# ADDIS ABABA UNIVERSITY

## Addis Ababa Institute of Technology

## School of Civil and Environmental Engineering

***Hydrological and Hydraulic Modeling of Rib Reservoir and Ribb River for Predicting Downstream Morphological Changes***

**A thesis Submitted to Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University**

**In partial Fulfillment of the Requirement for the Degree of Masters of Science in Civil and Environmental Engineering**

**Major in Hydraulics Engineering**

**By**

**Wasyihun Degu**

**Advisor Prof. Yilma Seleshi**

**Addis Ababa**

**Ethiopia**

**May 2017**

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Approved by Board of Examiners

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| Prof. Yilma Seleshi ________________________ | _____________ | ______________ |
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| Internal Examiner | Signature | Date |
| ________________________________________ | _____________ | ______________ |
| External Examiner | Signature | Date |
| ________________________________________ | _____________ | ______________ |
| Chairman (Department of graduate committee) | Signature | Date |

# Declaration

I, the undersigned, declare that the thesis is my original work, and has not been presented for a degree at any university and that all sources of materials used for the thesis have been fully acknowledged.

Name Wasyihun Degu
Signature ______________

Addis Ababa Institute of Technology
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## ABSTRACT

***Hydrological and Hydraulic Modeling of Rib Reservoir and Ribb River for Predict Downstream Morphological Changes***

*Dams apply profound impacts on downstream river systems, primarily through significant hydrological alterations and a substantial reduction in sediment transport. By blocking the movement of sediment produced in the upstream watershed, dams drastically reduce the sediment input to the downstream river. The aim of this study was HEC-HMS Erosion and Sediment transportation modeling to estimate reservoir sediment deposition.and.to determine the extent of downstream river bed degradation and bank erosion through the application of HEC-RAS. The Ribb River is located in Nile River basin of Amhara regional state. The dam and diversion weir are located in South Gonder zone and East of Lake Tana, on Ribb River, on the side of Woreta-Debretabor road.*

*Hydrologic modeling, calibration and validation were performed at Addis zemen gauging station. To simulate the precipitation-runoff model, this consists of developing a hydrological model operating the Soil moisture accounting method as loss method, Clark unit hydrograph model as transform method and erosion model using MUSLE in the application of HEC-HMS. Elevation data, river cross-sections, Manning's roughness coefficients, and reach lengths were used as key inputs to simulate steady and unsteady water surface flow profiles, as well as unsteady sediment transport, using HEC-RAS. Additionally, controlled flow hydrographs generated from HEC-HMS were imported via HEC-DSS and applied as boundary conditions, enabling integrated hydrologic–hydraulic modeling for more realistic representation of flow behavior and sediment dynamics in the river system. The sedimentation analysis indicates that the rate of silt deposition in the study area result shows that the siltation will be 367 ton/ km2/ year.  In the downstream steady 30 kilo meters Ribb River cross section data collected from field surveying. River channel contour was generated and exported to Auto CAD ROB, LOB and Channel measurements were taken from the polyline. Unsteady flow sediment transport analysis was performed using new HEC-RAS 5.0.1.* The magnitude of the morphological changes are felt more just downstream of the dam 7m of scouring and 33% of width reduction, as compared to other locations far from the dam; which indicates these changes come due to the influence of the dam.

Key words: **HEC-Geo HMS, HEC-HMS, HEC-RAS, Reservoir siltation, River degradation**

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## ABBREVATIONS

| | |
|---|---|
| *Cumecs* | Cubic meter per second |
| *DEM* | Digital Elevation Model |
| *GIS* | Geographic Information System |
| *GUI* | Geographic User Interface |
| *HEC-DSS* | Hydrologic Engineering Centre Data Storage System |
| *HEC-Geo HMS* | Hydrologic Engineering Centre Geospatial Hydrologic Modeling System |
| *HEC-HMS* | Hydrologic Engineering Centre Hydrologic modeling System |
| *HEC-RAS* | Hydrologic Engineering Centre River Analysis System |
| *LOB* | Left Over Bank |
| *MoWIE* | Ministry of Water, Irrigation and Electricity |
| *NBCBN* | Nail Basin Capacity Building Network |
| *NMA* | National Meteorological Agency |
| *ROB* | Right Over Bank |
| *TIN* | Triangular Irregular Network |
| *WWDSE* | Water Works Design and Supervision Enterprise |
| *USACE* | United States Army Corps of Engineers |

# LIST OF SYMBOLS

| | |
|---|---|
| *A* | Area |
| *C* | Expansion or Contraction loss coefficient |
| *he* | Energy head loss |
| *K* | Conveyance for sub division |
| *n* | Manning's roughness coefficient |
| *P* | wetted perimeter |
| *Q* | Discharge |
| *Qs* | Volumetric sediment Discharge |
| *R* | Hydraulic Radius |
| *Sf* | Slope of energy grade line |

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# 1. INTRODUCTION

## 1.1 Background

Dams apply profound impacts on downstream river systems, primarily through significant hydrological alterations and a substantial reduction in sediment transport. The natural flow system is typically modified, with peak discharges reduced due to flood storage and regulation, while low flows may be elevated as a result of controlled releases for water supply, hydropower generation, or environmental purposes.

Beyond changes in flow magnitude, dams also modify the duration, timing, and frequency of flow events. Seasonal flood pulses that naturally shape channel morphology, sustain floodplain connectivity, and support aquatic ecosystems are often suppressed or shifted. These alterations disrupt sediment transport continuity, leading to sediment trapping within reservoirs and sediment-starved conditions downstream.

By blocking the movement of sediment produced in the upstream watershed, dams significantly decrease the amount of sediment delivered to downstream reaches. This reduction in sediment supply can lead to channel score, riverbank erosion, loss of habitat, and changes in river morphology and ecosystem dynamics. Sediment deposition in dam reservoirs does not only result in loss capacity of storage, but also influences placement of boulders, design of structures such as dam walls and intake towers and gate levels.

The effect of dam construction on the river channel around the world has increased as dam construction has increased. In 1900, there were 427 large dams i.e. higher than 15m, around the world, while in 1950 and 1986, there were 5268 and about 39,000 respectively (International Commission On Large Dams, 2009). At the same time, the awareness and understanding of variable effects due to the different types of impoundments have grown (S. Andres Brandt, 2000).

In the United States the construction of more than 75,000 dams and reservoirs on rivers in (Graf, 2006) has resulted in alteration of the hydrology, geometry, and sediment flow in many of the river channels downstream of dams.

Downstream geomorphic and ecological impacts of dams vary with the operational strategies of dams and with the characteristics of downstream river channels. Studies of regulated rivers have revealed varying responses including narrowing, widening, degradation, and aggradation occurring at different temporal scales (Xu, 2003).

Channel degradation often requires extra intervention in terms of river bed and bank protection works. This potentially induces further geomorphic channel changes and takes time to channel recovery. A number of studies have recently investigated how connectivity approaches can be used to understand complex environmental systems in order to provide a better understanding of geomorphic system response to changes (Brierley et al. 2006; People et al. 2012) and Flood mapping and modeling on Fogera flood pain (Yigerem Tsigie, 2011) but all of them didn't use the combination of two models HEC-HMS to predict reservoir sediment deposition and HEC-RAS unsteady flow sedimentation transport modeling to predict river channel change and the impact on irrigation water supply level.

The Ribb River drains the western slope of the high mountainous area east of the town of Debretabor, with a peak elevation of approximately 3050 m. In the low and middle segments of the river, especially in the extensive alluvial plains bordering the lake, the river meanders its way and flows slowly, causing serious river channel deposit, high water table and overflow of river banks during the rainy season (WWDSE, 2009).
The hydraulic model used in this study were HEC-HMS version 4.0 2013 and HEC-RAS version 5.0.1 2016. They are the family of a public domain generalized simulation models which were available for the Hydrologic engineering center /HEC/ which were developed by U.S. Army of Corps of Engineers, USA since 1988 (USACE, 2013 and 2016). An integrated watershed–riverine modeling framework was developed to simulate upstream sediment inflow, reservoir sediment deposition, and unsteady sediment transport processes. The objective was to evaluate how changes in sediment load and transport dynamics affect reservoir storage capacity and the morphological behavior of the downstream river channel.

### 1.2 Statement of the problem

Reservoir sedimentation is the process of sediment deposition into a lake formed after a dam construction. Dam traps excessive amount contract of the suspended sediment carried by river and all of the coarse grain sediment. It is originate from the catchments area, rivers system and settle in reservoir. As a river enters the reservoir, its cross section is enlarged, the water velocity is decreased and the major part of the sediment will be deposited at that location. This will increase reservoir siltation problem. Siltation of the reservoir has a considerable impact on the reservoir functions.

On the other way, the downstream river flows have very low sediment transport rate. The sediment starved flows naturally seek recapture some of the lost sediment by eroding the banks and bed of the river. The river bed degrades directly below the dam and deposits this sediment further downstream.

The degradation of the river waterway directly downstream from the dams causes the river channel to become deeper and narrower. This results in the formation of straight, single channels as opposed to multi-channel braided streams. The results are reduced channel capacity and decreases in the main canal discharge capacity.

### 1.3 Objectives of the study

#### 1.3.1 General objective

The primary goal of this study is to develop an integrated hydrologic and hydraulic modeling framework using HEC-HMS and HEC-RAS to simulate watershed runoff, assess reservoir sediment deposition, and predict morphological changes in the Ribb River.

#### 1.3.2 Specific objectives

1) Ribb River catchment modeling using HEC-HMS
2) HEC-HMS Erosion and Sediment transportation modeling to estimate reservoir sediment deposition.
3) To determine the extent of river bed degradation and bank erosion through the application of HEC-RAS
4) To analyze Ribb River morphological changes

### 1.4 Thesis Outline

The whole study of the report consists of six chapters divided in to different sections the background information, statement of the problem, general and specific objectives, and Significance of the study are discussed in chapter one. Basic information on the state of the art and detailed reviews of the literature is presented in chapter two. The materials and methods were Used in this paper are discussed in chapter three. The detail data analysis processes, discussion integrated watershed and riverine modeling of Hydrologic Modeling System (HEC-HMS) and Hydrologic Engineering Center River Analysis system (HEC-RAS) are described in chapter three. A grouping of selected methods and parameters are presented, this consists of developing a hydrological model operating the Soil moisture accounting method as loss method, Clark unit hydrograph model as transform method erosion model using MUSLE in the application of HEC-HMS. Steady flow water surface flow profile, unsteady flow water surface flow profile and sediment transport modeling are discussed in the HEC-RAS modeling. Chapter four describes result and discussion part. Conclusion, discussion and recommendation included the fifth chapter and References included in the last part of the thesis.

# 2. LITERATURE REVIEW

## 2.1 Hydrologic modeling

Hydrological models are characterizations of the real world system. Modeling of the rainfall-runoff processes of hydrology is needed for many different reasons the main reasons being limited range of hydrological measurement techniques and limited range of measurements in space and time (Beven, 2000). Therefore, it is necessary to develop a means of extrapolating from those available measurements in space and time to not gauged catchments and into the future to assess the likely impact of future hydrological changes. A wide range of hydrological models are used by the researchers, however, the applications of those models are highly dependent on the purposes for which the modeling is made (Beven, 2000) stated that many rainfall-runoff models are carried out purely for research purposes as a means of enhancing knowledge about hydrological systems. He also added that other types of models are developed and employed as tools for simulation and prediction aiming ultimately to allow decision makers to improve decision making about hydrological problems.

## 2.2 Model selection

To select most suitable modeling tool for any research, there are various conditions to be applied. It depends on the required output the model, availability of input data (precipitation, land use, terrain data etc.), accessibility of the model and price.

### Model formulation

All the mathematical models in the programs are deterministic. This means that boundary conditions, initial conditions, and parameters of the models are assumed to be exactly known. This guarantees that each time a simulation is computed it will yield exactly the same result as all the former times it was computed. Deterministic models are sometimes compared to stochastic models where the same boundary conditions, initial boundary conditions and parameters are represented with probabilistic distributions. Plans are under way to develop a stochastic capability through the addition of a Monte Carlo analysis tool.

**Model**

Model means the equations that represent the behavior of hydrologic system components. Computer models play important roles in essentially all aspects of water management. There is a great diversity of ways in which they are applied. During the construction era of the1950s-1970s, model development was oriented toward the water management emphasis on planning and design of constructed facilities, and these types of applications continue to be important. Water management involves development, control, protection, regulation, and beneficial use of surface (rivers and reservoirs) and ground water resources (Wurbs, 1994).

System software regulates the operations of the computer and serves as an interface between applications programs and hardware. The operating system is the most important component of the system software. Applications programs include program development software; commercially or free available applications programs used in many fields including possibly water management; and models developed specifically for water management applications (Wurbs, 1994).

The USACE Hydrologic Engineering Center (HEC) was established in 1964 to develop generalized computer programs and related technical support services for the field offices involved in the USACE water resources development program. Over the years, the HEC has developed numerous computer programs. Many are widely used by other agencies, consulting firms, and universities, as well as by USACE offices (Wurbs, 1994).

## 2.3 HEC-HMS Hydrologic Modeling

The Hydrologic Engineering center’s Hydrologic Modeling System (HEC-HMS) version 4.0 was approved for public release December 2013. It is designed to simulate the Precipitation-runoff process of dendritic watershed arrangements. The fourth major release is called version 4.0 and focuses primarily on new component features. Existing areas of the program continue to be enhanced with more methods for representing physical process, particularly on meteorological model. Surface erosion and channel sediment have been added along with preliminary capability for nutrient water quality simulation (USACE, 2013).

**HEC-HMS Model Files**

There are different model files should be developed by HEC-HMS. These files include background shape files, the basin model file, the meteorological model file, and a project file. Basin model is the back ground map imported from Geo-HMS. To complete the model, hydrologic parameters need to be estimated and entered into the basin model using HEC-HMS. We need to develop a meteorological model to represent the precipitation and control specifications to define the simulation time window. When these three model components are completed, we can compute a simulation run and calibrate the hydrologic model.

**Model components**

Model components are used to simulate the hydrologic response in watershed. The primary Model components are basin models, Meteorological models, and control specifications. In addition to that input model components, such as time-series data, paired data and gridded data are often required as parameter or boundary conditions in basin and meteorological models.

**1) Basin Model**

Basin model is the physical description of a watershed. It is one of the main components of in a project. The main purpose is to convert the precipitation in to a stream flow at a specific location in the given catchment. Hydrologic elements are used to break the catchments/water shed in to manageable sub basins. They are connected in a dendritic basin network to simulate runoff processes. The descriptive data (basin) is imported from GIS extension tool HEC Geo HMS. The data can be edited using HEC-HMS.

Basin elements are: Sub basin, reach, tributary junctions, reservoir, diversion, source and sink. The development of a basin model requires the specification of such elements and data that controls their 'behavior’.

Ribb river catchment has three sub-basins with the stream gauge located near Addis zemen. The basin map is extracted from the Geo-HMS with the coordinate of the gauging station and provided with four reach and a common point junction.

The Basin Model uses the following spatial data:

- River reaches files for stream network with junctions and dam reservoir.
- Stream parameters (Muskingum K and X)

- Sub-basin data components: Loss parameters, routing parameters, and base flow values and computation methods.
- Dam outlet point

**2) Meteorological Model**

The Meteorological Model is one of the main components of in a project and it is responsible for preparing the boundary conditions that act on the basin during continuous simulation. The meteorological model can apply both point and gridded precipitation and has the capability to model frozen and liquid precipitation along with evapotranspiration.

In this study Debretabor and Nefasmewcha 25 years (1990-2015) daily time series data was used for continuous simulation.

**3) Control Specifications**

Control specifications are components in HEC-HMS model projects. Their principle purpose is to regulate when simulation starts and ends. Information in the control specifications includes a starting date and time, ending date and time and computation time interval. The time step for HEC-HMS model calibration for the catchment is divided into different time steps as for calibration, simulation and verification.

**4) Input data**

Time series data, paired data, and gridded data are often required as parameter or boundary conditions in basin and meteorological models.

**5) Parameters**

These are numerical measures of the properties of the world system. They control the relationship of the system input to the output and used as “tuning knobs” of the model. The parameter values are adjusted so that the model accurately predicts the physical system response.

**6) Boundary conditions**

These are the values of the system input-the forces that can act on the hydrologic and cause it to change. The common boundary condition in the program is precipitation and the upstream in flow, flow hydrograph to the channel reach.

## 2.4 HEC-RAS Hydraulic Model

The HEC-RAS software was developed at the Hydrologic Engineering Center (HEC), which is a division of the Institute for water resources (IWR), US Army Corps of Engineers. HEC-RAS allows to perform one-dimensional steady for hydraulics; one and two dimensional unsteady flow river hydraulics calculations, full unsteady flow sediment transport mobile bed modeling; water temperature analysis. The system is capable of modeling subcritical, supercritical, and mixed-flow regimes for streams consisting of a full network of channels, a dendrite system, or a single river reach.

**Working with HEC-RAS**

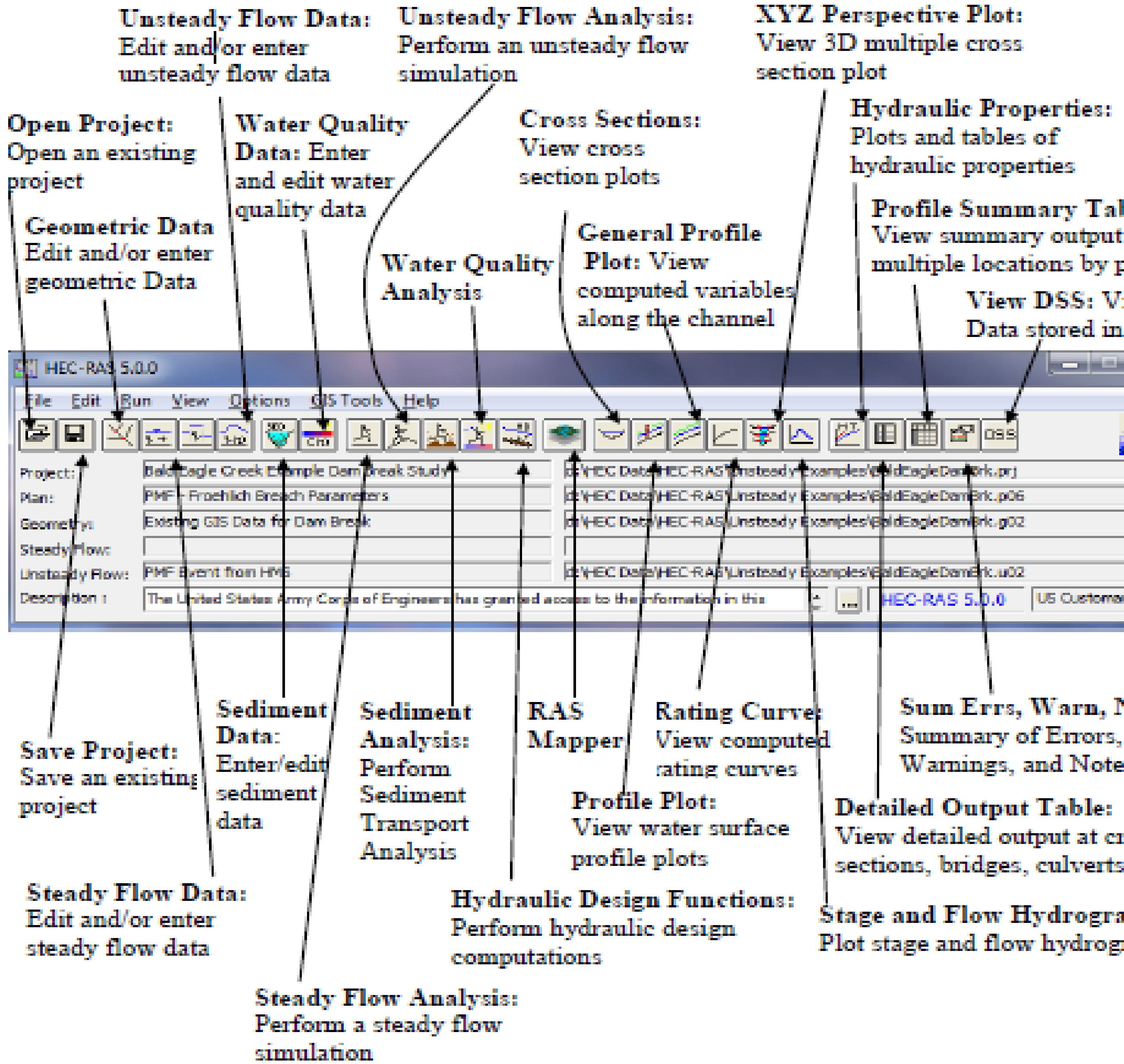



**Figure 2.1 HEC-RAS MAIN WINDOW BUTON BAR (HEC-RAS, 2016)**

**River Analysis Components**

Hydrologic Engineering Center River Analysis System (HEC-RAS) released a new version 5.0.1 February, 2016. The new version of HEC-RAS system contains four one-dimensional river analysis components for: (1) steady flow water surface profile computations; (2) unsteady flow simulation; (3) movable boundary sediment transport computations; and (4) water quality analysis (USACE, 2016) several new simulation features have been added to the software since the time.

**1) Steady flow water surface flow profile**

This component of modeling system is intended for calculated water surface profiles for steady gradually varied flow. The system can handle a full network of waterways, a dendritic system, or a single river reach. The steady flow component is capable of modeling subcritical, supercritical, and mixed flow regime water surface profiles. The basic computational procedure is based on the one-dimensional energy equation. Energy losses are calculated by friction (Manning's equation) and contraction/expansion (multiplied by the change in velocity head). The momentum equation is utilized in situations where the water surface profiles rapidly varied.

**2) Unsteady flow water surface flow profile**

Components of HEC-RAS modeling system capable of simulating; one-dimensional; two dimensional and combined one/two dimensional unsteady flow simulation through a full network of open channels, flood plains and alluvial fans. The unsteady flow component can be used to perform subcritical, supercritical, and mixed flow regime calculations in the unsteady flow calculations module.

Special features of unsteady flow component include; combined one/two-dimensional unsteady flow modeling; extensive hydraulic structure capabilities dam break analysis; levee breaching and overtopping.

**3) Sediment transport computations**

This component of the modeling system for simulation of one-dimensional sediment transport system/movable boundary conditions resulting from erode and deposition over moderate to long time periods.

The sediment transport potential is computed grain size fraction, by allowing the simulation of hydraulic sorting and armoring. Major features include the ability to model full network of streams, channel dredging, and the use of various equations for the computation of sediment transport.

The model is designed to simulate long term trends of scour and deposition in a stream channel that might result from modifying the frequency and duration of the water discharge and stage, or modifying the channel geometry. This system can be used to calculate deposition in reservoirs, design channel contractions required to maintain navigation depths, predict the influence of dredging on the rate of deposition, estimate maximum possible scour during large flood events, and evaluate sedimentation in fixed channels (USACE, 2016). Required data in HEC-RAS unsteady flow analysis.

Unsteady flow simulation and sediment transport analysis study was carried out using one dimensional HEC-RAS hydraulic model. The key data used in this model were field observation, Ribb River cross sectional survey works and the Ribb dam controlled flow series resulted from simulation of the HEC-HMS model.

**a) Geometry Data**

Ribb River cross section data represent the geometric boundary of the stream. Cross sections are located at relatively short intervals along the stream to characterize the flow carrying capacity of the stream and it’s over bank flow. To minimize unsteady modeling error the river cross section interval and unsteady flow computation interval time should be adjusted precisely.

**b) Flow Data**

Flow values can be imported directly from the HEC-HMS run for different hypothetical design storms or entered manually from the model run results. Steady Flow Data consist of: the number of profiles to be computed; the flow data; and the river system boundary conditions. At least one flow must be entered for every reach within the system. Additionally, flow can be changed at any location within the river system. Flow values must be entered for all profiles.

**c) Plan data**

Usually the first step in performing a simulation is to put together a Plan. The Plan defines which geometry and flow data are to be used, as well as provide a description and short identifier for the run. If the geometry and flow data do not exist, then this action is performed after their creation. Also included in the plan information are the selected flow regime and the simulation option.

## 2.5 Sediment transport numerical models

The transport of sediment particles by a flow of water can be in the form of bed-load, or suspended load, or both, depending on the size of the bed material particles and the flow conditions. The suspended load may also contain some wash load, which is generally defined as that portion of the suspended load which is governed by the upstream supply rate and not by the composition and properties of the bed material. Sediment transport plays an important role in the evolution of river beds, estuaries, and the coastlines; consequently it exerts a considerable influence on the evolution of the topography of the earth's surface. Therefore, the mechanism of sediment transport is of great interest to hydraulic engineers, coastal engineers, geologists, hydrologists, geographers, etc. ( Shervin Faghihirad,2014) Integrated modeling of sediment transport from watershed to dam reservoir and river bed degradation requires a quantitative and universally applicable law governing the motion of the transported sediment in all flow situations. One of the components of the new version of HEC-RAS system contains sediment transport/movable boundary computations, with details being given below (USAC, 2016): Sediment Transport/Movable Boundary Computations: This component of the modeling system is intended for the simulation of one-dimensional sediment transport/movable boundary calculations resulting from scour and deposition over moderate time periods (typically years, although application to single flood events will be possible ( Shervin Faghihirad,2014).

## 2.6 Reservoir sediment deposition

In most of the researches on dam reservoirs the observations focus on sediment deposition in the reservoir to increase the capacity of reservoir and its life time.

Reservoir sedimentation is a process that has been going on since the first dams were build and is a consequence of creating a calm reservoir lake where there used to be a fast flowing river. It eventually starts to influence the reservoir capacity and the river morphology. The siltation of the reservoir could hinder the usage of the dam and interfere with the functionality of the reservoir. With the sediments taking up space in the reservoir, the storage capacity of the reservoir is decreasing. If the sediments settle all the way towards the dam structure, the hydropower installation can be influenced by the sedimentation process as well. Also, the navigability of the river can be negatively influenced due to the fact that the river morphology is changing. It has an effect on the ecology too, since the continuous river flow is interrupted and fragile ecological equilibriums will be disturbed (K. Bronsvoort, 2013).

Sediment deposition in reservoirs does not only result in loss of storage, but also influences placement of sluices, design of structures such as dam walls and intake towers and effects flood lines upstream of reservoirs. The large number of methods available to model sediment deposition in reservoirs testifies to the need to predict its influence when designing such a facility. The complexity of the mechanism of sediment deposition is confirmed by the large number of empirical techniques (Annandale, 2000) that have been developed for this purpose.

## 2.7 River flow change

Dams change the pattern of flow of a river by both reducing the overall volume and changing its seasonal variations. The nature and extent of the impact depends on the design, purpose and operation of the dam. Gregory (1977) stated that the retention of water behind a dam and its gradual release downstream results in the reduction of peak discharge and regulation of flow regime. Reduction of peak flow discharges is achieved not only by the storage of flood water in the reservoir proper volume, responsible for reduction of 98% in peak flow when no over flow occurs, but also through the storage provided by the rise in water level above the over flow level.

The magnitude of mean annual flood has been reduced 60% of Colorado River downstream of Hoover dam in Gregory. Williams and Wolman (1984) have studied changes that occurred in alluvial channels downstream of 21 dams in semi-arid areas of western U.S, over a period of 70 years.

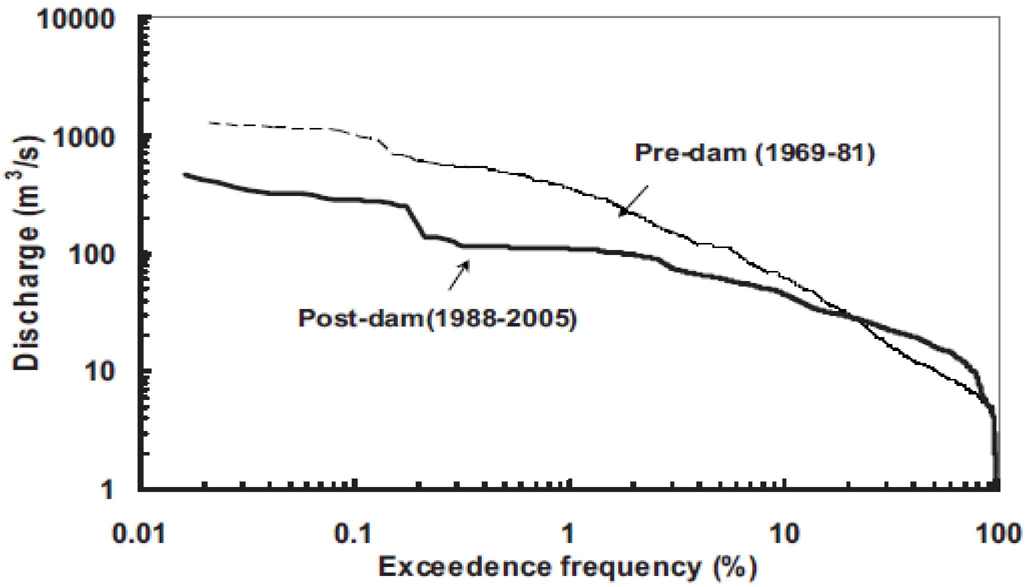



**Figure 2.0.1 Flow duration curves at Hapcheon Dam site from 1965-2005(Young and Julien, 2011).**

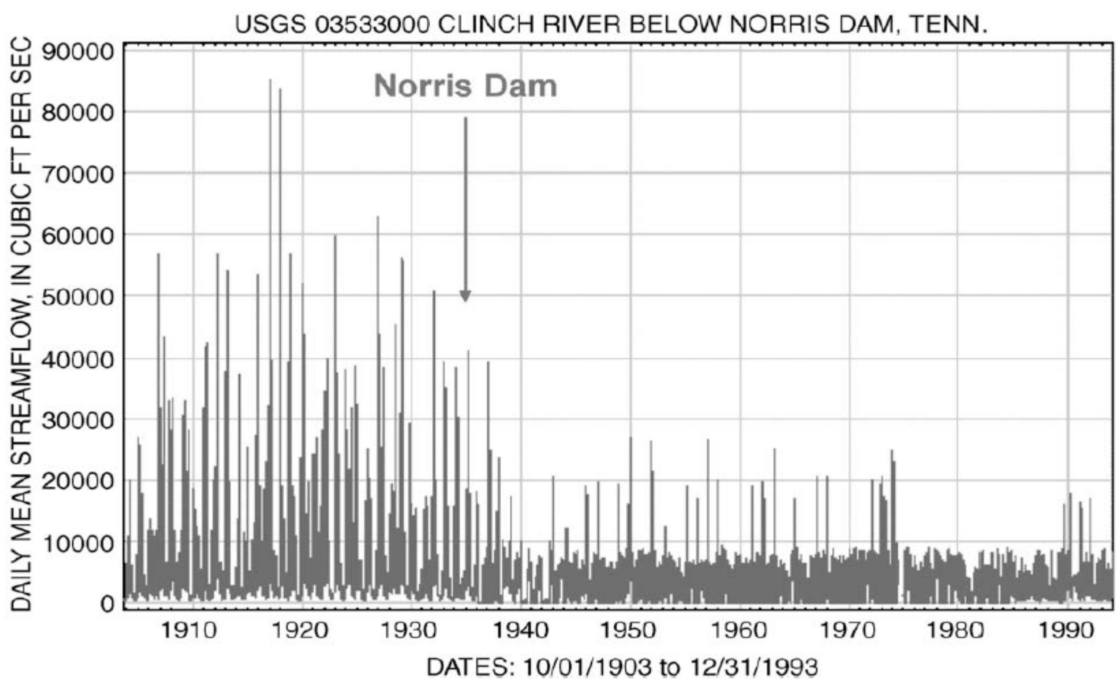



**Figure 2.0.2 Gage record of daily discharges on the Clinch River of eastern Tennesee shows the effect of the 1936 installation of Norris Dam with its 3.1 km3 (2,552,000 ac ft.) storage capacity. The annual yield of the river is 3.4 km3 (2,910,000 ac ft.). Source: U.S. Geological Survey.**

A number of papers in recent years (Williams and Wolman, 1984; Richard, 2001; Meyer, 2005; Ahmed, Ogiembo and others, 2010; Shin and Julien, 2011; Bronsvoort, 2013; ICOLD, 2015) have discussed the effects of dams on downstream flows. Because of the various purposes for which dams are built, there are large variations from one dam to another in the magnitude and duration of flow releases.

## 2.8 River degradation

The sediment free water released from the reservoir has the ability to cause erosion the river bed downstream of the dam, as bed load and suspended sediment are once again entrained, and degradation of the river bed occurs. Degradation continues as a role of discharge, time, and size of the bed materials, until a new equilibrium is established.

The deposition of sediment in a reservoir accompanied with clear water releases from the dam upsets the regime or state of quasi-equilibrium of the downstream river channel. A natural flowing stream transporting sediment is usually in equilibrium or regime (Lane, 1955) with no long-term trend toward aggradation or degradation. The release of clear water either through the gate outlets or spillway will increase this natural stable condition with degradation of the channel bed and banks. The degradation process moves progressively downstream until it reaches a point where the sediment being transported results in a stable channel or equilibrium (Williams and Wolman, 1984).

In addition to changing the flow regime, dams are effective sediment traps. Trap efficiency is higher in reservoirs of bed load streams than that of suspended load streams, which are reduced by sluice operation in flood control reservoirs, and increase with the water capacity; inflow ratio. The previous findings explanation on thalweg degradation were an increase in average mean bed elevation is quite simple. The bed has not actually aggraded with sediment. Aggradation or degradation line surveys were taken photogrametrically, not by surface surveys. The river was surveyed and means bed elevation is estimated using normal depth calculations. If the bed has narrowed and scoured, the channel geometry may have changed enough to make the average of all active channel elevations greater than that of the original waterway.

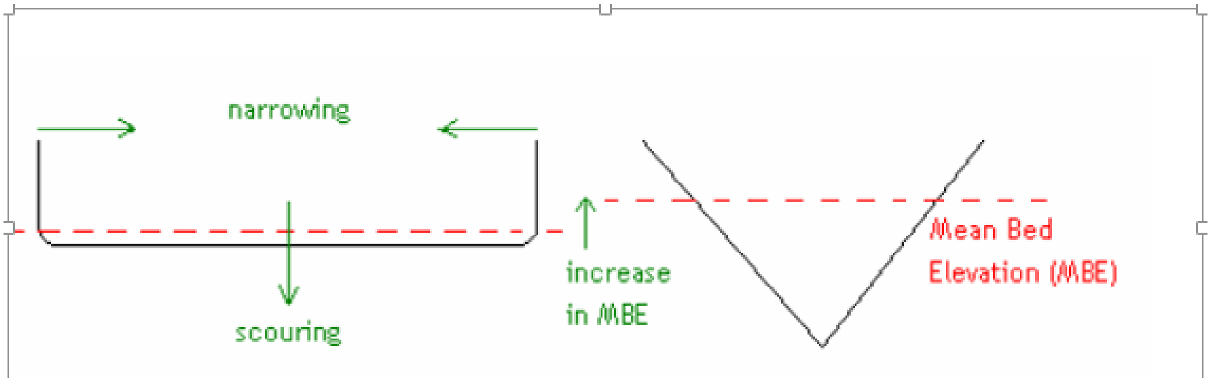



**Figure 2.0.3 shows how the mean bed elevation may have increased.**

Ahmed, Ogiembo and others have stated that areas experiencing serious river bank erosion are the Main Nile, Atbara River and Blue Nile. The White Nile banks are relatively stable with little or no erosion. Gully erosion degradation is usually extended as a trip bordering streams and cultivated or grazed land in semi-arid or grazed land in semi-arid zones. Upper Atbara River reaches and localized reaches lengthways the Blue Nile represent the most intensively degraded land by gully erosion due to the Atbara dam, forming the main sediment sources.

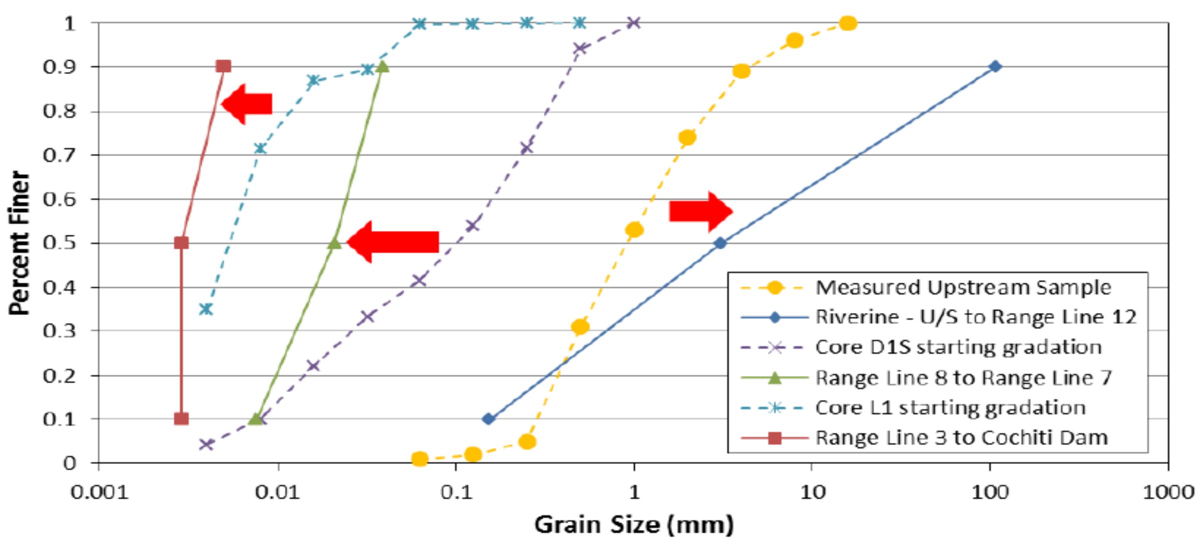



**Figure 2.0.4 Reach-averaged bed gradation results from the HEC-RAS model for the verification period (1975-2005) shown in solid lines compared to the initial conditions data used in the sediment transport model shown in dashed lines; arrows indicate the direction of coarsening or fining of the bed.**

Cochiti Dam, closed in 1973, was constructed primarily for flood control and sediment retention. The dam traps sediment, reducing the suspended sediment loads downstream between 87% and 98%, and has created a lacustrine delta in the reservoir headwaters. The reach below Cochiti Dam responded to dam closure in typical ways including: Bed degradation, bed armoring, and channel narrowing. The study reach is a highly complex system from a sediment transport view due to the two primary sediment inflows: the Rio Grande contributing primarily coarse-grained, non-cohesive sediment to Cochiti Lake, and the Rio Chama contributing primarily fine-grained, cohesive sediment (Davis, Bahner and others et.al 2014).

Susan Novak et.al 2006 study focuses on post-dam trends in the Cochiti Dam reach. The existing Middle Rio Grande database was updated and completed for facilitation of this analysis. The highly controlled dam reduced peak annual flow rates to less than 10,000 cfs. Decreasing trends in width, width/depth ratio, and cross-sectional area were well-known. Thalweg degradation averaged 2 feet over the entire reach. Median bed sediment sizes increased from an average of 0.1 mm in 1962 to an average of 24 mm in 1998. This was due to the 98% decrease in suspended sediment after the dam construction. The clear water discharge from the dam scoured the bed and has narrowed the channel slightly. The bed degradation and bed material coarsening seen in this reach is consistent with previous studies on the Middle Rio Grande River. The plan form has changed from a braided to single thread meandering channel from 1918 to 2004.

The sediment transport capacity of the river is very high at the outlet of Cochiti Dam due to the release of clear, sediment starved water. The capacity has decreased since 1972, however, because the bed has coarsened. The upstream bed has armored and the sediment-starved water may soon begin eroding the banks and increasing lateral motion (Susan J. Novak, 2006).

### 2.8.1 Types of degradation

The capacity of flow released to entrain sediment from the channel bed and banks degradation change will happen downstream of dam. This will involve changes in width, depth, and bed level of the channel, as a secondary effect, change in slope. Related with slope, discharge, and sediment transported changes are changes in bed material, both grain size and the resulting bed forms, plan form configuration.

### 2.8.2 Causes of Erosion

Most important factors considered in contributing to the degradation of the downstream degradation related to reservoir are change in water discharges, sediment load and sediment size. When a dam and reservoir are constructed on a natural river, and there is a high trap efficiency of the reservoir, the majority of the sediment being transported by the river will settle down in the reservoir.

The water released from the dam then becomes almost sediment free, especially during normal flow conditions. The clear water released has the ability to erode sediment particles from the stream bed and banks downstream of the dam. As a result of this erosion and sediment transport, degradation of the river bed occurs. Degradation continues as a function of discharge from the dam and time, until a new equilibrium is established. The rate of river bed degradation is rather rapid at the beginning but becomes small as the new stable profile is reached (gradual reduction in the stream slope (Heidargholi Massoudi, 1981).

Lane's 1955 model applies to the concept of equilibrium. Lane's balance, QS~QS D50, shows how a change in any of the four driving variables in a stream (discharge, slope, median grain size, and discharge) produces a response in the others to tend to towards equilibrium.

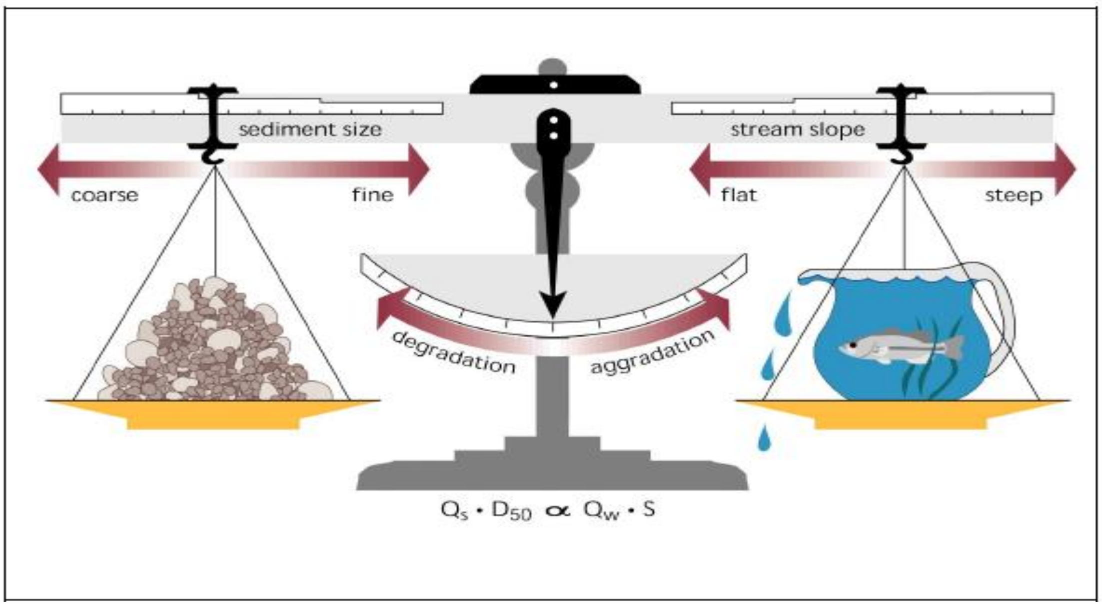



**Figure 2.5 Lanes balance (1955)**

## 2.9 Effects of degradation

There exist to much variation of dams and reservoirs with many differences in flow release policies. The difference in dam inputs to the downstream reaches introduces changes to the hydrological regime that will not be the same from dam to dam. This input can be divided into a water flow part and a sediment flow part, both of which will interact with downstream channel boundary. The relationship between the flow's transport capacity and released sediment load from the reservoir, together with the relationship between the erosivity of flow and the erodibility of the river banks, should determine changes that, in the long run, produce new stable conditions (S. Anders Brandt, 2000). The future change will include:

1. Effects on downstream wetlands
2. Sediment discharge
3. Slope changes
4. River cross-sectional changes
5. Plan form changes
6. Bed form changes may cause reduction of intake possibilities

## 2.10 Degradation models

In addition to changing the flow regime, dams are effective sediment traps. The limitation of sediment supply, as with the change in water discharge, could have an important effect on the downstream channel. Depending on the capacity of the reservoir, large amounts of sediment will be trapped, releasing only a proportion of the former load into the downstream reaches. According to Williams and Wolman 1984, the trap efficiency of what they call large reservoirs is commonly greater than 99%, whereas smaller reservoirs generally have lower values. As the result of this, there will be river bed degradation downstream of the Ribb dam. The hungry water released from the reservoir, having low sediment have high scouring and transporting capacity. This is a continuous process until the equilibrium state. Hence estimate of downstream effects of dam should be included in order to control the future consequences. Hydrological Engineering Center River Analysis System (HEC-RAS) model was used in this paper to predict the morphological change.

## 2.11 Previous Studies

In 1999, the Ribb Dam site area was studied by BCEOM in association with ISL and BRGM. This was a pre-feasibility level study for irrigating a total area of 19,925 ha, the irrigation area being commanded by a weir located downstream of the main dam. Even though there are different studies in the Ribb River, but there is no study in river morphology.

Research conducted by Zelalem Abera et.al (2011) is centered on Flood mapping and modeling on Fogera Flood plain. Using hourly time series hydrologic data flood extent and depth in the area for different flow conditions were determined. Another study was conducted by Tensay Getnet et.al (2011) focus on Sedimentation Modeling for Ribb Dam using SWAT modeling. He used 20 years daily metrological, flow and sediment rating curve equation for sediment data to estimate the sediment yield to Ribb dam reservoir.

# 3. MATERIAL AND METHODS

## 3.1 Description of the study area

### 3.1.1 Location

The Ribb River is located in Nile River basin of Amhara regional state. The dam and diversion weir are located in South Gonder zone and East of Lake Tana, on Ribb River, on the side of Woreta-Debretabor road.

River Ribb Watershed is located mainly in Farta Woreda (with small part engulfing into Ebinat Woreda) of South Gonder Zone in Amhara Region. It is located at a distance of 625 km north - West of Addis Ababa (60 km from Bahirdar town, capital city of the Amhara Region).

The catchment is located between the geographical coordinates 12˚35'N and 41˚25'E and 13˚ 54'N and 35˚ 55'E. The elevation in the watershed ranges from 1900masl around dam to 4135masl in the upper ridge. The mean annual precipitation and temperature is about 1295mm and 20.4˚c respectively. The minimum monthly rainfall is 1mm in January and maximum 411mm in July while mean minimum temperature is 19˚c in December and monthly maximum temperature is 23˚c in April. Average daily sunshine hours are 8.1 while average atmospheric humidity is 79% (WWDSE, 2009).

The topography of the area ranges from the high Guna Mountain to Lake Tana. The total area catchment at Addis zemen Gaging station outlet is 1500 km2 and upstream watershed area of the Ribb Dam is about 677.76 km2. The reach length of the river between the dam and the diversion weir, included in the study was the 30 kilometers.

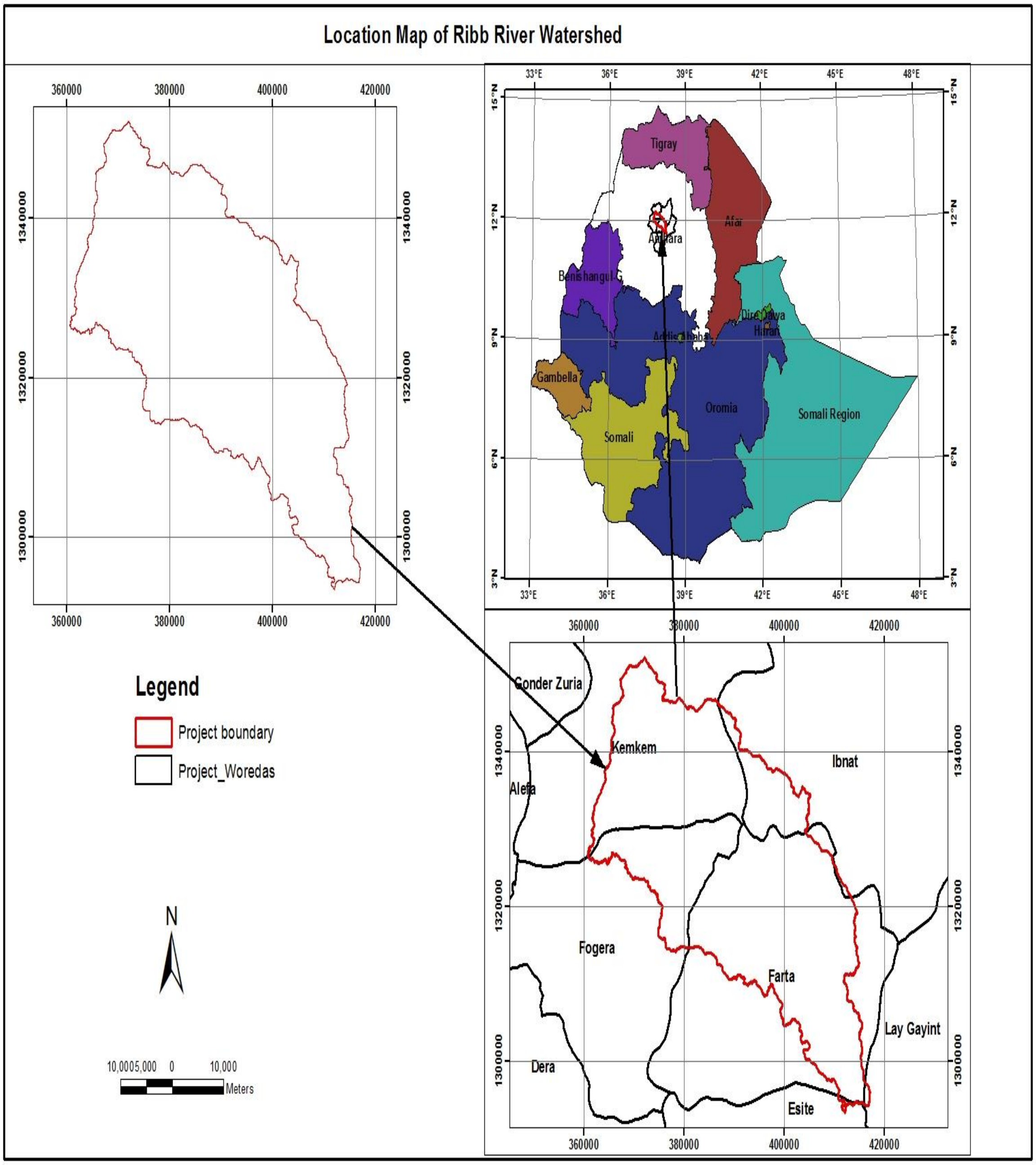



**Figure 3.0.1 Location map of Ribb watershed (research area)**

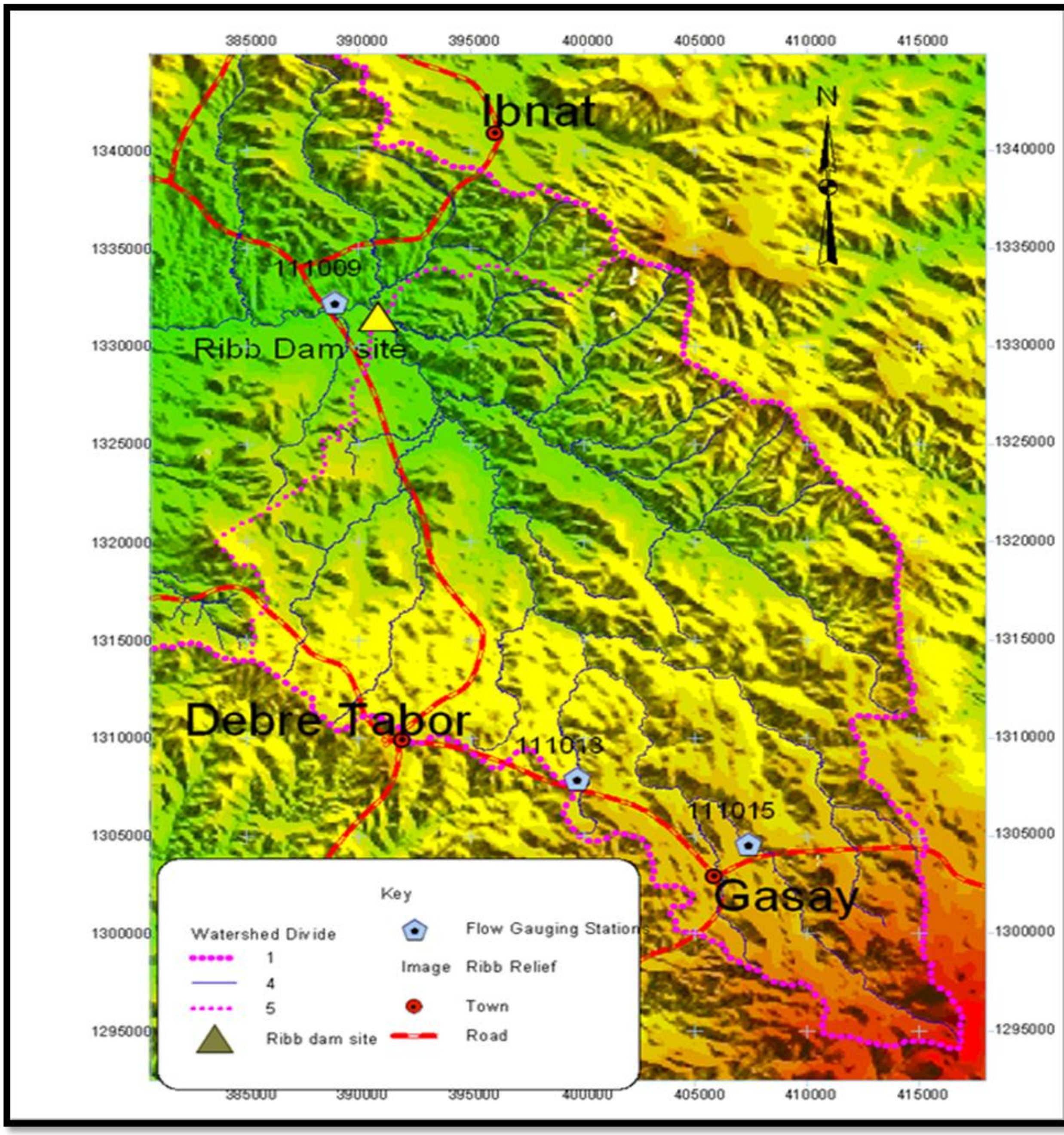



**Figure 3.0.2 Relief map of Ribb dam watershed**

### 3.1.2 Land Use

Land use of the flood plain is mainly dominated by cultivated land and some parts covered by shrubs. Most of the study area is characterized by cultivated lands, mountainous areas as most of the area is rural.

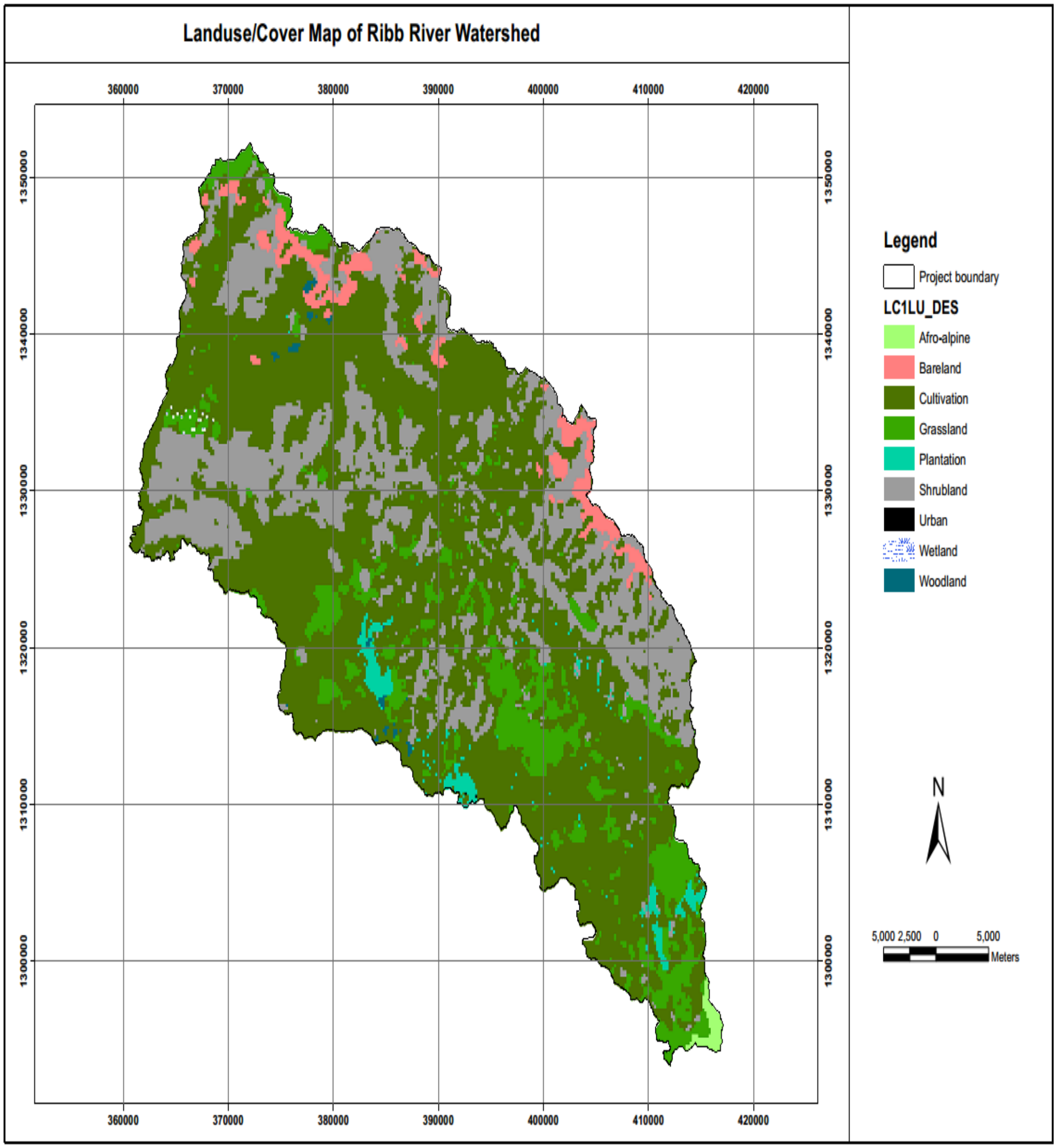



**Figure 3.0.3 Land use/ cover map of Ribb River watershed**

### 3.1.3 Soil Type

According to the soil map of North Western Ethiopia in Gondar area, the soils in the study area is dominated by the following categories: Luvisols, Leptosols, fluvisols, and vertisols.

The main types of soils of the watershed are Chromic Luvisols (57.3%), Eutric Leptosols (42%), and Eutric fluvisols (0.6%) in their respective area coverage with small pockets of vertisols on the hills' tops and river and streams' valleys and Chromic Luvisols as small pockets in different parts. The soils seem to have derived from basalts and tuffs. They are brownish to reddish in color, clay to clay loam and sandy to sandy loam in texture, well drained but very shallow on steep slopes.

The Luvisols, fluvisols and vertisols have good inherent fertility and agricultural productivity, although those Leptosols on the mountain ranges and hillsides are severely eroded and further prone to soil erosion. The soil erosion on the hillside slopes and sedimentation at the valleys have already taken place because of intensive annual crop cultivation without soil erosion protection measures (WWDSE, 2009).

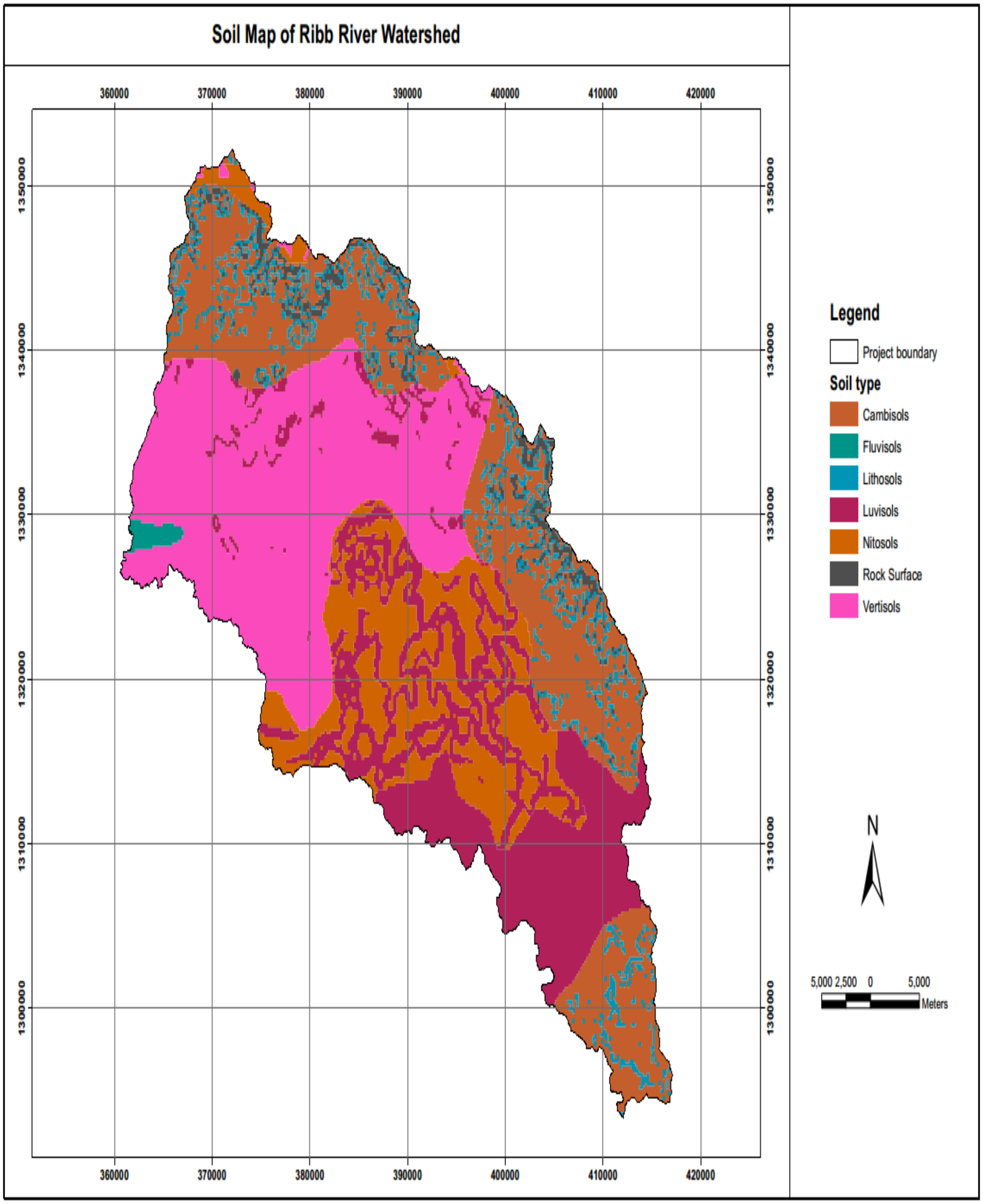



**Figure 3.0.4 Soil map of Ribb watershed**

### 3.1.4 Reach Description

The Ribb River stretches 87 kilometers from Guna Mountain through Farta, Fogera, Libo kemkem and Alefa Takusa woredas, to Lake Tana. The upper reaches of the Ribb River stretches from Rib dam to the diversion weir. The river valley includes cultivated, forest and grazing lands. In addition, the land is managed and maintained by different woredas and private landowners.

The part of the study area analyzed in this study Ribb dam reservoir and 30 kilo meters long stretch from Ribb dam to the Diversion weir, and upstream of Addis zemen Gaging station. Reservoir sedimentation and this reach were analyzed for sedimentology and geomorphic changes since the installation of Ribb Dam.

### 3.1.5 Climate

Based on the agro climatic classification of Ethiopia (Hurni, 1986), Ribb watershed is characterized with High wurch (on southern edges), wet dega and wet woyna dega (northern area) agro -climatic zones, with altitude ranges from 1900masl around dam (northern edge) to 4135masl in the upper ridge (southern edge). The watershed area represents humid, with moderately cool to high frost, agro-climate. Generally, the rainfall pattern in the watershed is unimodal distribution. The mean annual precipitation is about 1295mm with the minimum monthly rainfall of 1mm in January and maximum 411mm in July. Reliable rainfall varies from less than13mm during the dry season to 80 to 275 mm/month during the period of June to July/August, equivalent to 40 – 80% of the average values. The mean annual temperature is about 20.40c while mean minimum temperature is 19oc in December and monthly maximum temperature is 23.oc in May. Humidity values vary between 70% in December and 88% in August. Average daily sunshine hours are 8.1. Wind speed is reportedly low minimizing potential evapotranspiration values between 95mm in December and 140 mm in April. In general, a year in the area is divided into two seasons: a rainy season (Kiremt), which occurs from May to September and a dry season (Bega) from October to April. (WWDSE, 2008)

**Table 1 Summary of climatic variables of the study area**

| Elements | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max Temperature ($^{o}$ C) | 27.8 | 28.9 | 29.9 | 29.4 | 28.5 | 25.2 | 22.8 | 22.9 | 25.3 | 26.3 | 27.1 | 27.2 | |
| Min Temperature ($^{o}$ C) | 11.5 | 13.0 | 14.7 | 15.6 | 15.6 | 14.0 | 13.2 | 13.3 | 12.8 | 12.6 | 12.5 | 11.9 | |
| Relative Humidity % | 43.3 | 39.2 | 38.7 | 40.2 | 51.4 | 66.1 | 78.6 | 79.3 | 72.1 | 59.3 | 50.2 | 45.9 | |
| Sunshine hours | 9.4 | 8.8 | 8.4 | 7.5 | 7.1 | 4.9 | 4.2 | 5.0 | 7.2 | 7.6 | 8.7 | 8.8 | |
| Wind speed (m/s) | 1.6 | 1.8 | 1.9 | 1.8 | 1.9 | 1.9 | 1.4 | 1.3 | 1.4 | 1.4 | 1.5 | 1.5 | |
| PET (mm) | 126 | 123 | 149 | 141 | 146 | 122 | 101 | 105 | 123 | 128 | 121 | 118 | 1503 |
| Evaporation (mm) | 152 | 147 | 179 | 169 | 176 | 146 | 121 | 126 | 147 | 154 | 145 | 142 | **1803** |

### 3.1.6 Geomorphology

The Ribb River is one of the tributaries of Lake Tana, in the Nile River basin. The riverbed elevation at the is about 1,790m at the Addis zemen gauge site at coordinates E 37° 87' and N 12° 12' and it has a catchment area of 1500 km2. Approximate longitudinal section of the Ribb watershed lengthways the main river course shows that it is characterized as a steep mountainous watershed up to the Ribb dam site (at about 56 km course), below this point the river slope is getting flatter.

Upper Ribb watershed is characterized as a mountainous, wedge shaped and a steep sloped (3.6%). The highest elevation of the watershed is about 4,100 m in its south eastern part, where at the dam site the elevation drops below 1,873m.Debre Tabor, Ibnat and Gasay towns are located on the divide line, near, and inside the Upper Ribb watershed, respectively.

**Figure 3.0.5 Ribb River bed**

The overburden in the Ribb reservoir area and dam site can be classified in to three components: recent river bed silt sand and gravel deposit; residual clayey soil and colluvium deposit; and terraces of old alluvial silt sand and gravel layers.

The recent riverbed silt sand and gravel material is deposited along the current river channel. The riverbed is 200- 300 meters wide along most of its course upstream of the dam and it is even wider downstream. The average thickness of this alluvial deposit is of a few meters and more (BCEOM geophysical investigation/geo electric section and drilling data (WWDSE, 2009).

Ribb and Gumara watershed basins have relatively similar characteristics regarding rainfall intensity and soil erodibility. Brownish sandy clay loams and sandy loam dominate the watersheds corresponding to Hydrological soil group B. As a result of the above mentioned discussion, an attempt has been made to apply a regional approach in order to construct a composite sediment rating curve by using the Megech, Ribb, Gumara and Gilgel Abay Q-Qs data based on 1964-2005 period (WWDSE, 2009).

**Figure 3.0.6 Geotechnical investigation of the weir site (Source: TAHAL consulting engineers Geotechnical Report annex B.3.2.1)**

**Figure 3.0.7 Alluvial Terrace deposits in Ribb g.) Reservoir basin (Source: WWDSE with Sub-consultants TAHAL Consulting Eng.)**

## 3.2 Material and Analysis

### 3.2.1 Meteorological data

The collected data for hydrologic analysis should be homogenous, correct, sufficient and complete with no missing values. Generally, data should be properly adjusted for irregularity, corrected for errors, extended for insufficient, and filled for missing using different techniques. For this particular research work Meteorological, Hydrological, Sediment, Ribb River cross-section, and Digital Elevation Model (DEM) data setting was taken for Ribb watershed. 25 years(1990-2015 G.C) daily precipitation (Amedber, Amba Giorgis, Bahirdar, Debratabor, Gonder, Ebinat, Nefawmewcha and Woreta) and, maximum and minimum temperature from National Meteorological Agency (NMA) and 25 years(1991-2015 G.C) daily sediment and stream flow (Addis zemen, Gumera and Megech gaging stations) were collected from Ministry of Water, Irrigation and Electricity.

#### 3.2.1.1 Point Precipitation

Precipitation events were recorded by gauges at specific stations. The resulting data permit determination of frequency and character of precipitation events in the surrounding area of the site. Point precipitation data were used collectively to estimate areal variability of rain and were also used for developing design storm characteristics for watersheds.

#### 3.2.1.2 Estimating missing precipitation data

To estimate missing time series data there are different analysis methods. The station average method is the simplest one. The normal ratio and quadrant method provide a weighted mean, with the former biasing the weights on mean annual precipitation at each gauge and the later having weights that depend on the distance between gauges where recorded data are available and the point where the value is required. The Linear regression the most common method and the isohyet method is the fifth alternative.

Linear regression method is used in this study. The method is used an open software called hydro gnomon. it concerns two-dimensional sample points with one independent variable and one dependent variable ( x and y coordinates in a Cartesian coordinate system) and finds a linear function (a non-vertical straight line) that, as accurately as possible, predicts the dependent variable values as a function of the independent variables. The general formula for computing missing precipitation by this method is:

Linear regression method $Y = ax+b$ - - - - 21

#### 3.2.1.3 Consistency and Homogeneity

Estimating missed precipitation data is the primary process hydrologic analysis. Adjustment of the measured data is necessary to provide a consistent record. A reliable record is one where the characteristics of the record have not changed with time. Inconsistency may result from: change in gauge location, exposure, instrumentation, or an observational procedure is not real and on time. To overcome the problem in consistency a technique most widely applied called double mass curve is used. Double-Mass Curve (DMC) analysis is a graphical method for identifying or adjusting inconsistencies in a station record by comparing its time trend with those of other stations nearby (Shaw, 1988). Hyrognomon software was applied for DMC analysis by making Debretabor dependent and other stations independent. An Slope deviation of the Double-Mass Curve plot suggest some change not related to climatic variables, and modification should be made to the data on the basis of the ratio of the slopes of the two segments.

#### 3.2.1.4 Areal Precipitation

For hydrologic analysis, it is essential to know the areal distribution of precipitation. Usually, average depths for representative points of the watershed are determined and used for this purpose. There are many methods available to determine the areal rainfall over the catchments from the rain gauge measurement: Arithmetic Mean, Thiessen Polygon, Isohyetal, Grid Point, Percent Normal, etc. are available for estimating average precipitation over a drainage basin, (Shaw, 1988). Choice of methods requires judgment in consideration of quality and nature of the data, and the importance, use, and required precision of the result. The most direct approach is to use arithmetic averages of gage quantities. This procedure is satisfactory if gauges are uniformly distributed and the topography is flat. The other most commonly used methods are the isohyetal and the Thiessen polygon method. The reliability of rain fall measured at one gauge in representing the average depth over a surrounding area is a function of:

- The distance from the gauge to the center of representative area
- The size of the area
- The topography
- The nature of the rain fall concern
- The local storm pattern characteristics

Thiessen polygon method is also used to calculate the areal rain fall averages and selected for this paper. Arc GIS 10.2 and HEC Geo-HMS 10.2 were used to construct the polygons. In this procedure the watershed areas was sub divided in to polygon subareas using rain gauges as a centers. The sub areas are used as weights in estimating the watershed average depth. All the stations in and around the basins were considered and a linear variation in the precipitation between two gauge stations was assumed.

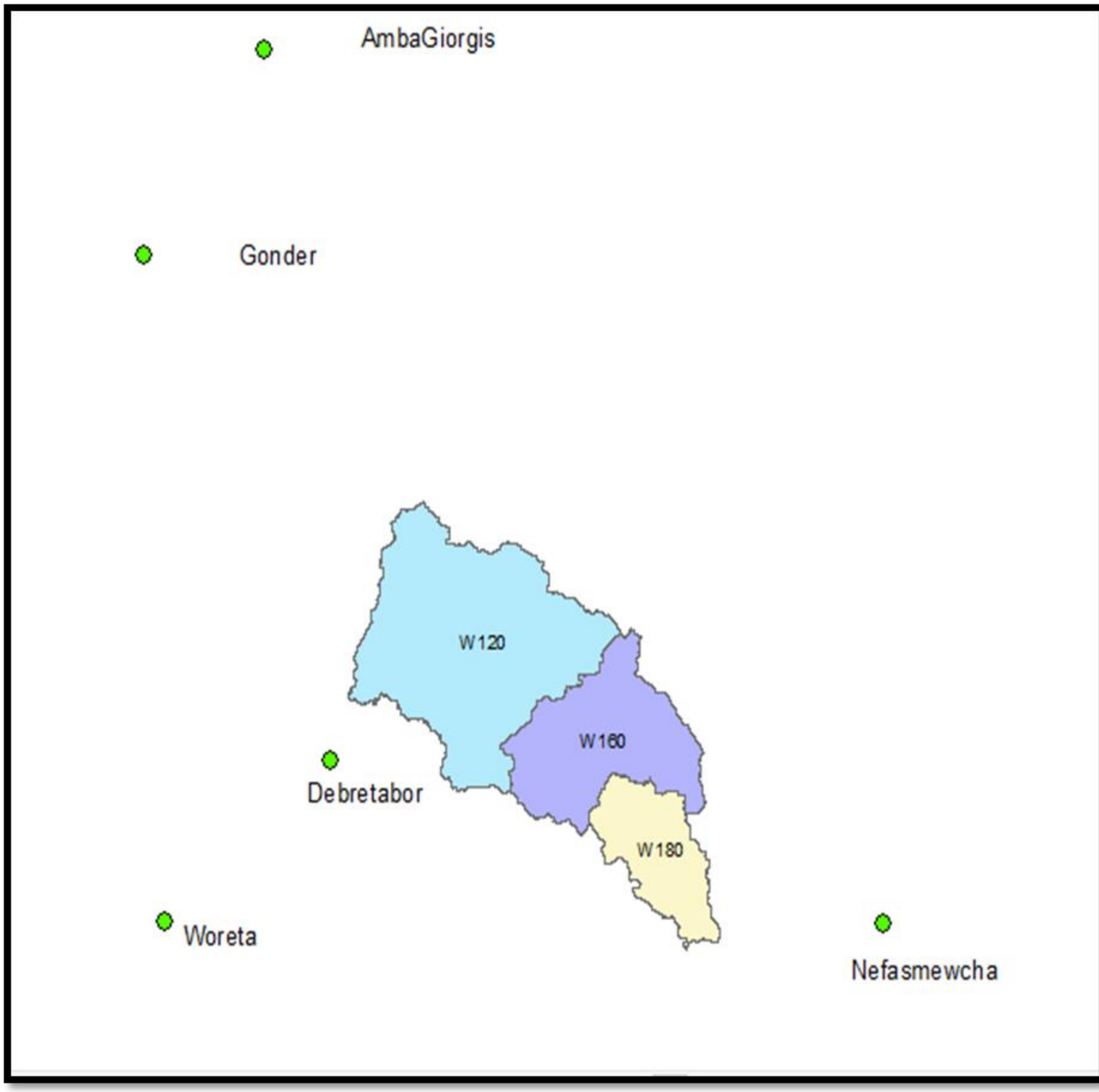



**Figure 3.0.8 Precipitation Gauge stations**

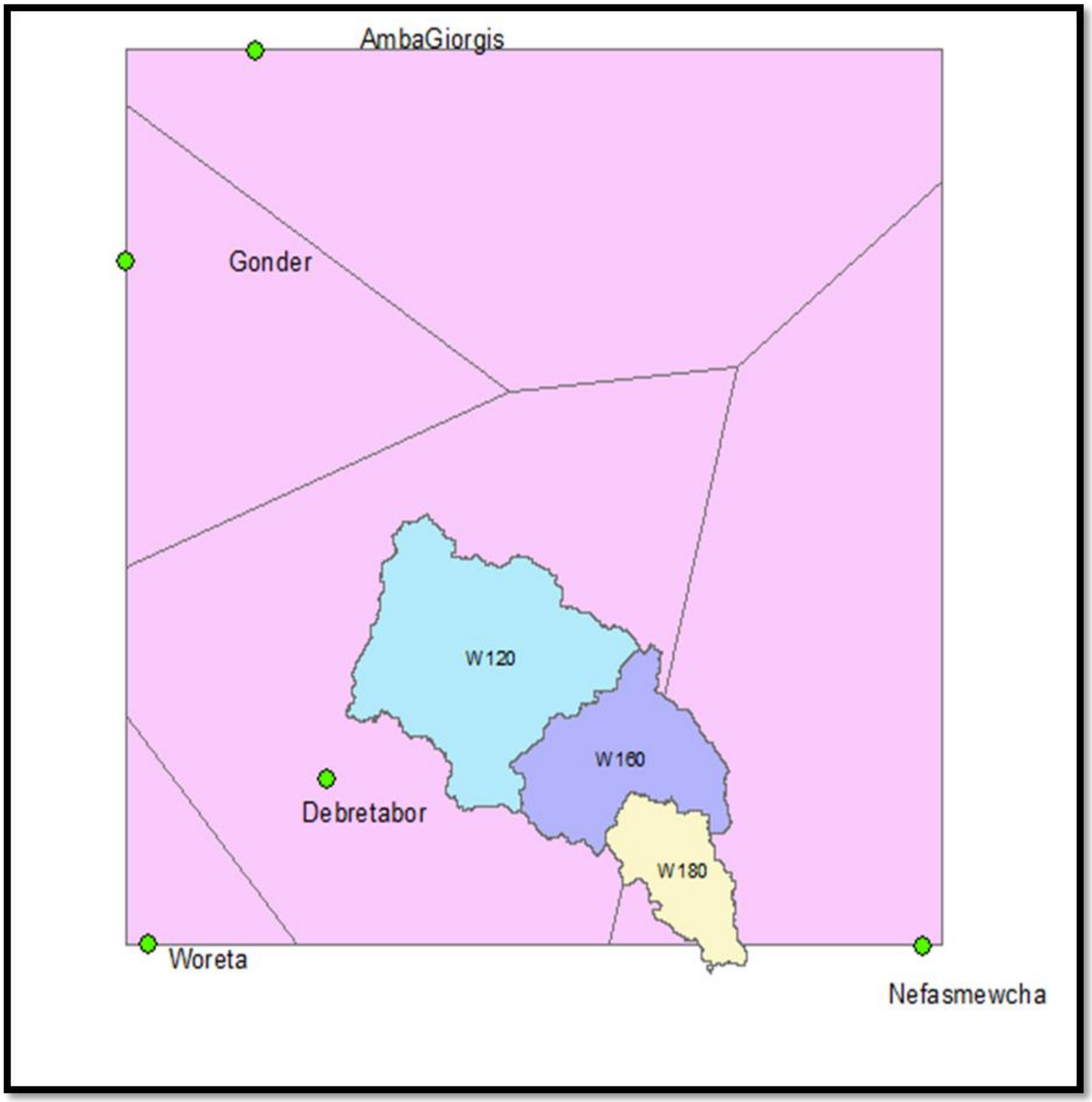



**Figure 3.0.9 Thiessen polygon**

### 3.2.2 Estimating Missing flow data

Missing river flow data records for the catchments were filled by developing correlation between Gumera and Megech River gauging station with the same data record periods. Consistency and extension of flow data is analyzed by regression technique. The correlation equations used for Ribb gauging station in terms of Gumera gauging station, which shows good correlation is expressed below.

**Table 2: Ribb and Gumera rive correlation**

| | Ribb | Gumera |
|---|---|---|
| Gumera | 0.877589 | 1 |
| Ribb | 1 | |

### 3.2.3 Ku-tools

Ku tools is an excel tool used to erect the raw data as a column. All the Precipitation data, stream flow data and sediment data were transformed to a column. Finally the transformed ta were exported to HEC-DSS.

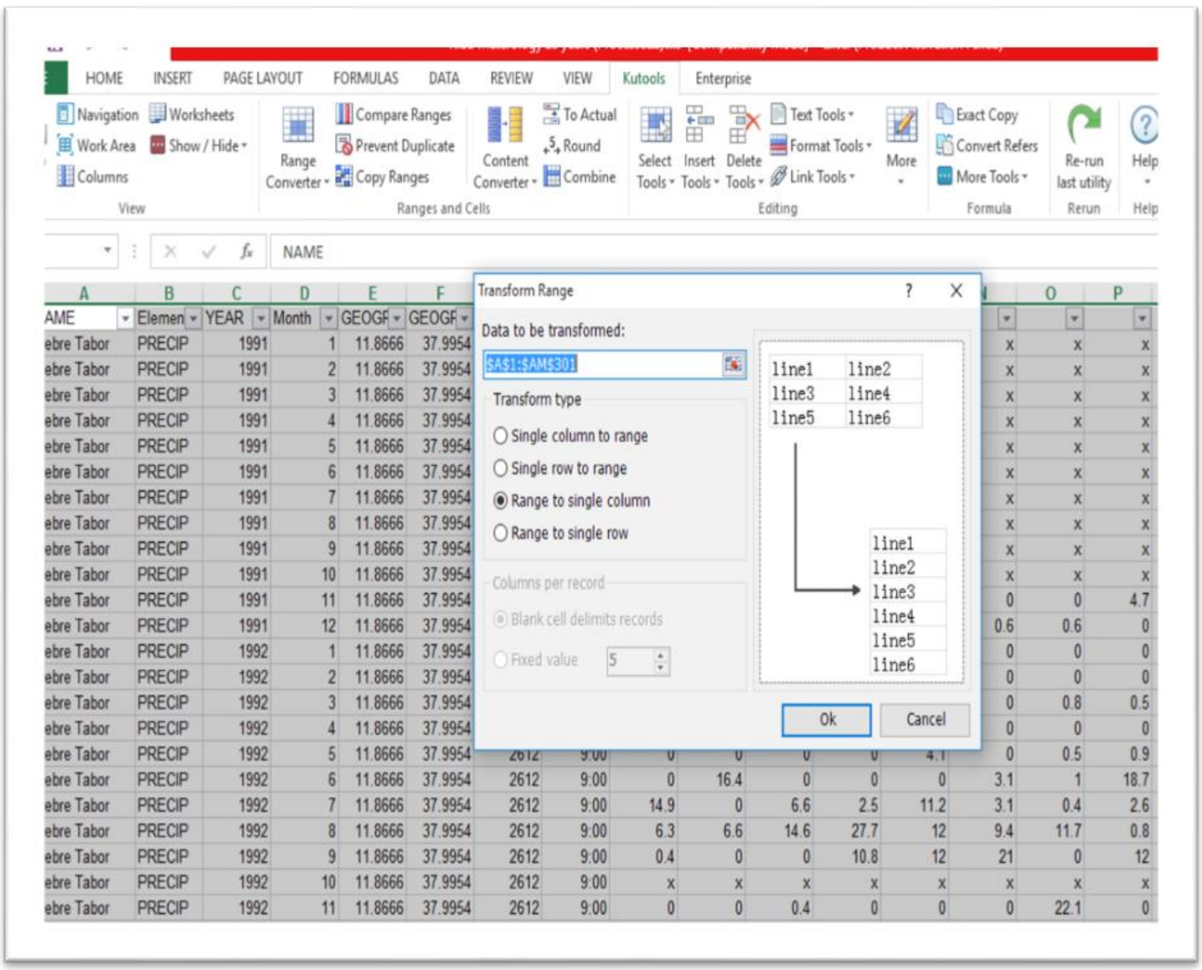



**Figure 3.0.10 transforming from raw to column using Ku-tools**

### 3.2.4 Hydrognomon

Hydrognomon is a software application appropriate for the process and analysis of hydrological time series data. Its main functions includes statistical analysis, regression and infilling of time series data, tests, Intensity Duration Frequency Curves, stage-discharge curves construction and calculations, hydrometry, hydrological simulation of water basins, evaporation and evapotranspiration calculations, etc. Hydrognomon version 4.0.1 was prepared by N.T. University of Athens (ITIA research teams, 1992-2012).

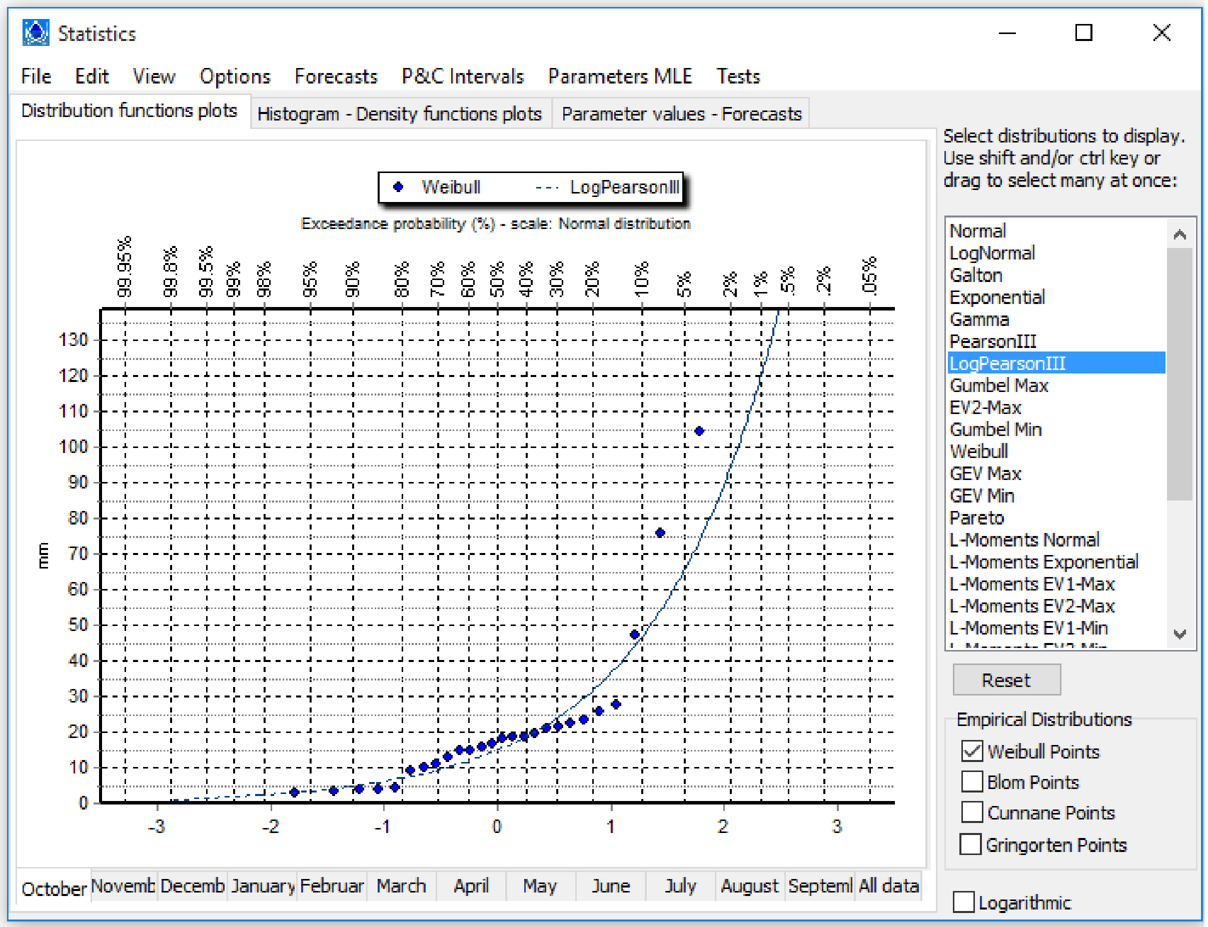



**Figure 3.0.11 Debretabor gauge precipitation statistical analysis**

Hydrognomon is an open sources software tool used for the processing of hydrological data. Data are usually imported through standard text files, spread sheets or by typing. The available processing techniques for the tool includes time step aggregation and regularization, interpolation, regression analysis and infilling of missing values, consistency test, data filtering, graphical and tabular visualization of time series. The program also include common hydrological application such as evapotranspiration modeling, stage discharge analysis, homogeneity test, areal integration of point data series manual(Department of Civil Engineering, Nigerian Defense Academy, Kaduna, Nigeria,2012).

ile Edit View Series Hydrology Help

| 015 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5.10 | 37.00 | 6.10 | 0.00 | 0.00 | 1.40 | 4.13 |
| 3 | 0.00 | 0.00 | 0.00 | 0.00 | 5.60 | 0.50 | 0.00 | 0.00 | 5.30 | 0.00 | 14.30 | 0.00 | 2.14 |
| 4 | 0.00 | 0.00 | 0.00 | 0.00 | 5.00 | 0.00 | 0.40 | 11.50 | 4.60 | 0.00 | 2.20 | 0.00 | 1.97 |
| 5 | 0.00 | 0.00 | 0.00 | 0.00 | 35.30 | 0.00 | 0.00 | 17.20 | 6.70 | 16.70 | 3.80 | 2.10 | 6.82 |
| 6 | 0.00 | 0.00 | 0.70 | 0.00 | 14.40 | 2.80 | 10.20 | 2.60 | 8.10 | 0.00 | 0.20 | 1.30 | 3.36 |
| 7 | 0.00 | 0.00 | 0.00 | 0.00 | 17.70 | 0.00 | 2.40 | 12.00 | 9.10 | 0.00 | 8.90 | 7.10 | 4.77 |
| 8 | 0.00 | 0.00 | 0.00 | 0.00 | 7.20 | 0.00 | 14.30 | 3.10 | 19.90 | 0.00 | 0.00 | 0.00 | 3.71 |
| 9 | 0.00 | 0.00 | 0.00 | 0.00 | 7.00 | 0.00 | 5.40 | 14.20 | 15.40 | 0.00 | 0.00 | 0.00 | 3.50 |
| 10 | 0.00 | 0.00 | 0.00 | 0.00 | 1.30 | 0.00 | 6.80 | 3.50 | 2.80 | 0.00 | 41.30 | 1.40 | 4.76 |
| 11 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.80 | 4.30 | 4.30 | 10.50 | 3.20 | 11.10 | 0.00 | 3.02 |
| 12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4.40 | 14.40 | 4.30 | 0.00 | 1.70 | 0.00 | 2.07 |
| 13 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 1.90 | 19.10 | 13.60 | 13.90 | 0.00 | 0.00 | 0.00 | 4.13 |
| 14 | 0.00 | 0.00 | 0.00 | 0.70 | 0.00 | 1.20 | 13.20 | 4.40 | 20.20 | 0.00 | 0.00 | 0.00 | 3.31 |
| 15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.70 | 9.10 | 9.00 | 24.40 | 0.00 | 0.00 | 0.00 | 3.68 |
| 16 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 2.60 | 17.70 | 27.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4.03 |
| 17 | 0.00 | 3.40 | 4.80 | 0.00 | 0.00 | 3.10 | 4.00 | 0.80 | 0.00 | 0.00 | 0.00 | 2.50 | 1.55 |
| 18 | 0.00 | 0.00 | 1.20 | 0.00 | 0.00 | 19.80 | 8.10 | 7.40 | 1.40 | 0.00 | 0.00 | 7.30 | 3.77 |
| 19 | 0.00 | 0.00 | 9.00 | 0.00 | 0.00 | 11.80 | 1.20 | 5.10 | 0.00 | 0.00 | 0.00 | 0.00 | 2.26 |
| 20 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4.00 | 8.30 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.03 |
| 21 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 14.50 | 6.40 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.74 |
| 22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.60 | 6.20 | 15.70 | 21.80 | 5.60 | 0.00 | 0.00 | 0.00 | 4.16 |
| 23 | 0.00 | 0.00 | 0.00 | 0.00 | 10.00 | 7.10 | 3.40 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.71 |
| 24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.80 | 0.00 | 3.50 | 18.80 | 0.00 | 0.00 | 0.00 | 0.00 | 1.92 |
| 25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.50 | 6.30 | 9.30 | 3.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.59 |
| 26 | 0.00 | 0.00 | 0.00 | 6.00 | 6.20 | 4.30 | 13.90 | 7.60 | 0.00 | 0.00 | 0.00 | 3.40 | 3.45 |
| 27 | 0.00 | 0.00 | 0.20 | 0.00 | 16.80 | 28.50 | 0.70 | 5.40 | 0.00 | 0.00 | 0.00 | 1.10 | 4.39 |
| 28 | 0.00 | 0.00 | 2.00 | 0.60 | 31.80 | 6.70 | 2.30 | 12.00 | 0.00 | 0.00 | 0.00 | 9.50 | 5.41 |
| 29 | 0.00 | | 0.00 | 0.00 | 1.40 | 0.00 | 13.00 | 5.00 | 26.40 | 0.00 | 0.00 | 0.00 | 4.16 |
| 30 | 0.00 | | 0.00 | 0.00 | 0.00 | 3.40 | 20.70 | 15.70 | 0.00 | 6.70 | 0.00 | 0.00 | 4.23 |
| 31 | 0.00 | | 0.00 | | 14.70 | | 3.50 | 5.40 | | 0.00 | | 0.00 | 3.37 |

**Figure 3.0.12 Daily precipitation data using Hydrognonomon**

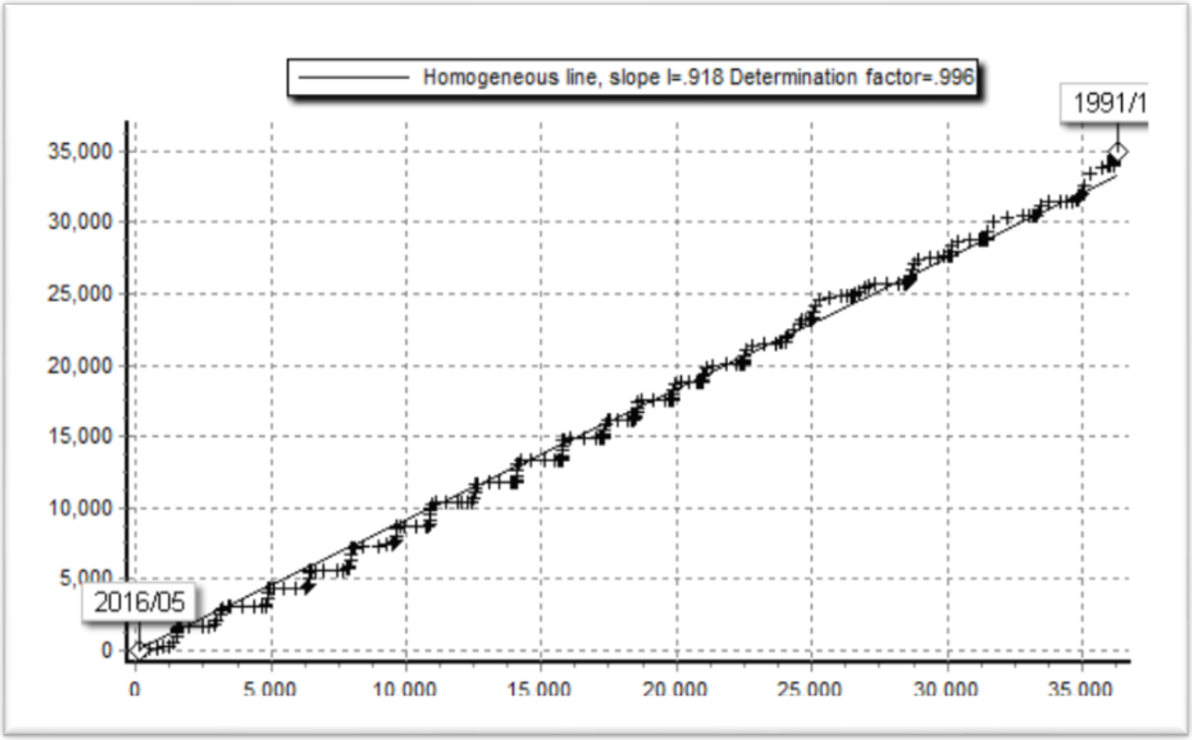



**Figure 3.0.13 DMC of Debretabor using Hydrognonomon**

### 3.2.5 HEC-DSS

The HEC-DSS (Hydrological Engineering Center Data Storage System Visual Utility Engine) is a graphical user interface program for viewing, manipulating editing, and the data storage system HEC-DSS is a data base system designed to efficiently store and recover scientific data that is typically sequential. Such data types include, time series data, curve data, spatial oriented-gridded data and textual data. The system was designed to make it easy for the users and application programs to recover, store data and to connect upstream HEC-HMS to downstream HEC-RAS modeling.

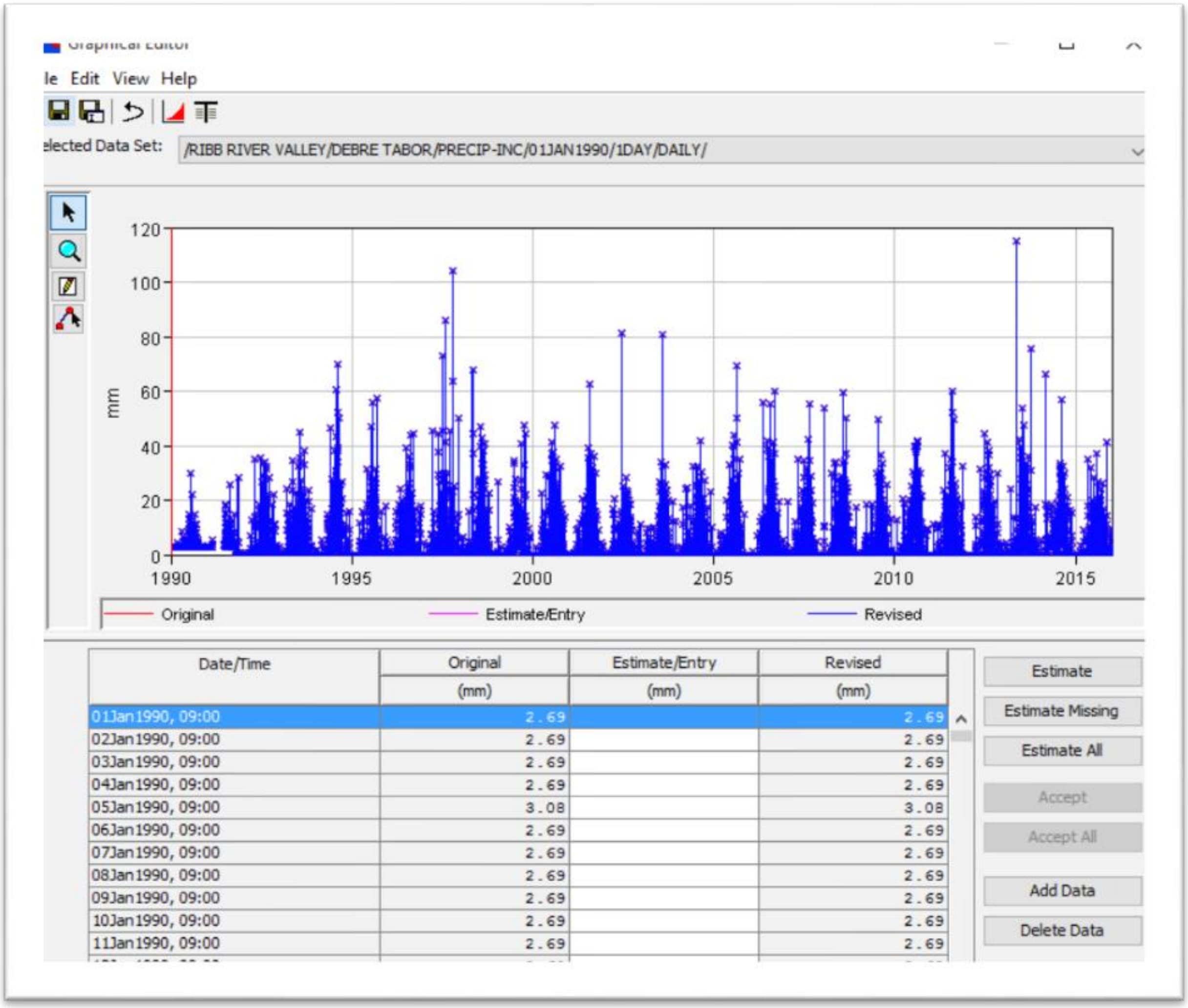



**Figure 3.0.14 Debretabor Daily precipitation using HEC-DSS**

### 3.2.6 Flow data

The principal source of stream flow data for Universities and Research centers is the Ministry of Water, Irrigation and Electricity. Daily river flow data of the Gumera, Megech and Ribb were collected analyzed for this thesis paper. Unlike the daily precipitation, the daily discharge has full data composition for the considered stations to represent the study area. The discharge gage of Ribb River is located near Addis Zemen downstream end of Ribb dam and diversion weir. The data was processed by Ku-tools, Hydrognomon, and HEC-DSS and exported to HEC-HMS. The flow series data, result from HEC-HMS model out was used for HEC-RAS model to integrate the model.

### 3.2.7 Sediment data

The suspended sediment concentration data available for Ribb River measured at Addis zemen gage station together with simultaneously flow were collected from Ministry of Water, Irrigation and electricity.

**Rating curve analysis**

The existing data sets from inflow gauge station were analyzed by fitting the power function regression on all values of least squares regressions. A rating curve specifying the total daily sediment load as a function of daily discharge was developed from the available daily record of daily sediment load as a function of daily discharge was developed from the available record of daily sediment data. This relationship was then applied to the entire 25 years data (1990-2015).

Sediment data is required in order to establish the potential loss of capacity in Ribb reservoir due to sedimentation over the design life of the project (often taken as 50 years). Estimate of sediment transport rate are very difficult to estimate reliably for a number of reasons. Observation techniques permit sampling of suspended sediment, although bed load sampling is possible but it is very inaccurate. Sampling is difficult and it is common to have significant variation in results of consecutive measurements of sediment load in the same flood event whether the sample is taken at the rising or falling portion of the flood hydrograph. There is also seasonal effect, with sediment load in the early wet months (June and July) higher than those on later months (August and September) for the same discharge (WWDSE, 2009)

Due to its low sediment yield value, neither the BCEOM sediment yield estimate nor the result based on the BCEOM rating curve should be adopted for the Ribb dam sedimentation study. Ribb and Gumara watersheds have relatively similar characteristics regarding rainfall intensity and soil edibility. As a result of the above mentioned discussion, an attempt has been made to apply a regional approach in order to construct a composite sediment rating curve by using the Megech, Ribb, Gumara and Gilgel Abay Q-Qs data based on 1964-2005 period (WWDSE, 2009).

The developed rating curve is given with the equation:

Qs = 34.17 Q 1.5084 - - - - - - - - 22

Where: Qs = Suspended sediment mass transport rate (ton/day)

Q = discharge (m3/s)

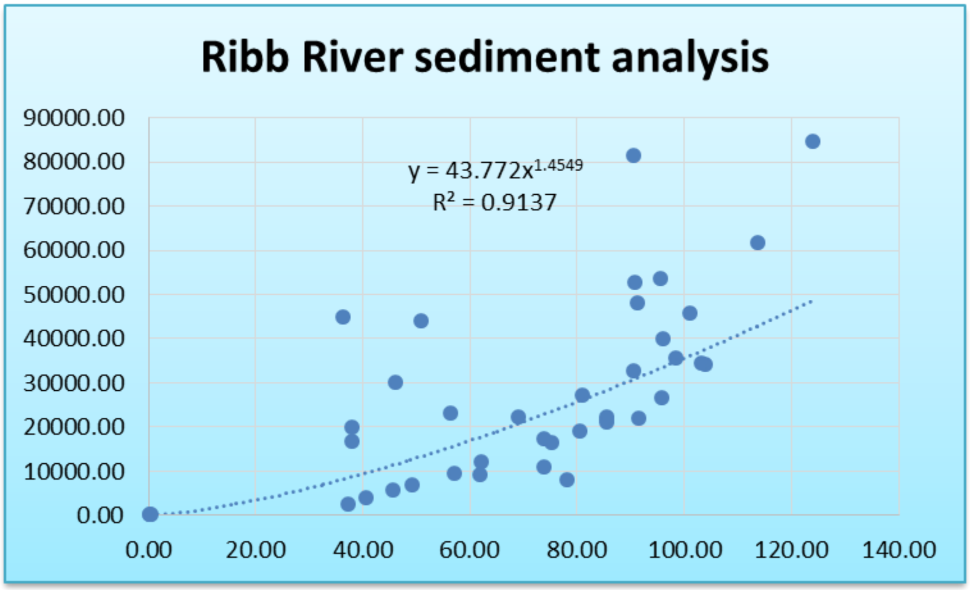



**Figure 3.0.15 Ribb River sediment rating curve**

Based on the graph the value of the coefficient of determination ($R^2$) is 0.9137. This shows that 91.37% of the information is in the observed data.

**Table 3: sediment data @ Addis zemen**

| River | Station | Subbasin | area (km2) | Mean Flow (m3/s) | Measured Sediments | | | | Sediment Transport (Ton/a) | Ton/km2-a) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Values | a | b | $R^2$ | 77888.45 | 77.89 |
| Ribb | Addis zemen | Ribb | 1500 | | | 43.772 | 1.459 | 0.913 | 45694.55664 | 0.00 |

### 3.3 Methodology

The methodology used in this research includes data collection, processing and analyzing integrated watershed riverine using hydrology and hydraulic model applications.

- ✓ Collect available data required for the reservoir sedimentation and morphological study
- ✓ Metrological data analysis, fill in missing data gaps as necessary using statistical methods.
- ✓ Stream flow data analysis, fill in missing data gaps as necessary using statistical methods
- ✓ Construction of sediment rating curves with the measured sediment concentration
- ✓ Evaluate the model for existing conditions with limited calibration
- ✓ Prediction of reservoir sediment deposition
- ✓ Prediction of certain River morphology changes
- ✓ Evaluate and compare model results
- ✓ Comparison of model simulated results to observed conditions measure to be taken to provide a basis for study recommendations

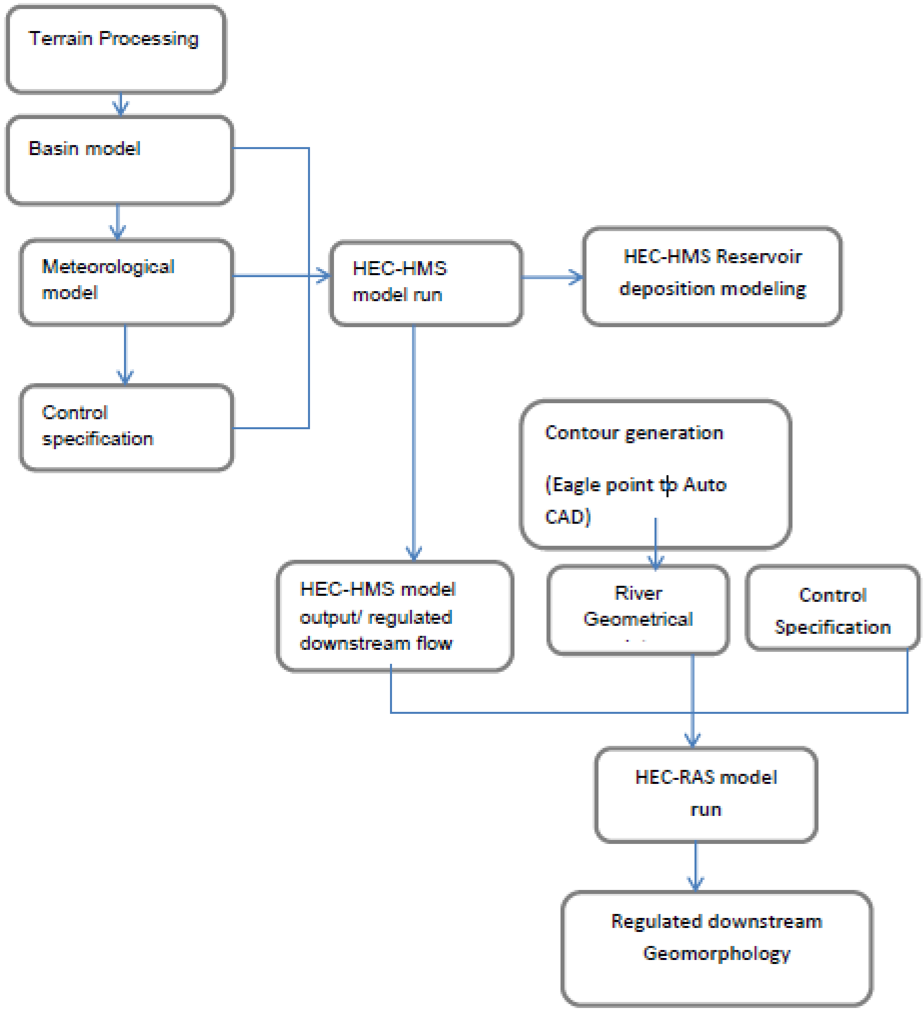



**Figure 3.0.16 Methodological flow chart (Modeling structure of rainfall runoff, erosion and sediment modeling and hydraulic modeling)**

## 3.3.1 HEC-HMS modeling

### 3.3.1.1 Overview of model simulation

Models are reduced dimension and central to the application of information technology by which the physical world is represented inside a computer. Models relate something unknown output to something known input. In the case of HEC-HMS model which was included in the program was the known input is precipitation and the unknown output is run-off and reservoir sediment deposition.

Ribb river watershed hydrologic modeling of is using the software developed by the United States Army Corps of Engineers‟ (USACE) software is Hydrologic Engineering Center's

Hydrologic Modeling System (HEC-HMS) Version 4.0 to perform the hydrologic modeling. The software used for hydrologic modeling HEC-HMS with interface of Arc Map version including their extension HEC-Geo HMS, Arc hydro.

**Working with HEC-Geo HMS**

HEC-Geo HMS is a set of ArcGIS tools specifically designed to process geospatial data and create input files for the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS). It provides the connection for translating GIS spatial information into model files for HEC-HMS. The GIS capability is used for data formatting, processing, and coordinate transformation. The end result of the GIS processing is a spatial hydrology database that consists of the digital elevation model (DEM), soil types, land use information, rainfall, etc.

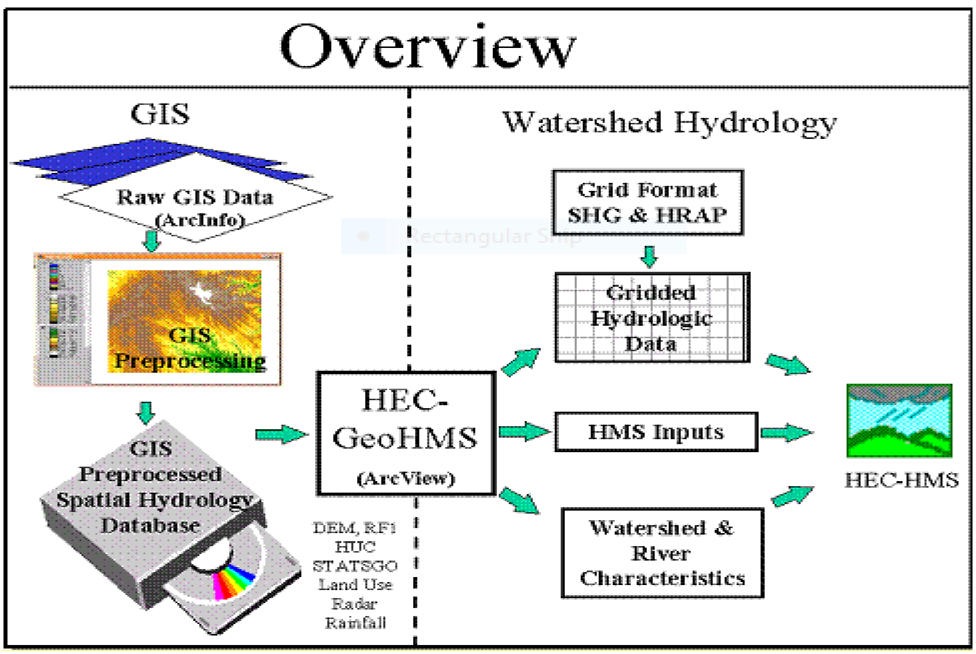



**Figure 3.0.17 GIS and HEC-Geo HMS Programs**

Currently, HEC-Geo HMS operates on the DEM to derive sub basin delineation and to prepare a number of hydrologic inputs. HEC-HMS accepts these hydrologic inputs as a starting point for hydrologic modeling. The following steps describe the major steps in starting a project and taking it through the HEC-Geo HMS process.

**Contents**

- Data Collection

- Data Assembly
- Terrain Preprocessing
- HMS Project Setup
- Basin Processing
- Stream and Watershed Characteristics
- Hydrologic Parameters
- HMS Model Files

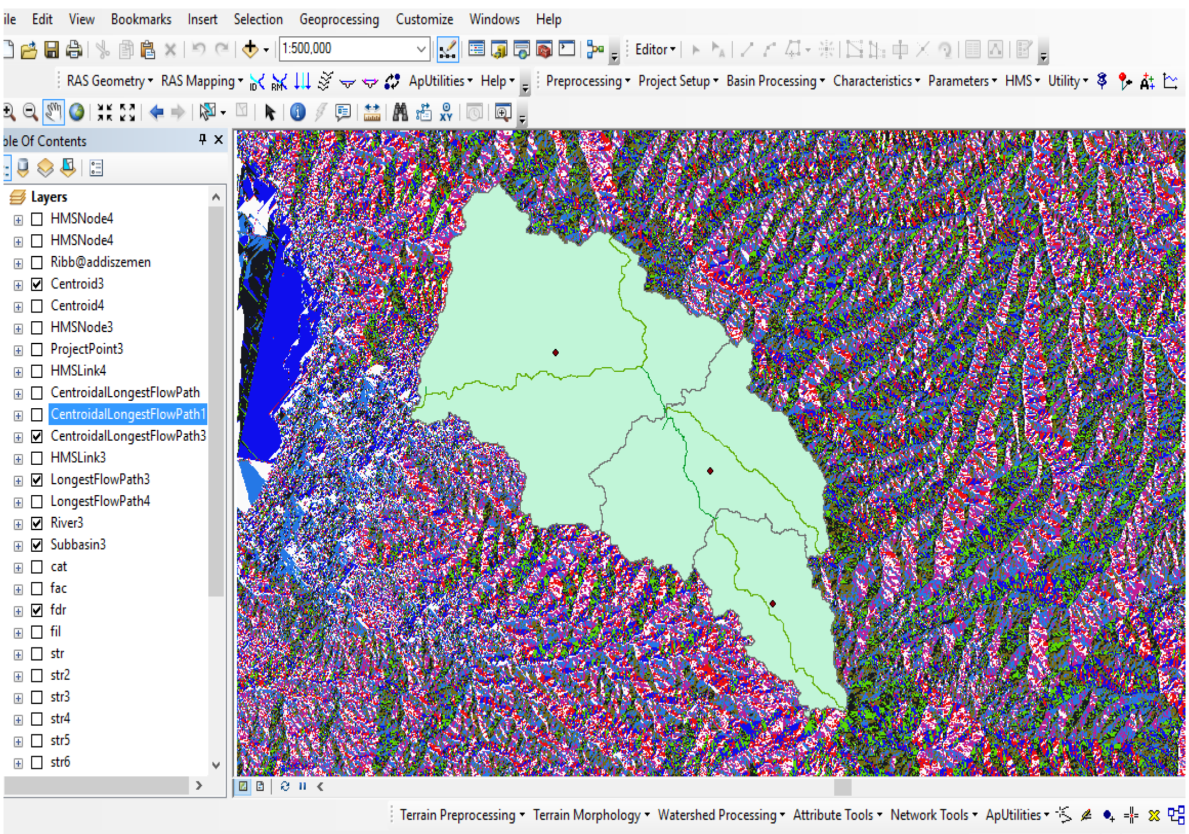



**Figure 3.0.18 Project area generation using Geo HMS**

## Data Collection

With the volume of spatial data available, it is important to identify the data that will meet project needs. Spatial data comes in many formats, resolutions, intended uses, quality, and prices. Prior to collecting data, the project specifications should be thoroughly reviewed for any recommendations. When a project does not specify a particular dataset, review the project's goals and objectives to help define acceptable data in terms of data storage, resolution, and accuracy. In addition, economic factors should be considered to determine the cost effectiveness in collecting and assembling the data or purchasing the data from a vendor. Whether the data are collected or purchased, metadata must also be acquired to provide necessary documentation.

**Data Assembly**

Data assembly often requires efforts and experiences of Arc GIS. Because GIS data have many forms and formats, we often need to convert the data into a common format and then into a common coordinate system.

**Terrain Preprocessing**

Using the terrain data as input, terrain preprocessing is a series of steps to derive the drainage network. The steps consist of computing the flow direction, flow accumulation, stream definition, and watershed delineation. These steps can be done step by step or in a batch manner. Once these datasets are developed, they are used in later steps for sub basin and stream delineation. It is important to recognize that the watershed and stream delineation in the terrain preprocessing steps is preliminary. Tools are available on the basin processing menu that gives the user the capability to delineate and edit basins in accordance with project specifications.

**HMS Project Setup**

The HMS Project Setup menu is used to define a study area that will be used to develop the input files for an HEC-HMS project. The user can define an outlet and HEC-Geo HMS will copy all the terrain prepossessing data for the area upstream of the outlet location. Then the user can use tools on the Basin Processing menu to modify the sub basin and stream network, subdivide and merge, to meet the study objectives. Multiple outlets and HMS projects can be defined in the same HEC-Geo HMS project.

**Basin Processing**

In this step, we can provided with a variety of interactive and batch-mode tools to delineate sub basins. In the interactive mode, the tools allow to see the delineation results, assess outcomes, and accept or deny the resulting delineation.

**Stream and Watershed Characteristics**

When the stream and sub basin delineation has been finalized, we can extract physical characteristics. Physical characteristics for a stream include the length, upstream and downstream elevations, and slope. This information is extracted from the terrain data and stored in attribute tables. Similarly, physical characteristics for a sub basin, such as longest flow lengths, centroidal flow lengths, and slopes, are extracted from terrain data and stored in the attribute tables. These physical characteristic could be exported and used externally to estimate hydrologic parameters.

**Hydrologic Parameters**

In addition to extracting physical characteristics, we have the option to estimate initial values of various hydrologic parameters. Hydrologic parameters, such as the curve number and percent impervious area, can be extracted as basin average and grid-based quantities from soil and land use data. Other hydrologic parameters, such as time of concentration, are computed from various datasets that include terrain and precipitation data.

**HEC-HMS Model Files**

HEC-Geo HMS produces a number of files that can be used directly by HEC-HMS. These files include background shape files, the basin model file, the meteorological model define the simulation time window. When these three model components are completed, we can compute a simulation run and calibrate the hydrologic model (USACE, file, and a project file. When the HEC-Geo HMS generated files are brought into an HEC-HMS project, the user has a partially completed HEC-HMS model. To complete the model, hydrologic parameters need to be estimated and entered into the basin model using HEC-HMS. In addition, we can add or remove hydrologic elements and their connectivity to reflect difficult modeling areas. Finally, we need to develop a meteorological model to represent the precipitation and control specifications to 2013).

#### *3.3.1.2 HEC-HMS Modelling*

The hydrologic modeling system (HEC-HMS) is designed to simulate the complete hydrologic process of dendritic watershed system. The program features a completely

integrated work including a data base, data entry functions, computation engine, and result reporting tools. To develop the model the features of the basin and sub basin should be demarcated. The basin is demarcated based on watershed physical data and their system connectivity such as sub basin, stream, and reservoirs. The hydrologic representation imported into HEC-HMS is then combined with precipitation data and control specifications to create flow and time series data for Hydrologic Modeling using HEC-HMS. Surface erosion and sediment routing model simulates with the combination of basin component, meteorological data, and control specification. The flow and time series data from HEC-HMS is imported into the hydraulic model HEC-RAS along with its geometry data to develop unsteady flow water surface profiles and unsteady flow sediment transport analysis.
HEC-HMS modeling may be taken considering different time series values such as hourly, daily, monthly, annually. Accuracy of the model output is very high using hourly and daily data. In this particular study for the respective sub basins, depending on the availability of time and data requirement simple canopy, Soil moisture accounting method, linear reservoir, Clark unit hydrograph, and Muskingum-Cunge and volume ratio parameters were used in the process of rain fall run-off and erosion and sediment transport simulation modeling. During hydrological model, the daily data by gage weight method was considered to compute watershed run-off and to predict reservoir sediment deposition. The MUSLE method has been selected for the surface erosion model based on land used.

#### 3.3.1.3 Basin model of the Study Area

The merged ASTER DEM (30m*30m) data exported from the global mapper was processed using Arc GIS using a tool called Arc hydro. The Arc Hydro data model provides a basic data base design for water resources. The Arc Hydro Tools are a series of tools built on top of the Arc Hydro data base that facilitates the analyses often performed in the water resources area.

The data model and the tools provide a foundation for water resources applications in GIS that can be built upon to meet the desired requirements. The Arc Hydro model and tools are designed to be flexible and easy to customize. The main terrain processing steps were processed by arc hydro are: DEM reconditioning, Fill sinks, Flow direction, Flow accumulation, Stream definition, Stream segmentation, Catchment grid delineation, Catchment polygon processing, Drainage line processing, Drainage point processing, longest flow path for the catchment and Slope determination. The results from terrain processing can be used to create input files for many hydrologic models using HEC- Geo HMS.

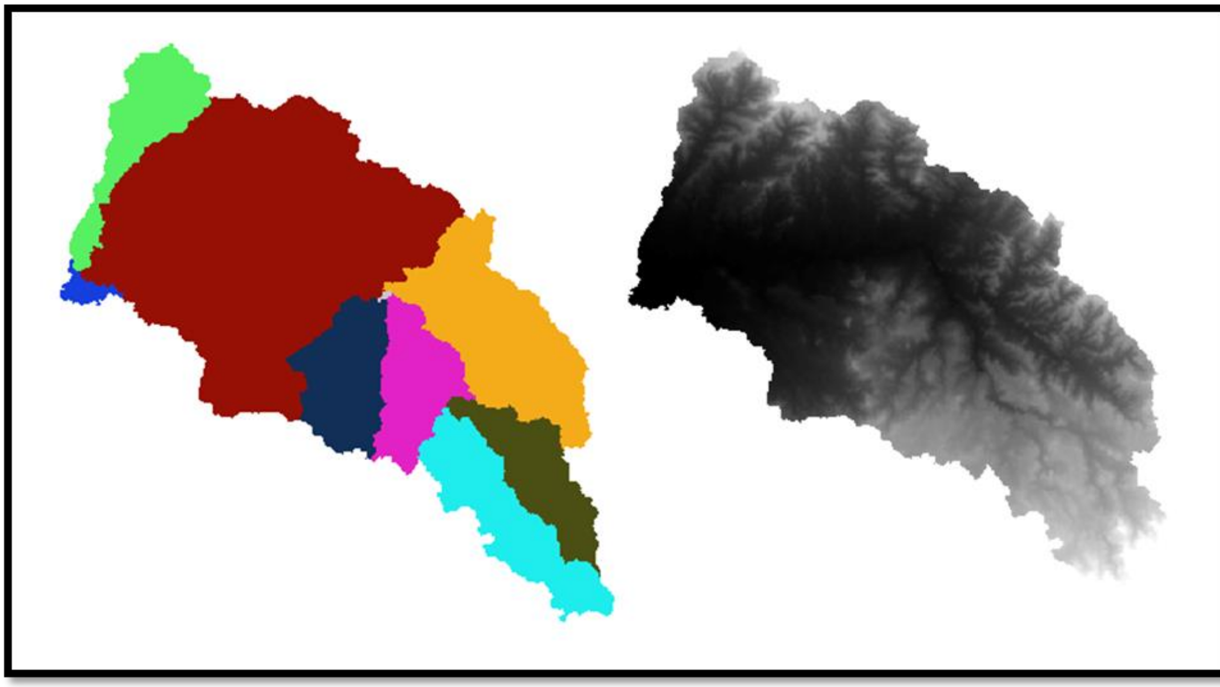


**Figure 3.0.19 a): Raw DEM b): Fill**

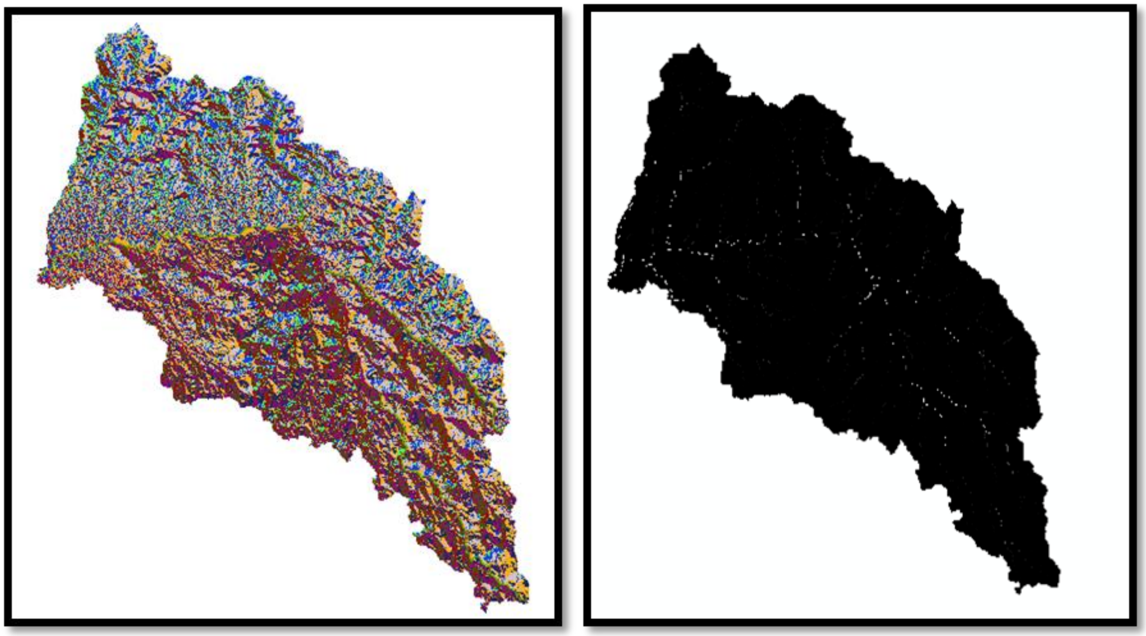


**Figure 3.0.20 a): Flow direction b): Flow accumulation**

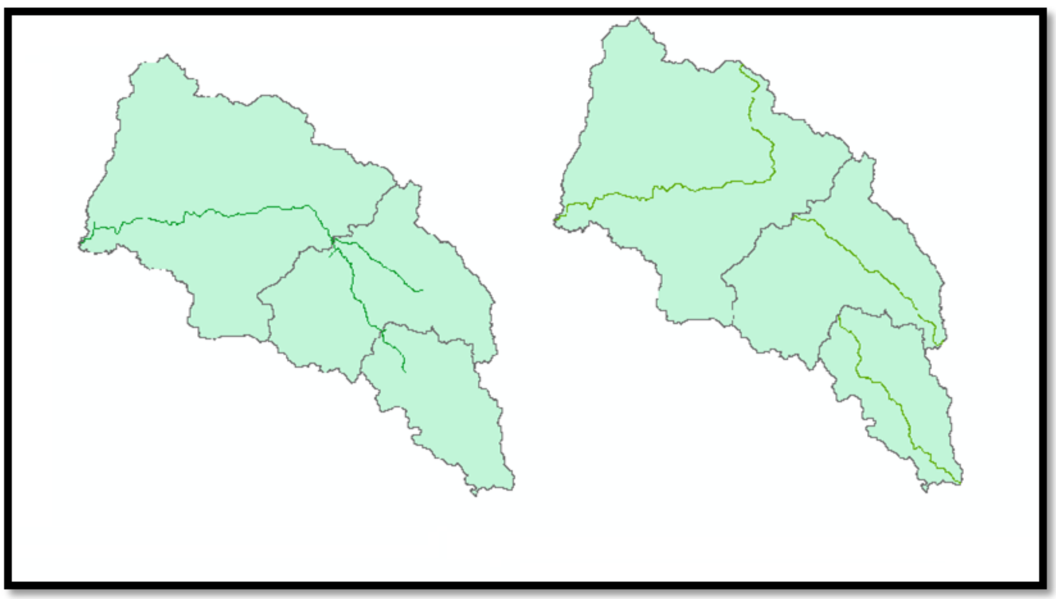


**Figure 3.0.21 a): project area b): Longest flow path**

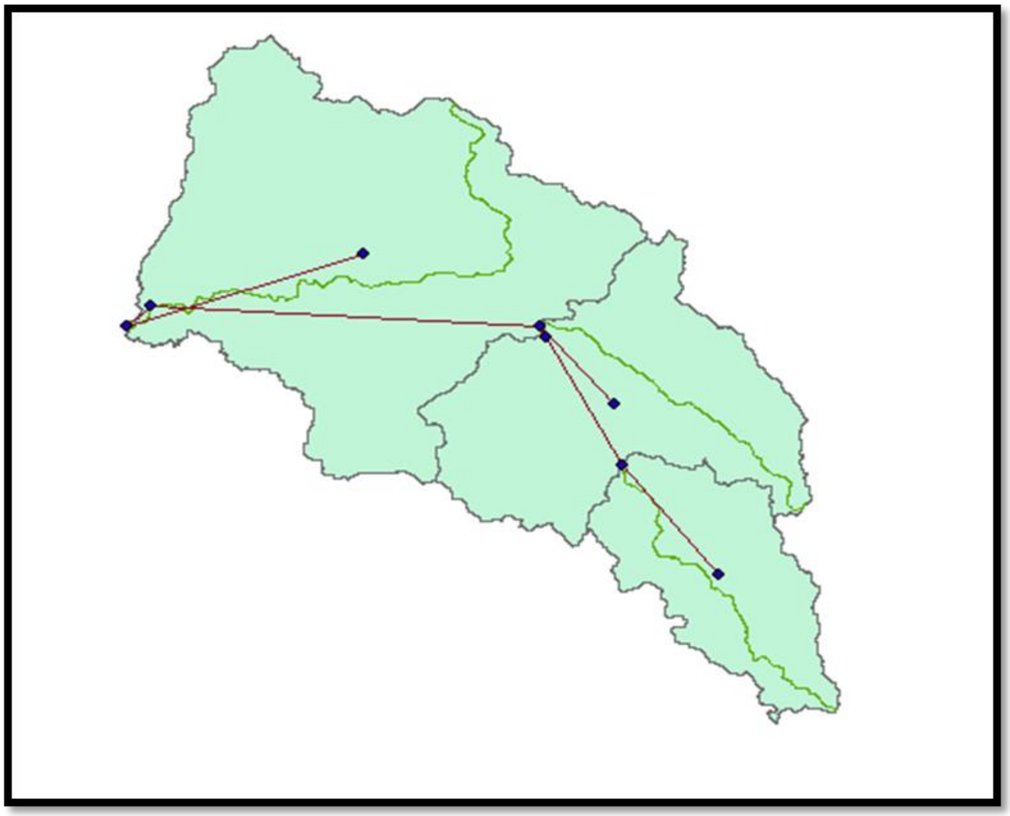


**Figure 3.0.22 HEC-HMS skeleton**

#### *3.3.1.5 Modeling using daily data*

**Input data and model components**

The hydrologic modeling System (HEC-HMS) was designed to simulate the complete hydrologic processes of dendritic watershed systems of Ribb River catchment. The main input data used for HEC-HMS were: areal precipitation, Evapotranspiration (optional), observed flow, base flow and watershed characteristics. HEC-HMS simulation was defined by three components: the Basin Model, the Meteorological Model, and the Control Specifications. The Basin Model contains a schematic consisting of any combination of the seven objects (sub-basin, reach, junction, source, and reservoir). The Basin Model stores information about the properties and connectivity Ribb River catchment in the schematic.

The Meteorological Model contains time series information consisting of catchment rainfall and evaporation data (optional). These data were associated with rain gages at Debretabor, Amba Giorgis, Gonder, Nefasmewcha and Woreta.

The Control Specifications component defines simulation properties such as duration and time step.

The HEC-HMS model for the Ribb catchment was done considering and dividing the sub-basin in to three sub-catchments. The calibrated model was used for runoff generation for 25 years continuous simulation. In this research paper the gage weight method was selected. The weights were specified by using Theissen polygon created in ArcGIS 10.2.

#### *3.3.1.6 Modeling approach*

**Basin model**

A general basin model consisting of sub-basin1, sub-basin2, and sub-basin3, reservoir, junction and outlet was set up in HEC-HMS exported from HEC-Geo HMS for the study area. The sub-basins, reservoir, and an out let element were used in the basin model to relate the simulated flow to the historical observed total flow of the sub-basins. In this particular study for the respective sub basins, depending on the availability of time and data requirement simple canopy, Soil moisture accounting method, linear reservoir, Clark unit hydrograph, and Muskingum-Cunge and volume ratio parameters were used in the process of rain fall run-off and erosion and sediment transport simulation modeling.

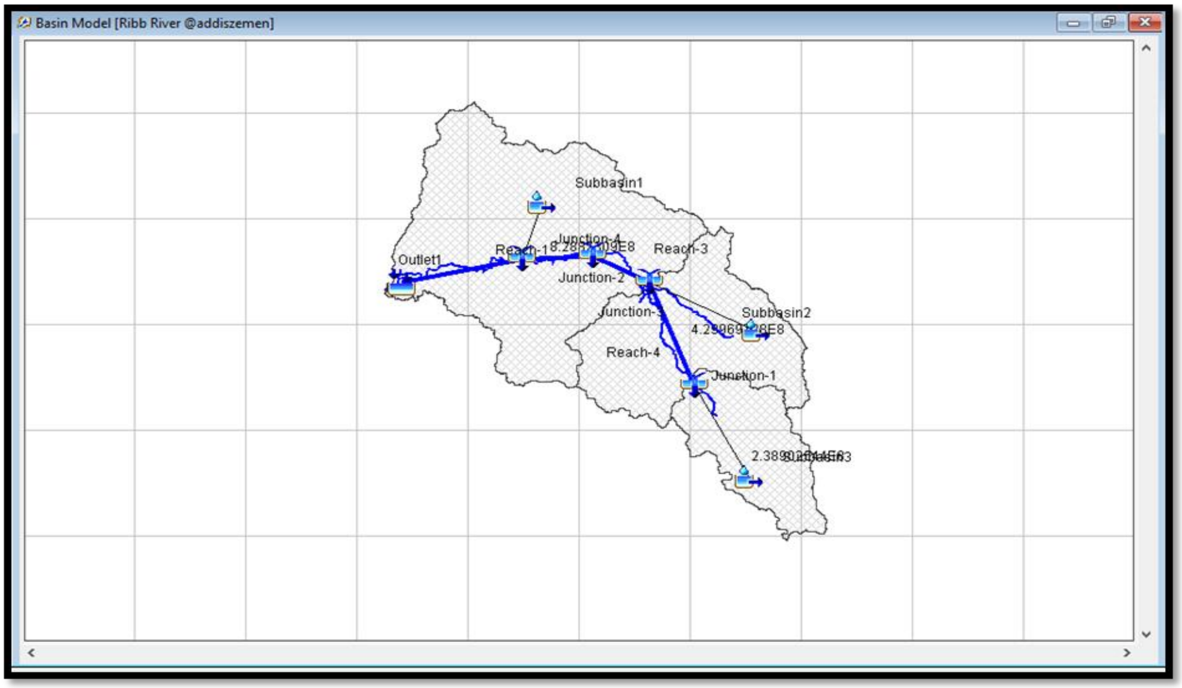



**Figure 3.0.23 HEC-HMS model of Ribb River basin**

### Canopy method

It is one of the components which is included the sub basin elements. It is used to represent the presence of plants in the catchment. Plants intercept some precipitation and reduces the amount of precipitation arrives on the surface of sub basins. Simple canopy method was used in this study. In this method all precipitation intercepted until the storage capacity filled.

### Loss method

It is one of the sub basin elements which are used to calculate the actual infiltration rate. The Soil moisture accounting method was used in this study. This method uses three layers to represent dynamics of water movement in the soil it is always used combine with canopy and surface method. The three layers are soil storage, upper ground water and lower ground water.

### Transform method

It is one of the sub basin elements which are used to calculate the actual surface runoff. Runoff transformations convert excess precipitation on a sub-basin to direct runoff at the sub-basin outlet. Clark's Unit Hydrograph model was used in this simulation model. It is a synthetic unit hydrograph used to develop translation hydrograph.

**Base flow**

It is one of the sub basin elements which used to calculate the actual subsurface runoff. Linear reservoir method was used for its suitability to the purpose of the study. The linear reservoir method used to model the depression of base flow after the storm event and used to conserve mass within the subbasin.

**Erosion**

It is one of the parameters of HEC-HMS in erosion and transportation modeling. These global properties are applied to all elements in the basin. The transport potential method specifies how the sediment carrying capacity of the stream flow will be calculated for non-cohesive and cohesive sediments. The modified Universal soil loss equation (MUSLE) method was used in this study.

**Routing method**

River routing is a process of computing the travel time and reduction of water flowing in open channels. IT is one of the parameters which are used to calculate the actual stream or river segment. The Muskingum-Cunge routing is based on the combination of the conservation of mass and the diffusion representation the conservation of momentum.

**Sediment**

Sediment method is one of the parameters of HEC-HMS in erosion and sediment transportation modeling. In this method the Ackers and white and Laursen and Copeland transportation potential, Report 12 fall velocity method and clay-silt-sand-gravel gradation grade scale system were used.

#### *3.3.1.7 Meteorological Model*

Gage weight Method Inputs

Sub-basin/station Spatial/depth weight Time/seasonal weight

**Table 4 Gauge weights**

| Sub basin | Gage stations | Gage weights |
|---|---|---|
| 1 | Debretabor | 0.85 |
| 2 | Nefasmewcha | 0.15 |
| 3 | Woreta | - |

#### *3.3.1.8 Model calibration*

Model calibration is the systematic process of adjusting model parameter value results until model results match acceptably the observed data. The quantitative measure of the match is described by the objective function. In the precipitation run-off models this function measures the degree of variation between computed and observed hydrographs. The calibration process finds the optimal parameter values that minimize the objective function (Cunderlik and Simonovic, 2004). Calibration can either be manual or automated (optimization).

Manual calibration depends on the user knowledge of the physical properties and knowledge in hydrologic modeling. In automatic calibration model parameters are iteratively adjusted until the value of the selected objective function minimalized. Systematic approach to the manual calibration was chosen as the only variable approach to the calibration of the continuous model.

HEC- HMS was calibrated for the run-off event of 01Jan2001-31Dec2005. The rainfalls used were the daily rainfalls beginning at 9:00 a.m. each day. Precipitation data was taken from six stations that are located within and near the watershed.

The HEC- HMS model was selected the most appropriate hydrologic modeling tool according to the Canadian Foundation for Climatic and Atmospheric sciences (CFCA) (Cunderlik and Simonovic, 2004).

To compare a computed hydrograph to an observed hydrograph, the program computes an index of the goodness-of-fit. Algorithm included in the program search for the model parameters that yield the best value of an index, also known as objective function. Out of four objective functions in HMS, Peak-weighted root mean square error is selected for this study.

This function is an implicit measure of comparison of the magnitudes of the peaks, volumes, and times of peak of the two hydrographs. Nealder and Mead Algorithm method of search parameter, that the value of the objective function is used for this study. This algorithm relies on a simple direct search. A total of 25 years historical data from (1990- 2015) is used, calibration (1993 -1998) and validation (2000-2005) for the selected watersheds of the sub basins. Manual and automatic calibration was used for optimization of observed and simulated flow data using initial parameter from watershed characteristics. Calibration was done by taking initial parameters generated from HEC-Geo HMS and Arc Hydro for the catchment. With the initial parameters, the calibration was then processed until the simulated value resembles the observed data.

**In continuous calibration**

**Parameter set:**

The parameters of continuous simulation of run-off were calibrated manually using systematic approach. The input data for continuous model are available in the daily time. The model calibrated depending on soil type, land use and vegetated cover and according to the range of possible values.

#### *3.3.1.9 Model efficiency*

The performance of a model must be evaluated on the extent of its accuracy, consistency and adaptability (Goswami, 2005). A forecast efficiency criterion is therefore necessary to judge the performance of the model. For Ribb River project area catchment study the model simulation has been evaluated using coefficient of determination and ($R^2$) and (Nash and Sutcliff, 1970).

$$E_{NS} = 1 - \left[\frac{\sum_{i=1}^{n} (q_{oi} - q_{si})^2}{\sum_{i=1}^{n} (q_{oi} - q_o)^2}\right] \text{ - - - - - - - - - - - - - } 22$$

$$R^2 = \quad E_{NS} = \frac{\sum_{i=1}^{n}[(q_{si} - q_s)(q_{oi} - q_o)]^2}{\sum_{i=1}^{n}((q_{si} - q_s)^2) \ \sum_{i=1}^{n} (q_{oi} - q_o)^2} \text{ - - - - - - - - - - - - - } 23$$

There coefficient of determination $R^2$=0.73 and Nash and Sutcliff value (ENS) =0.64

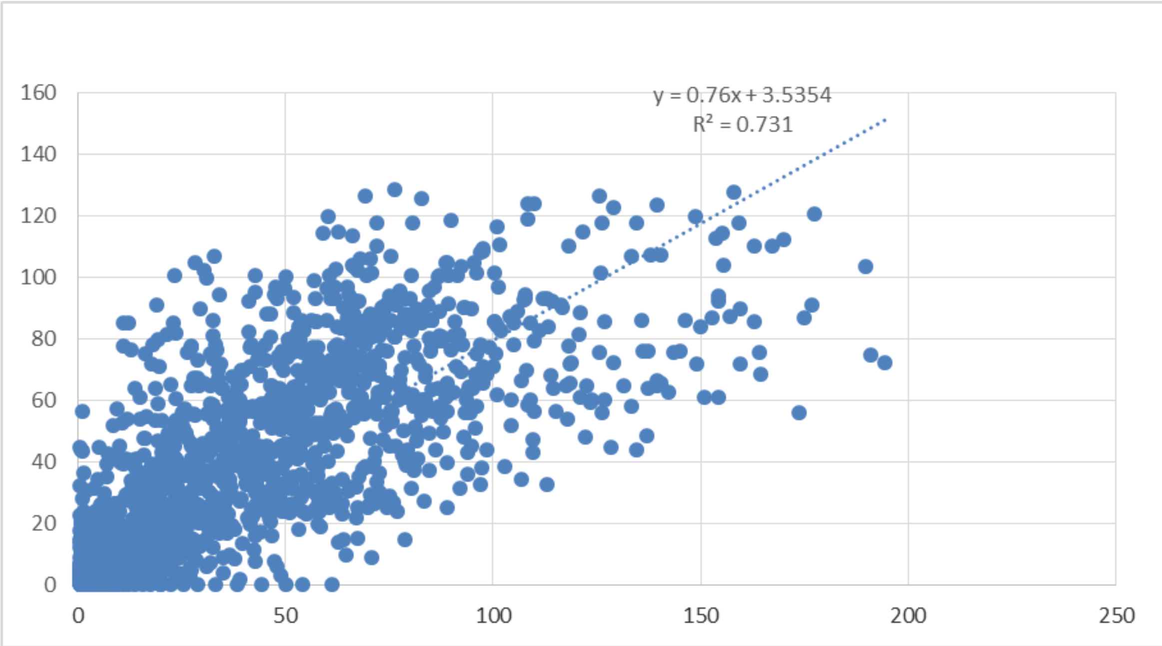



**Figure 3.0.24 Model validation**

### *3.3.1.10 Sediment Modeling using HEC-HMS*

Erosion and sediment transport in the basin model, by default component features are deactivated, data entry tools are not for sediment are not visible in the program interface, and no sediment results are computed during a simulation. The features become accessible when they are activated for the basin model.

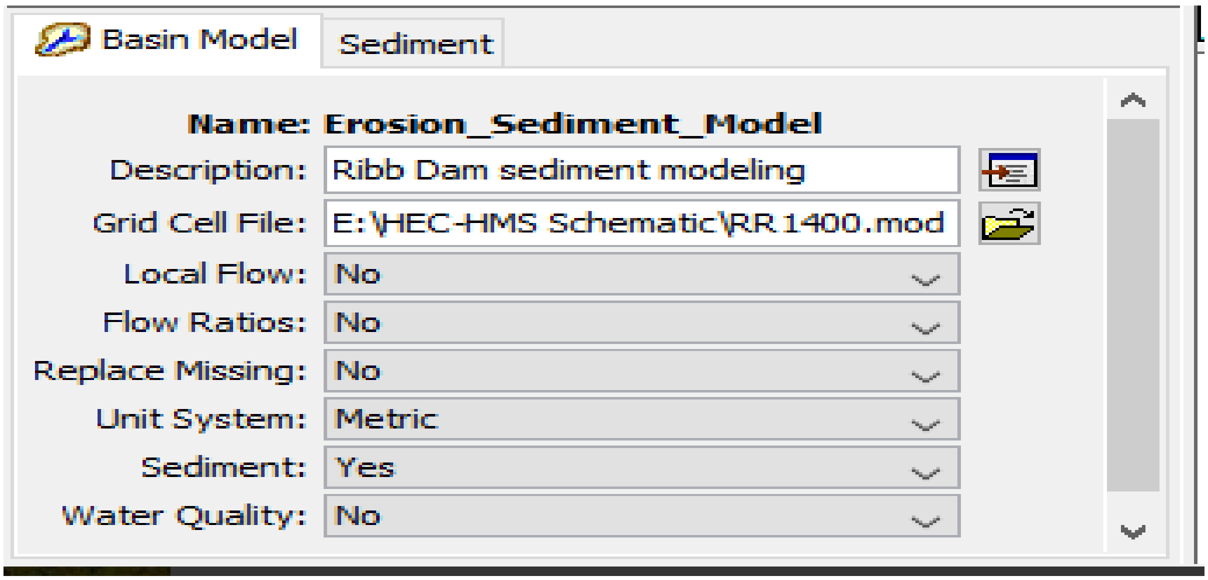


**Figure 3.0.25 HEC HMS sediment modeling**

Time-Series Results for Reservoir "Ribb Dam"

Project: Ribb River @ dam Simulation Run: Sediment@Dam
Reservoir: Ribb Dam

Start of Run: 01Jan1992, 09:00 Basin Model: SedimentwithDam
End of Run: 31Dec2014, 09:00 Meteorologic Model: Gage Wts.
Compute Time: 15Jun2016, 23:04:20 Control Specifications: Full Simulation

| Date | Time | Inflow (M3/S) | Storage (1000 M3) | Elevation (M) | Outflow (M3/S) |
|---|---|---|---|---|---|
| 01Jan1992 | 09:00 | 1.2 | 17688007.9 | 1895.0 | 15.8 |
| 02Jan1992 | 09:00 | 1.2 | 17686742.4 | 1895.0 | 15.8 |
| 03Jan1992 | 09:00 | 1.2 | 17685477.2 | 1895.0 | 15.8 |
| 04Jan1992 | 09:00 | 1.2 | 17684212.2 | 1895.0 | 15.8 |
| 05Jan1992 | 09:00 | 1.2 | 17682947.4 | 1895.0 | 15.8 |
| 06Jan1992 | 09:00 | 1.2 | 17681682.8 | 1895.0 | 15.8 |
| 07Jan1992 | 09:00 | 1.2 | 17680418.3 | 1895.0 | 15.8 |
| 08Jan1992 | 09:00 | 1.2 | 17679153.9 | 1895.0 | 15.8 |
| 09Jan1992 | 09:00 | 1.2 | 17677889.6 | 1895.0 | 15.8 |
| 10Jan1992 | 09:00 | 1.2 | 17676625.4 | 1895.0 | 15.8 |
| 11Jan1992 | 09:00 | 1.2 | 17675361.1 | 1895.0 | 15.8 |
| 12Jan1992 | 09:00 | 1.2 | 17674096.9 | 1895.0 | 15.8 |
| 13Jan1992 | 09:00 | 1.2 | 17672832.6 | 1895.0 | 15.8 |
| 14Jan1992 | 09:00 | 1.2 | 17671568.3 | 1895.0 | 15.8 |
| 15Jan1992 | 09:00 | 1.2 | 17670304.0 | 1895.0 | 15.8 |
| 16Jan1992 | 09:00 | 1.2 | 17669039.5 | 1895.0 | 15.8 |
| 17Jan1992 | 09:00 | 1.2 | 17667775.0 | 1895.0 | 15.8 |
| 18Jan1992 | 09:00 | 1.2 | 17666510.3 | 1895.0 | 15.8 |
| 19Jan1992 | 09:00 | 1.2 | 17665245.5 | 1895.0 | 15.8 |
| 20Jan1992 | 09:00 | 1.2 | 17663980.6 | 1895.0 | 15.8 |
| 21Jan1992 | 09:00 | 1.2 | 17662715.5 | 1895.0 | 15.8 |

**Figure 3.0.26 HEC HMS dam outflow series**

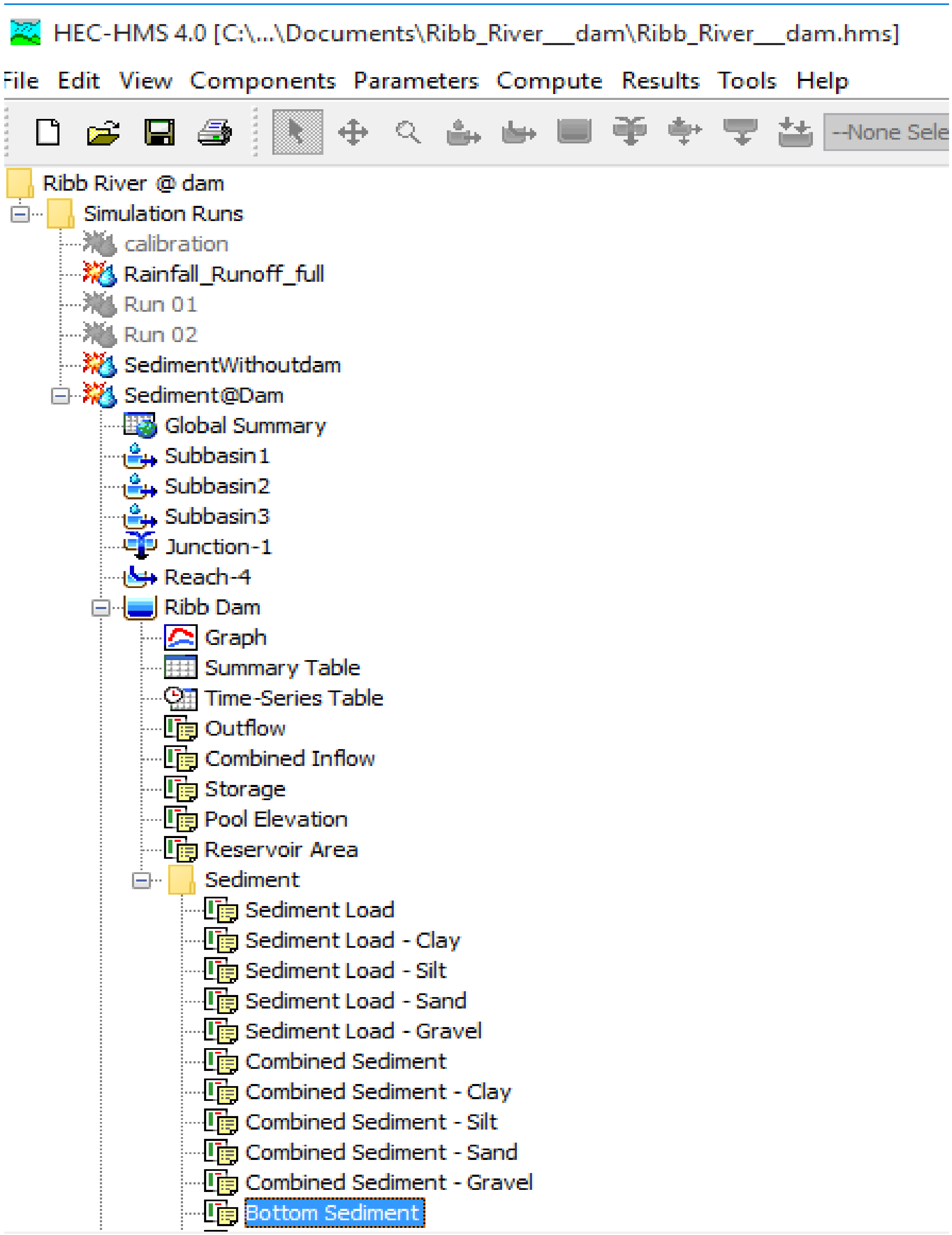



**Figure 3.0.27 Ribb reservoir sediment modeling**

#### *3.3.1.11 HEC-HMS erosion and transportation model governing equations*

When water flows over land surfaces and over the stream channels, it affects the land scape and in significant ways. Shallow surface flow erodes soil and carries the material over land to head water streams. Steep head water streams have high flow velocity that leads to stream bed erosion. Eroded surface soil and bed material can be carried by stream flow to lower reaches of the watershed. Sediment is often deposited in the lower reaches where the flow velocity slows. Reservoirs in the watershed will trap most of the sediment that enters with the inflow (USACE, 2013).

Erosion and transportation modeling requires a number of properties to be specified. These global properties are applied to all elements in the basin. The transport potential method specifies how the sediment carrying capacity of the stream flow will be calculated for non-cohesive and cohesive sediments. Transport potential functions for calculating the amount of sediment that can be carried by the stream flow. Ackers and white transportation function and Rubey fall velocity method were selected in this study.

The parameters included were

- Specific gravity of the sediment
- Density of clay sediment
- Density of silt sediment
- Density of sand and gravel sediments

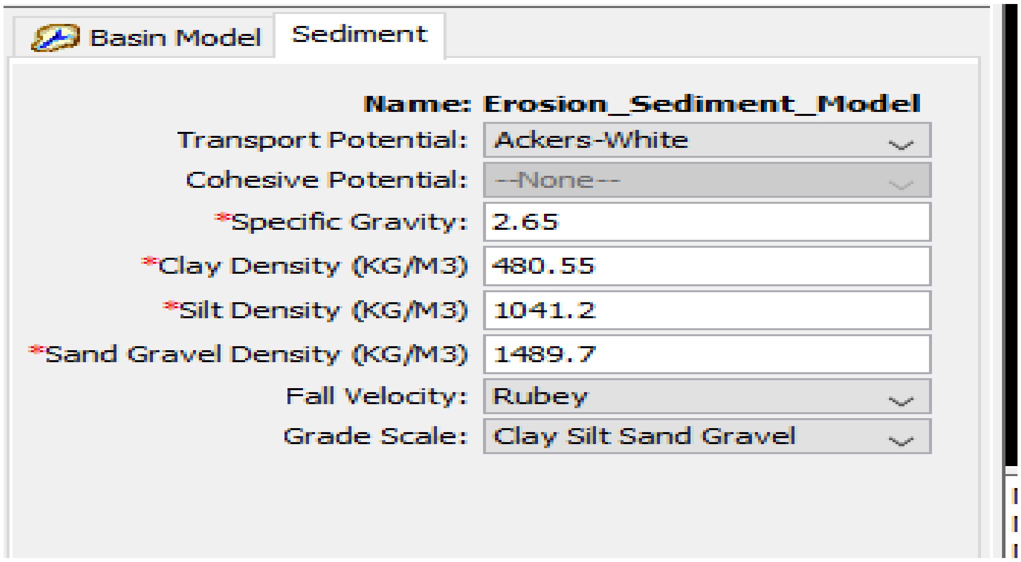



**Figure 3.0.28 Sediment methods and entering parameter**

**Selecting an erosion sediment method:**

The erosion method for a subbasin was selected on component editor for the subbasin element. In this study the subbasin methods selected were

- ❖ Canopy method-Simple canopy
- ❖ Surface method- Simple surface
- ❖ Loss method-Soil moisture accounting
- ❖ Transform method-Clark unit hydrograph
- ❖ Base flow-Linear reservoir
- ❖ Erosion method-Modified Universal soil loss equation (MUSLE)

**Modified Universal soil loss equation (MUSLE)**

The modified Universal soil loss equation (MUSLE) method (Williams, 1975) was adapted from the original Universal soil loss equation (USLE). The original equation was based on precipitation intensity and high infiltration. The modifications to the original soil loss equation changed the formulation to calculate erosion from surface run-off instead of precipitation. The method works best for agricultural environments where it was developed (USACE, 2013).

Modified soil loss equation

$$Sed = (11.8 \times Q_{surf} \times q)\ 0.56 \times K \times LS \times C \times P \quad - - - \ - \ 1$$

Where: *Sed* = sediment yield in the watershed, for a specific pluvial event (t/watershed)

$Q_{surf}$ = *the surface run-off volume* ($m^3$)

K =soil erodibility factor

LS = slope length, gradient factor

C = crop management factor

P =erosion control-practice factor

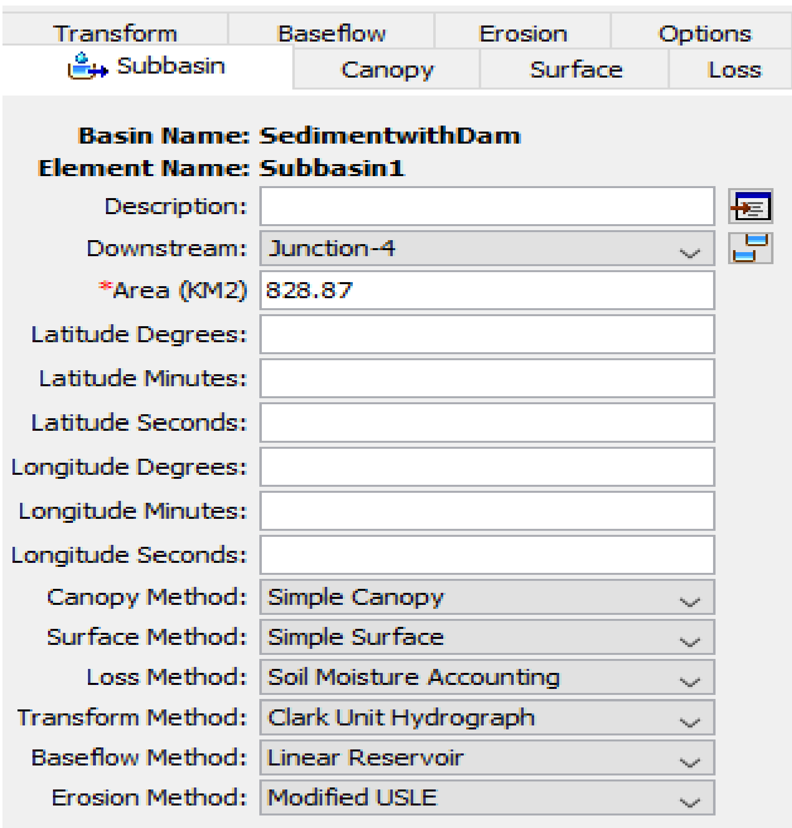



**Figure 3.0.29 Selecting surface erosion methods**

### 3.3.2 HEC-RAS modeling

In this study, the hydrological data generated from the HEC-HMS model is used as an input data to HEC-RAS sediment transport model, in addition to this another data such as Elevation, channel geometry, Manning's roughness, sediment concentration and sediment gradation data. To run the HEC-RAS model, it is necessary to know the particle size distribution for the sediment transport and this was found by collecting samples from both Ribb River. The samples were taken from the laboratory grain size analysis of WWDSE. HEC-RAS 5.0.1, 2016 is a one-dimensional modeling software package that allows the performance of four different river analyses: (1) steady flow, (2) unsteady flow, (3) water quality and (4) movable boundary sediment transport computation, which was used in this study. All four components of the model use common geometric data and common geometric and hydraulic computation routines (USACE, 2016).

#### 3.3.2.1 Model Geometry based on TINs

In addition to DEMs field surveyed Ribb River cross-section and elevation data Included to develop geometric data for HEC-RAS modeling. Contour was generated from field surveyed cross-section excel data by using Eagle point and Auto CAD. Triangular Irregular Network generated from the intersection of actual field survey data. The TIN for this research is done with good precision due to the availability of the field surveys on the Ribb River channel cross-section, which covers 30 Kilometers of the study area. The river cross-section was developed from the TIN.

The surveyed data contains information about the river layers (channel length /center line, right bank and left bank length).

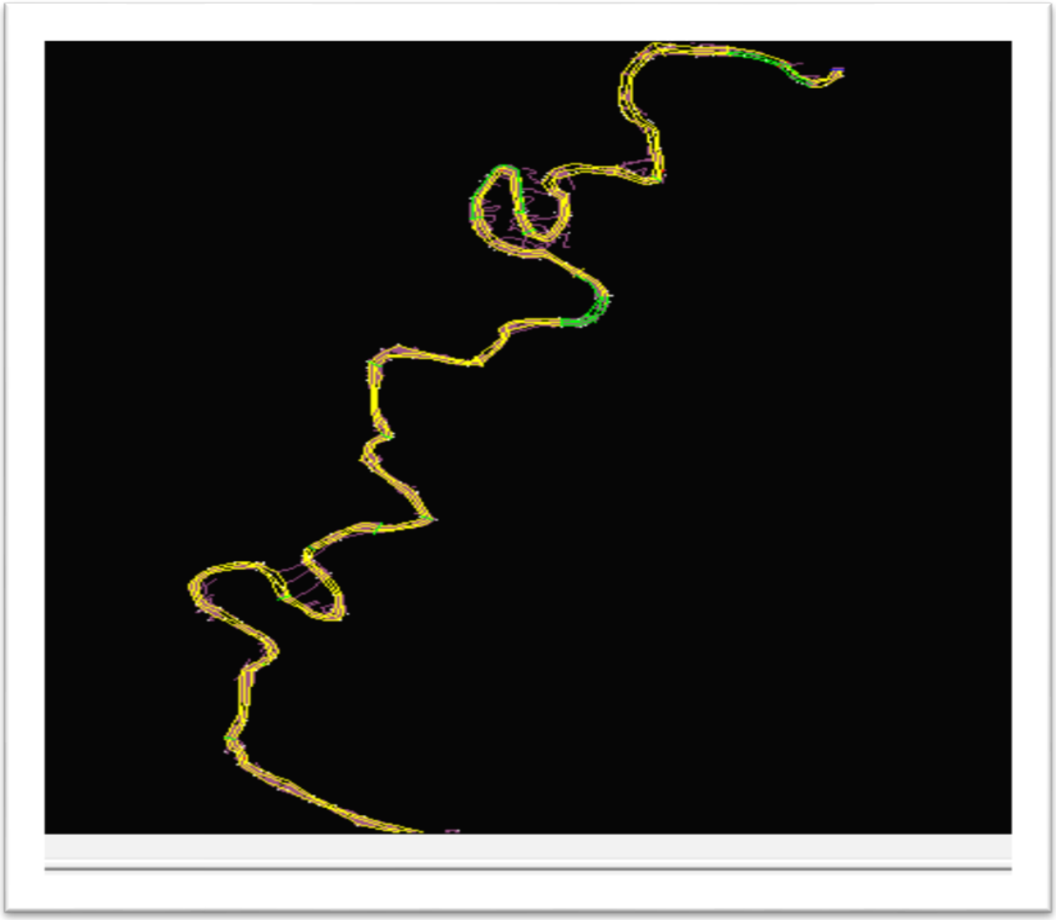


**Figure 3.0.30 Contour generated using Tera model and Auto CAD**

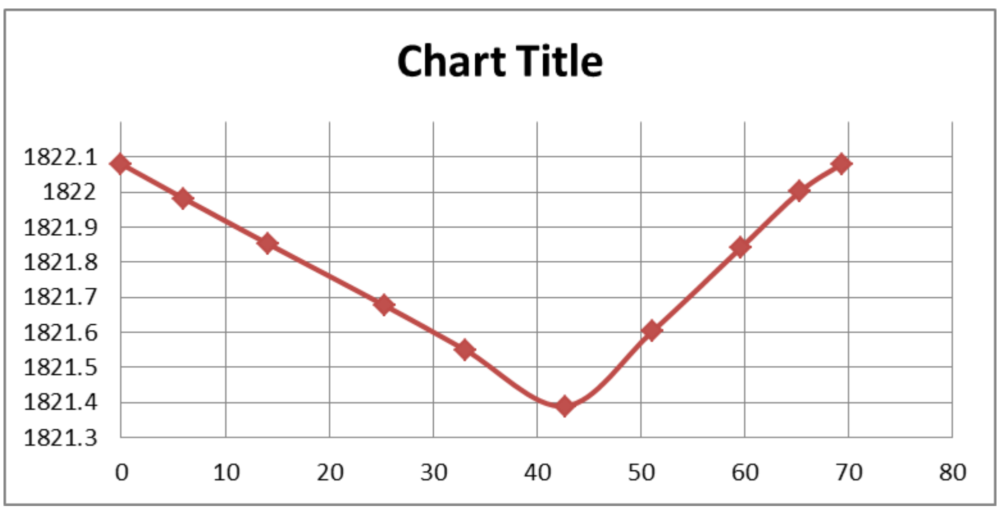



**Figure 3.0.31 Typical River cross section**

### 3.3.2.2 River Geometry development

The geometry of the downstream Ribb dam was developed using HEC-RAS 5.0.1. This study focuses on a 30 km long reach located Ribb dam and diversion weir up stream of Lake Tana. The modeled reach of the river was much longer than that to sufficiently separate the focus reach from the model boundaries and their influences. The first of the components is the channel geometry. To analyze stream flow, HEC-RAS represents a stream channel as a series of cross-sections along the channel. River cross-section data was needed to create geometric model, measured by using Auto CAD, which was imported from the contour generated by eagle point. This HEC-RAS geometry file contains physical parameters describing cross-sections. The measured cross-sections were at 82 stations. The geometry data consists of cross-section x-y coordinate, reach lengths, manning's n values, main channel bank stations, contraction and expansion.

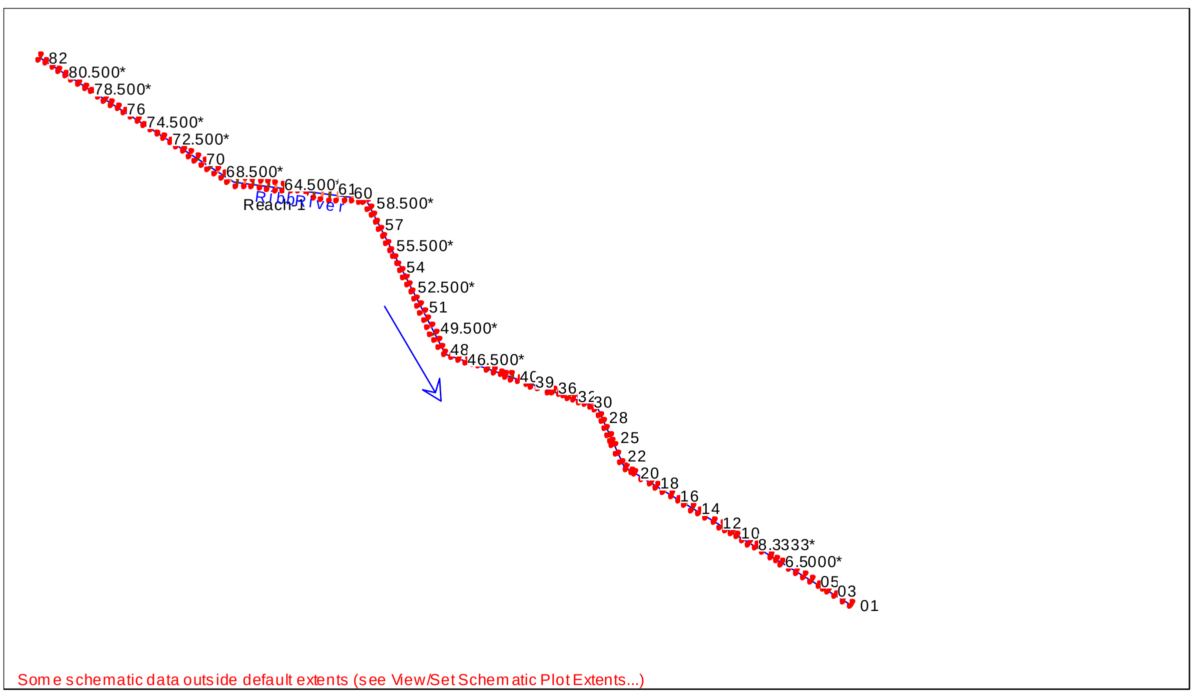



**Figure 3.0.32 Generated Ribb river cross-sections using HEC-RAS**

### 3.3.2.3 1D steady flow water surface profile

The methodologies used in performing the one dimensional (1D) steady flow and unsteady flow calculations. HEC-RAS currently capable of performing 1D water surface profile calculations for steady gradually varied flow river channel. Subcritical, supercritical, and mixed flow regime water surface profiles can be calculated.

**Equations for basic profile calculations**

Water surface profiles are computed from one cross section to the next by solving the energy equation with the standard step method. The energy equation is written as follows :( US Army Corps of Engineers Hydraulic Reference Manual version 5.0, 2016)

$$Z_2 + Y_2 + \frac{\alpha_2 V^2{}_2}{2g} = Z_1 + Y_1 + \frac{\alpha_1 V^2{}_1}{2g} \text{ - - - - - - - - - - - - -2}$$

Where: Z1, Z2 = elevation of the main channel inverts

Y1, Y2 = depth of water at cross sections

V1, V2 = average velocities

±α1, ±α2 = velocity weighting coefficients

g = gravitational acceleration

he = energy head loss

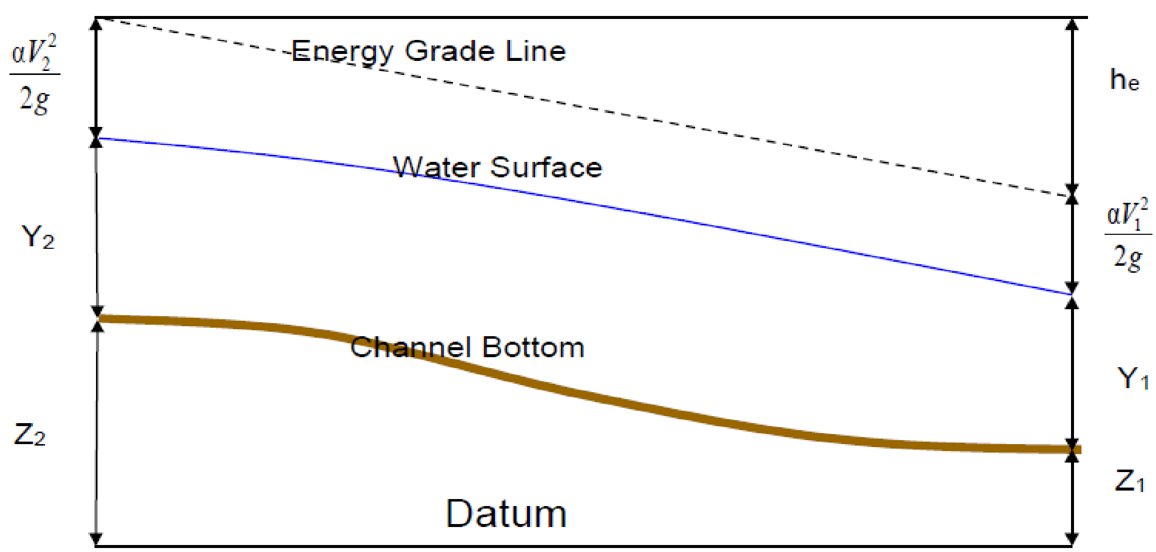



**Figure 3.0.33 Representation of terms of energy equation (G. Brunner, 2010)**

The energy head loss (he) between two cross sections is comprised of friction losses and contraction or expansion losses. The equation for the energy head loss is as follows:

$$he = LS_f + C\left|\frac{\alpha_2 V^2{}_2}{2g} - \frac{\alpha_1 V^2{}_1}{2g}\right| - - - - - - - - - - - 3$$

Where: L = discharge weighted reach length

Sf = representative friction slope between two sections

C = expansion or contraction loss coefficient

The distance weighted reach length, L, is calculated as:

$$L = \left[\frac{L_{lob}Q_{lob} + L_{ch}Q_{ch} + L_{rob}Q_{rob}}{Q_{lob} + Q_{ch} + Q_{rob}}\right] - - - - - - - - - - - - - - 4$$

Where: LIob, Lch, Lrob = cross section reach lengths specified for flow in the left overbank, main channel, and right over bank, respectively.

$\boldsymbol{Q_{lob} + Q_{ch} + Q_{rob}}$ = arithmetic average of the flows between sections for the left overbank, main channel, and right over bank, respectively.

**Cross section sub division for conveyance calculations**

The determination of total conveyance and the velocity coefficient for a cross section requires that flow be subdivided in to units for which the velocity is uniformly distributed.

$$Q = KS^{1/2}{}_f \quad - - - - - - - - - - - - 5$$

$$K = \frac{1.486}{n}AR^{2/3} \quad - - - - - - - - - - - - 6$$

Where: K = Conveyance for sub division

N = manning's roughness coefficient

A = flow area of for subdivision

R = hydraulic radius for subdivision (area/wetted perimeter)

Sf = slope of the energy grade line

The program sums up all the incremental conveyances in the overbanks to obtain a conveyance for the left over bank and the right over bank. The main channel conveyance is normally computed as a single conveyance element. The total conveyance for the cross section is obtained by summing the three subdivision conveyance (left, channel, and right)

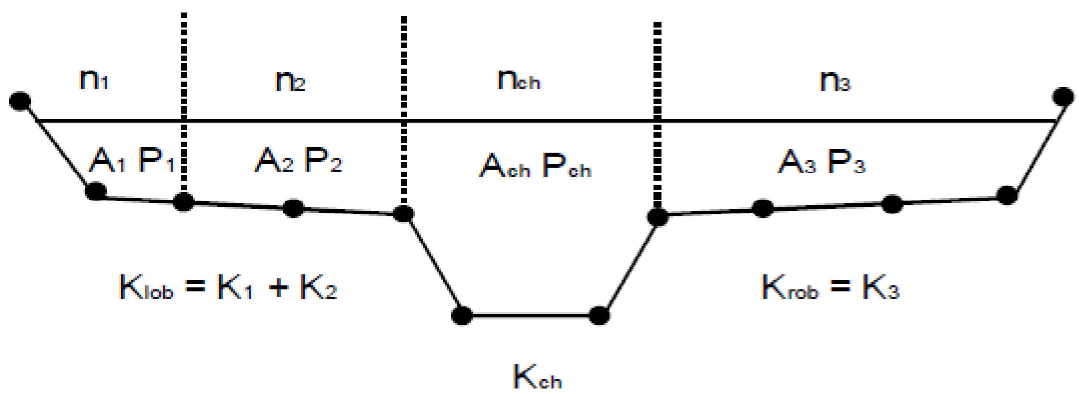



**Figure 3.0.34 HEC-RAs default conveyance sub division method**

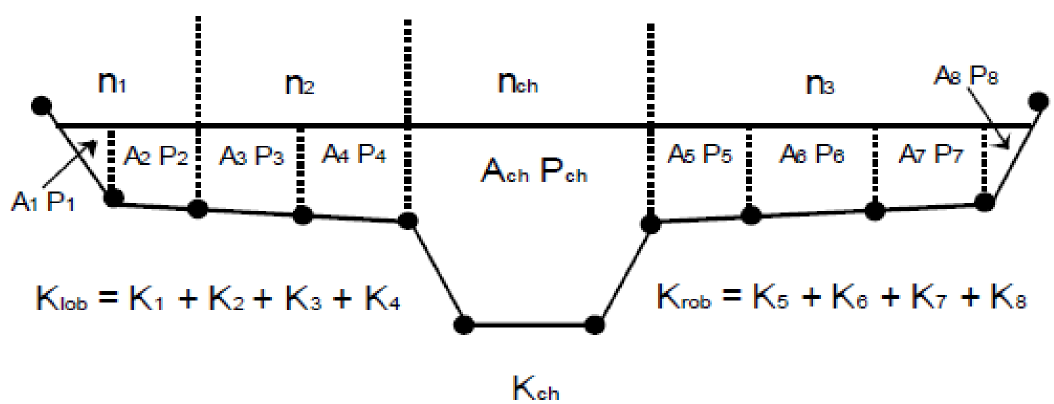



**Figure 3.0.35 alternative conveyance subdivision method**

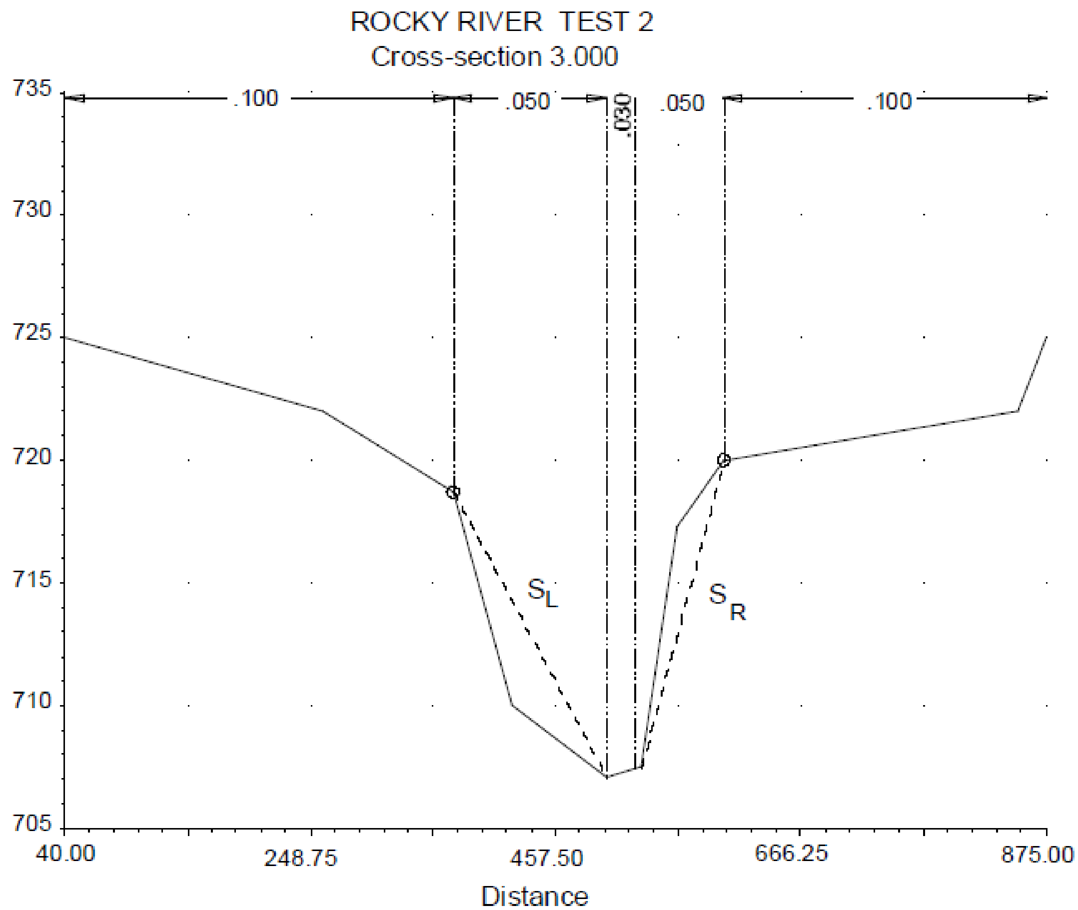



**Figure 3.0.36 Definition of bank slope for composite n calculation**

$$n_c = \left[\frac{\sum_{i=1}^{N}(P_i R^{2/3}{}_i)}{P}\right]^{2/3} \quad ------------- 7$$

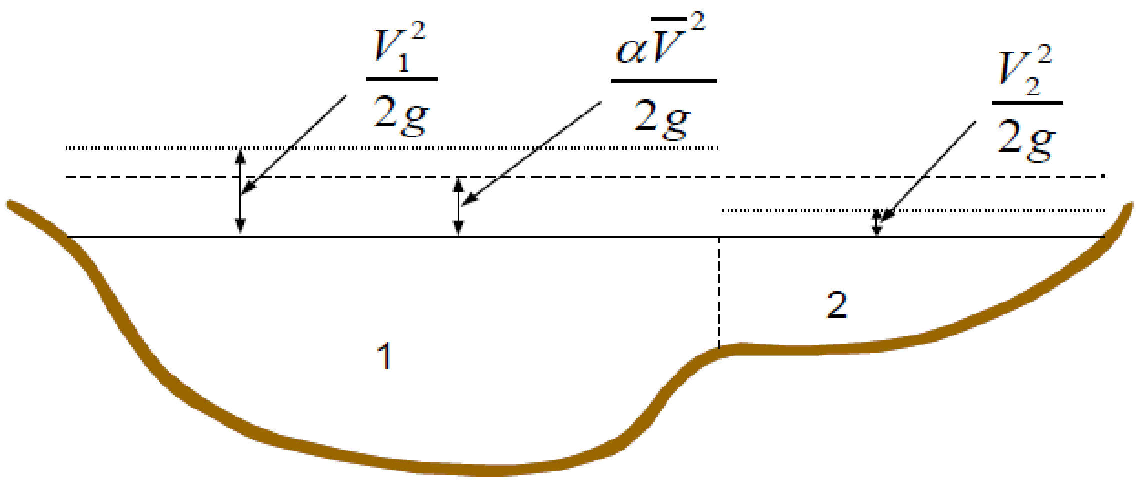
Where: nc = Composite or equivalent

P = wetted perimeter of entire main channel

Ni = coefficient of roughness for subdivision

**Evaluation of the mean kinematic energy head**

For a given water surface elevation, the mean energy is obtained by computing a flow weighted energy from the three sub section of cross section.




V1 = mean velocity of sub area1

V2 = mean velocity of sub area 2

To compute the kinetic energy it is necessary to obtain the velocity head weighting Coefficient alpha. Alpha is calculated as follows:

Mean Kinetic Energy Head = Discharge Weighted Velocity Head

$$\alpha\frac{V^2{}_2}{2g} = \frac{Q_1\frac{V^2{}_1}{2g} + Q_2\frac{V^2{}_2}{2g}}{Q_1 + Q_2} \text{------------------} 8$$

The velocity coefficient, α, is computed based on the conveyance in the three flow elements: Left over bank, Right over bank and channel. It can also be written in terms of conveyance and area as in the following equation:

$$\alpha = \left[\frac{(A_t)^2\left[\frac{K^3{}_{lob}}{A^2{}_{lob}} + \frac{K^3{}_{ch}}{A^2{}_{ch}} + \frac{K^3{}_{rob}}{A^2{}_{rob}}\right]}{K^3{}_t}\right] \text{----------------} 9$$

Where: At = Total flow area of cross section of cross section

AIob, Ach, Arob = flow areas of left over bank, main channel and right over bank, respectively.

Kt = total conveyance of cross section

KIob, Kch, Krob = conveyances of left over bank, main channel and right over bank, respectively.

**Friction loss evaluation**

Friction loss is evaluated in HEC-RAS as the product of Sf and L.

Where Sf is the representative friction slope for reach and L is define the given length L. The friction slope (the slope of the grade line) at each cross section is computed from manning's can be computed as follows

$$S_f = \left(\frac{Q}{K}\right)^2 - - - - - - - - - - - - - - - - - - - - 10$$

**Contraction and expansion loss equation**

Contraction and expansion losses in HEC-RAS can be evaluated by the following equation

$$he = C\left|\frac{\alpha_1 V^2}{2g} - \frac{\alpha_2 V^2}{2g}\right| - - - - - - - - - - - - - - - 11$$

Where C= the contraction or expansion coefficient

**Application of the Momentum loss equation**

Momentum Equation: will be applied whenever the water passes through critical depth i.e. during hydraulic jump, low flow hydraulics at bridges; at stream junctions.

Applying of Newton's second law motion to a body of water enclosed by two cross-sections can be expressed by the following equations.

$$P2 - P1 + Wx - Ff = Q\rho\Delta Vx \qquad \text{- - - - - -} \quad 12$$

Where: P = Hydrologic pressure force at location 1 and 2

Wx = Force due to the weight of water in the X direction.

Ff = Force due to external friction losses from 2 and 1.

Q = Discharge and

ρ = Density of water

Vx = Change on velocity from 2 to 1, in the X direction.

Estimation of manning's roughness coefficient:

The Manning roughness coefficient is the resistance factor against river flow. Therefore it will be estimated based on Ribb River bed material formed by moving bed materials and land use data.

**3.3.2.4 Unsteady flow modeling**

Unsteady flow analysis can be performed using HEC-RAS 5.0.1 without sediment analysis. This component of the HEC-RAS modeling system is capable of simulating one dimensional flow through a full network of river channel. For the case of Ribb River the 25 years controlled flow HEC-HMS 4.0 simulated series form dam outlet was used for the simulation of 25 years HEC-RAS unsteady flow modeling. To run unsteady flow analysis geometric, unsteady flow boundary conditions were required.

Unsteady flow hydrodynamics

The physical laws which govern the flow of water in the stream are:

1) The principle of conservation of mass(continuity)
2) The principle of conservation of momentum.

These laws are expressed mathematically in the form of partial differential equations as follows

**Continuity equation:**

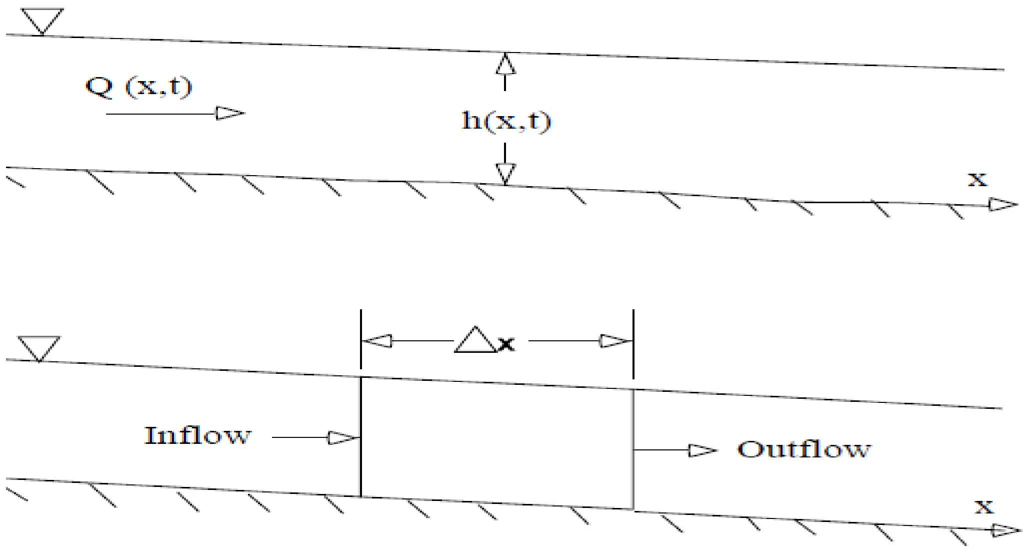



**Figure 3.0.37 elementary control volumes for derivation of continuity and momentum**

**Continuity equation:**

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \qquad \text{- - - - - - - - 13}$$

Where: A = area of the channel

Q =volume of discharge

x =distance along the channel

t =time

**Momentum equation:**

Conservation of momentum is expressed by Newton's second law of motion

$$\sum F_x = \frac{d\vec{M}}{dt}$$

Conservation of momentum for a control volume states that: the net rate of momentum entering the volume plus the sum of all external forces acting on the volume is equal to the rate of the accumulation of momentum.

**Application of 1D unsteady flow equation in HEC-RAS**

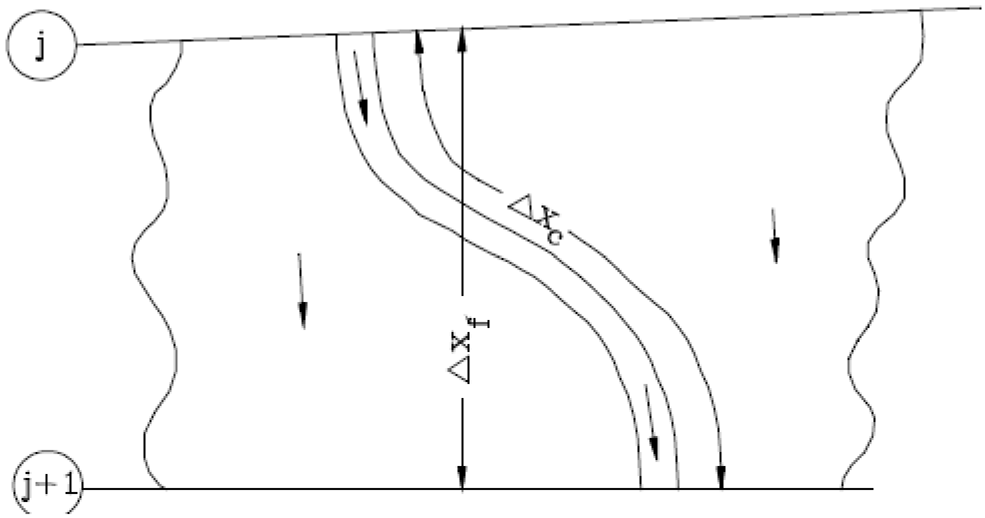



**Figure 3.0.38 Channel and flood plain flows**

$$\frac{\partial A}{\partial t}+\frac{\partial(\Phi Q)}{\partial x_c}+\frac{\partial[(1-\Phi)Q]}{\partial x_f}=0$$

**Momentum equation:**

The momentum equation states that the rate of change in momentum equation is equal to the external forces acting on the system.

$$\frac{\partial Q}{\partial t}+\frac{\partial(\alpha\frac{Q^2}{A})}{\partial x}+gA\left(\frac{\partial h}{\partial t}-S_f+S_o\right)=0 \quad - - - - - 14$$

Where: X =distance along the channel

t =time

Q = flow

A = Cross-sectional area

So = storage from non-conveying portions of cross-section

Sf = friction slope

q1 =lateral inflow per unit distance

### 3.3.2.5. Boundary conditions

Unsteady flow data are required in order to develop unsteady flow analysis and sediment modeling. The modeling requires geometric, flow series unsteady temperature and upstream and downstream boundary conditions. Boundary conditions must be established at all of the open ends of the river system to be modeled. The following figure shows the file structure of unsteady flow sediment modeling.

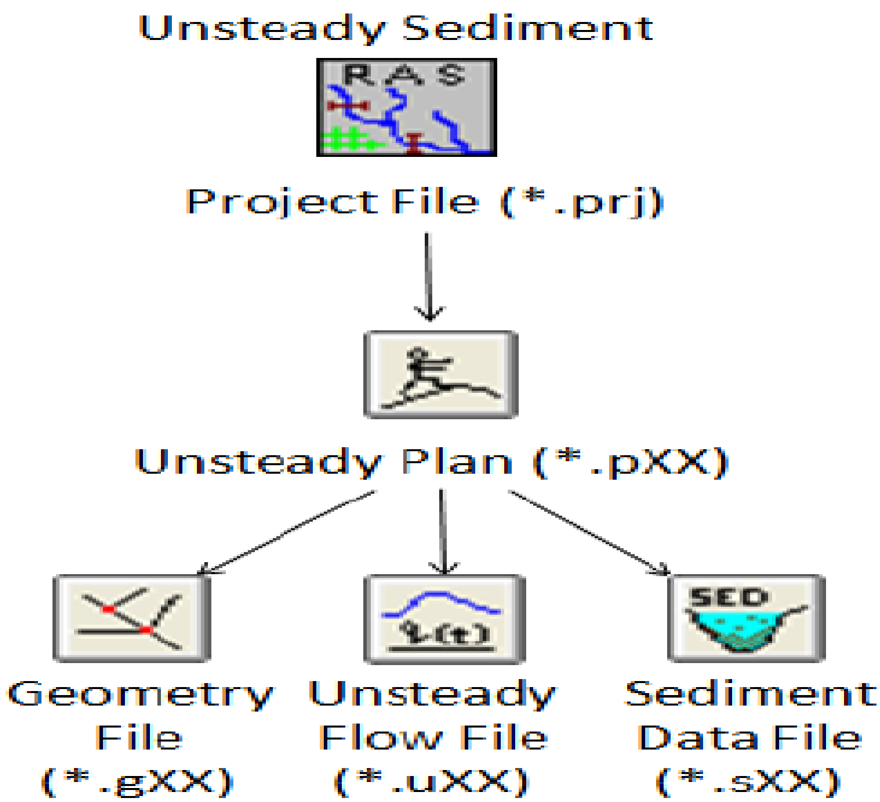



**Figure 3.0.39 File structure for unsteady flow sediment modeling**

Required data to unsteady flow HEC-RAS river modeling

1. Geometric data:
   - ❖ Ribb River cross section
   - ❖ Reach length
   - ❖ Manning's Coefficient
   - ❖ River contraction and expansion data
2. Flow data
   - ❖ Out flow boundary conditions: flow hydrograph

3. Sediment data
   - Sediment properties: Specific gravity , grain size
   - Inflow sediment data: time series data
   - Bed and bank material data: sieve sample percentage

**Upstream and downstream boundary conditions**

The boundary conditions were in the upstream and downstream ends of the river. Flow hydrograph was as upstream boundary condition and normal depth as downstream boundary condition.

**Flow hydrograph:**

Flow hydrograph is the unsteady flow boundary condition which can be used as upstream boundary condition.

**Normal Depth:**

The normal depth will be used as downstream boundary condition for upper ended reach. This option uses manning's equation to estimate a stage for each computed flow. The friction slope the grade line is required to use this method.

**Sediment time series:**

Sediment time series is applicable as an upstream boundary condition to model sediment bed degradation using unsteady flow sediment HEC-RAS modeling.

Hydrognomon is free software for time series analysis, which displays time series in tables and graphs.

In this paper in unsteady flow analysis different boundary conditions flow hydrograph for upstream and normal depth for downstream boundary conditions were used.

**Flow hydrograph**: 25 years Dam outlet controlled simulated flow series data extracted HEC-HMS was used as upstream boundary condition.

**Normal depth**: The normal depth boundary condition was used as upstream boundary condition for Ribb river reach. This option uses Manning's equation to estimate a stage for each computed flow. This method was used by entering the friction slope or slope of the grade line for the reach between the dam and the diversion weir.

**Performing unsteady flow calculation**: After the geometry and unsteady flow data entered, unsteady flow calculation was performed.

**Defining plan**: To start the simulation the plan was defined including the 30 kilometers reach Ribb river cross-section and 25 years flow series data.

**Running the program**: The components used in performing unsteady flow analysis with in HEC-RAS 5.0.1 were:

1. The geometric pre-processor
2. The unsteady flow simulator
3. The output post processor

**Saving plan:** Unsteady flow analysis calculated data result was saved in the file.

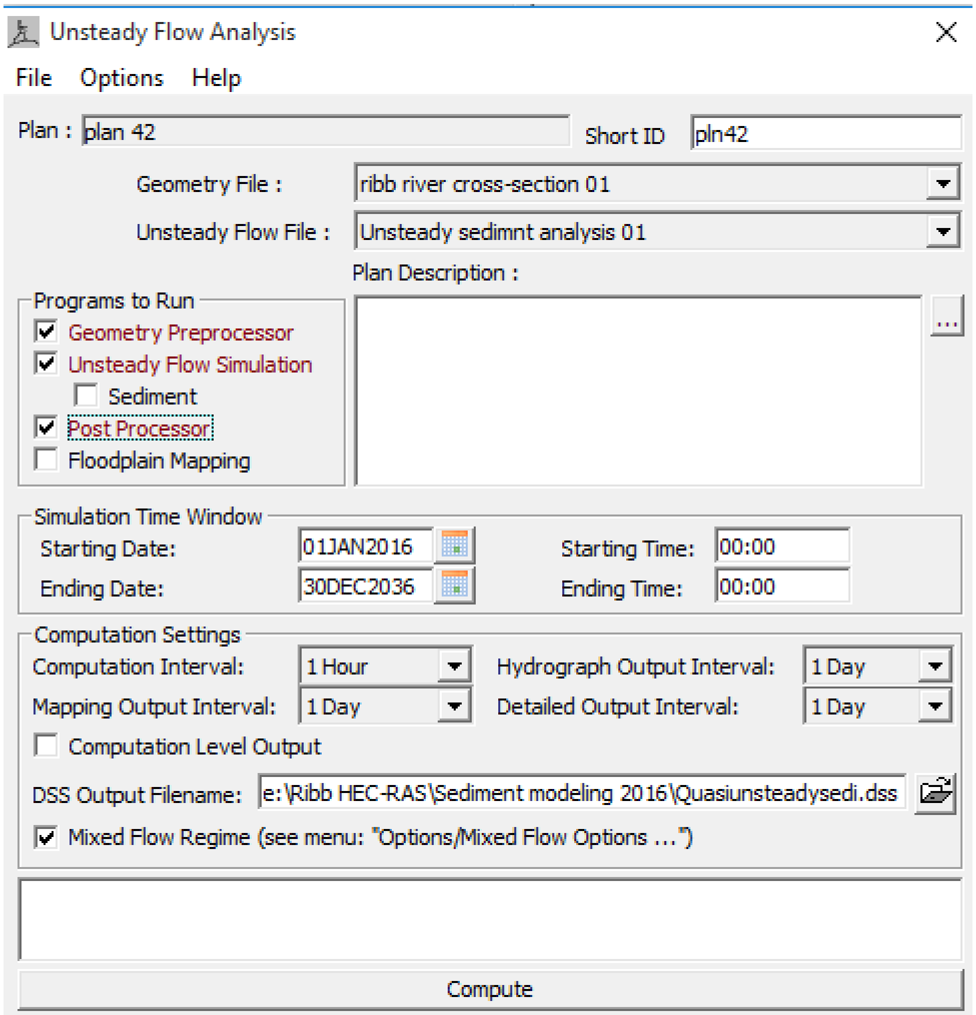



**Figure 3.0.40 HEC-RAS Unsteady flow simulation**

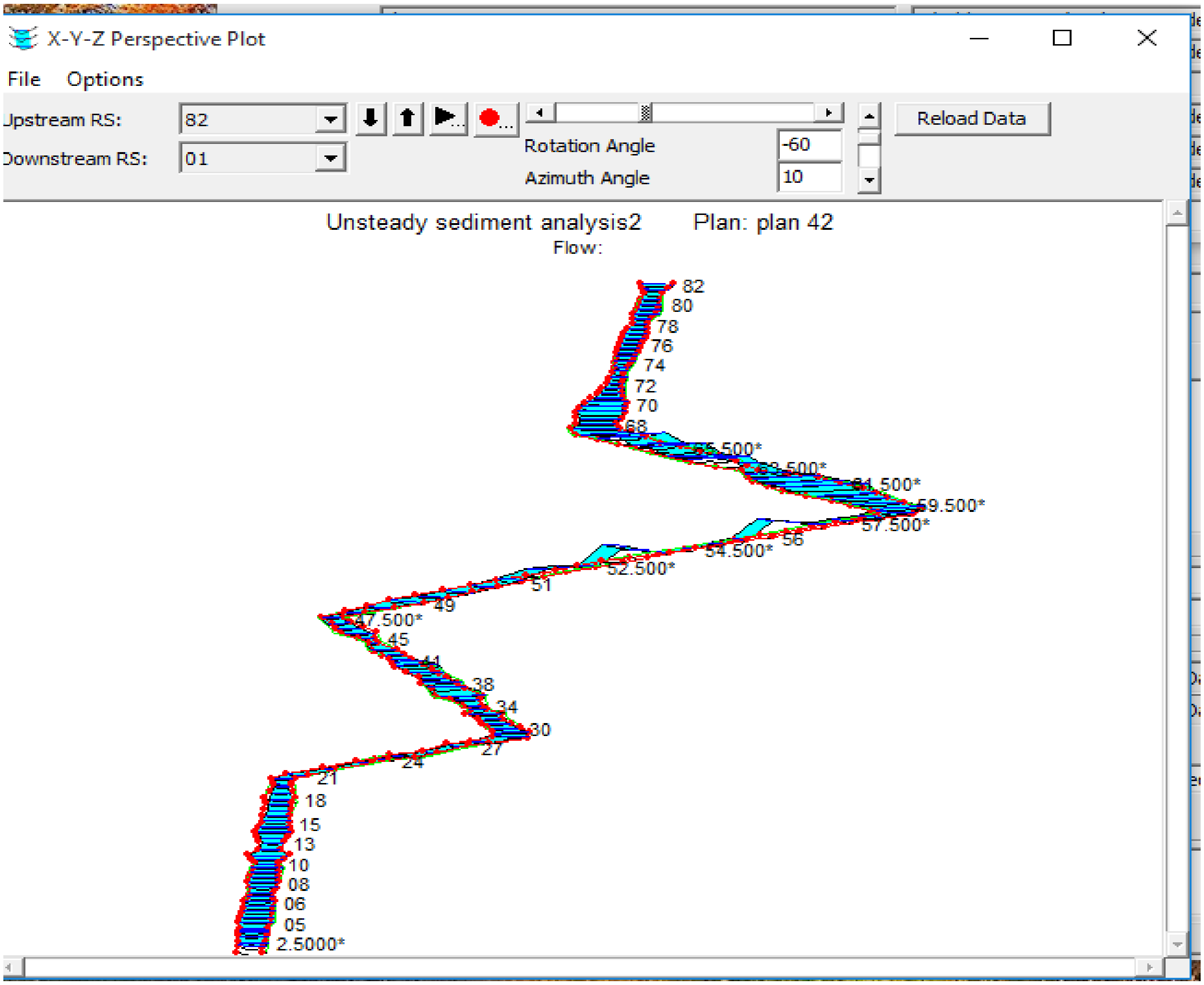



**Figure 3.0.41 Output of HEC-RAS unsteady flow modeling**

### 3.3.2.6 Unsteady Sediment transport modeling

Sediment transport modeling capabilities were calculated using unsteady flow sediment analysis new in HEC-RAS version 5.0.1. The 30 kilometers river channel cross-section (width, elevation), Channel length (ROB, CH and ROB), Manning's roughness value were used. For sediment transport computation, plan was created, which includes geometry file (.gxx), unsteady flow file (.uxx), and sediment file (.sxx). To predict river morphology change 20 years (01Jan, 2016 to 30Dec, 2036) unsteady flow sediment analysis were calculated using HEC-RAS 5.0.1.

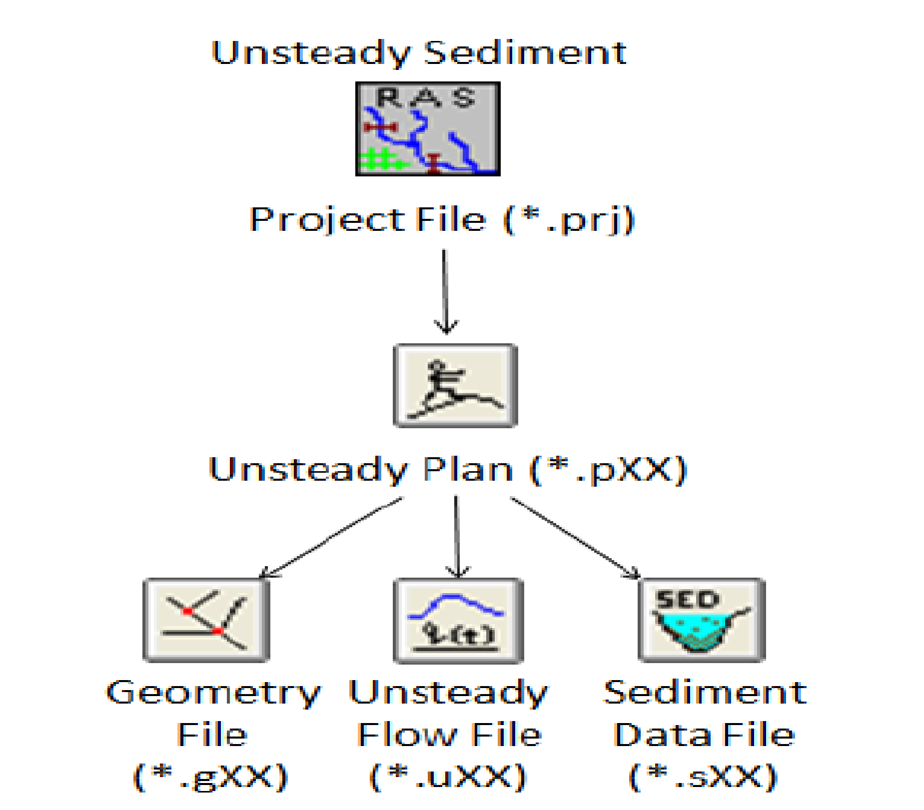



**Figure 3.0.42 Unsteady flow sediment modeling**

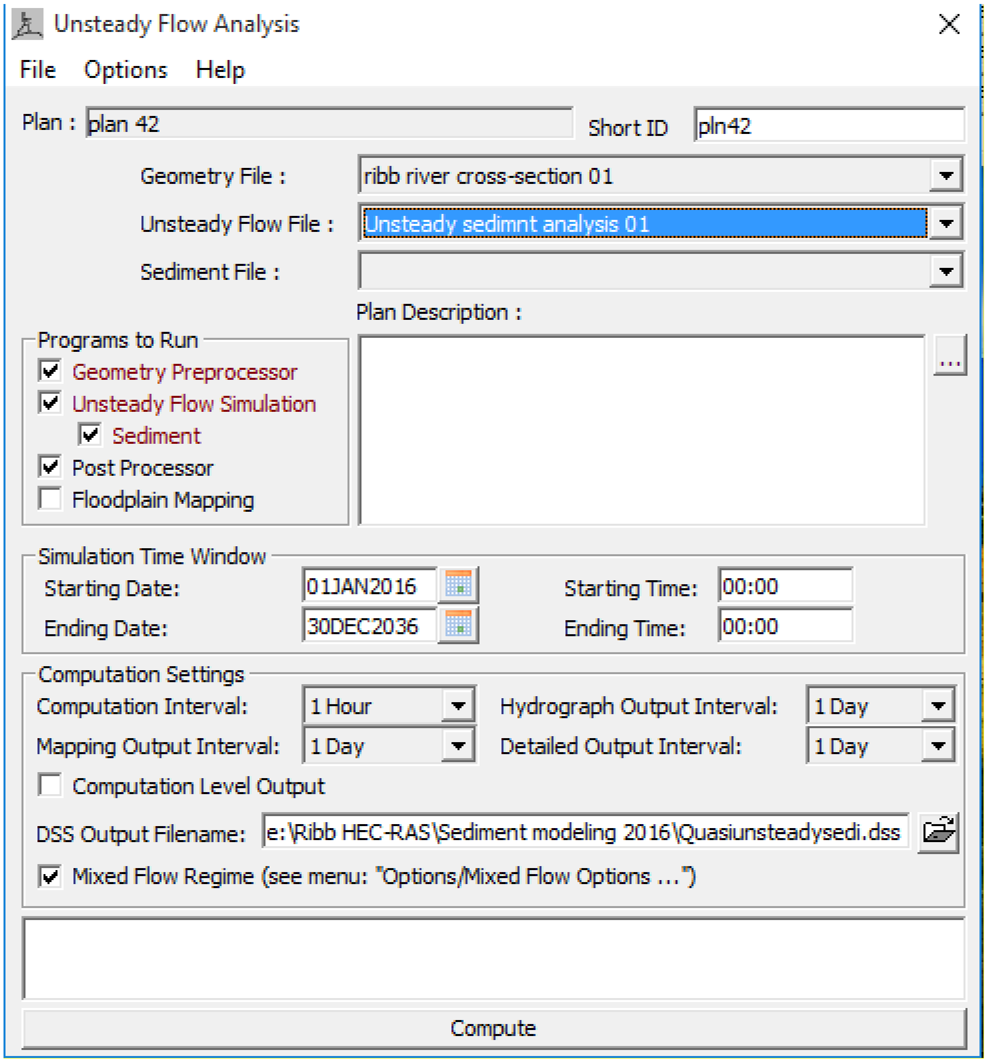



**Figure 3.0.43 Sediment analysis windows**

The HEC-RAS sediment transport module has been successfully implemented in studying both relatively short (Zhang and Duan, 2011) and long, exceeding 300 kilometers river reaches (Pereira et al., 2009; Adams and Chen, 2010). The capabilities of this sediment transport model are often commended due to their user-friendly interface and wide range of available outputs (Gibson et al., 2006; Herman et al., 2007). To estimate sediment transport for transient flow conditions, HEC-RAS uses an unsteady approach, which assumes that an event or a period of records is calculated as a series of steady flows. This assumption has been shown to produce similar results to those of models based on unsteady flow algorithms (Hummel et al., 2012). The primary input data for the sediment transport computations conducted here are (1) bed material, (2) stream geometry, (3) upstream and downstream flow boundary conditions (BC), and (4) upstream sediment load boundary conditions. The development of the downstream Ribb River model was divided into three steps: (1) river geometry development, (2) flow model development and (3) sediment transport model development.

**Initial condition and transport Parameters**

**Transport functions**: Ackers-White sediment transport quantification method was developed for river reach between Ribb dam and diversion weir.

**Sorting method**: this function compute the transport potential without accounting for availability. From the bed sorting / the mixing method or armoring methods Thomas (Ex5) was selected for this paper because it uses the layer bed model that forms an independent coarse armor layer which limits erosion of armor layer.

**Fall velocity methods**: The Rubey fall velocity method was selected this study.

**Unsteady flow water temperature:** The option allows putting time series of water temperature data used in conjunction with the unsteady flow sediment transport capabilities. Water temperatures are used for fall velocities in computing sediment deposition.

### 3.3.2.7 Performing sediment transport analysis

The sediment transport function in HEC–RAS has the capability of predicting transport capacity of sediment at different river cross-sections based on the given hydraulic parameters. Sediment transport capacity is consist of both bed load and suspended load both of which was accounted in the sediment transport prediction in HEC–RAS.

The initiation of motion of particles in the bed and banks of the river depends on the hydraulic characteristics in the near bed and bank of the river. Shear stress at the bed and bank represented as:

$\tau_b = \gamma R_s$ - - - - - - - - - 15

Where $\tau_b$ = Shear stress

ɣ = Unit weight of water

R = Hydraulic radius

S = Energy

**Fall velocity**

The suspension of sediment particles is initiated once the bed-level shear velocity approaches the same magnitude as the fall velocity of the particles. The particle will remain in suspension as long as the vertical components of the bed level turbulence exceed that of the fall velocity. Therefore determination of suspended sediment transport depends on the particle fall velocity. The selected method for computing fall velocity was Rubey (1993).

Rubey: (Rubey, 1993) Rubey developed an analytical relationship between fluid and sediment properties, and fall velocity.

$\text{W} = F_1\sqrt{(S-1)gd_s}$ - - - - - - - - - - 16

$\text{F}_1 = \sqrt{\frac{2}{3} + \frac{36v^2}{gd^3(s-1)}} - \sqrt{\frac{36v^2}{gd^3(s-1)}}$ - - - - - - 17

Where Ꞷ = fall velocity

S = specific gravity

d = particle diameter

v = kinematic viscosity

**Sediment transport function**

Sediment transport predicts rates of sediment rates of sediment transport from a given set of steady state hydraulic parameters and sediment properties. Ackers and White (1973) sediment transport function was selected for this study. Sediment degradation was obtained from the different cross-sections with in the river length.

**Ackers and White:** This transport function is a total load function developed under the assumption of that fine sediment transport is best related to the turbulent fluctuations in the water column and coarse sediment transport related to the net grain shear with mean velocity used as the representative variable. The transport function was developed in terms of particle size, mobility and transport (USAC, 2016). The general transport equation for Ackers and White function are the following:

$$X = \frac{Gg_r S d_s}{D\left(\frac{u}{v}\right)^n} \quad - - - - - - - - \; 18$$

$$Gg_r = \left(\frac{Fg_r}{A} - 1\right) \quad - - - - - - - \; 19$$

### 3.3.2.8 Bank Erosion and Mass Failure

Bank erosion process is either mass failure of the bank or direct erosion of the bank material. Cohesive soil shrinkage is the sole factor responsible for tension cracks development. Bank erosion occurs in conjunction with bed degradation, local scour, under mining and nick point mitigation. The main factors and forces that cause bank erosion are:

1) Shear stress: the induced flow shear stress contributes significantly instability of river banks.
2) Variation of water level: the stage variation of natural river flow results in large water drops in short period of time will causes significant bank erosion.
3) Structures: Downstream flow deflectors generate eddy which cause bank erosion (NBCN, 2010).
4)

The basic relation used in analyzing the stability of slopes: is the factor of safety defined by

$$S_f = \frac{F_R}{F_D} \quad - - - - - - - - - - - - - - - - - - - - - - - - \; 20$$

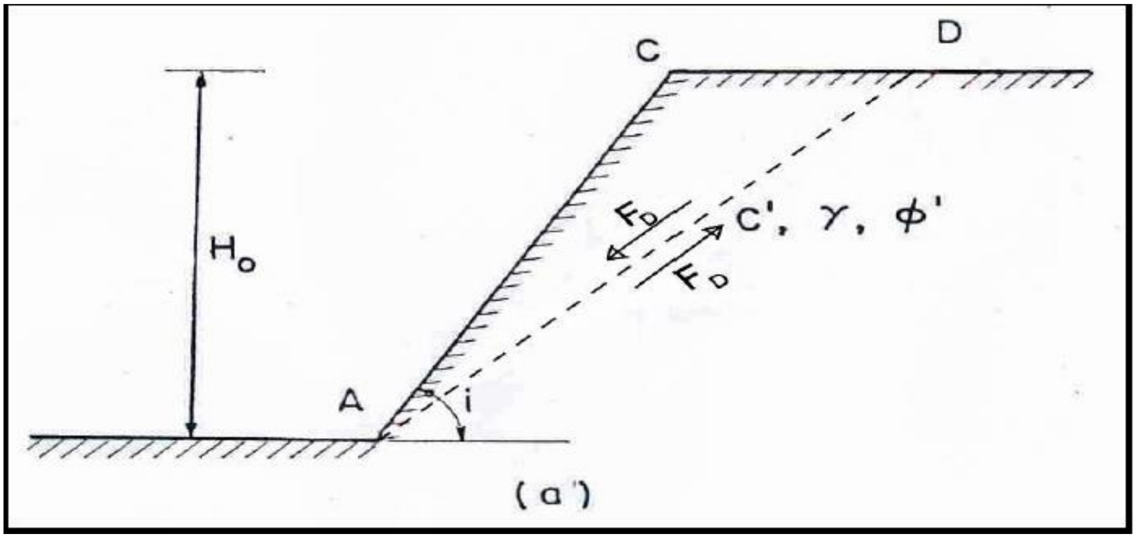



**Figure 3.0.44 River right banks at failure (NBCBN, 2010)**

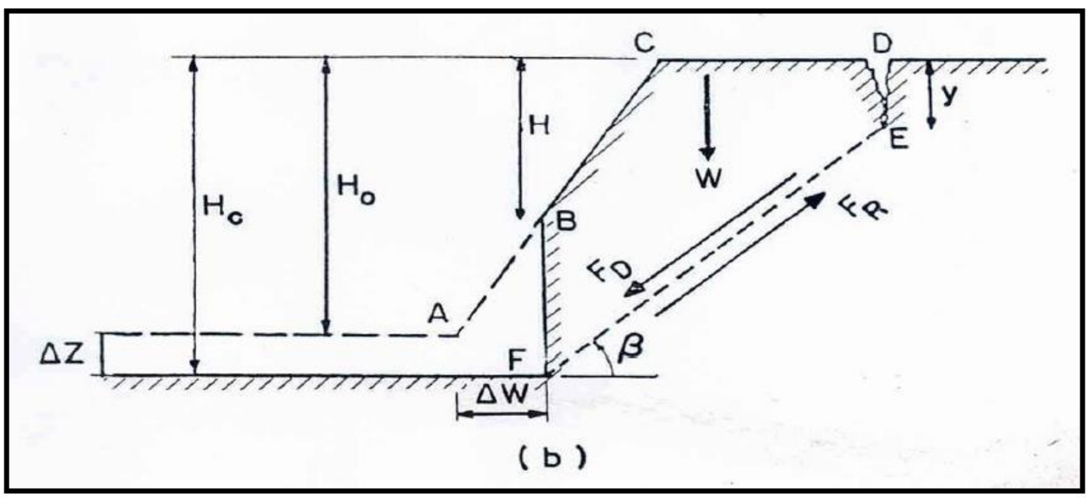



**Figure 3.0.45 Parallel bank retreat (NBCBN, 2010)**

Where: FD = the driving force due to weight component of the sliding block

FR = the resistance force due to cohesion C

Φ = Angle of internal friction

# 4. RESULT AND DISCUSSION

The Methodology of this research includes data collection, data processing and model calibration and application. The model simulating of the catchment was calibrated and verified before any flow and sediment transport simulation was carried out. The estimation of sediment inflow to the Ribb reservoir was demonstrated by using the HEC- HMS.

## 4.1 Sensitivity Analysis for Parameter Selection in Hydrologic Modeling

In Ribb River watershed hydrologic modeling sensitivity analysis in watershed hydrologic modeling is used to identify the most significant parameters affecting model performance and to determine optimal parameter values. In the HEC-HMS, a systematic procedure is used to evaluate different parameter values associated with the main hydrologic processes, including loss, transform, base flow, erosion, and routing. The model outputs are computed for each parameter variation and compared with one another. Parameters that produce significant changes in the simulation results are considered sensitive and are prioritized during model calibration.

For this study, the following modeling approaches were selected:

- **Loss Method:** The Soil Moisture Accounting (SMA) method was applied to all sub-basins to estimate infiltration and soil water storage losses.
- **Transform Method:** The Clark Unit Hydrograph method was used to transform precipitation into direct runoff.
- **Base flow Method:** The Linear Recession Method was applied to simulate groundwater contribution to stream flow.
- **Routing Method:** The Muskingum Method was used to route flow through the river reaches.

During the sensitivity analysis, individual parameters were varied while keeping the other parameters constant. The model was then run repeatedly to evaluate the effect of each parameter on the simulated hydrograph at the watershed outlet. Parameters showing greater influence on the peak discharge, runoff volume, and timing of flow were identified as the most sensitive parameters.

## 4.2 Model calibrated and validated

### 4.2.1 Calibration for Ribb river basin

The calibrated model has been run to simulate sediment transport in the basin and computing of sediment deposited in Ribb reservoir for the period (January 1993-December 1998). The figure (41) shows comparison of pool elevation for Ribb flow.

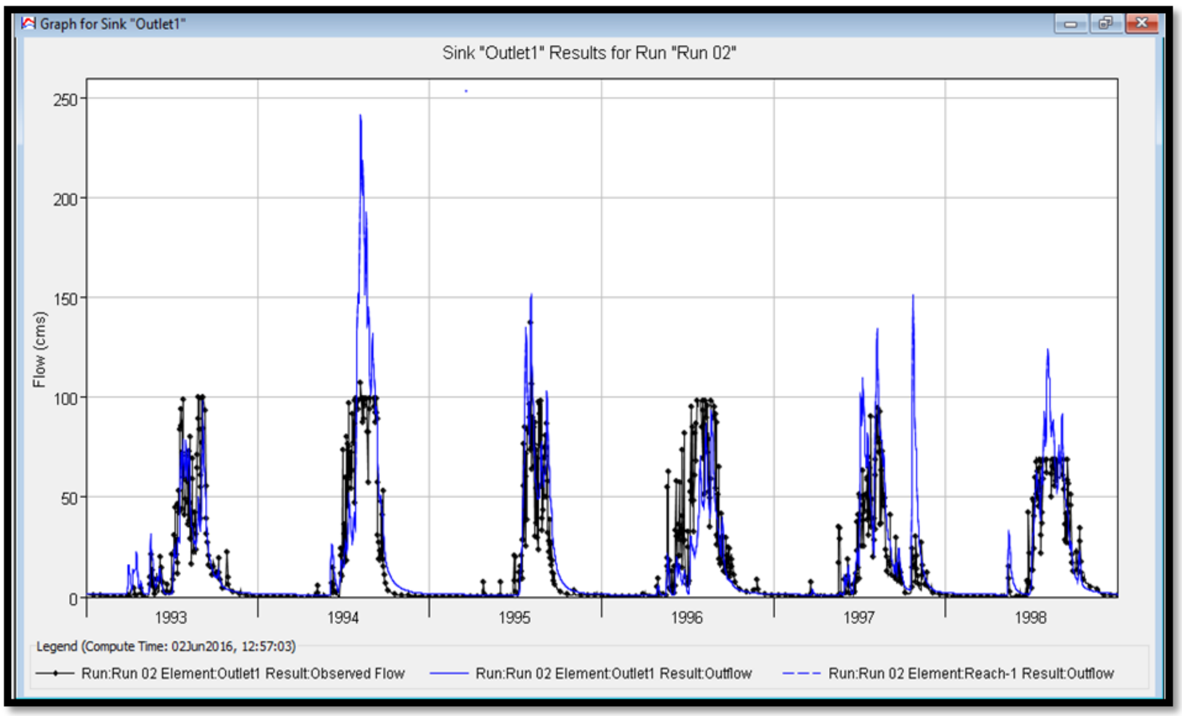
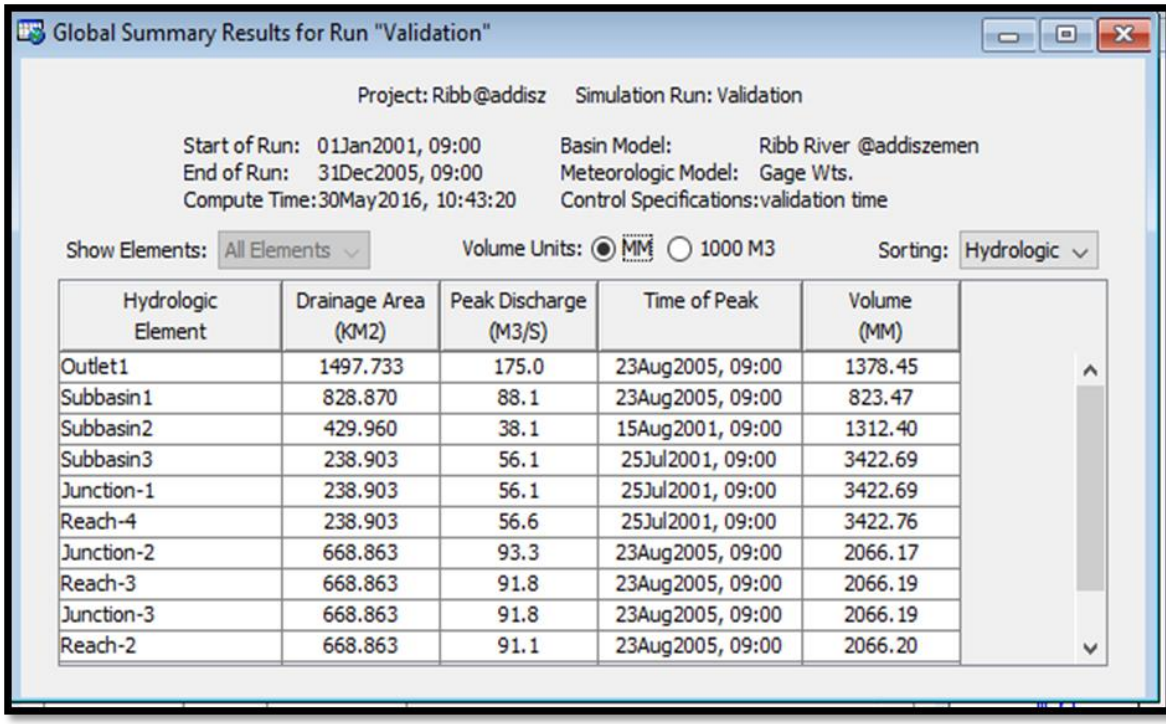



**Figure 4.0.1 Model calibration**

### 4.2.2 Validation for Ribb river basin

To validate the output of this model, validation is also performed at discharge stations from the year 01 Jan 2001- 31 Dec 2005. This is performed to check if the models were able to predict the runoff at the discharge stations for the period other than calibrated one or not. The resulting graphs for the validation period are shown in the figures 4.2.2.1.



Global Summary Results for Run "Validation"

Project: Ribb@addisz Simulation Run: Validation

Start of Run: 01Jan2001, 09:00 Basin Model: Ribb River @addiszemen
End of Run: 31Dec2005, 09:00 Meteorologic Model: Gage Wts.
Compute Time: 30May2016, 10:43:20 Control Specifications: validation time

Show Elements: All Elements Volume Units: MM 1000 M3 Sorting: Hydrologic

| Hydrologic Element | Drainage Area (KM2) | Peak Discharge (M3/S) | Time of Peak | Volume (MM) |
|---|---|---|---|---|
| Outlet1 | 1497.733 | 175.0 | 23Aug2005, 09:00 | 1378.45 |
| Subbasin1 | 828.870 | 88.1 | 23Aug2005, 09:00 | 823.47 |
| Subbasin2 | 429.960 | 38.1 | 15Aug2001, 09:00 | 1312.40 |
| Subbasin3 | 238.903 | 56.1 | 25Jul2001, 09:00 | 3422.69 |
| Junction-1 | 238.903 | 56.1 | 25Jul2001, 09:00 | 3422.69 |
| Reach-4 | 238.903 | 56.6 | 25Jul2001, 09:00 | 3422.76 |
| Junction-2 | 668.863 | 93.3 | 23Aug2005, 09:00 | 2066.17 |
| Reach-3 | 668.863 | 91.8 | 23Aug2005, 09:00 | 2066.19 |
| Junction-3 | 668.863 | 91.8 | 23Aug2005, 09:00 | 2066.19 |
| Reach-2 | 668.863 | 91.1 | 23Aug2005, 09:00 | 2066.20 |

**Figure 4.0.2 Model validation**

### 4.3 Flow Result

Sink outle1 Results for Run Full simulation

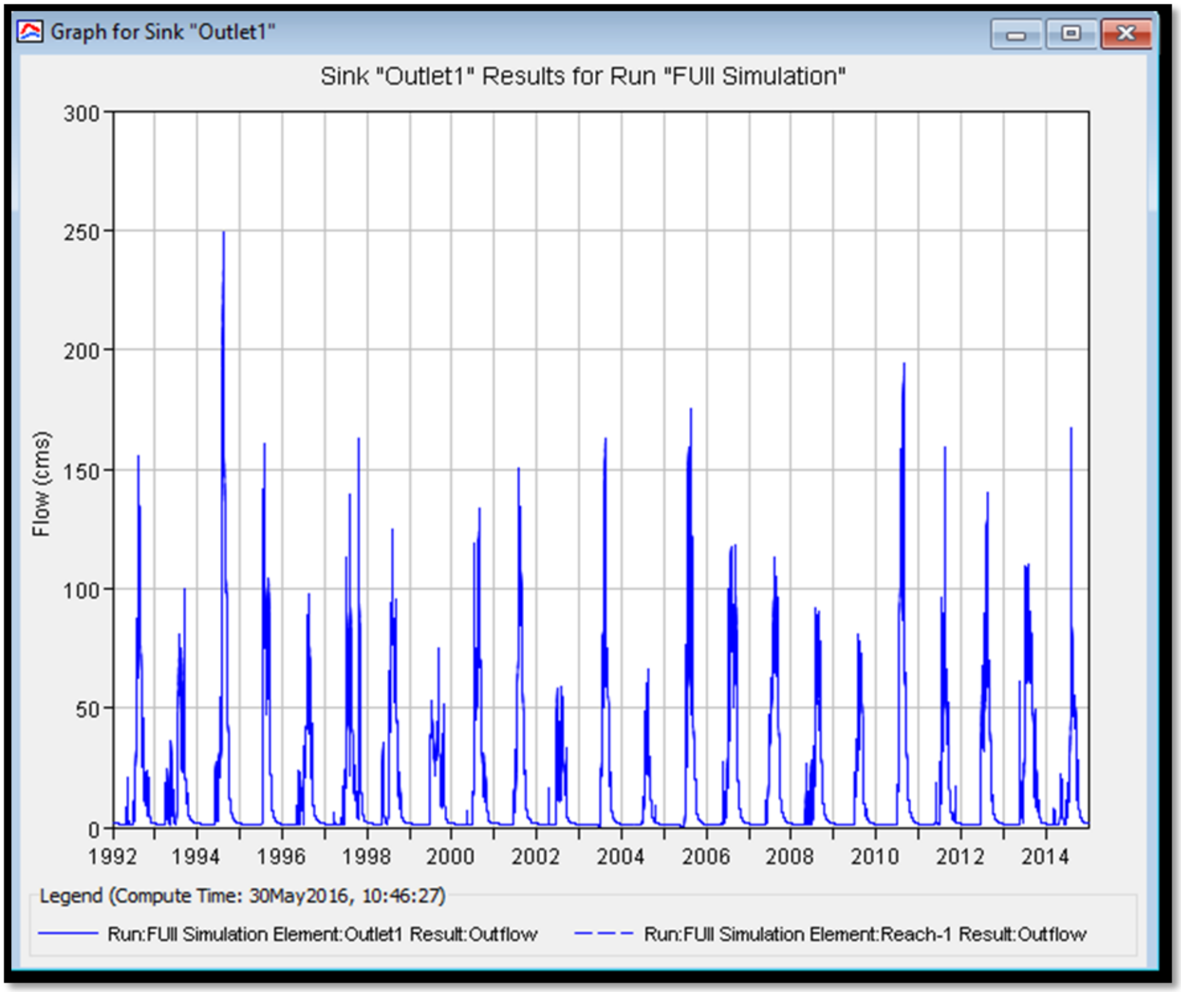



**Figure 4.0.3 Flow series**

#### 4.3.1 Sub basin

Flow result is the main boundary condition for the HEC-HMS erosion model. The erosion result of each subbasin includes the time series of total sediment load leaving the subbasin. The total sediment is the sum of all the grain size classes. The total sediment load in the out flow is included in the results. The organization of the result is as follows:

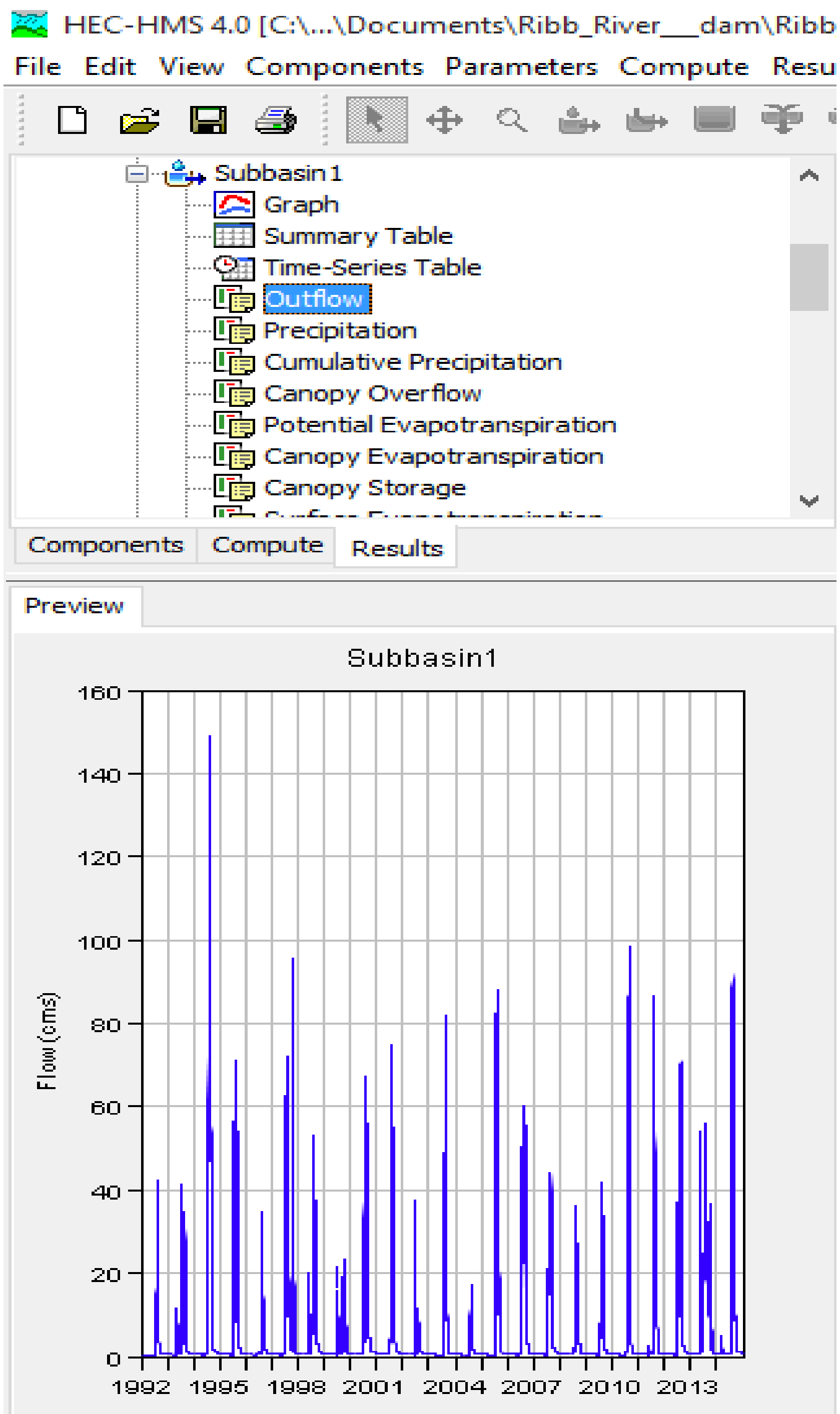



**Figure 4.0.4 Dam out flow subbasin-1 (HEC-HMS)**

## 4.4 Erosion and sediment transportation modeling

### 4.4.1 Subbasin

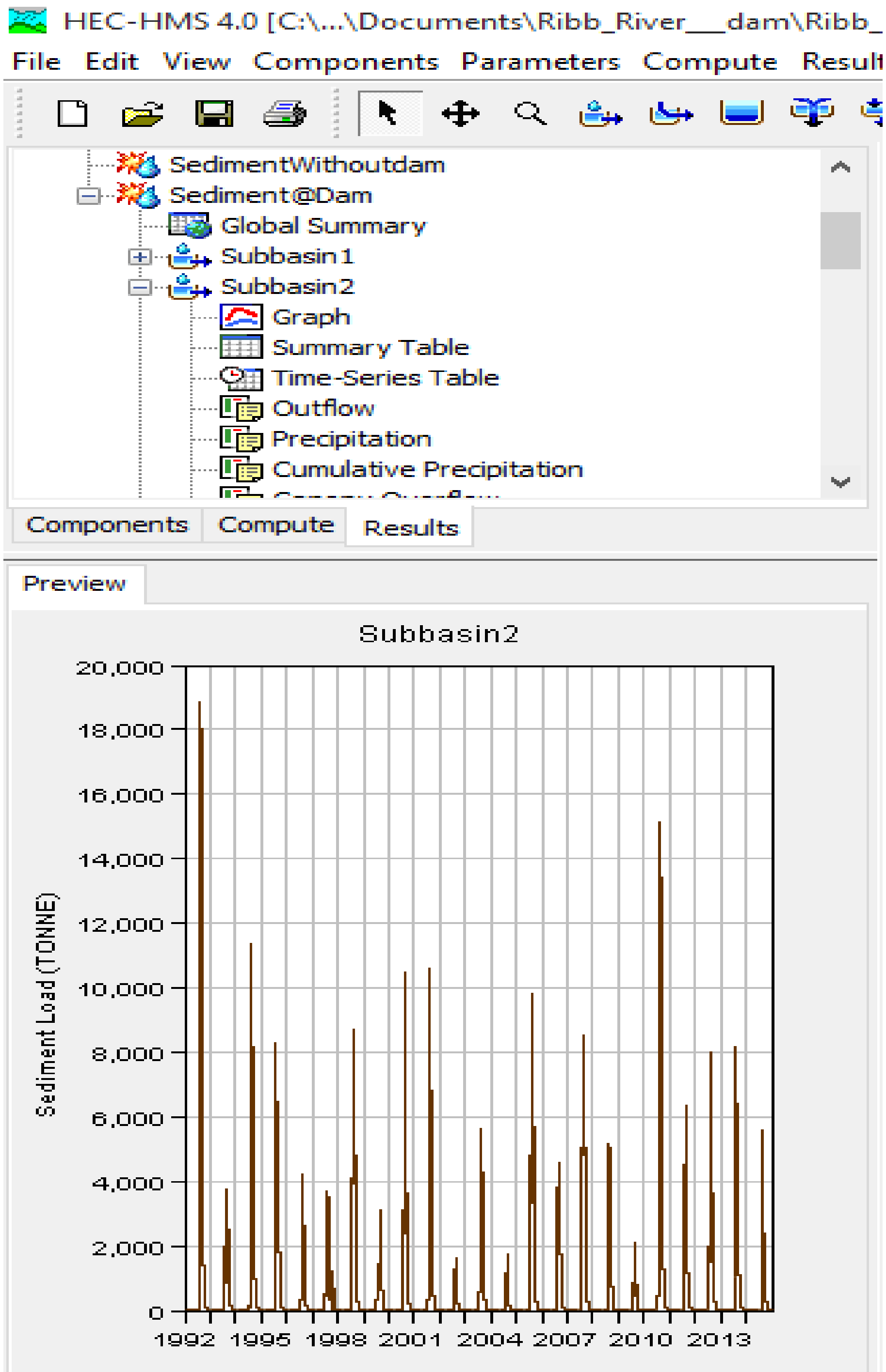



**Figure 4.0.5 HEC-HMS sediment results for a subbasin element**

### 4.4.2 Reach

The sediment result for each reach includes the time-series of total sediment load entering the reach, and the total sediment leaving the reach. The total sediment is the sum of all grain classes both coming in to the reach and leaving the reach.

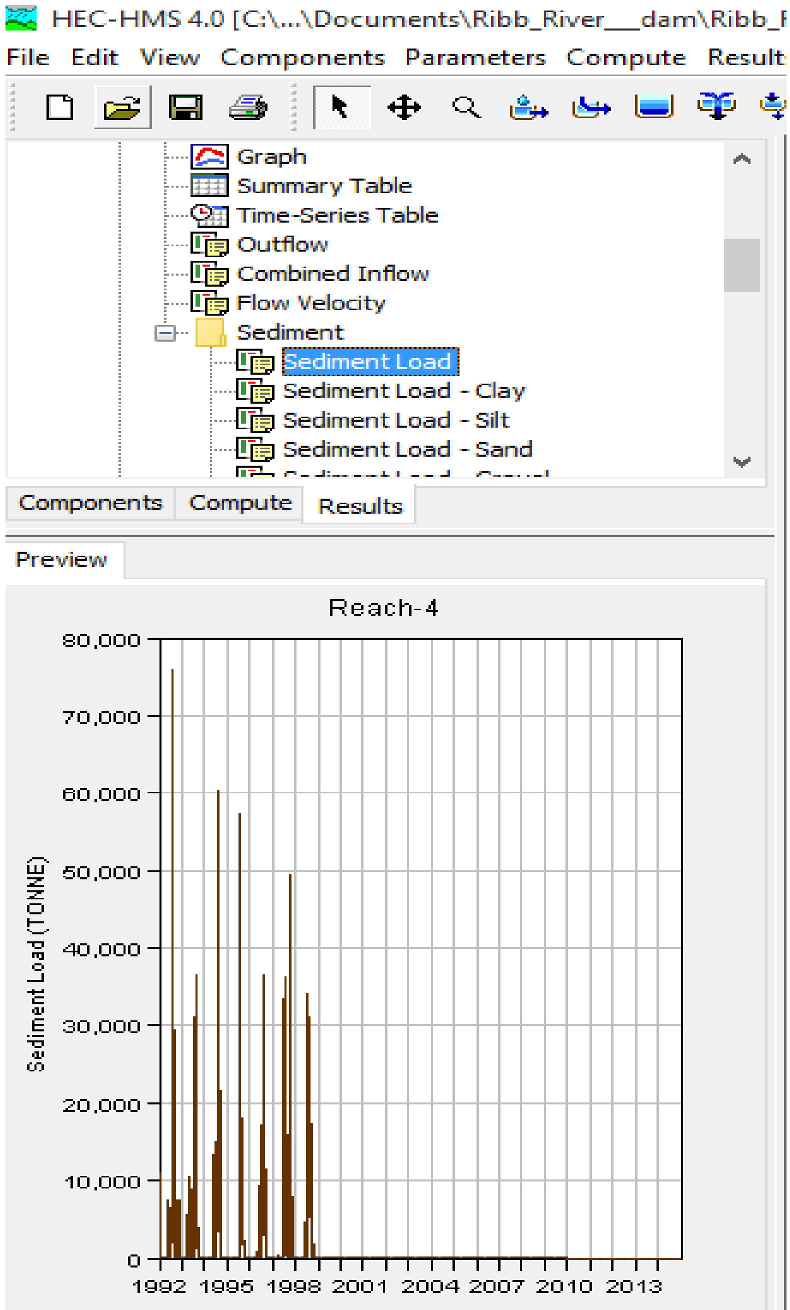



**Figure 4.0.6 HEC-HMS sediment results for reach elements**

### 4.4.3 Reservoir Deposition Results

The sediment result of the Ribb reservoir includes the time series of the total sediment load entering the reservoir, and the total sediment load leaving the reservoir. In addition to that the time series of total sediment load settled to the bottom of the reservoir is available, along with the time-series of sediment load in suspension in the reservoir.

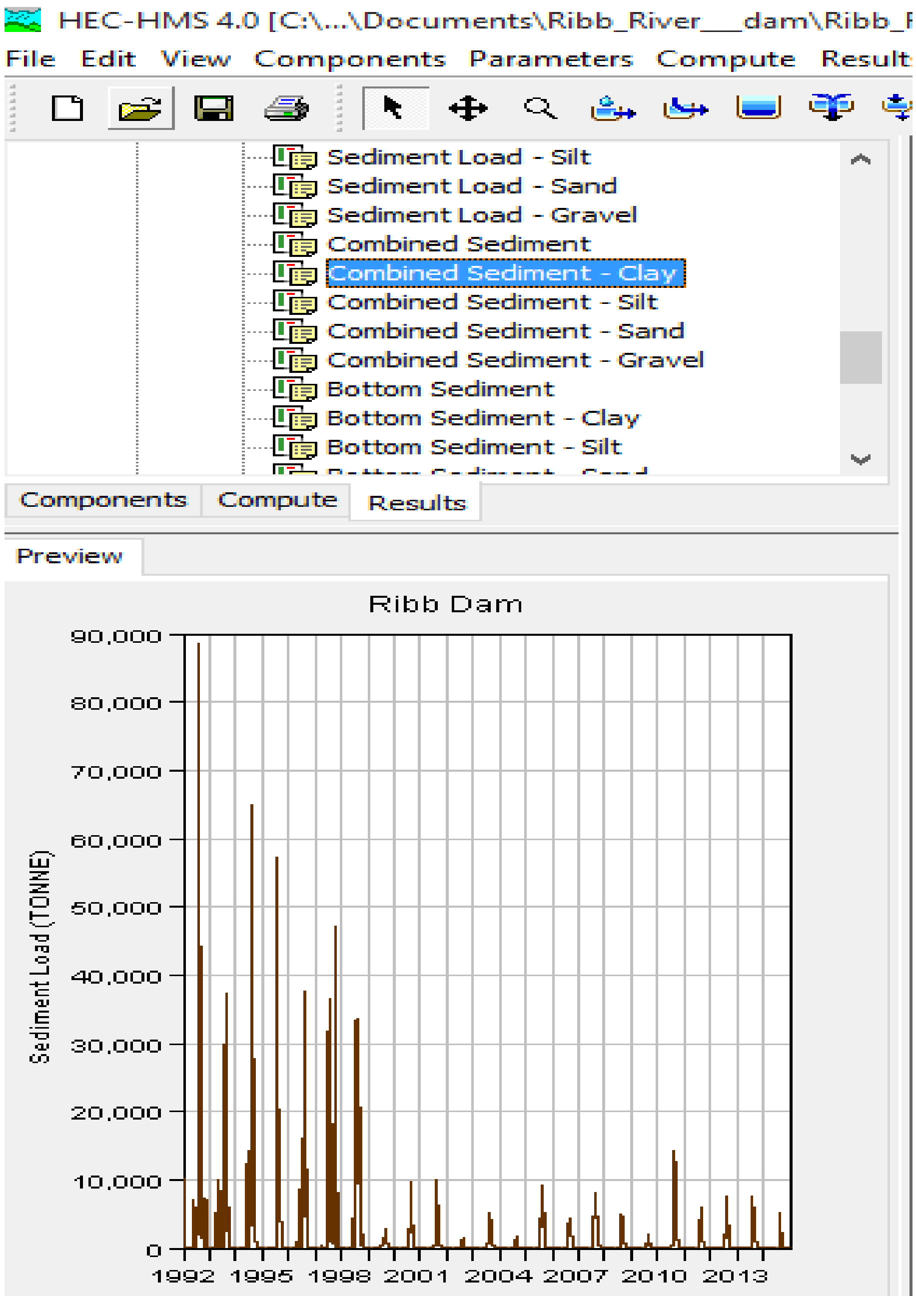



**Figure 4.0.7 HEC-HMS sediment results for reservoir elements**

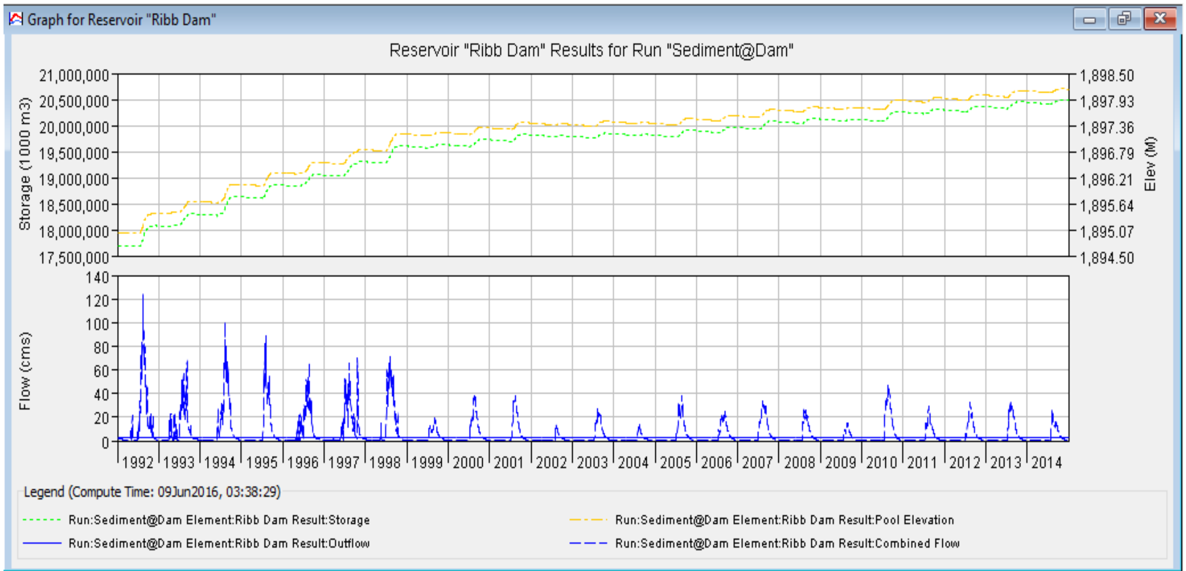



**Figure 4.0.8 Ribb dam Reservoir**

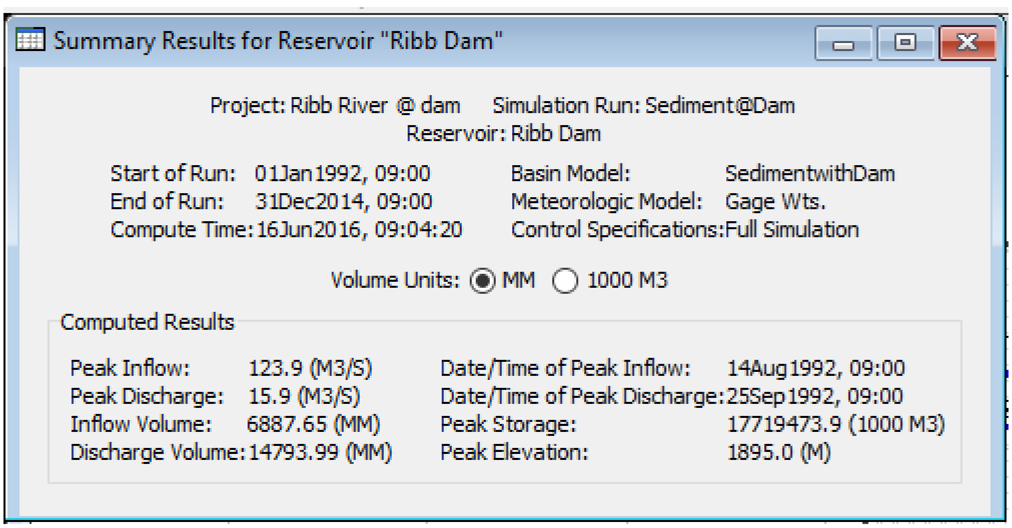



**Figure 4.0.9 HEC-HMS peak inflow and peak discharge @ the dam outlet**

Time-Series Results for Reservoir "Ribb Dam"

Project: Ribb River @ dam Simulation Run: Sediment@Dam
Reservoir: Ribb Dam

Start of Run: 01Jan1992, 09:00 Basin Model: SedimentwithDam
End of Run: 31Dec2014, 09:00 Meteorologic Model: Gage Wts.
Compute Time: 09Jun2016, 03:38:29 Control Specifications: Full Simulation

| Date | Time | Inflow (M3/S) | Storage (1000 M3) | Elevation (M) | Outflow (M3/S) |
|---|---|---|---|---|---|
| 01Jan1992 | 09:00 | 1.2 | 17688007.9 | 1895.0 | 2.3 |
| 02Jan1992 | 09:00 | 1.2 | 17687916.1 | 1895.0 | 2.3 |
| 03Jan1992 | 09:00 | 1.2 | 17687824.4 | 1895.0 | 2.3 |
| 04Jan1992 | 09:00 | 1.2 | 17687732.9 | 1895.0 | 2.3 |
| 05Jan1992 | 09:00 | 1.2 | 17687641.5 | 1895.0 | 2.3 |
| 06Jan1992 | 09:00 | 1.2 | 17687550.2 | 1895.0 | 2.3 |
| 07Jan1992 | 09:00 | 1.2 | 17687458.9 | 1895.0 | 2.3 |
| 08Jan1992 | 09:00 | 1.2 | 17687367.6 | 1895.0 | 2.3 |
| 09Jan1992 | 09:00 | 1.2 | 17687276.3 | 1895.0 | 2.3 |
| 10Jan1992 | 09:00 | 1.2 | 17687185.0 | 1895.0 | 2.3 |
| 11Jan1992 | 09:00 | 1.2 | 17687093.6 | 1895.0 | 2.3 |
| 12Jan1992 | 09:00 | 1.2 | 17687002.1 | 1895.0 | 2.3 |
| 13Jan1992 | 09:00 | 1.2 | 17686910.4 | 1895.0 | 2.3 |
| 14Jan1992 | 09:00 | 1.2 | 17686818.6 | 1895.0 | 2.3 |
| 15Jan1992 | 09:00 | 1.2 | 17686726.7 | 1895.0 | 2.3 |
| 16Jan1992 | 09:00 | 1.2 | 17686634.6 | 1895.0 | 2.3 |
| 17Jan1992 | 09:00 | 1.2 | 17686542.2 | 1895.0 | 2.3 |

**Figure 4.0.10 Output of reservoir simulation**

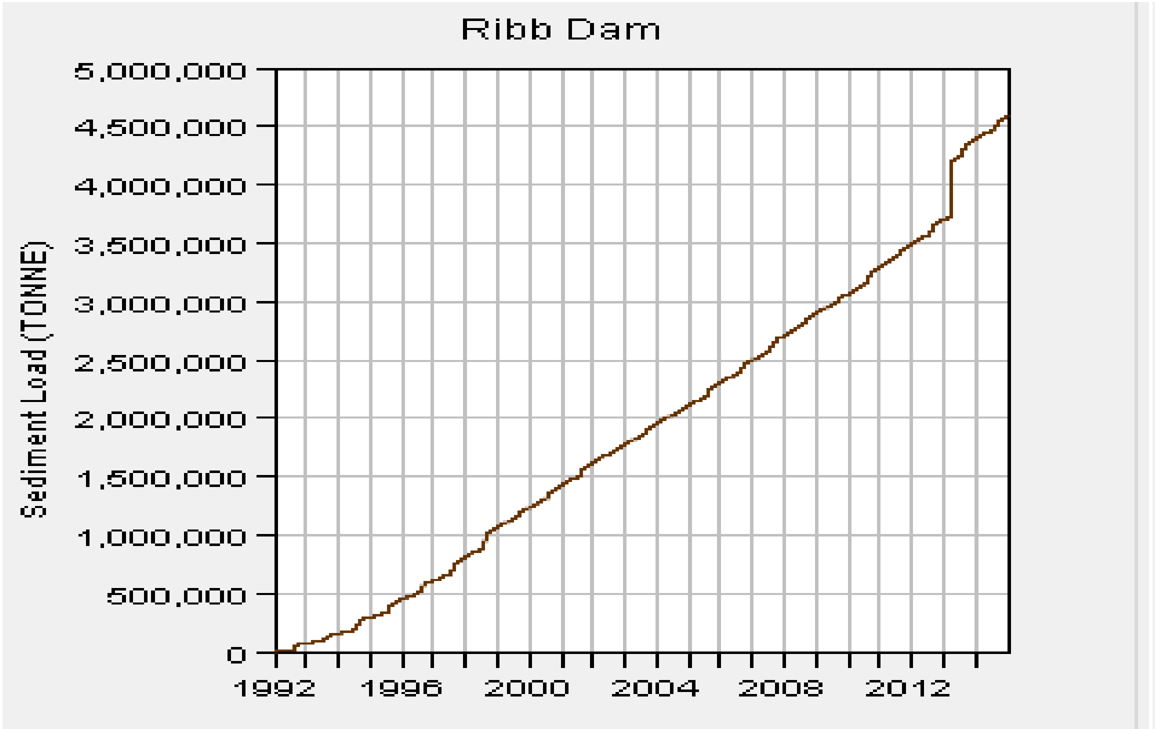



**Figure 4.0.11 Sediment deposited in the Ribb reservoir**

Considering an additional 20% contribution of suspended sediment, the mean annual sediment load increases to approximately 245,454 ton/year. Dividing this value by the watershed area (668.86 km²) gives a sediment yield of about 367 ton/ km²/year, during the year 1992 to 2014. Based on this study the estimate of the 50 year sediment accumulation with ~98% trap efficiency will be 18350 ton//km². This shows that relatively high sediment production within the catchment. This falls in the high sediment yield category, which is typical for Northern Ethiopian highlands watersheds with steep slopes and intensive cultivation.

### 4.4.4 Dam outlet

The sediment result of HEC-HMS modeling result shows that the entire sediment load entering the reservoir will settle in it. This shows that the suspension sediment load in the river flow decreases due to the construction of the dam. Cochiti Dam, closed in 1973, was constructed primarily for flood control and sediment retention. The dam traps sediment, reducing the suspended sediment loads downstream 98% and has created a lacustrine delta in the reservoir headwaters. The reach below Cochiti Dam responded to dam closure in typical ways including: Bed degradation, bed armoring, and channel narrowing.

The sediment simulation results obtained from HEC-HMS indicate that no suspended sediment is transported through the dam outlet. The sediment load at the outlet remains approximately zero throughout the simulation period, indicating that the reservoir traps nearly all incoming sediment. This suggests a very high trapping efficiency, resulting in clear water release downstream of the dam.

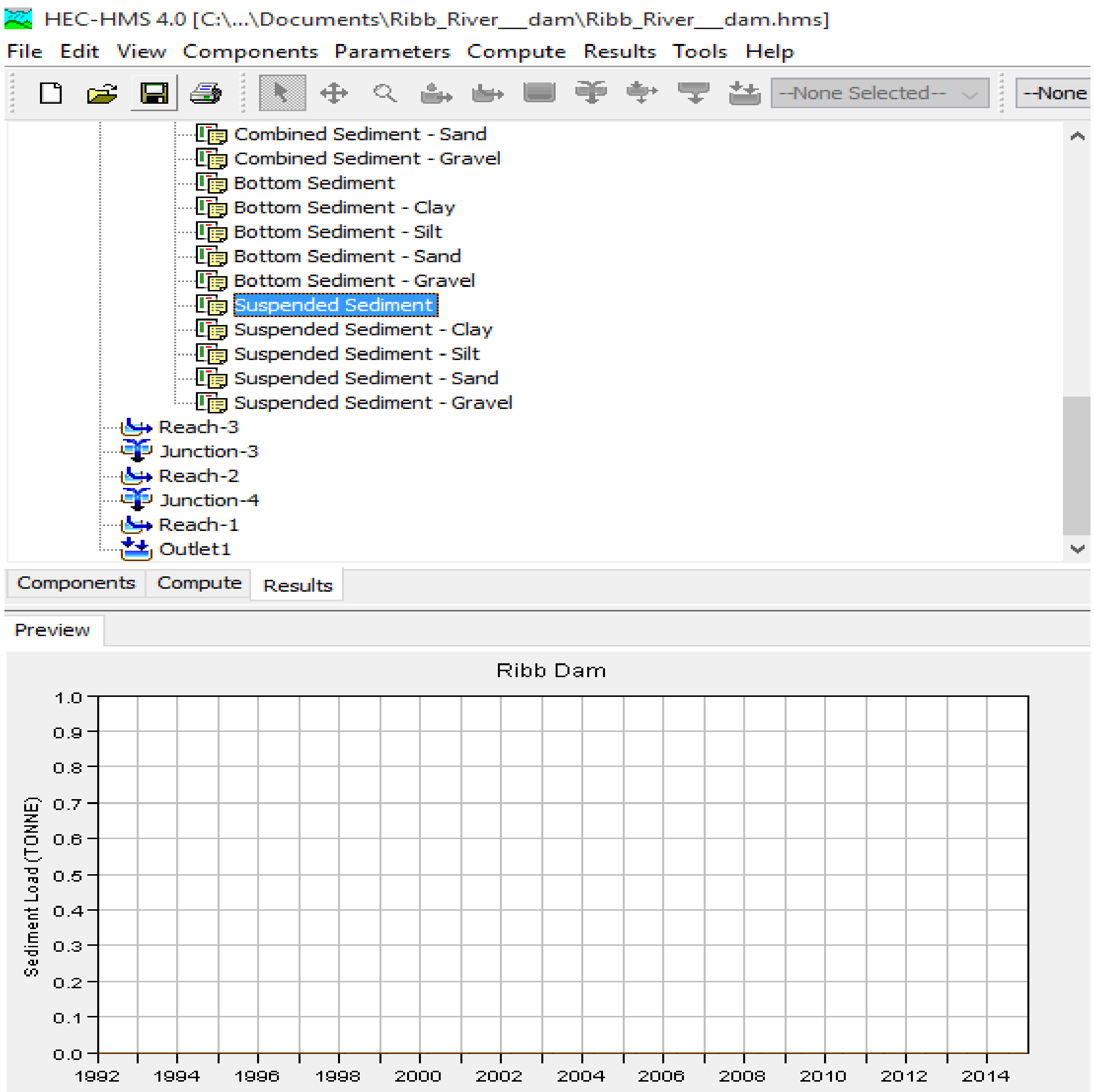



**Figure 4.0.12 HEC-HMS sediment results @ the dam outlet**

### 4.5 Comparing with previous Reservoir sediment studies and estimates

The mean annual sediment load estimates by USBR (1964) for the Ribb dam site were 260,000 ton (363 ton/km2/year). My estimate of 367 ton/km2/year based on the 1992 -2014 data is almost equal to USBR (1964) estimates for the dam site. This falls in the high sediment yield category, which is typical for Ethiopian highland watersheds with steep slopes and intensive cultivation.

### 4.6 HEC-RAS unsteady sediment analysis

In this study, a sample reach of 30 kilometers from Ribb dam to the diversion weir was studied. To do so, the geometric data, sedimentation and discharge rate of flow based on 1990-2014 flow data in 2016-2032 were studied. Accordingly, the geometric data related to 82 transverse sections were gathered and introduced to the model. In addition to that, the controlled flow discharge from the dam (flow series) of the river, which was simulated and calibrated by HEC-HMS, was also included into the model.

After adjusting the geometry, unsteady flow and sediment series, the model was used to simulate the unsteady flow sediment analysis. Then, the cross-section and longitudinal profile variation of the river, shear stress variation, sediment transport capacity and the volume of outflow sediment were studied at through 30 kilometers.

#### 4.6.1 Flow change

Dams are built to harvest river flow during high flow season and it releases by controlling flow of water. The river flow velocity profile shows that there is a variation in the longitudinal river flow profile the due to the controlled release flow from 2016-2032.

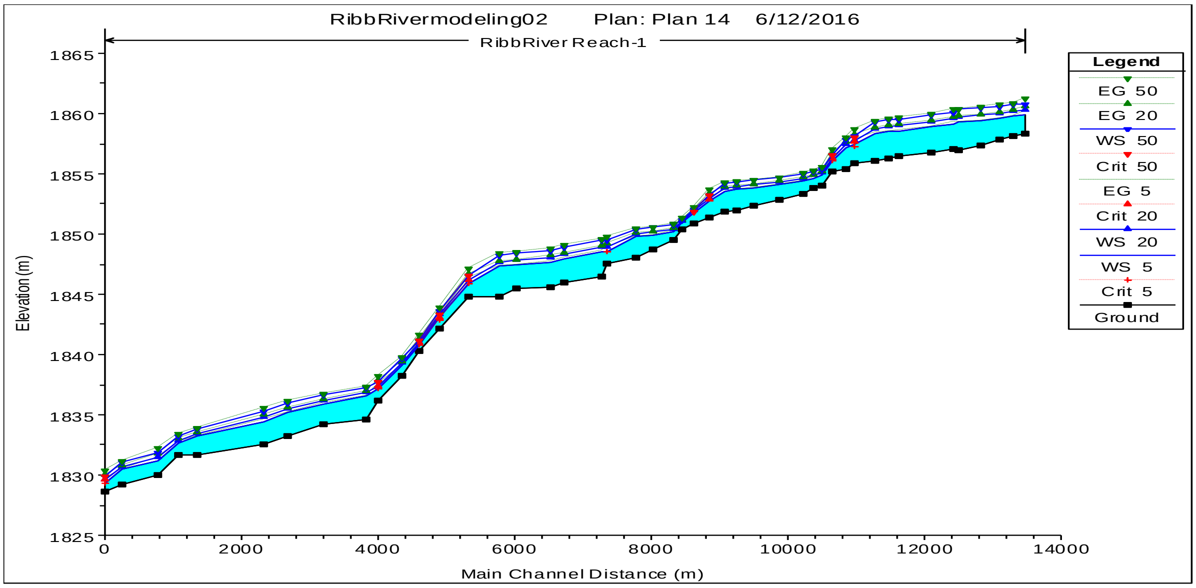



**Figure 4.0.13 longitudinal profile of Ribb River after dam construction**

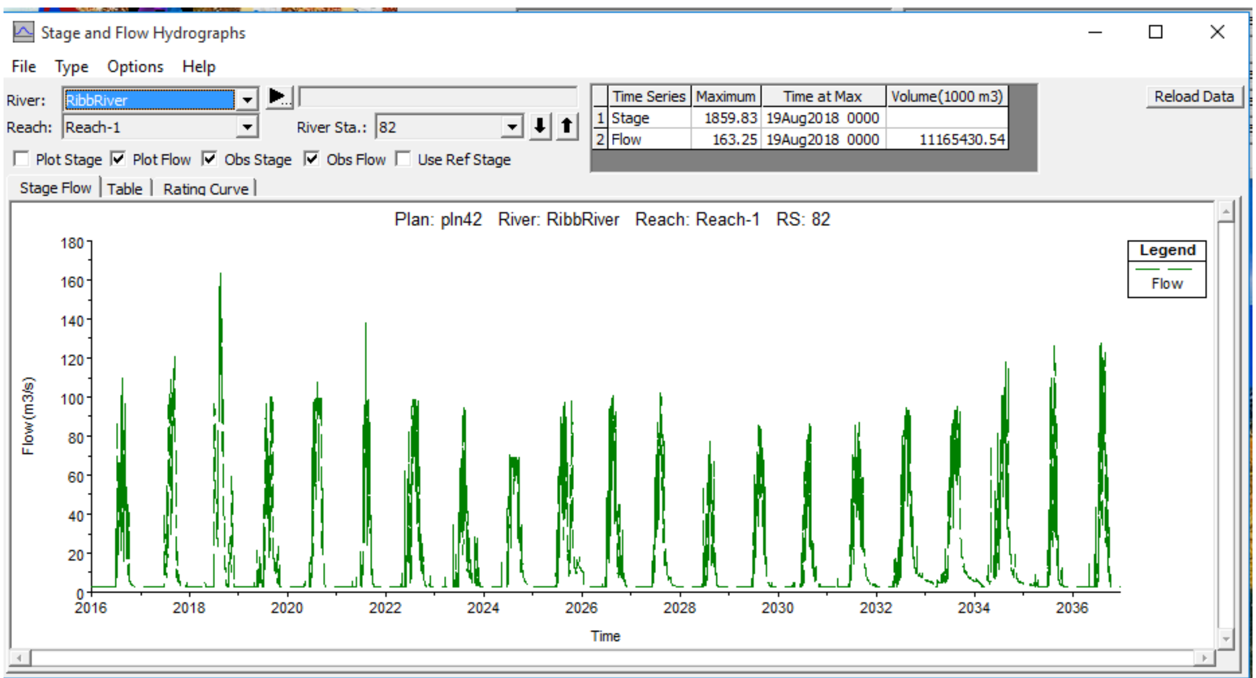



**Figure 4.0.14 longitudinal profile of Ribb River after dam construction**

### 4.6.2 River degradation

Degradation occurs downstream of dams due to the clear water released from the out let and spill way. Given the capacity of flow releases to entrain sediment from channel bed and banks, erosion of the bed and banks should continue downstream from a' dam until some factor or a combination of factors results in establishment of a new stable channel. Common to most of them is the reduction of flow, and also, therefore, reduction of stream power and related sediment-carrying capacity, as the result of storage abstraction and by evaporation from the water surface. Peak discharges are also commonly reduced. Some dams may release almost no water at all, while others do not change the releases to any great extent, as compared to pre-dam conditions. All dams affect the natural water discharges in some way, besides during extreme floods when only the major flood regulation dams have any major effect on the water flow (Higgs and Petts, 1988).

The sediment transport capacity of the river was reduced with the decreasing flow, and the bed began to aggrade. Aggradation of the bed caused seepage and an increase in water table elevation. The river became very shallow and wide with a high susceptibility to flooding (Burkholder 1929). The agricultural lands along the river experienced flooding, waterlogged land, and failed irrigation systems (Scurlock 1998). By 1925, irrigated agricultural area still in use was reduced to 40,000 acres (Leon 1998), Susan J. Novak, 2010.

The longitudinal profile of Ribb River after dam construction in 2016-2036 shows significant changes in the longitudinal profile of the Ribb River release of controlled flow, where of 82 cross-sections, the River bed and cross- sections were eroded through the given period. The results show that erosion or bed degradation and creating valley will be especially significant in the upstream cross-sections.

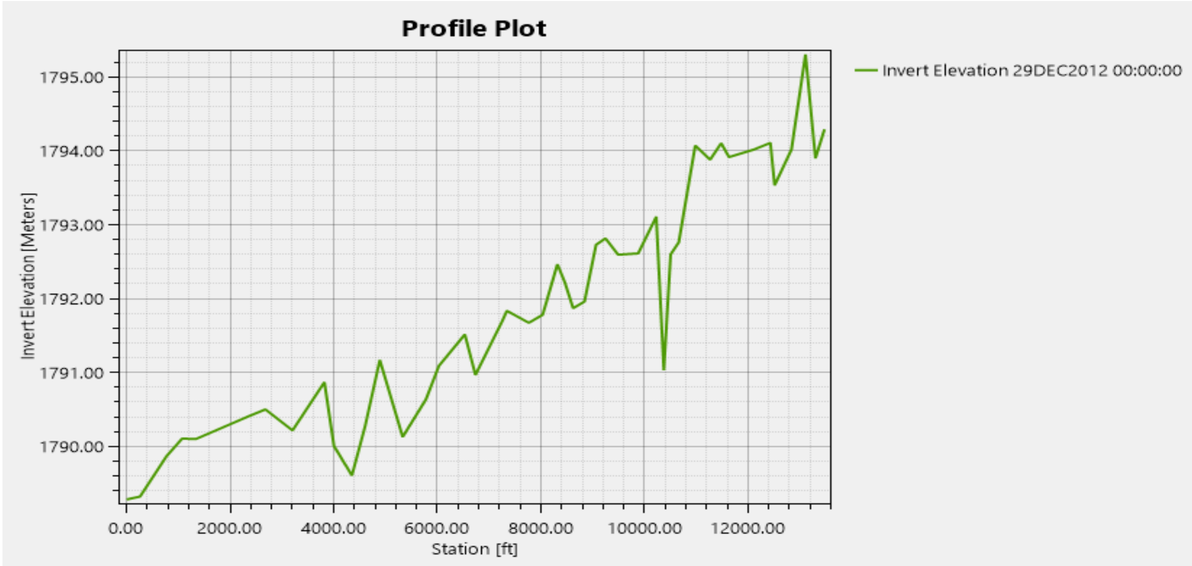



**Figure 4.0.15 Simulated River bed longitudinal profile downstream of Dam (with HEC-RAS)**

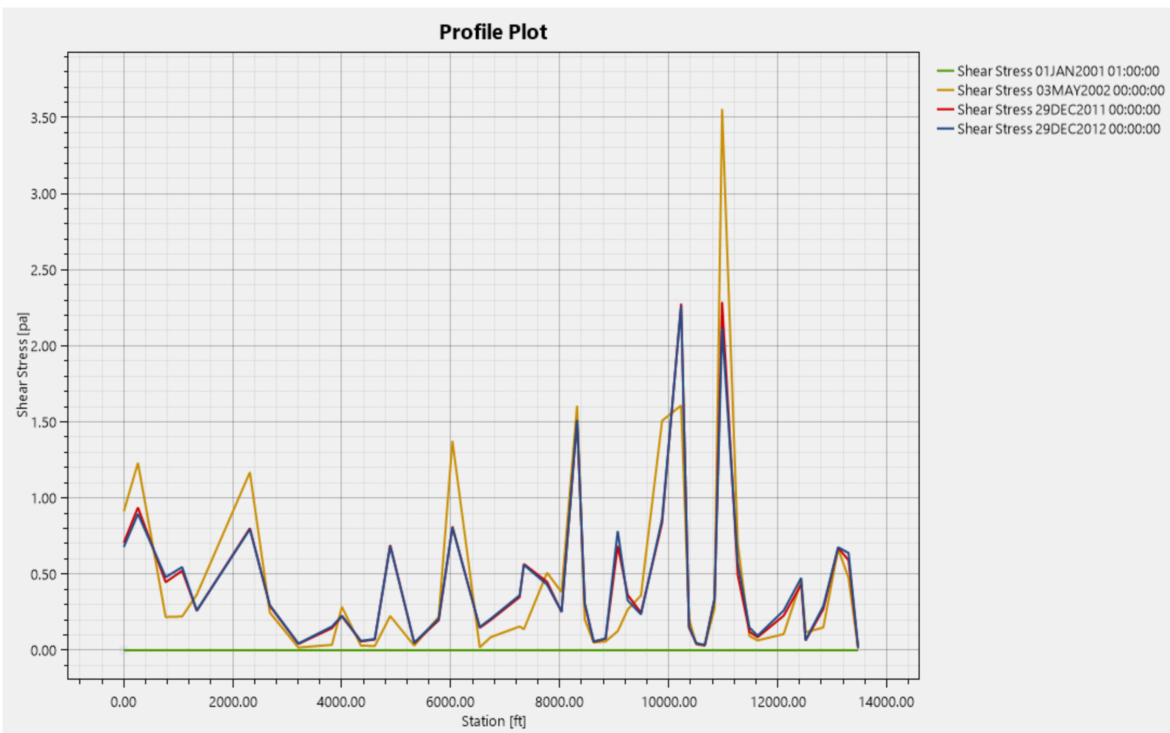



**Figure 4.0.16 Ribb River shear stress variation in the controlled flow discharge (HEC-RAS, downstream of dam)**

### 4.6.3 Bank erosion width change

River bank erosion is related with gully erosion because it is a process of lateral cutting. Gullies often begin in the river banks of natural water course and by water fall erosion and move bank in to adjacent lands. Due the clear water discharge and sediment load conditions cross section and longitudinal channel shape adjustment occurred. This will cause changes in depth, width, and bed level of the channel. Both bed and bank changes are simulated using HEC-RAS on Ribb River. The result is as shown below: Cross section change just downstream of dam.

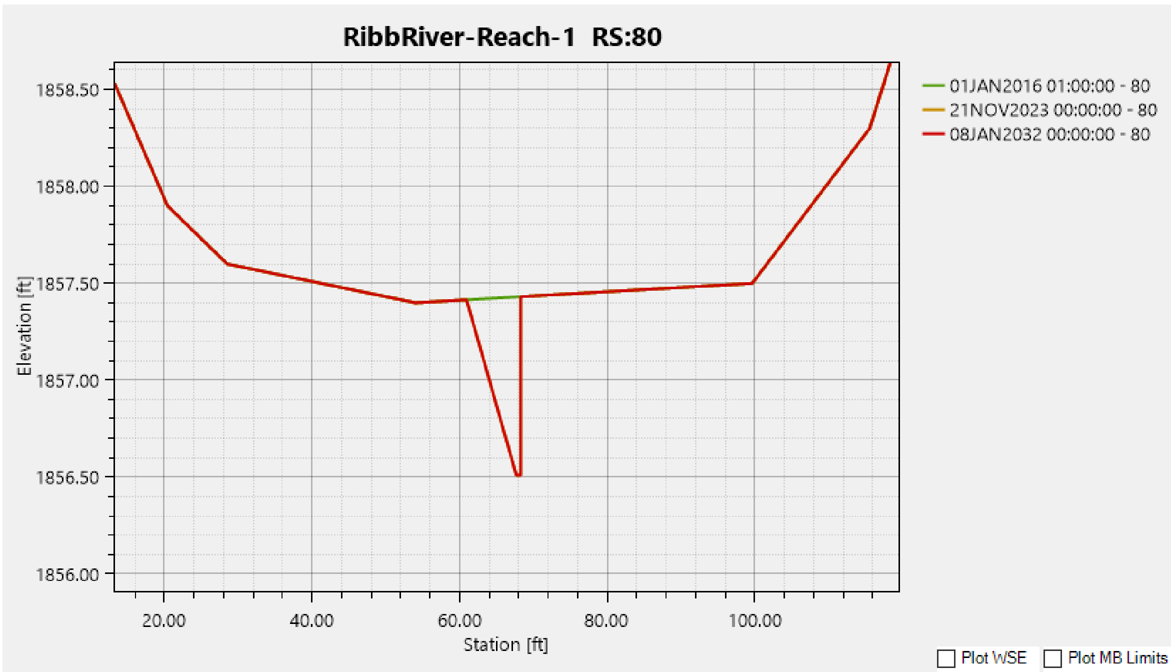



**Figure 4.0.17 Cross sectional shape change just downstream of dam**

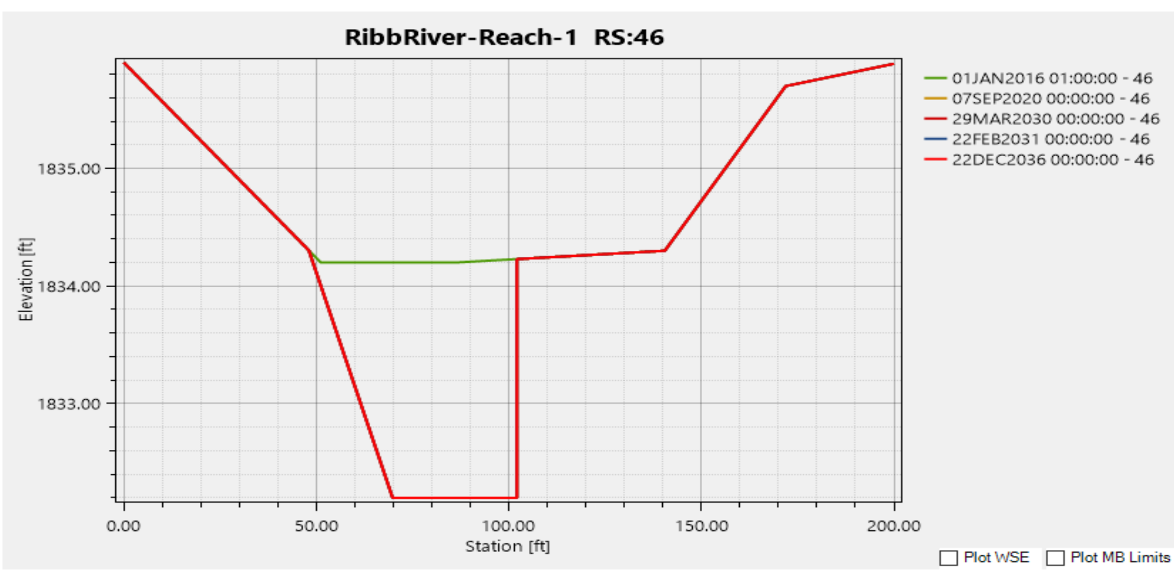



**Figure 4.0.18 Cross sectional shape change @ half-way the study reach**

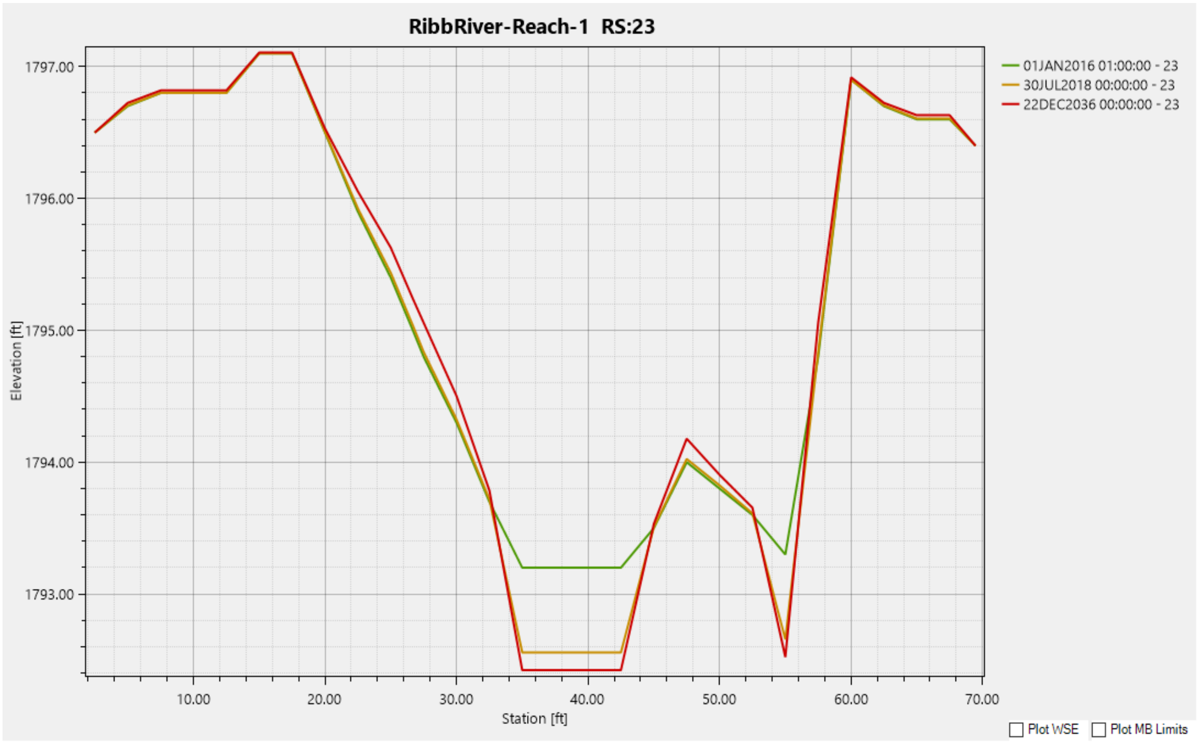



**Figure 4.0.19 Cross sectional shape change downstream of study reach**

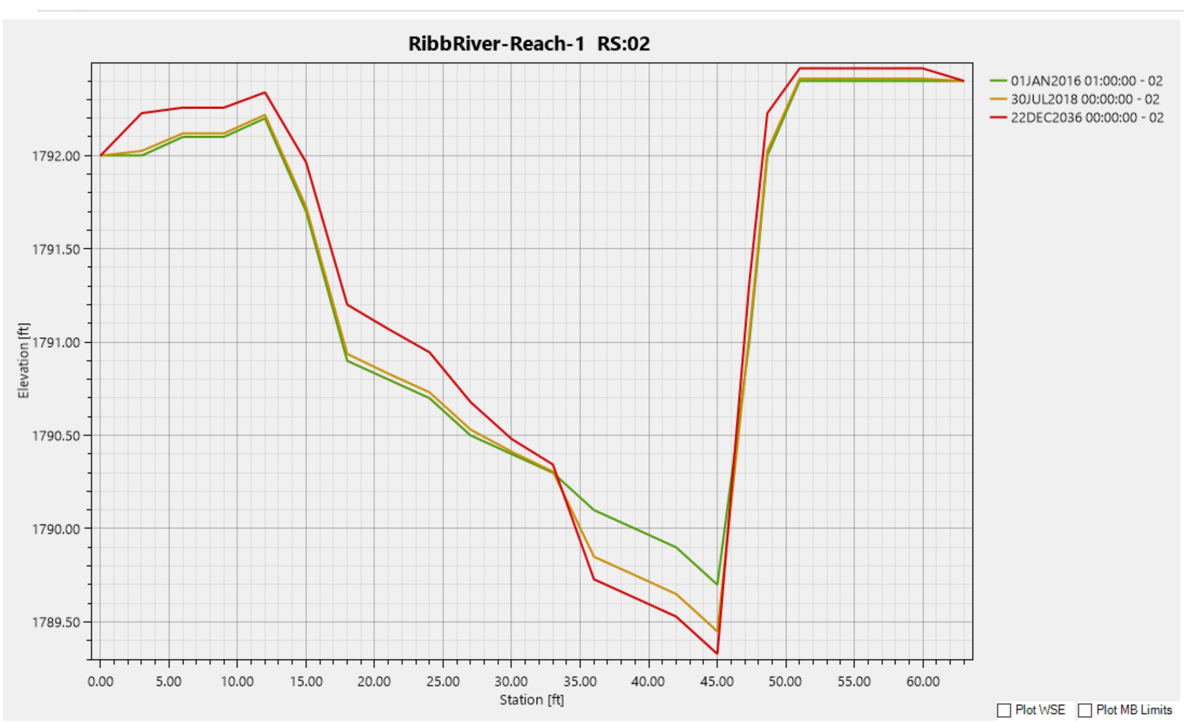



**Figure 4.0.20 River bed and bank erosion/Cross sectional shape change @ the outlet**

### 4.6.4 Verification of results

Downstream morphological impact prediction of Ribb dam reservoir was modeled using HEC-RAS, shows the degradation would continue in the future. The expected results were happened as a result of controlled dam unsteady flow sediment transport analysis. The degradation and bank erosion process happens in the same way as happening in the other rivers of the world and also much too theoretical hypothesis made by researchers. The width changes happened around the upstream of the diversion weir and bed degradation shows decrease in depth in different quantity at different location.

Within a year or two after dam closure, the length of the degraded reach can range from little or nothing to as much as 50 km. After 2 or 3 decades, the length downstream from some dams remained as short as a few kilometers (and theoretically could be much less), but downstream from Hoover Dam it was more than 120 km (Susan J. Novak, 2006)

Sedimentation in reservoirs is also of big influence downstream of the dam. A river system consists of a continuous balance between erosion and deposit, where sand is picked up due to the river flow and deposited elsewhere in the river. If the inflow of sediment is blocked due to a dam structure, the equilibrium of the river morphology is disturbed and the river channel downstream of the dam starts to erode to compensate for the lack in sand particles (Koen Bronsvoort, 2013).

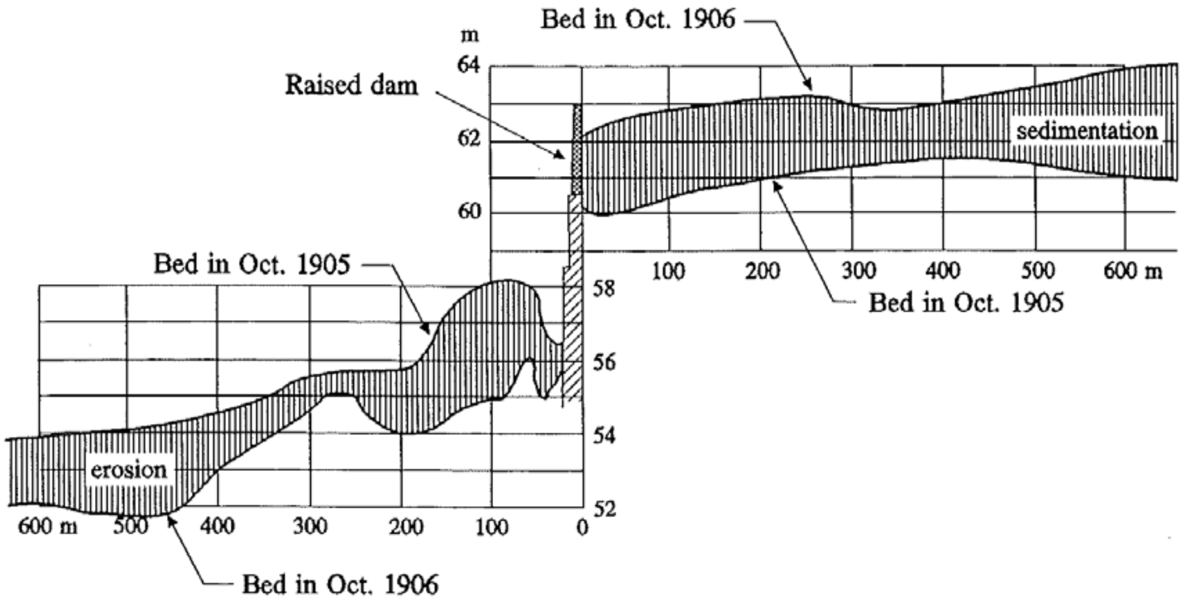



**Figure 4.0.21 Measured bed variations due to heightening of a dam in the Yuba River Adapted from (SLOFF, C.J., 1991)**

## 4.7 Comparison with other similar studies

Compare with Aswan High dam and other dams, the degradation of bed of the channel downstream of Aswan high dam and in many dams in the U.S. has shown a decrease in the downstream (William and Wolman 1984). The rate of bed degradation reduces with time until an equilibrium condition is reached either with armoring of bed of the river channel or reduction of slope to reduce the transport capacity.

Also studies conducted on the Nile River downstream Aswan dam have shown decrease in width of the channel due to reduction of dominant discharge. Even online observations ensure the decrease of width of the channel. That probably occurs due to reduction of discharge and the incision of the channel bed. The results of this particular in reach downstream of Ribb reservoir showed this change in the morphology of the river. The release of sediment deficit water causes the bed degradation.

# 5. CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusions

This study applied integrated hydrologic and hydraulic modeling using HEC-HMS and HEC-RAS to evaluate sediment dynamics in the Ribb River watershed, reservoir sediment deposition, and downstream morphological changes following dam construction.

### HEC-HMS modeling

HEC-HMS model performed well in predicting Ribb reservoir sedimentation i.e. the model perform the process of flow and sediment transport in Ribb dam reservoir. Based on this simulation Specific sediment yield were 367 ton/ $km^2$/ year. The reservoir life of Ribb Dam was estimated using the dead storage capacity (27 MCM) and the annual sediment inflow (630,000 ton/year). Assuming a sediment bulk density of 1.3 ton/ $m^3$, the annual sediment deposition volume is about 0.485 MCM/ year. Therefore, the estimated time required to fill the dead storage is approximately 56 years. Based on 1960-2004 flow data and the upper Ribb sediment rating equation, presents the monthly distribution of suspended sediments in the upper Ribb River. The dead storage, (settled sediments), amounts to about 27MCM in the 50 years lifespan of the reservoir (WWDSE, 2009).

The results indicate that sediment inflow from the upstream watershed contributes significantly to reservoir sedimentation, leading to a progressive reduction in storage capacity. This has direct consequences for the long-term functionality of the dam irrigation efficiency. In addition, sediment trapping within the reservoir changes the natural sediment regime, resulting in downstream channel adjustments such as bed degradation and bank instability.

### HEC-RAS modeling

The highly regulated and reduced downstream flow and clear water cause degradation in the channel. The longitudinal profile of Ribb River after dam construction in 2016-2036 shows significant changes in the longitudinal profile of the Ribb River release of controlled flow, where of 82 cross-sections, the River bed and cross- sections were eroded through the given period. The results show that erosion or bed degradation and creating valley will be especially significant in the upstream cross-sections. The degraded river bed and bank erosion sediment will be deposited in the downstream end of the river i.e. upstream of the diversion weir that will be affected the canal intake and will cause canal sediment deposition.

The continuous unsteady sediment simulation model result shows that the profile change over time 2016-2036. Cross sections will change over a given period of years.

- ❖ The magnitude of the morphological changes are felt more just downstream of the dam 7m of scouring and 33% of width reduction, as compared to other locations far from the dam; which indicates these changes come due to the influence of the dam.
- ❖ The change will be narrowed from 32m to 8m immediate downstream of the dam. But increase in width at half way and Upstream of the diversion weir.

The modeling results further demonstrate that unregulated sediment processes can negatively affect hydraulic structures and intake systems, and may increase maintenance requirements. Moreover, changes in flow and sediment transport downstream of the dam can lead to morphological instability, affecting riverbanks and surrounding infrastructure.

Overall, the study highlights the importance of integrating watershed management, reservoir operation, and sediment control strategies to ensure sustainable dam operation and minimize environmental and geomorphological impacts.

## 5.2 Recommendations

Given the increasing number of dam projects in the country for water supply, hydropower, and irrigation development, it is essential to incorporate sediment management and downstream impact mitigation into planning, design, and operation phases.

Based on the findings of the Ribb River study, the following policy-relevant recommendations are proposed:

### Sediment Management and Reservoir Operation

- ❖ Establish and enforce operational guidelines for periodic sediment flushing and sediment bypassing to maintain reservoir storage capacity.

- Develop adaptive reservoir operation rules that consider both water and sediment release to reduce downstream geomorphological impacts.
- Require sediment budgeting and long-term monitoring programs for all major dam projects.

**Watershed Management**

- Promote integrated watershed management approaches that combine land use planning, soil conservation, and water resource management.
- Implement biological and structural soil and water conservation measures, including afforestation, contour plowing, and check dams.
- Encourage the construction of hillside terraces based on slope characteristics to reduce upstream erosion and sediment yield.

**River Morphology and Infrastructure Protection**

- Conduct mandatory downstream impact assessments focusing on riverbed degradation, aggradation, and bank stability prior to dam construction.
- Apply riverbank stabilization techniques (e.g., gabions and bioengineering methods) in erosion-prone areas.
- Integrate sediment considerations into the design of hydraulic structures, including sluices, spillways, and intake towers.

Research, Monitoring, and Institutional Framework

- Support detailed and continuous research on reservoir sedimentation, sediment transport processes, and morphological changes.
- Establish a national framework for sediment management in dam projects, including technical guidelines and regulatory standards.
- Strengthen institutional capacity for data collection, modeling, and decision-making in sediment and river basin management.

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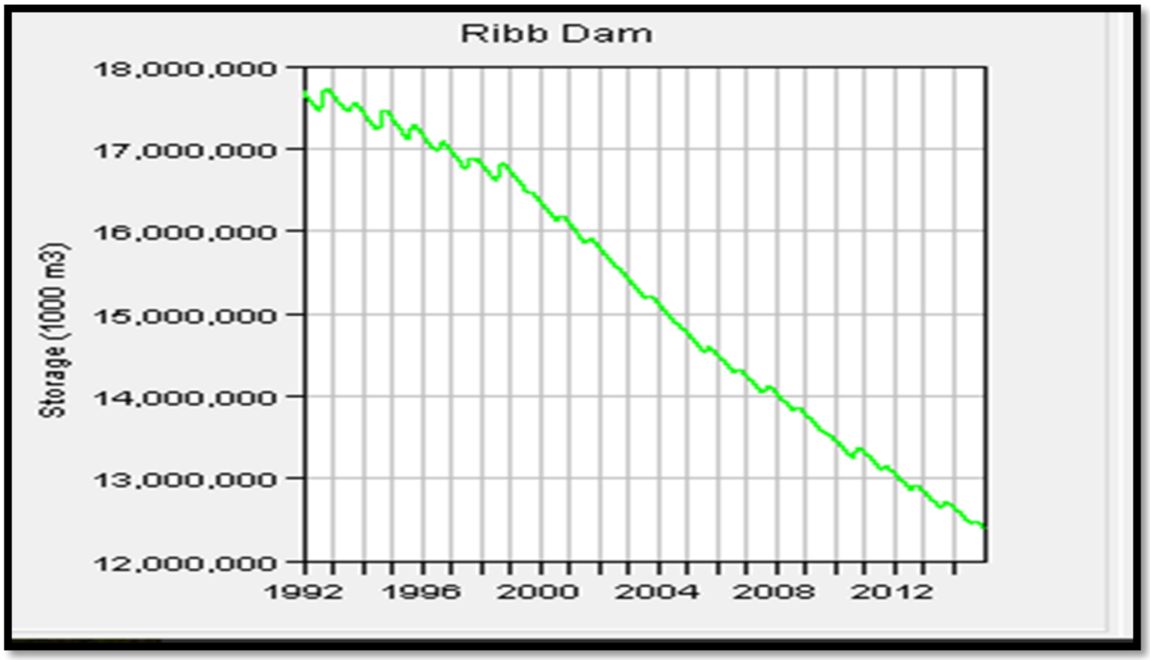
NTUA ITIA (National Technical University of Athens, Information Technology in Information Assessment) (2012) *Research and development of software for the management of water resources (1992–2012)*. Athens: National Technical University of Athens.

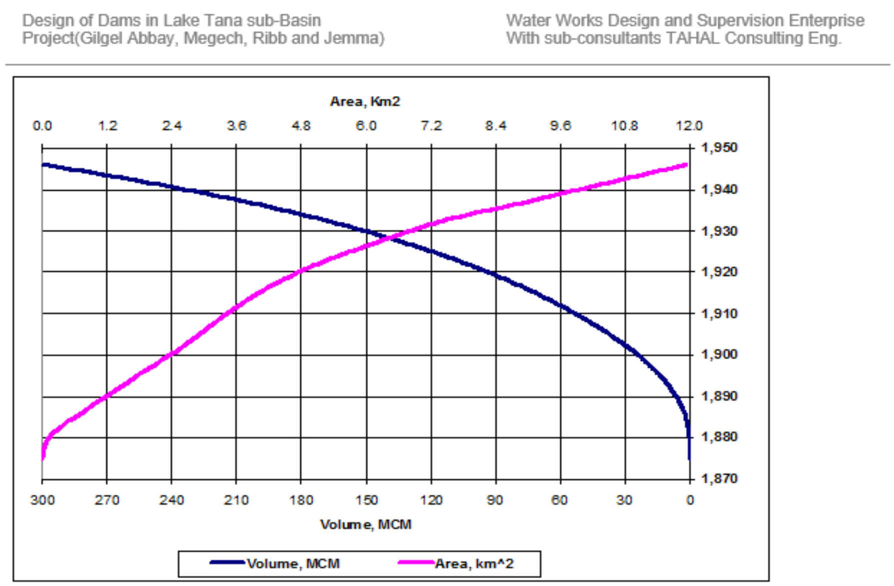
**APPENDIXES 1 Rainfall data**

| No | Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1990 | 1.511 | 1.245 | 0.865 | 1.287 | 0.674 | 11.72 | 88.101 | 109.924 | 96.846 | 40.395 | 3.458 | 2.715 |
| 2 | 1991 | 2.299 | 1.216 | 1.161 | 1.921 | - | - | - | - | 121.17 | 20.987 | 3.263 | 5.117 |
| 3 | 1992 | 0.602 | 0.258 | 0.459 | 5.619 | 2.891 | 12.667 | 96.246 | 163.249 | 108.639 | 28.426 | 59.177 | 2.221 |
| 4 | 1993 | 2.158 | 0.705 | 1.081 | 4.562 | 21.394 | 20.294 | 98.931 | 99.93 | 99.93 | 23.451 | 4.27 | 0.99 |
| 5 | 1994 | 0.47 | 0.163 | 0.307 | 1.776 | 5.721 | 73.934 | 99.468 | 107.661 | 99.468 | 4.884 | 0.919 | 0.689 |
| 6 | 1995 | 0.353 | 0.272 | 0.478 | 7.285 | 7.285 | 20.48 | - | 137.676 | 86.896 | 3.662 | 3.029 | 1.853 |
| 7 | 1996 | 0.67 | 0.492 | 2.106 | 9.334 | 62.953 | 82.992 | 98.588 | 98.588 | 65.491 | 21.442 | 8.593 | 2.287 |
| 8 | 1997 | 0.991 | 0.628 | 7.817 | 1.768 | 35.497 | 40.965 | 90.85 | 94.544 | 41.378 | 30.242 | 27.681 | 5.024 |
| 9 | 1998 | 1.109 | 0.4 | 0.736 | 0.358 | 15.454 | 42.633 | 70.214 | 69.011 | 69.011 | 34.761 | 5.995 | 1.172 |
| 10 | 1999 | 1.375 | 0.588 | 0.4 | 0.344 | 0.569 | 32.619 | 89.509 | 98.977 | 90.824 | 98.28 | 18.416 | 18.179 |
| 11 | 2000 | 10.911 | 0.596 | 0.388 | 2.741 | 4.382 | 24.986 | 94.844 | - | 92.152 | 46.417 | 10.911 | 2.097 |
| 12 | 2001 | 1.041 | 0.65 | 1.658 | 1.417 | 2.097 | 58.469 | - | - | - | - | - | - |
| 13 | 2002 | - | - | 0.786 | 1.121 | 0.495 | 55.303 | 55.749 | 77.042 | 67.116 | 4.785 | 1.25 | 1.25 |
| 14 | 2003 | 0.786 | 0.786 | 1.041 | 0.359 | 0.248 | 22.575 | 71.714 | 85.476 | 71.714 | 14.233 | 4.785 | 2.882 |
| 15 | 2004 | 1.963 | 1.739 | 1.739 | 4.785 | 4.987 | 20.571 | 66.616 | 86.057 | 72.761 | 13.281 | 4.207 | 2.022 |
| 16 | 2005 | 1.531 | 1.206 | 6.797 | 1.002 | 2.267 | 47.645 | 87.227 | 86.641 | 74.349 | 22.063 | 6.552 | 4.025 |
| 17 | 2006 | 3.264 | 2.598 | 2.204 | 2.082 | 17.776 | 41.042 | 89.596 | 94.45 | 93.222 | 37.434 | 12.015 | 9.557 |
| 18 | 2007 | 6.552 | 5.626 | 6.195 | 8.669 | 24.153 | 53.978 | 88.407 | 95.688 | 93.222 | 18.224 | 12.548 | 7.304 |
| 19 | 2008 | 8.669 | 5.408 | 3.675 | 16.049 | 75.419 | 81.474 | 100.739 | 118.263 | 114.759 | 15.023 | 19.142 | 5.408 |
| 20 | 2009 | 4.49 | 4.025 | 8.959 | 8.384 | 2.331 | 11.667 | 109.962 | - | 88.407 | 12.548 | 2.204 | 1.434 |
| 21 | 2010 | 1.041 | 0.786 | 1.002 | 1.849 | 14.428 | 43.688 | - | - | 109.962 | 10.179 | 1.386 | 0.691 |
| 22 | 2011 | 0.38 | - | - | 0.3 | 25.796 | 21.81 | 101.381 | 117.557 | 100.739 | 5.408 | 13.095 | 0.547 |
| 23 | 2012 | - | - | - | - | - | - | 126.198 | 117.557 | 87.816 | 6.674 | 4.207 | 0.602 |
| 24 | 2013 | - | - | - | - | 0.471 | 29.891 | 125.464 | - | 80.352 | 26.359 | 2.598 | 0.359 |
| 25 | 2014 | 0.115 | 0.021 | 1.582 | 4.49 | 29.283 | - | 60.329 | - | - | - | - | - |

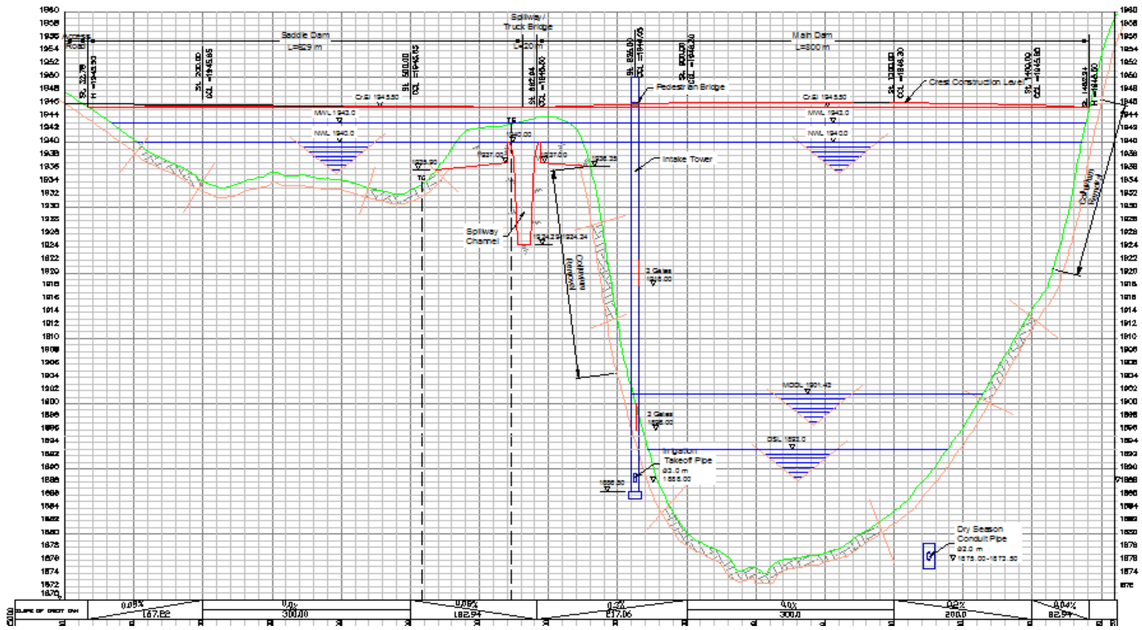
**APPENDIXES 2 Ribb River flow**




**APPENDIXES 3 Ribb Reservoir Elevation – Area – Volume Relationships**



**APPENDIXES 4 Ribb dam cross section (WWDSE)**



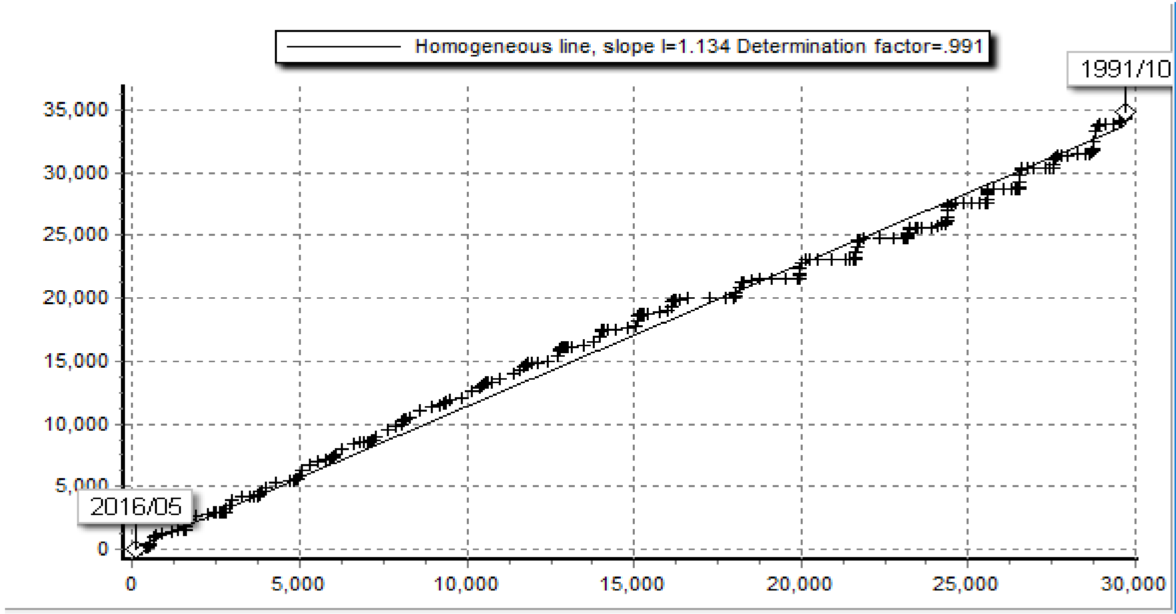
**APPENDIXES 5 DMC of Nefasmewcha**

## E-8 Computation for Ribb River Tailwater Rating Curve

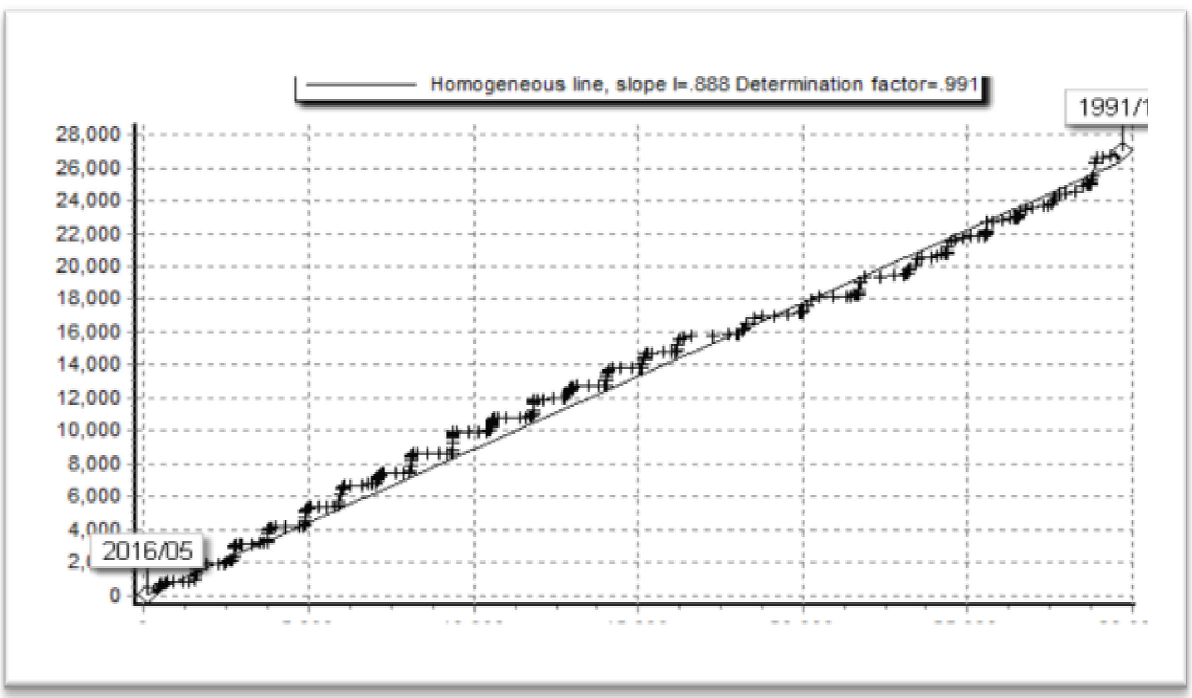
Mean bed slope 0.0027
Manning n 0.03

| Elevation | Area | W.perimeter | H.Radius | Discharge |
|---|---|---|---|---|
| 1873 | 0 | 0 | 0 | 0 |
| 1874 | 16.50 | 25.73 | 0.64 | 21.25 |
| 1875 | 81.00 | 116.26 | 0.70 | 110.26 |
| 1876 | 202.00 | 126.00 | 1.60 | 479.25 |
| 1877 | 331.87 | 135.67 | 2.45 | 1043.56 |
| 1878 | 470.96 | 145.41 | 3.24 | 1785.68 |
| 1879 | 619.34 | 155.23 | 3.99 | 2698.52 |
| 1880 | 777.02 | 167.89 | 4.63 | 3737.64 |
| 1881 | 946.34 | 175.95 | 5.38 | 5031.6811 |

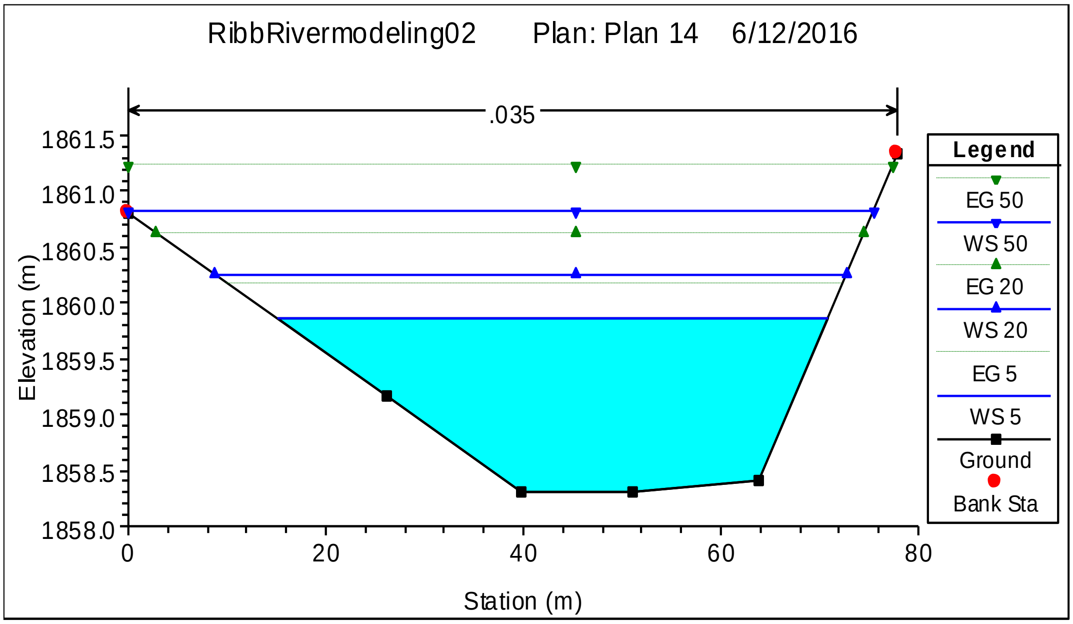
**APPENDIXES 6 DMC of Woreta**



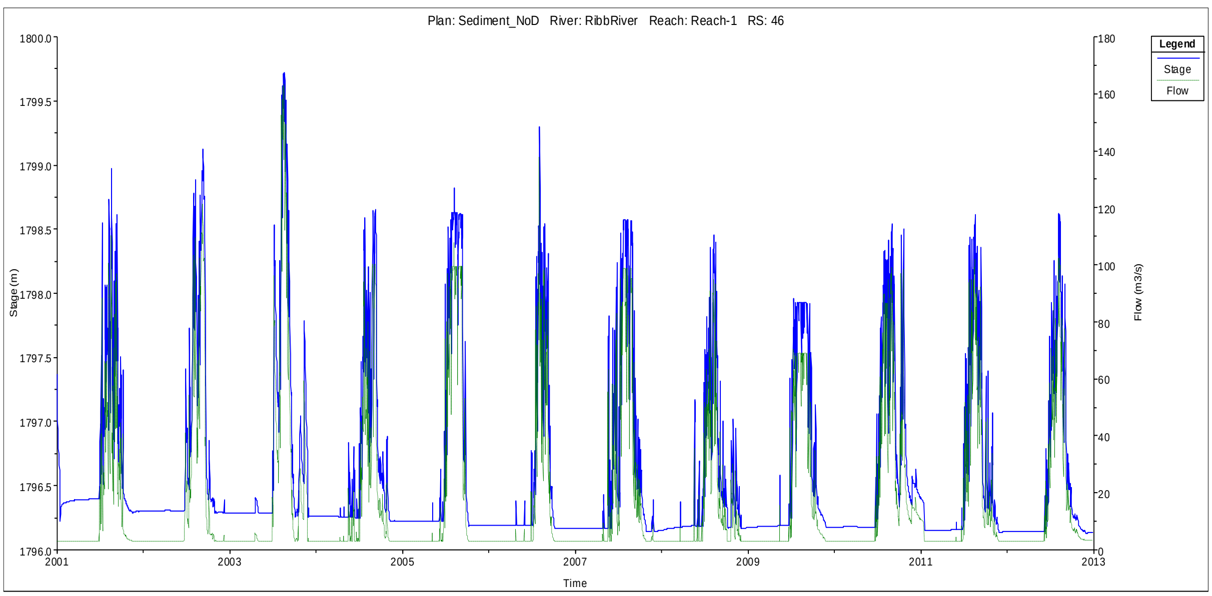

**APPENDIXES 7 DMC of Woreta**



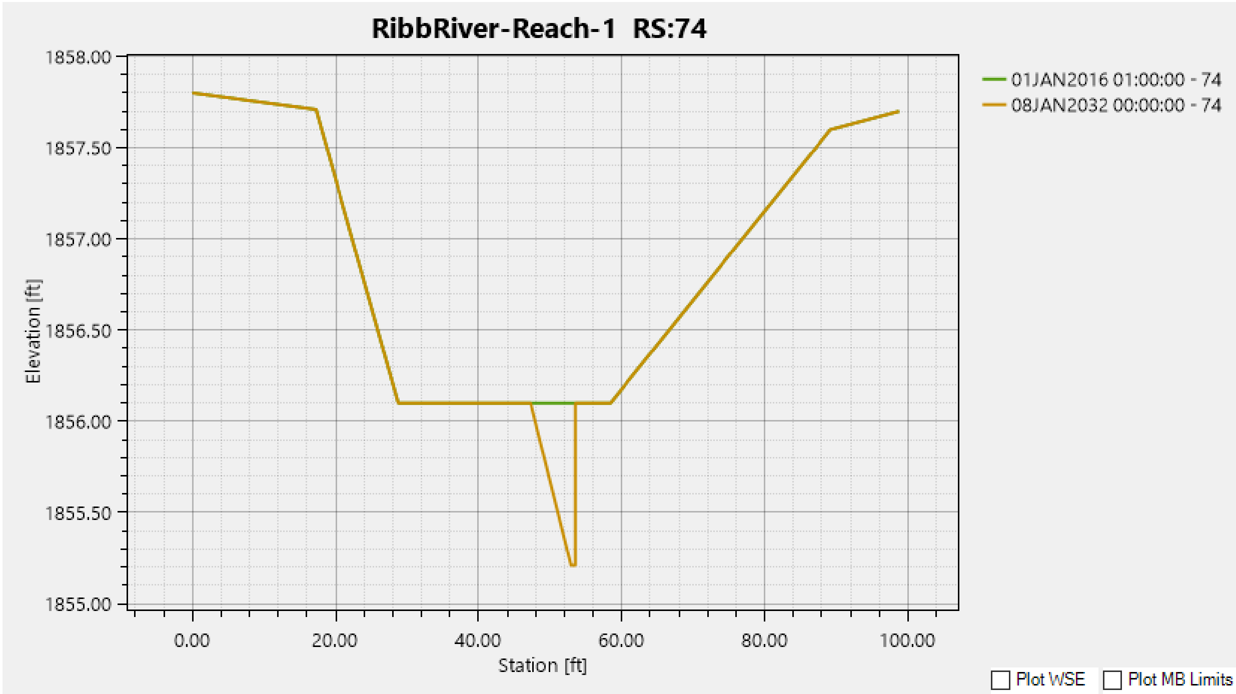

**APPENDIXES 8 Water surface**



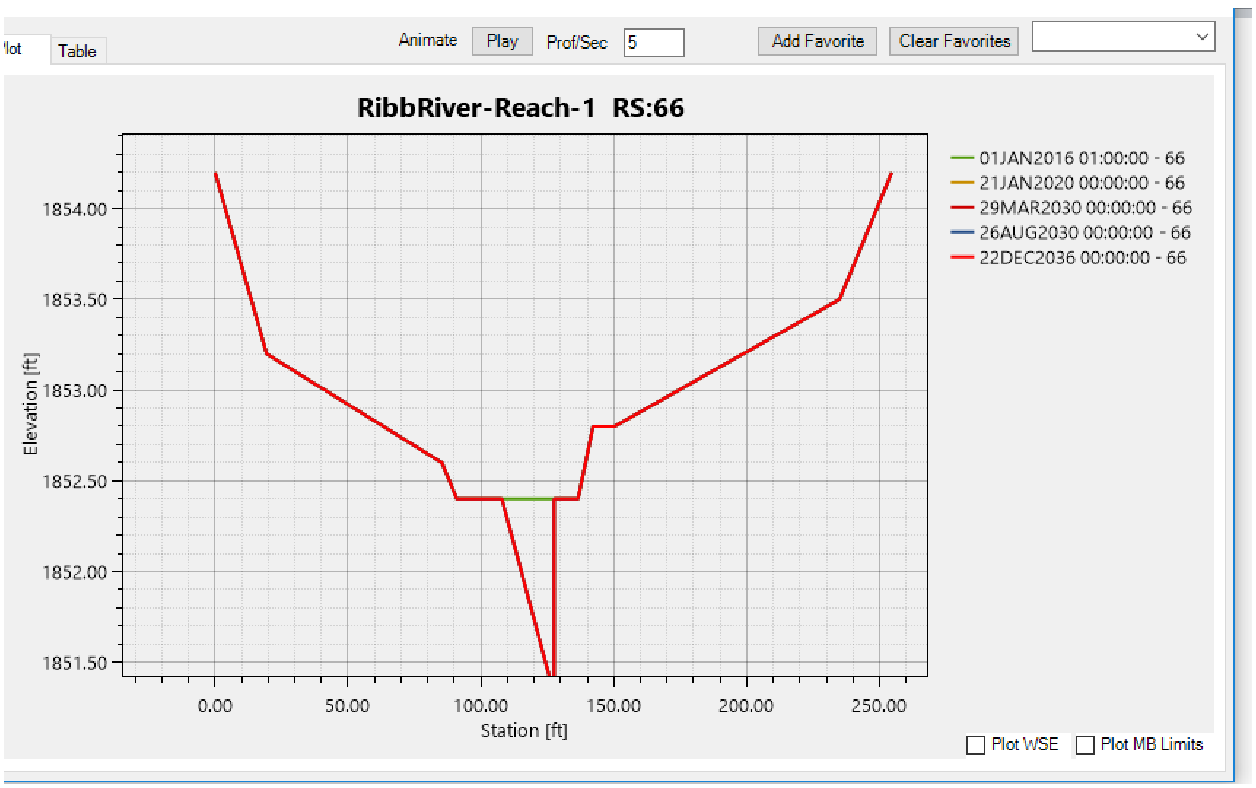

**APPENDIXES 9 Sediment modeling**



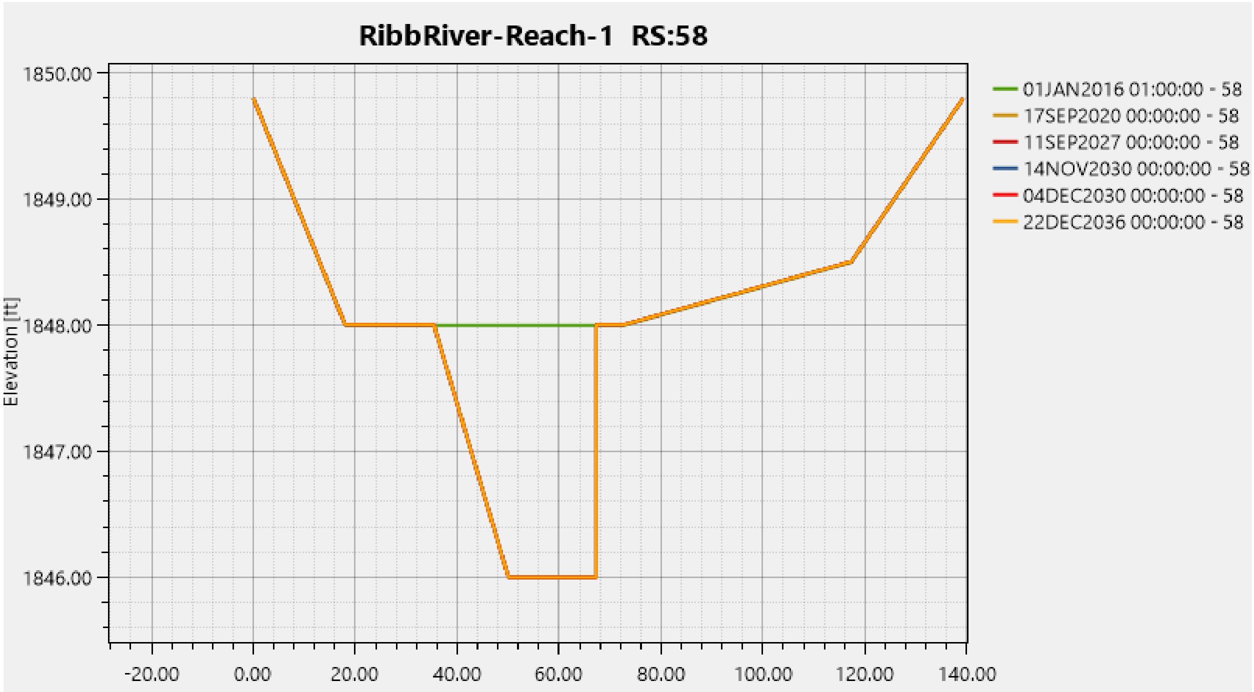

**APPENDIXES 10 Cross sectional shape change at river station 74**



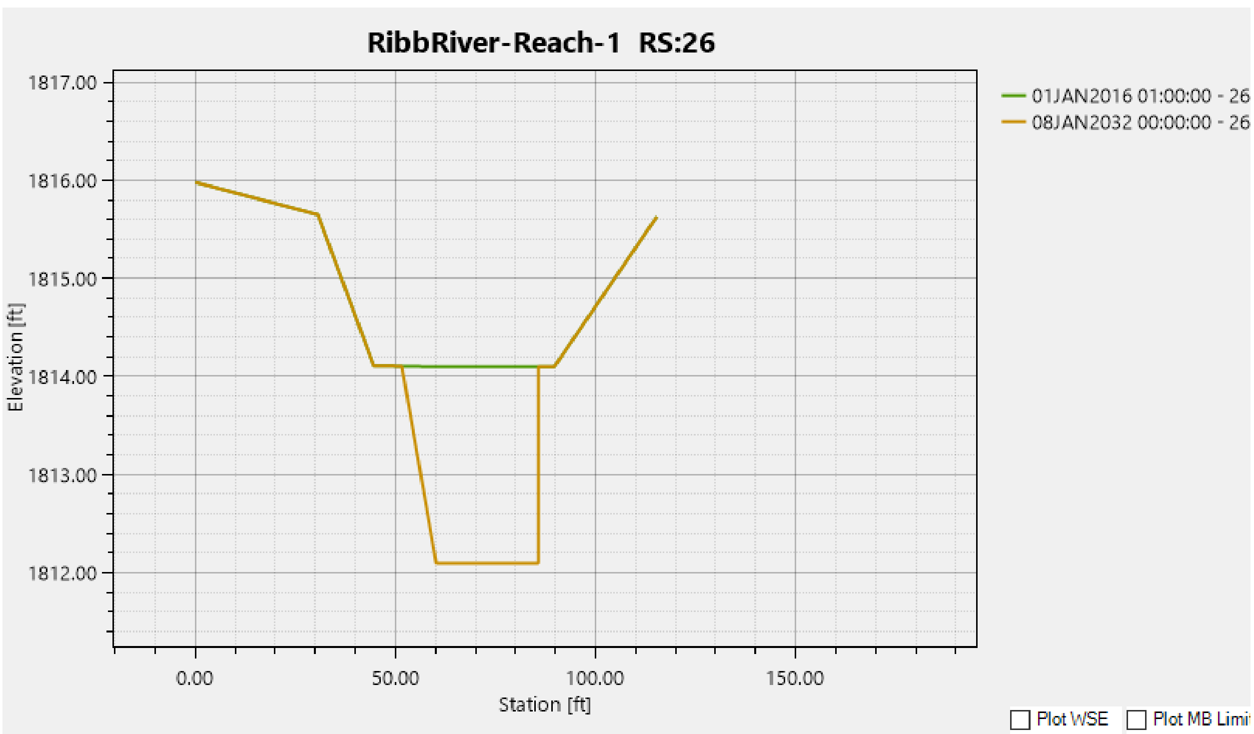

**APPENDIXES 11 Cross sectional shape change at river station 66**



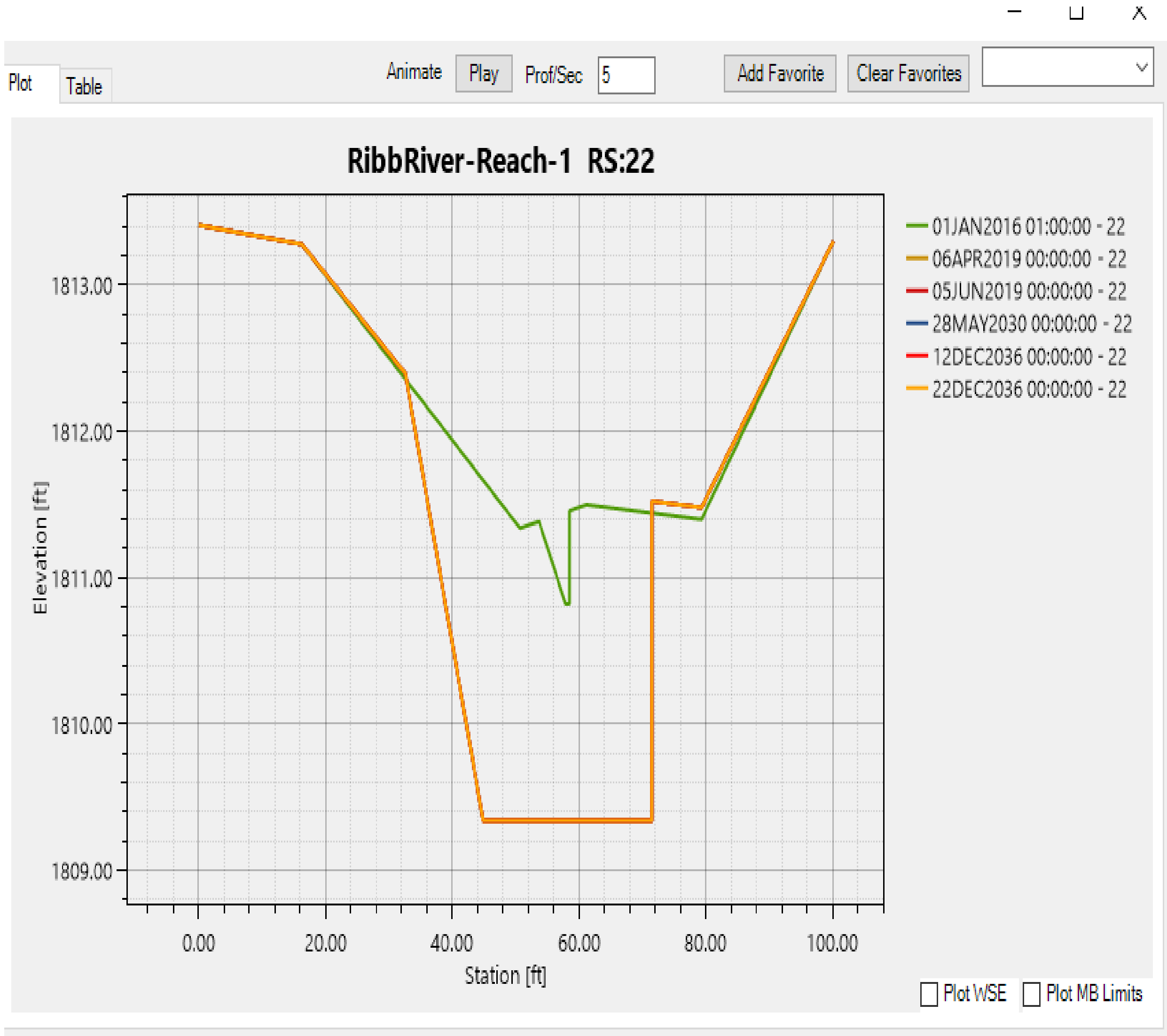

**APPENDIXES 12 Cross sectional shape change at river station 58**



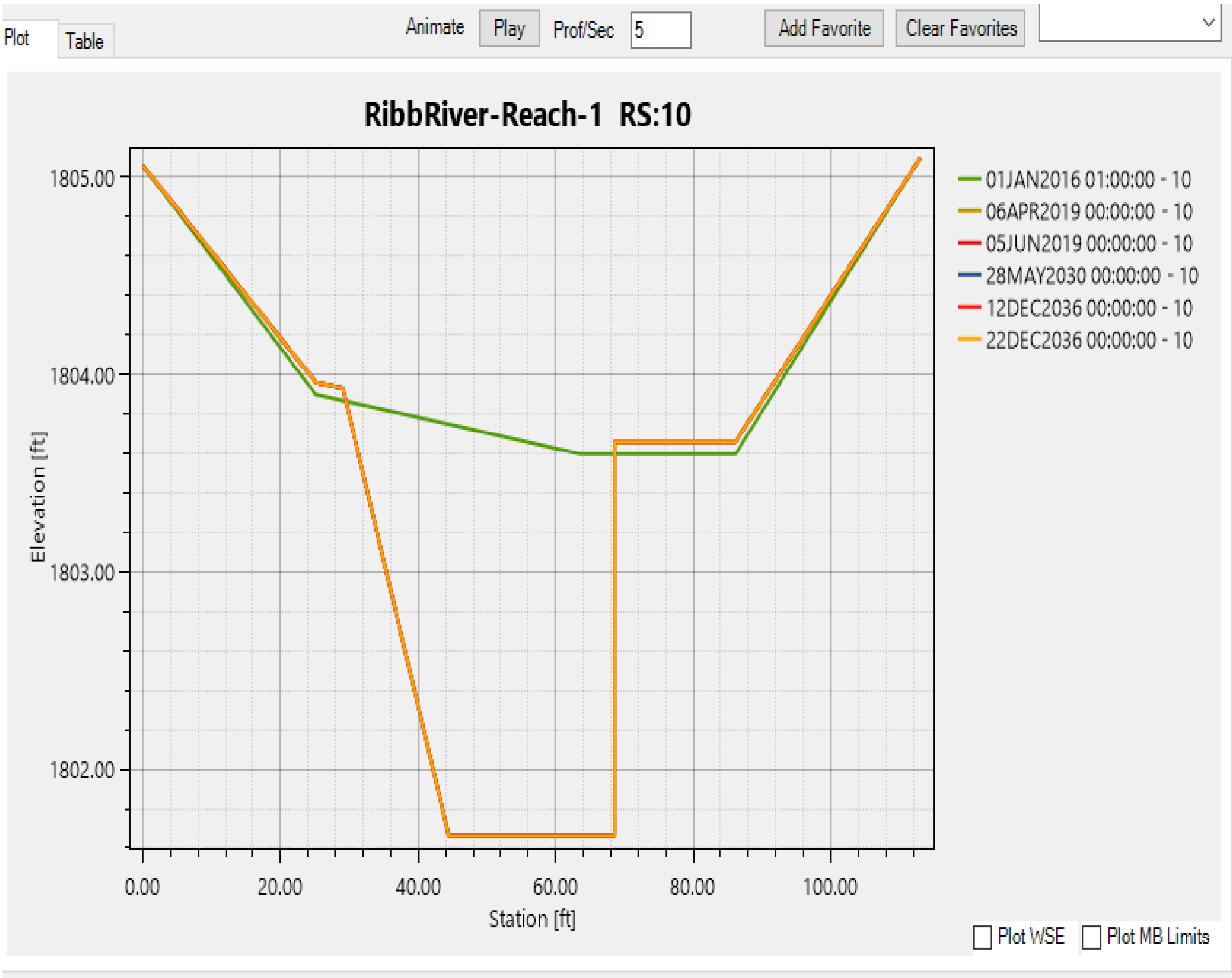

**APPENDIXES 13 Cross sectional shape change at river station 26**




**APPENDIXES 14 Cross sectional shape change at station 22**




**APPENDIXES 15 Cross sectional shape change station 10**




**APPENDIXES 16 Cross sectional shape change station 10**