Analysis of Reservoir Sedimentation Process Using Empirical and Mathematical Method: Case Study – Koga Irrigation and Watershed Management Project; Ethiopia

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Abstract

Artificial lakes created by dams are used for the development of water resources projects. The construction of dam for water storage changes dramatically the hydrodynamic of the river system by formation of sediment storage at the head of the reservoir to form delta and back water deposition. Suspended sediments are further transported by density currents through the old river channel in reaching at the end of the dam section and even some may pass through the bottom/irrigation outlets.
Koga reservoir is selected as a case study due to particularities and importance of this reservoir for water management. The river is one of the major tributary of Gilgel Abay River, which drains to Lake Tana.
The amount of sediment deposit and the distribution pattern could be estimated by using empirical methods but also could be simulated by using mathematical methods. Nowadays, due to advancement of technology, mathematical methods are more and more used tools to simulate the sedimentation process in time.
There are several models which take in consideration the two or three dimensional sediment distribution in the reservoir and DELFT3D model is selected to simulate the sedimentation process for this case study. The long duration simulation for sediment distribution pattern is carried out for fixed and variable water level at the downstream boundary. The second scenario represents the real situation of the dam operation whereas the first scenario is used for the comparison of the results.

Keywords: Koga reservoir, Reservoir sedimentation; Empirical methods; DELFT3D; Water balance; Delta formation, flushing.

1. INTRODUCTION

Dams alter morphological equilibrium due to changes in the hydraulic conditions as well as trapping of the sediment in the reservoir and reducing the flow velocity since the geometry is changed. A reservoir changes the hydraulics of flow by forcing the energy gradient to approach zero. This results in a loss of transport capacity with the consequent of deposition.

Agricultural cultivation is dependent on the amount and duration of the rainfall in the country as a whole and in the region particularly. Realizing the erratic nature, high temporal and spatial variability of rainfall in the region, the construction of dams for irrigation has been a priority for the government for the last decade with aspiration for food security. Due to this, several micro earth dams are constructed by Commission for Sustainable Agriculture and Environmental Rehabilitation for Amhara Region (CO-SAERAR). But some of them are not functional as planned due to sedimentation problem and hence; the bottom/irrigation outlet is clogged by the deposited sediment. This is due to inadequate and unreliable hydrological and sediment data availability, which are crucial for technical design.

2. PROJECT LOCATION

The case study project is located within the Koga Basin in Mecha Woreda of Amhara National Regional State, Ethiopia at latitude of 11^0 $10^{'}$ N to 11^0 $25^{'}$ N, and longitude of 37^0 $02^{'}$ E to 37^0 $17^{'}$ E. The Koga River is a tributary of Gilgel Abay River in the headwaters of Blue Nile that drains to Lake Tana. The reservoir has a capacity to impound a total volume of 83.1MCM of water at full supply level (2015.25masl) by inundating 18.56km^2 to irrigate 6,000ha command area.

2.1. Objectives of the Study

The main objective of this study is to study and forecast the sedimentation process and distribution pattern in the reservoir. Some specific objectives of the study are:-

- To estimate the volume of sediment deposited in the reservoir for the design period using empirical methods.
- To study hydrological water balance of the reservoir;
- To simulate different scenarios using mathematical model to study the sediment distribution pattern and flushing effects;

3. SEDIMENT YIELD ESTIMATION

The large variety of sediment yield estimation methods can be placed into two broad categories: methods based on direct measurement (i.e. measurements of hydrologic, hydraulic, and sediment parameters in the study area) and mathematical methods.

Sediment data is required in order to establish the potential loss of capacity in the reservoir due to sedimentation over the design life of the project. To estimate the quantity of sediments at the dam site, it is analyzed using the measured sample data at the stations and using empirical equations.

3.1 Using Measured Sample data

There is discharge measuring station at the dam site and there is also a long duration discharge data at Gigel Abay station. Using the measured suspended sediment sample data, sediment-discharge rating curve is developed and the expected load is calculated using the sediment rating equation given below.

$$\text{Load (t/d)} = 7.69 \times Q^{1.83} \tag{1}$$

Where: Q is daily discharge (m^3/sec)

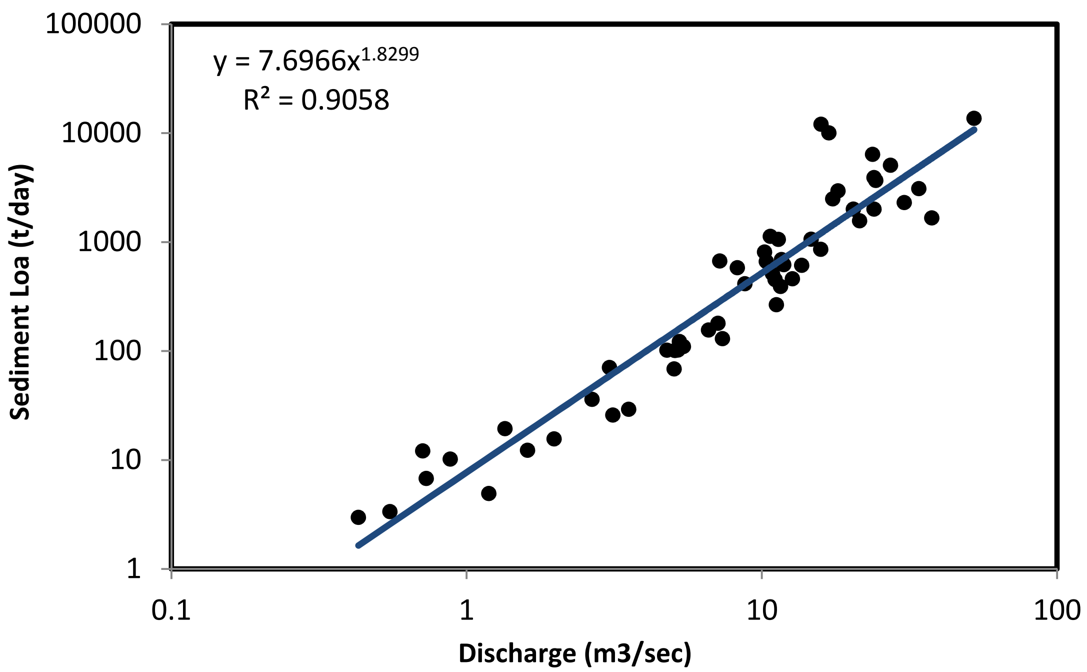


Figure 1: Koga river sediment rating curve

Hence the average yearly sediment volume coming to the reservoir is 46,318.01m^3, which is equal to 302.3t/km^2/year

3.2 Using Regional Sediment Yield Equation /USLE/

The total catchment area of Koga irrigation project is around 18,973 ha. Using different factors which affect the sediment yield from the catchment, the total sediment yield is estimated and is found to be 384,583.3t/yr which is around 2024.1t/km^2/year**.**

4. ESTIMATION OF SEDIMENT DEPOSITION VOLUME

4.1. Based on Trap Efficiency

The trap efficiency of the reservoir is the percentage of the total incoming sediment retained in the reservoir. The sediment particle fall velocity and rate of flow through the reservoir are two of the primary factors upon which the reservoir tarp efficiency depends. The trap efficiency by Brune (1953) method is given empirically as shown below:

$$E = 100 * 0.97^{0.19^{\log(C/I)}} \tag{2}$$

Where C= the capacity of the reservoir.
I= Inflow to the reservoir
Using the above equation, the average trap efficiency for the reservoir is around 97% and the accumulated sediment at the end of design period is 2.23*10^{6}m^3.

4.2. Area-Increment Method (AIM)

Chirstofano (1953) develops the Area-Increment method which is based on the assumption that: -The sediment deposition will take place in the 'dead storage' region of the reservoir, and The sediment distribution can be approximated by reducing the reservoir area at each elevation by a fixed amount called an 'area reduction factor'.

Area-increment method is used to evaluating the sediment distribution based on the assumption that the area curve, after sedimentation, will parallel the original curve. This means that the sediment area is constant at all elevation and the sediment volume is uniformly distributed vertically above the new zero elevation. Using the fixed irrigation/bottom outlet elevation, the deposited sediment volume is estimated for the design period.

For the fixed irrigation outlet level at 2004.20masl, the volume of sediment accumulated in the reservoir is 2.43*106m^3. Since much volume of sediment is stored in the reservoir than estimated using trap efficiency for the fixed irrigation outlet, the elevation of the irrigation outlet is at good location with respect of sediment accumulated volume for the design period.

4.3. Area-reduction method (ARM)

According to ARM, the sediment distribution within a reservoir depends mainly on the shape of reservoir, sediment volume which will be deposited, sediment characteristics and the operation schedule of the reservoir. Since it takes into consideration the shape of the reservoir more than the AIM, it is usually more accurate in predicting bed elevation change near the dam.

The method consists of two main steps:

a. Classification of a reservoir as one of four standard types, and
b. An iterative calculation procedure to determine volume/surface area/depth relationship.

Reservoir Type Determination: - The shape of the reservoir, defined by the depth to the capacity relationship is considered the major factor in determining the sediment distribution within the basin.

According to Borland and Miller (1958), reservoirs are classified according to their shape and configuration as Lake, Floodplain-foothill, Hill and Gorge. For the koga reservoir, the type of the reservoir is lake.

The accumulated sediment volume using this method is $4.86*10^6$ m^3 at the end of the design period. The volume of the accumulated sediment is much greater than the estimated sediment volume using trap efficiency and hence the bottom outlet is at safe elevation.

5. WATER BALANCE AND RESERVOIR OPERATION

Water balance analysis and reservoir operations are used to determine the required capacity of the reservoir to irrigate the command area. The water balance of the reservoir is the water exchange between the inflow, stored water and the outflow. It is expressed mathematically by continuity equation as follows:

Change in storage (ΔS) = Inflow (I)-Outflow (O) (3)

Where: The inflow to the dam is: average river discharge, and outflows from the dam are seepage, environmental flow to downstream users, evaporation and water requirement for crops.

The data used for reservoir water balance analyses are obtained from Koga Irrigation and Watershed design documents and the average values are used to analyze. The water balance analysis is done by assuming the reservoir will start to accumulate water at the start of rain fall. The water level variation in the reservoir obtained after water balance analysis is used as a downstream boundary condition to simulate the reservoir for variable head case. The result shows that, the reservoir is filled by one year rainfall.

6. MATHEMATICAL MODEL SETUP

Mathematical modeling of the silting process in reservoirs has at present become an extremely powerful means of determining and forecasting sediment distribution within reservoirs. The erosion/deposition of sediments is analyzed by two dimensional depth average model of DELFT3D and the reservoir area under full supply level is selected for model setup.

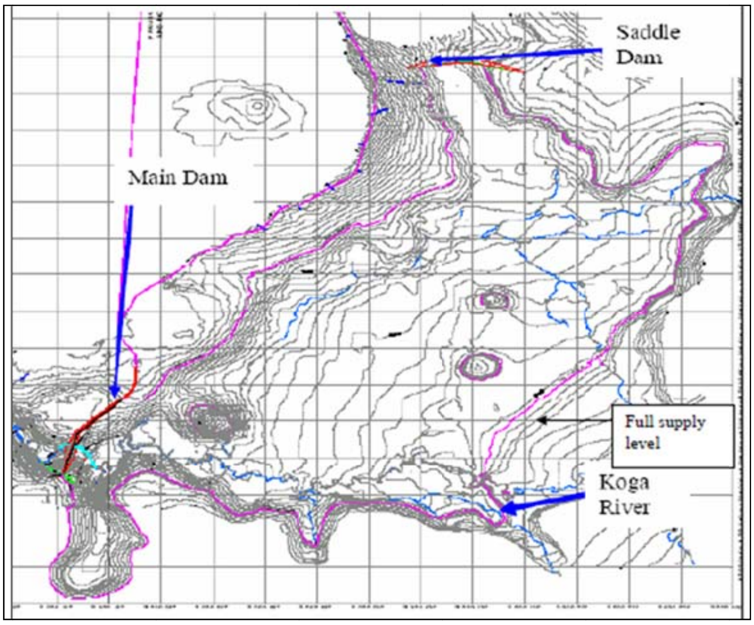


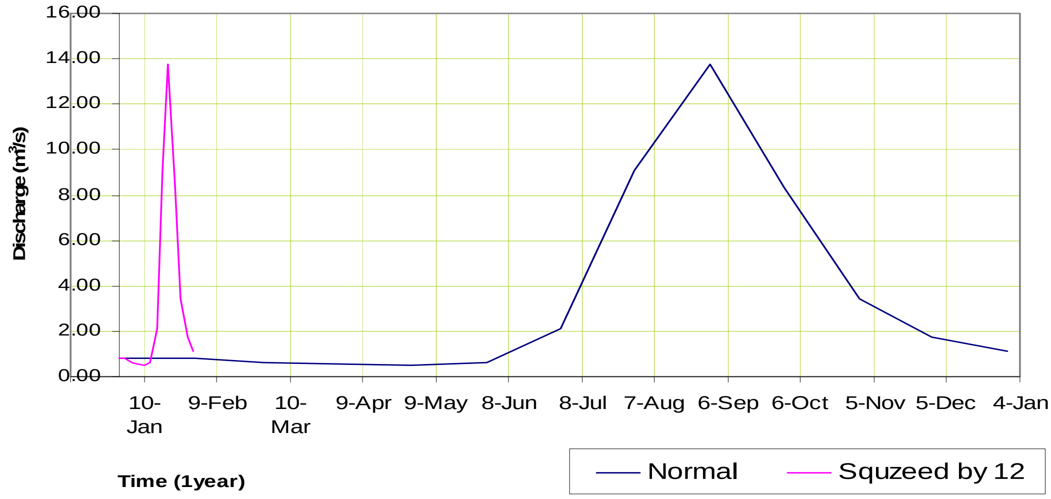
Figure 2: Topographic map of koga reservoir area

The FSL contour is used as a guide in REFGRID to develop a grid. The grid is smoothened and orthogonalized as much as possible. The final grid is used to do the sediment deposition simulation.

6.1. Data Required for Upstream and Downstream Boundary Condition

The data used for the study of sedimentation and deposition are squeezed by a factor called morphological time scale factor. It is used to multiply the erosion and deposition phenomenon. After trial tests, morphological factor of 12 is selected. Hence, simulation of the model for one month squeezed hydrological data using a morphological factor of 12 results one year morphological change.

U/s data for sediment deposition: - the normal and squeezed river discharge; and the corresponding sediment load hydrograph are used as shown below.



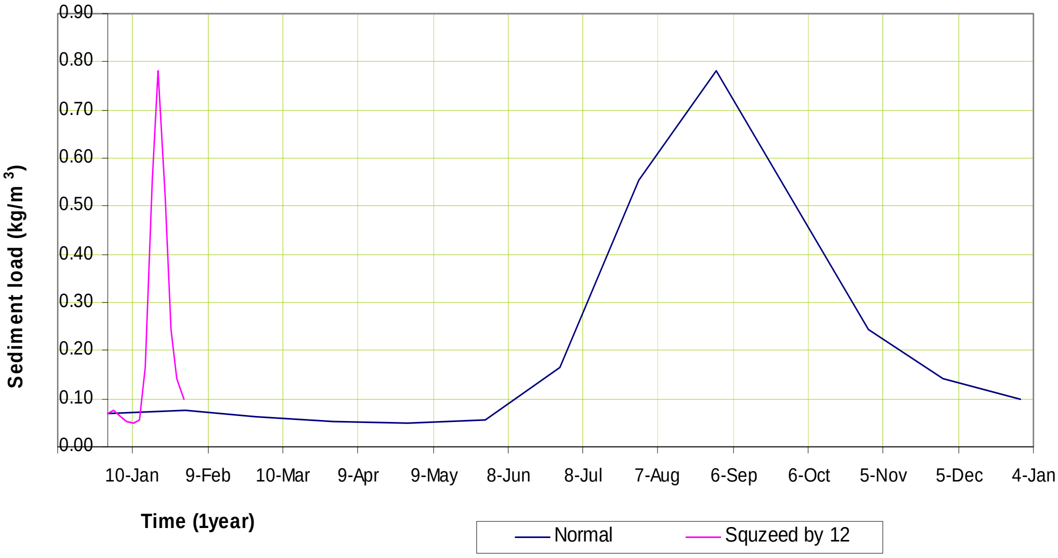
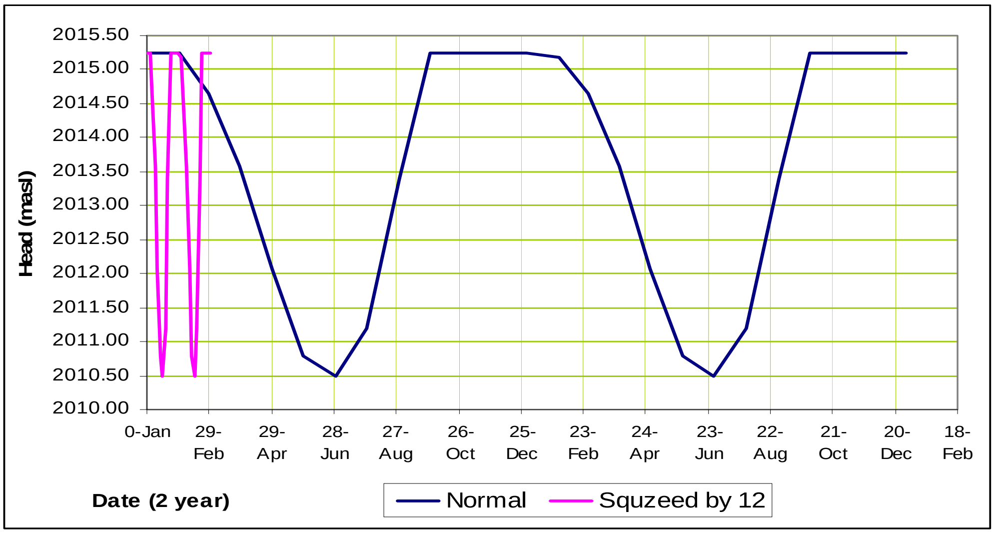


Figure 3: Normal and squeezed discharge hydrograph (SQ=12) (Left) and Normal and squeezed sediment load hydrograph (SQ=12) (right)

U/s data for flushing: - the daily river discharge and sediment load is used, since the flushing will be done within 35 days.

D/s data for sediment deposition: - The long duration simulation is done for two different scenarios: *variable* and *constant water level*. So, the downstream boundary is set either variable water level, according to the water needs at the downstream.

D/s data for flushing: - the water level drawdown within 35 days using open boundary is used as shown on Figure 4-B below.



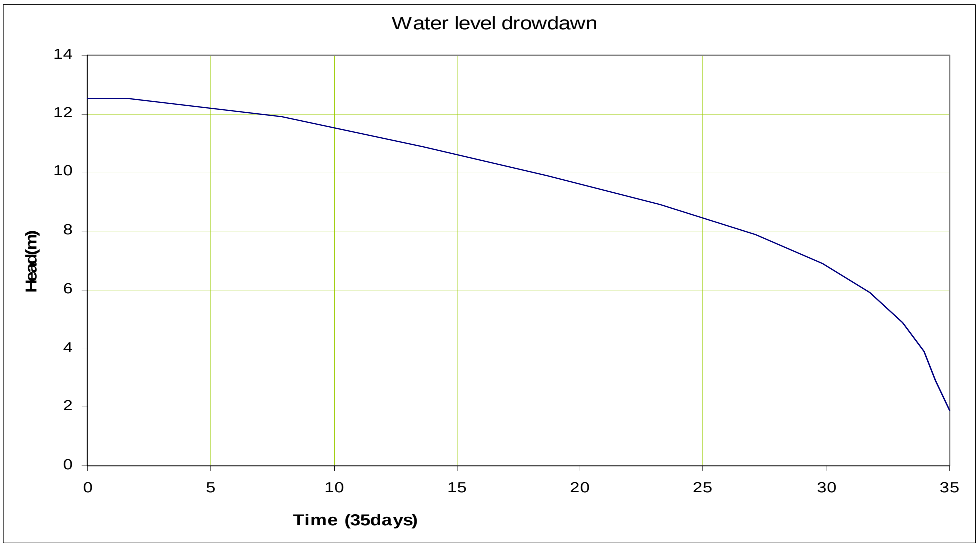


Figure 4: Normal and squeezed head level variation (SQF= 12) [Upper] and Head draw dawn during flushing [Lower]

The parameters used to simulate the model are introduced by using Flow sub-module of DELFT3D and adjusted according to the model stability. To select the stable parameter test simulations are also done and the following parameters are selected:

- Time step = 30 seconds
- Morphological time scale factor =12
- Squeezing factor = 12
- Horizontal eddy viscosity (V_H) = 0.5m^2/s
- Horizontal eddy diffusivity (D_v) variation = 1m^2/s

The Chezy's coefficient of the river is calculated and it is 32.

6.2. Result of Model Simulation for Constant Water Level

The model is simulated for 15years of morphological change using constant head at Full supply level as downstream boundary. For this case, most of the incoming sediments are deposited at the head of the reservoir and, back water and delta deposits are formed due to sudden increase of the geometry of the flow channel. The aggradation of the bed level is the most pronounced phenomena at the entrance to the reservoir.

6.3. Result of Model simulation for variable water level

The water level variation is the result of water balance analysis for average inflow and outflow discharge data's of the reservoir. This case is set as to represent the real situation of the reservoir water level variation. This model is also simulated for long duration (15 years).

There is much discharge going out from the model when the water level changes from full supply level to minimum operation level. And, when the water level changes from minimum operation level to full supply level, there is negative flow to the model due to the effect of squeezing the input data both upstream and downstream. This may have unexpected results near the dam area but may not influence the result near the entrance of the river as the effect doesn't reach there due to long distance. So, the model is simulated for time series head level variation at the downstream boundary accepting the effects near the dam.

When the water level is around full supply level, the delta deposition at the head of the reservoir increases in height and, when the water level is around minimum operating level, the deposit is pushed further by erosion of the materials along the channel and the incoming sediments are transported and deposited further to the middle of the reservoir resulting relatively steep slope of delta deposit. The figure below presents the cumulative erosion and depositions through time for the two case simulations. The initial bathymetry is used as a reference for the comparison of sediment deposition for the simulations done for constant and variable head.

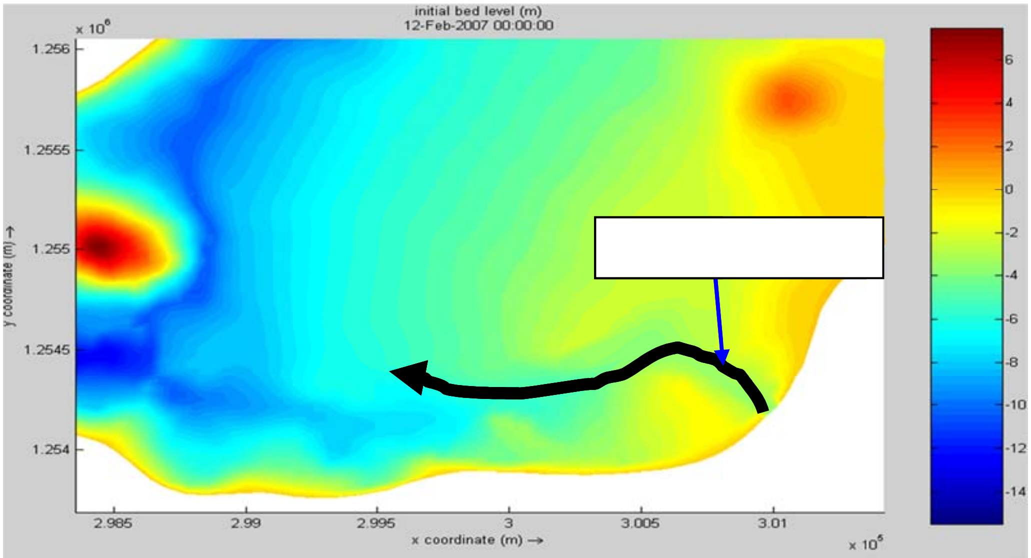


Figure 5: Initial bathymetry

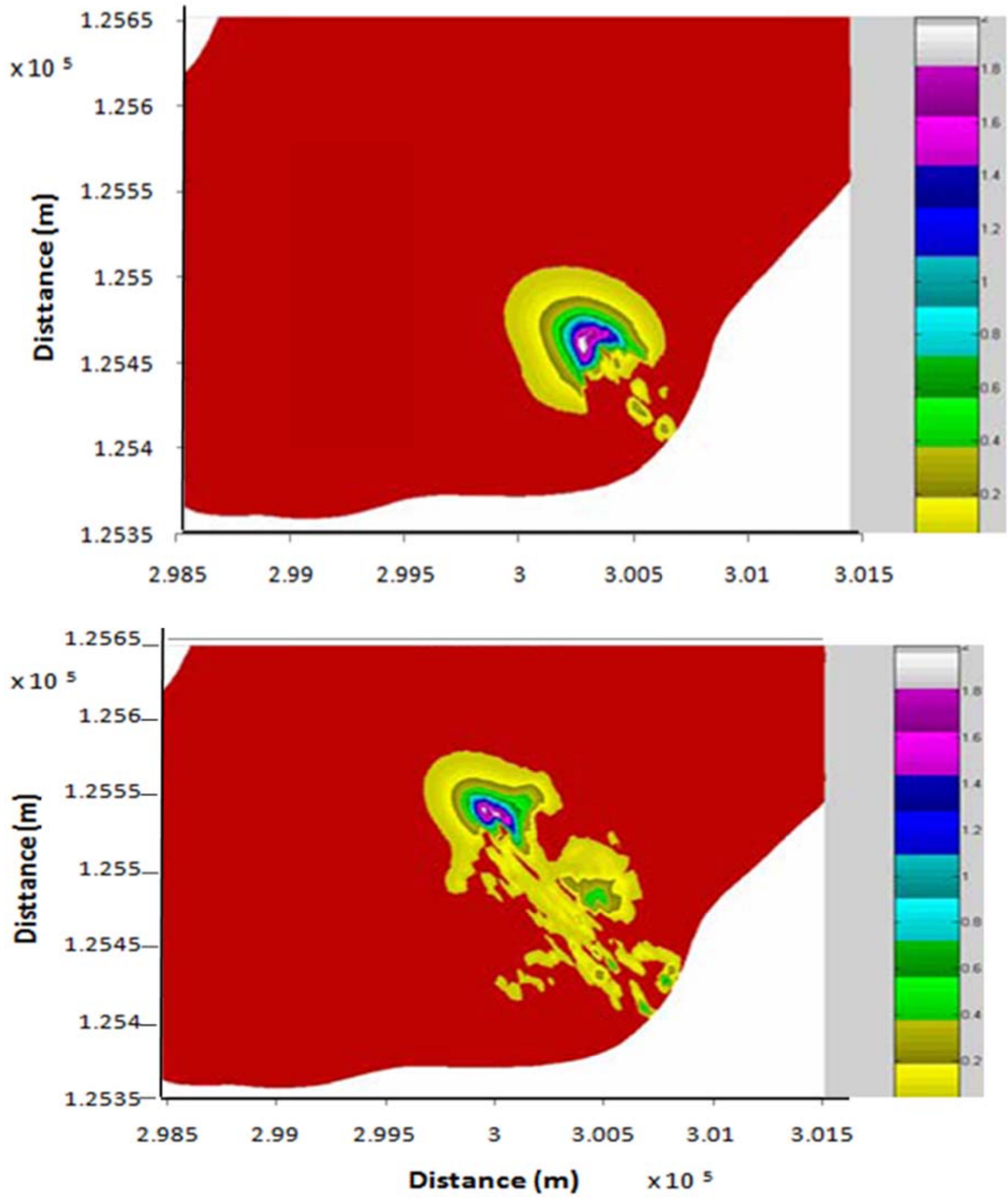


Figure 6: Sediment deposition at the end of ten year (Upper: constant, Lower: variable head)

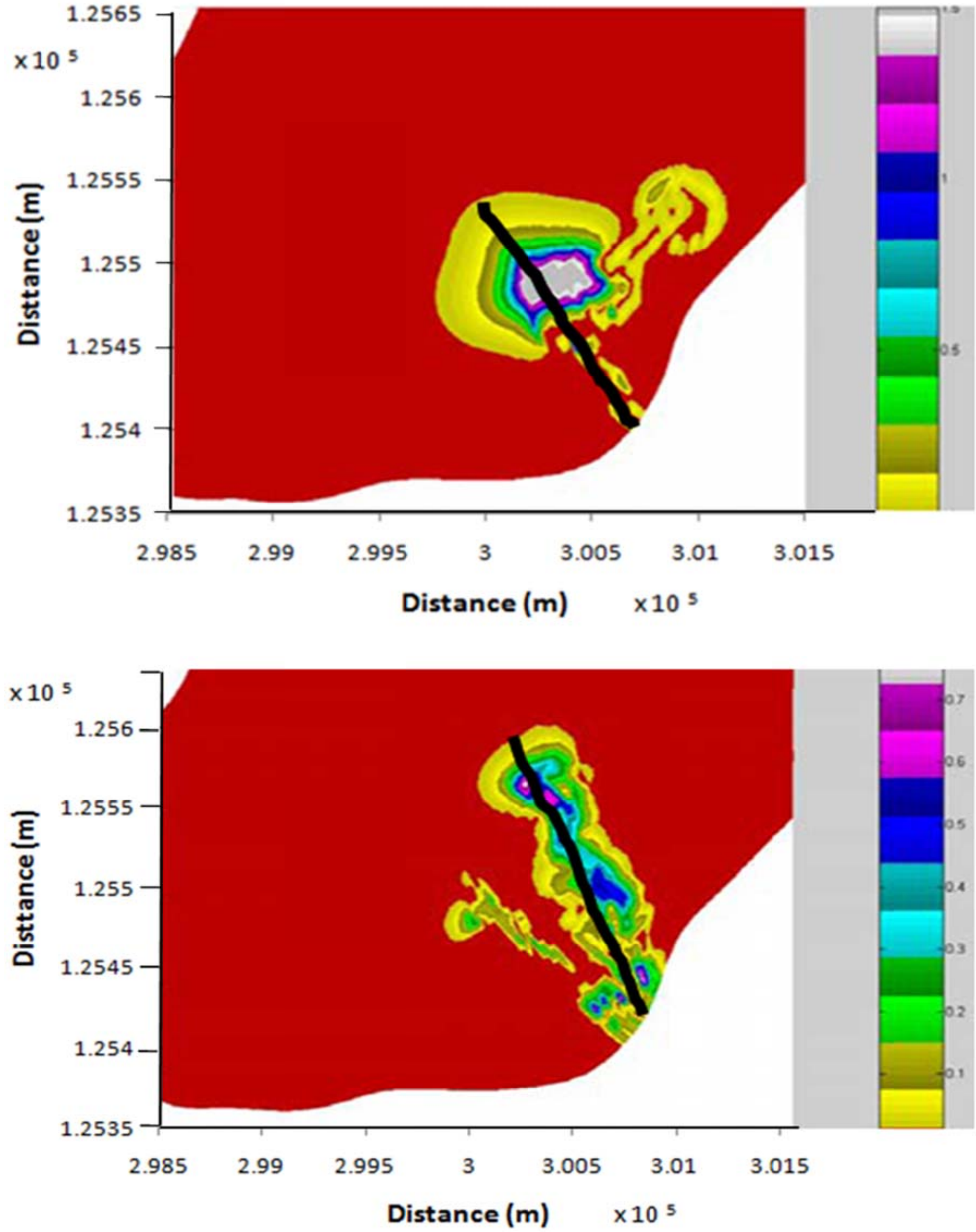


Figure 7: Sediment deposition at the end of fifteen year (Upper: constant, Lower: variable head)

To compare the bed level change through time, a seethe river bed variation is as shown below.

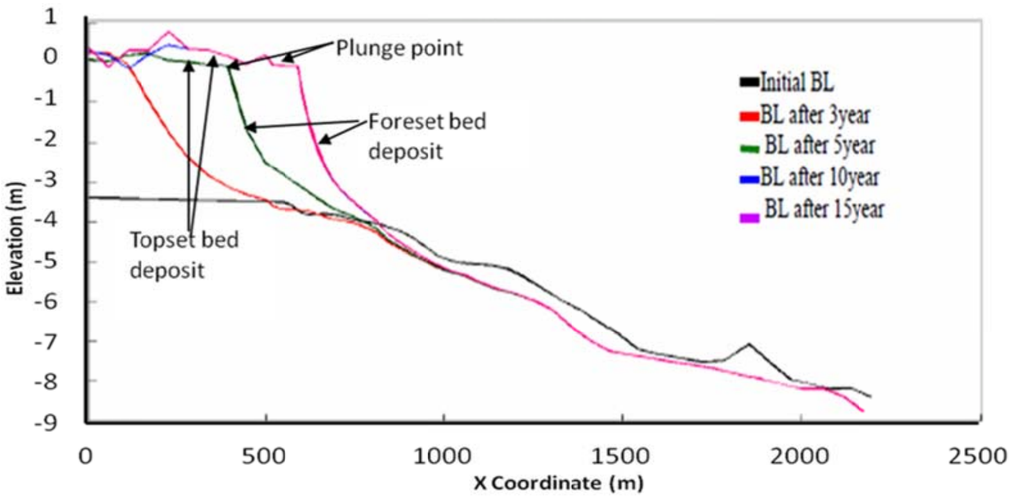


Figure 8: Bed level change through time for Constant Head Simulation

The cumulative deposition of sediments has gentle slope on the topset depsit and the bed level starts to rise through time and even becomes above the full supply level. Here, the plunge point, the foreset and topset delta deposits are clearly seen.

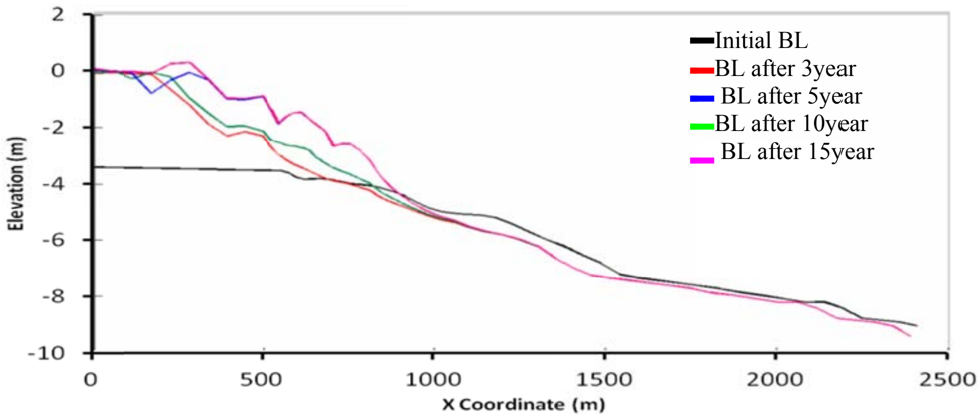


Figure 9: Bed level change through time for Variable Head Simulation

6.4. Result of Model Simulation for Flushing and Discussion

The water level is dropped from the full supply level to the bottom outlet level in short period of time during flushing. For this simulation, morphological factor of unity is used since the data is not squeezed by a factor and there is no need to accelerate the flushing process as the simulation time is small. The other parameters are kept the same with the constant and variable head model simulation.

Even if all the reach of the reservoir is eroded according to the material property of the reservoir area and compaction rate, the sediment source for flushing is set the deposited area after 15year simulation using variable head at downstream. The selected area is introduced to the model as eroadable layer and it is assumed that the deposited sediment is eroded during flushing.

During flushing simulation, an accelerated flow possess an increased stream power and consequently, both fine and coarse sediment particles from the deltaic deposits will be re-entrained, carried on towards the outlet. Retrogressive erosion is observed during drawdown of the water level. As the water level drops, the channel geometry is decreased; resulting high velocity of flow and this has a capacity to erode the deposited. The incoming sediment from the catchment is also carried to down wards and pass through the bottom/irrigation outlet.

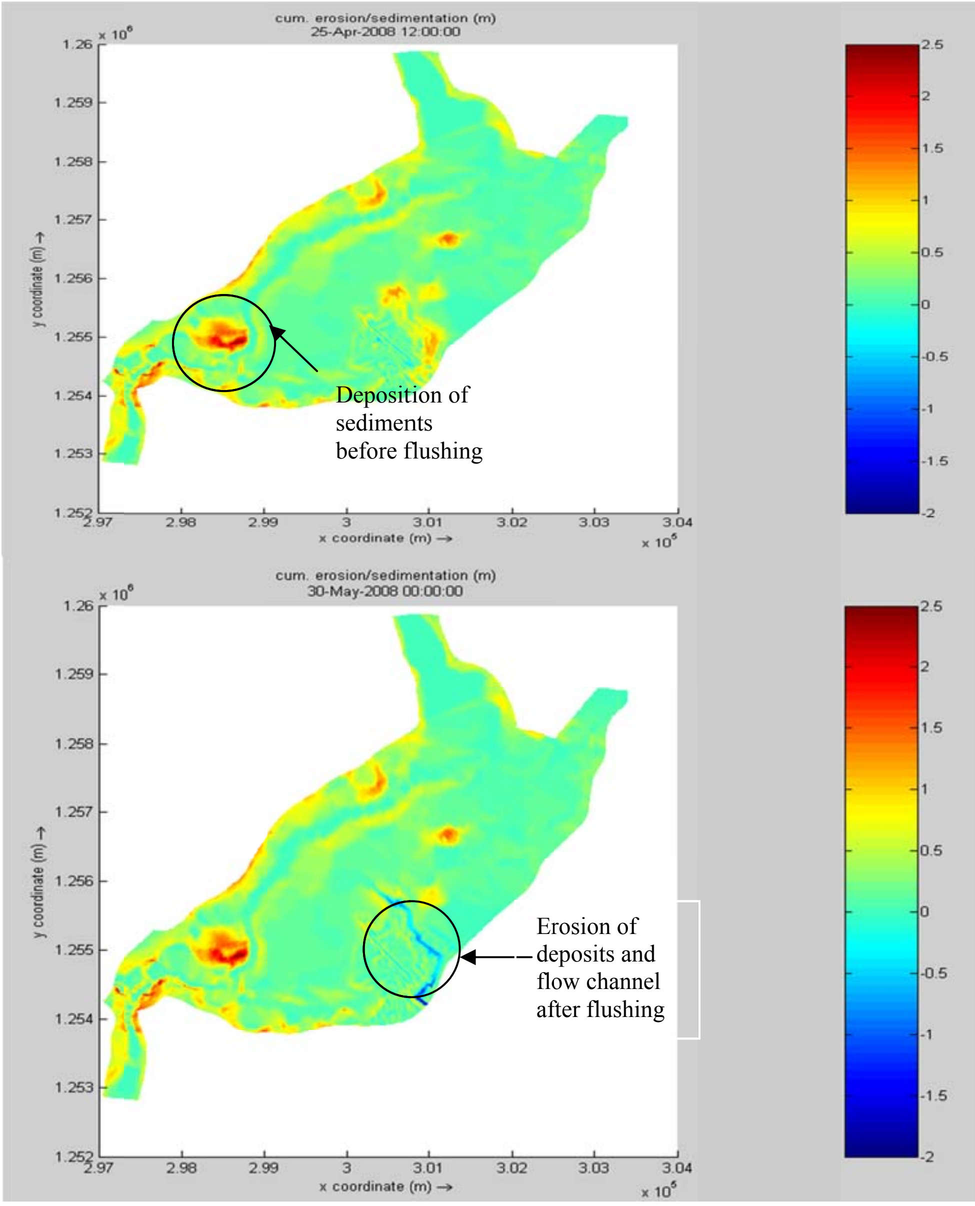


Figure 10: Initial bathymetry for flushing [upper] and Bathymetry after flushing [lower]

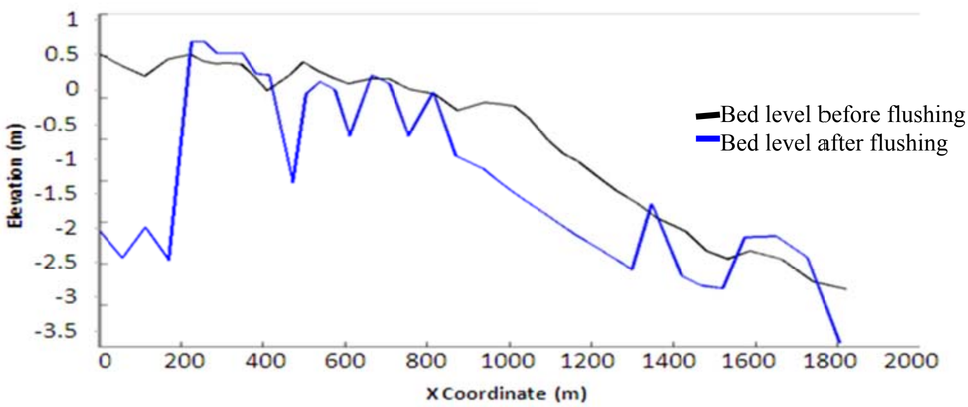


Figure 11: Bed level change before and after flushing along eroded channel

7. CONCLUSIONS

The following conclusions are formulated after analyzing the reservoir sedimentation based on empirical and mathematical methods.

- According to the result of empirical methods (Area-Increment and Area-Decrement), the location of the bottom outlet is at good position in relative to the sediment volume accumulated within fifty years.
- The developed delta has relatively steep slope in case of variable head simulation than constant head simulation.
- Plunge points, foreset bed and topset bed delta deposits are more clearly seen on the case of constant head than variable head simulation.
- The river bed aggradation created by backwater and delta deposits has greater height in case of constant head than variable head simulation.
- koga reservoir is wide, and flushing of sediments is not effective

8. RECOMMENDATIONS

The following recommendations are formulated for better analyses of the sedimentation process for the case study reservoir either using empirical or mathematical methods.

- There is large discrepancy on the volume of estimated sediment volume; hence it needs a detail study.
- Water balance the analysis using average value shows that the river discharge is enough to fill the reservoir in one year and the excess water is spill over. It is advisable to open the bottom outlet at the start of rainfall to bypass the sediment laden flow.
- The catchment treatment should be done by selecting hot spot areas,
- Detail water balance analysis and reservoir operation schedule should be done by determining parameters from measurement at the site rather than estimation from secondary data,
- It will be very important to study the formation of density currents for the case study. Koga reservoir is located on temperate zone where the temperature varies from 7^0c to30^0c according to nearby metrological station (Merawi). The river discharge also has high suspended sediment concentration. It will be very important to study the formation of density currents for the case study.

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