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Simulating bathymetric changes in reservoirs due to sedimentation

Application to Sakuma dam, Japan

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Abstract

Currently sedimentation is one of the major issues to deal with, for professionals, as it causes continuous loss of storage and hinder the intended purposes of a dam. More research and case-specific studies are required to understand the behavior of sediment transport mechanism in order to propose remedial measures. Sakuma dam on Tenryu River in Japan is one of the largest dams in Japan and it is rapidly losing its storage capacity due to sedimentation. The dam started its operations in 1957. To study the bathymetric changes upstream of the dam, a mathematical modeling approach was selected using HEC RAS to simulate the existing changes and predict future trends.

Before going into the detailed modeling, a literature review has been made about different sediment-related studies on the river and Sakuma dam to get deeper insight and to build a conceptual model. Then a reach of about 32 km of Tenryu River, from Hiraoka dam to Sakuma dam was modeled. Google Earth and AutoCAD were used to extract the geometrical data of Tenryu River to be used as input in HEC-RAS. Other data about flow and sedimentation were obtained from the Department of Civil Engineering, University of Tokyo. As necessary, simplifications and assumptions were also made, and sometimes data was extracted indirectly. After initial data input, it was required to do calibration and validation of the model from 1957 to 2004, when the data were available.

Once the model was validated, prediction of future bathymetric changes was also made through model simulation. For this prediction it was assumed that the existing flow data could be recycled. Predictive simulation shows that the dam would probably not serve its intended purpose after year 2035 ± 5. Therefore it is recommended to employ some suitable remedial measures to remove sediment and to prevent loss of storage in order to increase the useful age of the dam. Some prospective study options are also identified at the end.

Key words: HEC-RAS, sediment transport, bathymetric change, Sakuma dam, Tenryu River.

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Table of Contents

Abstract i

Acknowledgements: ii

List of figurers v

List of tables vi

1 Introduction 1

1.1 Background 1

1.2 Purpose of Study 2

1.3 Procedure 2

2 Sediment Transport and Reservoir Sedimentation 3

2.1 General Overview 3

2.2 Sediment Transport 4

2.2.1 Sediment Transport in Watersheds 5

2.2.2 Sediment Transport in Rivers 5

2.2.3 Sedimentation in Reservoirs 5

2.3 Controlling Reservoir Sedimentation 6

3 Modeling Reservoir Sedimentation 8

3.1 Modeling of Reservoir Sedimentation 9

3.2 Basic Procedure of Mathematical Modeling 9

3.3 Types of Numerical Models 11

4 Case Study: Sakuma Dam and Tenryu River 12

4.1 Background 12

4.2 Sakuma Dam 13

5 HEC-RAS 16

5.1 Steady flow 17

5.1.1 Water surface profiles calculations 17

5.1.2 Steady Flow Boundary Conditions 19

5.2 Sediment Transport Calculations 19

5.2.1 Sediment Transport Boundary Conditions 20

5.2.2 Transport Functions 21

5.2.3 Fall Velocity 23

6 Model Input Data 24

6.1 Geometrical Data ... 24
6.2 Flow Data ... 25
6.3 Sediments Data ... 27
6.4 Assumptions ... 29
6.5 Limitations ... 29
7 Simulation and Results ... 30
7.1 Sensitivity Analysis ... 30
7.2 Calibration ... 30
7.3 Validation ... 33
7.4 Predictive Run Based Upon Prospective Flow ... 35
7.5 Results and Discussions ... 36
7.5.1 Visual Resemblance ... 36
7.5.2 R^2 (Coefficient of Determination) ... 37
7.5.3 Percentage of (area) Difference ... 38
7.5.4 Loss of Storage ... 38
8 Conclusions ... 41
Bibliography ... 43
Appendices ... 46
Appendix – I: Tenryu River and its Cross Sections ... 46
Appendix – II: Average Yearly and Monthly Flow ... 47
Appendix – III: HEC – RAS Geometry Data (x-coordinates, elevations and lengths) ... 49
Appendix – IV HEC – RAS Interface For Sediment Input Data ... 52
Appendix – V Precipitation Data in Catchment of Tenryu River ... 54
Appendix – VI Temperature in Region Around Sakuma (^{0}C) ... 56

List of figurers

Figure 1: Reservoir sedimentation zones (Palmieri, et al., 2003) 6
Figure 2: Average monthly precipitation in Tenryu River catchment during 1957 to 2004........ 12
Figure 3: Tenryu River and its dams (Huang, 2011), study area is marked........ 13
Figure 4: Path of Tenryu River at the upstream of Sakuma dam (Shimizu, 2010)........ 14
Figure 5: Flow Time Series from Sakuma dam (1957 - 2004) 14
Figure 6: Sakuma dam and its reservoir (Tenryu-gawa Somabito no kai, 2011)........ 15
Figure 7: Main interface of HEC - RAS (Brunner & HEC, 2010)........ 16
Figure 8: Graphical representation of energy equation (Brunner, 2010) 17
Figure 9: Control Volume used in sediment calculations in HEC-RAS (Brunner, 2010) 20
Figure 10: HEC-RAS interface for cross-section data entry and its graphical representation........ 24
Figure 11: HEC-RAS window for setting quasi unsteady flow boundary conditions 25
Figure 12: Stage discharge curve used as boundary condition in quasi unsteady flow data in HEC-RAS 26
Figure 13: River bed profile and bed gradation curves at four different locations at Tenryu river in 1982 (Morris & Fan, 2008) 27
Figure 14: Comparison between Observed and HEC-RAS bed profile of 2004 after final calibration. 31
Figure 15: Grain size distribution for river bed of (a) soil type S3 and (b) soil type S4 used in the model as initial conditions in 1957. 32
Figure 16: Model generated progression of river bed profile, after calibration and validation has been finalized........ 33
Figure 17: Comparison of Observed and HEC-RAS bed profiles for years 1975, 1980 and 1989 34
Figure 18: Comparison of Observed and HEC-RAS bed profiles for years 1998, and 2003 35
Figure 19: Difference in area under model and observed bed profile of 2004 38
Figure 20: Comparison of rate of storage lost between model and observed data. The line showing model value also shows predictive loss of storage after 2004. 39
Figure 21: Selection of River stations at Tenryu River (Base map was taken from Google Earth (2012)) 46
Figure 22: HEC - RAS window for X - Section data for River station 100........ 52
Figure 23: HEC RAS graphical sketch of X – Section for River station 100 52
Figure 24 HEC - RAS window for X - Section data for River station 99........ 53
Figure 25: HEC RAS graphical sketch of X – Section for River station 99 53

List of tables

Table 1 Worldwide reservoir storage, hydropower, and sedimentation (Palmieri, et al. 2003) 4
Table 2: Sediment grain diameters (mm), user defined grain classes (Brunner & HEC, 2010) 27
Table 3: R^2 and percent difference of model bed profiles for some selected years 37
Table 4: Comparison of storage lost storage due to sedimentation... 39
Table 5: Actual average annually flow (m^3/s) (Taken from Civil Engineering Department, University of Tokyo, Japan).. 47
Table 6: Extracted monthly flow based upon precipitation (m^3/s).. 47
Table 7: Geometric data of Tenryu River 49
Table 8: Monthly Precipitation data (mm) (JMA, 2012). 54
Table 9: Average monthly temperature in region around Sakuma dam (Celsius) (JMA, 2012) 56

1 Introduction

1.1 Background

Water in streams and lakes has been a source of civilization and industrial development throughout the history. Advancement of technology has enabled us to manage and control the water resources in order to maximize the benefits gained through water. This was done by making dams, barrages, and man-made streams. However, this development also caused imbalances in different natural systems in addition to its benefits, for example eco-system imbalance and disturbance of sediment transport equilibrium. As a result, in order to regain the balance, some undesirable and previously unforeseen phenomena also happen within the system that affect the system efficiency and reduce their benefits. Sediment entrapment and bed aggradations upstream of dams are among such phenomenon.

Sediments deposited upstream a dam reduce its storage capacity hence reducing its usefulness. However, this problem can be addressed by considering the sedimentation at design stage and careful planning and management of dam operations. These efforts cannot be achieved unless a detailed case-specific sediment transport analysis and reliable future predictions are made. Sediment transport is a complex natural phenomenon, and is still not fully explored. Although many theories have been presented to explain the phenomenon, all of them satisfy sediment transport behavior only under certain conditions to a specific level of accuracy. These theories or empirical and semi-empirical expressions, however, are the only scientific and reliable foundations to analyze and study the sediment transport behavior for any particular case.

Scaled down replicas of original or proposed systems have been made to test and analyze the system behavior under certain circumstances in the laboratory. Sometimes the tests were run even for years to get optimized conditions. These replicas or prototypes are known as physical models. Physical models are used even now as well but mainly for purely research purposes. Widespread use of physical models had been gradually reduced due to their inherent limitations. Most importantly set up time, budget to maintain it, difficulty to transfer the results elsewhere, and time required to study and analyze the system are the key reasons that have made physical models unfavorable. On the other hand, theories predicting sediment behavior under certain circumstances are gradually getting matured and more reliable due to continuous research in this field. So tendency to practice analytical approaches have become more popular than using physical models for a specific case study

However, these analytical approaches are useful only to understand the sediment movement in a stream for simplified conditions. Future trends and effects of different changes require temporal changes to be involved in calculations. It is necessary to calculate the sediment behavior and predict resulting bathymetric changes and using these changed condition, e.g., cross section change etc., as input for next time period. This procedure complicates the calculation process making it almost impossible to do with analytical methods. Thus, it has led to the making of numerical models that are solved on computers. Numerical modeling codes have not only decreased the calculation time, by making use of rapidly increasing processing power, but also made it easier to test effects of different sets of input variables in an improved way.

1.2 Purpose of Study

Despite advancement of science and technology, sediment transport still remains a branch of science and engineering that is not fully explored. Numerical modeling is a common technique to study sediment transport behavior and resulting bathymetric changes. This helps in gaining an insight into the prospective behavior of sediment transport, which provides a background for policy making. Some of benefits of such studies may include estimation of possible expenditure in coming years to remove deposited sediments and approximation of the dam life to serve its intended purposes.

The purpose of study is to model the existing sediment transport behavior of Tenryu River upstream of Sakuma dam and associated sedimentation in the reservoir. Furthermore, the effects of different parameters are studied and future bathymetric changes upstream of Sakuma dam are predicted. Reliable predictions are required in order to plan effective mitigation and expected budget estimation. The sub-objectives of the study are:

i. Quantifying the sediment volume in future.
ii. Estimating the useful life of Sakuma dam.
iii. Suggesting recommendation to improve the current conditions.

1.3 Procedure

First, the literature was reviewed about sediment transport theories and other sediment-related works. Specifically, the studies concerning Tenryu River and Sakuma reservoir were reviewed to get more insight into the case study. A conceptual model was formalized before going into the mathematical modeling. For mathematical modeling, the software HEC RAS 4.1 was selected. Primary input data, which included yearly sedimentation rates, bed profiles, and yearly flow data, was obtained from Department of Civil Engineering, University of Tokyo. These average annual flow data was converted to average monthly values based upon monthly precipitation data from the catchment. Initial bed gradation was not known initially, but was extracted during the literature review from different studies.

Google Earth and AutoCAD were used to extract the geometrical data from the Tenryu River to be used as input in HEC-RAS. A reach length of about 32 km of Tenryu River, from Hiraoka dam to Sakuma dam, was modeled. As necessary, simplifications and assumptions were also made during the preparation of the input data. After initial data input, normal modeling steps including sensitivity analysis, calibration, and validation were made before starting predictive modeling. In order to forecast the sediment transport behavior and deposition in the reservoir, the recorded flow time series was recycled, since there have been negligible changes in the flow or precipitation trends.

The software MS Excel 2007, Grapher 8, Graph 4.4, and Origin Pro 8 were also used for analysis.

2 Sediment Transport and Reservoir Sedimentation

2.1 General Overview

Reservoirs are man-made structures and considered as important water bodies that are primarily used to collect, store, and save water behind dams and manage water that is essential to fulfill basic human needs and requirements. Water stored in reservoirs are essential for all forms of life and serves several different functions that mainly include drinking and industrial uses, hydropower generation, irrigation and water supply, and flood control (Palmieri, et al., 2003).

Water reservoirs in any country are considered to be the largest water harvesting projects. There are huge amounts of water collected either from precipitation, surface runoff, or snow melt from glaciers that pass through streams or rivers and are collected in the dams' reservoir. These prevent water from being wasted and it can be stored for many other useful purposes. Therefore dams have their strategic importance that is essential for the civilization of the country and the strength of its economy.

However, these man-made obstructions cause an imbalance to the natural water flow and associated systems. Sediment transport is also one of the affected systems. One of the phenomena occurring in reservoirs is the settlement of sediments carried with the water flow. This happens in the dam because the velocity of the water is extremely low in these areas. Reservoirs have been designed and operated assuming that they have a limited life as short as 100 years, after which they will finally be depleted by sediment deposition over time. The massive amounts of sediments that come along with river flow often make the useful life of a dam shorter. This is because these sediments, instead of passing through it, settle down in the dams due to reduced velocity of water near embankment (Morris & Fan, 2008).

Sediments reaching the reservoir over time can be expressed as the total amount of particulate materials (suspended or bed load) per unit time. The transport processes of these sediments are greatly influenced by several factors such as sediment type and particle size, size of drainage area, land use cover and vegetation adjacent catchment areas, climate changes pattern and temperature, flood events, and basin slope. (Morris & Fan, 2008).

Palmieri, et al. (2003) mentioned some previous studied which showed that over 40,000 dams exist in the world. The total estimated storage capacity of these reservoirs as a volume worldwide is about 7000 km^3 that is operated for different purposes. It is estimated that because of sedimentation, approximately 0.5% - 1.0% is lost annually as a storage volume of the water, in the other words the loss of storage volume is about 45 km^3 per year. Table 1 gives an overall picture of storage capacity, power generation, and sedimentation rates worldwide.

Table 1 Worldwide reservoir storage, hydropower, and sedimentation (Palmieri, et al. 2003)

Region	Number of large dams	Storage (Km^3)	Total Power (GW)	Hydropower production in 1995 (TWh/yr)	Annual loss due to sedimentation (% of residual storage)
World wide	45571	6325	675	2643	0.5-1.0
Europe	5497	1083	170	552	0.17-0.2
North America	7205	1845	140	658	0.2
South and central America	1498	1039	120	575	0.1
North Africa	280	188	4.5	14	0.08-1.5
Sub Saharan Africa	966	575	16	48	0.23
Middle East	895	224	14.5	57	1.5
Asia (excluding china)	7230	861	145	534	0.3-1.0
China	22000	510	65	205	2.3

To achieve a sustainable reservoir use, it is necessary to manage both incoming water and sediments. Tarbela reservoir in Pakistan, a mega-storage reservoir that was built in 1974 to store 14.34 km^3 (Haq & Abbas, 2007), is experiencing a sediment inflow of 0.132 km^3 per year. This has resulted in a reduction of its storage capacity of about 28 %. The delta which is currently at 16 km from the dam embankment is advancing at about 1 Km per year (Haq & Abbas, 2007). The dam is expected to end its useful life in just 80 years after construction, if no proper attention will be given to the problem. Significance of sediment management is also apparent in the example of the Camaré reservoir in Venezuela, where all storage was lost in just 15 years of its operations (Morris & Fan, 2008). The only difference between these and any other reservoir is the lack of sediment management practices.

2.2 Sediment Transport

Sediment transport process can be defined as general expression used for the transfer of materials of different particle sizes in rivers, streams, and channels such as silt, clay, sand and gravel. The transported materials by flow as suspension or bed materials is called total sediment load which is the whole volume of transported sediments. When the particles are rolling along the bed it is called bed load, whereas suspended load denotes when the particles are maintained in suspension by turbulence (Chanson & James, 1998). This suspended load tends to interact with the bed load at lower velocities and even settles down at extremely low velocities, especially in storage areas. However some particles have grain size so small, that even the lowest velocities are much greater than their fall velocities. These particles are almost in a permanent suspended state and are called wash load. Wash loads are carried away along with the water in the reservoirs and transported to the downstream.

In order to determine the long-term sediment yield, it is important to have average annual sediment load measurements. For this purpose many methods can be used and the most accurate one is to measure the deposition volume of sediments in the reservoir directly. Also, direct measurements of river flow together with suspended and bed load concentrations may be carried out. However, if long-term measurements are not available for the site of interest, then short-term measurements are possible to perform and empirical relationships can be developed. Furthermore, correlation with nearby watersheds having the same drainage characteristics is possible (Randle, et al., 2008).

Sediment transport is a notoriously complex process. Several forces together play their role and result in the movements of sediment particles through the flow. These forces could be drag and lift forces that depend on turbulence forces of flow, frictional forces caused by collision, which is not easy to measure, and gravitational forces (Zhang, 2011).

2.2.1 Sediment Transport in Watersheds

The sediment load carried along with rivers is often an indication of topsoil erosion in the associated catchment area. The outcome of different environmental factors and human activities results in loosening of the soil surface and then its transport to the stream. Due to this reason the concept of "Watershed management" has evolved and it is based upon the principle to reduce or control the sediment transport from the source. Activities such as deforestation, construction works, and agriculture cause increased sediment transport compared to what would naturally happen.

Many authors, including Bowonder et al. (1985), have pointed out that it is the land use policy and lack of knowledge about soil conservation measures and its value that have increased the surface erosion. The eroded soil is then transported along with any surface runoff, mainly due to precipitation, and becomes a part of the sediment load in rivers. A portion of it is deposited on the river bed, flood plains, and in reservoirs, whereas the remaining amount is transported to the oceans. Topsoil erosion is not only responsible for depleting the storage capacity of reservoirs, but it also affects the land arability. Soil degradation as a result of erosion is considered as one of the top ten stresses our planet is facing (Earth Leadership, 2006).

2.2.2 Sediment Transport in Rivers

Rivers are considered as a part of the hydrological cycle and natural water courses that can transport water with sediments towards a lake, sea, dam reservoir, or towards another river. Generally, water is following through the river and this water is collected from precipitation through a drainage basin from surface runoff, springs, or from ground water, if surrounding areas of the river are fully saturated and hereby feeding the river with water. However, all rivers transport sediments in addition to water over long periods of time, either as suspended load, bed load, or wash load that finally reaches the outlet of the basin (Morris & Fan, 2008).

2.2.3 Sedimentation in Reservoirs

Sediment transport within the rivers and its accumulation in reservoirs has become an important issue that often must be considered. When the water is flowing into the dam reservoir, it carries some amounts of sediments embedded within turbid inflow into the reservoir. These sediments will deposit along the bed in the dam reservoir as the water velocity is reduced. The longitudinal accumulation of sediments in a reservoir may be separated into three main zones depending on sediment characteristics, namely the zone of coarse sediments, delta, and fine sediments (Morris & Fan, 2008), as conceptually illustrated in the Figure 1.

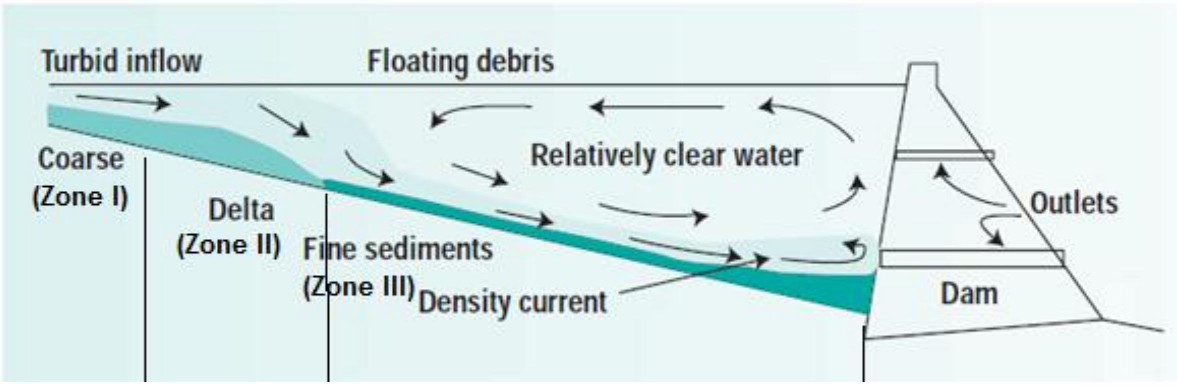


Figure 1: Reservoir sedimentation zones (Palmieri, et al., 2003)

There are three major processes affecting the sediments transported to a reservoir regarding the deposition (Palmieri, et al., 2003):

1- The large particles of the sediment load (coarse materials) deposit and accumulate as bed load along the topset delta which is formed at the upstream end of the reservoir.
2- Transport of fines in turbid density currents deposit at a distance closer to the dam embankment.
3- Transport of fines as non-stratified flow.

The longitudinal deposition along the bed profile and the settling patterns differ from one reservoir to another. This is because it is affected by many factors such as geometrical shape of the reservoir, discharge conditions, flood events, size of sediment particles of the inflowing load, and operating conditions of the reservoir (Morris & Fan, 2008).

2.3 Controlling Reservoir Sedimentation

Reservoir sedimentation control can only be achieved by adopting an integrated approach covering interconnected efforts from the watershed scale to the actual place of the problem. This encompasses study of processes individually and their effect on other processes, which are involved from top soil erosion in the watershed to deposition of sediments in the reservoir. Currently the sediment management practices revolve around three basic principles (Sangroula, 2007), which are:

i. Reduction of sediment inflow to rivers and reservoirs
ii. Removal of already accumulated sediments
iii. Sediment bypassing, that is, to let sediments pass through the reservoirs without being accumulated in reservoirs

Due to its dependence upon many parameters, complexities involved in data collection, and the scale of study involved, this area of science is still not fully covered. However, based upon the present knowledge about sediment transport, the following can be useful for controlling sedimentation in reservoirs (Morris & Fan, 2008):

1. Soil conservation should be an integral part of all land use policies at the watershed scale.

2. Vegetation cover should be increased in the associated watershed and activities like deforestation should be discouraged.
3. Sedimentation studies including prospective forecasts should be made using proper modeling techniques before construction of reservoir or dam.
4. Selection of dam location and its design should include consideration of sedimentation and sediment flushing.
5. Different scenarios of dam operations should be modeled and the resulting effects on sedimentation should be analyzed. Furthermore, actual policy regarding dam operations should be formulated considering such investigations.

3 Modeling Reservoir Sedimentation

Although modeling has evolved as a fundamental scientific and engineering problem-solving methodology, different disciplines express their definitions and types. However, in its simplest form, modeling is the reproduction of reality in a controlled environment made to understand the effects of many different variables on a phenomenon or object. This is normally done for new research or for policy making by using the forecasting ability of models. Much of the discussion here will be in sediment transport modeling context. A model can be physical or mathematical. Example of a physical model is a scaled-down replica of an object or structure, for example a dam or river system using an appropriate scale (Morris & Fan, 2008).

Mathematical models use mathematical expressions to solve real world problems. Mathematical techniques can be further subdivided into analytical modeling and numerical modeling. Analytical modeling involves solving a set of simplified mathematical equations (ABPmer, 2008) that relate sediment flow to other parameters and variables of system in question. These mathematical expressions may be based upon laws of physics, derived empirically by laboratory or theoretical studies or a combination of both. However, when the system is too complex for analytical solution, a numerical modeling approach is used to analyze the problem. This type of mathematical modeling involves the numerical solution of complex differential equations. It helps to study the combined effects of different theories on the system and it is almost impossible to do this without the aid of computing power and special computer codes or software (Yip & Rubia, 2009).

Mathematical modeling has also been continuously evolving for simulation and prediction of sediment transport and reservoir sedimentation. Sediment deposition cause bathymetric changes upstream in a reservoir. Knowledge of these bathymetric changes and their pattern constitutes an important part for sedimentation studies. Such studies are required in order to develop measures for reducing sedimentations, hence increasing the life of a dam. To predict the changes in the bed profile upstream of a dam caused by the sediments being deposited into the reservoir, physical or computer models can be developed. Several modeling programs and software have been developed for this purpose (Morris & Fan, 2008) including the most famous HEC-RAS and HEC-6 developed by U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, CCHE 1D and CCHE 2D developed by National Center for Computational Hydroscience and Engineering, and SRH 1D developed by U.S. Bureau of Reclamation.

3.1 Modeling of Reservoir Sedimentation

To learn the effects of different external factors and their temporal and spatial variability, physical and mathematical modeling is extensively used in reservoir sedimentation studies. Modeling results provide essential feedback to finalize the design and operational practices for sediment management of reservoirs. Morris & Fan (2008) divided the purpose of modeling for sediments behavior in four categories:

i. Estimation of sediment yield from the catchment area
ii. Rate of sediment influx and its deposition pattern
iii. Scouring and deposition of sediment nearby hydraulic structures
iv. Effect of dam on scoring and deposition pattern downstream of the dam

While mathematical modeling is considered to be the most cost and time efficient approach, the importance of physical models for sedimentation studies cannot be denied. Such models are still used to describe complex forces and their effects on the different sediment transport modes in a reservoir. For example, a physical model with a horizontal scale of 1 to 200 and a vertical scale of 1 to 100 was constructed to reproduce the Gezhouba dam Project of Yangtze River in China. Modeling studies involved the simultaneous study of bed load, suspended load, and density currents for various ranges of grain sizes (Morris & Fan, 2008).

3.2 Basic Procedure of Mathematical Modeling

A numerical modeling approach was selected for studying sediment transport behavior of Sakuma dam in this thesis. Thus, in the following some of the basic elements of the mathematical modeling process, as discussed by many, for example Morris & Fan (2008) and Papanicolaou, et al. (2008), are reviewed. However these elements should be taken in context of numerical modeling of sediment transport instead of generalizing them for all modeling types, although this can be done to some extent.

i. Problem Identification

This implies any question related to a case study, which is posed by a research team, an administration body, or by policy makers. Modeling work begins after problem identification, and when the problem cannot be solved by other means.

ii. Conceptual Model

After problem identification a conceptual model is formed to define the analytical approach to solve the problem. Conceptual modeling mean to conceive the problem from an engineering point of view or in simple visualization of the river or reservoir conditions mentioned in the problem, and defining steps required to control the solution. A good conceptual model leads to reliable modeling results. It also involves studying historical record of floods, information about river geometry, cross section, geology, and hydrology. The modeling team may have to carry out site visits for data collection and in order to better visualize the water body.

iii. Data Collection

Required data as identified in the conceptual modeling process should be gathered by hydrological records, old studies, or by field visits and surveys.

iv. Defining model purpose, scope, selection and methodology

On the basis of available data and the conceptual model scope, the purpose of the modeling activity is defined. This step helps in choosing the most appropriate modeling program. There are various modeling codes that are available to choose from regarding problems related to sediment transport. However, this requires having extensive knowledge and experience about the capabilities and limitations of each program (Papanicolaou, et al., 2008). There are many 1D, 2D and 3D modeling codes for sediment transport available and used in engineering modeling community with varying input data requirements, output capabilities, ease of use, limitations etc.

v. Assumptions and Data Derivation

Ideally every data has to be available before start of the modeling, but normally that is not the case because of time or budget constraints. Then, for simplicity or because of deriving new data from available data sets, assumptions have to be made.

vi. Sensitivity Analysis

When the data about historical events has been fully incorporated, the model sensitivity should be investigated by changing different parameters such as channel roughness, grain size, transport and coefficients, one by one keeping other parameter values the same. Record of the results for every change is kept for comparisons later. This helps the user to know what parameters or set of parameters the model is most sensitive towards. In other words, for some parameters a small change in input value will bring a large difference in the output results, implying pronounced model sensitivity to these parameters. This information will help in later modeling activities.

vii. Calibration

The model is now run using historical data to simulate known events and check for deviation from the known data. No model will produce 100 % agreement with actual results due to assumptions in data or limitations of the model. However, in order to proceed further a reasonable match between observed data and model results has to be achieved. Now using information acquired through sensitivity analysis, by changing selected parameter values, model training or calibration is performed. This is a repetitive process and many model runs have to be made for a reasonable match between model results and actual data.

viii. Validation

Validation is another process following model calibration in which the model is being run for another period with known values that were not previously used in the calibration process. This is a method to test if the model results for future events can be used with confidence or not. If the model run gives almost the same agreement as for the calibration, it implies that it can be further used to forecast future events with confidence as well. However, if the results deviate too much from the observed values, then there may be a need to improve the calibration.

ix. Predictive Modeling and Problem Analysis

After gaining reasonable confidence in the model results, the model is run to predict future events. This can be done by running model for future prediction of flows, the river behavior for some extreme flow events etc., as required by the problem analysis and conceived in the conceptual modeling stage. Furthermore, it is also essential to interpret the model results and relate them to the reliability of the model. Useful recommendations also have to be made based upon the model results within the scope of the conceptual modeling (Morris & Fan, 2008).

3.3 Types of Numerical Models

In the past three decades considerable development of numerical modeling related to hydrodynamics and sediment transport has been made. This is largely due advancement of computer hardware, software enhancements, ease of use of such models, and the possibility to check system behavior under different scenarios very quickly. These benefits cannot be gained through physical modeling as this requires heavy time and cost investment. Model results are typically difficult to transfer to the prototype and to other conditions not explicitly studied in the laboratory.

Available numerical models for sediment transport can be divided according to their range of application, such as for suspended load, bed load, or physical-chemical transport. The models can also be classified according to their formulation in space, for example 1D, 2D, or 3D models. The 1D models were the first group of models that were developed in the 70's or early 80's, and they were used mainly for research purposes. With the newer versions of such models the maturity of these models was enhanced so that they are considered to be useful even today. The 1D model usually solve differential conservation equations of mass and momentum for the water, along with sediment transport mass continuity equations using finite difference methods (Papanicolaou, et al., 2008). Normally, the models employ rectilinear coordinate system; however, some of them also use curvilinear systems (Papanicolaou, et al., 2008).

The 2D models are depth-averaged and solve Navier-Stokes equations, with sediment transport models having capabilities to describe both bed load and suspended load (Johnson & Schwarz, 2008). By depth-averaged it means that these models assume the velocity of water and the concentration of sediment to be uniform through the water column. So these models do not take into account secondary flow effects (Fang, et al., 2006). Thus, at times the 2D models do not fully describe the physics, for example the flow and sediment deposition near piers or in the vicinity of hydraulic structures, where one may be has to use 3D models (Papanicolaou, et al., 2008). The 3D models also solve the Navier-Stokes equation using numerical approaches such as the finite element, finite difference or finite volume method (Papanicolaou, et al., 2008).

In spite of the development of 2D and 3D models, these are still considered relatively less mature compared to the 1D models and are typically not used until they are judged to be essentially required.

4 Case Study: Sakuma Dam and Tenryu River

4.1 Background

Japan is an island nation of East Asia, surrounded by North Pacific Ocean and Sea of Japan. It has four main Islands Hokkaidō, Honshū, Shikoku, and Kyūshū, whereas there are more than 3000 small islands with a combined area of 377,727 km^2. Due to its stretch from north to south, the weather in Japan varies from subtropical in the south to temperate in the north (Central Intelligence Agency , 2012). The annual precipitation in Japan is 1718mm (MLIT Japan, 2008), which is almost double the 1050 mm (Pidwirny, 2006) global average precipitation. This large amount of precipitation is unevenly spread over the year. It fluctuates heavily in different months and in different days. The rainy season is June to July (see Figure 2), while there is relatively reduced rainfall occurring in other months.

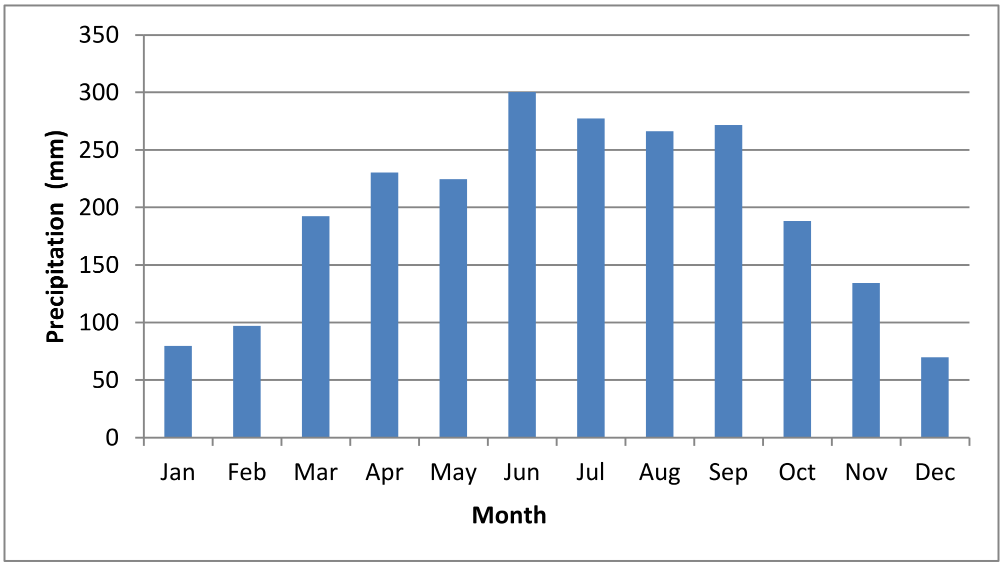


Figure 2: Average monthly precipitation in Tenryu River catchment during 1957 to 2004

Due to this large monthly fluctuation, water availability in natural streams is not the same throughout the year. This issue has mainly been addressed by constructing dams all over the country on different streams at suitable locations. Along with dams or barrages constructed for agriculture or domestic use, they also serve one or more purposes like hydroelectric power generation, water regulation downstream, fisheries, and recreation. There are more than 15 major rivers in Japan, which have catchment areas more than 2000 km^2 or lengths more than 100 km (MLIT Japan, 2007).

Tenryu river (or Tenryu-Gawa *in Japanese*) is among the major rivers, with a total main stream channel length of 213 km and a catchment area of 5090 Km^2 (MLIT Japan, 2007). The catchment is

Figure 3: Tenryu River and its dams (Huang, 2011), study area is marked

located where the Median Tectonic Line is passing (Sato & Liu, 2008). It originates from Lake Suwa and flows toward south of Japan, and ultimately falls into the Pacific Ocean at Enshu coast (see Figure 3). This is at the west of Shizuoka Prefecture, where the delta of Tenryu River is formed. Tenryu River has good hydroelectric potential as its high volume of flow and high slopes can set it apart. Most of its flow path lies in the hilly areas, where it passes through a valley between two hills (see Figures 4 and 6). The annual average discharge is $112m^3/s$ as from the records of river flow between 1939-92 (MLIT Japan, 2007). Due to sloping terrain and frail geologic composition of catchment area, the sediment discharge of the Tenryu River is considered to be one of Japan's highest, being approximately 38×10^6 m^3/yr (Sato & Liu, 2008). There are five major dams along the main river, namely Yasuoka dam, Hiraoka dam; Sakuma dam, Akiha dam and Funagira dam (see Figure 3). The largest one is Sakuma dam (Huang, 2011), which was the 10th biggest dam in Japan at the time of its construction in 1956.

4.2 Sakuma Dam

Sakuma dam was built on Tenryu River and is located in Toyone city of Kitashitara District on the border of Aichi Prefecture. The construction of the dam started in 1953 and finished in 1956 and the dam began to operate in 1957. The length and height of embankment are 293.5 m and 155.5 m, respectively (Japan Commission on Large Dams, 2009). It is a concrete gravity dam and located in the mountainous area where Tenryu River flows into a valley. The location of Sakuma dam is about 70 km upstream of the river mouth. The upstream dam on the Tenryu River is Hiraoka Dam. The total length of the Tenryu river reach between Hiraoka and Sakuma dam is about 32 km.

Figure 4: Path of Tenryu River at the upstream of Sakuma dam (Shimizu, 2010)

Because Sakuma dam lies in a hilly area it does not have a well-developed lake as normally can be seen in other dams. Therefore, it stores water along the length of the river. The effect of the storage can sometimes felt even just downstream of Hiraoka dam. The average annual flow typically varies from 79 m^3/s to 171 m^3/s (see Figure 5).

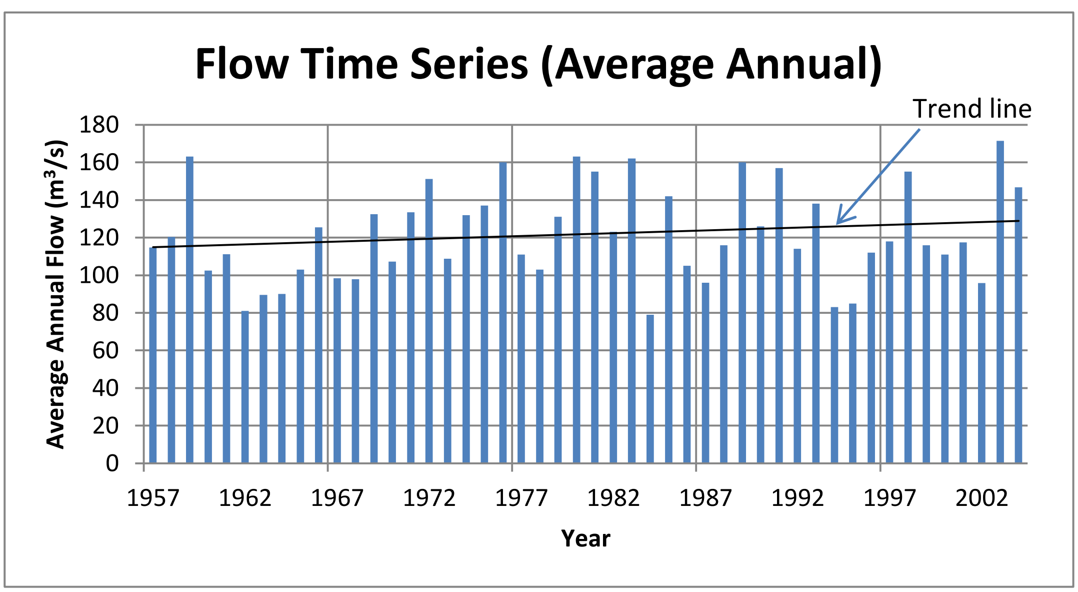


Figure 5: Flow Time Series from Sakuma dam (1957 - 2004)

The dam was constructed in order to exploit the hydropower generation capacity of Tenryu River. However, since 1957, when it started operating, it has continuously faced the problem of sediment retention, which has resulted in reduction of storage capacity. In average 2 x 10^6 m^3 of sediments are retained yearly. This huge amount of sediment retention is not only risking the dam's useful life, but is also creating problems downstream of dam. The water which leaves Sakuma dam has lesser sediment concentration and is much capable of eroding the river bed downstream to balance its energy. The river bed at the downstream end has been degraded 1m – 1.5 m (Sato & Liu, 2008) and the sedimentation in upstream dams has also become the cause of coastal erosion.

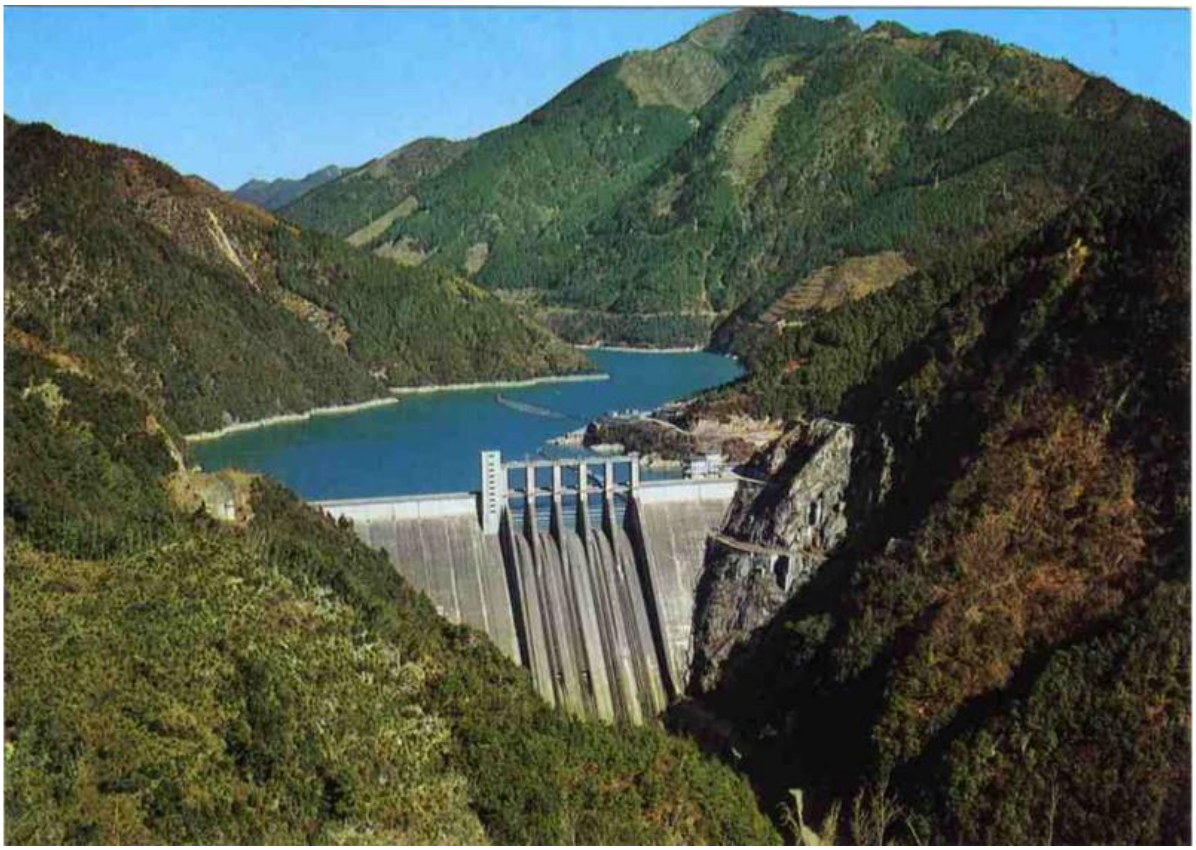


Figure 6: Sakuma dam and its reservoir (Tenryu-gawa Somabito no kai, 2011)

5 HEC-RAS

Hydrologic **E**ngineering **C**entre-**R**iver **A**nalysis **S**ystem (HEC-RAS) is one-dimensional software, which is designed to perform steady flow water surface profile computations through natural rivers and full networks of natural and engineered channels, unsteady flow simulations, and movable boundary sediment transport computations. Furthermore, HEC-RAS is also capable to perform water quality analysis. A key element is that all three components will use a common geometric data representation and hydraulic computation routines (Brunner & HEC, 2010).

HEC-RAS was first released in 1995 and since that time there have been several major versions of HEC-RAS of which 4.1 is the latest version released in 2010. In this project, version 4.1 of HEC-RAS was used. The development of the program (HEC-RAS) was done at the Hydrologic Engineering Center (HEC), which is a part of the Institute for Water Resources (IWR), U.S. Army Corps of Engineers. Figure 7 shows the main window of HEC-RAS.

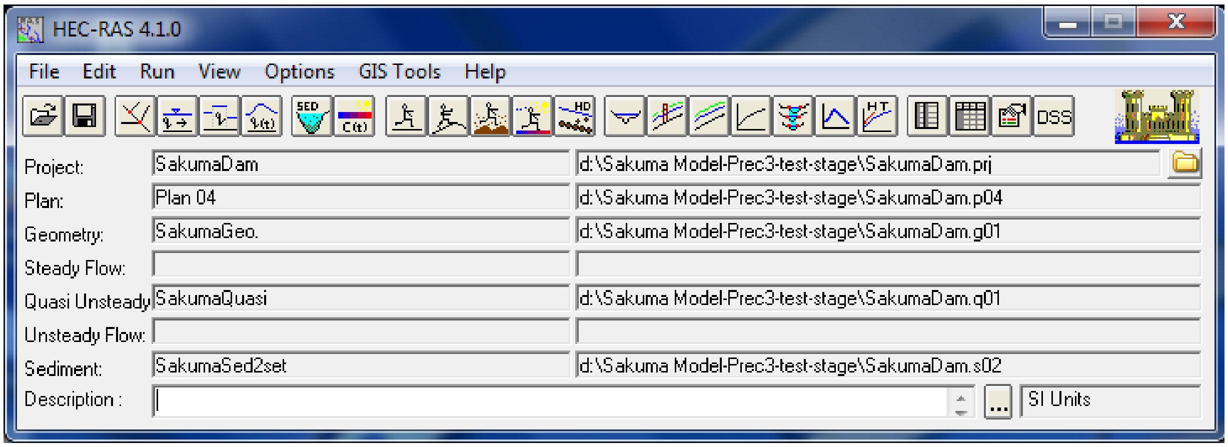


Figure 7: Main interface of HEC - RAS (Brunner & HEC, 2010)

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

For making such calculations, HEC-RAS requires boundary conditions for each type of data. These boundary conditions are important to determine the mathematical solutions to the problems. Boundary conditions are required to obtain the solution to the set of differential equations describing the problem over the domain of interest. In HEC-RAS, there are several boundary conditions available for steady flow and sediments analysis computations. Boundary conditions can be either external specified at the ends of the network system (upstream or downstream) or internal used for connections to junctions.

5.1 Steady flow

5.1.1 Water surface profiles calculations

The background for the computational methods and the equations used for modeling components in steady flow, unsteady flow, and sediment transport can be found in HEC-RAS Hydraulic Reference Manual and User's Manual, which are published by the US Army Corps of Engineers (Brunner, 2010), (Brunner & HEC, 2010).

One-dimensional steady flow and water surface profiles computations are based on solving of one-dimensional energy equation and the continuity equation. In HEC-RAS, water surface profiles are computed from one cross section to the next according to the energy equation and its components are illustrated in the figure 8. The method used for calculating water surface profiles, and other hydraulic parameters such as water velocity, hydraulic depth, hydraulic roughness, energy slope, and width at each cross section is called the standard step method.

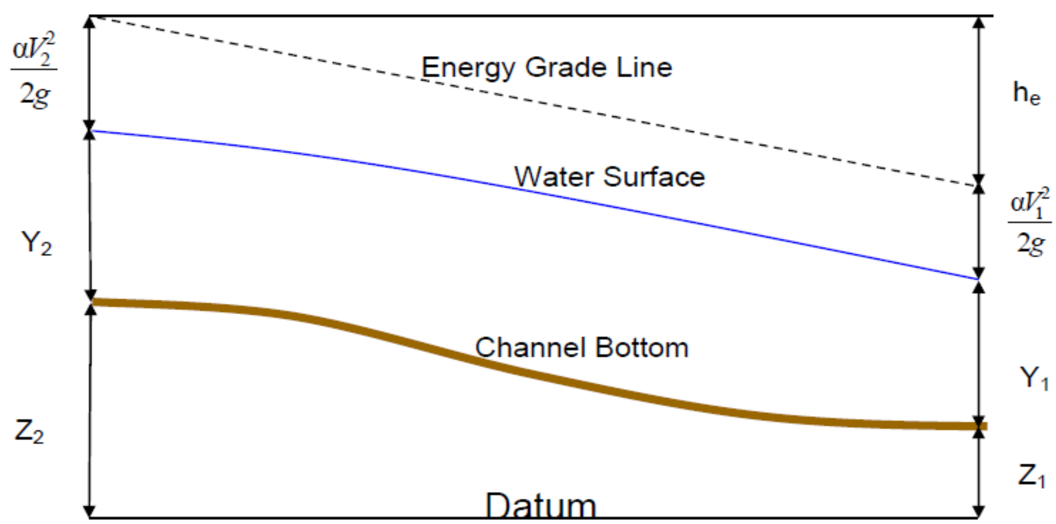


Figure 8: Graphical representation of energy equation (Brunner, 2010)

If water surface profiles are rapidly varied, then the energy equation is not considered to be applicable anymore. In such situations momentum equation is going to be used for calculating water surface profiles and other hydraulic parameters. The energy equation can be written as follows (Brunner, 2010).

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} + h_e \qquad 5.1$$

Where:

Y_1, Y_2 = water depths at cross sections one and two respectively [L].

Z_1, Z_2 = elevations of the channel inverts at cross sections one and two respectively [L].

V_1, V_2 = average water velocities at cross sections one and two respectively [L/T].

a_1, a_2 = velocities correction coefficients at cross sections one and two respectively.

h_e = energy head loss [L].

g = gravitational acceleration [L/T^2].

The energy head losses (h_e) can be calculated from the following formula:

$$h_e = L\overline{S_f} + C\left|\frac{a_2 V_2^2}{2g} - \frac{a_1 V_1^2}{2g}\right| \quad 5.2$$

Where:

L = distance weighted reach length [L].

$\overline{S_f}$ = friction slope between two sequence cross sections.

C = contraction or expansion loss coefficient.

And the distance weighted reach length L is calculated from the following equation:

$$L = \frac{L_{lob}\bar{Q}_{lob} + L_{ch}\bar{Q}_{ch} + L_{rob}\bar{Q}_{rob}}{\bar{Q}_{lob} + \bar{Q}_{ch} + \bar{Q}_{rob}} \quad 5.3$$

Where:

L_{lob}, L_{ch}, L_{rob} = cross section reach lengths specified for flow in the left overbank, main channel and right overbank respectively [L].

$\bar{Q}_{lob} + \bar{Q}_{ch} + \bar{Q}_{rob}$ = arithmetic average of flows between cross sections for left overbank, main channel, and right overbank respectively [L^3/T].

The friction slope $\overline{S_f}$ is calculated according to the formula as follows:

$$\overline{S_f} = \left[\frac{Q_1 + Q_2}{K_1 + K_2}\right]^2 \quad 5.4$$

Where:

Q_1, Q_2 = discharge at two sequence cross sections [L^3/T].

K_1, K_2 = conveyance for the cross sections calculated from the following equation

$$K = \frac{1}{n} A R^{2/3} \quad 5.5$$

Where:

n = Manning's coefficient roughness.

A = flow area [L^2].

R = hydraulic radius determined from the following relationship [L].

$$R = \frac{A}{P}$$

Where

P = wetted perimeter [L].

5.1.2 Steady Flow Boundary Conditions

In steady flow, setting boundary conditions are important in order for the program to establish the water surface conditions and start the calculations. Flow regimes in rivers could be one of the following:

- Subcritical flow regime
- Supercritical flow regime
- Mixed flow regime

If subcritical flow regime is assumed then boundary conditions are required only at the downstream ends of the system, whereas if supercritical flow regime is assumed then boundary conditions are required only at the upstream ends. Mixed flow regime implies that both upstream and downstream boundary conditions are required. The following are the available boundary conditions in HEC-RAS for steady flow:

- Known water surface
- Critical depth
- Normal depth
- Rating curve

5.2 Sediment Transport Calculations

The background to the computational methods and equations used for modeling sediment transport can be found in HEC-RAS Hydraulic Reference Manual and User's Manual, published by the US Army Corps of Engineers. A brief summary of different calculation methods is mentioned below.

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

Generally, sediment transport through rivers, streams and channels occurs through two modes which depend on parameters such as particle size, water velocity, and bed slope. The two modes are known as bed load and suspended load. The basic principle of evaluating sediment transport capacity within HEC-RAS is by computing sediment capacity associated with each cross section as a control volume and for all grain sizes in that particular case, as can be seen in the figure 9.

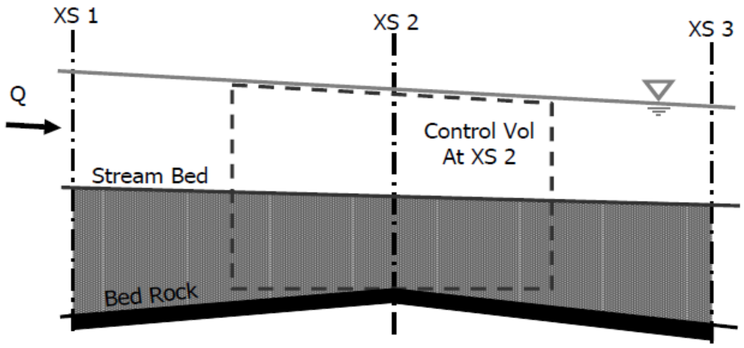


Figure 9: Control Volume used in sediment calculations in HEC-RAS (Brunner, 2010)

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

$$(1-\lambda_p)B\frac{\partial \eta}{\partial t} = -\frac{\partial Q_s}{\partial x} \qquad 5.6$$

Where:

λ_p= porosity of active layer

B= width of channel [L].

η= channel elevation [L].

Q_s= transported sediment load [L^3/T].

x= distance [L].

t= time [T]

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

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

5.2.1 Sediment Transport Boundary Conditions

Sediment transport analysis starts with creating quasi-unsteady flow file. Flow series as a boundary condition is required for the most upstream end of the river system. For the downstream end, one of the following boundary conditions can be used:

- Normal depth
- Stage time series
- Rating curve

For sediment transport, the following boundary conditions are available:

- Rating curve
- Sediment load time series
- Equilibrium load

5.2.2 Transport Functions

In HEC-RAS, several sediment transport functions are available:

1) Ackers-White:

Ackers-White is a total load sediment transport function developed for non-cohesive soils of grain size range of 0.04mm to 7mm. The application of this function is also not valid for sediment transport under upper phase of bed configuration, e.g., anti-dunes with Froude number greater than 0.8. This transport function has been developed assuming that the transport of fine sediments are more related to turbulent variations in the water. However, the transport of coarse sediments is associated to net grain shear with mean velocity (Brunner, 2010).

2) Englund-Hansen

Englund-Hansen's transport function estimates total load of sandy rivers which have significant amount of suspended load. Although it was developed using flume data of bed soil with grain size from 0.19mm to 0.93mm, it has successfully been applied to field data with results consistent to flume data (Brunner, 2010).

3) Laursen

Laursen is total load function for prediction of sediment transport. It is making use of the hydraulic characteristics of the mean channel, depth of flow, fall velocity of sediment grains etc. to calculate the total sediment load of a stream. Its range of applicability is between grain sizes from 0.011mm to 29mm (Brunner, 2010).

4) Meyer-Peter-Müller

The Meyer-Peter-Muller (MPM) formula is one of the earliest developed sediment transport functions to determine the sediment load of a running stream. It was developed for larger sediment particles ranging from 0.4mm to 29mm, with a specific gravity of 1.24 to 4.0 (Brunner, 2010).

5) Toffaleti

The sediment transport function by Toffaleti considers that a stream is carrying sediment load in four vertical different zones, upper zone (see eq. 5.9), middle zone (see eq. 5.8), lower zone (see eq. 5.7) and bed zone (see eq. 5.10). It then calculates the sediment load in each zone and adds them to obtain the total load. Although the method was developed using flume data for sediment with a diameter from 0.3 to 0.93mm, it was successfully applied to sediment particles of size 0.095mm (Brunner, 2010).

Calibration of the model to Sakuma dam and its upstream river reach was finalized using the Toffaleti transport function with appropriate transport parameters. The Toffaleti formula is considered to be most suitable for large rivers since it was developed using data sets from suspended load systems.

A general form of the Toffaleti function for a single grain size can be represented by:

$$g_{ssL} = M\frac{\left(\frac{R}{11.24}\right)^{1+n_v-0.756z} - (2d_m)^{1+n_v-0.756z}}{1+n_v-0.756z} \qquad \textit{Sediment load in lower zone} \qquad 5.7$$

$$g_{ssM} = M\frac{\left(\frac{R}{11.24}\right)^{0.244z}\left[\left(\frac{R}{2.5}\right)^{1+n_v-z} - \left(\frac{R}{11.24}\right)^{1+n_v-z}\right]}{1+n_v-z} \qquad \textit{Sediment load in middle zone} \qquad 5.8$$

$$g_{ssU} = M\frac{\left(\frac{R}{11.24}\right)^{0.244z}\left(\frac{R}{2.5}\right)^{0.5z}\left[R^{1+n_v-1.5z} - \left(\frac{R}{2.5}\right)^{1+n_v-1.5z}\right]}{1+n_v-1.5z} \qquad \textit{Sediment load in upper zone} \qquad 5.9$$

$$g_{sb} = M(2d_m)^{1+n_v-0.756z} \qquad \textit{Sediment load in bed zone} \qquad 5.10$$

$$M = 43.2C_L(1+n_v)VR^{0.756z-n_v} \qquad 5.11$$

$$g_s = g_{ssL} + g_{ssM} + g_{ssU} + g_{sb} \qquad 5.12$$

Where

g_{ssL} = Suspended sediment transport in lower zone (tons/day/ft)

g_{ssM} = Suspended sediment transport in middle zone (tons/day/ft)

g_{ssU} = Suspended sediment transport in upper zone (tons/day/ft)

g_{sb} = Bed load sediment transport (tons/day/ft)

M = Sediment concentration parameter

C_L = Sediment concentration in lower zone

R = Hydraulic radius (ft)

d_m = Mean particle diameter (ft)

z = Exponent describing the relationship between the sediment and hydraulic characteristics

n_V = Temperature exponent

6) Yang

The sediment transport function developed by Yang is also a total load function for sand and gravel. It relates sediment load to the stream power, velocity, and shear stress. This function is very sensitive to fall velocity and the stream power, compared to most other functions. The range of applicability of this function is for grain sizes from 0.062 to 7mm (Brunner, 2010).

5.2.3 Fall Velocity

Fall velocity is one of the important parameters that influences the sediment transport within the water flow and consequently affects the particles deposition on the river bed. If the fall velocity is reduced then the sediment tends to be in suspension mode longer in the moving water. Settling velocity depends on many factors such as sediment particle size, flow, viscosity, and shape factor. In HEC-RAS there are four available methods to calculate the fall velocity:

i. Ruby (default method in HEC-RAS)
ii. Toffaleti
iii. Van Rijn
iv. Report 12 (default method in HEC-6)

In the present application, after the calibration and validation processes had been carried out, it was found that the Van Rijn method was best suited for use in the model. The Van Rijn method consists of three formulas depending on the grain size:

$$\omega = \frac{(S-1).gd)}{18\nu} \qquad 0.001 < d < 0.1mm \qquad 5.13$$

$$\omega = \frac{10\nu}{d}[\left(\frac{1+0.01(S-1)^{0.5}}{\nu^2}\right) - 1] \qquad 0.1 < d < 1mm \qquad 5.14$$

$$\omega = 1.1[(S-1)gd]^{0.5} \qquad d \geq 1mm \qquad 5.15$$

Where: ω = Fall velocity of sediment grains [L/T].

ν = Kinematic viscosity [M/(L·T)].

S = Specific gravity of sediment particles.

d = Particle diameter [L].

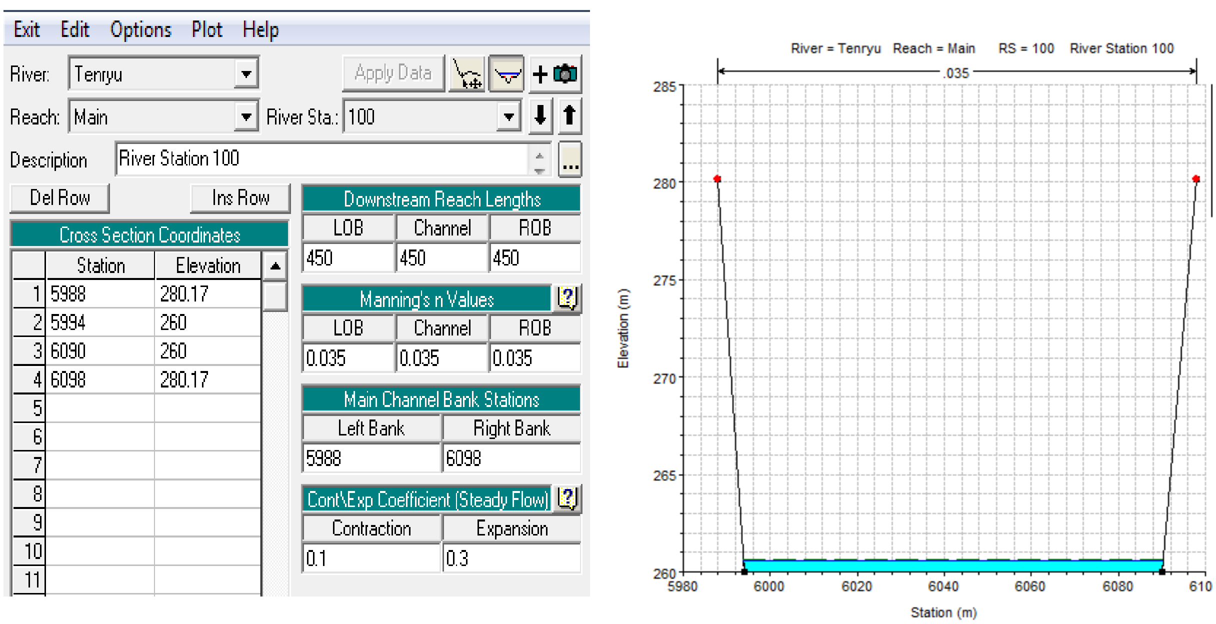
6 Model Input Data

In order to calculate the sediment transport by the flow into the reservoir, three input data files are needed:

i. Geometric data
ii. Quasi-unsteady flow data
iii. Sediment data

6.1 Geometrical Data

Geometric data in HEC-RAS consists of linking the river cross sections along the whole reach to create the schematic river system. The modeled portion of Tenryu River consisted of a 32 km long reach between Hiraoka dam to Sakuma dam that was divided into 48 river stations (see Appendix I) . River station (RS) 100 was the most upstream cross section and RS 53 was the most downstream one located just before the dam embankment. The average distance between the river stations is about 670 m. The data mainly include stations and elevations for each cross section. Furthermore, some other data are required such as downstream reach lengths for left over bank (LOB), main channel, and right over bank (ROB). Also Manning's values for LOB, channel, and ROB, as well as contraction and extraction coefficients are input data required to create the geometric data file. Figure 10 shows input data for cross section 100. The input data for all other river stations through all the reach lengths can be found in Appendix III.



(a) Data entry for river station cross section (b) Graphical representation of cross section data

Figure 10: HEC-RAS interface for cross-section data entry and its graphical representation

Since it was difficult to get the detailed geometric data to use in the model, Google Earth was employed to obtain the river width and downstream lengths at different cross sections along the reach. Then AutoCAD was used to draw the river schematic at appropriate scale.

During the modeling, some assumptions and simplifications for the geometrical shapes for all cross sections at river stations have been made, implying that a trapezoidal geometric shape was considered appropriate for all cross sections (see Figure 10b).

6.2 Flow Data

The sediment transport simulations are dependent on the quasi-unsteady hydraulics data. In this study, evaluation of sediments transported into Sakuma reservoir is required from 1957 to 2004. Average annual flow data was available, and these flow values are converted into average monthly values for all years (1957-2004) based on precipitations measurements in the catchment. For this, it was assumed that, as the catchment of Tenryu River is a hilly area, the response time of rainfall would be very quick compared to the time scale of the flow model. Therefore monthly precipitation can be directly related to the flow in Tenryu River. So average annual flow values were converted to monthly average flow based upon monthly to annual precipitation ratio for respective year. Appendix II shows the required data that have to be considered in the quasi-unsteady flow modeling.

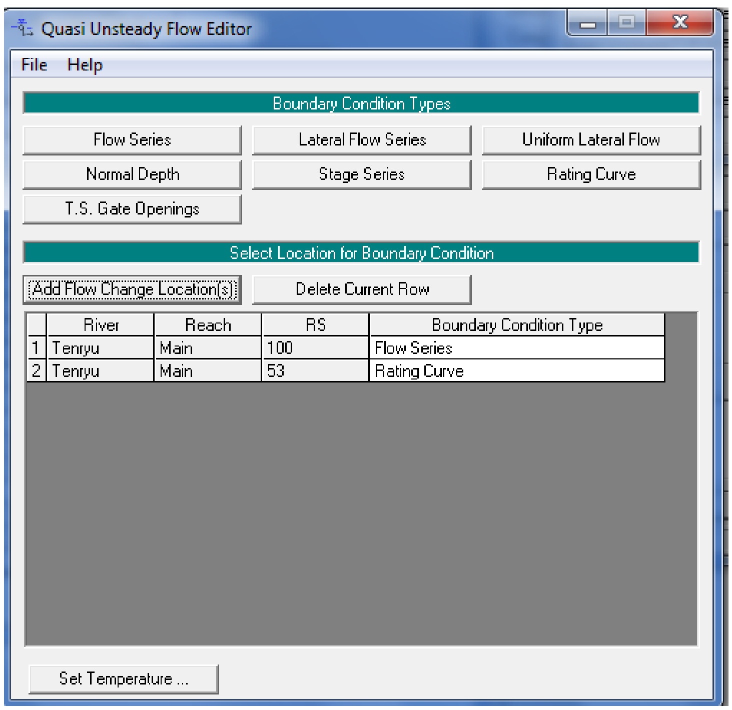


Figure 11: HEC-RAS window for setting quasi unsteady flow boundary conditions

There are several boundary conditions (see Figure 11) available in HEC-RAS that can be used in the quasi-unsteady flow file and these boundary conditions are: flow time series, lateral flow time series, uniform lateral flow, normal water depth, stage time series, and a rating curve.

In the model, a flow time series is used as the boundary condition in the most upstream river station (100). This boundary condition mainly consists of the computational increment and the amount of flow and its duration. Computational increment means the time step for which the program will update the cross sections, and that was initially set to be 10 days in simulations.

For the downstream boundary condition a rating curve was employed. This rating curve was developed to model the effect of the dam embankment on the discharge. The discharge structures of the dam were described in a simplified manner to yield the appropriate flows at the minimum and maximum water levels in the dam. Thus, it was assumed that flow through the dam is regulated by the following equation:

$$Q = Q_{max}\left(\frac{z - z_n}{z_{max} - z_n}\right)^2 \qquad 5.16$$

Where:

Q = River flow (m3 / sec)

Q_{max} = Maximum monthly flow (m3 /sec)

z = water level in the dam (i.e. stage)

z_{max} = maximum water level in the dam (260 m)

z_n = water level at the outlet (180 m)

The stage discharge curve after solving equation for different flow values can be seen in Figure 12.

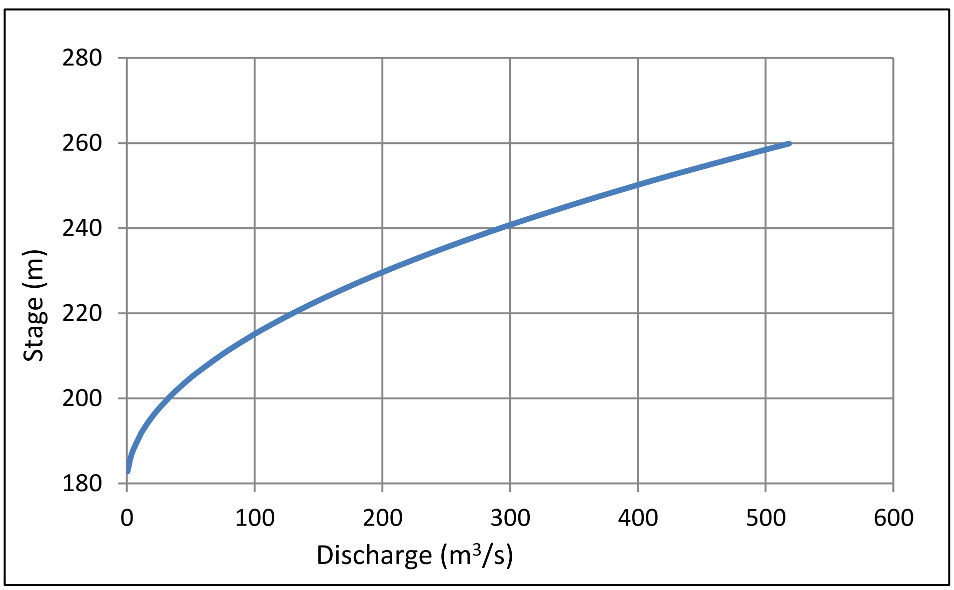


Figure 12: Stage discharge curve used as boundary condition in quasi unsteady flow data in HEC-RAS

6.3 Sediments Data

Sediment data consists of the following main input quantities,

i. Bed gradation at each river station

Bed gradation data of Tenryu River in 1957 was not known; however, the bed gradation curves that Morris & Fan (2008) presented (see Figure 13), provided some information. Although the figure shows bed gradation curves for the river bed in 1982, it was initially assumed that the bed gradation in 1957 was also the same. In later model runs during calibration the results matched the measured ones better when the same bed gradation curve was used for all river stations.

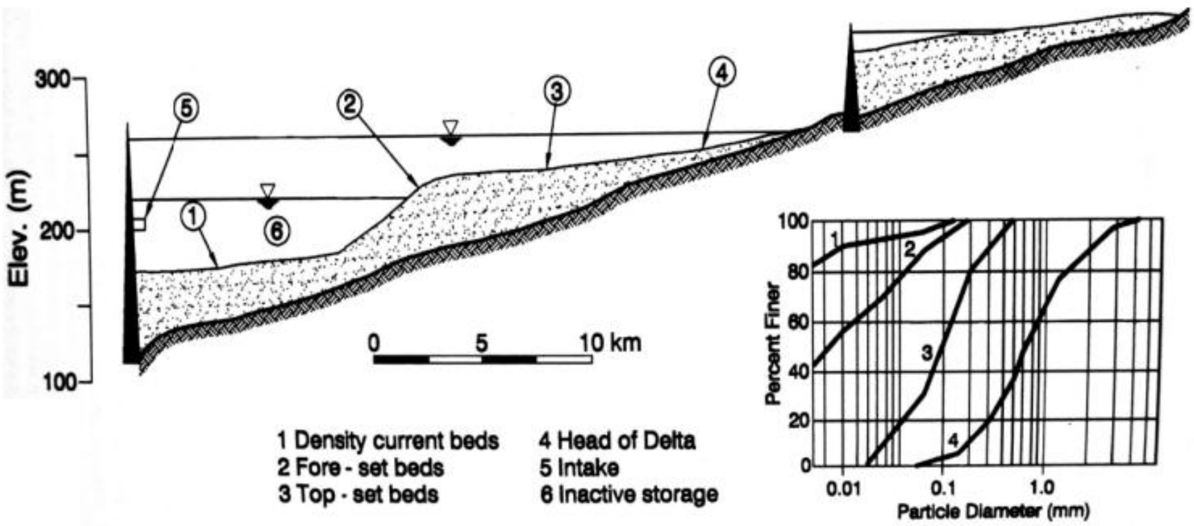


Figure 13: River bed profile and bed gradation curves at four different locations at Tenryu river in 1982 (Morris & Fan, 2008)

HEC RAS can accept sediment size input in 20 predefined grain size classes (see table 2), but the grain sizes can also be modified by the user if required.

Table 2: Sediment grain diameters (mm), user defined grain classes (Brunner & HEC, 2010)

Class	Label	Min	Max	Mean
1	Clay	0.002	0.004	0.003
2	VFM	0.004	0.008	0.006
3	FM	0.008	0.016	0.011
4	MM	0.016	0.032	0.023
5	CM	0.032	0.0625	0.045
6	VFS	0.0625	0.125	0.088
7	FS	0.125	0.25	0.177
8	MS	0.25	0.5	0.354
9	CS	0.5	1	0.707
10	VCS	1	2	1.41
11	VFG	2	4	2.83
12	FG	4	8	5.66
13	MG	8	16	11.3
14	CG	16	32	22.6

15	VCG	32	64	45.3
16	SC	64	128	90.5
17	LC	128	256	181
18	SB	256	512	362
19	MB	512	1024	724
20	LB	1024	2048	1448

Selection of different calculation methods like transport function, sorting method etc.

ii. General sediment properties such as shape factor, specific gravity etc.

iii. Sediment boundary conditions

Sediment boundary conditions for the most upstream and downstream river stations are required, whereas optionally such conditions can be defined for any number of cross sections in between.

Boundary condition for the most upstream river station was initially selected as "equilibrium load" and a sediment "rating curve" was selected for the downstream boundary condition. Sediment rating curve provides what amount of sediment load is there that is going out at any instance or time step of model run at the most downstream river station. HEC-RAS calculates the sediments out from most downstream river station (from rating curve), makes a bed change calculation based upon transport function, sediment properties and other hydraulic parameters till it reaches most upstream river station. At the upstream river station the boundary condition "Equilibrium Load" was selected, which means that the sediment coming into the system is based upon its transport capacity. The transport capacity is determined by prevailing hydraulic and sediment parameters (Brunner & HEC, 2010).

The sediment rating curve was developed from available data using the hypothesis that sediment influx is governed by a regime-type equation. So, from known values of sediment inflow against river flow, a regime type equation was developed according to:

$$q_s = 0.063Q^{1.7} \quad (5.17)$$

Where

q_s = Sediment load (ton/day)

Q = River flow (m^3/s)

Sediment properties:

Specific gravity = 2.65

Shape factor = 0.6

Density of sand/gravel (kg/m^3) = 1489

Density of silt (kg/m^3) = 1041

Density of clay (kg/m^3) = 480

6.4 Assumptions

During the course of modeling, not all the data were readily available and assumptions and simplifications had to be made in several parts of our study. These assumptions included:

1. Channel cross sections were taken as trapezoidal throughout the modeled river reach
2. It was assumed that the bed gradation of river bed is same throughout the river reach at the start of model. Also, the actual bed gradation was not available before Sakuma dam was constructed; however, the bed gradation from 1982 at four places was known. However, two of these curves, bed gradation curves 3 and 4 were used as the initial bed gradation.
3. The fraction of different grain sizes in the incoming sediment load was not available so the bed gradations from 1982 were used to obtain this input. As it can be seen from Figure 13, sediments are divided into four deposition zones according to their grain size. These different sediment grain sizes were used as initial sediment input and then changed during sensitivity analysis and calibration processes.
4. Only the annual average flow data from Sakuma dam was available. Also this data was not at the desired temporal resolution for the modeling. So it was assumed that, as the river reach is in hilly areas, that rainfall response time is small with respect to the flow modeling time step. Based upon this assumption we interpolated the annual average flow data to monthly flow data based upon the measured monthly precipitation in the catchment.
5. The flow rating curve used as downstream boundary condition in quasi unsteady flow data was developed based on general information about the discharge and the water level in the dam.

6.5 Limitations

There are two types of limitations with this modeling: first those which are the limitations of the HEC-RAS model itself and second those that are the result of lack of input data, which makes it necessary to employ different assumptions and simplifications. These include:

- The model is based on a 1D algorithm, which means that it can only model the sediment transport along the length of river and it does not take into account velocity variations along the depth or width of the river.
- Japan is in a zone of high seismic activity as extracted by historical records of earthquakes and their spatial distribution, which might have some effects, especially on the shape of delta by the energy released by earth quakes. A change in topset slope of Tarbela dam due to seismic activities was observed in a study by Khan et al. (2012). HEC-RAS does not model such effects on the bathymetry.
- Transversal movement of water, meandering, point bar formation etc. are ignored in 1D Models
- Due to assumed cross sections, either the channel invert or sediment volume can be selected as primary quantity for comparison with data.

7 Simulation and Results

7.1 Sensitivity Analysis

It required many test runs to reach a final model that yielded satisfying results. In these test runs, the values of different parameters were changed, including mainly the following:

- Sediment transport function (7 different functions available)
- Fall velocity (from 4 approaches)
- Grain-size sorting method (from 2 methods)
- Manning's roughness (0.018 to 0.07)
- Different computational options to overcome numerical instability (time steps)
- Different set of channel bed gradations and sediment rating curve

Sensitivity analysis of model indicated that the model is highly sensitive to following parameters:

- Manning's roughness (n)
- Bed gradation

Changes in Manning's n and bed gradation have the strongest influence. For example, if Manning's n was increased, the sediment transport was decreased. It also affected the stability in bed profile, which affects the channel invert plots. On the other hand, the model was also sensitive to bed gradation and it had a great influence to the model instability especially the sediments were settled down in different locations as they had different grain sizes through the whole reach. The model tended to be more stable and give more realistic results when assuming a gradation that depicted a sandy soil. However, if coarser or finer sediments were assumed in bed gradation, the results showed unrealistic sedimentation patterns or amounts.

7.2 Calibration

Sediment aggradation or degradation in the river, upstream of Sakuma dam, will be represented by the change in the channel invert over time. As previously discussed, the data channel cross-sectional shapes were not available, so for simplification a trapezoidal cross section was assumed. Furthermore, since this cross section may differ from the actual one, it was difficult to compare and relate the model result in terms of sediment volume. This is because different initial cross-sectional geometries in the model, implying different cross-sectional areas for the same amount of sediment deposition or erosion, would had produced different bed profile. Therefore, the channel invert was selected as criterion for comparison of model results with observed values during calibration and validation of model.

Procedure:

Initial runs of the model for sensitivity analysis, suggested that model results are quite sensitive to bed gradation, which was proved in the calibration process as well. The bed profile selected for model calibration at the start of simulations was a variant of the bed gradation at different locations on bed profile of 1982 (see Figure 13). The observed channel invert in year 2004 was employed for the calibration of the model. Initially the model results did not match the observed river bed evolution. However, after rigorous trial runs for testing the model with a changing set of governing input parameters, the model produced a channel invert that was visually approximately similar to the recorded channel invert of 2004. Value of the coefficient of determination, R^2, was 0.8 for this bed profile. Considering that a lot of input data were assumed or indirectly extracted, this R^2 value was considered satisfactory and the model was considered to be satisfactory calibrated (see Figure 14).

Hiraoka dam is located upstream Sakuma dam, just before the most upstream river station used in model. Considering that, one may expect some erosion downstream Hiraoka dam. However, Hiraoka dam is already filled up with sediments and consequently the entire incoming sediment load is transported through the dam without deposition. For this reason, there is no degradation taking place at river stations nearby Hiraoka dam, neither in observed bed profile nor in modeled.

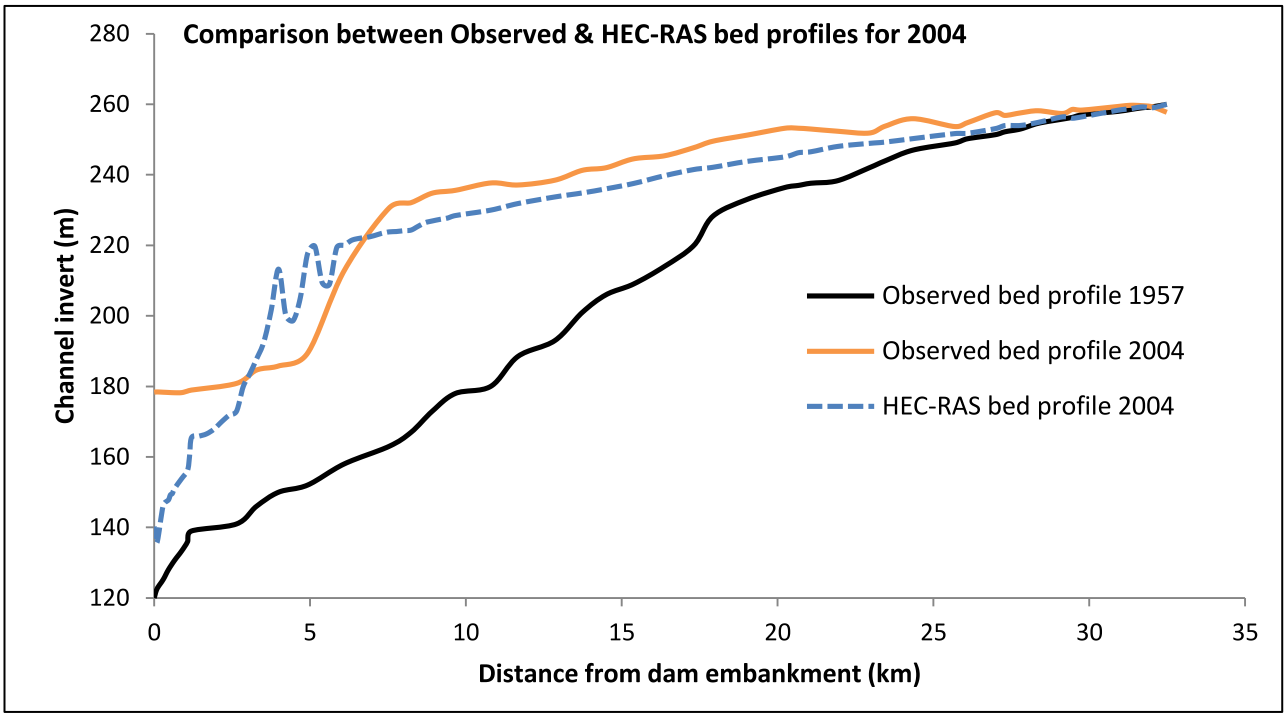


Figure 14: Comparison between Observed and HEC-RAS bed profile of 2004 after final calibration

The most important parameter values of the run for which initial calibration was finalized, included:

a) Manning's n is a mix of 0.03, 0.035 and 0.04 for different river stations along the whole reach.
b) The transport function is Toffaleti, the sorting method is Exner 5, and the fall velocity was calculated using Van Rijn.
c) Sediment rating curve was calculated using a regime type equation as explained in chapter 6.1.3 (iii), equation 5.17.
d) Initial bed gradation is a mix of two bed gradation samples, see Figure16. The soil type names S4 and S3 were just arbitrary given to specific soil type in HEC-RAS.

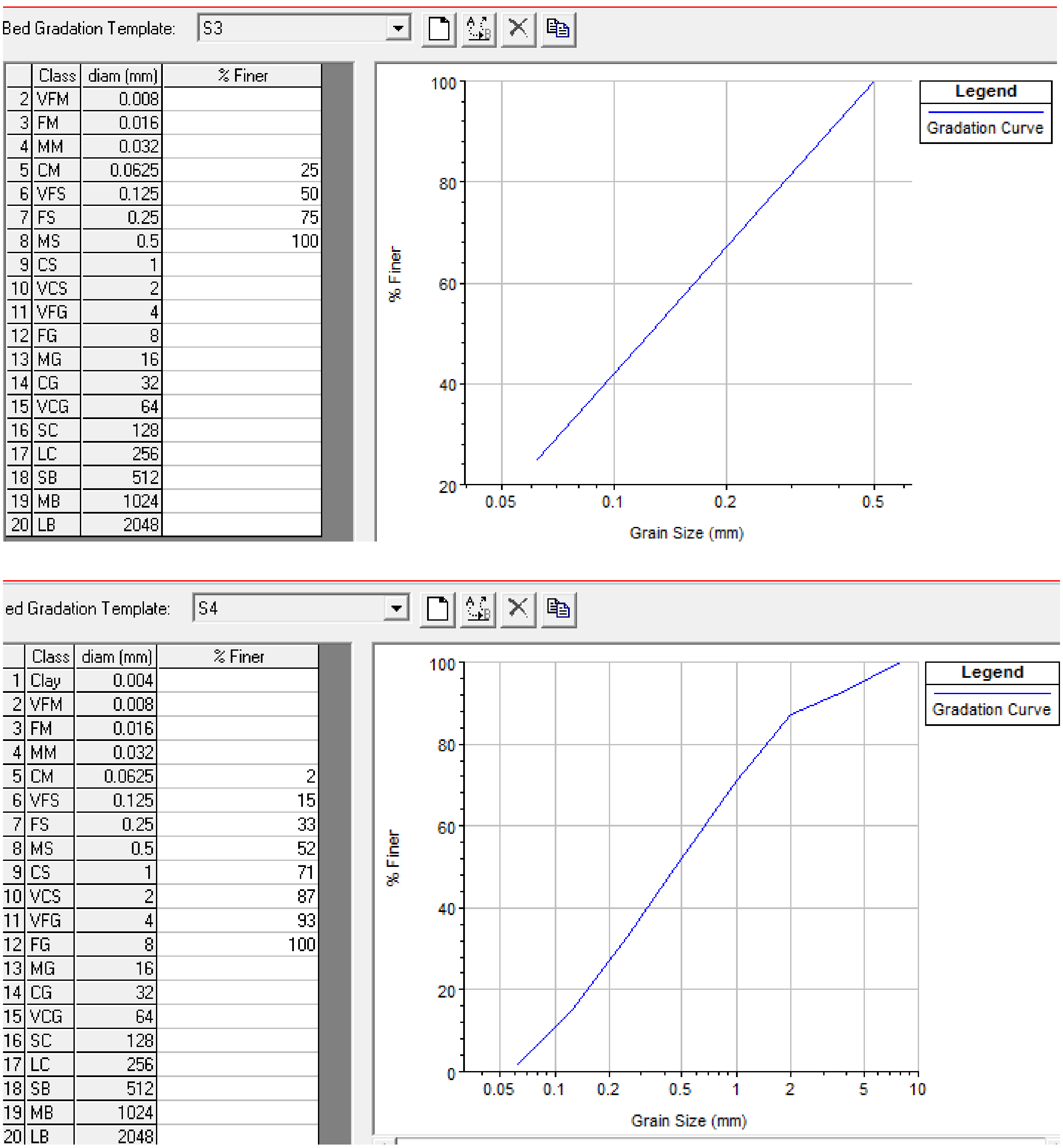


Figure 15: Grain size distribution for river bed of (a) soil type S3 and (b) soil type S4 used in the model as initial conditions in 1957.

Although the above-mentioned parameters were obtained after a lot of trial runs, checking different combinations of input parameters, these final parameter values were rational for the following reasons:

- Toffaleti is considered a sediment transport function for "large river" systems (Brunner, 2010) and the model is employed to simulate Tenryu River and Sakuma dam. Tenryu River is considered to be among the large rivers of Japan (MLIT Japan, 2007).
- The grain-size validity range for Toffaleti is from 0.062mm to 4mm (Brunner, 2010), and our final grain sizes used for calibration and later in validation were in the same range. See Figure

15(a) and 15(b). For soil type S4 (Figure 15 (b)) about 7 % is between 4mm to 8mm grain size, which is a little above the validity range of Toffaleti; however, this small deviation can be neglected.

- Applicable conditions of the Van Rijn fall velocity method are also in line with the actual environment of Tenryu River. Van Rijn used a shape factor of 0.7 (Brunner, 2010) for calculation of particle fall velocity, natural sand also has a shape factor of 0.7 (Jimenez & Madsen, 2003). As can be seen from the grain-size distribution curves (Figure 15), most of the bed material consists of sand.
- Exner 5 was used as sorting method for evaluating the thickness of active layer and vertical bed layer. This is the default method in HEC RAS and includes the capability of forming a coarser layer to limit the erosion of deeper materials. However, another sorting method "active layer" can also be chosen by the user for modeling of mobile armor systems, which is not the case here. So the use of Exner 5 as sorting method for the model is more logical than the active layer method.

7.3 Validation

After the calibration was done for the 2004 bed profile, validation of the model was done for the intermediate bed profiles of the years 1975, 1980, 1985, 1993, 1998, and 2003. However, the calibrated model did not yield quite as good agreement for the intermediate profiles, compared to the results for the 2004 bed profile during the calibration process.

However, the validation results matched the measurements within satisfactory limits. Figure 16 shows the development of the river bed profile from 1957 to 2004. Figures 17 and 18 show model generated river bed profiles for some selected years and their comparison with observed river bed profiles.

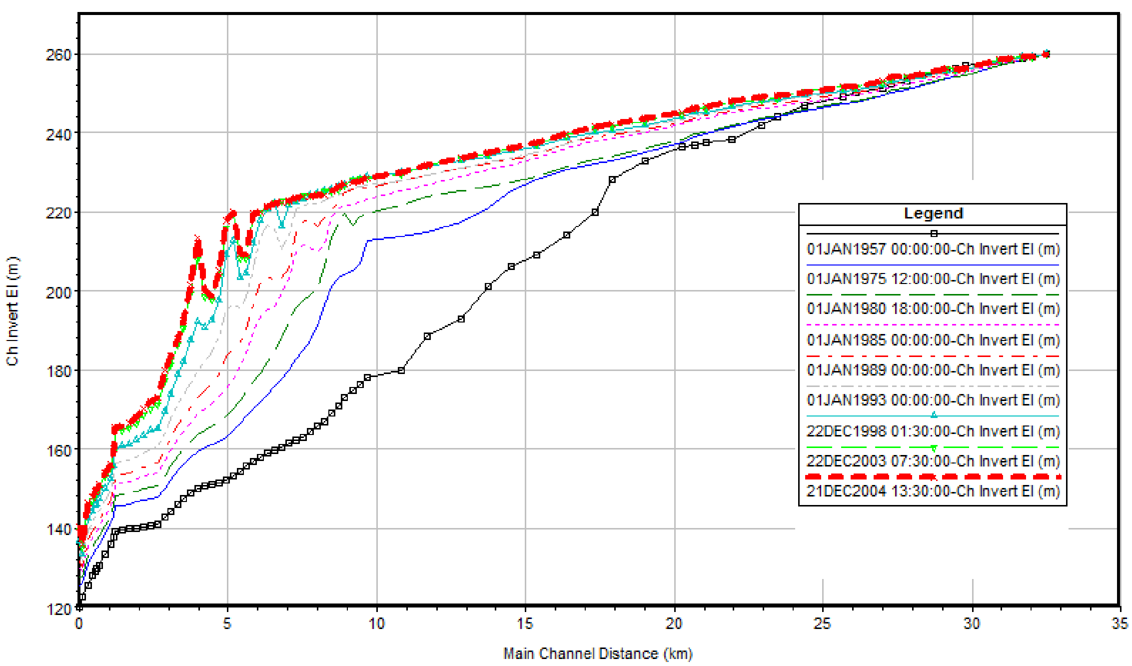


Figure 16: Model generated progression of river bed profile, after calibration and validation has been finalized

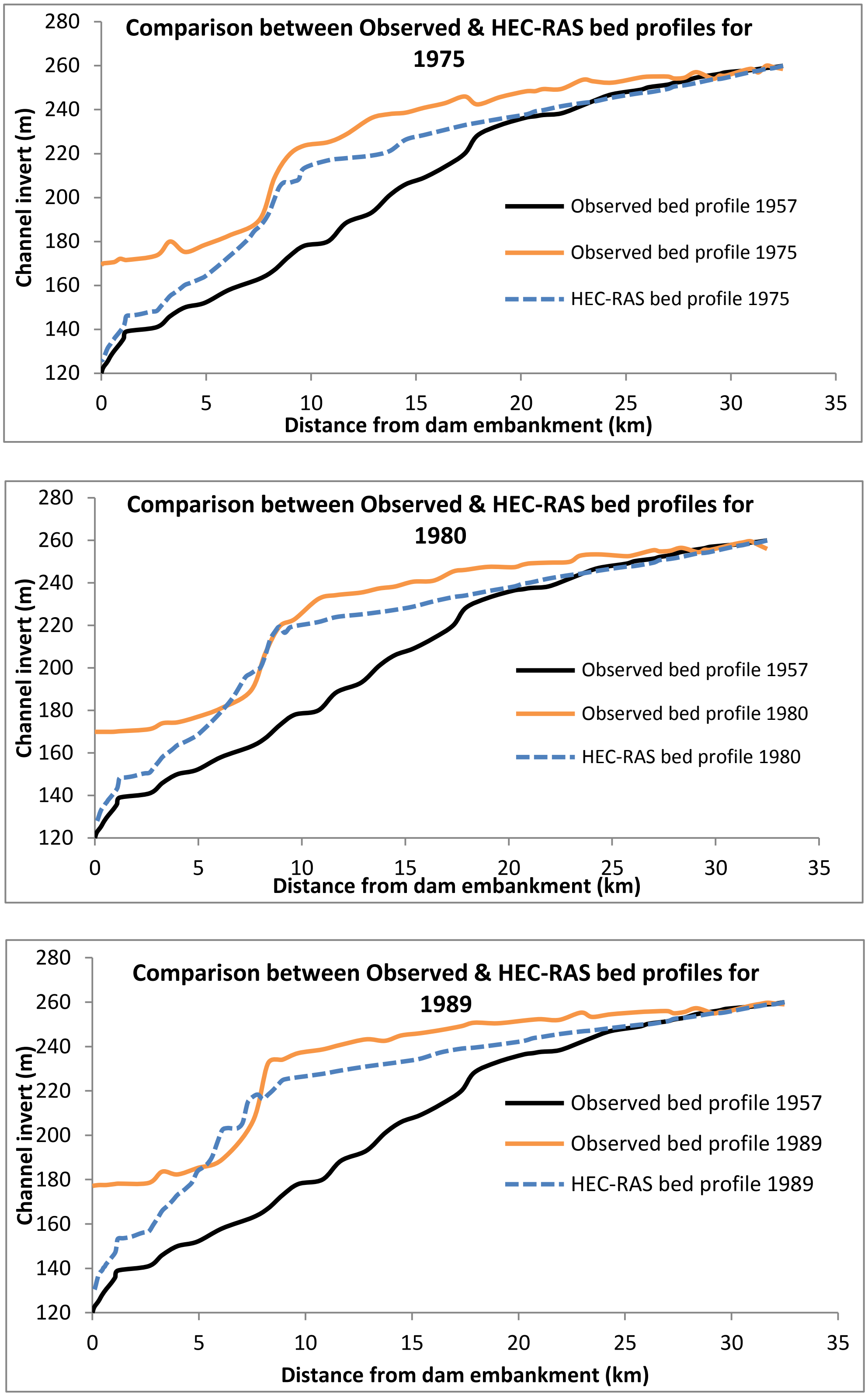


Figure 17: Comparison of Observed and HEC-RAS bed profiles for years 1975, 1980 and 1989

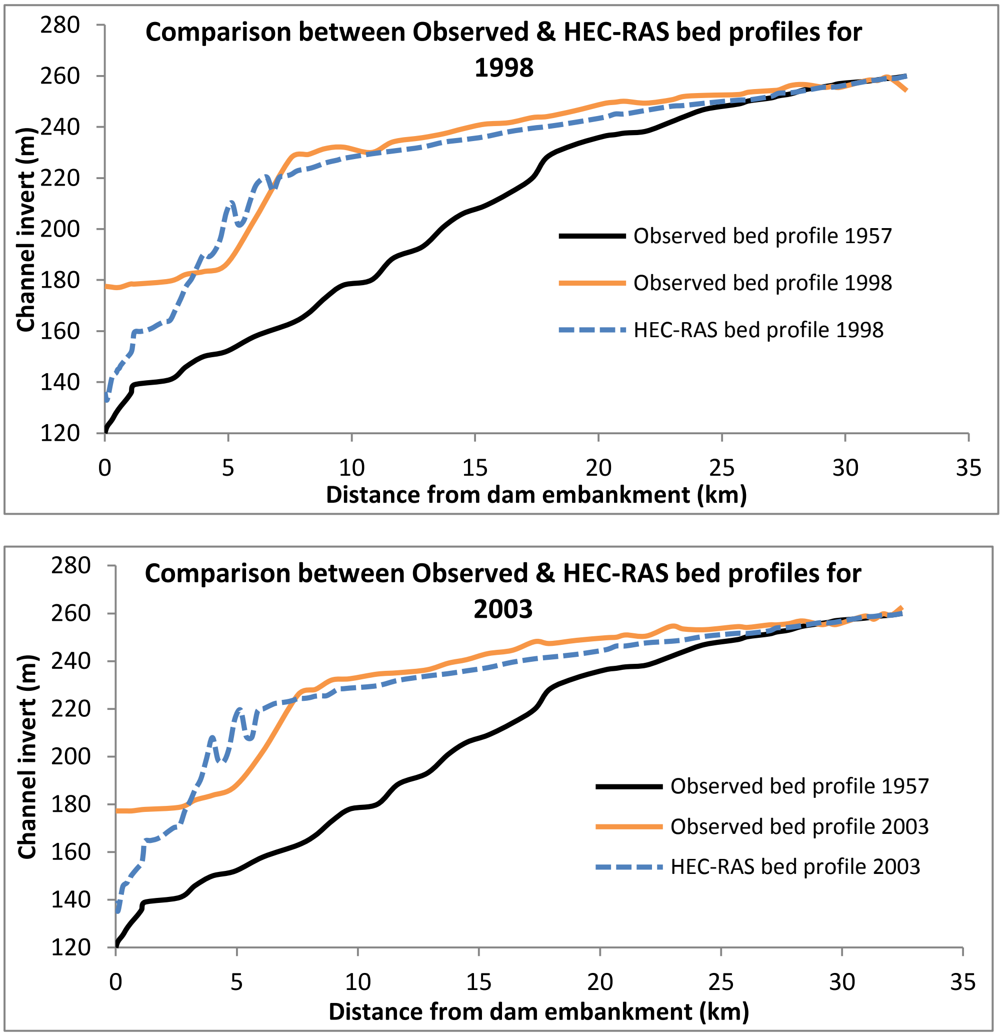


Figure 18: Comparison of Observed and HEC-RAS bed profiles for years 1998, and 2003

In addition to the visual resemblance between the model-generated bed profiles and the observed data, the deviation between model results and observed data was quantitatively estimated. This included finding R^2, percentage difference of area under channel invert, and dam fill up ratio. These results will be discussed more in chapter 7.5 (Results and discussions).

7.4 Predictive Run Based Upon Prospective Flow

Once the model had been calibrated and validated to a satisfactory level, it was used to forecast the possible future bathymetric changes using different future flow conditions. Thus, initially the model was considered to simulate the sediment transport situation until 2040 for two conditions. These are following scenarios:

i. Simulating the model with flow recycling
ii. Simulating using recycling flow values but increasing the values by a percentage

Simulation with recycling of flow values after 2004 has its importance because it involves natural variation in flow occurrences. This variation reflects the prospective behavior of the sediment transport that may be as close to reality as possible.

Recycling the flow but assigning a rate of increase in flow values each year could be a good approach, if we consider that climate change is an issue. In order to approximate the trend of flow increase, a trend line was fitted to the time series of flow values from 1957 to 2004. However, the trend in flow is very slightly increasing (see Figure 5), therefore only recycling of flow values as from 1957 was assumed as flow after 2004.

So, the predictive modeling was done with just recycling of flow. In this scenario, the model parameters and river flow until 2004 remained the same as those used in the final calibration run of the model. However, flow values from 2005 to 2040 were added from the measured flow series, for forecasting the river behavior during these years. Year 2040 was just initially selected rather arbitrarily, but later it proved to be reasonable when the results of run were obtained.

7.5 Results and Discussions

Model results were compared with observed data using the following four approaches:

i. Visual resemblance between model and observed bed profiles
ii. R^2 (coefficient of determination) of model and observed bed profiles
iii. Percentage difference in area under observed and model bed profiles
iv. Observed versus model dam fill-up ratio, that is, loss of accumulative storage due to sedimentation

7.5.1 Visual Resemblance

At the time of model build-up and general testing, several input data were either assumed or indirectly extracted. Initially, the main input data available were average annual flow, channel invert at the start of simulation and selected years after that, and approximate top width. This was the reason that initially quantitative comparison with observed sediment volumes was not given high priority. Instead, visual resemblance between model and observed bed profiles were given more weight to just quickly check the result of a specific model run.

During the calibration and validation period (see Figures 16, 17, and 18) it can be noticed that initially the slope of the modeled bed is almost consistent with the observed slope, but the modeled level is slightly lower than the observed one. The location of the delta is a bit ahead of the observed location, causing a slight overestimation of the behavior in this region. Near the embankment, the modeled bed profile again drops below the observed one and in this region the difference is larger than in any other region.

In general the underestimation at the start and the end of the bed profile may be attributed to the temporal resolution of the input flow data. The available recorded flow consisted of annual averages, although monthly values were derived based on the measured rainfall. Thus, the representation of extreme events was not satisfactory. Limited information on particular flows such as the highest and lowest flow during a certain period existed, but without any details about their occurrence in time. Considering the fact that a lot of the sedimentation may take place during high flood events, the lack of modeling such events may be the primary reason for underestimating the bed evolution in the model. Although as explained previously, monthly flow values were extracted from the annual average flow based on the precipitation data, even the highest flow values achieved through this process were smoothed out at a time scale significantly longer than the extreme events.

The reason for the delta location being closer to the dam embankment in the model than that of the observed bed profile could be due to dredging measures at the site which were not modeled. Also there is high sedimentation closer to the dam embankment in observed profiles as compared to model profiles (See figures17 and 18). In reality, some sediment removal measures were undertaken in Sakuma dam that may also affected and caused minor destabilization in delta due to its steeper slope. These events may have caused minor soil mass sliding from delta region to the area near the embankment. Another possible reason of such land sliding could be high seismic activity in Japan. As pointed out by the High Sensitivity Seismograph Network, NEID Japan (2001) Japan is an earthquake prone zone and has almost 400 minor earthquakes daily. It is beyond the capability of HEC-RAS to model the changes in river bed due to earthquakes or any other external forces.

7.5.2 R^2 (Coefficient of Determination)

Quantitatively, the model results can be compared with the measurements by calculating the coefficient of determination, R^2. It is a statistic measure that estimates how well model-generated results are matching with the observed data. The R^2 value varies from 0 to 1, and a value of 1 means that the model data is exactly matching the observed data, whereas a lesser value denotes some discrepancy between modeled and observed data.

As can be observed from Table 3, the R^2-values for of all available profiles vary from 0.68 to 0.96, which indicate good agreement between model results and observed data for most of the profiles.

Table 3: R^2 and percent difference of model bed profiles for some selected years

S No.	Year of comparison	R^2 value	Percent area difference	Comments
1	1960	0.96	74.9	
2	1965	0.79	71.3	
3	1970	0.71	68.2	
4	1975	0.72	54.6	
5	1980	0.79	38.9	See Figure 17
6	1985	0.68	36.1	
7	1989	0.7	30.9	See Figure 17
8	1993	0.72	27.4	
9	1998	0.78	14	See Figure 18
10	2003	0.8	8.8	
11	2004	0.8	10.5	See Figure 14

7.5.3 Percentage of (area) Difference

Modeled bed profiles were also compared with the recorded ones by finding the percentage of difference in the area between the two bed-profiles normalized with the recorded profile change from the start of the simulation. The result can be found in Table 3, whereas Figure 19 shows graphically the difference in the modeled and observed bed profile. The difference is shown in blue and orange shaded areas, representing the under- and overestimation of the model, respectively.

By looking at the results in Table 3 for "Percent area difference", it can be observed that the difference is too large in 1960 and it gradually becomes less. One of the reasons for this large difference in initial years could be due to simplifications in geometry and use of 1982's river bed gradation for 1957's bed gradation. Furthermore, there are three tributaries joining Tenryu River between Hiraoka and Sakuma dams that are in the modeled river reach as shown by Google Earth's satellite images. This means that there are three river stations for which we can define flow and sediment load boundary conditions between most upstream and most downstream river stations. But these were not considered for simplicity as the respective data regarding these tributaries were not available. Considering these tributaries during modeling might affect the model and resulting sedimentation pattern.

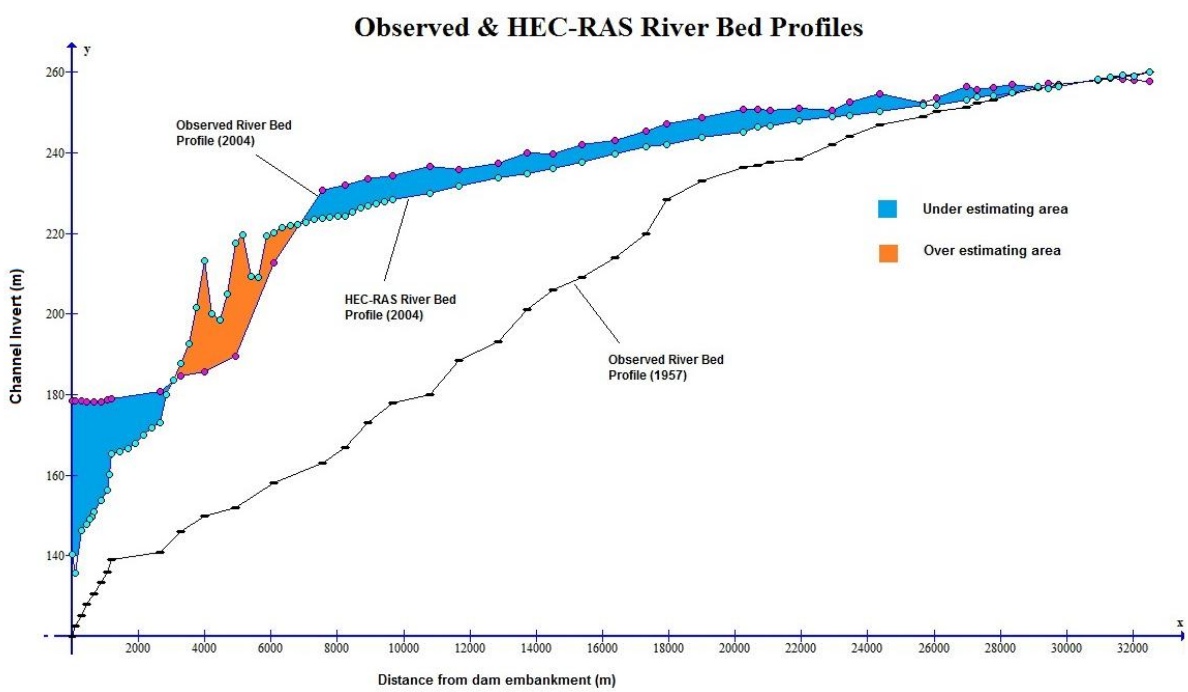


Figure 19: Difference in area under model and observed bed profile of 2004

7.5.4 Loss of Storage

In an effort to assess the model performance from another point of view, the loss of storage as a percentage of the entire initial reservoir volume for the measurement period was calculated and compared with the observed one. These percentages are shown in table 4, which also confirms the underestimation of the sedimentation in the reservoir by the model.

Table 4: Comparison of storage lost storage due to sedimentation

Year	Percentage of cumulative storage lost due to sediment accumulation (%)	
	Model	Actual
1960	2.52	3.39
1965	5.19	10.58
1970	8.67	17.44
1975	13.08	20.63
1980	17.46	22.44
1985	21.64	28.73
1989	24.11	30.61
1993	26.57	32.20
1998	28.91	32.97
2003	31.25	34.08
2004	31.73	34.68
2010	32.08	
2020	37.07	
2030	40.73	
2040	43.60	

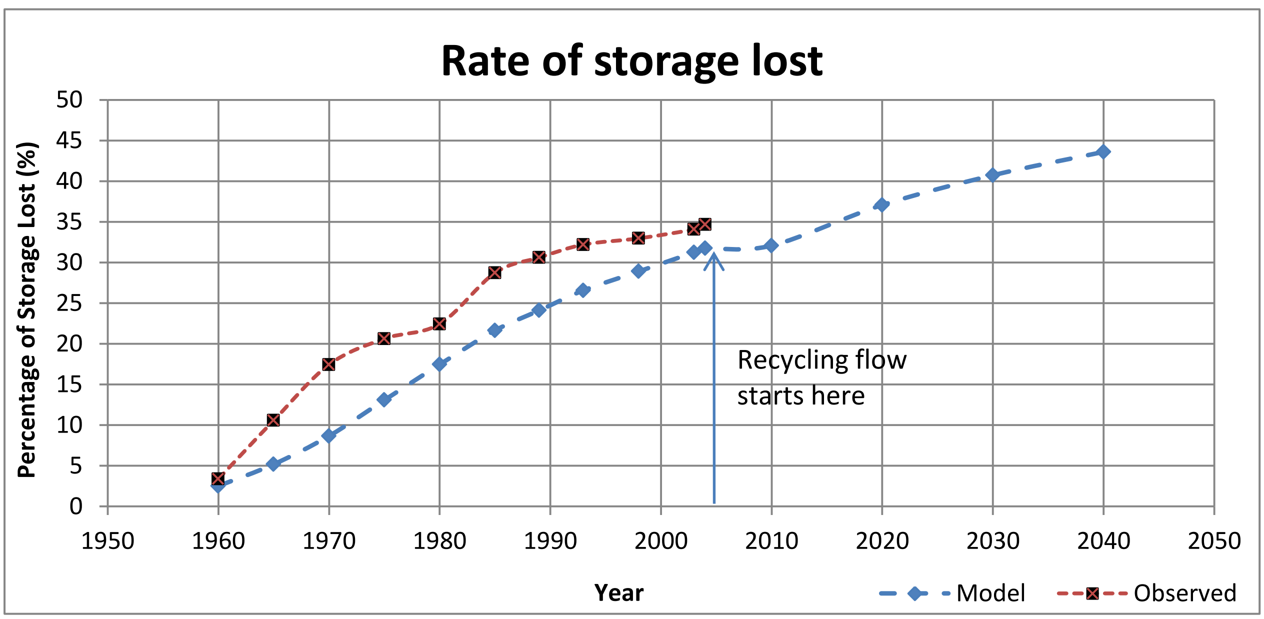


Figure 20: Comparison of rate of storage lost between model and observed data. The line showing model value also shows predictive loss of storage after 2004.

Morris & Fan (2008) discussed that interference with the original design purposes of a dam occurred at a significant level when half of the volume of the dam is lost due to sedimentation, and sometimes even before that. Thus, it was considered that Sakuma dam's useful life will approximately end when 50% of its storage volume is lost. Now considering the general underestimation (see Figure 19 and 20) and uncertainty in the model simulation results (Table 4), the useful life of Sakuma dam can be reasonably expected to end in 2035±5 year, if no measures will be taken to limit the sedimentation.

8 Conclusions

The focus of this report was to simulate bathymetric changes taking place in Tenryu River due to the construction of the Sakuma Dam. The simulations were used further for prediction of possible future changes in river bed profile and the estimation of prospective time until the Sakuma dam cannot be operated while serving all its intended purposes.

The HEC-RAS model was employed in the simulations and in general the model performed well, once all parameters were set within their effective ranges. Despite many simplifications HEC-RAS has produced reasonably matching results with the data available for the period of study. Model results have R^2-values from 0.68 to 0.96 and the percentage of difference in river bed profile change between model and observed data is 8% – 75%. The percentage difference is greater in the beginning of the simulation period when the changes are smaller, but it is becoming less towards the end (see section 7.5.3). Loss of storage volume due to sedimentation in percentage was also close between observations and model results.

The bed of the river consists of sand within the range of applicability of Toffaleti's transport function, and this formula gave the best results compared with the other available transport functions in HEC-RAS. However, the Englund-Hansen formula also gave somewhat reasonable results for some of test runs. The equation of Van Rijn to predict the fall velocity produced the best agreement during the calibration.

The same model was run until 2040 to forecast possible changes in the river bathymetry. Although the flow was not available after 2004, the measured flows were recycled from 1957. This predictive study shows that there are limited possibilities for the dam after 2035 ± 5 years to be used for its intended purposes. It is therefore highly recommended to employ some cost-effective sedimentation remedy well before this time. The following possible solutions for sediment management that can be applied, individually or in combination:

- The watershed management of Tenryu River can be an option to reduce sediment inflow into the river from its basin. This can be achieved by regulating land-use types.
- Dredging of deposited sediments can be carried out, especially in the delta area, to modify the shape of delta and to reduce the sedimentation in dead storage capacity. This method, however, cannot be used to approximately remove 5% – 10% sediments, due to its cost and arrangements.
- The sediment bypassing may be an option and it has been effectively used in some other dams in Japan like Nunobiki dam and Asahi dam (SumiI, et al., 2004). This can be done by introducing a system of tunnels at the bottom of the dam embankment letting the incoming sediment going out with no or very less deposition upstream of the dam.

It would be interesting to identify some possible scenarios for future studies. So the following are prospective options to improve the results from the current study in future investigations:

- Study of same case with 2 or 3 other software and compare their results with observed data.

- Study the same case with 1D, 2D, and 3D models and see if they offer the same results or if they differ and to what extent.
- Study of two or more cases with the present model and by comparing results trying to find out under which circumstances the model performs well.
- A combination of two or more of the above options.

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Appendices

Appendix – I: Tenryu River and its Cross Sections

Figure 21: Selection of River stations at Tenryu River (Base map was taken from Google Earth (2012))

Appendix – II: Average Yearly and Monthly Flow

Table 5: Actual average annually flow (m^3/s) (Taken from Civil Engineering Department, University of Tokyo, Japan)

Year	Flow	Year	Flow	Year	Flow
1957	114.7	**1973**	108.7	**1989**	160
1958	120.4	**1974**	132	**1990**	126
1959	163.1	**1975**	137	**1991**	157
1960	102.5	**1976**	160	**1992**	114
1961	111.1	**1977**	111	**1993**	138
1962	81.1	**1978**	103	**1994**	83
1963	89.5	**1979**	131	**1995**	85
1964	90.1	**1980**	163	**1996**	112
1965	102.9	**1981**	155	**1997**	118
1966	125.4	**1982**	123	**1998**	155
1967	98.4	**1983**	162	**1999**	116
1968	97.9	**1984**	79	**2000**	111
1969	132.4	**1985**	142	**2001**	117.5
1970	107.3	**1986**	105	**2002**	95.9
1971	133.4	**1987**	96	**2003**	171.4
1972	151.2	**1988**	116	**2004**	146.7

Table 6: Extracted monthly flow based upon precipitation (m^3/s)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1957	26.40	62.91	34.31	98.86	154.82	209.36	141.82	223.15	231.58	49.85	81.79	61.55
1958	82.76	99.98	68.48	104.58	79.74	41.45	241.75	149.25	262.27	155.08	65.46	94.01
1959	95.81	189.96	100.20	270.02	130.17	92.19	140.48	402.00	193.16	112.61	102.78	127.80
1960	22.48	10.97	91.37	150.86	141.96	131.90	160.07	225.27	100.94	68.28	87.67	38.23
1961	49.74	21.75	113.98	225.36	168.31	290.17	46.00	111.72	55.24	130.53	92.23	28.16
1962	11.43	6.61	32.05	120.42	128.88	165.15	133.65	122.73	57.45	62.34	83.91	48.57
1963	2.84	19.49	62.64	126.47	245.96	179.39	110.95	107.46	69.62	97.43	30.70	21.04
1964	104.18	54.85	73.03	105.06	56.43	299.12	28.92	59.54	187.54	62.53	21.29	28.69
1965	26.61	22.97	30.61	107.29	265.51	154.71	141.78	85.24	154.03	78.96	118.87	48.22
1966	31.64	112.13	151.36	136.12	178.37	236.22	165.60	155.92	156.60	111.76	63.40	5.67
1967	84.08	35.82	122.16	148.75	48.04	155.43	158.43	117.80	41.47	121.03	134.89	12.90
1968	29.60	26.26	127.72	68.04	97.64	139.90	231.33	245.66	16.95	40.82	35.33	115.55
1969	68.45	93.55	137.24	149.62	99.75	356.29	197.87	234.05	102.36	51.18	69.11	29.34

Continued..

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1970	60.82	64.93	48.78	103.26	147.29	272.72	172.00	131.77	100.73	85.52	40.23	59.55
1971	33.72	62.45	163.61	170.50	164.37	85.83	161.69	305.75	176.25	186.59	12.64	77.40
1972	49.65	105.79	178.81	194.06	162.26	205.75	349.51	113.58	277.79	37.64	73.34	66.20
1973	164.22	54.22	18.38	157.67	164.53	81.95	110.00	151.44	116.85	173.57	52.35	59.21
1974	11.86	61.96	85.95	241.24	80.15	176.91	416.04	146.06	200.11	89.90	22.15	51.68
1975	78.04	87.74	127.70	156.07	120.60	117.99	203.87	181.46	123.22	258.38	120.60	68.33
1976	160.00	180.17	169.57	145.19	249.76	253.65	152.97	126.47	202.78	117.64	77.72	84.08
1977	19.44	32.41	188.23	147.37	125.96	182.60	95.53	151.88	208.52	17.47	105.39	57.20
1978	24.58	45.51	66.10	154.46	120.25	186.35	123.23	90.68	191.33	126.89	76.40	30.23
1979	44.80	93.61	177.19	161.81	147.10	82.24	152.79	183.21	156.13	180.54	152.45	40.12
1980	97.57	16.95	184.98	213.98	215.11	252.03	354.51	159.74	195.52	125.83	111.51	28.26
1981	17.02	55.78	216.25	263.70	126.05	122.07	240.51	261.16	169.88	245.59	127.50	14.49
1982	26.17	55.84	108.44	78.03	60.33	112.43	220.61	261.25	346.75	55.34	123.64	27.17
1983	35.86	27.79	155.73	246.51	179.64	307.58	124.39	390.93	309.52	128.91	26.17	10.98
1984	27.08	67.51	71.03	87.91	74.19	261.62	36.57	149.80	60.83	23.91	54.85	32.70
1985	18.15	117.77	246.35	186.50	143.25	373.00	68.73	213.92	161.79	78.00	86.11	10.43
1986	17.00	36.93	143.16	116.03	191.53	120.93	177.81	167.02	112.76	47.07	18.63	111.13
1987	56.56	33.15	147.85	47.88	167.31	97.34	134.69	182.57	184.41	50.25	31.57	18.42
1988	18.58	25.09	129.16	147.13	73.41	275.36	132.57	196.38	291.78	40.89	43.05	18.58
1989	127.24	236.57	142.60	195.25	131.63	266.55	170.02	168.20	191.96	125.78	140.04	24.13
1990	48.12	141.44	103.37	99.94	211.51	180.57	122.14	134.83	287.91	66.10	100.47	15.60
1991	47.77	49.55	193.21	149.72	87.69	223.51	156.14	125.48	411.38	303.72	89.12	46.70
1992	26.33	38.88	129.18	166.22	170.81	167.14	93.36	89.08	126.42	147.24	134.08	79.28
1993	68.00	101.82	62.77	59.63	94.50	190.39	395.78	104.26	184.12	177.14	127.28	90.31
1994	42.77	46.63	98.73	142.15	166.59	94.87	108.06	23.80	162.41	47.92	41.81	20.26
1995	48.86	19.86	129.23	158.23	197.32	78.80	157.29	11.66	60.52	83.21	70.92	4.10
1996	43.77	25.60	254.11	39.69	66.40	162.85	245.21	108.69	95.34	93.11	103.50	105.72
1997	12.61	50.44	113.86	188.40	84.19	203.61	297.07	35.23	129.81	15.95	250.34	34.49
1998	98.77	66.76	111.91	256.37	200.56	198.37	172.92	266.22	265.13	199.74	164	21.62
1999	17.79	57.58	163.04	132.96	236.47	230.01	136.84	109.02	166.28	32.67	108.69	0.65
2000	64.71	15.60	102.84	114.11	70.49	250.45	118.44	112.37	204.52	131.15	135.19	12.13
2001	129.84	66.67	71.59	43.51	83.52	140.72	19.30	184.58	307.06	221.43	104.57	37.20
2002	75.32	25.11	114.46	43.19	87.19	151.71	215.15	82.87	133.09	156.03	13.50	53.18
2003	90.71	37.59	133.89	149.42	155.95	78.59	437.70	518.47	134.82	86.67	208.44	24.54
2004	14.01	48.53	76.56	119.38	134.18	332.72	90.32	121.20	150.01	496.74	95.51	81.23

Appendix – III: HEC – RAS Geometry Data (x-coordinates, elevations and lengths)

Table 7: Geometric data of Tenryu River

River St.	X-coord.	Elevation	LoB	Channel	RoB	River St.	X-coord.	Elevation	LoB	Channel	RoB
100	5988	280.17	450	450	450	**91**	4399	279.18	477	507	540
	5994	260					4409	253			
	6090	260					4480	253			
	6098	280.17					4489	279.18			
99	5881	280.06	314	352	395	**90**	4199	279.07	350	301	253
	5888	259.3					4210	252.2			
	5963	259.3					433 0	252.2			
	5971	280.06					4339	279.07			
98	5568	279.95	353	378	404	**89**	4350	278.96	897	906	915
	5575	259					4358	251.4			
	5690	259					4417	251.4			
	5698	279.95					4426	278.96			
97	5221	279.84	422	379	310	**88**	4506	278.85	295	405	428
	5228	258.5					4513	250.3			
	5320	258.5					4558	250.3			
	5328	279.84					4567	278.85			
96	4873	279.73	1158	1162	1164	**87**	4266	278.74	1360	1334	1309
	4879	258					4275	249			
	4990	258					4334	249			
	4999	279.73					4343	278.74			
95	3946	279.62	349	306	263	**86**	3224	278.63	922	890	859
	3956	257					3230	247			
	4026	257					3303	247			
	4034	279.62					3311	278.63			
94	3776	279.51	342	321	301	**85**	3982	278.62	426	522	535
	3782	256.3					3988	244			
	3847	256.3					4057	244			
	3853	279.51					4062	278.62			
93	3996	279.4	696	780	823	**84**	4078	278.41	981	1016	1052
	4005	255.8					4085	242			
	4106	255.8					4175	242			
	4112	279.4					4183	278.41			
92	3938	279.29	580	560	541	**83**	4791	278.3	826	852	878
	3946	254.6					4798	238.3			
	4030	254.6					4930	238.3			
	4037	279.29					4937	278.3			

Continued..

River St.	X-coord.	Elevation	LoB	Channel	RoB	River St.	X-coord.	Elevation	LoB	Channel	RoB
82	3965	278.19	465	393	330	**73**	2882	277.2	816	880	944
	3973	237.6					2890	201			
	4080	237.6					3048	201			
	4090	278.19					3056	277.2			
81	3844	278.08	464	441	428	**72**	3446	277.09	1170	1185	1201
	3852	237					3457	193			
	4065	237					3600	193			
	4073	278.08					3612	277.09			
80	4196	277.97	1207	1220	1234	**71**	2987	276.98	901	872	844
	4204	236.4					2994	188.5			
	4290	236.4					3200	188.5			
	4301	277.97					3209	276.98			
79	3087	277.86	1111	1088	1065	**70**	3672	276.87	1029	1135	1243
	3097	233					3680	180			
	3210	233					3800	180			
	3219	277.86					3814	276.87			
78	2692	277.75	556	607	659	**69**	2764	276.76	773	738	703
	2699	228.3					2772	178			
	2810	228.3					2958	178			
	2821	277.75					2968	276.76			
77	2617	277.64	960	948	936	**68**	2159	276.65	819	682	547
	2629	220					2169	173			
	2806	220					2397	173			
	2817	277.64					2407	276.65			
76	1661	277.53	1107	998	890	**67**	1880	276.54	680	707	734
	1669	214					1889	167			
	1910	214					2075	167			
	1921	277.53					2085	276.54			
75	1430	277.42	944	874	805	**66**	2117	276.43	1306	1443	1580
	1439	209					2129	163			
	1560	209					2334	163			
	1569	277.42					2344	276.43			
74	2139	277.31	751	763	775	**65**	1285	276.32	1186	1174	1163
	2149	206					1287	158			
	2290	206					1531	158			
	2300	277.31					1533	276.32			

River St.	X-coord.	Elevation	LoB	Channel	RoB	River St.	X-coord.	Elevation	LoB	Channel	RoB
64	396	276.21	1094	928	764	**56**	362	275.33	243	164	86
	408	152					373	128			
	625	152					719	128			
	633	276.21					728	275.33			
63	100	276.1	721	710	700	**55**	319	275.22	231	200	224
	110	150					328	125.3			
	334	150					621	125.3			
	342	276.1					632	275.22			
62	692	275.99	562	638	719	**54**	168	275.11	159	90	149
	699	146					177	122.6			
	944	146					690	122.6			
	952	275.99					699	275.11			
61	596	275.88	1458	1447	1437	**53**	267	275	0	0	0
	607	141					276	120			
	930	141					540	120			
	939	275.88					550	275			
60	951	275.77	107	125	185						
	959	139									
	1207	139									
	1217	275.77									
59	852	275.66	120	190	263						
	861	136									
	1240	136									
	1250	275.66									
58	742	275.55	223	232	241						
	750	133.3									
	1117	133.3									
	1127	275.55									
57	554	275.44	237	195	155						
	561	130.6									
	924	130.6									
	932	275.44									

Appendix – IV HEC – RAS Interface For Sediment Input Data

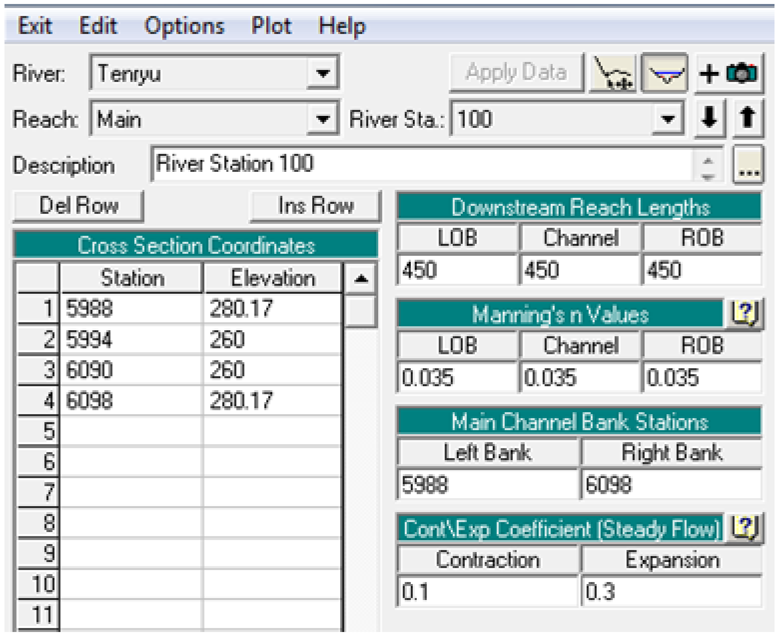

Figure 22: HEC - RAS window for X - Section data for River station 100

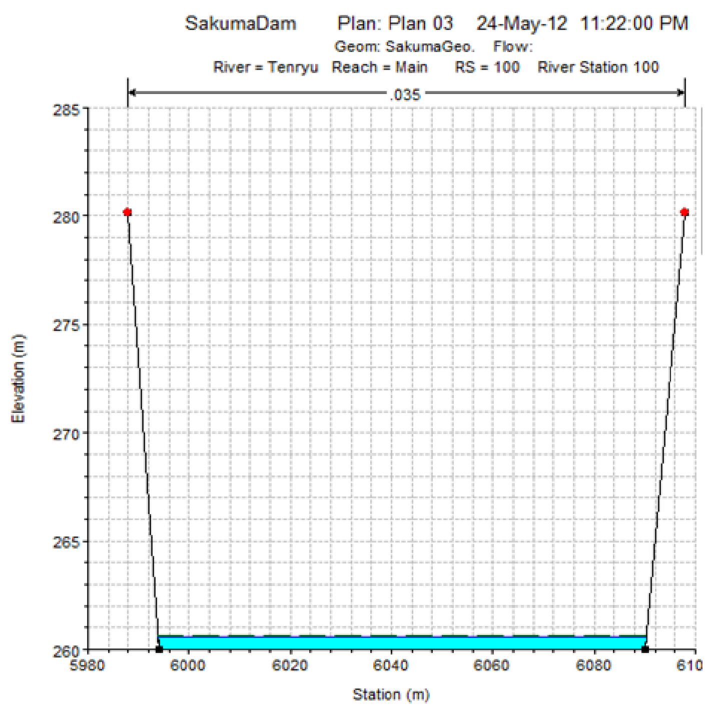

Figure 23: HEC RAS graphical sketch of X – Section for River station 100

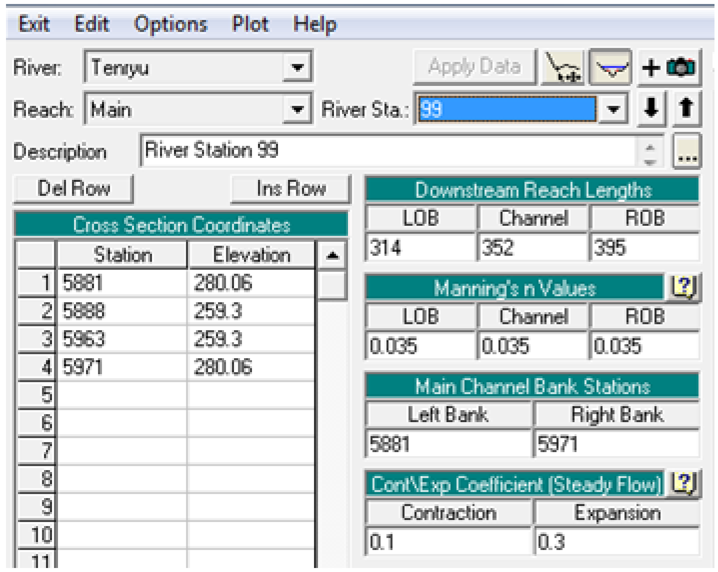

Figure 24 HEC - RAS window for X - Section data for River station 99

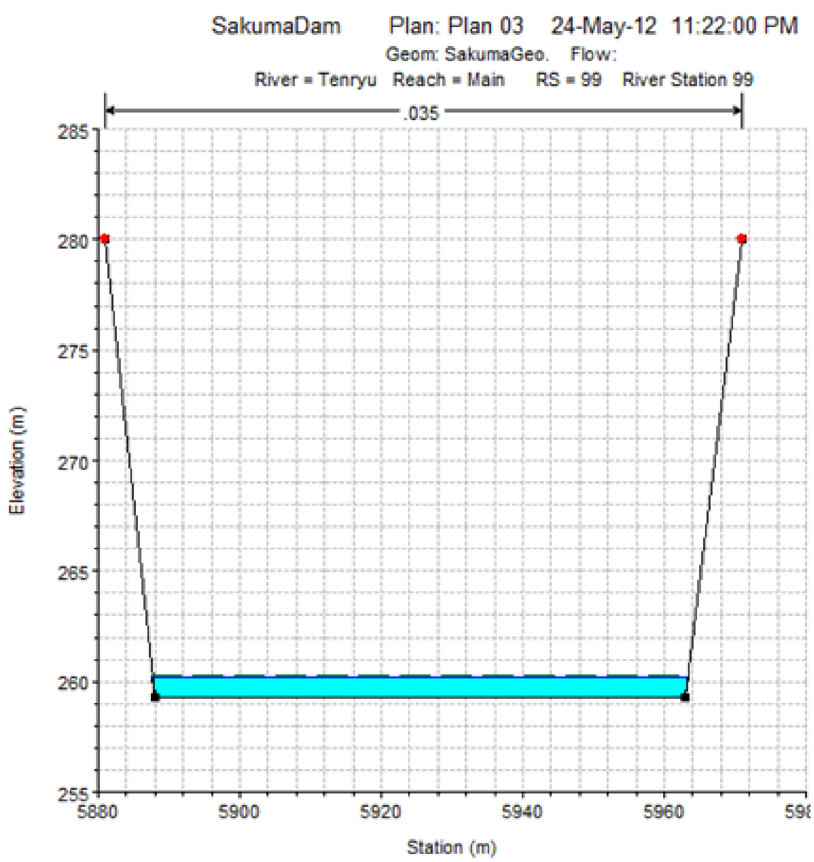

Figure 25: HEC RAS graphical sketch of X – Section for River station 99

Appendix – V Precipitation Data in Catchment of Tenryu River

Table 8: Monthly Precipitation data (mm) (JMA, 2012).

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1957	46.7	111.3	60.7	174.9	273.9	370.4	250.9	394.8	409.7	88.2	144.7	108.9
1958	120.6	145.7	99.8	152.4	116.2	60.4	352.3	217.5	382.2	226	95.4	137
1959	137.5	272.6	143.8	387.5	186.8	132.3	201.6	576.9	277.2	161.6	147.5	183.4
1960	37.1	18.1	150.8	249	234.3	217.7	264.2	371.8	166.6	112.7	144.7	63.1
1961	87.8	38.4	201.2	397.8	297.1	512.2	81.2	197.2	97.5	230.4	162.8	49.7
1962	29.2	16.9	81.9	307.7	329.3	422	341.5	313.6	146.8	159.3	214.4	124.1
1963	5.3	36.3	116.7	235.6	458.2	334.2	206.7	200.2	129.7	181.5	57.2	39.2
1964	177.6	93.5	124.5	179.1	96.2	509.9	49.3	101.5	319.7	106.6	36.3	48.9
1965	43.2	37.3	49.7	174.2	431.1	251.2	230.2	138.4	250.1	128.2	193	78.3
1966	51.3	181.8	245.4	220.7	289.2	383	268.5	252.8	253.9	181.2	102.8	9.2
1967	148.6	63.3	215.9	262.9	84.9	274.7	280	208.2	73.3	213.9	238.4	22.8
1968	62	55	267.5	142.5	204.5	293	484.5	514.5	35.5	85.5	74	242
1969	105	143.5	210.5	229.5	153	546.5	303.5	359	157	78.5	106	45
1970	96	102.5	77	163	232.5	430.5	271.5	208	159	135	63.5	94
1971	44	81.5	213.5	222.5	214.5	112	211	399	230	243.5	16.5	101
1972	76.5	163	275.5	299	250	317	538.5	175	428	58	113	102
1973	263.5	87	29.5	253	264	131.5	176.5	243	187.5	278.5	84	0
1974	22.5	117.5	163	457.5	152	335.5	789	277	379.5	170.5	42	98
1975	104.5	117.5	171	209	161.5	158	273	243	165	346	161.5	91.5
1976	0	255	240	205.5	353.5	359	216.5	179	287	166.5	110	119
1977	34.5	57.5	334	261.5	223.5	324	169.5	269.5	370	31	187	101.5
1978	37	68.5	99.5	232.5	181	280.5	185.5	136.5	288	191	115	45.5
1979	67	140	265	242	220	123	228.5	274	233.5	270	228	60
1980	129.5	22.5	245.5	284	285.5	334.5	470.5	212	259.5	167	148	37.5
1981	23.5	77	298.5	364	174	168.5	332	360.5	234.5	339	176	20
1982	52.5	112	217.5	156.5	121	225.5	442.5	524	695.5	111	248	54.5
1983	55.5	43	241	381.5	278	476	192.5	605	479	199.5	40.5	17
1984	38.5	96	101	125	105.5	372	52	213	86.5	34	78	46.5
1985	23.5	152.5	319	241.5	185.5	483	89	277	209.5	101	111.5	13.5
1986	26	56.5	219	177.5	293	185	272	255.5	172.5	72	28.5	170
1987	107.5	63	281	91	318	185	256	347	350.5	95.5	60	35
1988	30	40.5	208.5	237.5	118.5	444.5	214	317	471	66	69.5	1
1989	174	323.5	195	267	180	364.5	232.5	230	262.5	172	191.5	33
1990	91	267.5	195.5	189	400	341.5	231	255	544.5	125	190	29.5
1991	67	69.5	271	210	123	313.5	219	176	577	426	125	65.5
1992	43	63.5	211	271.5	279	273	152.5	145.5	206.5	240.5	219	129.5
1993	97.5	146	90	85.5	135.5	273	567.5	149.5	264	254	182.5	129.5
1994	66.5	72.5	153.5	221	259	147.5	168	37	252.5	74.5	65	31.5
1995	77.5	31.5	205	251	313	125	249.5	18.5	96	132	112.5	6.5
1996	59	34.5	342.5	53.5	89.5	219.5	330.5	146.5	128.5	125.5	139.5	142.5
1997	17	68	153.5	254	113.5	274.5	400.5	47.5	175	21.5	337.5	46.5
1998	180.5	122	204.5	468.5	366.5	362.5	316	486.5	484.5	365	3	39.5
1999	27.5	89	252	205.5	365.5	355.5	211.5	168.5	257	50.5	168	1
2000	112	27	178	197.5	122	433.5	205	194.5	354	227	234	21
2001	185	95	102	62	119	200.5	27.5	263	437.5	315.5	149	53

2002	139.5	46.5	212	80	161.5	281	398.5	153.5	246.5	289	25	98.5
2003	146	60.5	215.5	240.5	251	126.5	704.5	834.5	217	139.5	335.5	39.5
2004	27	93.5	147.5	230	258.5	641	174	233.5	289	957	184	156.5

Appendix – VI Temperature in Region Around Sakuma (^oC)

Table 9: Average monthly temperature in region around Sakuma dam (Celsius) (JMA, 2012)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1957	7.8	5.6	8.3	14.5	17	20.3	24.7	26.6	21.1	17.9	13.7	9.1
1958	6.1	7.6	9.8	15.2	18	22	25	26.3	23.8	16.9	12.7	9.4
1959	5.5	9.2	10.7	15.1	18.5	20.8	26	26.4	24.5	18.5	14.2	9
1960	6.2	8	10.8	14	18.2	21.5	25.8	26.6	24	18.6	14.1	7.8
1961	5.1	5.7	9.5	15.1	18.9	22.2	27	26.8	25.2	20.4	14.3	8.5
1962	5.5	6.8	9.3	14	17.7	21.2	25.2	27.3	24.2	17.5	12.7	8.9
1963	3.3	4.8	8.6	14.5	18.6	22.4	25.6	26.1	21.5	17.6	13.3	9.2
1964	7	5.8	8.7	16.4	19.1	21.2	25.6	27.1	23.5	17.9	12.7	8.4
1965	6.4	6.2	7.9	11.6	18	22.3	25.6	26.3	22.1	17.2	14.3	7.8
1966	5.3	8.7	10.8	14.7	17.7	20.6	25	26.4	23.7	18.3	13.5	7
1967	5.1	5.5	9.8	14.3	19.1	22.6	25.8	27.1	23.7	17.6	14.2	6.8
1968	6	4.2	10.2	14.1	17.7	21	24.2	26.2	22.6	17.5	13.7	10.5
1969	6.8	7.5	9.1	14.9	19.6	20.9	24.3	26.6	23.4	18	13.2	7.7
1970	5.4	7.4	6.9	13.5	19	20.7	25.1	26.3	24.4	18.3	13.3	7.9
1971	6.3	7.4	9.3	14	18.3	21.7	25.9	27	23.1	17.2	13.2	9.3
1972	9	8	10.3	14.3	19	22.1	25.8	26.7	23.6	19.4	13.6	9.1
1973	7.7	8.2	9.5	16.7	18.1	20.7	25.8	27.3	22.7	17.9	12.5	6.6
1974	4.9	7.1	8.9	15.3	19.1	22.4	24.1	27.1	22.9	18.7	12.6	8.2
1975	5.9	6.1	9.3	14.7	18.7	22.1	25.5	26.3	25.1	18.3	14	7.6
1976	5.6	8.6	10.3	13.7	18.2	21.9	24.2	26.2	22.6	18.1	12.7	8.1
1977	4.6	5.7	10.8	15.4	18.7	21.8	25.8	25.7	24.4	19.4	15.4	9.8
1978	6.8	5.5	9.2	14.4	18.8	22.9	27.1	27.8	23.8	18.5	13.7	9.1
1979	7.3	9.4	10.2	14.5	17.9	23.7	24.8	27	24.3	19.6	14.9	10.1
1980	6.5	5.7	9.7	14.3	18.7	22.9	24.8	24.9	23	18.6	14.2	7.3
1981	4.4	6.3	10.1	14.4	18.1	21.7	25.9	26.1	22.1	17.7	11.7	8
1982	6.3	6.4	10.5	14.3	20	21.3	22.7	25.6	22.5	18	15	9.3
1983	6.5	6.2	9.3	15.7	19.4	21.1	24.9	27.2	23.6	18.3	12.2	6.9
1984	4.4	4.3	6.7	13.1	17.7	22	26.4	27.4	23.6	18.3	13.5	8.5
1985	4.8	7.4	10.6	15	19.1	20.8	26.9	26.9	23.8	18.4	13.1	7.8
1986	4.6	5.1	9.2	14.3	17.8	21.3	24.6	26.3	24.1	17.5	13.5	9.5
1987	7	7.6	10.6	14.6	18.8	21.9	26.4	27	23.7	19.6	14.2	9.3
1988	8.3	6.3	9.7	14.6	18.3	22.1	23.5	26.4	24	18	11.7	7.7
1989	8.9	8.4	10.2	15.1	17.9	20.7	24.4	26.9	24.9	18.3	13.8	9

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1990	6.5	9.5	10.9	15	18.2	22.8	25.8	27.8	24.7	19.6	15.1	9.4
1991	6.4	6.3	10.7	15.6	18.5	23.5	26.6	26.2	24.6	19.2	13.8	9.7
1992	7.9	7.7	11.3	15.5	17.3	21.1	25.3	26.2	23.5	17.9	13.9	9.5
1993	7.9	8.8	9.4	14	17.7	21.5	23.2	25.5	22.9	17.7	14.4	9.5
1994	7.3	6.8	9.2	15.9	19.4	22.2	27.9	28.1	24.7	20.7	14.4	10.1
1995	6.7	7.1	10	14.7	18.6	21.2	26.2	28.7	23.6	19.8	12.5	7.3
1996	6.8	5.8	9.9	12.2	18.3	22.4	25.8	26.3	22.9	18.3	14.6	8.7
1997	6.4	7.2	11.3	15.1	18.8	21.8	26	26.8	24	18.2	14.8	9.9
1998	6.4	8.4	11	17.1	20.9	22.6	25.8	27.5	24.6	20.6	14.4	9.9
1999	6.8	7	11.2	14.8	19.3	22.2	25.8	27.6	25.9	20.3	14.5	8.9
2000	8.3	5.9	9.6	14.9	19.6	21.8	26.2	27.2	24.4	19.3	14.9	9
2001	5.9	7.3	10.4	15.3	19.1	23.3	27.5	26.6	23.6	19.2	12.8	8.2
2002	7.4	7.8	12.3	16.4	18.7	21.4	27.3	27.9	23.5	18.8	11.9	8.8
2003	6.1	7.7	9.5	16	18.8	22.8	23.4	25.9	24.7	18	15.8	9.5
2004	6.2	8.4	10.4	16.3	20.3	23.6	27.8	27	25.4	18.7	15.6	10.8