550	677.984	680.754	683.823	686.501
14000	667.190	670.883	674.776	677.422	680.044	682.455
13000	663.440	666.580	670.397	673.056	675.507	677.774
12000	660.370	661.638	663.135	664.173	665.198	666.147
11000	655.180	656.658	658.498	659.825	661.212	662.524
10000	651.690	652.448	653.387	654.117	654.848	655.526

Continued on the next page

9000	649.360	649.770	650.293	650.734	651.311	651.742
8000	646.450	646.794	647.232	647.614	648.036	648.414
7000	648.370	648.900	649.575	650.154	650.812	651.423
6000	646.280	646.674	647.169	647.617	648.096	648.559
5000	645.710	646.111	646.614	647.067	647.556	648.032
4000	640.580	640.994	641.513	641.984	642.492	642.993
3000	636.980	637.286	637.667	638.020	638.393	638.765
2000	637.490	637.724	638.015	638.289	638.574	638.861
1000	641.170	641.366	641.607	641.834	642.069	642.304
100	641.170	642.980	643.966	645.355	646.138	648.687
100	641.170	641.173	641.176	641.179	641.181	641.185

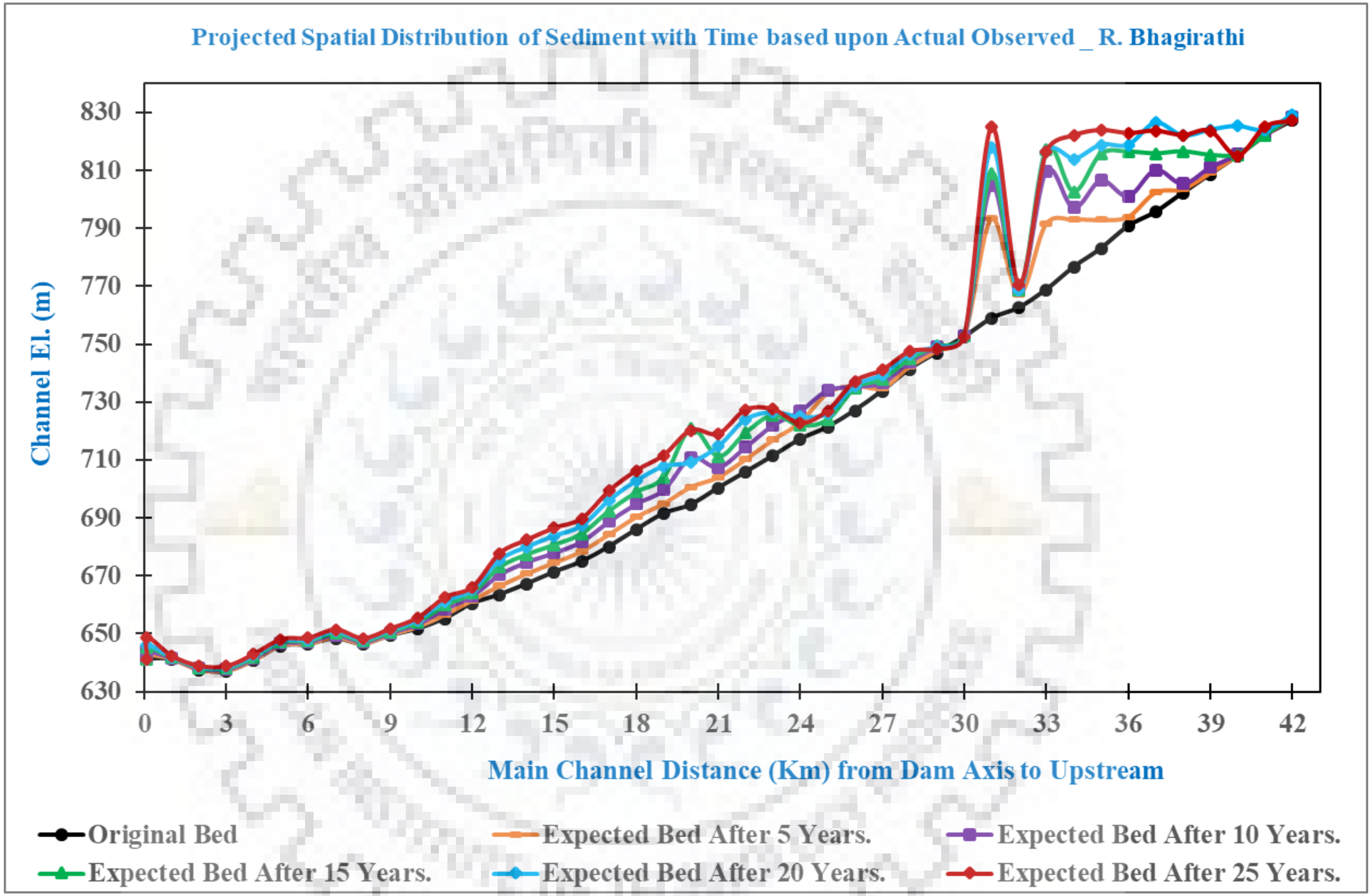

Figure 4. 39: Spatial Sediment Distribution in R. Bhagirathi based upon Average Sediment Actually Observed

Table 4. 12: Expected Longitudinal Bed Changes (m) in R. Bhilangna after 25 Years

Chainage (m).	Original Bed	Expected Bed After 5 Years.	Expected Bed After 10 Years.	Expected Bed After 15 Years.	Expected Bed After 20 Years.	Expected Bed After 25 Years.
24000	831.090	831.158	834.293	835.686	831.087	831.087
23000	823.930	824.480	825.220	830.698	833.851	827.807
19000	787.470	788.489	797.946	811.965	821.939	800.470
18000	780.650	823.067	834.165	835.397	838.169	780.647
17000	775.720	775.769	775.777	775.786	775.788	779.558
16000	764.220	768.314	764.646	764.217	765.650	774.601
15000	749.020	750.904	749.052	749.213	749.565	755.496
14000	735.680	739.658	735.937	736.006	736.298	748.653
13000	726.700	729.988	729.904	727.981	726.818	731.868
12000	712.790	716.536	718.232	720.130	721.095	735.827
10000	692.920	694.791	696.034	697.468	698.150	700.588
9000	686.260	687.730	688.749	690.253	691.013	693.196
8000	681.120	683.362	684.267	685.500	686.075	687.593
7000	659.410	660.913	661.532	662.398	662.810	664.616
6000	665.890	671.603	675.694	681.626	685.049	691.781
5000	661.250	664.226	666.130	668.708	670.332	673.125
4000	656.850	659.069	660.494	662.559	663.776	666.559
2000	650.440	654.041	655.793	658.446	660.012	663.845
0	650.440	652.128	653.554	655.096	656.188	660.183

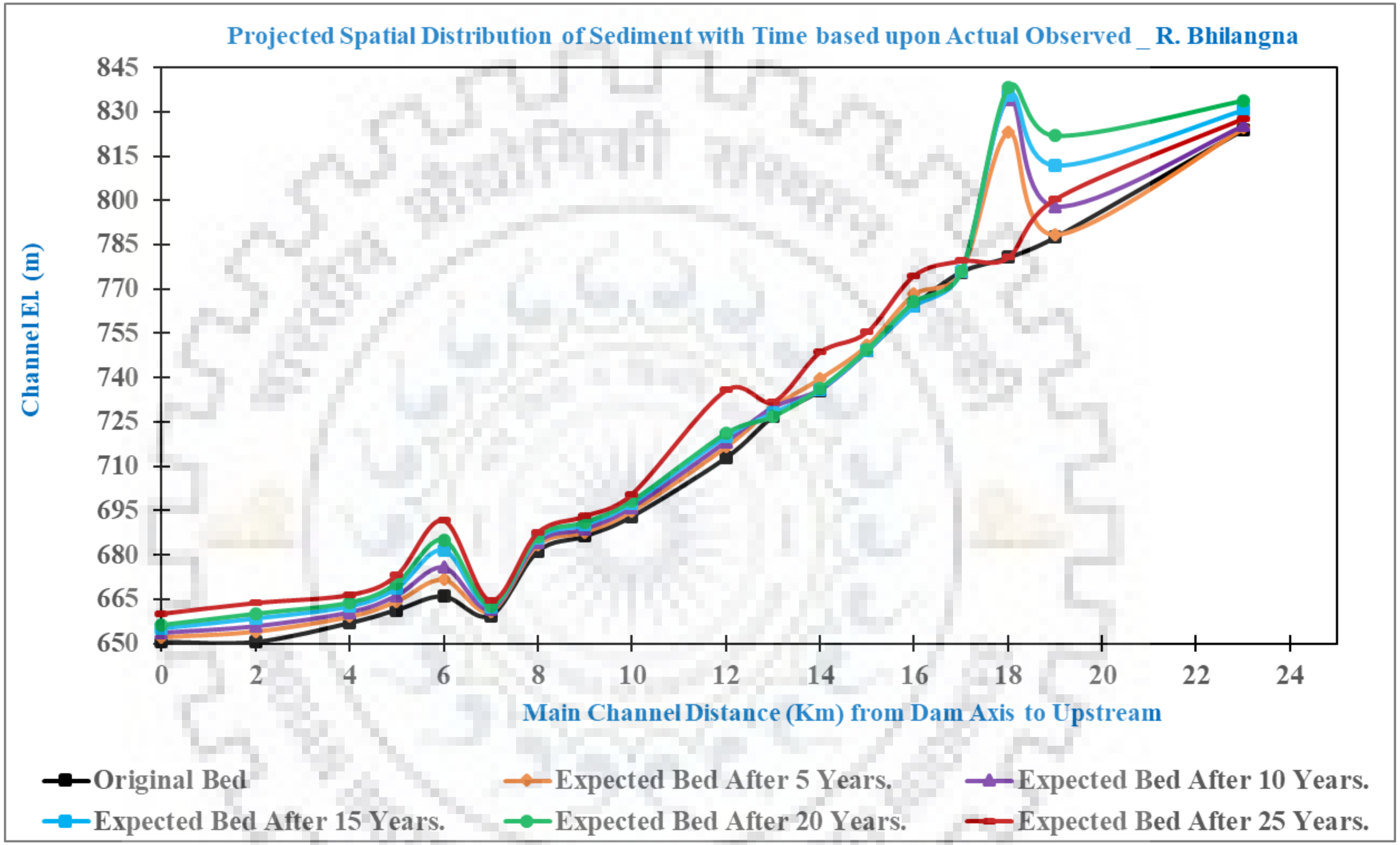

Figure 4. 40: Projected Spatial Sediment Distribution in R. Bhilangna based upon Average Sediment Actually Observed

Table 4. 13: Expected Mass Bed Change (Tons) in R. Bhagirathi in 25 Years

Chainage (m)	Original Bed	After 5 Years	After 10 Years	After 15 Years	After 20 Years	After 25 Years
42000	0	3.98E+04	6.33E+04	9.55E+04	1.11E+05	7.38E+05
41000	0	9.82E+03	9.82E+03	9.82E+03	2.06E+05	6.62E+05
40000	0	-2.13E+04	5.45E+03	4.98E+04	9.53E+05	1.48E+06
39000	0	3.07E+04	1.64E+05	1.10E+06	3.20E+06	3.21E+06
38000	0	1.78E+05	8.49E+05	2.86E+06	4.46E+06	4.91E+06
37000	0	1.54E+06	3.02E+06	4.47E+06	7.77E+06	7.25E+06
36000	0	1.00E+06	3.52E+06	9.61E+06	1.12E+07	1.39E+07
35000	0	4.90E+06	1.20E+07	1.94E+07	2.23E+07	2.74E+07
34000	0	3.70E+06	5.48E+06	8.10E+06	1.37E+07	1.84E+07
33000	0	3.14E+06	7.39E+06	1.03E+07	1.06E+07	1.17E+07
32000	0	1.89E+06	3.00E+06	2.79E+06	2.75E+06	4.04E+06
31000	0	6.40E+06	1.03E+07	1.32E+07	2.22E+07	**2.97E+07**
30000	0	6.26E+05	7.31E+05	7.54E+05	8.42E+05	8.40E+05
29000	0	7.22E+05	3.18E+06	4.58E+06	6.09E+06	7.84E+06
28000	0	9.07E+05	2.64E+06	3.70E+06	4.81E+06	6.36E+06
27000	0	1.57E+06	2.92E+06	3.94E+06	4.88E+06	6.22E+06
26000	0	2.02E+06	3.27E+06	4.07E+06	4.86E+06	6.13E+06
25000	0	1.76E+06	2.66E+06	3.26E+06	3.93E+06	4.86E+06
24000	0	9.35E+05	1.83E+06	2.38E+06	2.99E+06	3.71E+06
23000	0	1.20E+06	2.30E+06	3.08E+06	3.58E+06	4.26E+06
22000	0	9.86E+05	1.91E+06	3.08E+06	4.18E+06	5.04E+06
21000	0	7.72E+05	1.48E+06	2.32E+06	3.12E+06	3.91E+06
20000	0	9.33E+05	2.71E+06	4.58E+06	5.98E+06	7.52E+06
19000	0	8.04E+05	2.01E+06	3.26E+06	4.33E+06	5.42E+06
18000	0	7.30E+05	1.64E+06	2.59E+06	3.44E+06	4.29E+06
17000	0	6.12E+05	1.30E+06	1.95E+06	2.54E+06	3.12E+06
16000	0	6.74E+05	1.35E+06	1.97E+06	2.55E+06	3.10E+06
15000	0	5.04E+05	1.08E+06	1.60E+06	2.12E+06	2.61E+06
14000	0	5.88E+05	1.27E+06	1.79E+06	2.28E+06	2.75E+06
13000	0	5.30E+05	1.20E+06	1.73E+06	2.20E+06	2.65E+06
12000	0	6.52E+05	1.46E+06	2.08E+06	2.66E+06	3.21E+06
11000	0	4.48E+05	1.03E+06	1.50E+06	1.96E+06	2.41E+06
10000	0	4.47E+05	1.02E+06	1.50E+06	1.96E+06	2.40E+06
9000	0	4.15E+05	9.61E+05	1.43E+06	2.03E+06	2.48E+06
8000	0	3.66E+05	8.47E+05	1.28E+06	1.74E+06	2.16E+06
7000	0	3.75E+05	8.70E+05	1.32E+06	1.80E+06	2.26E+06
6000	0	3.04E+05	7.03E+05	1.07E+06	1.46E+06	1.83E+06
5000	0	3.10E+05	7.19E+05	1.10E+06	1.49E+06	1.88E+06
4000	0	2.88E+05	6.68E+05	1.03E+06	1.39E+06	1.76E+06
3000	0	2.71E+05	6.28E+05	9.71E+05	1.31E+06	1.66E+06
2000	0	2.27E+05	5.27E+05	8.10E+05	1.09E+06	1.39E+06
1000	0	8.87E+04	2.04E+05	3.15E+05	4.24E+05	5.37E+05
100	0	1.01E+05	1.55E+05	2.34E+05	2.76E+05	4.19E+05
100	0	3.68E+02	6.31E+02	9.98E+02	1.21E+03	1.75E+03
TOTAL		**0.44E+08**	**0.91E+08**	**1.37E+08**	**1.84E+08**	**2.28E+08**

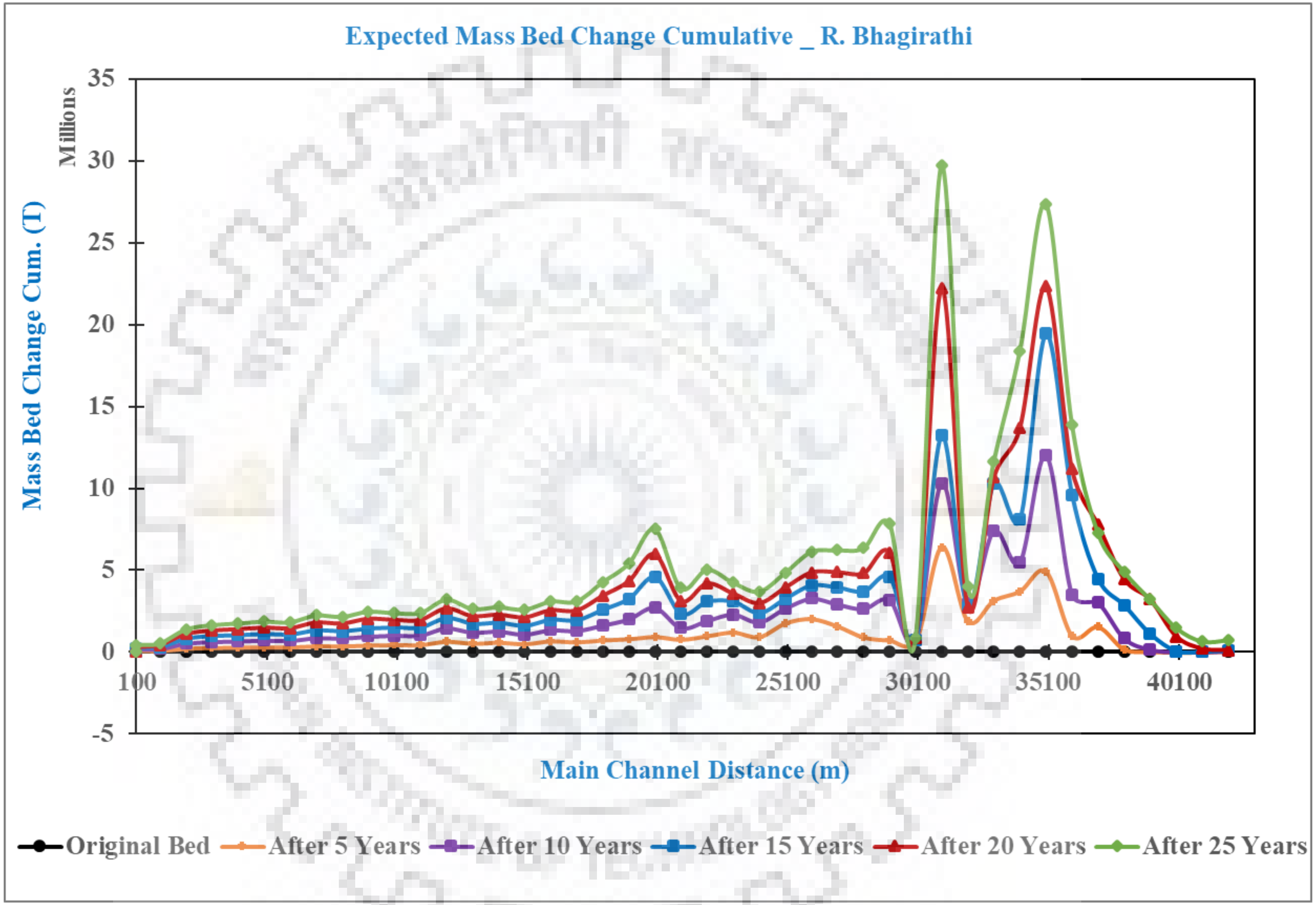

Figure 4. 41: Expected Mass Bed Change (T) in 25 Years at each Cross Section in R. Bhagirathi

Table 4. 14: Expected Mass Bed Change (Tons) in R. Bhilangna in 25 Years

Chainage (m)	Original Bed	After 5 Years	After 10 Years	After 15 Years	After 20 Years	After 25 Years
24000	0	8.24E+02	5.69E+04	9.39E+04	2.95E+05	3.29E+05
23000	0	1.40E+05	5.14E+05	2.43E+06	3.90E+06	2.61E+06
19000	0	4.16E+05	4.72E+06	1.19E+07	1.76E+07	**1.94E+07**
18000	0	2.95E+06	4.61E+06	4.51E+06	5.36E+06	3.81E+06
17000	0	2.85E+05	2.87E+05	2.90E+05	2.90E+05	1.34E+06
16000	0	1.72E+06	2.52E+06	3.74E+06	4.19E+06	6.82E+06
15000	0	9.51E+05	1.36E+06	1.93E+06	2.20E+06	3.02E+06
14000	0	9.14E+05	1.25E+06	1.76E+06	1.99E+06	3.68E+06
13000	0	1.36E+06	1.74E+06	2.20E+06	2.41E+06	3.71E+06
12000	0	6.78E+05	1.04E+06	1.50E+06	1.73E+06	3.71E+06
10000	0	4.31E+05	7.21E+05	1.07E+06	1.24E+06	1.78E+06
9000	0	4.35E+05	7.56E+05	1.25E+06	1.50E+06	2.13E+06
8000	0	7.89E+05	1.11E+06	1.53E+06	1.74E+06	2.23E+06
7000	0	5.71E+05	8.09E+05	1.15E+06	1.31E+06	2.02E+06
6000	0	1.60E+06	2.79E+06	4.50E+06	5.51E+06	7.37E+06
5000	0	9.47E+05	1.59E+06	2.47E+06	3.02E+06	3.94E+06
4000	0	1.03E+06	1.71E+06	2.71E+06	3.29E+06	4.58E+06
2000	0	1.03E+06	1.56E+06	2.40E+06	2.88E+06	4.02E+06
0	0	2.41E+05	4.39E+05	6.75E+05	8.32E+05	1.37E+06
TOTAL		**0.17E+08**	**0.3E+08**	**0.48E+08**	**0.61E+08**	**0.78E+08**

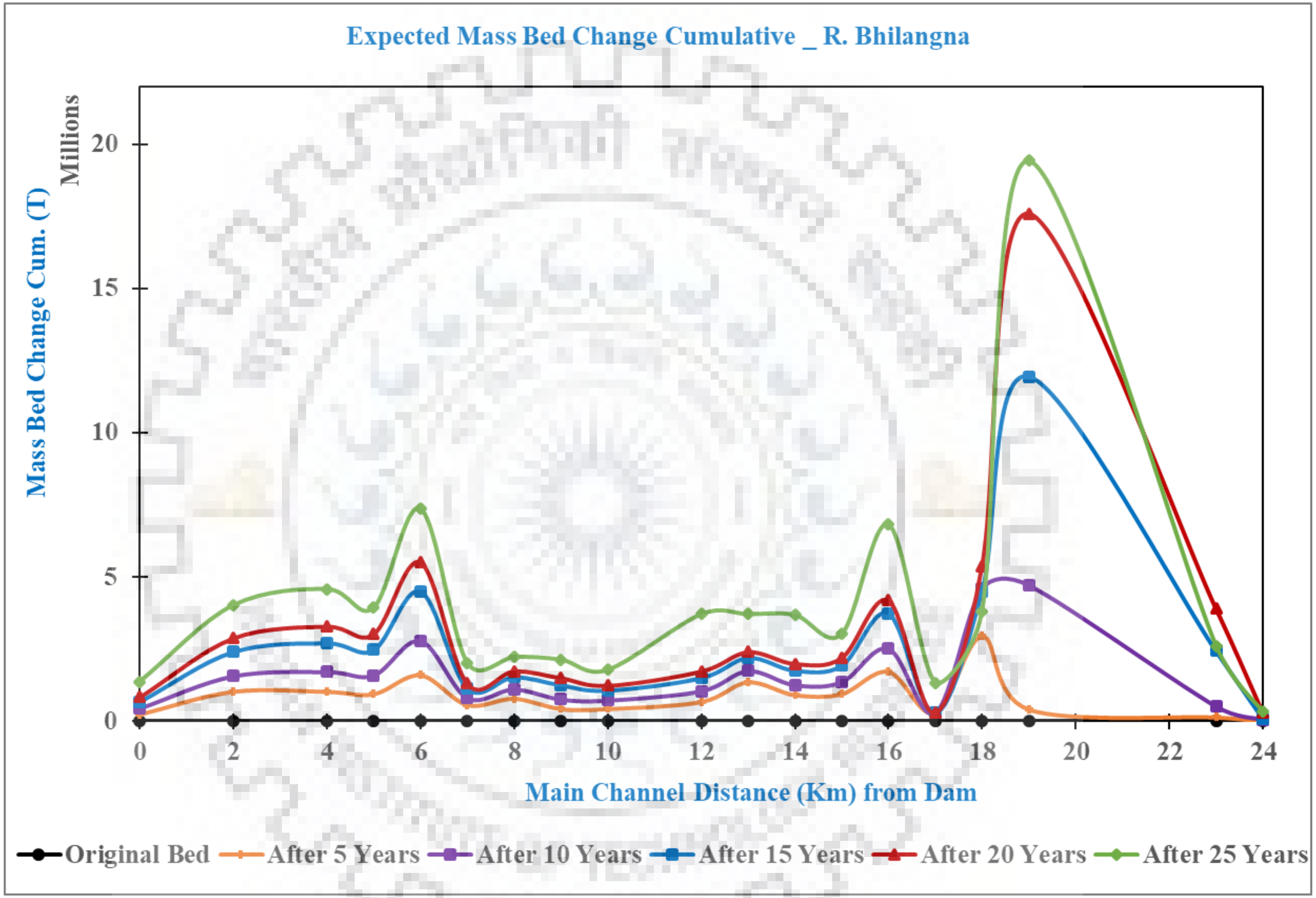

Figure 4. 42: Expected Mass Bed Change (T) in 25 Years at each Cross Section in R. Bhilangna

Table 4. 15: Expected Mean Effective Channel Invert and Change (m) in 25 Years in R. Bhagirathi

Chainage (m)	Original Bed	After 5 Years	Invert Change (m) in 5 Years	After 10 Years	Invert Change (m) in 10 Years	After 15 Years	Invert Change (m) in 15 Years	After 20 Years	Invert Change (m) in 20 Years	After 25 Years	Invert Change (m) in 25 Years
42000	830.815	831.637	0.822	831.899	1.085	832.300	1.485	832.741	1.927	841.517	10.702
41000	827.358	827.426	0.068	827.426	0.068	827.426	0.068	827.426	0.068	832.141	4.783
40000	821.784	821.499	-0.286	821.674	-0.110	822.012	0.227	822.684	0.900	833.296	11.512
39000	816.250	816.436	0.186	817.240	0.990	816.970	0.720	823.994	7.744	824.781	8.531
38000	808.930	809.702	0.772	812.094	3.165	814.569	5.640	820.947	12.017	829.336	20.406
37000	803.381	806.977	3.595	808.633	5.252	814.058	10.677	820.726	17.345	819.177	15.796
36000	800.032	802.279	2.247	807.829	7.797	813.216	13.184	820.924	20.891	827.548	27.516
35000	794.739	803.014	8.275	805.457	10.718	812.525	17.786	820.356	25.617	820.806	26.067
34000	789.835	798.517	8.682	806.845	17.010	812.945	23.110	817.830	27.994	824.523	34.688
33000	790.771	802.787	12.016	808.402	17.631	813.753	22.982	817.458	26.687	820.061	29.291
32000	772.961	775.714	2.753	780.692	7.731	784.336	11.375	786.088	13.127	788.993	16.032
31000	785.661	799.587	13.926	807.357	21.696	813.395	27.734	818.624	32.962	823.923	38.262
30000	764.688	766.052	1.364	766.016	1.328	766.033	1.345	766.072	1.384	766.066	1.378
29000	762.618	763.848	1.230	767.813	5.195	770.076	7.458	771.922	9.304	773.732	11.115
28000	761.637	763.054	1.418	765.849	4.213	768.219	6.583	769.812	8.175	771.485	9.848
27000	754.650	757.172	2.522	760.357	5.708	762.387	7.737	764.241	9.592	765.527	10.878
26000	758.877	763.568	4.691	765.641	6.764	768.192	9.315	769.644	10.767	771.518	12.641
25000	756.949	764.078	7.129	766.812	9.864	765.899	8.950	768.232	11.283	769.660	12.711
24000	757.948	762.109	4.161	763.625	5.677	766.965	9.018	767.193	9.246	769.278	11.330
23000	741.091	744.344	3.253	746.980	5.889	749.481	8.390	750.821	9.730	752.280	11.188

Continued on the next page

22000	733.752	736.966	3.214	740.010	6.258	742.571	8.819	744.814	11.061	747.321	13.569
21000	739.412	741.905	2.493	744.195	4.782	746.095	6.683	747.654	8.242	749.581	10.169
20000	732.910	736.631	3.721	742.665	9.755	747.946	15.036	752.668	19.758	752.787	19.877
19000	730.049	732.347	2.298	735.428	5.378	738.105	8.055	740.188	10.138	742.604	12.554
18000	734.727	737.162	2.435	739.888	5.160	742.127	7.400	743.891	9.163	746.052	11.324
17000	723.570	726.359	2.789	729.564	5.995	731.896	8.326	733.795	10.225	735.949	12.380
16000	718.256	720.638	2.382	723.134	4.878	724.946	6.690	726.411	8.155	728.046	9.790
15000	722.336	724.416	2.080	726.914	4.578	728.727	6.391	730.277	7.942	731.908	9.572
14000	714.949	717.300	2.350	720.110	5.161	721.961	7.012	723.412	8.462	724.973	10.024
13000	710.393	712.442	2.049	715.355	4.962	717.089	6.696	718.556	8.163	720.028	9.635
12000	697.679	698.577	0.899	699.702	2.023	700.482	2.803	701.152	3.473	701.809	4.131
11000	703.190	704.189	0.999	705.463	2.273	706.399	3.209	707.226	4.035	708.031	4.841
10000	691.454	692.018	0.564	692.725	1.271	693.274	1.820	693.758	2.304	694.233	2.779
9000	673.664	674.009	0.345	674.447	0.783	674.808	1.144	675.151	1.487	675.559	1.896
8000	673.907	674.195	0.287	674.557	0.650	674.864	0.957	675.162	1.254	675.466	1.559
7000	697.417	697.761	0.343	698.195	0.777	698.563	1.145	698.933	1.515	699.308	1.891
6000	676.720	677.037	0.316	677.432	0.711	677.776	1.055	678.123	1.403	678.477	1.757
5000	685.838	686.123	0.285	686.477	0.640	686.791	0.953	687.109	1.272	687.434	1.597
4000	690.856	691.134	0.278	691.478	0.622	691.787	0.930	692.102	1.246	692.427	1.571
3000	685.630	685.845	0.215	686.111	0.480	686.352	0.721	686.597	0.967	686.852	1.222
2000	662.340	662.538	0.198	662.783	0.443	663.007	0.667	663.236	0.897	663.476	1.136
1000	672.911	673.070	0.158	673.263	0.352	673.442	0.530	673.623	0.712	673.812	0.901
100	672.911	674.292	1.381	675.088	2.177	676.129	3.218	676.894	3.983	678.269	5.357
100	672.911	672.914	0.003	672.916	0.005	672.918	0.007	672.920	0.009	672.923	0.012

Table 4. 16: Expected Mean Effective Channel Invert and Change (m) in 25 Years in R. Bhilangna

Chainage (m)	Original Bed	After 5 Years	Invert Change (m) in 5 Years	After 10 Years	Invert Change (m) in 10 Years	After 15 Years	Invert Change (m) in 15 Years	After 20 Years	Invert Change (m) in 20 Years	After 25 Years	Invert Change (m) in 25 Years
24000	832.690	832.726	0.035	832.726	0.035	837.622	4.932	839.058	6.367	839.058	6.367
23000	827.517	828.207	0.689	828.048	0.530	832.785	5.268	831.511	3.993	829.221	1.703
19000	801.270	801.971	0.701	809.533	8.263	819.131	17.861	827.709	26.439	810.907	9.637
18000	799.339	825.485	26.145	833.456	34.117	838.904	39.565	830.352	31.013	811.437	12.098
17000	785.074	785.716	0.642	785.845	0.770	785.858	0.783	785.862	0.787	791.937	6.863
16000	775.041	778.912	3.871	780.302	5.261	782.337	7.296	783.859	8.818	798.876	23.835
15000	770.788	773.444	2.656	774.178	3.391	775.400	4.612	776.683	5.895	777.384	6.596
14000	759.059	761.736	2.677	761.664	2.605	762.503	3.444	763.173	4.113	768.598	9.539
13000	745.325	747.877	2.552	748.352	3.028	748.770	3.446	749.197	3.872	750.661	5.336
12000	744.950	746.789	1.840	747.854	2.904	748.892	3.942	749.656	4.706	751.985	7.035
10000	729.306	730.550	1.245	731.437	2.132	732.332	3.027	732.982	3.676	734.152	4.847
9000	729.610	730.553	0.942	731.290	1.679	732.220	2.610	733.039	3.428	733.955	4.344
8000	717.968	719.661	1.693	720.397	2.428	721.214	3.245	721.907	3.939	723.056	5.088
7000	711.819	712.940	1.121	713.436	1.617	714.007	2.188	714.484	2.665	715.451	3.631
6000	703.412	707.835	4.422	711.269	7.856	715.308	11.896	719.598	16.186	724.937	21.525
5000	699.799	702.108	2.309	703.652	3.853	705.511	5.711	707.072	7.272	708.920	9.120
4000	692.214	693.936	1.722	695.075	2.861	696.551	4.337	697.668	5.454	699.608	7.394
2000	697.078	699.629	2.550	700.851	3.772	702.759	5.680	704.372	7.293	706.555	9.476
0	694.323	695.541	1.219	696.577	2.255	697.708	3.386	698.588	4.265	700.150	5.828

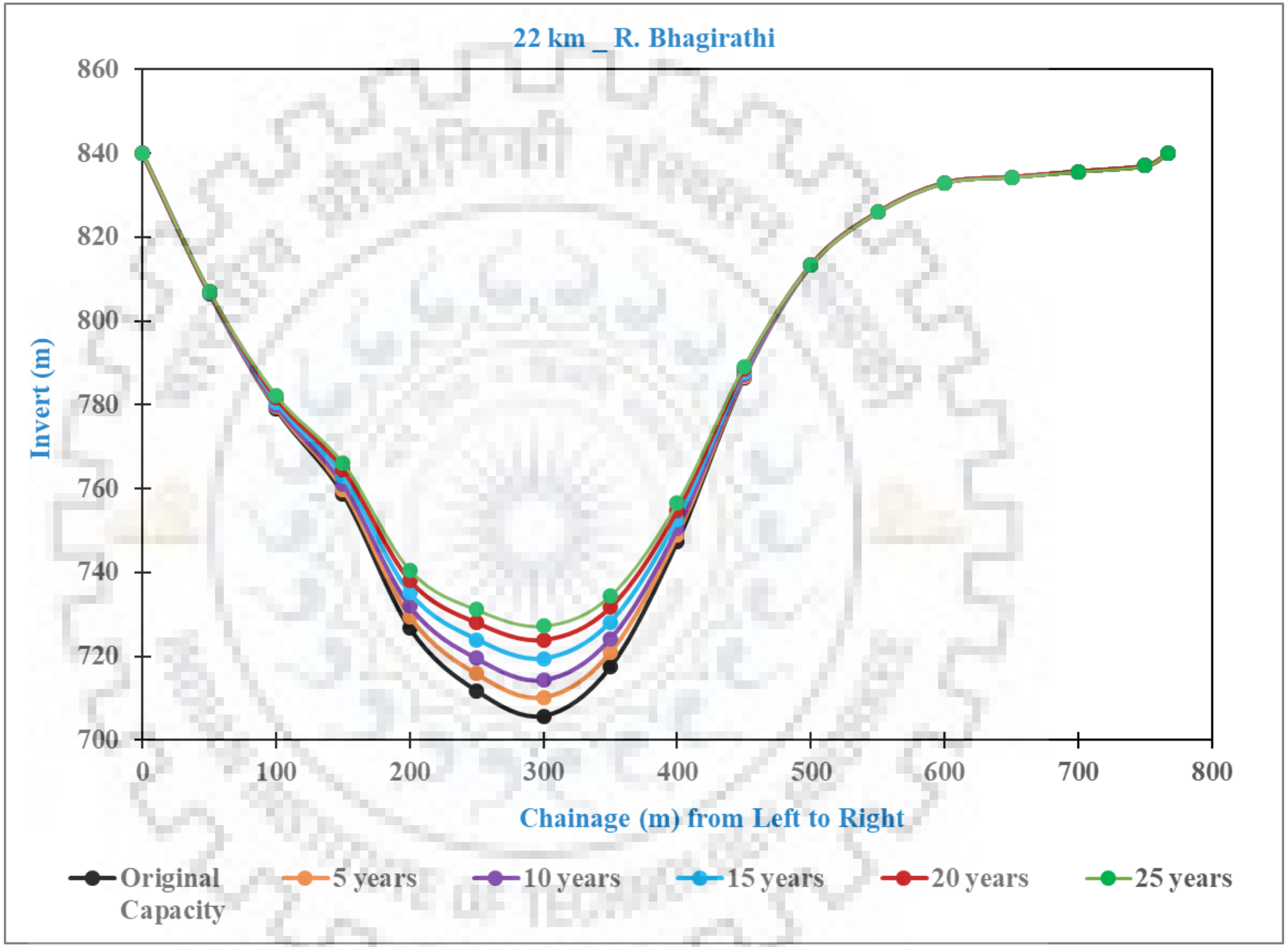

Figure 4. 43: Cross Section Change Upstream of R. Bhagirathi

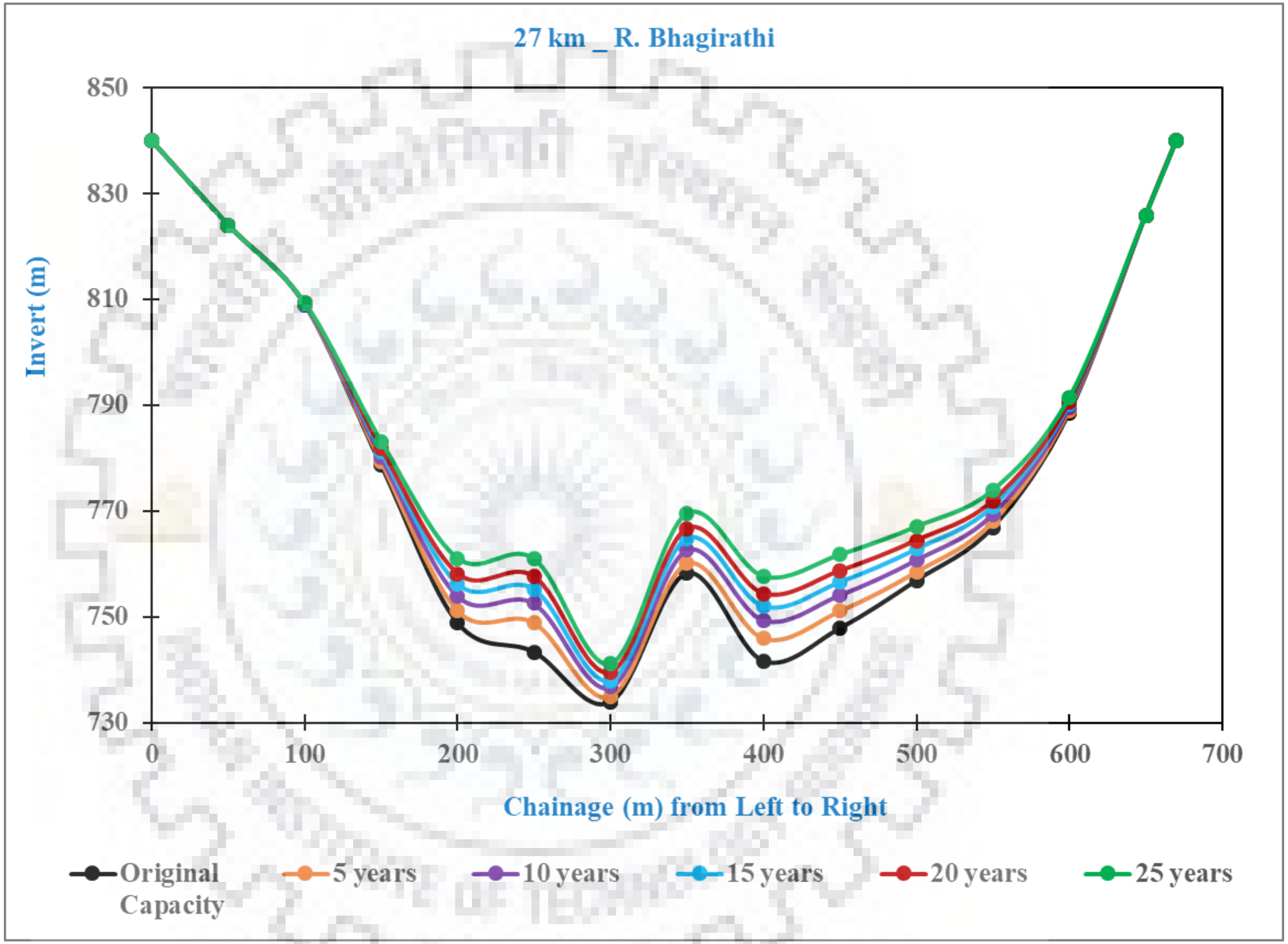

Figure 4. 44: Cross Section Change Upstream of R. Bhagirathi

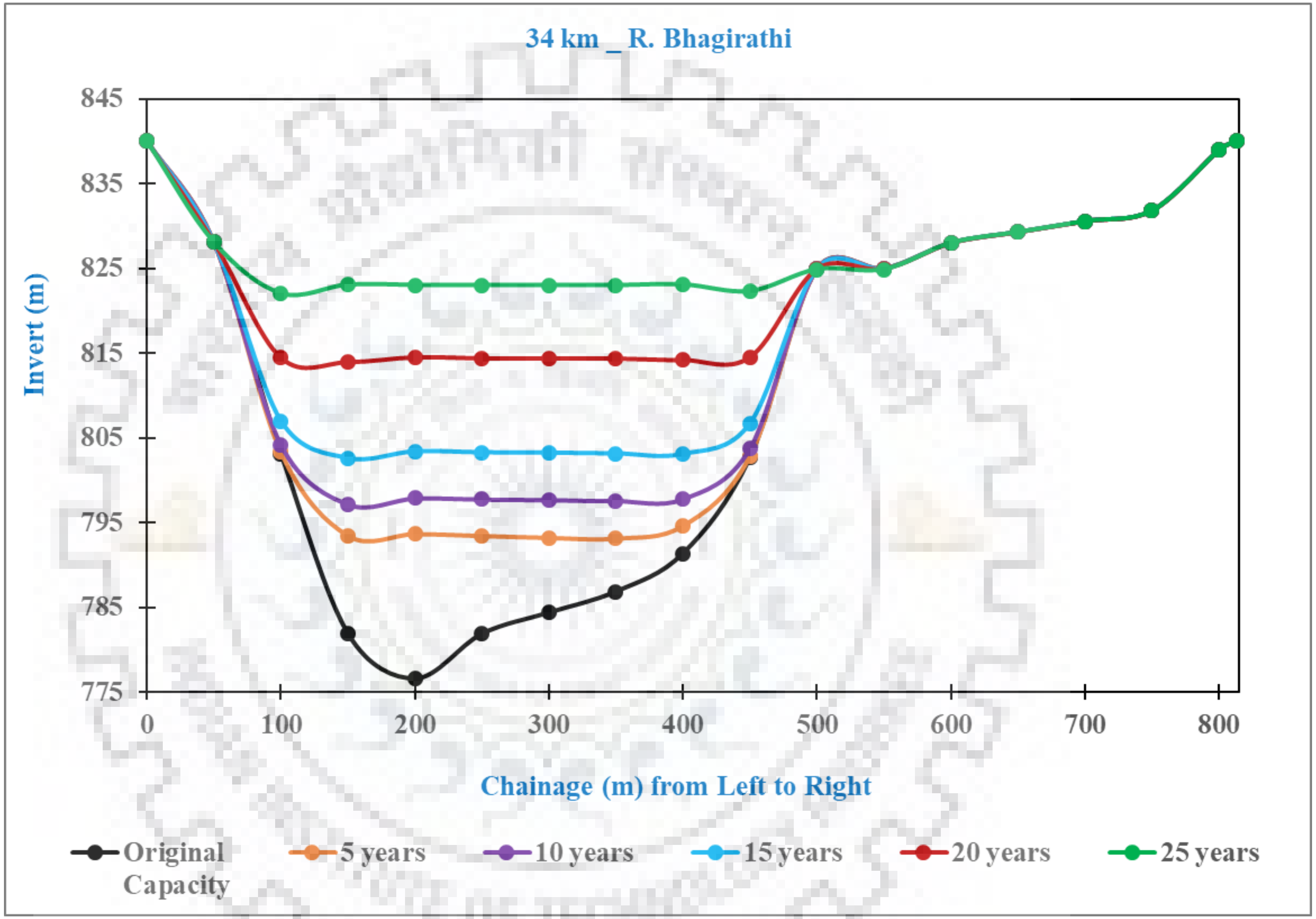

Figure 4. 45: Cross Section Change Upstream of R. Bhagirathi

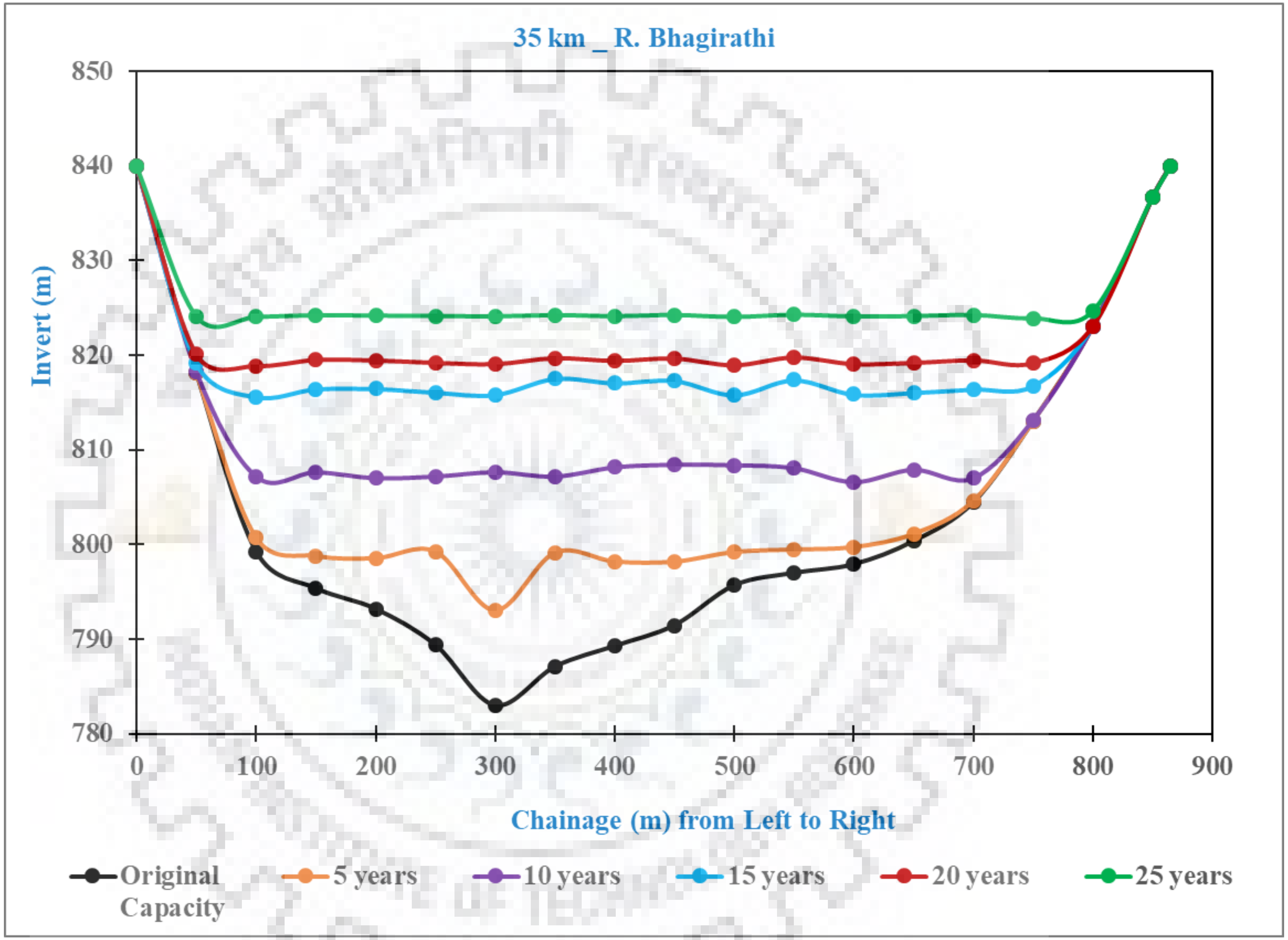

Figure 4. 46: Cross Section Change Upstream of R. Bhagirathi

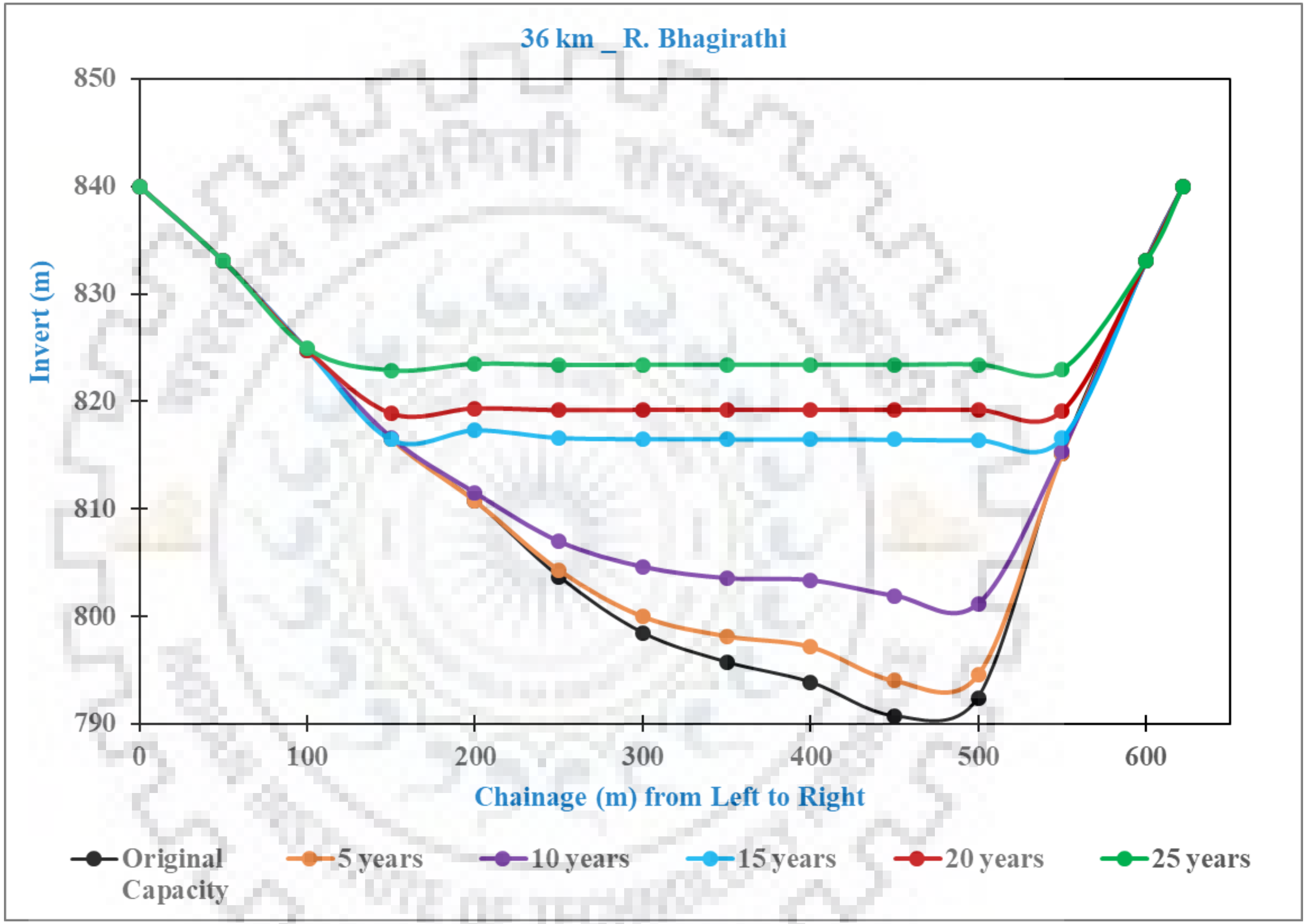

Figure 4. 47: Cross Section Change Upstream of R. Bhagirathi

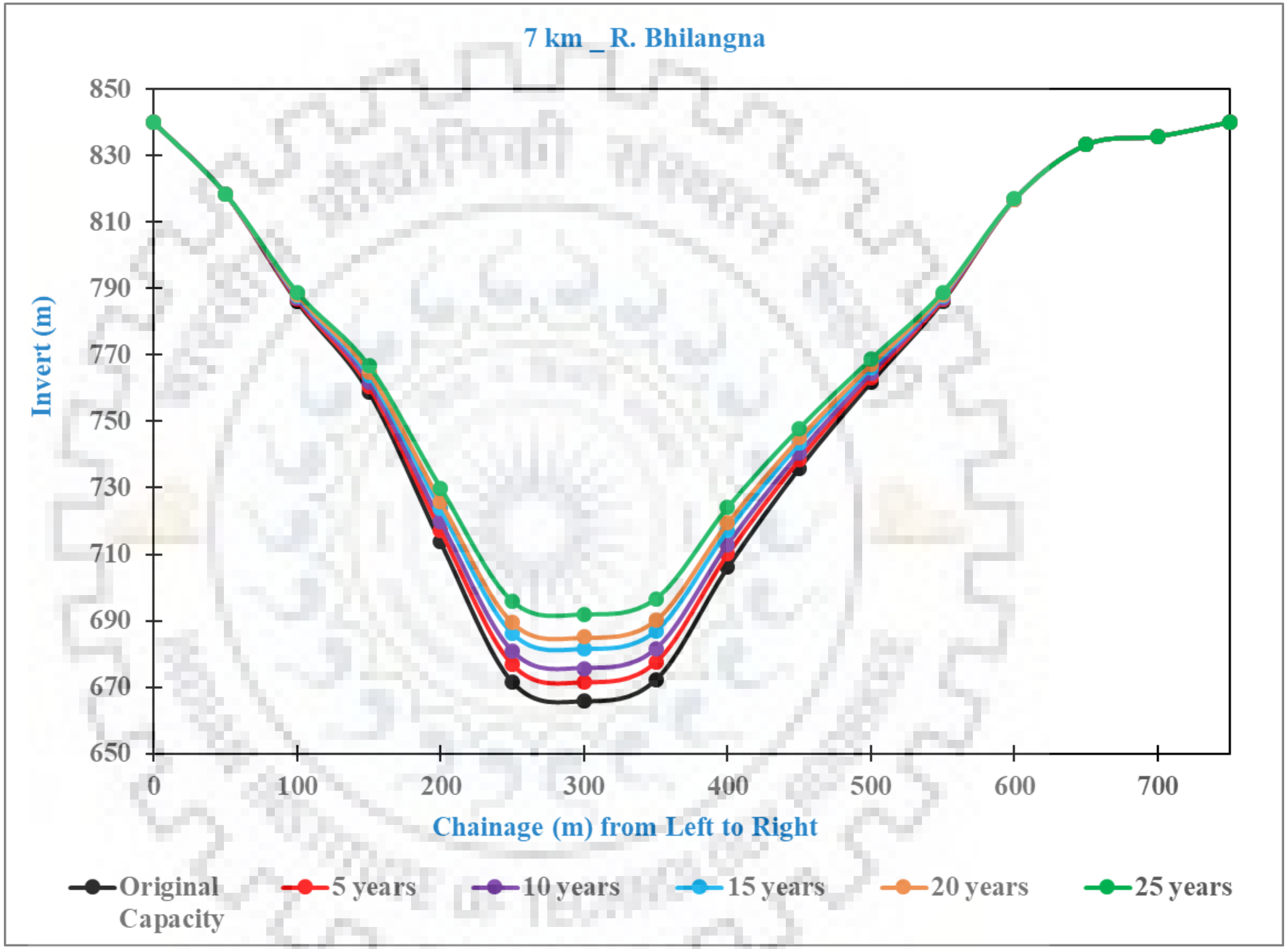

Figure 4. 48: Cross Section Change Upstream of R. Bhilangna

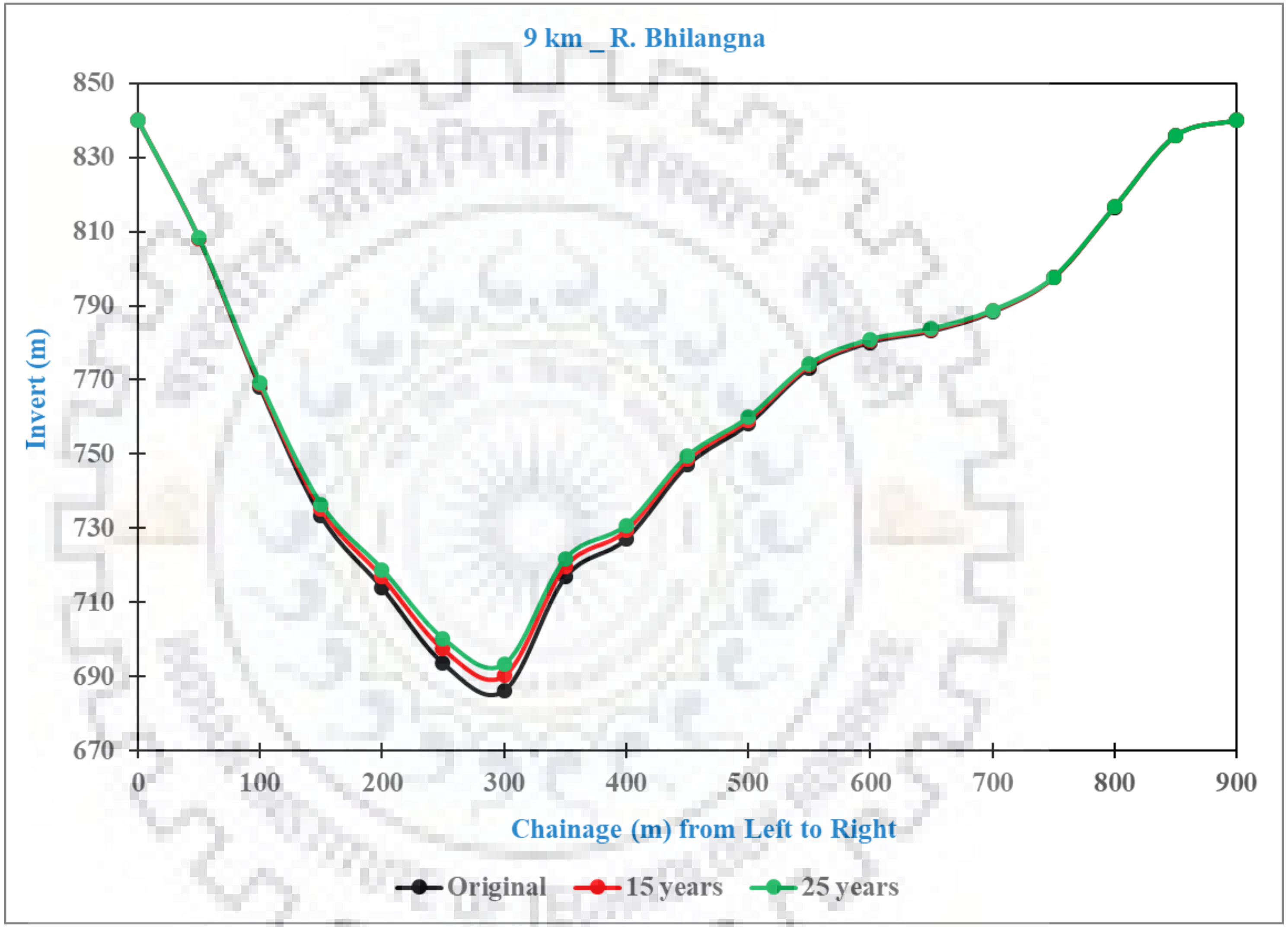

Figure 4. 49: Cross Section Change Upstream of R. Bhilangna

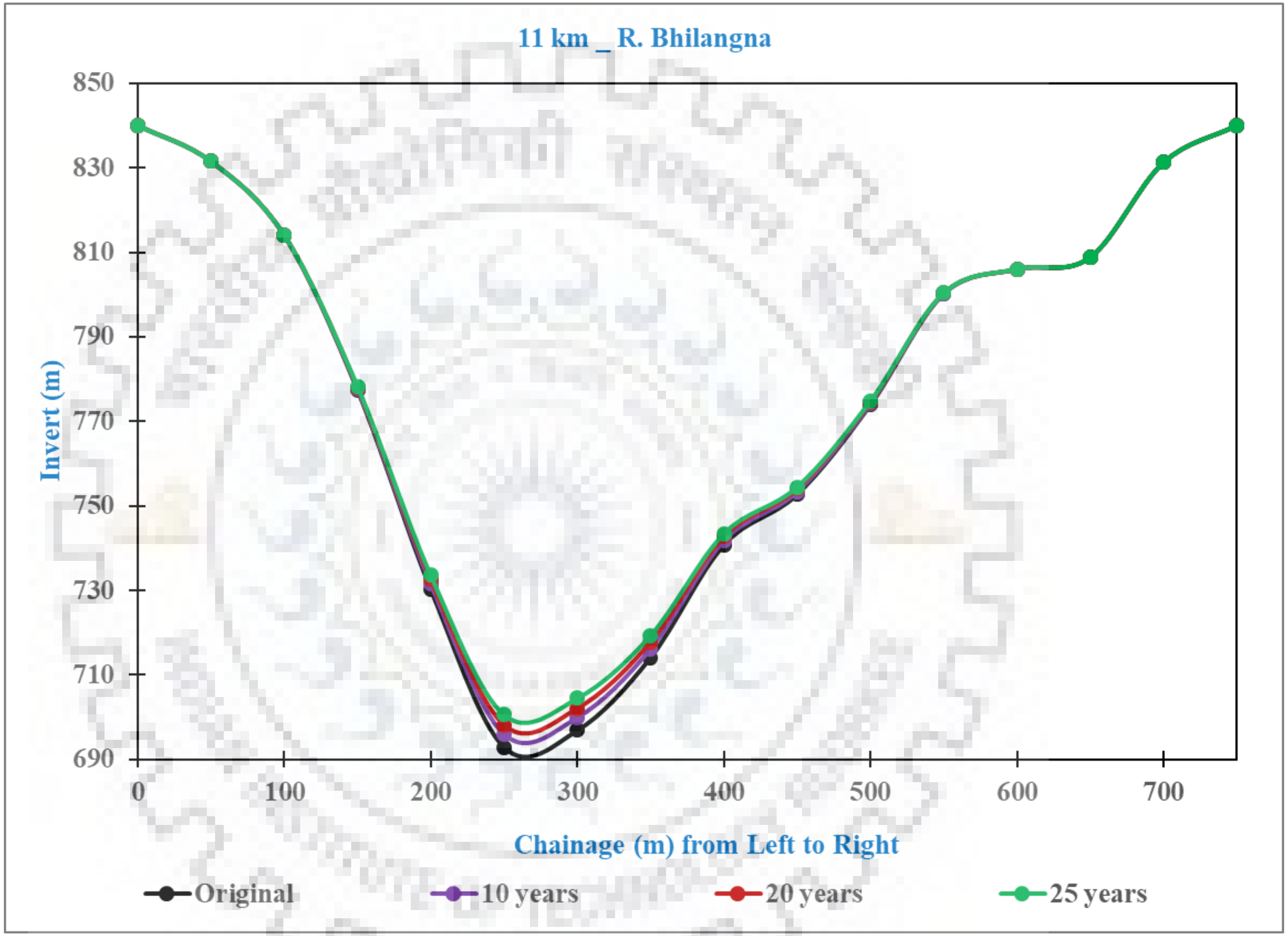

Figure 4. 50: Cross Section Change Upstream of R. Bhilangna

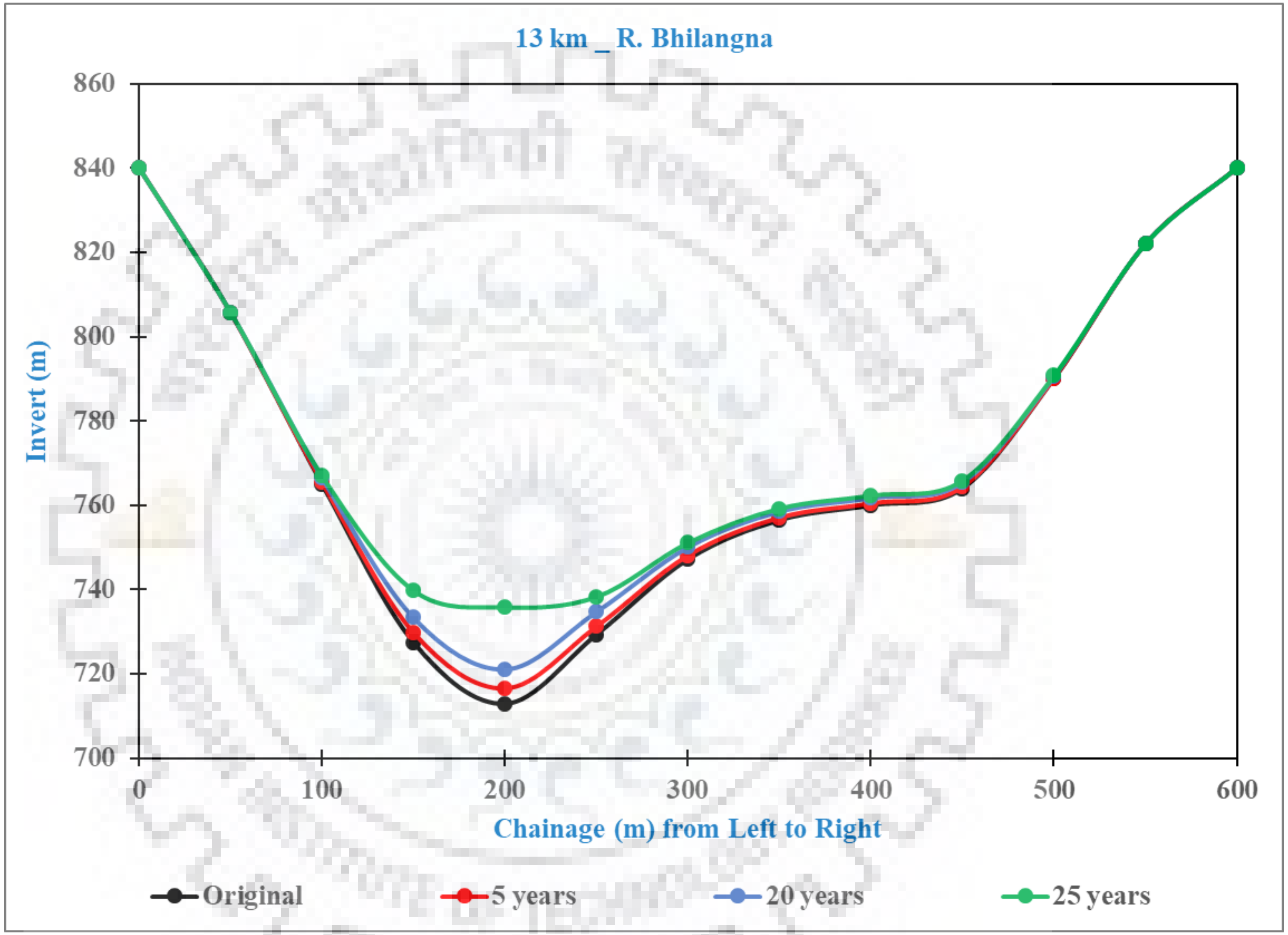

Figure 4. 51: Cross Section Change Upstream of R. Bhilangna

CHAPTER FIVE: CONCULSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

The final part of this dissertation writing include the conclusions and recommendations regarding reservoir sedimentation and capacity restoration, using HEC-RAS 5.0.5 mathematical modeling in both projects (Bajoli Holi and Tehri).

5.2 CONCLUSIONS FOR BAJOLI HOLI SCHEME

The simulation of this project was done on the basis of proto data (sediment inflow and gradation), 3-D physical modeling data (Manning's n values), hydrographic survey (river cross sections), arbitrary flow and sediment hydrographs, and observed flow hydrograph (for model validation) from 3-D modeling site.

The simulation results indicated that the worst sedimentation condition was attained after 20 months of sedimentation, when only about 1.28 MCM out of about 3.03 MCM was left.

As shown on the Fig. 5.1 below, after depleting flushing for 72, 96, and 120 hours respectively in each sedimentation period, maximum capacity (about 2.81 MCM) was restored from 8 months' operation and 120 hours depleting flushing. While the lowest restored capacity (about 2.02 MCM) after 120 hours depleting flushing was from 20 months' operation.

During monsoon, a discharge of 300 cumec or more, associated with 200 ppm is sufficient for flushing the reservoir for 120 hours, following 8 months' operation.

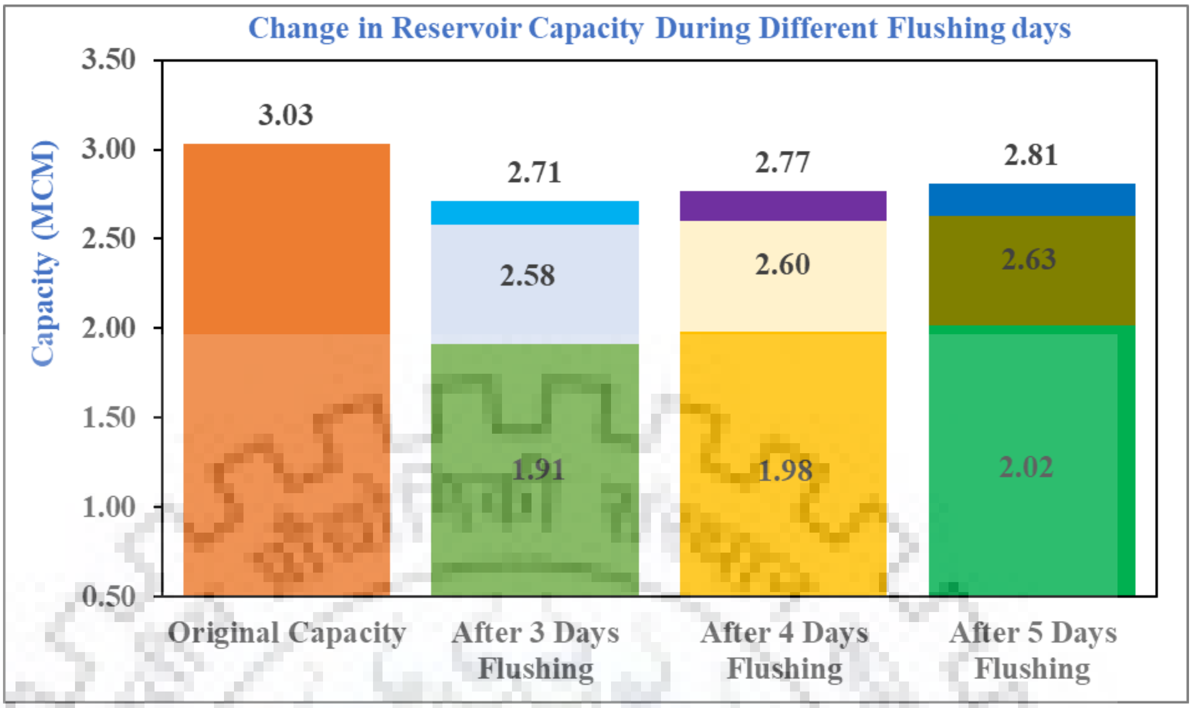

Figure 5. 1: Capacity Restoration after 3, 4, and 5 Days Flushing after 8, 12 and 20 Months' Operation Respectively.

Legend

- Original Capacity.
- 8 Months' Operation and 3 Days Flushing.
- 12 Months' Operation and 3 Days Flushing.
- 20 Months' Operation and 3 Days Flushing.
- 8 Months' Operation and 4 Days Flushing.
- 12 Months' Operation and 4 Days Flushing.
- 20 Months' Operation and 4 Days Flushing.
- 8 Months' Operation and 5 Days Flushing.
- 12 Months' Operation and 5 Days Flushing.
- 20 Months' Operation and 5 Days Flushing.

5.3 CONCLUSIONS FOR TEHRI MULTI-PURPOSE PROJECT

The mathematical modeling for sedimentation prediction in Tehri reservoir was conducted using HEC-RAS 5.0.5 with annual average discharge in R. Bhagirathi and R. Bhilangna and corresponding average annual reservoir level as given in Appendix (Tab. 2).

With sediment at 9.46 million tons/year (corresponding to observed loss of capacity from 2014 to 2038) in R. Bhagirathi and proportional sediment in Bhilangna river, the total loss of capacity in 25 years, is of the order of 149.51 MCM indicating loss of MDDL capacity in 155 years. This translates to **0.17 %** loss of capacity per annum.

With sediment at 13.37 million tons/year (as actually observed at steel girder bridge Tehri from 1973 to 1993) in R. Bhagirathi and proportional sediment in Bhilangna river, the total loss of capacity in 25 years, is of the order of 216.88 MCM indicating loss of MDDL capacity in 107 years. Where by the annual loss of capacity is **0.25 %.**

5.4 RECOMMENDATIONS FOR BAJOLI HOLI HEP

From the analysis of simulation results of sedimentation and capacity restoration of Bajoli Holi reservoir, it is recommended that after 8 months of operation the reservoir should be flushed for 5 days (120 hours) during monsoon, using a discharge of 300 cumec or more associated with 200 ppm.

In addition, since the scope of this simulation was concentrated on reservoir sedimentation and capacity restoration, more study is essential to scrutinize whatever the effects are d/s of the dam once the high silt peaks of the created density currents are let through the dam.

A further investigation is necessary to find out under which circumstances the capacity of the river downstream of the dam can cope with the large amounts of sediment released during depleting flushing exercise.

Given the complexity of the sedimentation problem and where possible it is recommended that sedimentation approaches like layout of the project, reservoir operation, design of structure for future projects among others be considered during the planning and design phases before the actual construction begins for sustainable use. The various techniques employed or adopted for sediment removal in reservoirs as remedial measures are usually very costly and challenging to implement in an operative manner.

Optimisation of sluice gates in every RoR should be done to get the best results for frequent flushing although depleting flushing always give the best flushing than the operational flushing.

5.5 RECOMMENDATIONS FOR TEHRI MULTI-PURPOSE PROJECT

Although predicted rate of sedimentation in Tehri reservoir is almost at par with the design rate of sedimentation, still frequent hydrographic survey of the reservoir is required to study rate of sedimentation.

A further strengthening of Catchment Area Treatment Plan (CAT) shall also decrease sediment yield in the catchment area.

After impounding water in huge reservoir mineral contents of flowing water in the upstream and d/s need to be monitored.

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APPENDIX

Table 1: Observed Silt Data (Lakh Tons) for River Bhagirathi at Steel Girder Bridge, Tehri.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Total Runoff (MHACM)
1973	0.00	0.00	0.10	0.21	5.09	42.47	101.47	99.01	10.55	0.14	0.02	0.01	259.07	0.88
1974	0.01	0.00	0.00	0.01	0.18	1.32	16.39	45.62	6.04	0.34	0.09	0.08	70.08	0.64
1975	0.08	0.41	0.76	0.33	0.58	14.30	15.71	17.90	18.90	3.09	0.35	0.17	72.58	0.79
1976	0.10	0.10	0.09	0.92	0.94	5.96	59.80	26.20	5.91	0.20	0.04	0.01	100.27	0.76
1977	0.00	0.00	0.01	0.01	0.03	1.34	56.84	78.62	43.69	6.12	0.84	0.05	187.55	0.79
1978	0.05	0.04	2.09	1.98	4.40	25.65	57.01	183.56	103.3	6.41	0.54	0.11	385.14	1.26
1979	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1980	0.10	0.41	0.02	0.05	0.35	13.51	70.11	63.99	30.32	1.70	0.02	0.00	180.58	0.89
1981	0.00	0.00	0.01	0.17	2.38	3.14	25.27	42.28	10.92	2.42	0.09	0.08	86.76	0.76
1982	0.04	0.02	0.17	0.31	7.13	26.47	37.02	29.25	11.33	1.18	0.86	0.29	114.05	0.63
1983	0.08	0.04	0.04	0.76	4.01	11.36	32.56	41.65	11.82	1.22	0.43	0.17	104.14	0.77
1984	0.02	0.06	0.03	0.05	2.05	13.32	32.23	35.08	13.71	0.85	0.07	0.02	97.49	0.63
1985	0.01	0.01	0.02	0.09	0.61	7.85	49.73	84.77	29.47	8.61	0.92	0.08	182.17	0.79
1986	0.24	0.43	0.58	1.70	3.10	29.85	44.01	22.45	9.30	4.96	2.62	1.86	121.10	0.96
1987	0.25	0.21	1.34	1.78	0.74	13.73	8.75	7.87	3.54	0.35	0.21	0.16	38.93	0.56
1988	0.09	0.08	0.90	1.80	4.31	10.40	60.17	92.75	21.48	4.79	0.81	0.54	198.12	0.92
1989	0.51	0.34	0.38	0.52	2.81	8.67	21.06	41.33	30.38	5.96	1.33	0.13	113.42	0.69
1990	0.15	0.10	0.93	0.68	7.39	19.94	63.13	66.99	4.84	0.14	0.07	0.04	164.40	0.74
1991	0.04	0.03	0.10	0.11	0.84	9.37	36.05	20.10	8.69	0.11	0.04	0.02	75.49	0.72
1992	0.02	0.02	0.11	0.19	0.51	2.49	20.16	27.52	7.08	0.68	0.15	0.07	59.00	0.81
1993	0.05	0.04	0.19	0.22	0.39	1.11	43.96	12.20	9.30	0.10	0.02	0.01	63.63	0.80
												Total	**2673.98**	**15.79**
												Average	**133.70**	**0.79**

Table 2: Sediment Corresponding to Actually Observed Loss of Capacity in Tehri Reservoir

Date	Res. El.	3 months average prototype (actual data) discharge			Model Run in Hours.	G.O for Res. El.	ppm	Silt_Bhil. (10^5)	Silt_Bhag. (10^5)
		Q (cumec) in_Bhil.	Q (cumec) in_Bhag.	Total Q (cumec) in					
	739.81	29.35	160.84	190.18	2184.00	0.04	905.46	2.09	1.15
	767.14	90.99	393.28	484.26	2208.00	0.06	895.62	6.48	2.80
2006	781.21	22.07	54.11	76.18	2208.00	0.01	895.62	1.57	3.85
	759.50	11.14	32.55	43.70	2160.00	0.01	1384.73	1.20	3.51
	742.33	32.10	121.60	153.70	2184.00	0.02	1369.52	3.46	1.31
	787.96	144.92	399.70	544.62	2208.00	0.05	1354.63	1.56	4.30
2007	811.43	33.34	49.80	83.15	2208.00	0.01	1354.63	3.59	5.36
	780.91	13.76	33.42	47.18	2160.00	0.01	1253.76	1.34	3.26
	748.65	49.93	163.80	213.73	2184.00	0.03	1239.98	4.87	1.60
	799.99	207.95	395.50	603.46	2208.00	0.05	1226.50	2.03	3.86
2008	818.16	17.73	73.99	91.73	2208.00	0.01	1226.50	1.73	7.21
	792.62	9.24	35.28	44.52	2160.00	0.01	1891.43	1.36	5.19
	750.76	29.56	97.75	127.30	2184.00	0.01	1870.65	4.35	1.44
	787.75	130.86	242.80	373.66	2208.00	0.03	1850.32	1.92	3.57
2009	817.57	20.43	66.11	86.54	2208.00	0.01	1850.32	3.00	9.72
	789.23	7.88	35.24	43.12	2160.00	0.01	1613.52	9.89	4.42
	747.85	97.74	21.62	119.36	2184.00	0.01	1595.79	1.23	2.71
	797.28	383.06	411.83	794.89	2208.00	0.08	1578.44	4.81	5.17
2010	819.25	72.73	49.38	122.11	2208.00	0.01	1578.44	9.12	6.20
	812.13	9.96	43.24	53.20	2160.00	0.01	1087.95	8.42	3.66
	761.24	45.48	155.20	200.68	2184.00	0.02	1075.99	3.85	1.31
	796.72	252.13	498.80	750.93	2208.00	0.08	1064.30	2.13	4.22
2011	816.31	25.90	71.09	96.99	2208.00	0.01	1064.30	2.19	6.01
	790.83	11.17	36.73	47.91	2160.00	0.01	1315.90	1.14	3.76
	751.08	32.69	105.46	138.15	2184.00	0.02	1301.44	3.34	1.08
	796.84	205.26	425.57	630.82	2208.00	0.06	1287.30	2.10	4.35
2012	821.60	20.68	67.47	88.16	2208.00	0.01	1287.30	2.12	6.90
	792.89	12.00	62.57	74.57	2160.00	0.01	995.96	9.30	4.85
	761.54	101.43	216.17	317.60	2184.00	0.04	985.02	7.85	1.67
2013	811.50	244.62	485.72	730.33	2208.00	0.06	974.31	1.89	3.76
	821.38	32.08	74.84	106.91	2208.00	0.01	974.31	2.48	5.80
	795.72	10.94	39.92	50.86	2160.00	0.01	2532.47	2.16	7.86
2014	754.00	27.95	125.12	153.07	2184.00	0.02	2504.64	5.50	2.46