SUSTAINABLE RESERVOIR MANAGEMENT-
A CASE STUDY OF TARBELA RESERVOIR

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A Thesis submitted in partial fulfillment of
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This is to certify that the

Thesis entitled

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Submitted by

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has been accepted in partial fulfillment of the requirements

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THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS thesis written by **Mr. Ali Sikandar Rasheed Khan ,** Registration No. **(NUST201362916MSCEE15313F),** of MS Water Resources Engineering and Management 2013 Batch (NICE) has been vetted by undersigned, found completed in all respects as per NUST Statutes/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have been incorporated in the said thesis.

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Signature (HoD) __________________________

Date____________________________________

Signature (Dean/Principal) __________________

Date: ____________________________________

This Thesis is Dedicated to My Parents

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(Ali Sikandar Rasheed Khan)

ABSTRACT

Rivers contain a large amount of sediments and when they approach a hydraulic structure, the sediments in the water settle down and gradually deplete the reservoir capacity. This study was carried out to understand the process of sedimentation in the reservoir-river system, leading to the formation of the delta, by using the model HEC-RAS. The data input to the model was divided into three categories; Geometrical, Hydrological and that related to sediments. The observations of river-reservoir bathymetry collected from the annual field surveys served as the basis of calibration and validation of the model results. Model was calibrated and validated for three (2000-2003) and eight (2000-2008) years, respectively. Two statistical parameters were used to predict the simulation efficiency of HEC-RAS model. Model calibration and validation results were compared with actual bed profiles of 2003 and 2008, respectively. The statistical parameters showed good agreement between observed and simulated bed profiles. Manning's roughness coefficient was optimized for different values ranging from 0.02 to 0.05, and found out that 0.03 was the most suitable one on the basis of Nash Sutcliff Coefficient, Coefficient of Determination and RMSE. Different transport functions and fall velocity methods were applied to calibrate the model and found that Ackers and White as transport function and Van Rijn as fall velocity method predicted results close to the 2003 observed bed profile.

Tarbela dam is playing a key role in the food security of the country by ensuring adequate water supply all the year round to the agriculture sector-the backbone of the economy. In addition, it is generating cheap hydropower which helps to offset the effect of the costly thermal generated electricity on the overall tariff for the consumer. Apart from the gradual reservoir sedimentation depleting the live storage capacity, the immediate concern to dam functioning is posed by the advancement of the sediment delta towards the main dam. It is thought that the delta could choke the power tunnels inlet structures triggered by any seismic activity thus forcing the supply cut-off from the dam. These apprehensions to dam safety have caused the WAPDA, the dam managing authority to commission several studies to ponder ways and means to slow down the delta advancement rate.

The studies have revealed that the delta advancement has been the maximum during the drought years when the dam was drawn down to satisfy the agriculture demand. This has suggested controlling the minimum reservoir level as one of the ways to slow down the advance of the delta.

Three different dam operation scenarios were developed in this research by increasing the minimum reservoir level by 1m, 2m and 3m every year starting from 417m, and in the fourth scenario, the minimum reservoir level was kept at 417m for the next eight years (2008-2016). By increasing minimum reservoir level every year predicted a slowdown in delta advancement rate. The rate was found to be 153, 63 and 57 meter per year for first, second and third scenario, respectively. The fourth scenario had the fastest delta advancement rate of 191 meter per year which was the worst one as the pivot point of delta would reach the dam face in less time. Overall the results of this study showed that 1D HEC-RAS model can predict sediment dynamics within a reservoir for longer duration of time with less computation cost and less data requirement as compared to 2D and 3D models.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

No.	Abbreviation	Description
1	BCM	Billion Cubic Meter
2	D or d	Dimensional
3	El.	Elevation
4	EPA	Environmental Protection Agency
5	GUI	Graphical User Interface
6	HEC-RAS	Hydrologic Engineering Centre-River Analysis System
7	LC	Laursen-Copeland
8	LSCS	Linearized Soil Conservation Service
9	MAF	Million Acre Feet
10	MCM	Million Cubic Meter
11	MDE	Maximum Design Earthquake
12	MST	Million Short Ton
13	MW	Mega Watt
14	NS	Nash Sutcliff
15	OBE	Operational Basis Earthquake
16	PGA	Peak Ground Acceleration
17	RMSE	Root Mean Square Error
18	SMST	Sediments Managements Study Tarbela
19	SOP	Standard Operating Procedure
20	TDP	Tarbela Dam Project
21	WAPDA	Water And Power Development Authority

Chapter 1

INTRODUCTION

1.1 GENERAL

Construction of Tarbela dam was completed in 1976. Dam is providing 30 % of the total energy needs of Pakistan (Roca, 2012). Since the construction of dam, sedimentation is a main problem that is reducing its storage capacity with time. Around 90% of the water inflow in Tarbela reservoir is contributed by snow melt and rest 10% is contributed by Monsoon rainfalls from July to September, every year (Roca, 2012). Sedimentation is mainly because of erosive action of melting glaciers on mountain surfaces. According to Lowe and Fox (1982), 200 million tons of suspended sand and silt washloads deposit in reservoir every year. According to Roca (2012), one-third of the volume of reservoir has filled with sediments and delta is growing towards dam body.

Any natural River - reservoir system is exposed to sedimentation. Sedimentation takes place in reservoirs due to change in flow field. When the flow is obstructed to store water, back water effect is generated and velocity is reduced in the upper reach. When the flow velocity is reduced, settling velocity comes into action and coarser sediments tend to deposit in upper reach of the reservoir. Finer sediments are carried forward even by the lower flow velocities and tend to settle when the flow velocity further reduces (Sloff 1997). Excessive deposition of huge quantum of coarse and fine sediments due to above mentioned changes in flow field, cause a huge body of sediments in shape of delta on the river bed. Delta can be formed by various combinations of sediments but main contents can be categorized as sand, silt and clay. Cohesive sediments (the finest sediments like very fine silt and clay) tend to remain in suspension since sedimentation is no more function of sediment size, flow velocity or settling velocity, rather it becomes function of concentration of sediments, flocculation and ionization of the fluid (Fathi-Moghadam et al. 2011). Boundary between cohesive and non-cohesive sediments is not precisely defined in literature but some experimental studies have assessed that silt of 0.03 mm and less behaves like cohesive sediments (Fathi-Moghadam et al. 2011) whereas certain analysts have observed similar behavior of silt with sediment size of 0.05 mm (Ahmad et al. 2011). Cohesive sediments consolidate and consolidation is function of sediment size and time (Morris and Fan 1997). Consolidation takes place due to expulsion of water from the sediments without being replaced by air. It is natural capability of cohesive sediments (due to illite, kaolinite and montmorillonite elements) to make bond with each other. Initially the flocs are made by the sediments and the sediments tend to settle, but when concentration of cohesive sediments exceeds certain limit, even flocs interact with each other and a lattice like structure is formed underneath which affects the conditions of fall velocity (Fathi-Moghadam et al. 2011).

Apart from the sediment carried by the flows from the upstream catchment, another sediment source is the bank erosion. The bank failure is due to transverse currents, caused by meandering, skewed cross sectional geometry of reservoir and outflow from one end (left or right) of the reservoir. This is confirmed through analysis of the field data.

In design and planning phase of reservoir construction, numerical modeling should be carried out to determine the life of the reservoir. Presently, this hypothesis is followed in developed countries prior to the construction of reservoir but there are number of reservoirs already constructed without such modeling in many developing countries. In case of such reservoirs, physical surveys are carried out to keep record of sedimentation. The record of those survey reports can be utilized as input data for modeling. In case the reservoir is used for power generation, the tunnels are exposed to choking and power generation turbines are exposed to damage due to sediment outflow. In order to improve sustainability of such reservoirs, a computing tool is required which may help predicting sediment deposition in reservoir and visualize different scenarios leading to possible solutions for de-silting of reservoir. This augment necessity of numerical simulation for such reservoirs and Tarbela reservoir is one of them.

1.2 PROBLEM STATEMENT

The Indus River carries a very high sediment load. It is estimated that over 200 million tons of suspended sand, silt and washload are deposited annually in the reservoir accumulating in the form of a delta that grows toward the dam (Lowe and Fox, 1982). Sediments have reduced 30% the initial capacity of the reservoir (11,600Mm3). The advance of the foreset slope towards the dam also increases the risk of blocking the low level outlets that provide flows downstream to the irrigation system and to the power station (M. Roca, 2012).

1.3 OBJECTIVES

The objective of this study is to predict sediment dynamics within the reservoir using 1d sediment transport model (HEC-RAS) and to carry out sensitivity analysis for the calibration of model using different flow parameters. The delta advancement towards the dam face is a major problem that compromises the dam stability. Several sediment management strategies are discussed to slowdown the delta advancement rate.

1.4 RESEARCH SCOPE

Average annual rate of reduction in capacity of Tarbela reservoir is 0.107 MAF and capacity of the reservoir has reduced by 30 %. The present location of Delta is (10 km) away from the main embankment. The Delta is moving forward with an average speed of almost 0.218 miles (0.35 km) per year. Tarbela reservoir is presently exposed to seismic activity, in case of which, liquefaction of sediments may take place choking the tunnels, thus incapacitating Tarbela reservoir. It is imperative to mention here that Tarbela Dam produces 3478 Mega Watts (MW) electricity, which is 50 % of total hydropower electricity generation. Surveying effort is launched annually to find out the actual position of Delta. Numbers of interpolations and repetitions are carried out to confirm the exact location of Delta, which makes the calculations even more complex. This study focuses to enable Tarbela dam engineers and Reservoir operators to locate / predict position of delta by means of numerical simulation.

1.5 THESIS LAYOUT

Chapter 1 will provide the introduction, problem statement, objective and scope of the research. Chapter 2 will give details of the literature review, which describes in detail reservoir sedimentation occurring in the world. And also strategies for sediment management in Tarbela reservoir. Chapter 3 will provides a general description of the Tarbela reservoir characteristics. And also describes the flow data and estimation of sediment inflow to the reservoir. Chapter 4 will presented the deposition pattern in the reservoir and in the influence zone immediately upstream with no sediment management option is assessed with a 1D model, HEC-RAS. Several reservoir management scenarios are also discussed in chapter 4. Chapter 5 will conclude the research with conclusions and recommendations.

Chapter 2

LITERATURE REVIEW

2.1 GENERAL

The purpose of this chapter is to have insight about the Tarbela Dam project and specifically its problem regarding sedimentation. Previous studies related to sedimentation in Tarbela reservoir, its consequences, suggested remedies and their feasibilities are also highlighted.

Importance of numerical simulation of reservoir sedimentation was realized in end seventies, however, partially successful 1d modeling was carried out in early eighties (Papanicolaou et al. 2008). Lot of research has been carried out on various parameters involved in numerical simulation like causes of reservoir sedimentation, 1d sediment transport in rivers and streams, role of bed roughness and meandering in modeling, sediment transport formulas in 1d modeling, cohesive sediments and consolidation, effects of settling velocity of cohesive sediments and critical shear stress. Previous research on all the critical parameters, their observations, results and conclusions are evaluated and certain deductions are made to pursue a well-directed research.

2.2 RESERVOIR SEDIMENTATION

When stream enters the reservoir, cross sectional area is increased and flow velocity is reduced, thus facilitating the sediment deposition conditions. The dam hinders the passage of sediments downstream, thus the sediments passage may be directed to run off through the spill way and the ducts. The sediments settled due to the influence of the reservoir, expand to upstream and downstream, and are not equally distributed even within the lake. The upstream deposition is called backwater deposit, named after the hydraulic phenomenon, being also ascending since the deposits in that area increase (Althaus and Cesare 2006). The depositions within the reservoir are called delta, overbank and bottom-set deposit. Coarse sediments make up the delta, while the inland deposits are made up by finer sediments. As the cross-section increases, the bottom shear-stress as a factor governing sediment transport decreases, and the solids start settling (Althaus and Cesare 2006).

2.3 1 DIMENSIONAL SEDIMENT TRANSPORT

In 1d models, parameters like mean velocity and mean bed shear stress are section averaged and thalweg (lowest pt in each cross section) bed elevation is determined (Ferguson et al. 2001). There are two kinds of coordinate systems in which 1d models are generally formulated; rectilinear coordinate system and curvilinear coordinate system (Papanicolaou et al. 2008). Most of 1d models are developed in rectilinear coordinate system, in which they solve the differential conservation equations of mass and momentum of flow and of sediment continuity equation (Exner equation) by using finite-difference schemes (Papanicolaou et al. 2008).

Few use theory of minimum stream power to determine the optimum channel width and geometry for a given set of hydraulic and sediment conditions, whereas, some models introduce adjustment coefficient for shifting from 3d to 2d and 1d models (Zhou et al. 2003) or using improved version of sediment transport equations used in the model, to cater for additional parameters (Papanicolaou et al. 2008).

Results of such models should be validated with 2d model or any 1d model which cater for secondary currents and their effects, with same data to check the accuracy of development of meanders and bedforms. Because of their lesser data requirements, modest computer resources required, and simplicity of use, 1 d models remain useful predictive tools even today, especially in consulting, for rivers and stream ecological applications where 2d or 3d models may not be needed and are computationally expensive (Papanicolaou et al. 2008).

2.4 BED ROUGHNESS IN MODELING

The usual practice in one dimensional analysis is to select a value of *n* depending on the channel surface roughness and take it as uniform for the entire surface for all depths of flow (P.P.Nayak et al. 2009). The influences of all the parameters are assumed to be lumped into a single value of *n*. The larger the value of *n*, the higher is the loss of energy within the flow, thus lower will be the flow velocity. This provides a very interesting observation; if *n* is higher, flow velocity is less due to more energy loss and as per the velocity and depth relativity in perspective of sub-critical, critical and super-critical flow, water depth is more when velocity is less. This provides a logical relationship between value of *n* and flow depth; if value of *n* is higher, flow depth will be more as compared to the lesser value of *n*. This becomes very important relationship on meanders to define value of *n*. On a meander, flow velocity is more nearer to the inner curve and lesser near the outer curve (Graf, 1971) at the start of the meander. As we proceed further into the meander, the maximum velocity line tends towards the outer curve (Anwar, 1986). The same effect is also confirmed by (Hersberger, 2002).

It is interesting to note here that depth is lesser towards the inner curve and more towards the outer curve which confirms that velocity should be more towards the inner curve since depth is reduced by sediment deposition but centrifugal force plays its role to push the maximum velocity line towards the outer curve (Hersberger, 2002) as shown in Figure 2.1.

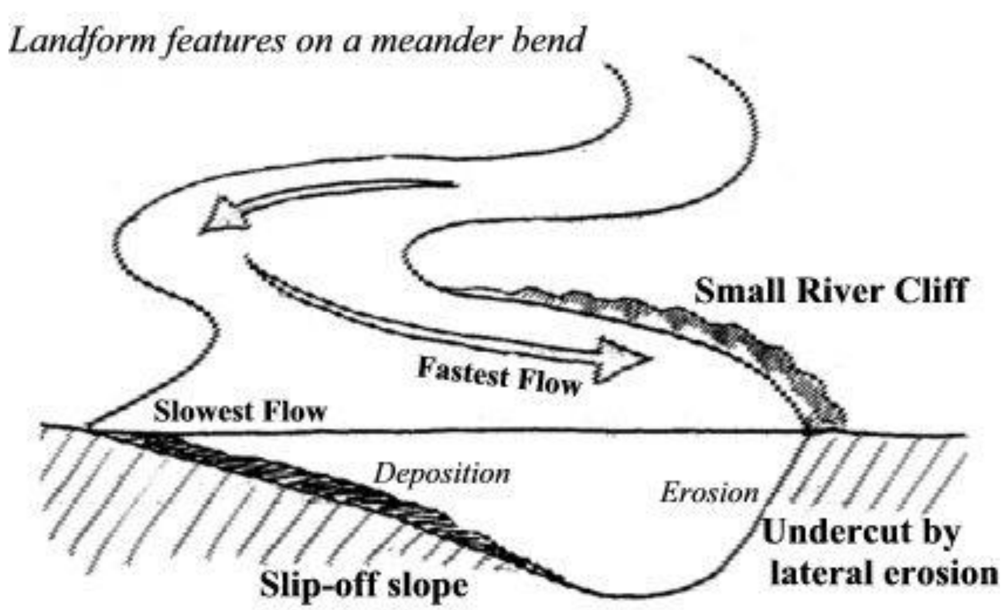

Figure 2.1: Maximum velocity line and transverse currents generated in a meander (http://vudeevudeewiki.blogspot.com)

Due to velocity variation along the cross section, secondary currents are generated causing scouring at outer curve and deposition at the inner curve (Graf, 1971). Since flow velocity is lower towards the inner curve and higher towards the outer curve, the value of *n* should be higher towards the inner curve and lower towards the outer curve. The value of *n* as compared to depth should be higher towards the outer curve and lower towards the inner curve since depth is more towards the outer curve and less towards the inner curve. This clearly shows the complex flow behavior on river bends which needs to be dealt with meticulously. This happens due to simultaneous action of centrifugal force, transverse currents and erosion-deposition of sediments.

Calculations of Friction or roughness parameter have, most of the times, been referred to Darcy–Weisbach equation relating pressure head loss due to friction along a given length of pipe to mean velocity of the fluid flow (Brunone et al. 2002). For unsteady flow in pipe, (Brunone et al. 1995) gave an expression which added a factor in Darcy Weisbach friction factor. This factor is based on decay coefficient, internal diameter, mean velocity, pressure wave speed and rate of change of velocity with respect to time and distance (Brunone et al. 2000). LSCS method was proposed by (James and Wark 1992) for calculation of Manning's *n*, considering different value of meandering effect in simple meandering channel. Manning's *n* is inversely proportional to aspect ratio, which clearly indicates that meander channel consumes more energy with increase in depth. Even for simple meandering channels carrying in bank flows, the resistance coefficients are found to vary with depth of flow in the channel. Manning's *n* is found to decrease with depth for narrow channels while for wide channels it is found to increase with depth of flow in the channel (P.P.Nayak et al. 2009).

2.5 SEDIMENT TRANSPORT EQUATIONS IN 1D MODELING

The mean sediment transport can be predicted from different empirical formulas for river discharge; however, such formulas are site-specific and need careful calibration to be applicable (Camenen et al., 2011). To reduce ambiguity in prediction of sediment transport rates, the methods used should be upgraded. 1d hydraulic models are used worldwide to predict sediment transport capacity of a river.

The sediment transport rates are mostly predicted applying classical sediment transport formulations, such as the Ackers and White (1973), Meyer-Peter and Müller (1948), Engelund and Hansen.

A study has been carried out on the results of two similar formulas named Meyer-Peter-Muller (1948) and Camenen and Larson (2005) in which they differ only in the way they handle critical bed shear stress (Camenen et al. 2011). (Wong and Parker 2006) re-analyzed the data used by Meyer-Peter and Müller and found that the energy slope correction in the equation is unnecessary (Huang and Greimann, 2011).

Size of sediment and relative adjustment of critical bed shear stress by means of an exposure factor is well addressed in Laursen formula (1958) and modified version Madden (1993).

The Laursen-Copeland (LC) transport equation is used when very fine sand and coarse silt dominates as well as gravel and cobbles also exist in sediments. LC is the only commonly used transport function that was developed over the coarse silt range and out performs other functions for non-cohesive fine materials. It is also a 'blended function' that includes separate transport relations for sand/silt and gravel/cobbles. LC is a versatile function and it outperformed the other options in early evaluations, but unsurprisingly required calibration to replicate the site specific conditions on the Cowlitz River (Gibson et al. 2010).

2.6 COHESIVE SEDIMENTS AND CONSOLIDATION

The cohesion of a sediment particle is associated with soil type and particle size. The three most common minerals which have electrochemical forces causing individual particles to stick together are illite, kaolinite, and montmorillonite (U.S.Army 1995). Clays are much more cohesive than silts. Cohesive sediment is characterized by the dispersed particle fall velocity, flocculated fall velocity of the suspension, the clay and non-clay mineralogy, organic content, and the cation exchange capacity (U.S.Army 1995).

Consolidation is process which involves decrease in water content of a saturated soil without replacement of water by air. Consolidation for sand and coarser sediments is zero due to high permeability whereas, finer sediments remain un-drained due to low permeability even after being loaded and consolidation of finer sediments becomes function of time and sediment size (Morris and Fan 1997). In 1d modeling, consolidation factor of sediments volume which is mixture of sand and cohesive sediments (may be silt or clay or both) is required to be precisely calculated (Ahmad et al. 2011). For a specific sand particle size, critical shear stress increases as the percentage of mud increases in the sand-mud mixture which means sediments are likely to retain their deposition status for more time since critical shear stress for incipient motion has increased (Ahmad et al. 2011). For always submerged sand-silt mixture, specific weight varies ranging from 1200 – 1520 kg/m^3. Similar conditions for clay-silt mixture ranges from 640-1040 kg/m^3(Morris and Fan 1997).

2.7 EFFECTS OF SETTLING VELOCITY OF COHESIVE SEDIMENTS

Fall velocity of sediment particles is a key parameter for estimation of sediment transport and evaluation of trap efficiency of reservoirs. The settling velocity of discrete clay particles is given by Stoke's law. As the concentration of clay particles increases, flocculation produces particle aggregates having much larger effective diameters than discrete clay particles. Settling velocity of cohesive sediments initially increases as a function of concentration of particles, however, at some higher concentration, the flocs begin to contact with one another, creating a structural lattice which greatly hinders fall velocity (Fathi-Moghadam et al. 2011).

In the reservoirs of longer reaches, only fine and cohesive suspended particles are able to reach dam walls. As per reports on tested samples collected from nearby large reservoir walls over three different rivers have estimated texture of 58 % silt and 42 % clay, 59 % silt and 41 % clay and 63 % silt and 37 % clay for the Maroon, Karkheh and Karoon dams respectively.

Silt particles with a diameter of less than 0.03 mm have reasonable cohesive sediment properties. After an experimental study, it was concluded that lower concentration samples appeared to have higher maximum fall velocities than the higher concentration samples but for a much shorter duration (Fathi-Moghadam et al. 2011).

2.8 CRITICAL SHEAR STRESS

Critical shear stress is the minimum amount of shear stress exerted by the flow to initiate sediment particle motion. The erosion resistance of sediment is parameterized by critical shear stress and erosion rate (Ahmad et al. 2011). Deposition takes place when bed shear stress is lower than the critical shear stress and sediments start moving when bed shear stress is more than critical shear stress. Range of critical shear stress varies in case of cohesive and non-cohesive sediments. Research has been carried out on variation of critical shear stress with varying mud fractions in sand – silt / clay mixture (Ahmad et al. 2011). Shield was the first one to introduce concept of shield parameter and critical shear stress. Shield parameter is a dimensionless number depending upon the bed shear stress and diameter of the sediment. Increase in bed shear stress increases the shield parameter, whereas it decreases with reduced sediment size. Critical bed shear stress can also be related to mean flow velocity and a critical mean flow velocity for a specific sediment size can be defined. Critical mean flow velocity is used in Yang's formula in which difference between mean flow velocity and critical mean flow velocity affects the total sand concentration calculation. The concept of critical flow velocity can be used to define sediment movement (erosion / deposition) on meanders using velocity profile all along the cross section. The phenomenon is that if mean flow velocity is greater than critical mean flow velocity, erosion takes place and vice versa.

2.9 SEDIMENTATION IN TARBELA RESERVOIR

Indus River water carries large quantity of sediments because 90% of inflow is by snow melts and glaciers tend to cast erosive action on mountains. Resultantly, due to the steep gradients of Indus River, the sediments tend to travel with water towards lower areas (downstream side). When sediments enter the reservoir, coarse sediments tend to deposit in the upper reaches of the reservoir, while the finer particles travel downstream towards the dam due to reservoir operations and settle in the reservoir. A portion of these sediments settles in the downstream reaches and form bottom set slopes, while some quantity of these suspended sediments flushes from outlets during the reservoir operation. Pivotal point of sediments delta is progressing year to year towards dam, it can be seen in

Table 2.1. The velocity of sediments laden water reduces when it enters Tarbela reservoir, this decreases sediment carrying capacity of inflow water and sediments tend to deposit.

Table 2.1: Delta pivotal point details (Haq, 2014)

Year	Elevation (m)	Distance from Dam (Km)
1979	397.5	22.9
2009	418.3	9.6
2010	420.7	9.6
2011	420.7	9.6
2012	421.3	8.7

Every year, snowmelt runoff begins to enter Tarbela reservoir from late May to June. During this period, there is great demand of water at downstream side for some crops, which causes reservoir to run at minimum level. Since, there is great demand of water for irrigation purpose during the period of high inflow, only surplus inflow is stored in reservoir. Such operations render reservoir to fill after mid of July when downstream water demand reduces. During the period of high inflows and downstream irrigation demands, sediment deposits are rolled from upper reaches of dam towards downstream face. Every year, pivotal point of sediments delta shifts towards dam body as shown in Figure 2.2. Delta will not move if sufficient head of water is maintained in reservoir. When water demand at downstream is reduced due to rainfall, high inflow still continues and reservoir keeps filling till it achieves its maximum elevation of 472 m (1550 ft). Reservoir achieves it maximum level, i.e. 472 m, till mid of August and remains full till mid of September. During this period, deposition of new sedimentary layers begins on existent sedimentary profile. Then reservoir is depleted for irrigation needs. Till next year’s April or early May, reservoir remains in drawdown phase and reaches its lowest level. During that time of year, river inflows are also low. Then in next year, snow melt runoff again starts accelerating from late May to June, continuing onwards and this cycle repeats. The fluctuation in reservoir level, recorded form 1974-2012, is represented in Table 2.2.

Table 2.2: Reservoir level of Tarbela Dam (Babar, 2014)

Months	Reservoir Level (m)		Remarks
May	423.64	Transition period: Minimum to Maximum	Simple average on daily basis
June	430.59		
July	450.50		
August	468.28	Water Level: Maximum	Average maximum on monthly basis
September	469.80		
October	461.51		
November	452.83	Transition period: Maximum to Minimum	Simple average on daily basis
December	433.00		
January	442.48		
February	433.00	Water Level: Minimum	Average minimum on monthly basis
March	422.70		
April	421.09		

According to Lowe and Fox (1982), every year, around 200 million tons of sediments enter Tarbela reservoir. TAMS and HR Wallingford consultants (1998) estimated annual sediments inflow to be between 100 and 300 million tones. White (2001) estimated that annually around 40 million ton sediments pass downstream to the dam. TAMS and HR Wallingford consultants (1998) conducted a survey in Tarbela reservoir and concluded that about one-third of total incoming sediments is sand and remaining two-third is fines (silt and clay). Figure 2.3 shows sediments composition of inflowing water at Besham Qilla Gauging Station from year 2000 to 2009. It can be seen, from the graph that during the year 2000 to 2009, sand content in sediment samples varied between 20-35 %, silt content varied between 40-70 % and clay content varied between 10-22 %.

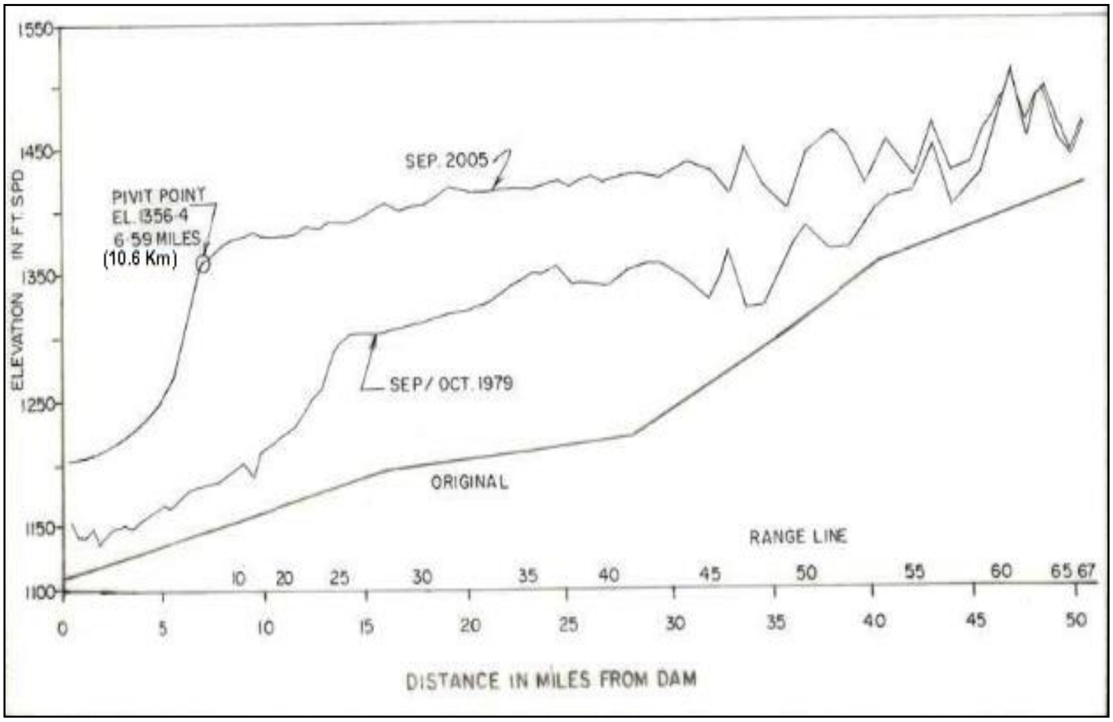

Figure 2.2: Tarbela Reservoir delta profile (Haq and Abbas, 2006)

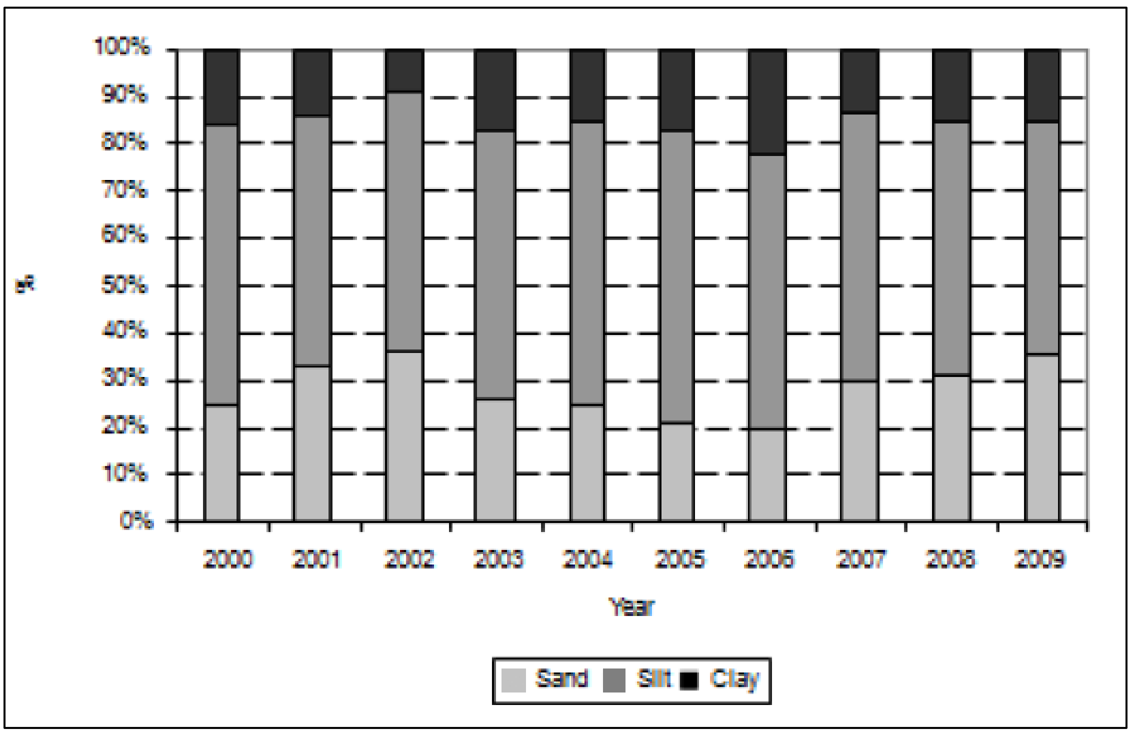

Figure 2.3: Annual average sediment composition (in percentage) at Besham Qilla Gauging Station from 2000-2009 (Roca, 2012)

2.10 BATHYMETRY OF TARBELA RESERVOIR

Reservoir of Tarbela Dam is surveyed annually to estimate the growth of sediment delta and loss in live storage capacity of dam. It is evident from the Figure 2.2, as years passed by, the pivotal point of delta did not only elevate but it also moved closer to the dam. In 1979, sediment delta was almost 23 Kilometers away from the dam and in year 2009, it was moved up to 10 Kilometers upstream of dam.

Another survey conducted by WAPDA, shown in Figure 2.4, shows how gross, live and dead storage capacities of Tarbela reservoir affected with increase in minimum operating level from El. 396.3 m (1300 ft) to El. 425.6 m (1396 ft), from 1979 to 2004. Due to sedimentation, gross capacity of dam reduced from 11.62 MAF to 8.415 MAF (28% reduction), live storage capacity reduced from 9.679 MAF to 7.112 MAF (26% reduction) and dead storage capacity was reduced from 1.941 MAF to 1.3 MAF (33% reduction).

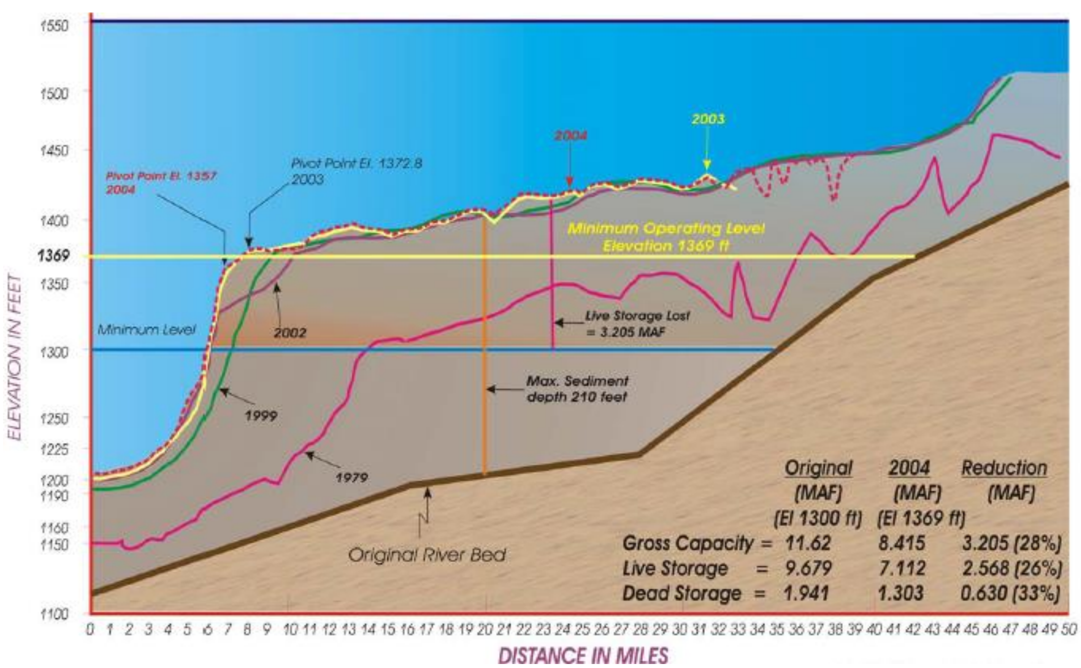

Figure 2.4: Tarbela Reservoir Sediment Profile up to Year 2004 (Survey and Hydrology Dept. of Tarbela Dam)

Bed level of sediment delta in front of dam influences whether it can clog intake tunnels. Bed levels of sediment delta during different years are shown in Figure 2.5. In 2010 and afterwards, bed level rose above the level of tunnel intakes and turbulence of inflowing water takes sediments with it forming cup shaped depression in front of tunnel intakes (Haq, 2014).

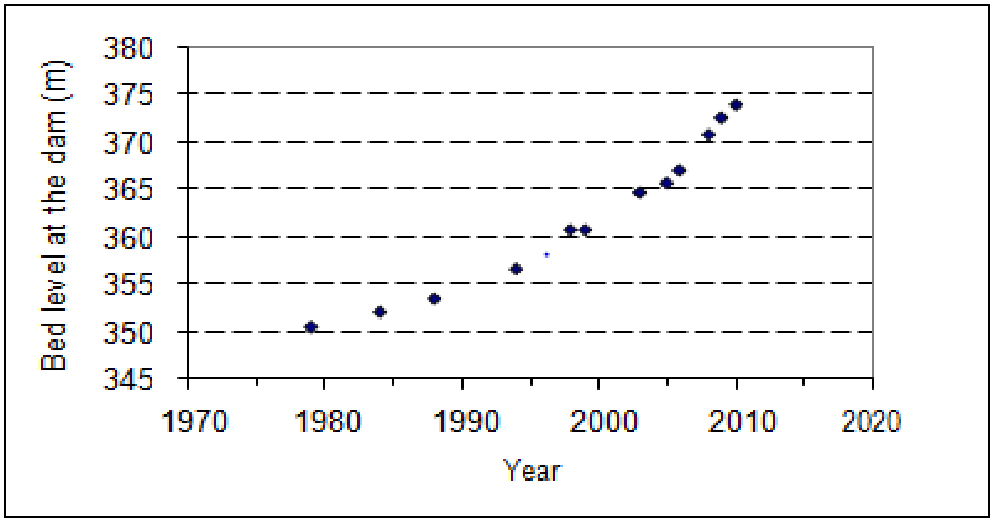

Figure 2.5: Bed Levels at Dam during different years (Roca, 2012)

2.11 FLUSHING AND DREDGING OPTIONS FOR TARBELA DAM RESERVOIR SEDIMENTS

Flushing is an option to preserve storage life of reservoir. Research shows that flushing can keep Tarbela reservoir sediments in balance but since flushing causes sediments laden water to pass out of tunnels, so this is not a feasible option in Tarbela Dam’s case. Flushing can cast exorbitant effects on tunnels due to the erosive action of sediments and environment effects of flushing on infrastructure in downstream side are also considerable (Haq, 2014).

If the duration of flushing is increased, more water will get discharged and the efficiency of flushing to remove deposited sediment in reservoir will also be increased. According to a study conducted by (Haq, 2014), among all the flushing options available, the most optimum one to sustain storage life of Tarbela reservoir was with flushing duration of 30 days, water discharge of 5000 cumec and the drawdown till 400 m elevation. In order to do this, cost extensive and risky arrangements were also recommended for flushing of sediments. Among such arrangement, one technique was to construct a guard bund in front of tunnel intakes to keep sediments from entering the tunnels.

In aforementioned study, 3-D modeling was also done to anticipated sediments deposition after flushing (Figure 2.6). It is clearly depicted from model that sediments will start moving closer to the dam. Sediments will build up their level from 390 to 393 m near power station intakes for 5000 Cumecs and from 400 to 403 m with 3000 Cumecs discharge and this level is far above from the level of tunnel intakes i.e. 373 m. So, to prevent the ingress of sediments into tunnels some guard bunds will also be required.

Sediments Management Study Tarbela (SMST) in 2013, worked for the feasibility of flushing and recommended sand filled geo tubes to be placed as guard bunds before tunnel intakes but the cost estimate is the order of US$0.2 Billion.

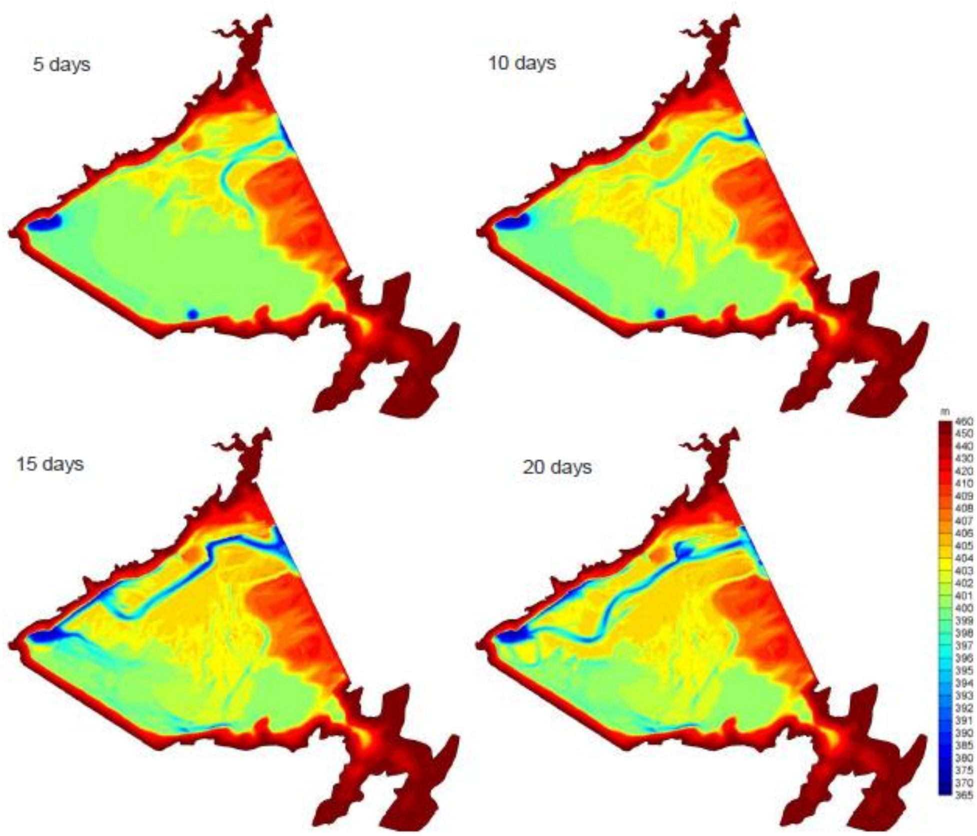

Figure 2.6: Advancement of delta after Tarbela Reservoir flushing (Haq, 2014)

Among other infeasibilities associated with the flushing of sediments stored in Tarbela reservoir, few are:

- Power generation loss in the flushing duration and loss of energy between the drawdown and refilling of reservoir
- Altered water flow regime
- Extensive sediment loads in downstream river and lakes and its damages to Ghazi Brotha Hydropower project in downstream. Special maintenance will be required for downstream water bodies during the period of high sediment loads
- Risk for dam operations during construction of flushing tunnels and guard bunds
- Erosion in turbines due to passage of sediments laden water. Due to the estimate carried out for Tarbela 4th extension; turbines will require repairs and maintenance within 1 to 2 years if high sediment concentrated water is allowed to pass through tunnels.

Dredging option is evaluated to be feasible technically but not viable economically (Rashid et al., 2014). According to a survey, dredging will cost USD 10-12 bn. whereas, the total cost of dam project was USD 2.85 bn.

2.12 HEC-RAS MODEL

HEC-RAS model is developed by US Army Corps of Engineers which carry out 1d hydraulic calculations for a full system of natural and manmade channels (HEC-RAS, 2010). Major capabilities are explained below.

2.12.1 Graphical user interface

HEC-RAS is user friendly and maintain a high level of efficiency for the user, interacting in graphical user interface.

2.12.2 Hydraulic analysis components

The model contains four 1d river analysis components for:

i. Water quality analysis
ii. Unsteady flow simulation
iii. Steady flow water surface profile computations

iv. Movable boundary sediment transport computations

2.12.3 Data Storage and Management

This modelling system component is proposed for calculating water surface profiles for steady gradually varied flow. The system can handle a dendrite system, a full network of channels, or a single river reach. The steady flow component is capable of modelling supercritical, subcritical and mixed flow regimes water surface profiles.

2.12.4 Graphics and Reporting

Graphics include X-Y plots of the river system schematic, profiles, cross-sections, hydrographs, rating curves and many other hydraulic variables. Multiple cross-sections of three-dimensional plot are also provided and Tabular output is available.

After comparison (Table 2.3) of several sediment transport models HEC-RAS 5.0 was selected for River Simulation and bed profile for the case study in the next chapters due to its several advantages over other.

Table 2.3: Comparison of different sediment transport model

Sr. #	Description	MIKE II	GSTARS	HEC-RAS	RESSASS	SHARC
1	Developer	DHI	USBR	HEC USACE	HR Walling ford	HR Walling ford
2	Capability (with reference to present study)	Sediment Transport	Sediment Transport	Sediment Transport	Sediment Transport	Sediment Transport
		Reservoir Operation	Sediment Transport	Sediment Transport	Sediment Transport	Sediment Transport
3	Dimension	1-D	Semi 2-D	1-D	1-D	1-D
4	Availability	Freely Available	Commerci al Model	Freely Available	Not Available	Not Available

Chapter 3

TARBELA RESERVOIR

3.1 GENERAL

Tarbela reservoir was constructed as a result of the Indus Water Treaty in 1962 between Pakistan and India. The plan was to store, control and regulate water of Indus River at a location almost 100 km North-West of Islamabad. Tarbela is world's largest earth-filled dam and one of the world's greatest water resource development projects constructed on Indus River. The primary aim of Tarbela reservoir construction was to provide continued and improved water supply for irrigation, whereas the secondary purpose was to generate electricity and control floods. The project commenced in 1968, completed in 1974 and was commissioned in 1976. The Layout of rivers in Pakistan is shown in Figure 3.1.

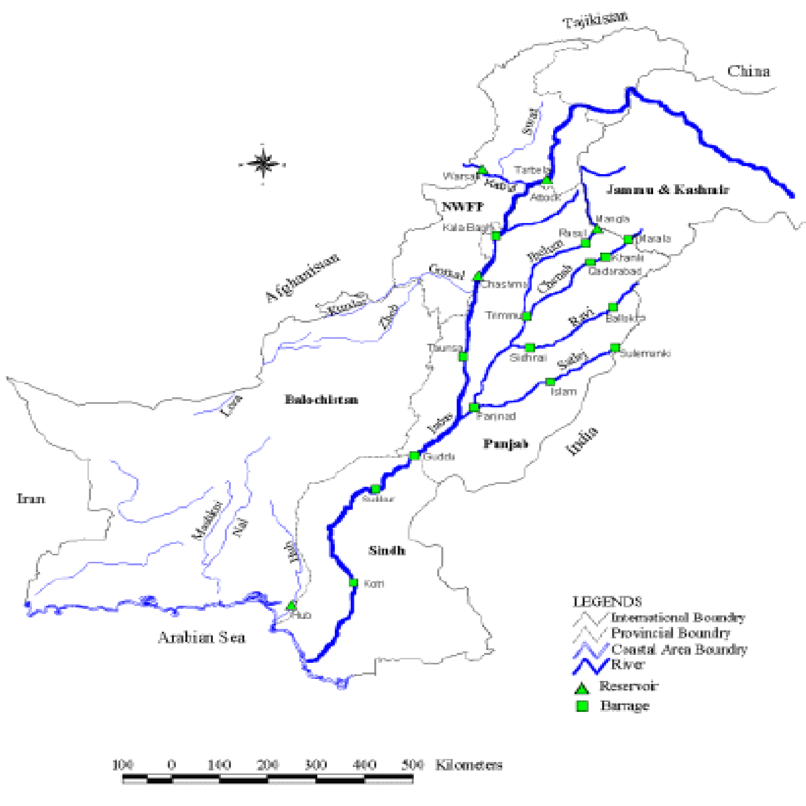

Figure 3.1: . Layout of rivers in Pakistan (http://talib.pk/pakistan/information-rivers-pakistan-urdu)

It originates from the glacial lands of Kailash ranges, having elevation of almost 5,182 meters above sea level, having source from Lake Mansrowar in the Himalayas. Its total length is almost 2900 km and it drains an area of about 963,480 km^2. As stated by (Izhar-ul-Haq and Abbas 2005), *"The catchment area of Indus at Tarbela is 169,600 km^2, which is unique in the sense that it contains seven of the world's ten highest peaks and seven of the world largest glaciers. The mean annual flow at Tarbela is 79 Gm^3 of which at present only 13 % can be impounded at Tarbela."*

3.2 OVERVIEW OF TARBELA DAM PROJECT

Tarbela dam is the world's largest earth and rock filled dam. Tarbela dam is constructed on Indus River and dam site is located approximately 60 Km north-west of Islamabad. The project is situated on a narrow site in Indus River between Haripur and Swabi District (Figure 3.2). Construction work of Tarbela dam was started in 1968 and completed in 1976. Primary purpose of the dam was irrigation and water supply during the periods of low flow (winter), by storing flows during the periods of Monsoon. There is 1126 Km long Indus River basin on upstream of Tarbela dam site.

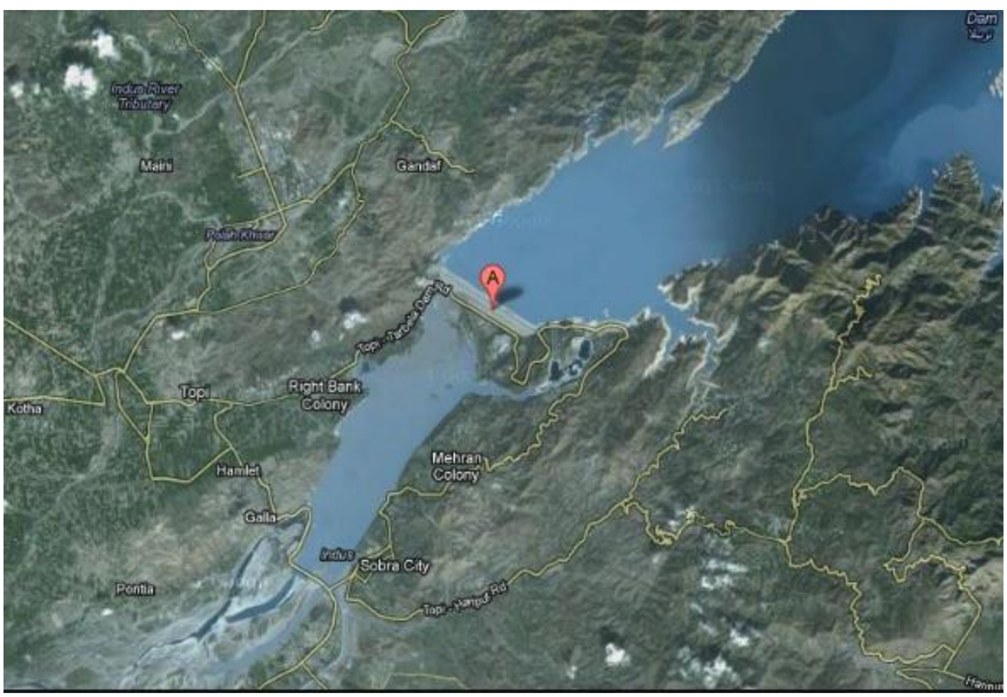

Figure 3.2: Tarbela Dam Site (google earth image)

Project consists of three dams, main embankment is 2,750 m long and its height is 143 m above river bed level (Mahdi, 1988). Tarbela reservoir length extends up to 70 Km upstream of dam body and had capacity of 11,600 Mm^3 when built (Roca, 2012). Total power generation of Tarbela dam is 3,478 MW after 4^{th} and 5^{th} extension it is expected to be raised to 4,888 MW and 6,200 MW, respectively .Tarbela dam has two spillways, one is service spillway with seven gates and other one is auxiliary spillway with nine gates. Dam is comprised of five main tunnels, three of which are used for hydro power generation and irrigation releases and two are dedicated for the purpose of irrigation (Rashid et al., 2014). Tunnels 1, 2 and 3 were dedicated for power generation and irrigation. Tunnels 1 and 2 have intake level at 373 m and Tunnel 3 has intake level at 373.4 m above mean sea level (Haq, 2014). To cater the problem of seepage, an upstream blanket of 2225 m length was provided which is 12.5 m thick near upstream shell and is tapered to 1.5 meter near its end.

Indus River emerges from glaciers on northern slopes of Kailash Ranges. Four main rivers join Indus River in its course towards Tarbela Dam site, Shyok River joins Indus River near Skardu, Gilgit and Hunza Rivers join near Bunji (town in Astore, Gilgit Baltistan) and Siran River joins Indus River near dam site. According to Roca (2012), over 90% of the Indus basin above Tarbela dam site lies between the Great Karakoram and the Himalayan ranges and snow melt from this area contributes major chunk of annual flow to the dam reservoir (Figure 3.3). Rest of the basin, which is present on upstream of dam, is subjected to monsoon every year from July to September (Haq and Abbas, 2006). Snow melt runoff comes into reservoir with slower pace while short duration monsoon rains cause flash flooding. Tarbela dam is providing half of the irrigation demands and one-third of the energy needs of Pakistan (Roca, 2012).

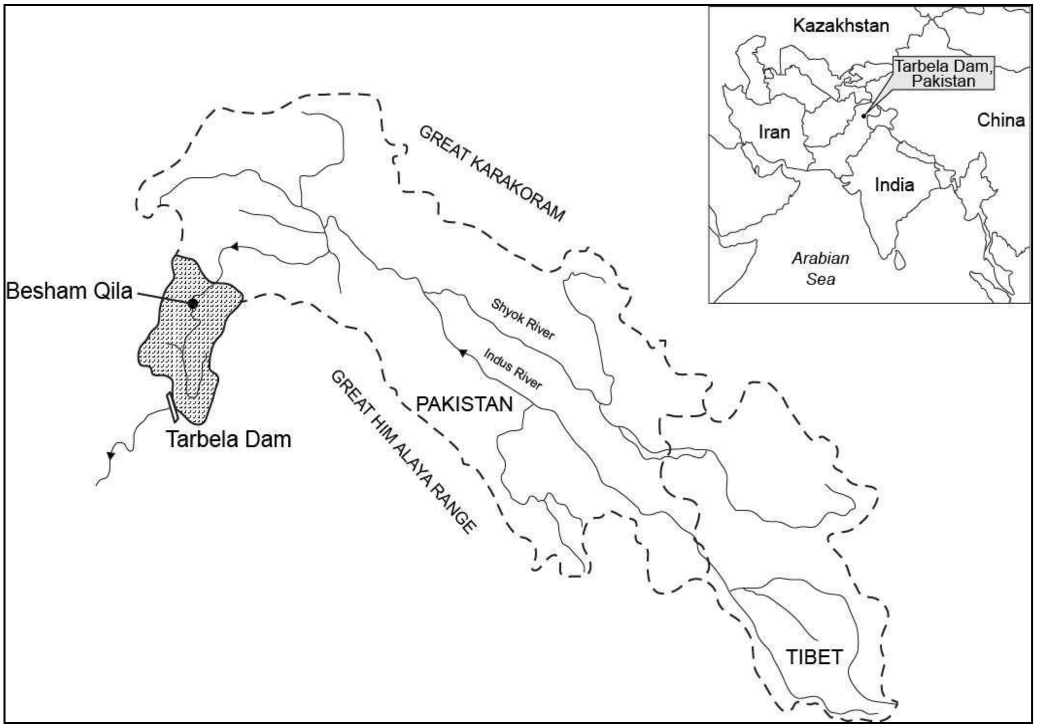

Figure 3.3: Indus River Catchment at Tarbela Dam with monsoon area shaded (Roca, 2012)

3.3 RIVER INDUS HYDROLOGY

Length of Indus River upstream of Tarbela reservoir is 1126 km. Most of the area of Indus basin upstream of Tarbela consists of high altitude mountains, however some percentage of the area falls in the monsoon region. Majority (90 %) of the inflow is constituted by snow melt. In summer season, apart from the base flow from snow and glacier melt, monsoon contributes further inflow to generate peak discharges. Since commissioning of Tarbela reservoir till floods of 2012, a maximum of 14727 m^3/s and minimum of 8495 m^3/s has been observed (Izhar-ul-Haq and Abbas 2005). The Mean Annual inflow of Tarbela Reservoir from 1970 to 2000 is shown in Figure 3.4. The post Tarbela data reveals that floods ranging from to over 14727 have been observed since 1974. As stated by (Izhar-ul-Haq and Abbas 2005), *"Considering recorded data, annual inflow to Tarbela less than 74 M m^3 is termed as dry year, between 74000& 79000M m^3 is called an average year and above 79000M m^3 is known as wet year."* (Ahmed and Sanchez 2011) plotted mean annual flow data on Tarbela reservoir against each month of the year (Averaged from 1970 – 2000).

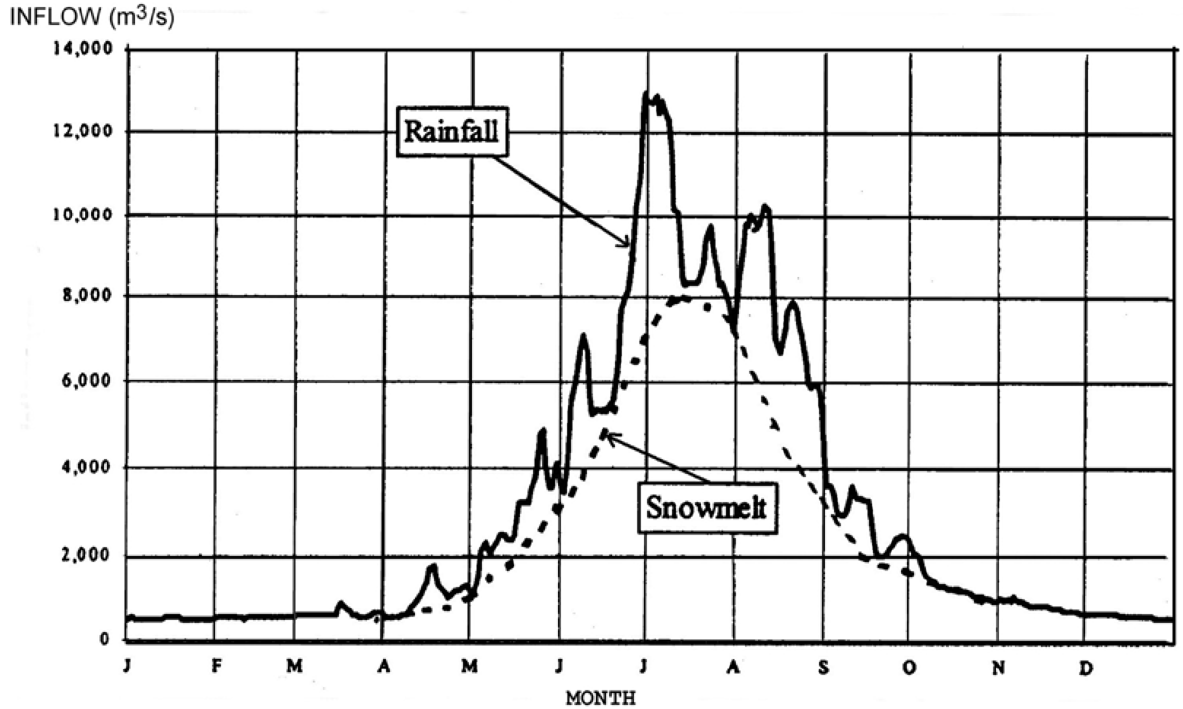

Figure 3.4:Mean Annual inflow of Tarbela Reservoir (Averaged from 1970 to 2000) (Ahmad et al. 2011)

3.4 SEDIMENTATION PROCESS

When the sediment laden flow enters the reservoir, the velocity is reduced and sediments tend to deposit. A landform generated due to sediment deposition on the river bed is called delta. Coarser sediments tend to deposit earlier in closer to the river mouth to form initial part of topset and foreset beds. The intersection of topset and foreset beds is called pivot point of delta. As one proceeds further downstream, the composition of topset and foreset beds changes from coarser to finer sediments, whereas, the bottomset beds are composed of finer sediments only.

The high sediment yield in Indus River is due to abrasive nature of geological formations in its catchment area. In the summer season, the glaciers are melted and big glacial formations move downstream on steep slopes. These glacial formations crush abrasive material in upper catchment area, thereby generating lot of sediments, which are carried by the flow. To carry out the annual bathymetric survey, a network of 73 cross sections named

"Range lines" is established at Tarbela reservoir. The annual survey is carried out in the month of September and October when the reservoir level is high.

3.5 TRAP EFFICIENCY

Trap efficiency is the ratio of sediments deposited within the reservoir to the total inflow of the sediments (Morris and Fan 1997). The coarser sediments settle on entering the reservoir and form top set bed. Due to the outflow, finer sediments are carried forward by the flow towards the downstream end. These fine sediments form fore set and bottomset beds, however some percentage of these particles flows with the outflow. Intersection of top set slope and bottomset slope is called delta pivot point. Tarbela reservoir trap efficiency is reducing with the passage of time, as the delta pivot point is advancing towards the outlet tunnels. A comparison of the sediment accumulations in Tarbela Reservoir and sediment yields of the Indus River at Bisham Qila, from 1980 to 1990 was carried out by (Faran and Boer 2003).

3.6 SEDIMENT BEHAVIOR IN THE RESERVOIR

High inflows enter Tarbela reservoir in late May to early June when the reservoir level is minimum and delta is exposed. Since Monsoon is yet to start, irrigation demand is high in the irrigated farmlands of Sindh and Punjab, therefore, Tarbela authorities are compelled to release water to fulfill irrigation demands. High outflow increase the velocity and lots of sediments of exposed delta are carried forward by the flow towards the main dam embankment. After the monsoon starts, the reservoir is filled in less than a month time with fresh sediment laden inflows. The reservoir level reaches its maximum elevation in almost all the years except one odd exception like year 2004. Generally, the reservoir remains at maximum elevation till mid-September.

When the outflow is increased to fulfill the further irrigation demands, the reservoir level starts receding unless it reaches its minimum elevation level, generally in early May next year. The reservoir operation plays key role for advancement of delta which accelerates in the year when high outflow over exposed delta continues for longer duration. The elevation of delta rises along the slope of topset bed, especially in the years when minimum operating level is kept higher. Apart from the sediment load mobilized by the glacier movement, bank erosion is also a major source of sediment generation in the Indus River. The sediments brought by the flows are deposited in the main reservoir causing the delta to rise and advance downstream towards the main dam. Longitudinal profiles of Tarbela reservoir till year 2004 are shown in Figure 3.5.

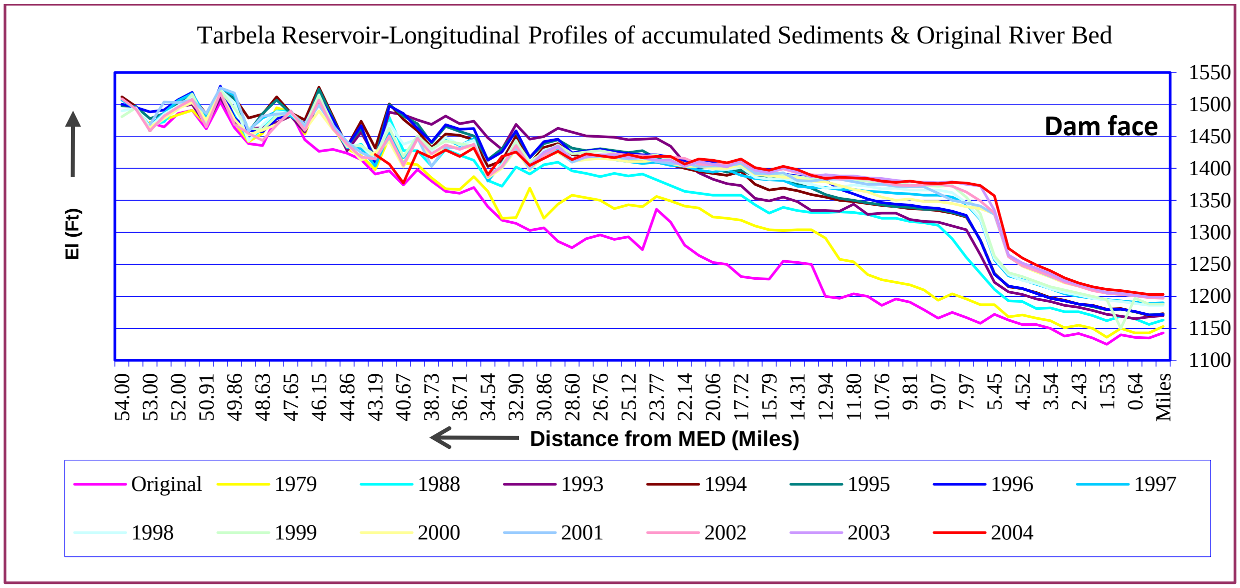

Figure 3.5: Longitudinal profiles of Tarbela reservoir till year 2004 (SMST, 2004)

3.7 RESERVOIR OPERATION

The high flow season begins in mid-May due to increased melting in the upper catchment when the reservoir is at its lowest elevation. The water starts entering the reservoir in increasingly larger quantities but since the irrigation demand downstream is high, large outflows are released and the filling of the reservoir does not start till about middle of June. This early period in summer is very important for the reservoir since the sediment delta is covered by a depth of water which is the least during the entire year. High flows during this period cause sediment to be deposited closer to the delta pivot point, thereby hastening the advance of the delta (Izhar-ul-Haq and Abbas 2005). This realization has made the Dam Authorities to refix the drawdown point to elevation 417m from 396m until 2006 (Ahmed and Sanchez 2011).

High flows continue and the reservoir is filled up in about less than a month as the monsoon rains in the farmlands of Sindh and Punjab reduce the irrigation demand. The dam is filled up to elevation 472.4 m above MSL and this level is maintained up to mid-September. The sediment deposition during this stage is mainly in the upper reaches of the reservoir.

Throughout the winter season, the inflows are low and the reservoir level keeps going down due to outflows made to fulfill the downstream irrigation requirements, reaching the drawdown point in April. The cycle then repeats itself with high flows due to rising summer temperatures.

3.8 DATA COLLECTION BY THE DAM AUTHORITIES

Tarbela Dam River Survey and Hydrology division is responsible for collecting data about the reservoir. This department carries out annual surveys to ascertain the impact of sedimentation on the reservoir. Following data is available with the Tarbela Authorities:

- Points of known location along the reservoir-river are selected, 73 in number, where river cross-sections are taken each year: these are termed as ‘range lines’.
- Following data concerning Range lines is available with Tarbela Authorities:-
    - Annual Survey Reports from 1979 till to date.
    - Northing and Easting of both Bench Marks (left and right extreme) of each Range line.
    - Bearing of each Range line.
    - Length of each Range line.
    - Horizontal distance of centre point of each Range line from centre of main embankment
    - Horizontal Distance between centre point of each Range line
    - Horizontal distance from the bench mark and depth at points all along the cross section is noted in the survey.
- Discharge inflow at upstream end (Bisham Qila Guaging station) and outflow at downstream end (tunnels, spillways etc.) is noted on daily basis.
- Sediment Discharge in noted on daily basis at both upstream and downstream end.
- Reservoir level at upstream and downstream end is noted on daily basis.

Chapter 4

SIMULATIONS AND ANALYSIS

4.1 GENERAL

Numerical simulation is very much dependent on the quality and detail of field data used in building the model. There are number of parameters like roughness coefficient, active layer thickness, time step, space step, bends and meanders etc., which affect the results of simulations. These factors need careful calibration for obtaining reasonable results.

4.2 DATA FOR BUILDUP OF THE MODEL

The data used for building the model can be classified as topographical, hydrological and hydraulic that related to sediments. The data source in all cases was Dam Survey Division of Tarbela Dam Project (TDP).One of the prime tasks of the Dam Survey division is to calculate the sedimentation in the reservoir. They achieve this by annual surveys of the reservoir and the river to gauge the volume lost to sediments. For this purpose, the Survey Division has selected 73 salient points named ‘range lines’ where cross-sections are measured annually(Izhar-ul-Haq and Abbas 2005) which can be referred to as topographical data. Range lines are located on straight reach as well as on meandering reach, as shown in Figure 4.1.

Hydraulic data refers to time series of inflows to the reservoir as measured at a gauging station Bisham Qila at a distance of 86 km upstream from the reservoir. The time series of inflows spanned the whole duration of the simulation from 2000 to 2008 on daily basis which is plotted in the Figure 4.2.

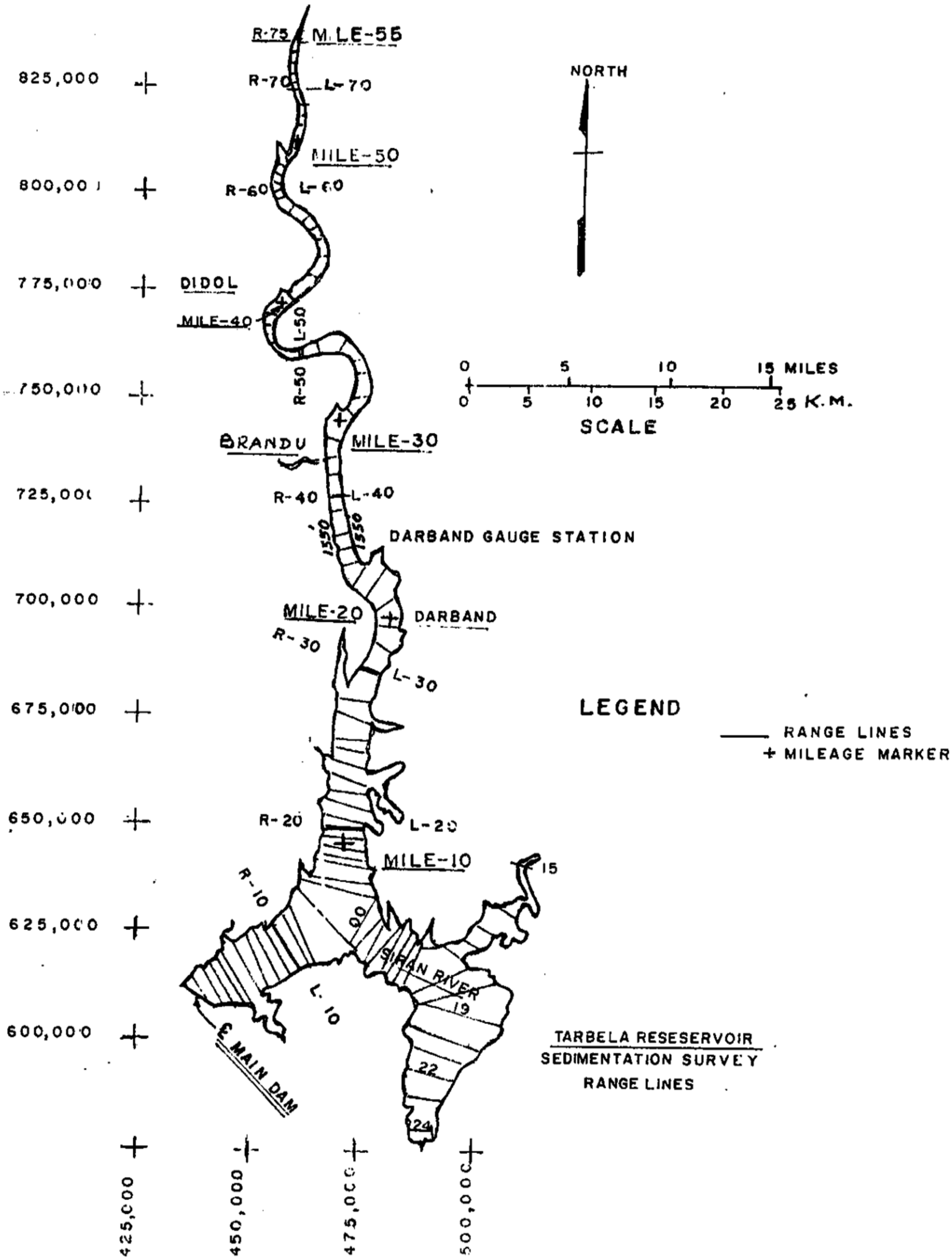

Figure 4.1: Range lines at Tarbela dam (SMST)

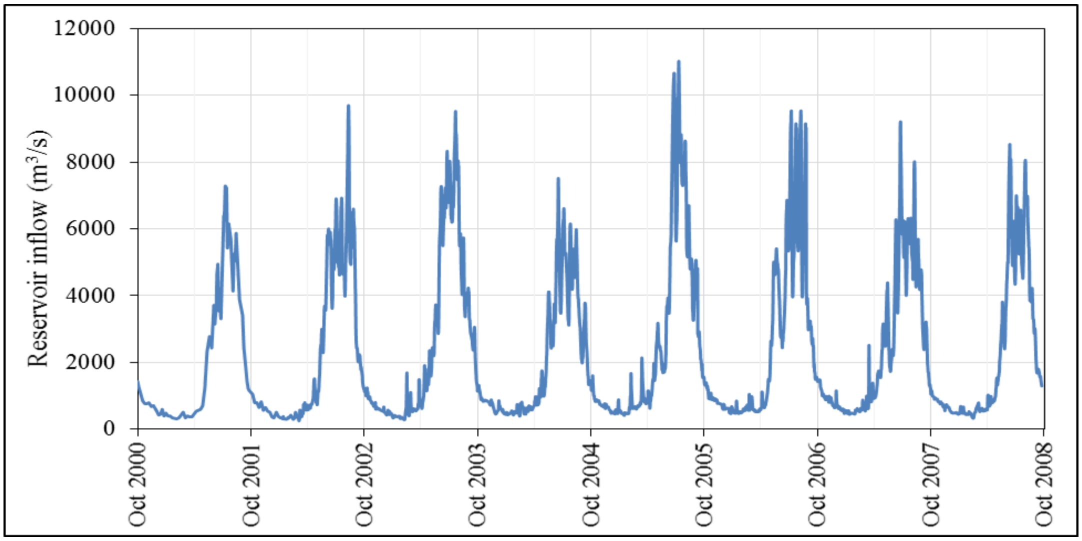

Figure 4.2: Daily inflow of Tarbela dam from year 2000 to 2008

Another type of data collected from the Dam Authorities is the reservoir water surface elevations on daily basis as shown in Figure 4.3.

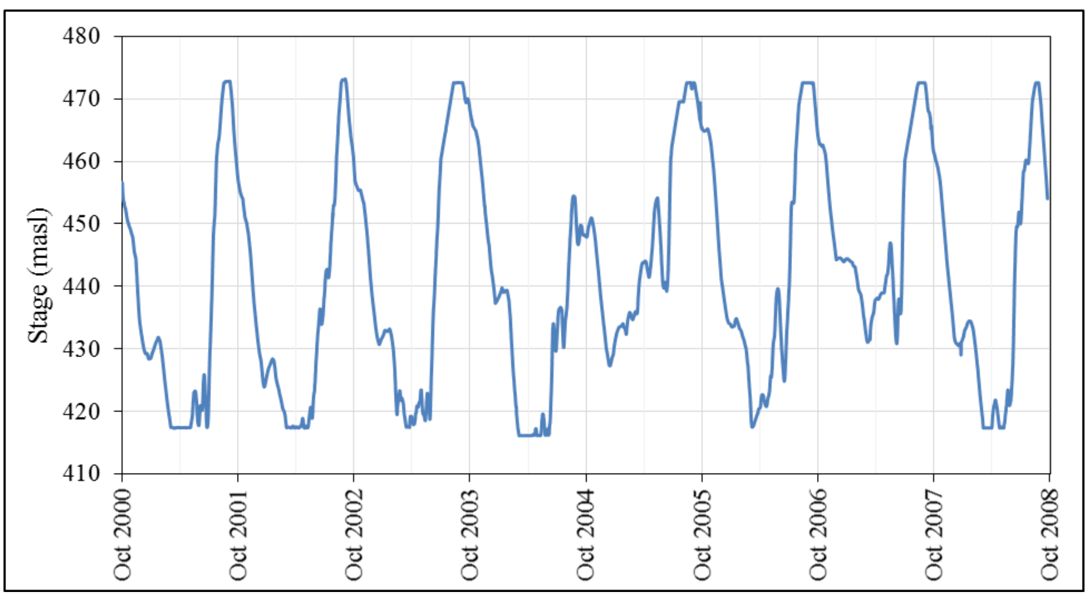

Figure 4.3: Daily reservoir level elevation from year 2000 to 2008

Sediment data consist of suspended sediment concentration measured at Bisham Qila gauging station on daily basis for the period simulated (2000-2008) as shown in Figure 4.4.

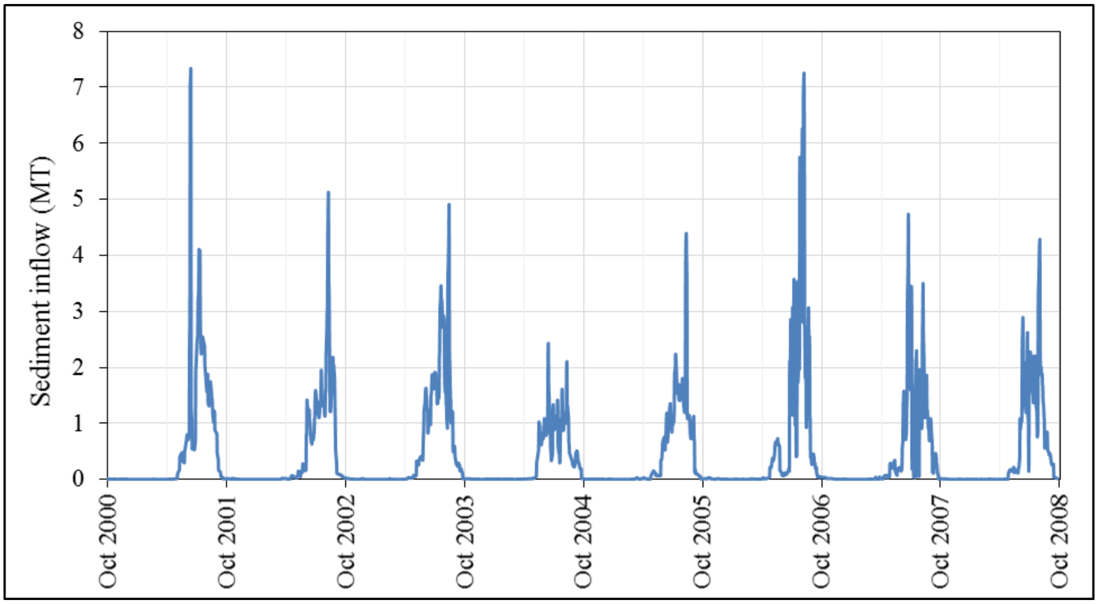

Figure 4.4: Daily sediment inflow at Tarbela dam from year 2000 to 2008

As regards to soil type, brief descriptive information is available at different range lines giving percentages of soil samples as ‘clay’, ‘sand’ and ‘silt’.

4.3 SALIENT FEATURES OF FLOW AND SEDIMENT DATA

Indus River is highly seasonal with about 70% of annual flow volumes occurring in only four months from May to August when snowmelt of Himalayas is at its peak. The flow is at its lowest from December to February. Summary of minimum and maximum flow from year 2000 to 2008 is given in

Table 4.1.

Table 4.1: Summary of maximum and minimum flows from year 2000 to 2008

No.	**year**	**Total Vol of flow ($x10^4$) (m^3)**	**peak flow (m^3/s)**	**Min flow (m^3/s)**	**% of volume of flow occurring from May to August**
1	2000	77.92	10570	368	70
2	2001	68.65	7283	312	75
3	2002	79.12	9692	252	74

4	2003	90.72	9519	283	73
5	2004	72.12	7510	394	69
6	2005	94.95	10998	411	71
7	2006	89.00	9510	467	72
8	2007	82.96	9204	442	69
9	2008	78.67	8530	326	74

The maximum volume sediment concentration C_s remains below 1% on almost all the time, even in flood season when sediment inflows are very large, meaning that the mixture remains Newtonian (Graf, 1971) and no special treatment is warranted due to heavy sediment content.

4.4 CALIBRATION OF ROUGHNESS COEFFICIENT

Water that flows in a natural channel is a real fluid for which the action of viscosity and other forces cannot be ignored completely. Owing to the viscosity, the flow in a channel consumes more energy. Usually Chezy's, Manning's or Darcy-Weisbach equation is used to calculate the velocity of flow in an open channel. Due to its popularity, the field engineers mostly use Manning's equation to estimate the velocity and discharge in an open channel. While using Manning's equation, the selection of a suitable value of *n* is the single most important parameter for the proper estimation of velocity in an open channel. Major factors affecting Manning's roughness coefficient are (P.P.Nayak et al. 2009):-

- Surface roughness
- Vegetation
- Channel irregularity
- Channel alignment
- Silting and scouring
- Shape and the size of a channel
- Stage-discharge relationship

Accurate determination of roughness coefficient must precede sediment simulations. For calibrating Manning's 'n', model is run only for water flow with given inflow and downstream boundary conditions. Due to absence of any intermediate gauging station in the reach, water stage data are not available to calibrate for *n*. Ideally, one should select appropriate roughness coefficient for each channel reach as a function of discharge Q, however, a distributed variation of Manning *n* requires extensive field data. (Duan et al. 2008) reports that Manning value is very much dependent on vegetation and discharge. At low flows, the effect of vegetation is preponderant and roughness varies from 0.1-0.6; at medium flows (Q>21000 cfs) roughness is from 0.02-0.05, while at flows exceeding 35000 cfs, the Manning roughness is probably around 0.022-0.03. In the absence of such data, assigning varying roughness values to different sections would tend to be arbitrary and hence is not adopted. The practice adopted is selecting a constant roughness value for the entire reach.

4.5 SELECTION OF MODEL PARAMETERS

4.5.1 Solution algorithm for water flow and sediment equations

The solution advances in time by time step Δt and in each time step first, water flow is simulated by the solution of Saint Venant equations followed by the sediment routing step. The method of solution either can be quasi-unsteady flow and unsteady flow. Given the fact that our flow and sediment data are spaced at daily interval, and our ultimate objective is to predict long term variation in bed levels, it is reasonable to select quasi-unsteady flow method for both water and sediment equations because in unsteady flow the computational increment time step used for sediment simulation should be very small which take long time and it creates very unstable model for higher values.

4.5.2 Duration of simulation

The simulated period is eight years from 1/10/2000 to 1/10/2008 i.e. 72000 hrs.

4.5.3 Boundary conditions for water flow

At inlet, daily inflow data for entire duration of simulation is imposed while at the outlet, reservoir level is applied as the boundary condition.

4.5.4 Distance between sections *(Δx)*

The data obtained from the Survey section related to 67 river cross-sections, named as range lines by the survey section. The range lines are at varying distances apart along the river axis with average, maximum and minimum values being 1190 m, 2200 m and 688 m respectively. The recommended value for the initial spacing between section is 20 times the channel width (Huang and Greimann 2011). The channel width is variable and depends upon the discharge; at a discharge of 1473 Cumecs (which is such that 60 % of the time, flows exceeded that value for the 8 years of the period of simulation) the minimum top width is 112 m. Hence the spacing should not exceed 112×20=2240 m. It is, therefore valid to calculate between the original range lines as the maximum spacing is less than the recommended value. The initial simulation is, hence, carried out based on 67 range lines as obtained from the authorities without additional sections being generated (Δx_{max}=2200 m).

4.5.5 Variation of roughness along the channel width

HEC-RAS allows to vary roughness values along the channel width to represent the floodplains, levees etc. In our case we know that the river flows in an incised channel. The channel slope and bed gradation before the dam construction indicate that it is a gravel-bed river (Drisko 1962). The roughness variation along the width is hence not taken into account for initial computation.

4.5.6 Sediment boundary condition

Sediment entering a reach at an upstream boundary must be specified for each size fraction. In our case, total sediment load entering the upstream section is imposed on daily basis for the entire duration of the simulation.

4.5.7 Sediment bed material

The percentage of each sediment size fraction present in the initial river bed is required for each river reach. The information is given at specific locations or selected cross sections and interpolated to the rest of the river. The data supplied by the Survey section is sampled at few range lines and classified into ‘clay’, ‘silt’ and ‘sand’ fractions.

4.5.8 Sediment transport parameters

The Exner 5 method is a bed zone of different thickness of layer that is proportional to the geometric mean of the largest size class. The constant of proportionality is input by the user. The thickness of the active layer can control the rate at which the bed armors. The active layer methodology assumes that all sediment particles of a given size class inside the active layer are equally exposed to the flow.

4.5.9 Cohesive sediment parameters

The deposition pattern is influenced mainly by bed shear stress, near-bed turbulence, settling velocity, type of sediment, depth of flow, and sediment concentration (Mehta and Partheniads 1973). When the bed shear stress is less than the critical shear stress for full deposition $\tau_{d,full}$, only then, will the flocs deposit on the bed.

- Since flood flows are the events during which the cross-sections undergo maximum change and it affects the whole cross section, therefore, the flow is allowed to deposit and erode from the entire section.
- The data relating to sediments forming the channel bed is obtained from the Dam Authorities. The data reports percentages of 'clay', 'silt' and 'sand' in the soil samples collected from the river bed. As per verbal communication with the Authorities, the sand is fine sand hence maximum particle size did not exceed 1 mm. However, the photographs of the Indus river upstream of the dam show a fair quantity of coarse material on the banks (Ahmed and Sanchez, 2011). The average composition of the deposits determined from samples collected from Tarbela reservoir is 28% of sand, 55% of silt and 17% of clay (TAMS and Wallingford 1998).
- The model also requires the fractions of different sediment sizes carried by the flow, as input data. The same is obtained from the Dam authorities and only relates to suspended flow, since bed load measurement in a mountain river is a challenging task, the same have not been carried out so far in Indus river upstream of Tarbela (Faran and Boer, 2003).
- Active layer thickness determines the bed material that can be sorted during the simulation. As its thickness increases, bed armoring is slowed down, while a decrease in its thickness leads to rapid armoring. It is related to the dune height in a sand bed streams and to the size of the largest particle in a gravel bed stream. The coefficient that is multiplied by the largest particle size to get the active layer thickness is an important calibration parameter (Huang and Greimann, 2010) used a value of 10 for the active layer thickness based on previous experience.
- The deposition of fine sediments in the reservoir is mainly dependent upon the value of bed shear stress, τ, vis a vis critical shear stress for full deposition, $\tau_{d,full}$

and critical shear for partial deposition, $\tau_{d,p}$. (Krone, 1962) carried out experiments to determine $\tau_{d,full}$. He found that $\tau_{d,full}$ =0.06 Pa when concentration, c < 300 mg/l; $\tau_{d,full}$=0.078 Pa when 300 mg/lit< c < 10000 mg/lit. Other researchers have estimated the value of $\tau_{d,full}$ to be in the range 0.06 Pa to 1.1 Pa depending upon sediment type and concentration(Krone, 1962) and (Mehta and Partheniads, 1973). From the flume experiments of (Krishnappan and Stephens, 1996) the critical shear stress for deposition in case of Athabasca river is 0.1 Pa. The variation of critical shear stress for full deposition for various sediment and flow types is not well understood and it is the key model parameter for determining the sedimentation rates (Ziegler and Nisbet, 1995).

- The erosion of cohesive sediments is also modeled by HEC-RAS. (El-Kadi and Jodeau, 2009) simulated the cohesive sediment accumulation in Grangent reservoir Loire river, France. He divided the reservoir into three zones based on cohesive sediments content. The values of critical shear stress for surface erosion and surface erosion constant used by him are as shown in Table 4.2.

Table 4.2: Values of critical shear stress used by El-Kadi and Jodeau 2009

Description	**Mud & sand (70% sand)**	**Mud (10% sand)**	**Mud (no sand)**
τ_{ce} (Pa)	3.5	1.5	0.85
M (kg/m^2-hr)	54	36	1.44

The fall velocity can be specified either by user input or by using two datasets of cohesive material provided by the model. The dry density of clay is another input required by the model; a value of 641 kg/m^3 was input based upon recommended value for a reservoir with significant level variations (Carvalho et al., 2000).

4.5.10 Simulations performed

Series of simulations were performed in order, first to calibrate the model and then run it to gauge the influence of different parameters. The parameters kept constant through all the simulations are as under:

- Upstream boundary condition for discharge: Inflow hydrograph on daily basis at upstream end from Bisham Qila gauging station.
- Upstream boundary condition for sediments: Suspended sediment data from WAPDA on daily basis.
- River-reservoir geometry based on 67 transects collected during October 2000 reservoir sedimentation survey. This formed our initial bed geometry.
- No structures and bridges are simulated.
- No lateral flows, or tributaries are simulated.

4.6 CALIBRATION OF ROUGHNESS COEFFICIENT

Velocity and discharge is inversely related to roughness of the channel. Sinuosity and slope have significant influences for the evaluation of channel discharge. Owing to the viscosity, the flow in a channel consumes more energy. Manning's equation to estimate the velocity and discharge in an open channel was used, which leads to selection of most appropriate value of Manning's "n".

Accurate determination of roughness coefficient must precede sediment simulations. For calibrating Manning's 'n', model is run only for water flow with given inflow and downstream boundary conditions. Due to absence of any intermediate gauging station in the reach, water stage data are not available to calibrate for *n*. Ideally one should select appropriate roughness coefficient for each channel reach as a function of discharge Q, however, a distributed variation of Manning *n* requires extensive field data. Manning value is primarily dependent on vegetation and discharge (Duan, Acharya et al., 2008). At low flows, the effect of vegetation is preponderant and roughness varies from 0.1-0.6; at medium flows (Q>21000 cfs) roughness varies in range of 0.02-0.05, while at flows exceeding 35000 cfs, the Manning roughness is around 0.022-0.03. In the absence of such data, assigning varying roughness values to different sections would tend to be arbitrary and hence is not adopted. The practice adopted is selecting a constant roughness value for the entire reach.

Model was run for different manning's values that are from 0.02 to 0.05 with the interval of .005.The results for calibration at year 2003 were shown in Figure 4.5. The simulated bed profile for manning's value of 0.03 was close to the actual bed configuration. Further statistical analysis were performed to check the accuracy of precision which were shown in Table 4.3.

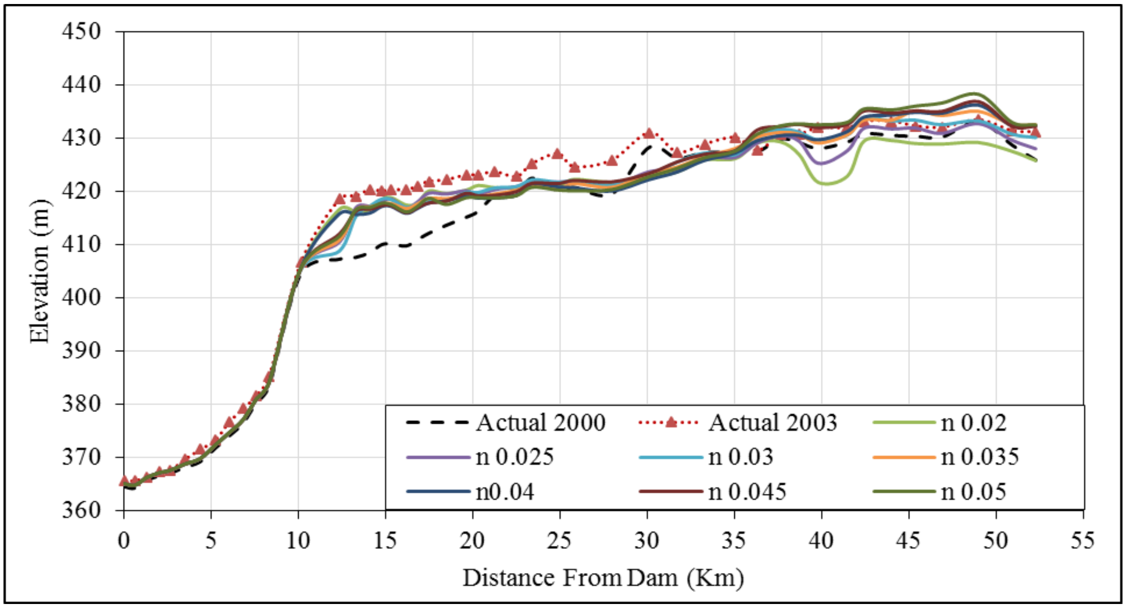

Figure 4.5: Calibration of Manning's "n" from year 2000-2003

Furthermore, the model was run for different manning's values that start from 0.02 to 0.05 with the interval of .005 for validation of the model at year 2008. Figure 4.6 shows the bed profiles for different manning's values for the year of 2008. The simulated bed profile for manning's value of 0.03 was similar to the actual bed configuration. Furthermore statistical analysis were performed to judge the best suitable value which were shown in Table 4.3.

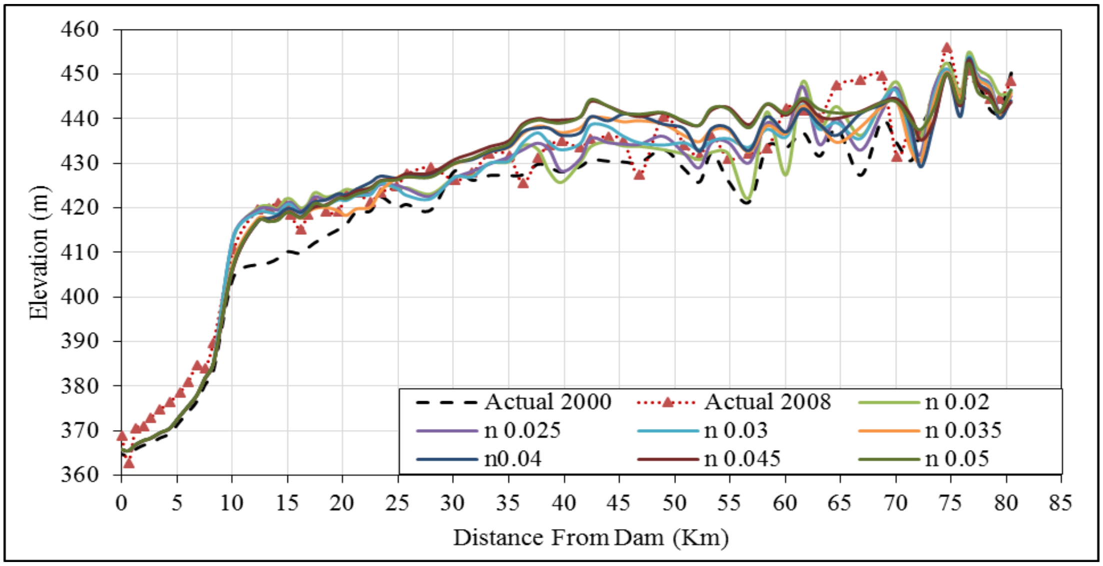

Figure 4.6: Validation of Manning's "n" from year 2000-2008

Model was calibrated for the most ideal transport function which could simulate the delta advancement rate closer to the actual movement. Figure 4.7 shows the bed profiles for different transport functions for the year of 2003. Ackers and white was found to be the most ideal function that could simulate the delta movement close to the observed bed profile. All three transport functions under estimated the true location of delta pivot point but overall a good agreement was found between the observed and simulated bed profile.

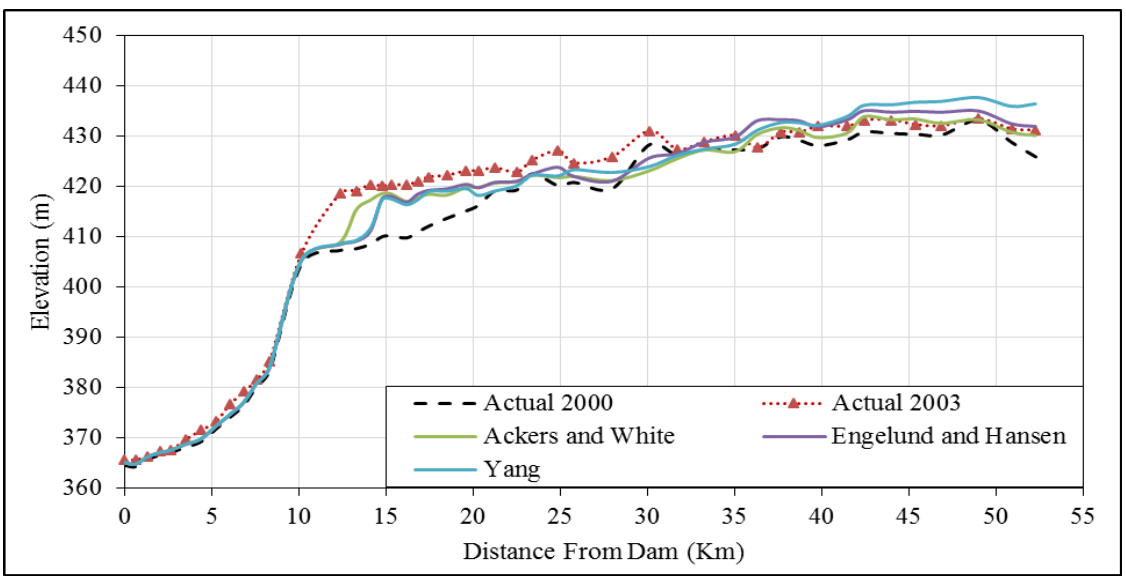

Figure 4.7: Calibration of Transport Function from year 2000-2003

Model was validated for the most ideal transport function which could simulate the delta advancement rate close to the actual movement. Figure 4.8 shows the bed profiles for different transport functions for the year of 2003. Ackers and white was found to be the most ideal function that could simulate the delta movement close to the observed bed profile. Yang function over predicted the deposition in the upstream from 35 Km onwards from the dam face as compared to other two transport functions. Engelund and Hansen function also over predicted the sediment deposition from 35 to 60 Km reach from the embankment of the dam. All three functions underestimated the deposition close the dam face, earth quake of 2005 could be the reason behind the movement of the foreset slope.

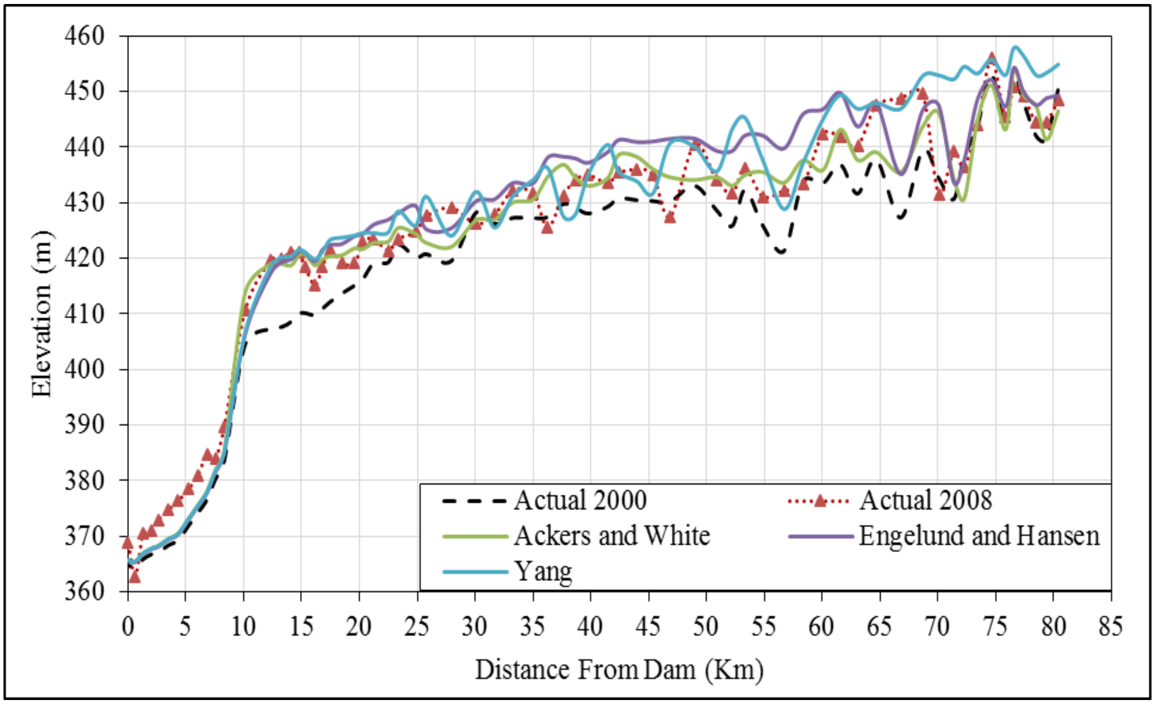

Figure 4.8: Validation of Transport Function from year 2000-2008

Three fall velocity methods were used to calibrate the model. All three methods underestimated the sediment deposition in the topset slope when compared with observed values but Van Rijn was the most suitable one. Furthermore deposition in bottomset slope was in co- relation with the observed values as shown in the Figure 4.9.

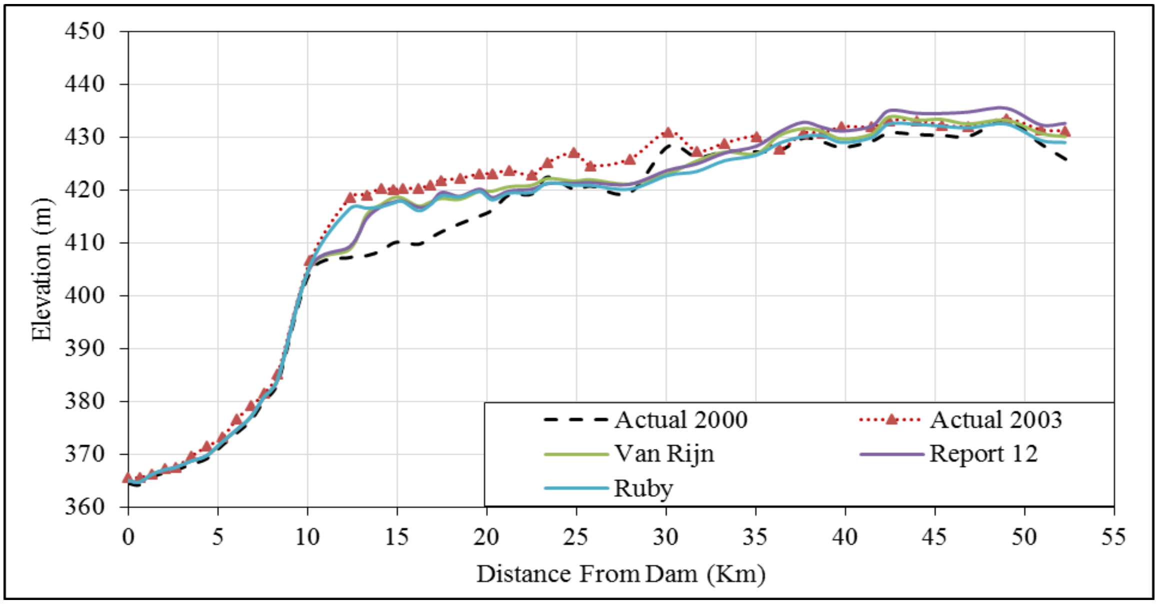

Figure 4.9: Calibration of Fall Velocity method from year 2000-2003

Three fall velocity methods were used to validate the model. In the most upstream cross sections the model for all three methods underestimated the deposition but was in correlation in topset slope close the pivot point of delta. Over all Van Rijn estimated the most suitable results. Furthermore the model estimated deposition in bottom set slope less than the observed values as shown in the Figure 4.10.

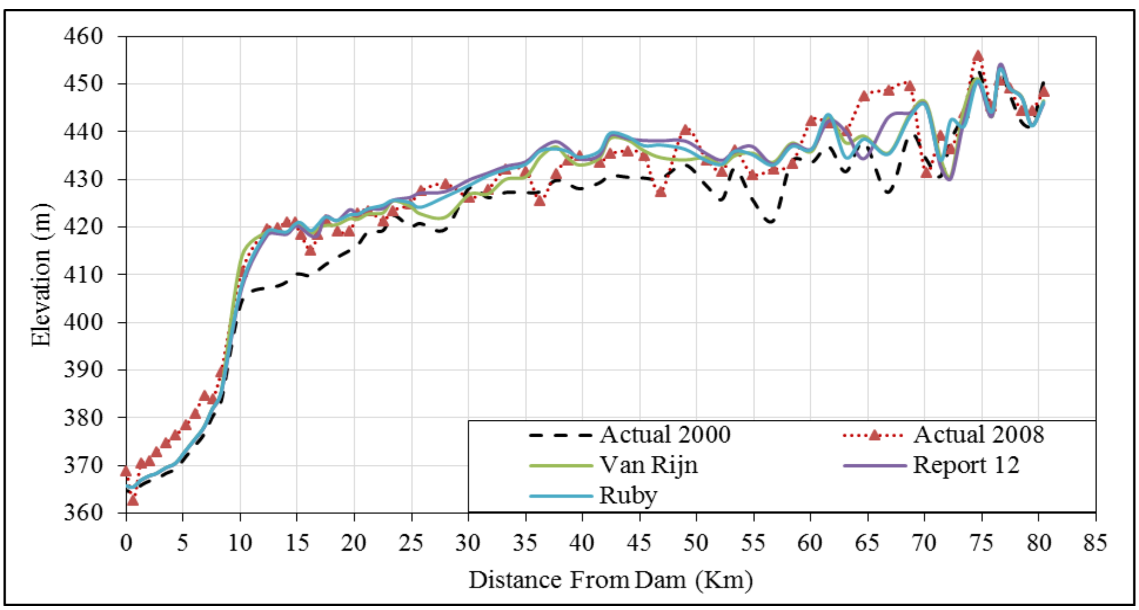

Figure 4.10: Validation of Fall Velocity method from year 2000-2008

4.7 STATISTICAL MEASURES FOR COMPARING THE SIMULATIONS

The goodness-of-fit measures employed to evaluate different simulations representing different choices of parameter are mean error, Nash-Sutcliffe coefficient, correlation coefficient, and root mean square error. These parameters were calculated as follows,

$$\text{Nash-Sutcliff Efficiency} = 1 - \frac{\sum_{i=1}^{n}(O_i - C_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O}_i)^2} \rightarrow (4.1)$$

$$\text{Root Mean Square Error} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(C_i - O_i)^2} \rightarrow (4.2)$$

$$\text{Co-Efficient of determination} = \left(\frac{n(\sum O_i C_i) - (\sum O_i)(\sum C_i)}{\sqrt{[n\sum O^2 - (\sum O)^2][n\sum C^2 - (\sum C)^2]}}\right)^2 \rightarrow (4.3)$$

Where C is the calculated value and O is the observed value at each cross section. The value with a subscript indicates a measured or simulated data while the overhead bar indicates average values.

Table 4.3: Statistical analysis for calibration of bed elevation

Calibration at 2003		Nash Sutcliffe	RMSE	R^2
Selection For Different Values of ‘n’	n 0.02	0.98	3.57	0.9916
	n 0.025	0.98	2.98	0.9916
	n 0.03	0.99	2.90	0.9918
	n 0.035	0.98	2.99	0.9903
	n0.04	0.98	3.15	0.9894
	n 0.045	0.98	3.00	0.9884
	n 0.05	0.98	3.38	0.9846
Selection For Different Fall Velocity Method	Van Rijn	0.99	2.90	0.9918
	Report 12	0.98	3.04	0.9885
	Ruby	0.99	2.92	0.9947
Selection of Sediment Transport Function	Ackers and White	0.99	2.90	0.9918
	Engelund - Hansen	0.98	3.38	0.9844
	Yang	0.98	3.82	0.9791

The statistical analysis were performed for the selection of appropriate parameters of sediment transport model. Results show that the value of 0.03 of Manning's roughness co-efficient is the most suitable one because it has minimum RMSE value and Nash Sutcliffe value which is the closest to value 1 as shown in Table 4.3. Furthermore among the three fall velocity methods, Van Rijn outperform the other two methods and the best transport function to predict the delta progression is Ackers and White as shown in the Table 4.3 and Table 4.4

Table 4.4: Statistical analysis for validation of bed elevation

Validation at 2008		Nash Sutcliffe	RMSE	R^2
Selection For Different Values Of 'n'	n 0.02	0.95	5.08	0.9599
	n 0.025	0.96	4.61	0.9668
	n 0.03	0.97	4.41	0.9698
	n 0.035	0.96	4.74	0.9660
	n0.04	0.96	4.83	0.9640
	n 0.045	0.95	5.28	0.9625
	n 0.05	0.95	5.13	0.9651
Selection For Different Fall Velocity Method	Van Rijn	0.97	4.41	0.9698
	Report 12	0.96	4.49	0.9692
	Ruby	0.96	4.52	0.9682
Selection of Sediment Transport Function	Ackers and White	0.97	4.41	0.9698
	Engelund - Hansen	0.94	5.68	0.9654
	Yang	0.93	6.33	0.9647

4.8 DISCUSSION OF RESULTS

The operation of the reservoir used to study the impact on reservoir sedimentation was prescribed by simplified reservoir water level curves. The curves have their maximum level (full supply level at 472.44 m), minimum level and their durations prescribed. Between them there is a linear decrease, which corresponds to releases of water, and increase, which corresponds to filling of the reservoir. This is a common approach used in studies that predict reservoir sedimentation (TAMS and HR Wallingford, 1998; HR Wallingford, 2011; Roca, 2012). It should be noted that the water levels are used by the model as target values. If they cannot be reached due to lack of inflow or structure outflow capacity, the model calculates the water level so that it approaches to the target level as much as possible, given the outflow capacity constraints. The duration of releasing the water from the reservoir is between day 243 (01/09) till day 75 (15/03). The duration of filling of the reservoir is from day 152 (01/06) till day 227 (15/08).

Four scenarios were considered to simulate the effect of reservoir operation on sediment deposition and progression of delta. In the first scenario, minimum reservoir level was increased 1m every year from 417m to 426m as shown in Figure 4.11.

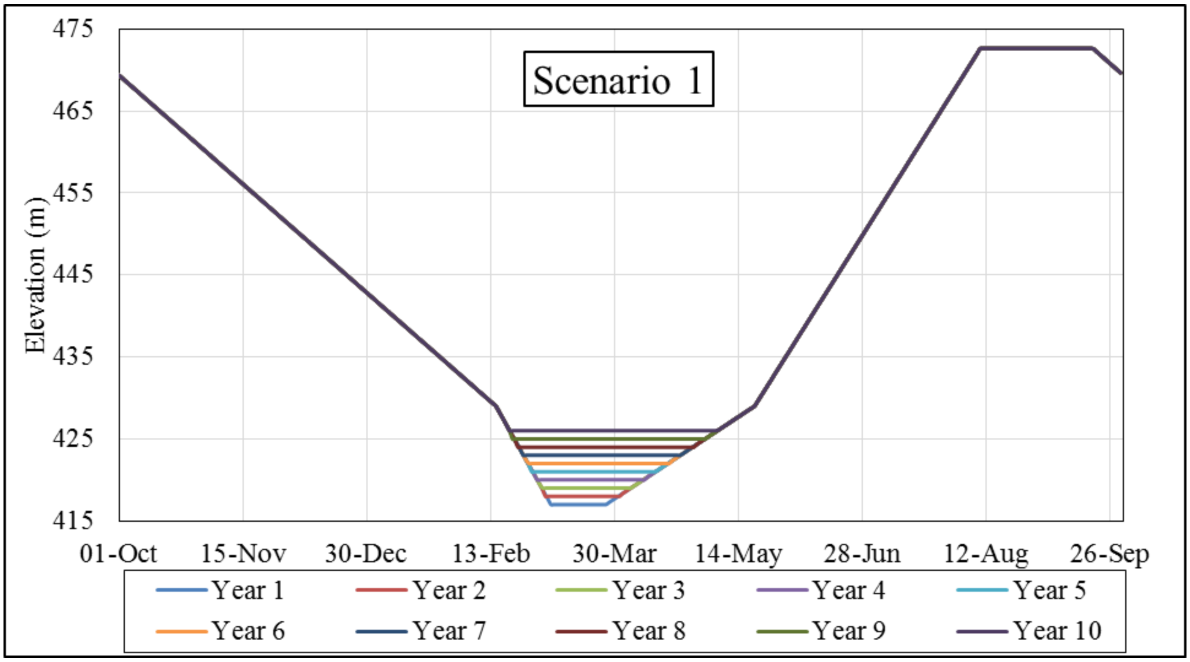

Figure 4.11: Reservoir operation curve for Scenario 1

In the second scenario, minimum reservoir level was increased 2m every year from 417m to 435m as shown in Figure 4.12.

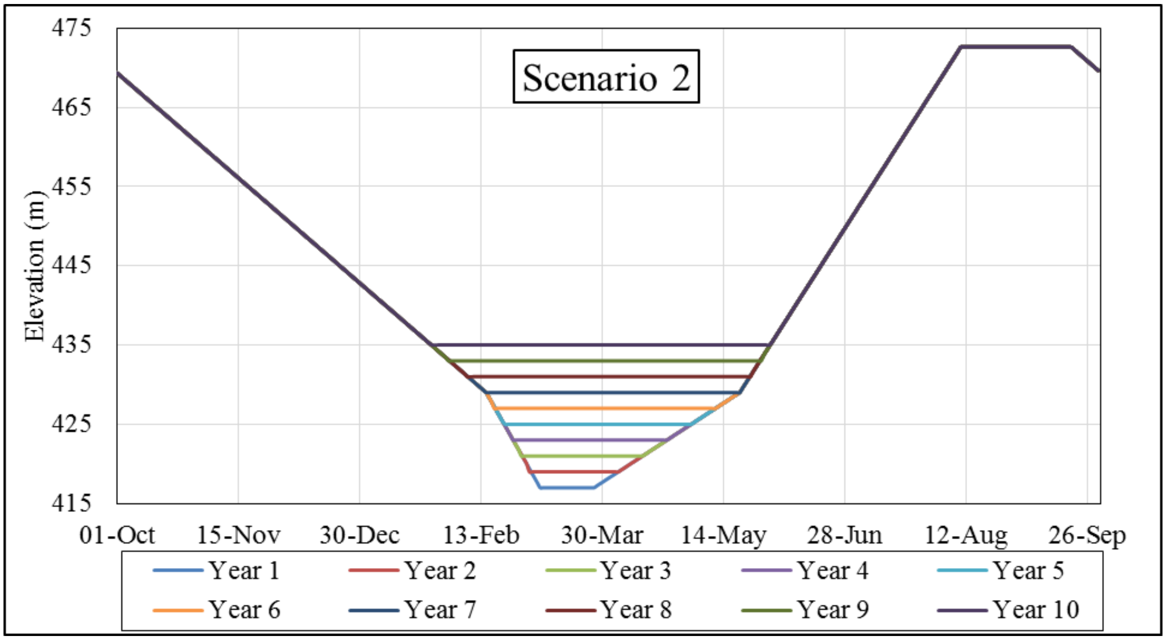

Figure 4.12: Reservoir operation curve for Scenario 2

In the third scenario, minimum reservoir level was increased 3m every year from 417m to 444 m as shown in Figure 4.13.

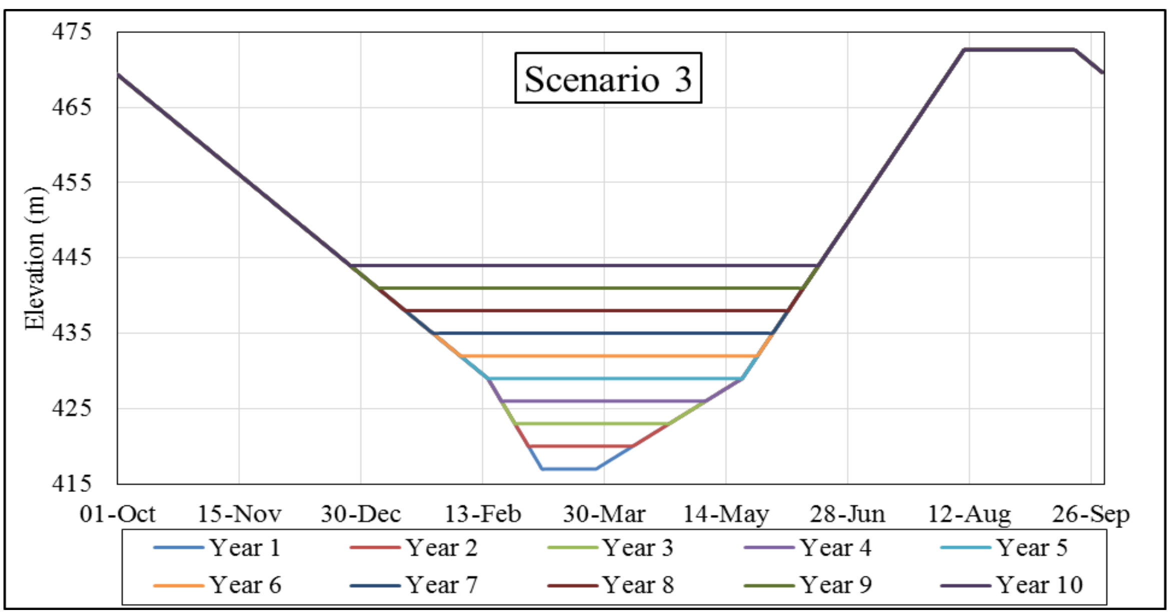

Figure 4.13: Reservoir operation curve of Scenario 3

In the final scenario, minimum reservoir level was maintained at 417m for 8 years as shown in Figure 4.14.

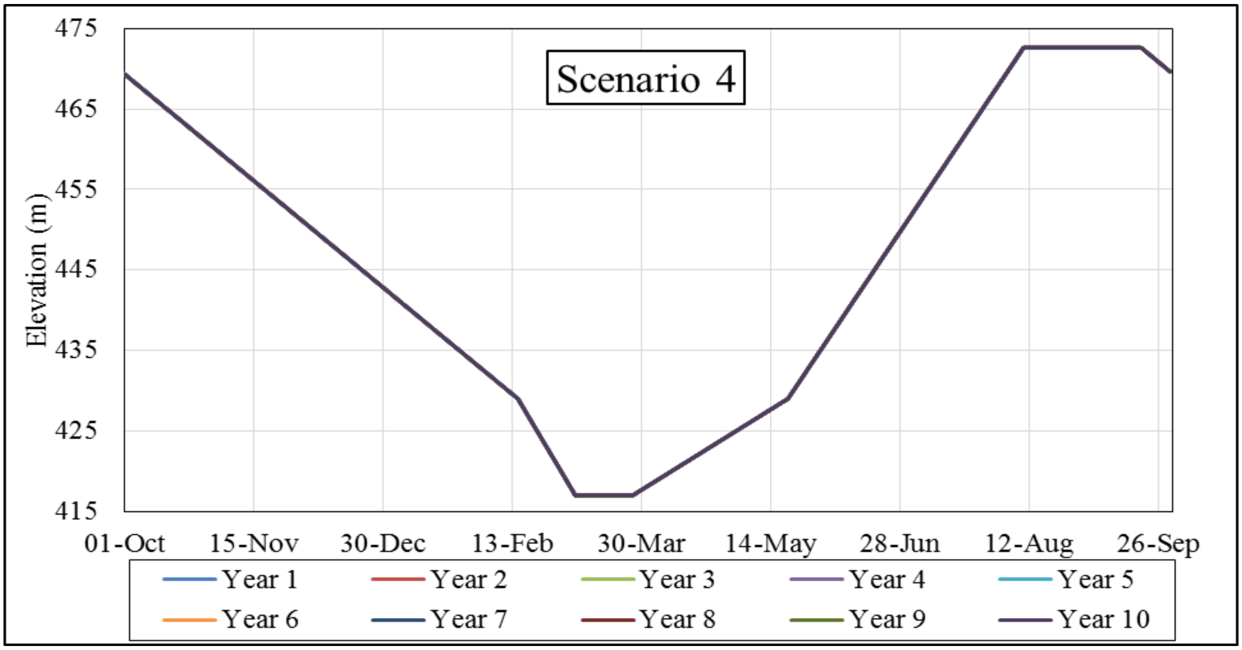

Figure 4.14: Reservoir operation curve of Scenario 4

Minimum levels and corresponding live storages are listed in the Table 4.5. The initial bed level at the dam structure is about 340 m above mean sea level.

Table 4.5: Minimum levels and corresponding live storages

Minimum Level (m)	Live Storage (BCM)
400	11.0
410	10.0
420	8.8
430	7.5
440	6.0

Finally, four simulations with the change in minimum operation level were run. For eight years, the minimum level was set at 417 m, and later it was changed to increase 1m every year in the second, 2m increase in the third and 3m increase in the fourth scenario. In practical terms, such a change may be prescribed in response to reduce the rate of approach of the sediment deposits towards the dam.

Simulation for scenario 1 was run for 8 years which showed that the rate of delta movement slowed down and sediments start depositing in the upstream reach as shown in Figure 4.15.

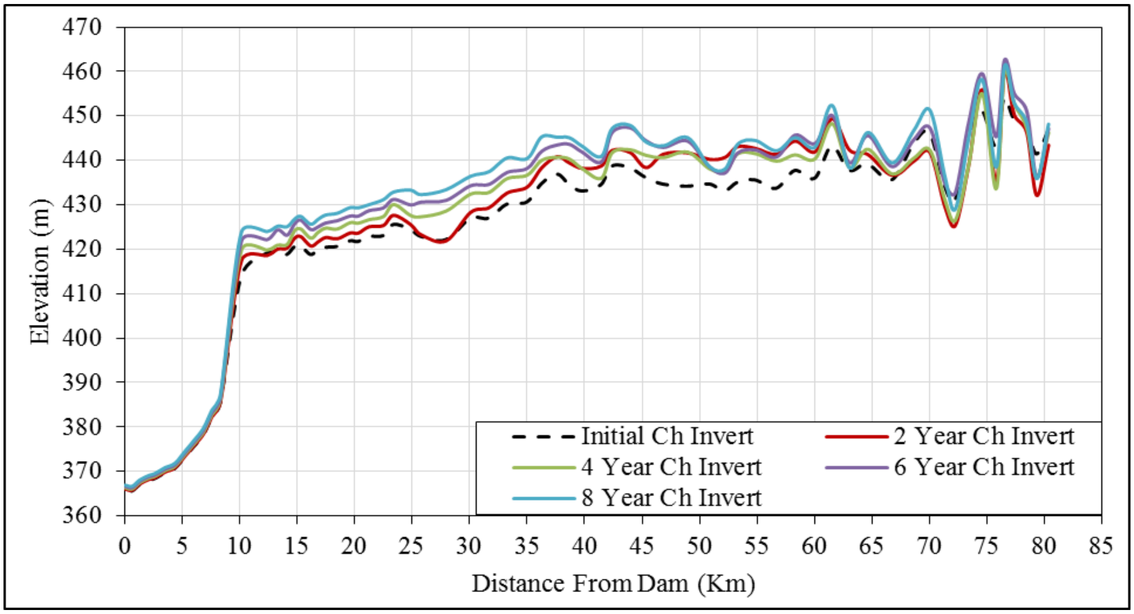

Figure 4.15: Bed profile of the deposited sediment for scenario 1

It also showed that the advancement of the delta pivot point gradually reduced after every year by increasing the lowest reservoir level by 1m and the resulted thalweg level for every second year and progression of the delta was shown in Figure 4.15. It was clearly observed that by increasing minimum reservoir level the live storage capacity decreases gradually and the dead storage remains intact. If this scenario would have not carried out then the chances of coarser sediment entering low level tunnels would have enhanced which may cause choking of the tunnels. The delta travels at a rate of 152.5 meter per year which is slower as compared to 191.25m for keeping the minimum reservoir level at 417m for eight years.

Simulation for scenario 2 was run for 8 years which showed that the rate of delta movement slowed down and sediments start depositing in the upstream reach as shown in Figure 4.16. It also showed that the advancement of the delta pivot point gradually reduced after every year by increasing the lowest reservoir level by 2m. The resulted thalweg level for every second year and progression of the delta was shown in Figure 4.16. It was clearly observed that by increasing minimum reservoir level the live storage capacity decreases gradually and the dead storage remains intact. The delta travels at a rate of 62.5 meter per year which is slower as compared to 191.25m for keeping the minimum reservoir level at 417m for eight years.

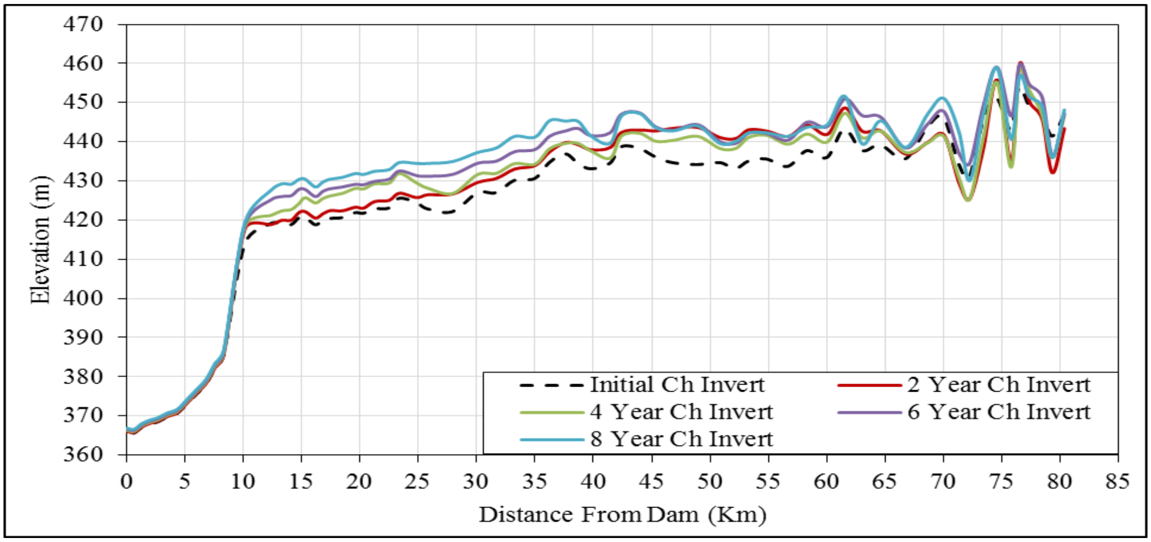

Figure 4.16: Bed profile of the deposited sediment for scenario 2

In scenario 3, the minimum reservoir level increased by 3m every year as shown in Figure 4.17. The progression of the delta reduced significantly as compared to other scenarios because by increasing the water depth, bed movement reduced directly and the sediments deposited in the most upstream part of reservoir where velocity is close to zero. Furthermore fall velocity of courser particles increases as compared to the flow velocity which aggradation.

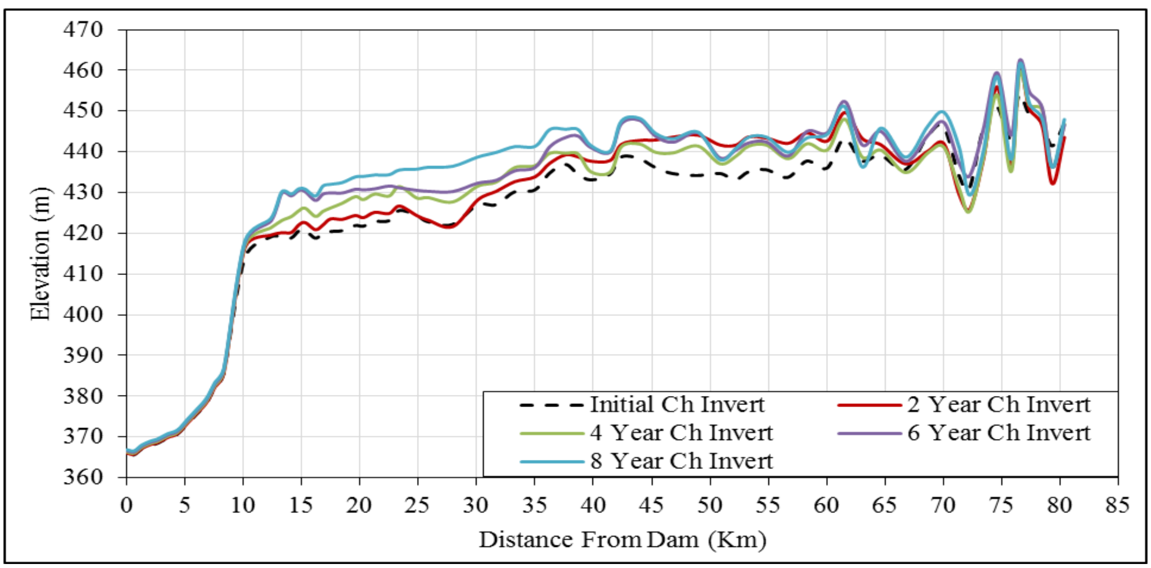

Figure 4.17: Bed profile of the deposited sediment for scenario 3

Simulations have been run for 8 years and the obtained storage capacities, bed profiles of the deposited sediment and amount of sediment outflow were saved. From bed profiles, position of the sediment delta pivot point was obtained. The position of the delta was calculated as the distance where the bed profile reaches 1 m below the minimum operation level. Figure 4.18shows profiles of the deposits after 8 years for four operation curves. Sediment deposits have advanced further in the case of the low minimum operation level, however the total amount of the deposits is higher in the case of higher minimum operation levels, due to greater thickness of the deposits layer. Table 4.6 shows the rates at which the delta advances. It can be observed that the rate of approach is faster with lower minimum levels.

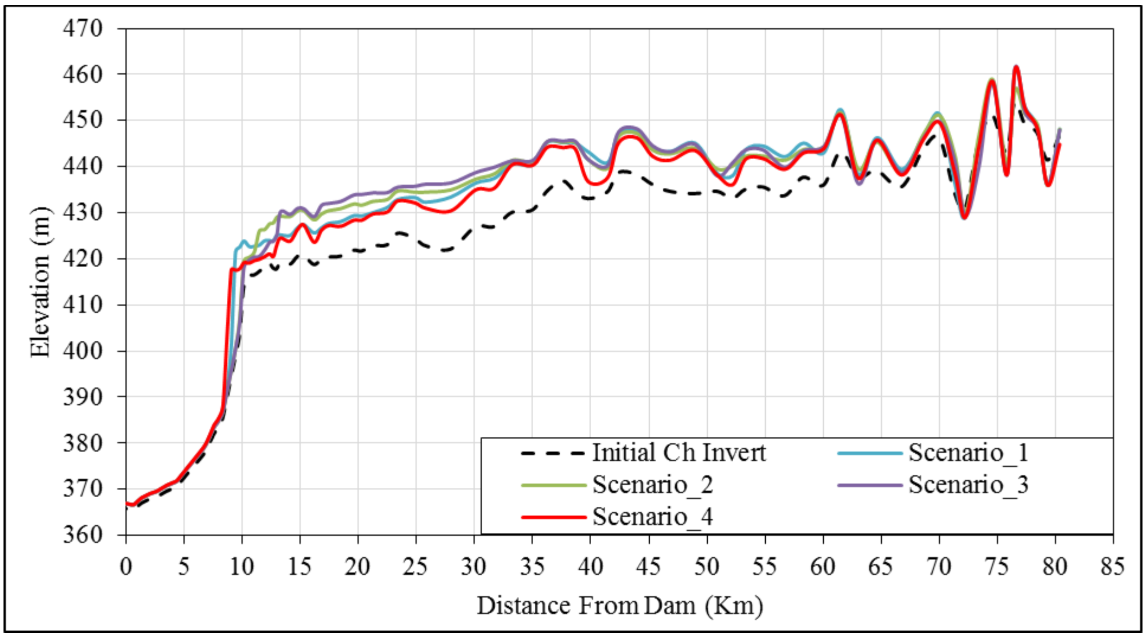

Figure 4.18: Comparison of thalweg level of the deposited sediment after 8 years for four reservoir operation curves

Table 4.6: Rates at which the delta advances

Scenarios	**Distance From Dam Face After 8 Years**	**Delta Advancement Rate Per Year**
1	9.28 Km	152.5 m
2	10.00 Km	62.5 m
3	10.045 Km	56.87 m
4	8.97 Km	191.25 m

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 GENERAL

Delta movement of Tarbela reservoir's due to sedimentation was evaluated in this research study.1D sediment transport model (HEC-RAS) was used to carry out sensitivity analysis for the calibration of model using different flow parameters. Several reservoir management scenarios were developed for sustainable reservoir management.

5.2 CONCLUSIONS

- The numerical model was applied on Tarbela reservoir for two time periods (3 & 8 years) and achieved reasonable agreement with the observed bed levels.
- For numerical simulation of Tarbela dam using HEC-RAS 5.0.3, the most appropriate value of Manning's 'n' is 0.03, sediment transport function is Ackers and White, and Van Rajin formula for fall velocity of Tarbela Reservoir.
- For eight years, the minimum level was set at 417 m, and later it was increased 1m, 2m and 3m every year in the second, third and fourth simulations, respectively. 3m increase every year predicted a significant decrease in delta movement towards the dam face.
- An increment 2 meter in minimum reservoir level every year from 417m to 435m is most suitable choice to reduce the delta advancement rate with less live storage loss of Tarbela reservoir.
- The data scarcity was main limitation to perform 2D modeling. Upstream of range line 60 no bed gradation data was available and one had to resort to extrapolation which probably, introduced errors into the results.

5.3 RECOMMENDATIONS

- For detailed study of sediment behavior, 2D numerical simulation of reservoir sedimentation at Tarbela is recommended.
- Accurate field data be obtained in order to improve and refine the existing model of the Tarbela reservoir so as to enhance its utility.
- Sediment transport modeling upstream of Tarbela reservoir can be done to evaluate the likely effects of Diamer Basha dam construction on the life of Tarbela.
- A detailed 2D simulation of reservoir stability under static and dynamic loads by including the detailed tunnel layout be performed for Tarbela Reservoir.

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