

## 2D HYDRODYNAMIC MODELING OF RIB RIVER



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## **2D HYDRODYNAMIC MODELING OF RIB RIVER FLOODING**

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A Thesis submitted to School of Graduate Studies, Addis Ababa Institute of Technology in partial fulfilment of the requirements for the degree of masters of Science in Hydraulic Engineering.

Ethiopia  
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## **CERTIFICATION**

I, the undersigned, certify that I read and hereby recommend for the acceptance by the Addis Ababa University a dissertation entitled: **2D HYDRODYNAMIC MODELING OF RIB RIVER FLOODING** in partial fulfilment of a degree of Masters of Science in Hydraulic Engineering.

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Thesis Submitted to Addis Ababa Institute of Technology, School of Graduate Studies in partial fulfilment of the requirements for the Degree of Masters of Science in Civil Engineering with Hydraulic Engineering.

Date defended-----

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**Dedicated to my Father Ato Shiferaw Amogne and Mom W/ro Tobiyaw Meherete: You deserve even more.**

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## Abstract

Flood occurs repeatedly in Ethiopia and cause tremendous losses in terms of property and life, particularly in the lowland areas. The majority of flood disasters' victims are poor people living in nearby stretch of floodplain. Therefore, the study was carried out to perform floodplain analysis and risk assessment of Fogera and nearby areas. This research involves the integration of 2D Structured Mesh Generator (CCHE-MESH) and hydrodynamic numerical model (CCHE2D model) with Geographic Information Systems (GIS) to develop a regional model for floodplain determination and representation.

The study describes the flood extent and depth in the area for flow condition derived from the historical flow data of the Rib River. Triangulated Irregular Network (TIN) was prepared from shape file generated from spot elevations of the floodplain through field survey data and the DEM of the study area in ArcGIS. Triangulated Irregular Network (TIN) is converted to an ASC II format, which is supported by the CCHE-MESH and CCHE2D model.

Boundary condition for the inlet is specified as total discharge and discharge hydrograph for steady and unsteady simulation respectively and for the outlet a constant water level of Lake Tana (1788m) is specified as a downstream BC which allows for simulation of the free flow condition at the river outlet. Initial conditions are defined based on information on gauges or through introducing a so called warm-up that precedes the actual simulation period and boundary conditions are generally specified from hydrometric data such as time series data of discharge and stage or simulated discharge hydrograph.

Maps of flood Extent, Level, Depth and Velocity are developed using 100 years return period flood. The Flood has the inundation area of 47.13km<sup>2</sup> while the simulated flood extent has flood depths less than 5.9m. The depth between 5.9m and 2m is located along the river channel and on the pond which is located south of the rib river. However, the depths below 2m exist largely on the flood plain which extend 4 km and 3 km outside right bank and the left bank of the main river respectively. The simulated water level ranges between 1798.4m ASL at the upstream and 1788m ASL at the downstream end of the main river. The simulation result indicates much of the flooding occur in the middle part of the river where the flow behaviour is mainly dominated by the inflow from the Rib River. Most of the areas around the flood plain are cultivated land with less proportion of Agro-pastoral, Marsh and Pastoral. 85-90% of the flood inundated areas are covered by agricultural land. The remaining 10-15% is covered by Agro-pastoral near inlet to Lake Tana.

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## **List of Acronyms**

EU: European Union

DEM: Digital Elevation Model

TIN: Triangular Irregular Network

MoWE: Ministry of Water and Energy

AMSL: Above Mean Sea Level

ASL: Above Sea Level

CN: Curve Number

DEM: Digital Elevation Model

DTM: Digital Terrain Model

DMC: Double Mass Curve

EV: Extreme Value

FA: Frequency Analysis

CCHE2D: Centre for Computational Hydro science and Engineering two dimensional model

HEC-RAS: Hydraulic Engineering Center for River Analysis System

HEC-HMS: Hydraulic Engineering Center for Hydrologic Modeling System

FLDWAV: Flood Wave routing model

BC: Boundary condition

NCCHE: National Centre for Computational Hydro science and Engineering

GPS: Global Positioning System

DFO: Dart mouth Flood Observatory

LN: Log Normal

LP: Log Pearson

LIDAR: Light Detection and Ranging

NMA: National Meteorological Agency

RF: Rain Fall

TIN: Triangular Irregular Network

UH: Unit Hydrograph

1D: one Dimensional

2D: Two Dimensional

CFD: Computational fluid dynamics

P.D.E: partial differential equations

FDM: Finite Difference Method

FVM: Finite Volume Method

FEM: Finite Element Method

## 1 Introduction

### 1.1 Background

A flood is an overflow of an expanse of water that submerges land. The EU Floods directive defines a flood as a temporary covering by water of land not normally covered by water. The need to study the cause and effect of flooding has begun since flooding has become a problem to society when people and their valuables become affected. Historically many solutions have been proposed to mitigate the effects of flooding but knowledge on the actual cause effect relation is lacking. With the advent of digital computers, much emphasis has been on simulating and modelling of flood events and related characteristics and such is the main concern of this paper. The challenge here is to develop a reliable flood model to simulate flood events for Rib catchment.

The consequences of flooding are complex and far-reaching. These consequences include direct damage to property and structures, as well as disruption of economic activity and displacement of affected population, with the attendant costs of evacuation and temporary accommodation. It also includes loss of agricultural productivity, including both opportunity as well as direct damage to crops in various stages of cultivation. Although damage is often associated with depth of flooding, other factors influence the extent of damage, including the duration of flooding, velocities associated with peak flows, the sediment content of flood waters, and potential disruption associated with re-alignment of rivers following major floods.

Mitigation on flood effects requires information on the flooding characteristics and how such characteristics propagate. Such information can be obtained through hydrodynamic models that are able to simulate flood extents, depths, levels, velocity and timing over a distributed model domain and over time dimension. Hydrodynamic flood models solve governing flow equations that are based on the law of mass, energy and momentum conservation. CCHE2D is one of such model approaches and is able to model flooding characteristics given that sufficient input data of good quality is available.

In hydrodynamic flood modelling, availability of data in the required spatial and temporal resolution is vital. Topographic data is one of such data used as input in hydrodynamic flood modelling. Digital Elevation Model (DEM) and/or its derivative Triangular Irregular Network (TIN) is major source of topographic data for representing floodplain and river topography. However availability and quality of the geometric data of river cross sections is a major limitation. For such availability of basic data sources, a high resolution DEM is a

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prerequisite. Even though there is still a gap to find this high resolution DEM to represent the topography of the study area, the 30M DEM is selected to best represent. The DEM coupled with the survey data aids to have a greater accuracy for construction of river topography and other properties.

In this research it is intended to analyze the extent of the flood damage using CCHE2D, which is an integrated package for two-dimensional simulation and analysis of river flows, and to develop Vulnerability and risk maps for the area.

### *1.2 Statement of the problem*

The rainy season in Ethiopia is concentrated in four months from June to September. Large scale flooding is rare and limited to the lowland areas where major rivers cross to neighbouring countries. However, intense rainfall in the highlands causes flooding of settlements close to any stretch of river courses.

The flood from the Rib River, which is usually formed by out banking of the river channel, is causing direct damage to property and structures, as well as disruption of economic activity and displacement of affected population and the loss of agricultural productivity in the Fogera plain. The lower part of the Rib catchment is known as one of the flood prone areas by the annual flooding in the Fogera floodplain. In 2006, as shown in Figure 1.1 extreme flooding affected 12,500 people in the region.

This thesis will simulate the rib river flow using two-dimensional hydrodynamic model to explore the extent of the flood in the plain in the form of Vulnerability and risk maps and suggest structural and non-structural control measures to be under taken for the problem.

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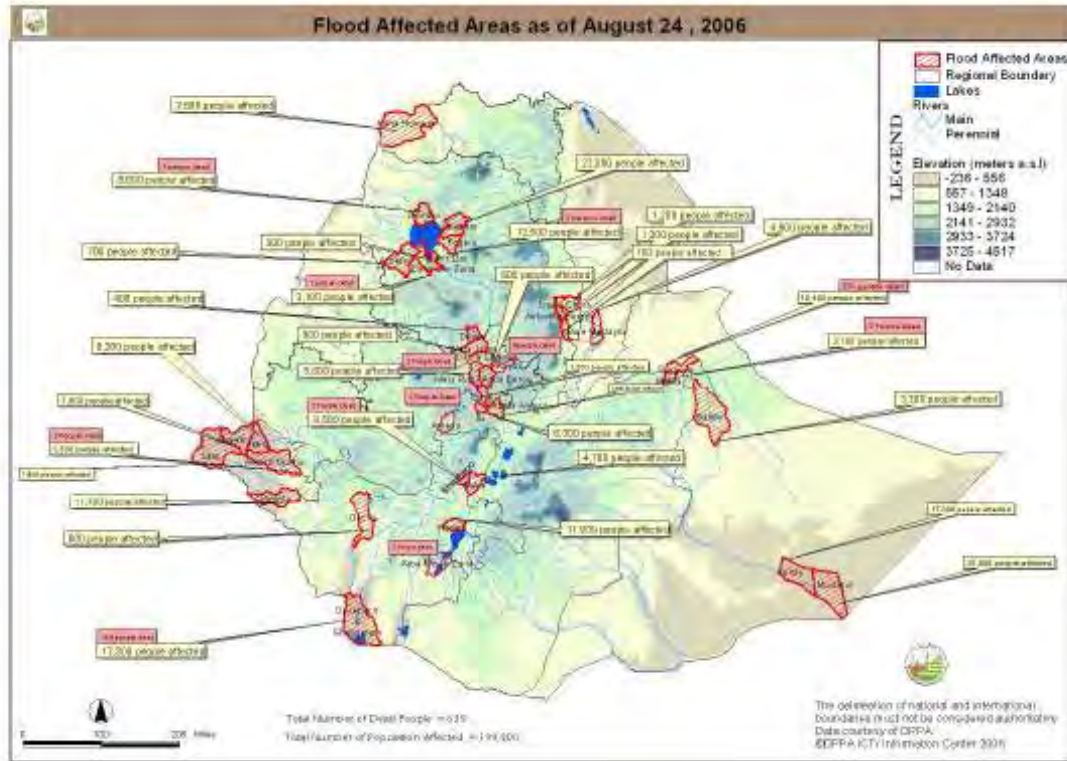


Figure 1-1 flood affected areas in Ethiopia (Disaster and emergency commission, 2006)

## 1.3 Objectives

### 1.3.1 General objectives

The overall objectives of the research is to simulate flooding event in the rib catchment by using the 2D hydrodynamic model (CCHE2D) and to develop Vulnerability and risk maps

### 1.3.2 Specific objective

The specific objective of the research is

- To generate mesh from the river geometrical data
- To simulate the river flow for 100 years return period flood
- To produce maps of flood depth, level ,extent and risk for floods of 100 year return period flood

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### 1.4 Study area

#### 1.4.1 Location

Rib catchment is one of the largest sub-catchment in Tana basin found in the eastern part of the Lake. The catchment is located between  $10^{\circ}43'$  and  $11^{\circ}53'$  N Latitude and  $37^{\circ}47'$  Longitude. It has an area extension of  $1540\text{km}^2$ . This catchment is drained by the Rib River which originates from Guna Mountain and finally joins Lake Tana in the vicinity where the River causes flooding. The downstream part of the catchment is part of the wide flat floodplain (Fogera floodplain) with a total area of  $490\text{km}^2$ . In the Fogera plain, flooding occurs from the Gumera River near the southern end of the plain, and the Rib River approximately 15 km to the north. Both rivers flow west across the plain, which extends approximately 12 km to 15 km south-east from the lake shore to the highway between Bahir Dar and Gondar. This study considers the flooding in the northern part of the floodplain is primarily caused by bank overflow of the Rib River and tributaries to the Rib in the lower stretch of the river near Lake Tana



Figure 1-2 Topographic map of the Fogera area

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### 1.4.2 Topography

The elevation of the catchment ranges from 1777 to 2150m AMSL. The slope of the flood plain Approximates 0.032% which is quite mild. The upstream of the catchment is highly mountainous while it is very flat at its lower reaches.

### 1.4.3 Land use and soil

Land use of the flood plain is mainly dominated by cultivated land. Most of the study area is characterized by cultivated lands as most of the area is rural.

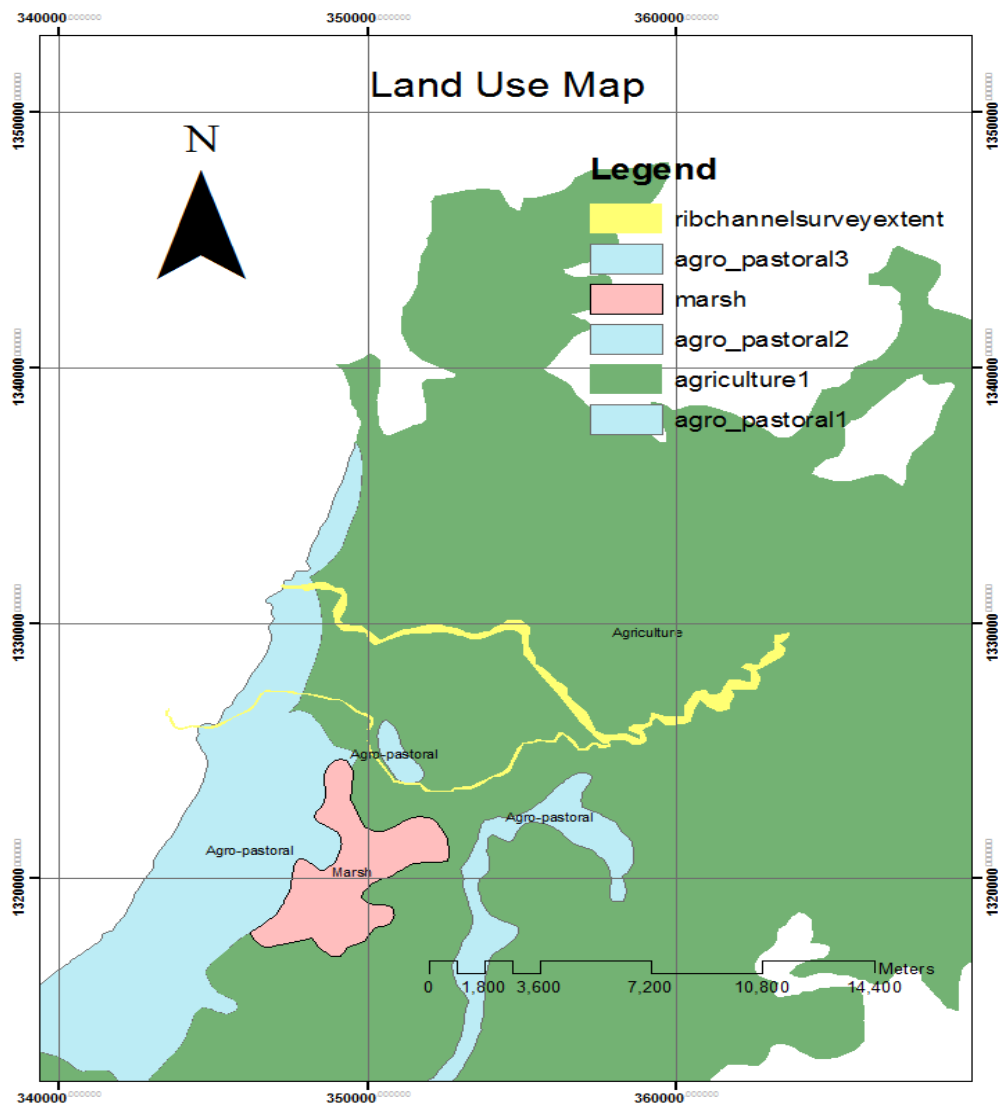


Figure 1-3 Land use map of the Fogera area (MoWE)

### 1.4.4 Nature of the river channel

The Rib River is formerly flowing what is now called old channel of the river. The new channel is made diverted at about 5KM downstream of the bridge from the main road of the Gonder- Bahir Dar highway. The separation of the two river channels is by the earthen embankment (dyke) for about 4- 5KM. There may be little or no over flow from the new channel to the old. The only contribution of flow to the old channel is mostly local flows and very little overflow which are very difficult to quantify.

### 1.4.5 Rainfall distribution and flooding of the area

The catchment is characterized by a rainfall which amounts from 1100mm to 1500mm per year. These highest rainfalls were experienced during the months June, July, August and September. The rainfall distribution over the catchment is mono-modal; nearly 79% of the annual rainfall occurs from June to September. Peak flow in the River occurs in August with average monthly flow of 52 m<sup>3</sup>/s.

Flooding is the major problem in the downstream reach of the catchment. Severe flooding of the 1996, 1998, 1999, 2000, 2001, 2003 and 2006 are among the most events. The August 2006 flooding in the catchment was known for its long flood duration and devastation. Many people are forced to evacuate to other kebele for more than two months. Figure 1-4 shows the average monthly distribution of rainfall (1964-2005)

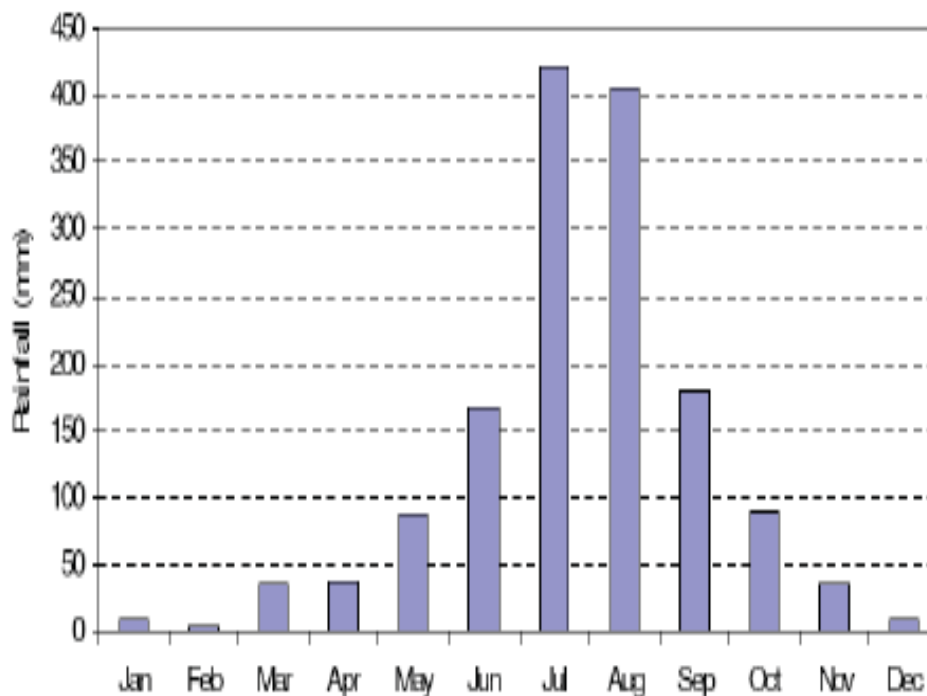


Figure 1-4 Mean monthly rainfall of the rib catchment (MoWE)

## 2 Literature review

### 2.1 Flood modeling

#### 2.1.1 General

Flood models are a representation of the hydrologic and hydraulic process in the river channel and flood plain. The technology of capturing high qualitative parameterisation data especially DEM and the development of efficient numerical and computational tool has brought big contribution for the development of flood models (Hunter et al. 2007)

#### 2.1.2 Flood modeling approaches

The most common modelling approach include planar water surface approach ,small and large cell approach ,one dimensional hydrodynamic model ,two dimensional hydrodynamic model ,couple one dimensional two dimensional hydrodynamic model.

In planar water surface approach a planar surface of water level observed at gauges is overlain on to a DEM and all areas below this surface are counted as flooded (Tesfaye.H.T 2009).

Hydrodynamic models in general solve the Adhemar Jean Claude Bare De Saint Venant (1797-1886) equation of continuity and momentum developed in 1871 (Horritt et al. 2002) .One dimensional (1D) model approach assumes flow is transit only in longitudinal direction and water level is horizontal in transverse direction and solve the one dimensional flow governing equation at series of cross section of the main river channel and the flood plain (Tesfaye.H.T 2009).Unlike the one directional ,two dimensional model approach considers variations of flow in longitudinal and transverse direction of the main river channel. It is very efficient to characterise flow in undefined and heterogeneous flood plain where the direction of flow is affected by other factors besides channel and floodplain slopes (Haile.A.T and Rientjes.T.H.M , 2003)

Even though all modelling approaches have their own specific limitation a wide range of application to real world problem are known. For instance, 1D hydrodynamic flood model are less suited to a condition where floodplain flow is complex but they are better suited to a condition where there is a single dominant flow direction such as valley flooding (Tesfaye.H.T 2009).

### 2.1.3 Solution approaches to hydrodynamic models

Flow governing equation used in hydrodynamic model is a complex set of continuous differential equation. The differential equations developed by St.Venant are flow governing equations that are applied in two dimensional hydrodynamic flood modelling. Solving these equations through analytical methods' is not possible (Dyhouse et al. 2003). They are solved through a numerical method which solves continuously varying (in time and space) differential terms at discrete points in space and discrete moments in time. The solution is obtained at a number of discrete points for which derivatives are approximated by their finite difference.

The numerical solution involves conversation of the continuous differential equation in to a system of discrete algebraic equation which is solved through iteration and this gives an approximate solution. The most common methods include finite difference approach, finite element approach and finite volume approach. In these approaches the continuous real world space and time dimensions are replaced by discrete finite increments to give an approximate of the differential equation or its solution. The finite element method used in CCHE2D is called Efficient Element Method which was initiated by (wang sam S.Y. and Hu, k.k. 1992). Collocation approach of the finite element method is adopted to discretize the mathematical equation system.

### 2.2 Mesh generation

Computational fluid dynamics (CFD) is based on solving a set of highly non-linear partial differential equations (P.D.E) on a physical domain, which is usually discretized and represented by a computational mesh.

Basically, there are two types of meshes used in CFD: the structured and the unstructured. The structured meshes consist of families of mesh lines with the property that members of a single family do not cross each other and cross each member of the other families only once, while the unstructured mesh does not have such a restriction (Yaixin Zhang and Yafei Jia, feb 2009). The advantage of the structured mesh is that any mesh node is uniquely identified by a set of two (2D mesh) or three indices (3D mesh) and thus is easy to access. In the unstructured meshes, a connection table is required to identify the relationship of the mesh nodes. Usually, the structured mesh is used for the Finite Difference Method (FDM) and the Finite Volume Method (FVM), while the Finite Element Method (FEM) often uses the

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unstructured mesh. The CCHE-MESH Mesh Generator is developed to generate the structured meshes (Wang, Yafei Jia and Sam S.Y. 2001).

There are two kinds of methods to generate structured meshes: numerical methods and algebraic methods. The numerical methods solve the partial differential equations; usually Poisson equations, to generate boundary-fitted mesh, while the algebraic methods, and determine the mesh directly according to some desired nodal distribution (Yaixin Zhang and Yafei Jia, feb 2009). The numerical methods are global approaches, which can provide very good meshes with smooth transition of nodal distribution, smoothness, and orthogonality guaranteed. Although the algebraic method can always be used to resolve a mesh, its' global smoothness, even local smoothness, uniformity properties are not guaranteed. As a result, smoothing methods are often applied to optimize the mesh. For cases with complicated domain geometry, the multi-block approach could be applied to simplify a complex mesh to several small meshes with simpler geometry (Wang, Yafei Jia and Sam S.Y. 2001).

Different approaches are described to represent the naturally occurring flood plain mesh by different scholars. Usually Channel elements describing the meandering river are usually discretized separately from those comprising the model floodplain. Firstly, this is so that element sides can be aligned with the channel banks, and so that at least three elements can be guaranteed to span the width of the channel to crudely capture variations in bathymetry and flow velocity (David M.cobby et al. 2002). Secondly, having fixed the number of elements across the channel, the elements can be elongated in the downstream direction, which reduces the number of elements both in the channel and on the floodplains (As the floodplain elements must be coupled to those in the channel), and limits the Courant number, thus ensuring numerical stability. The elongation of the channel elements was fairly arbitrary (e.g. Bates et al. (1995) recommend a rule-of-thumb aspect ratio of 5 : 1) until Horritt (2000) showed that element length should be a function of channel curvature. In his Cheesy mesh generator, uniform angular deviation of elements replaces uniform element length, so that shorter elements are produced around tight meanders where computational resources should be concentrated, and longer elements along straighter sections.

### *2.3 Initial and Boundary Conditions*

The numerical simulations of flow based on solving Navier-Stokes Equations are initial-boundary value problems. The initial conditions are very important, since inappropriate initial conditions may slow down the convergence process or even cause the simulation to fail.

While applying flood model to a certain catchment, the model parameter, the initial (model) condition and boundary condition have to be specified. Boundary condition serve to introduce the influence of the external force to the model domain such as river inflows and lake levels. The initial condition is the hydraulic state (water level or flux) in the model domain as defined prior to the actual simulation (Tesfaye.H.T 2009).

Initial conditions can be defined based on information on gauges or through introducing a so called warm-up that precedes the actual simulation period and boundary conditions are generally specified from hydrometric data such as time series data of discharge and stage or simulated discharge hydrograph. Mathematically, three types of boundary conditions could be identified: Dirichlet condition (specified head boundary), Neumann condition (specified flow boundary), and Cauchy condition (head dependent flow boundary)

The CCHE 2D hydrodynamic model uses the essential boundary conditions, velocity vectors are specified along inlet(s), outlet(s) and wall boundaries and water surface elevation are needed to be specified along the computational domain (Wang, Yafei Jia and Sam S.Y. 2001).

### *2.4 Topographic Representations*

In flood modelling floodplain the DEM and surface roughness are very important model inputs. The outputs from hydrodynamic models such as flow depth, velocity and flood extent depends on the values of inputs from DEM as flow governing factors such as slope, flow direction and inundation area are affected by DEM resolution. Selecting the appropriate DEM resolution in flood modelling is very important for two reasons: to accurately represent the flood plain and channel topography and to consider the simulation time (Tesfaye.H.T 2009).

The sensitivity analysis to DEM resolution revealed that topographic representation is critical and that model output is significantly affected by the resolution of the DEM (Haile.A.T and Rientjes.T.H.M , 2003). In two dimensional hydrodynamic models it is very important to represent the geometric information of the river channel and the flood plain as a continuous surface. For better representation of the hydraulic process in the river, a river terrain model can be developed and then burned in to flood plain DEM using GIS techniques and the resulting DEM is used as input to 2D modelling (Merwade.V, Cook.A and Coomod.J , 2008)

### *2.5 Surface Roughness*

The main calibration parameters in flood modelling are roughness values of the floodplain and the main channel. A value for this parameter is assigned based on the land cover or land use type of the flood plain and the type of bed material in the main channel and its alignment. Manning roughness values for different surface materials and channel alignment are indicated in Arcement and Schneider (Arcement.G.J.and Schneider.V.R, 1989) and (Chow, Open Channel hydraulics 1959) . Manning's -N and chezy-C roughness values are widely applicable for roughness parameterisation in flood modelling (Werner. M, 2004)

### *2.6 Flood mapping*

#### **2.6.1 General**

People have always settled near rivers and coasts, but population growth and the commensurate expansion of the built environment have increased their risk of losses to flooding over time. Mankind primarily dealt with flood hazards by building flood control structures, such as dams and levees. However, escalating flood losses and disasters relief coast enforce people to identify and map flood prone communities and to make flood insurance available in communities that adopt and enforce flood plain management regulation such as zoning, building requirements, special purpose flood plain ordinance (Committee on FEMA Flood Maps 2009).

#### **2.6.2 Flood hazard, Flood Vulnerability and risk**

**Flood Hazard** – a representation of areas subject to flooding, together with probability of occurrence. Flood damage refers to all varieties of harm caused by flooding. It encompasses a wide range of harmful effects on humans, their health and their belongings, on public infrastructure, cultural heritage, ecological systems, industrial production and the competitive strength of the affected economy. Some of these damages can be specified in monetary terms, others – the so called intangibles – are usually recorded by non-monetary measures like number of lives lost or square meters of ecosystems affected by pollution (Frank Messner , VolKer Meyer 2005). Flood damage effects can be further categorised into direct and indirect effects. Direct flood damage covers all varieties of harm which relate to the immediate physical contact of flood water to humans, property and the environment. This includes, for example, damage to buildings, economic goods and dykes, loss of standing crops and livestock in agriculture, loss of human life, immediate health impacts, and contamination of ecological systems. Indirect or consequential effects comprise damage, which occurs as a

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further consequence of the flood and the disruptions of economic and social activities. This damage can affect areas quite a bit larger than those actually inundated. One prominent example is the loss of economic production due to destroyed facilities, lack of energy and telecommunication supplies, and the interruption of supply with intermediary goods. Other examples are the loss of time and profits due to traffic disruptions, disturbance of markets after floods, reduced productivity with the consequence of decreased competitiveness of selected economic sectors or regions and the disadvantages connected with reduced market and public services (Frank Messner , Volker Meyer 2005)

**Vulnerability** – a measure of how easily damaged the elements in flood prone areas are as a function of the magnitude or depth of flooding. The actual amount of flood damage of a specific flood event depends on the vulnerability of the affected socio-economic and ecological systems, i.e., broadly defined, on their potential to be harmed by a hazardous event (Cutter 1996, Mitchell 1989). Generally speaking, an element at risk of being harmed is the more vulnerable, the more it is exposed to a hazard and the more it is susceptible to its forces and impacts. Therefore, any flood vulnerability analysis requires information regarding these factors, which can be specified in terms of element-at-risk indicators, exposure indicators and susceptibility indicators (see figure 2-1). In this regard, natural and social science indicators are highly significant.

**Risk** - the product of hazard and vulnerability

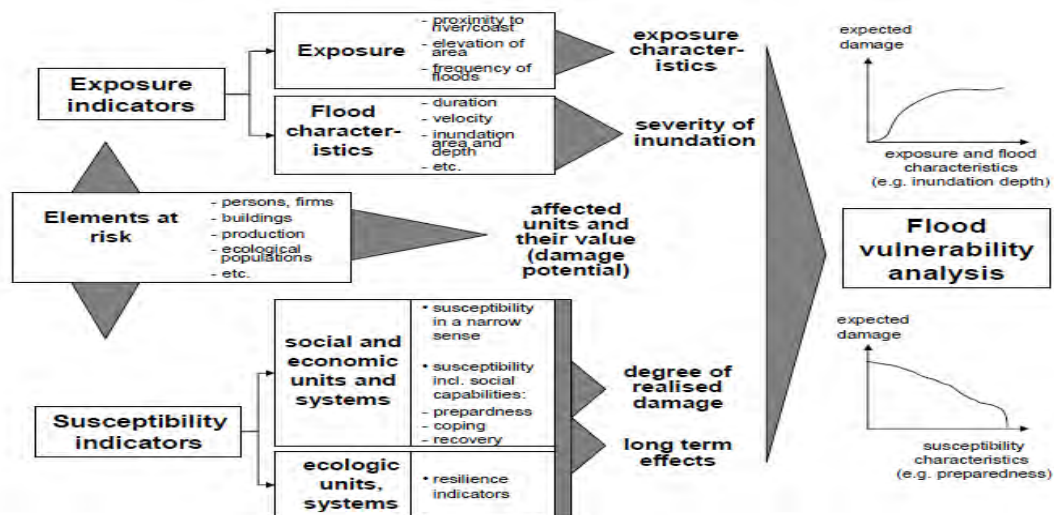


Figure 2-1 Indicators to be used in flood vulnerability analysis (Frank Messner, Volker Meyer, 2005)

### *2.7 Model Calibration, Sensitivity Analysis and Validation*

There is always a need to analyse the difference between the values of a model output with observed values under the same time frame. It is likely to find simulated values that deviate from observed, so it is essential to bring the difference to an acceptable and reasonable limit.

Model calibration is a procedure of adjusting model inputs to match the model output with measured/observed data for selected period and simulation entered to the model. Its accuracy is usually tested by Nash-Sutcliffe model efficiency parameter and RMSE (Tesfaye.H.T 2009).

Sensitivity analysis is process of analysing the influence of each parameter by changing the value of one or more of them. In flood modelling, hydrodynamic models are sensitive to physical model parameters (DEM resolution and surface roughness) (Giuliano Di Baldassarre et al. 2009) , initial and boundary conditions.

In flood modelling data for calibration and validation include flood inundation data (satellite imagery or flood inundation maps) (Giuliano Di Baldassarre et al. 2009), field observation (distribute flood depth observation), and hydrometric data (gauged river stage or flow).

### *2.8 Model Selection*

There are various criteria which can be applied for choosing the most suitable model. The choice mainly depends on the requirements and needs of the research or project under interest (Cunderlik, J.F. and Simonovic,S.P, 2003). Cunderlik and simonovic (2003) put the following as criteria

- Required outputs of the model
- Availability of input data
- Prices and availability of the model
- The model structure

There are different flood modelling tools which have their own distinct model structure and solution procedures. Most widely used one dimensional flood modelling tools include HEC-RAS, FLDWAV, ISIS, FLUCOMP and MIKE 11. Two dimensional flooding models include MIKE21, DELEFT-FLS, DELEFT 3D, RMA2 and CCHE 2D and integrated one two dimensional models include MIKEFLOOD, SOBEK and LISFLOOD. If the vertical variations of flow and sediment quantities in a water body are sufficiently small or can be determined analytically, their variation in the horizontal plane can be approximately described by a depth-averaged 2D model (Wu, 2008). In addition, many open channel flows are of shallow water problems, the effect of vertical motions is usually of insignificant

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

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magnitude. The depth integrated two-dimensional equations are generally accepted for studying the open channel hydraulics with reasonable accuracy and efficiency (Wang, Yafei Jia and Sam S.Y. 2001). In this research the CCHE2D model is used for its availability and its computational capability.

### *2.9 Previous Studies on Rib Catchment*

Problem of river flooding in Ethiopia is getting more and more acute due to human intervention in the fragile highland areas at an ever-increasing scale. Although flooding is a common problem in the flood plain of rib catchment little is done in the area.

A 2D hydrodynamic modelling of flooding using ASTEM –DEM in Rib catchment (Tesfaye.H.T 2009) focuses on studying the flooding characteristics in the flood plain of the catchment using 2D hydrodynamic modelling and GIS techniques. The study applied the 2D overland flow module of SOBEK 1D 2D hydrodynamic flood model. The study proves that geometric description of channel topography and topographic data at a required resolution has significant effects on the outputs of hydrodynamic model. It also reveals that any change on the water level of Lake Tana affects the flooding pattern in the flood.

In 2008-2009, Riverside Technology, Inc (Riverside) in cooperation with its partners, Tropics Consulting Engineers (TCE) and Shebelle Consult, has completed a flood risk mapping study for pilot areas surrounding Lake Tana in Ethiopia. Riverside used several existing and custom tools to perform geographic information systems (GIS), remote sensing, and hydrologic/hydraulic modelling including ArcGIS, ERDAS Imagine, HEC-RAS, HEC-GeoRAS, HEC-HMS, and HEC-GeoHMS. To automate much of the GIS processing Riverside used ArcGIS Model Builder and Python Geoprocessing. In addition two key elements of Riverside's approach are the use of readily available open-source models and full employment and integration of local partners and experts; the latter aimed at extending existing expertise and capacity in the engineering community.

A study by Dagnachew.L (PhD) and Woubet. G (Dagnachew L. 2008) focuses on flood hazard and risk assessment in Fogera woreda using GIS and remote sensing. The study results flood hazard and risk maps. Although the study has produced useful input for developing strategies for decision makers, it was not based on the actual cause and effect relationship.

Research conducted by Assefa et.al(2008) is centered on developing flood forecasting and early warning decision tools for the study area( Fogera flood plain) based on rainfall forecasts

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

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and hydrological model (HEC-HMS). It mainly focuses on a quantitative precipitation forecast based flood forecasting model using HEC-HMS rainfall runoff model for supporting flood early warning decision making.

Another study was conducted by the two researchers Gashaw and Legesse (2008) concentrates on flood mapping of hazard and risk in the area. They tried to show land cover change in the upstream (degradation) is contributing to flooding.

Korean consultants undertook flood frequency analysis and estimated the discharge conveyance capacity of the river channels downstream of the highway. This study concluded that flooding of the adjoining floodplain would occur every year due to the low conveyance capacities.

### 3 Methodology

#### 3.1 Data collection and Analysis

##### 3.1.1 Metrological Data

- Daily rainfall within the water shed and of nearby stations
- Daily temperature (minimum and maximum)

The Meteorological data were obtained from the National Meteorological Agency (NMA) of Ethiopia. Data of daily rainfall, maximum and minimum temperature were collected from the same Agency from stations within and around the watershed.

Table 3-1 location of Meteorological station within and around the water shed (NMA)

S.No	Station name	Elevation(m) ASL	Latitude	longitude
1	Bahir Dar	1780	11.6	37.42
2	Woreta	1980	11.92	37.68
3	Debretabor	2690	11.88	38.03
4	Nefas Mewcha	3000	11.75	48.45

##### 3.1.1.1 DATA ANALYSIS

###### *Filling Missing Rainfall Data*

Rainfall data play a central role in developing rainfall – runoff models. Measured precipitation data are important to many problems in hydrologic analysis and design. For gages that require periodic observation, the failure of the observer to make the necessary visit to the gage may result in missing data. Damage of recording gages is another problem that results in incomplete data records, and instrument failure because of mechanical or electrical malfunctioning can result in missing data.

The two procedures for estimating daily totals rely on the data from any adjacent stations. The locations of the adjacent stations are such that they are close to and approximately evenly spaced around the site with the missing data. When the average annual precipitation at each of the adjacent stations differs from the average at the missing data station by less than 10%, the following formula can be used to estimate the missing daily data.

$$P_x = \frac{N_x}{3} \left[ \frac{P_1}{N_1} + \frac{P_2}{N_2} + \frac{P_3}{N_3} \right]$$

Where  $P_x$  = is the precipitation for the station with missing records

$P_1$ ,  $P_2$  and  $P_3$  are the adjacent stations' precipitation values

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

N1, N2, N3 are the long-term mean annual precipitation values at the respective stations and '3' is the number of stations surrounding the station X. When the difference between the average annual rainfall at any of the adjacent stations and the missing data station is greater than 10% a normal ratio method is normally used.

### *Consistency and Homogeneity*

Estimating missing precipitation is one problem that hydrologists need to address. A second problem occurs when the catchment rainfall at rain gages is inconsistent over a period of time and adjustment of the measured data is necessary to provide a consistent record. A consistent 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. Here accumulated annual values at the station in question are plotted against those of nearby reliable station or group of stations. An abrupt deviation in the slope of the Double-Mass Curve plot suggest some change not related to climatic variables, and adjustment should be made to the data on the basis of the ratio of the slopes of the two segments.

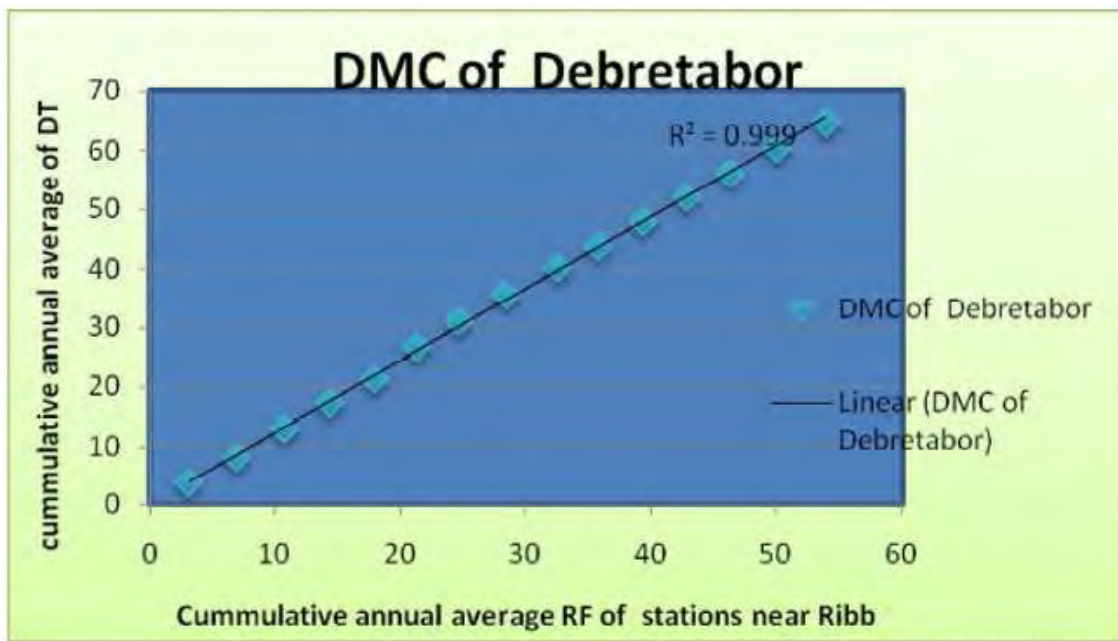


Figure 3-1 DCM of Debre Tabor Station Showing High Data Consistency

### 3.1.2 Determination of Areal Rainfall

Rain gauges represent only point sampling of the areal distribution of a storm. In practice, however, hydrological analysis requires knowledge of the rainfall over an area. The following methods are in use to convert the point rainfall values at various stations into an average value over a catchment:

These methods are the Arithmetic mean, the Thiessen polygon and the Isohyetal method etc. However, the Thiessen polygon was used for this study for its sound theoretical basis and availability of computational tools. But the method is dependent on a good network of representative rain gauges.



Figure 3-2 Thiessen polygon created from stations near Rib

#### Assumption

There is a linear variation in the precipitation between two gauge stations. The According to Thiessen, the average rainfall,  $R_{\text{areal}}$  over the area can be computed from:

$$R_{\text{areal}} = \sum_{i=1}^n \frac{R_i A_i}{A_t}$$

Where,  $R_i$  is the rainfall at station  $i$ ,  $A_i$  is the polygon area of station  $i$ ,  $A_t$  is total catchment area, and  $n$  is the number of stations. The area functions  $\frac{A_i}{A_t}$  are known as the Thiessen coefficients and once they are determined for a given stable station network, the areal rainfall can be computed for the set of rainfall measurements.

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

### 3.1.3 Flow data

Daily Flow data of Rib River is available from 1959 to 2006 at the ministry of water and energy. The data is collected at a gauging station which is located near Addis Zemen at 12o00” N and 37o34”E at elevation of 1795 m ASL.

#### *Data filling and consistency*

Missing flow data records for the sub basin is filled by developing correlation between the station with missing data and any of the adjacent stations with the same hydrological features and common data periods. Consistency and extension of flow data is analyzed by regression technique. The correlation equations used for Rib gauging station in terms of Gumera gauging station, which shows good correlation is expressed below.

Table 3-2 Correlation between Rib and other nearby Rivers

	GA	Gumera	Koga	Megech	Rib
GA	1	0.69	0.66	0.3	0.72
Gumera	0.69	1	0.59	0.33	0.74
Koga	0.66	0.59	1	0.25	0.64
Megech	0.3	0.33	0.25	1	0.34
Rib	0.72	0.74	0.64	0.34	1

Table 3-3 Equation relating the Gumera flows with the Rib River flow

	Rib	Gumera
Rib	1	0.32X+2.14
Gumera	2.3X+3.78	1

$$R=0.32G+2.14$$

Where R= missed flow value at Rib gage

G= flow value at Gumera gage

### Hourly time series data availability and filling

The hourly precipitation processing doesn't follow the same procedure as the daily precipitation does. This may be because of various cases. The absence of sufficient hourly gauging stations (synoptic stations) in the area is the major problem. The presence of hourly precipitation data at Bahir Dar gauging station is not enough to execute the hydrologic model for the study.

An hourly discharge data is also another problem. Although daily missed flow can be filled out by regression equation relating the neighbouring station to the gage in study, the hourly

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## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

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consideration doesn't hold true. For this research work the discharge data is developed from the rating curve. The rating curve developed as:

$$Q = \alpha * (h' - h_o)^b$$

Where a and b are constants, h'= water surface level and h<sub>o</sub>=level of the ground at zero flow.

Thus h' - h<sub>o</sub>= gage reading of depth of the water

The above equation can be rewritten as a liner equation

$$Y = C + BX$$

Where  $y = \log Q$  ,  $X = \log (h' - h_o)$  and  $c = \log \alpha$

The values corresponding to each of these constants was found from MoWE

a=2.15092, b=2.786876, h<sub>o</sub>=-3.609129

### 3.1.3.1 Frequency analysis

The objective of frequency analysis of hydrologic data is to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions (Chow, Applied hydrology 1988). The hydrologic data employed should be carefully selected so that the assumptions of independence and identical distribution are satisfied. In practice, this is often achieved by selecting the annual maximum of the variable being analyzed in our case the annual maximum discharge, which is the largest instantaneous peak flow occurring at any time during the year with the expectation that successive observations of this variable from year to year will be independent.

The flow data ministry of water and energy is used for this analysis, it ranges from 1959 to 2006. In order to maintain the independence and identically of the data series the annual maximum flow is selected as shown in appendix 1

#### 3.1.3.1.1 Probability distribution

Different probability distribution functions are used to compute the discharge for different return period. The magnitude  $X_T$  of a hydrologic event may be represented as

$$X_T = \bar{X} + K_T * s$$

Where  $\bar{X}$  is the mean discharge of the series.

$K_T$  is the frequency factor.

S is the standard deviation.

In the event that the variable analyzed is,  $Y = \log X$  then the same method is applied to the statistics for the logarithms of the data, using

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

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$$Y_T = \bar{Y} + K_T * S_Y$$

The frequency factor for different distribution is given by the following formula

### Extreme value I (EV I)

$$K_T = \frac{-6}{\pi} \left\{ 0.5772 + \ln \left( \ln \frac{T}{T-1} \right) \right\}$$

### Normal distribution

$$K_T = Z = w - \frac{2.515517 + 0.802853w + 0.010328w^2}{1 + 1.432788w + 0.189269w^2 + 0.001308w^3}$$

$$w = \left[ \ln \left( \frac{1}{P^2} \right) \right]^{1/2} \quad P = \frac{1}{T} \quad 0 < P \leq 0.5$$

When  $P > 0.5$ ,  $1-P$  is substituted for  $P$  and  $Z$  is given negative sign

### Log Person Type III distribution

$$K_T = z + (z^2 - 1)k + \frac{(z^3 - 6z)k^2}{3} - (z^2 - 1)k^3 + zk^4 + \frac{1}{3}k^5$$

$$k = \frac{C_s}{6}$$

The discharge corresponding to 10, 20,50,100,200,1000 return period using different distribution is shown in table 3.1.

Table 3-4 Discharge corresponding to different return period

Return period (T)	$X_T$ ( m3/s),EV I	$X_T$ (m3/s) Normal	$X_T$ (m3/s) Log pear III
10	180	179	179
20	204	195	201
50	235	212	229
100	258	224	251
200	281	235	272
500	312	247	299
1000	335	257	321

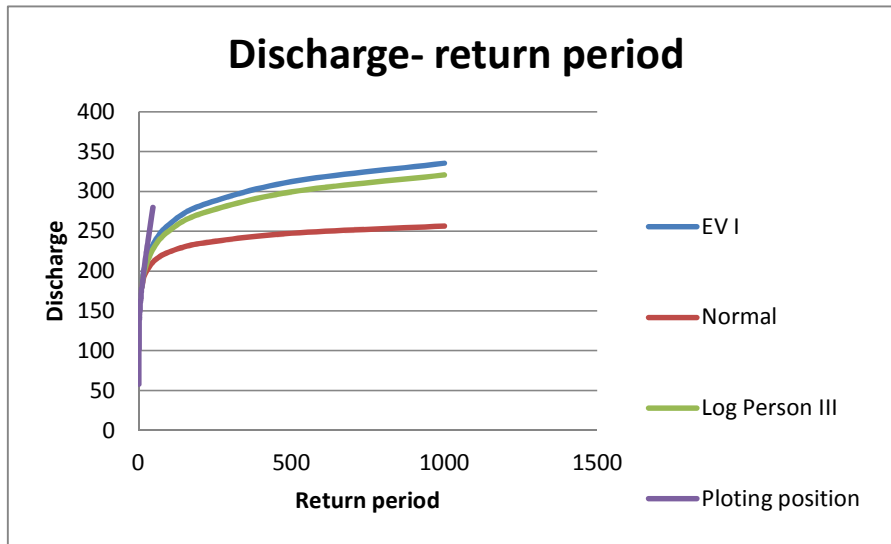


Figure 3-3 comparison of the flow values of the rib river

### 3.1.4 Digital Elevation data

The CCHE –MESH and CCHE-GUI uses different data type for development of mesh and to run the simulation. This include the 24-bit Bitmap image file, the topography database file (\*.mesh\_xyz), the measured cross section file (\*.mesh\_mcs), the ASCII coded Digital Elevation Model file (\*.asc), the shape files (\*.shp) and the CCHE geometry file (\*.geo), the block boundary file (\*.mesh\_mb).

For our case the development of mesh is undertaken by using the ASCII coded Digital Elevation Model file (\*.asc) and the shape files (\*.shp) which is done by The Riverside Technology, Inc In cooperation with its partners, Tropics Consulting Engineers (TCE) and Shebelle Consult.

#### ***THE ASCII coded Digital Elevation Model file.***

DEMs exist in grid (raster cell) format which can be displayed within Arc GIS. The quality of this data is based on its resolution, or cell size. The smaller the cell is, the greater the resolution and accuracy. However, the smaller the cell size, the greater the memory and computation requirements. The usefulness of DEMs for developing terrain models should be determined based on the cell size and the level of hydraulic analysis to be performed. The more approximate the analysis is to be, the greater the cell size that may be used. This can best be represented by TIN of the study area. The TIN is generated from the spot heights acquired from different sources in Arc GIS which included:

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

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- 1) GPS surveyed data collected along the two river banks, with good accuracy.
- 2) The spot heights of the flood plains taken from the surveyed data which extend approximately far from both the left and right bank stations and cover the floodplain if topography permits.
- 3) River bed cross section elevation data.

In two dimensional hydrodynamic modelling river and floodplain topography are represented as continuous surface. The representation of the river and floodplain is by the use of the TIN generated from the intersection of actual field data and the existing DEM of the study area. The TIN used for this research is done by The Riverside Technology, Inc In cooperation with its partners, Tropics Consulting Engineers (TCE) and Shebelle Consult. It is in high precision due to the availability of the field surveys on the Rib River channel which covers almost the entire reach. The surveyed data contains information about the river layers (centre line, right bank and left bank).The spot elevations are processed in Arc GIS to form shape files for the layers. When creating these shape files, there are meandering points which are in lack of data for further processing. The points are then filled with successive interpolation and with additional field surveys.

The TIN is then further processed to make it Compliant by the CCHE-MESH, which load topographic data in the form of ASCII coded Digital Elevation Model file (\*.asc).

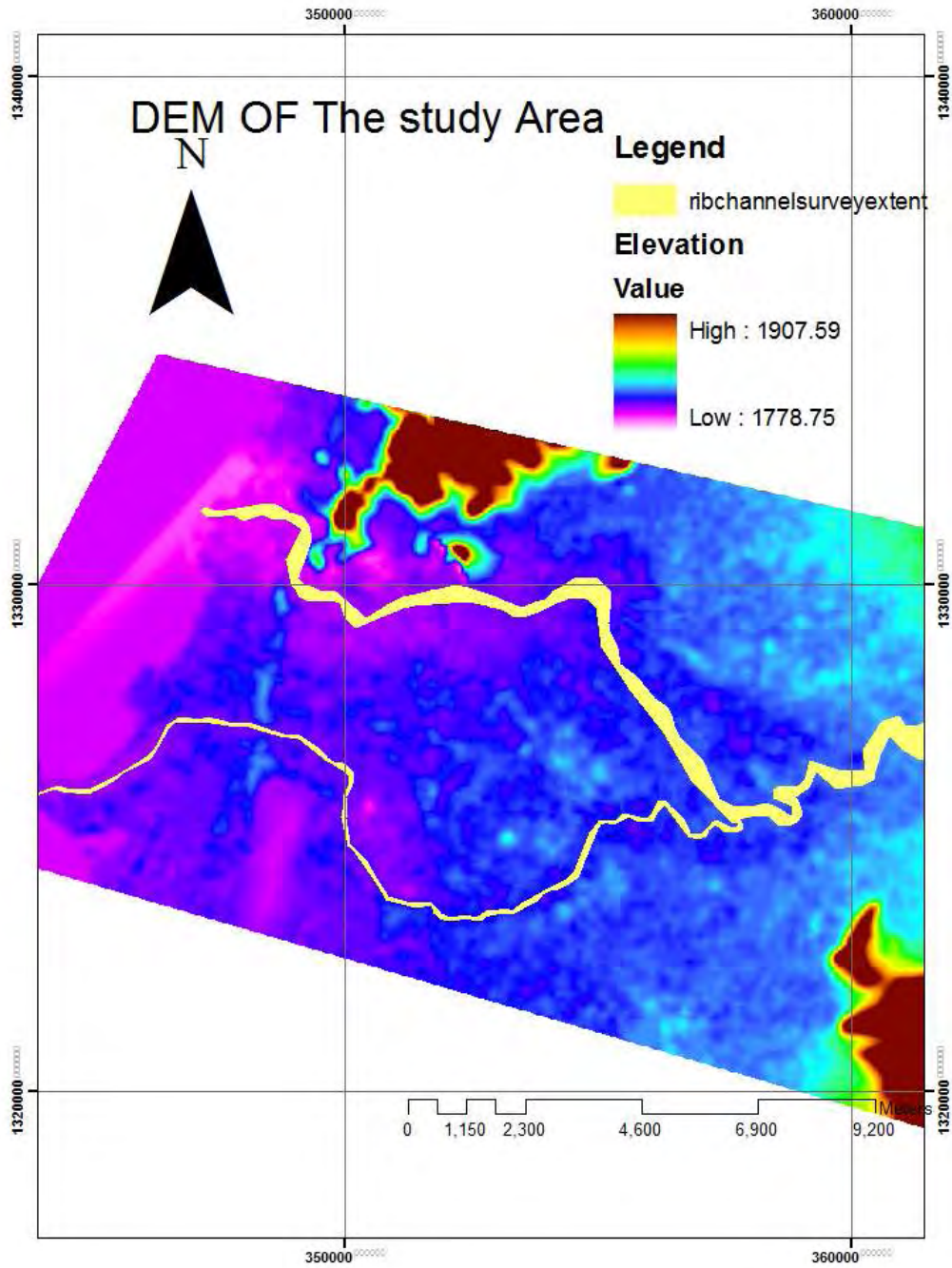


Figure 3-4 Digital elevation Model of the Fogera area (The Riverside Technology, Inc)

### *3.2 Hydrologic modeling with HEC-HMS*

HEC-HMS modelling may be taken considering different time series values such as daily, hourly, annually and even in minute. Accuracy of the model output is high if it is in reverse order. Although most flood studies are undertaken considering hourly time steps, there are cases where daily data are taken. In this paper both daily data by gage weight method and frequency storm method are considered to compare the output result for each. The first portion covers modelling on daily basis. The hourly data for the study area has only precipitation and flow value for one month. The rainfall has a full data for Bahir Dar station only thus making the result unreliable. Consequently, HEC-HMS outputs considering daily data using gage weight method and frequency storm method are used for further modelling approaches. Then the model output is compared with frequency analysis results which are selected by software called easy fit.

#### *Input data and model components*

The main input data used for HEC-HMS are:

- Areal precipitation,
- Evapo-transpiration (optional),
- Observed flow
- Base flow
- Different watershed characteristics.

HEC-HMS simulation is 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, sink and reservoir). The Basin Model stores information about the properties and connectivity of the objects in the schematic. The Meteorological Model contains time series information consisting of rainfall and evaporation data (optional). These data are associated with rain gages that the user defines in the Meteorological Model. The Control Specifications component defines simulation properties such as duration and time step.

The HEC-HMS model for the Rib catchment is done considering and dividing the sub-basin in to three sub-catchments. The calibrated model is used for runoff generation for different frequency storms. In this research paper the gage weight method is selected. The weights are specified by using Thiessen polygon created in ArcGIS9.3

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

### 3.2.1.1 Modelling By Frequency Storm Method

#### Using ERA Intensity -Duration-Frequency Curve

ERA has developed rainfall intensity-duration curves by dividing the country into different hydrological regions as shown below.

Table3-5 ERA Hydrological Regions

Meteorological Region	Station	Years of Record	Meteorological Region	Station	Years of Record
A1	Axum	18	B	Bedele	19
	Mekele	35		Gore	45
	Maychew	24		Nekempte	27
A2	Gondar	40		Jima	45
	Debre Tabor	22		Arba Minch	11
	Bahir Dar	35		Sodo	28
	Debre Markos	44		Awasa	26
	Fitche	25	C	Kombolcha	46
	Addis Ababa	33		Woldiya	23
A3	Nazareth	40		Sirinka	17
	Kulumsa	31	D1	Gode	29*
	Robe/Bale	19		Kebri Dihar	38
A4	Metehara	28	D2	Kibre Mengist	24
	Dire Dawa	46		Negele	45
	Mieso	35		Moyale	18
* max 24 hour rainfall not given				Yabelo	34

After the model is calibrating using the daily data series and the loss parameters are fixed ,the HEC- HMS model is simulated for rainfall intensity of 2, 10, 50, and 100 year return periods. The frequency intensity values are taken from the Ethiopian Roads Authority drainage manual (ERA 2002). Thus as the study area is found in A2 meteorological region the values for the return period are tabulated as shown in the model below.

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

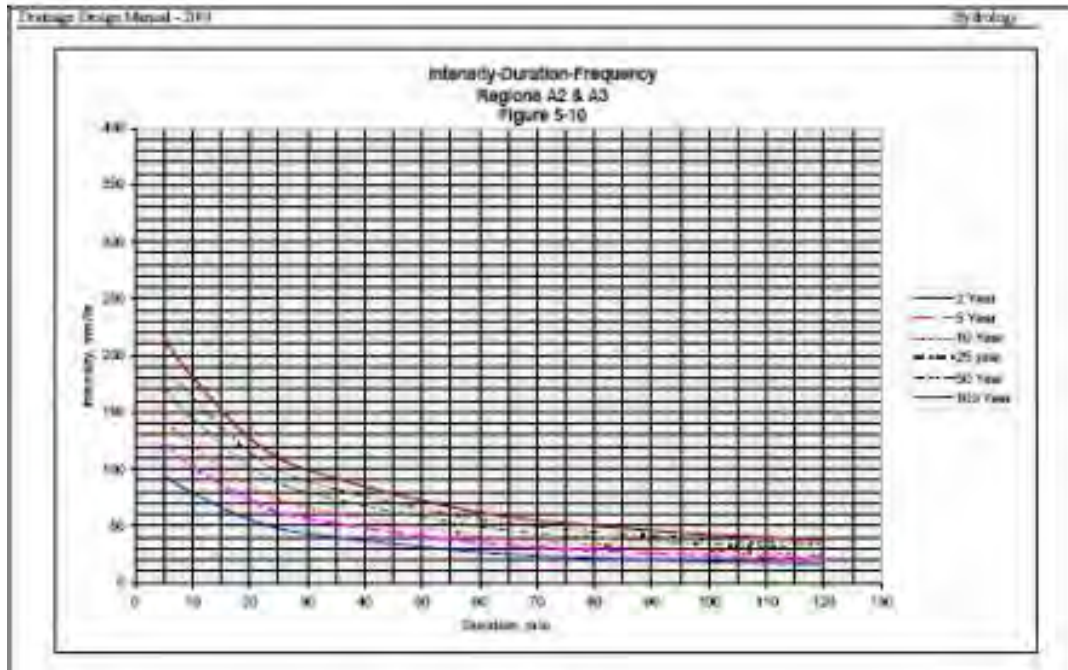


Figure 3-5 ERA Drainage Manual Rainfall Intensity-Duration Curves

The frequency intensity values are found from the Ethiopian Roads Authority drainage manual (ERA 2002).

Table 3-6 IDF table for the study area (ERA Drainage Design Manual, 2002)

D(hr)	RF depth with return period			
	2	10	50	100
1	27	41.5	55.7	62.5
2	32	49.8	66.7	74.2
3	37	57.1	72.1	81
6	45	66.1	78	90
12	50.2	72	84	93
24	52	74	88	94

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

### *Output of HEC-HMS by frequency storm*

The model has a capability to produce and generate values for different flow conditions (return periods). Given the above input parameters, the flow values are found accordingly. From the result table minimum peak flow for the Rib River is occurred for 2 year return period for 24 hour storm duration and the maximum obtained with 100 year frequency storm for the same duration. The value being  $91.8\text{m}^3/\text{s}$  and  $308.4\text{m}^3/\text{s}$  for 2 year and 100 year frequency respectively.

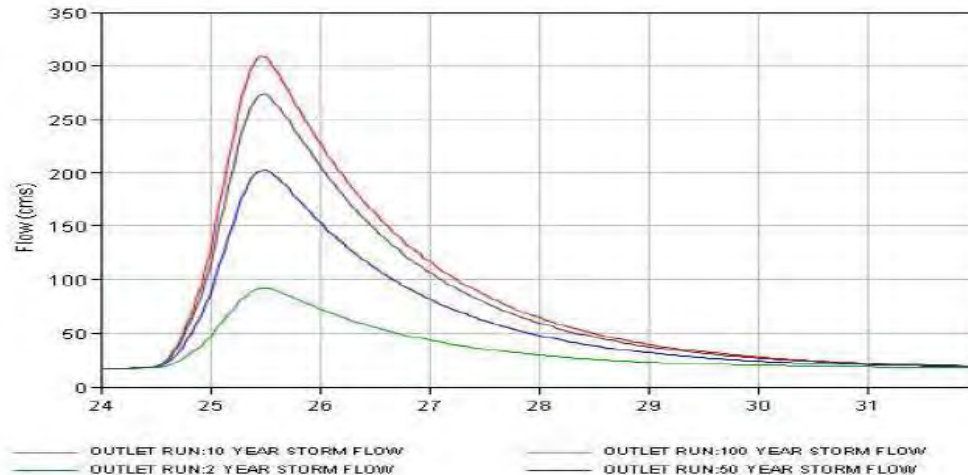


Figure 3-6 Frequency flow values of the Rib River for 2, 10, 50 and 100 year storms

Finally the HEC-HMS model result is compared with the frequency analysis results considering different techniques. The methods applied in this paper are selected based on their efficiency and simplicity. But the primary criterion is their correlation with the simulated flow data of the Rib River. They are selected using software called best fit for selection of methods. According to the output the following four popular methods are selected.

Table 3-7 Comparison of flow values (frequency analysis and the HEC-HMS)

Method		$Q_t(M^3/S)$		
		10	50	100
FA	EVI	180	235	258
	Normal	179	212	224
	Log pear III	179	229	251
HEC-HMS		202.4	273.1	308.414

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

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In the above figure the frequency discharge value derived using EV I method show high Similarity to the HEC-HMS. The other three are much lower than the result of the HEC-HMS. In most flood study, either the model result or that found by the frequency analysis may be taken based on different considerations. Previous studies and observations on the Rib River shows there is high transportation, accumulation and concentration of sediment. This may be due to the nature of soil near the River which is very loose. Frequent washing and sedimentation of the channel has the effect on the gage recoding of the river. The deviation on the gage reading due to this sedimentation and manual error results in less reliability of the historical data of the river. For the above mentioned and other minor cases, the HEC-HMS result is taken as a good representation of discharge scenarios for studies on and around the area.

### 3.3 Hydrodynamic numerical model (CCHE2D model)

#### Governing equations

The depth integrated two-dimensional equations solved in CCHE2D model are:

##### Continuity Equation:

$$\frac{\partial Z}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0 \dots\dots\dots 1$$

##### Momentum Equations:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial \eta}{\partial x} + \frac{1}{h} \left( \frac{\partial h \tau_{xx}}{\partial x} + \frac{\partial h \tau_{xy}}{\partial y} \right) - \frac{\tau_{bx}}{\rho h} + f_{cor} v \dots\dots\dots 2$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -g \frac{\partial \eta}{\partial y} + \frac{1}{h} \left( \frac{\partial h \tau_{yx}}{\partial x} + \frac{\partial h \tau_{yy}}{\partial y} \right) - \frac{\tau_{by}}{\rho h} - f_{cor} u \dots\dots\dots 3$$

Where u and v are depth-integrated velocity components in x and y directions, respectively; t is the time; g is the gravitational acceleration; η is the water surface elevation; ρ is the density of water; h is the local water depth; f<sub>cor</sub> is the Coriolis parameter; τ<sub>xx</sub>, τ<sub>xy</sub>, τ<sub>yx</sub> and τ<sub>yy</sub> are depth integrated Reynolds stresses; and τ<sub>bx</sub> and τ<sub>by</sub> are shear stresses on the bed and flow interface.

#### Turbulence Closure

In Equations (2) and (3), the Reynolds stresses are approximated based on Boussinesq’s assumption:

$$\tau_{xx} = 2v_t \frac{\partial u}{\partial x} \dots\dots\dots 4$$

$$\tau_{xy} = \tau_{yx} = v_t \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \dots\dots\dots 5$$

$$\tau_{yy} = 2v_t \frac{\partial v}{\partial y} \dots\dots\dots 6$$

### 3.3.1 CCHE 2D MODEL Components

CCHE2D model is an integrated package for two-dimensional simulation and analysis of free surface flow, sediment transport and morphological process. The model is developed at the National Centre for Computational Hydro science and Engineering (NCCHE), the University Of Mississippi School Of Engineering. The package is composed of a Graphical Users Interface (CCHE-GUI), a separate hydrodynamic numerical model (CCHE2D model) and a structured mesh generator (CCHE2D Mesh Generator).

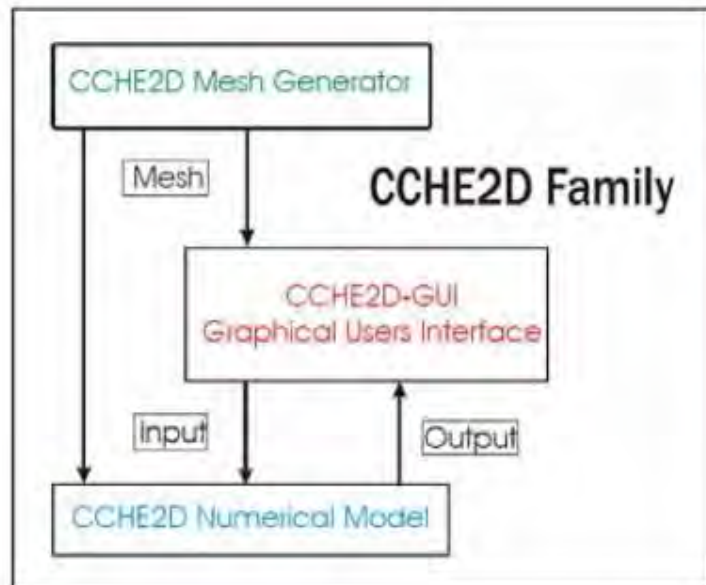


Figure 3-7 the CCHE2D model components

#### **CCHE2D Mesh generator**

CCHE2D Mesh generator allows rapid quality mesh generation from topography map and database. Also, it provides the users the file input and output (I/O) management, the algebraic mesh generation, the numerical mesh generation, the mesh editing, and the operation on topography database.

#### **Graphical user interface (GUI)**

GUI provides a convenient environment for input data preparation and model operation. It provides file management, run management, results visualization, and data reporting etc.

### 3.3.2 Model setup

#### 3.3.2.1 Mesh generation

Computational fluid dynamics (CFD) is based on solving a set of highly non-linear partial differential equations (P.D.E) on a physical domain, which is usually discretized and represented by a computational mesh. Despite the numerical method used, the success of solving this P.D.Es depends largely on the mesh quality. As the general academic criteria, the orthogonality and smoothness are often used to evaluate the mesh quality quantitatively (Yaixin Zhang and Yafei Jia, feb 2009). The adaptivity, referring to the control of the mesh density distribution according to the physics of a particular problem, is often required to evaluate the mesh quality (Yaixin Zhang and Yafei Jia, feb 2009).

The CCHE-MESH is a 2D structured mesh generator with professional and friendly graphical users interface. It allows rapid quality mesh generation from topography map and database. And, it provides the users the file input and output (I/O) management, the algebraic mesh generation, the numerical mesh generation, the mesh editing, and the operation on topography database.

The methods applied in the structured mesh generation are grouped into two categories: the algebraic methods and the numerical methods. The numerical methods solve a set of P.D.Es to determine the mesh distribution while the algebraic methods generate mesh directly by interpolation.

In practice, the algebraic method, numerical method and multi-block method are used in combination to take the advantage of each other. The interactive GUI is important to make the combination efficiently.

In this research 3 blocks are created to represent the river channel and flood plain. The two blocks represents the flood plain above and below the river channel and the third block represents the river channel.

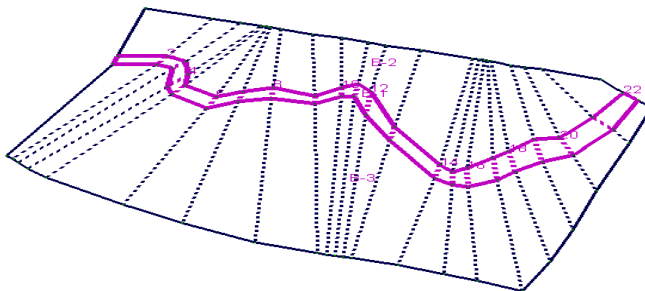


Figure 3-8 blocks of the study area

### 3.3.2.2 Algebraic Mesh Generation

The algebraic generator adopted here is to create the mesh points in the computational domain by interpolating the nodes according to the nodal distribution along the boundaries of the domain. Stretching functions are used to distribute computational nodes along boundaries with several control parameters. The distribution for a specific problem should be determined according to the conditions of flow, boundary shape, etc. Interpolation is simply to connect the corresponding nodes along opposite sides with straight lines. Fast computation and direct control of mesh nodes are the two main advantages of the algebraic mesh generation which interpolates the interior mesh nodes directly from the boundaries.

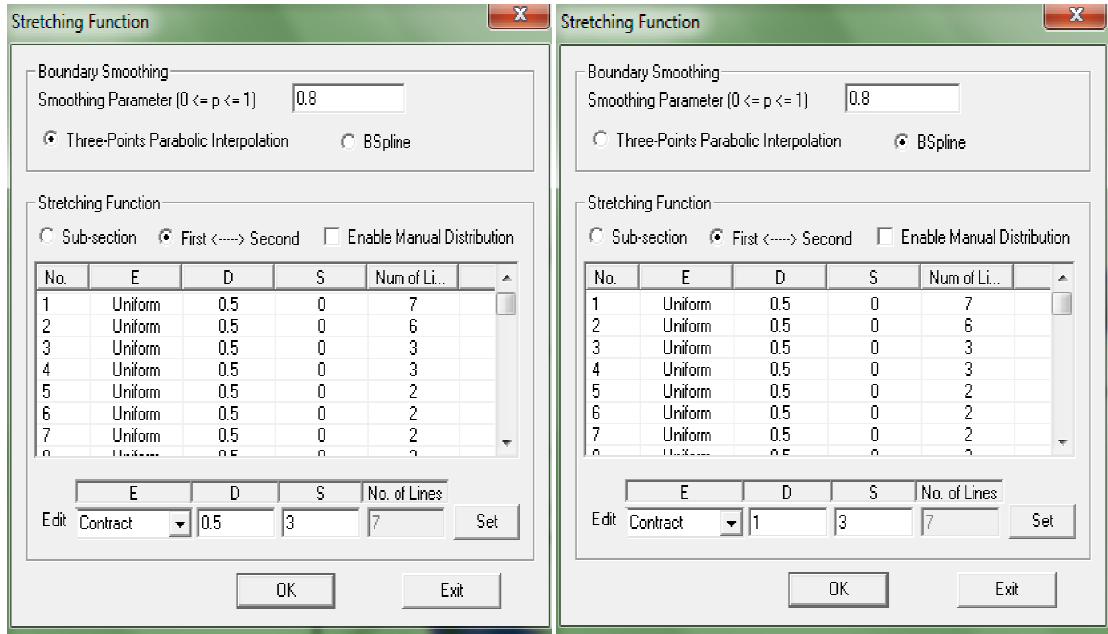
In this research the version of CCHE mesh generator, an improved more flexible and powerful two-direction stretching function is used.

$$S_j = \sum_1^{j-1} \left[ \frac{2}{\exp(\phi) + \exp(\phi)} \right]^E / \sum_1^{N-1} \left[ \frac{2}{\exp(\phi) + \exp(-\phi)} \right]^E$$

$$\phi = \left[ \frac{j-1}{N} - D \right] * S$$

Where  $S_j$  is the relative location;  $j$  is the label of one point;  $N$  is the total number of points along a mesh line;  $E$  ( $= -1, 0, 1$ ) is the exponential parameter;  $D$  ( $0 \leq D \leq 1$ ) is the deviation parameter;  $S$  ( $>0$ ) is the parameter used to control the degree of stretching, called scale parameter.

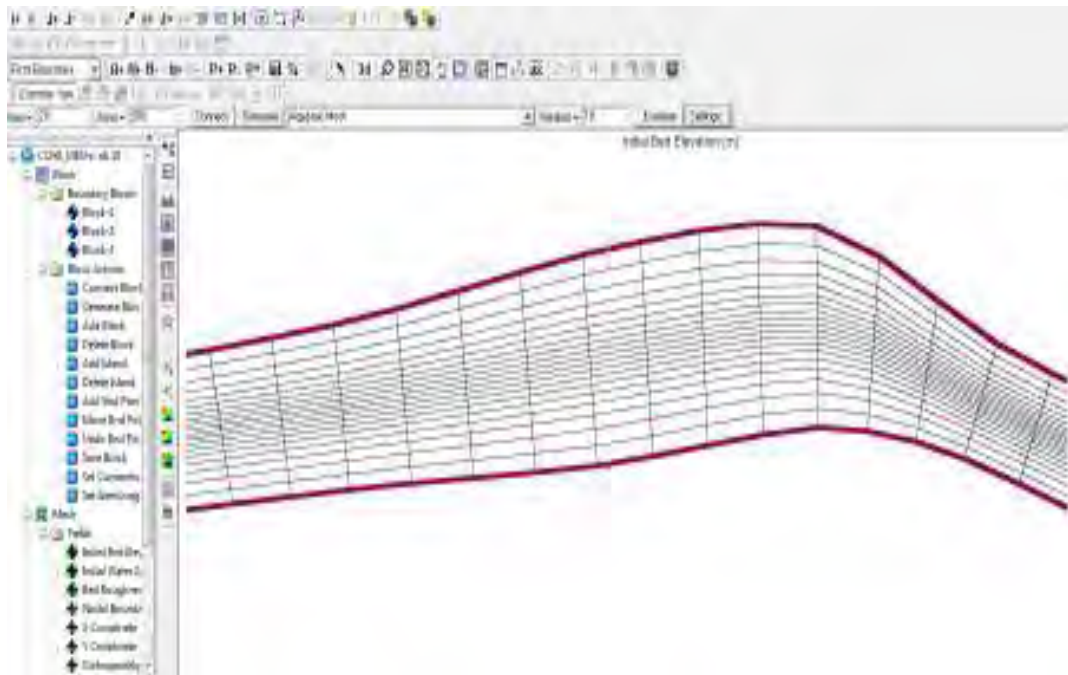
## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER



a)

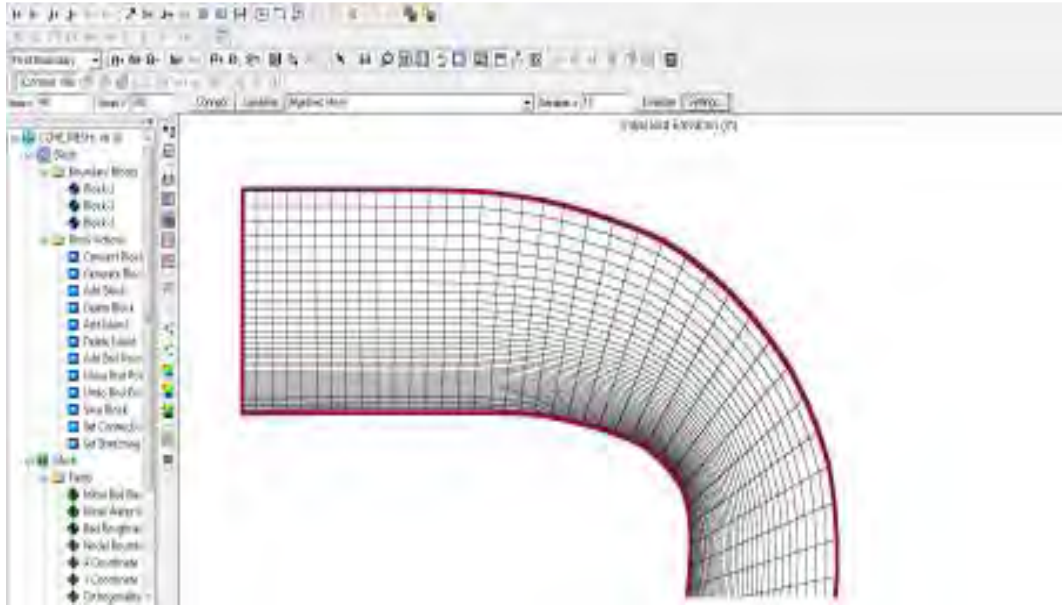
b)

Figure 3-9 Stretching function values for a) rib channel, b) flood plain



a)

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER



b)

Figure 3-10 mesh distribution for the above stretching function values

In this research Channel elements describing the meandering rib river is discretized separately from those comprising the model floodplain. Firstly, at least three elements can be guaranteed to span the width of the channel to crudely capture variations in bathymetry and flow velocity (Bates et al., 1995). Secondly, having fixed the number of elements across the channel, the elements can be elongated in the downstream direction, which reduces the number of elements both in the channel and on the floodplains.

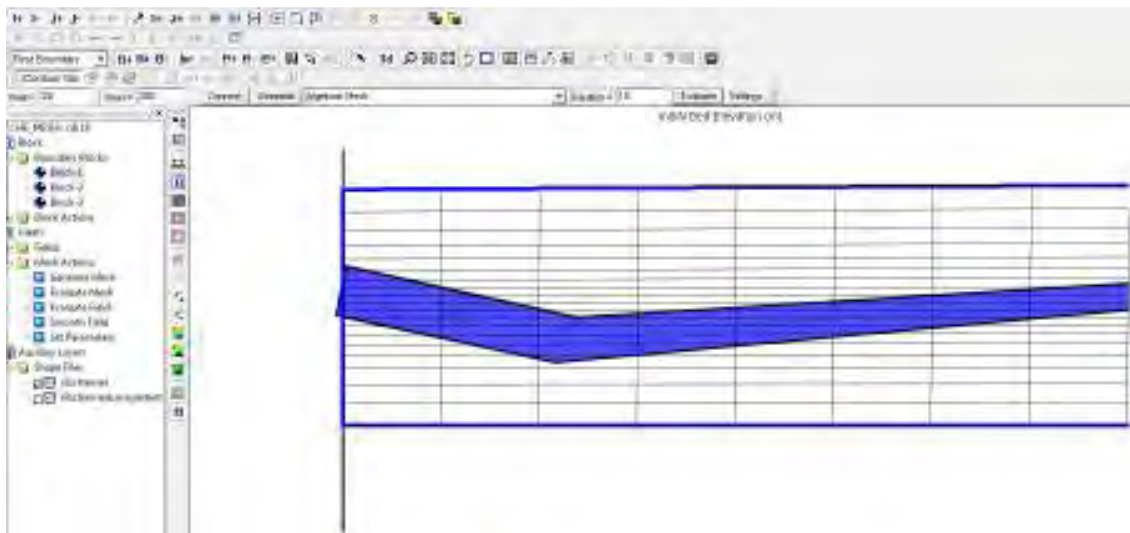


Figure 3-11 elements spanning the width of the channel

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

The mesh to represent Channel elements for the rib catchment is divided in to two component one representing the channel and the other representing the flood plain.

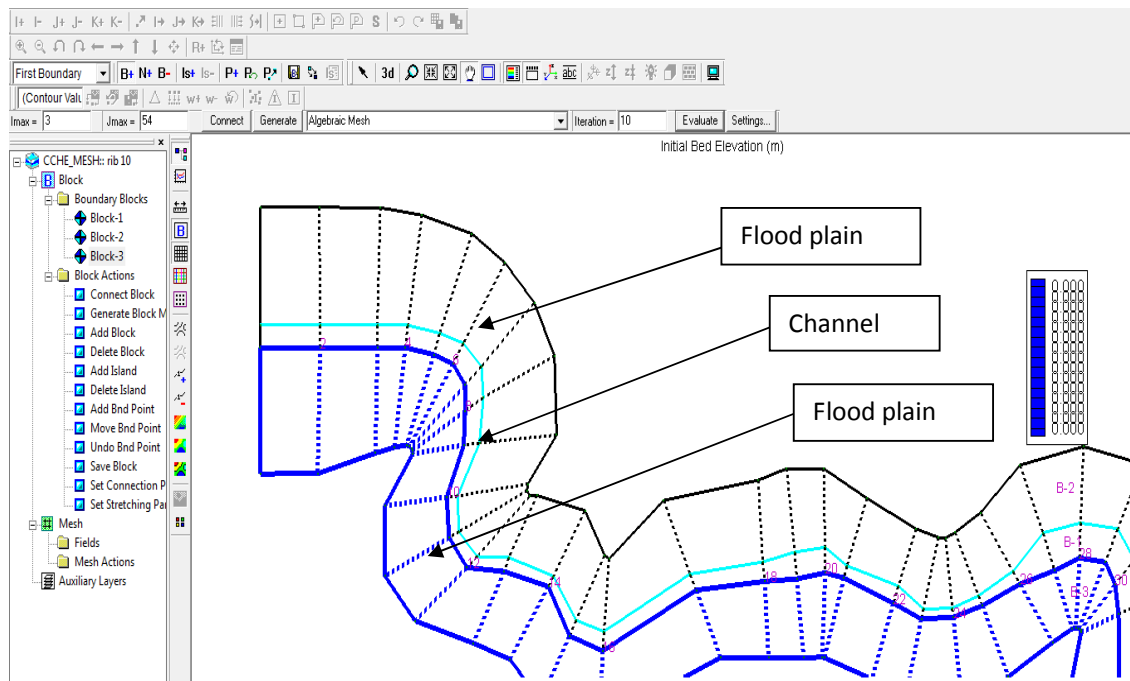


Figure 3-12 blocks representing the flood plain

### 3.3.3 Numerical Mesh Generation

Compared to the algebraic mesh generation, the numerical mesh generation is more sophisticated and thus can produce more reliable meshes with higher quality. The disadvantages lie in two aspects: (1) it requires more computation efforts, and (2) it is more difficult to use. In the numerical mesh generation, a set of P.D.Es is solved to obtain the desired mapping between the physical domain and the computational domain. The P.D.E systems used for the numerical mesh generation include the elliptic systems, the hyperbolic systems, the parabolic systems and the Variational Laplacian systems (Yaixin Zhang and Yafei Jia, feb 2009).

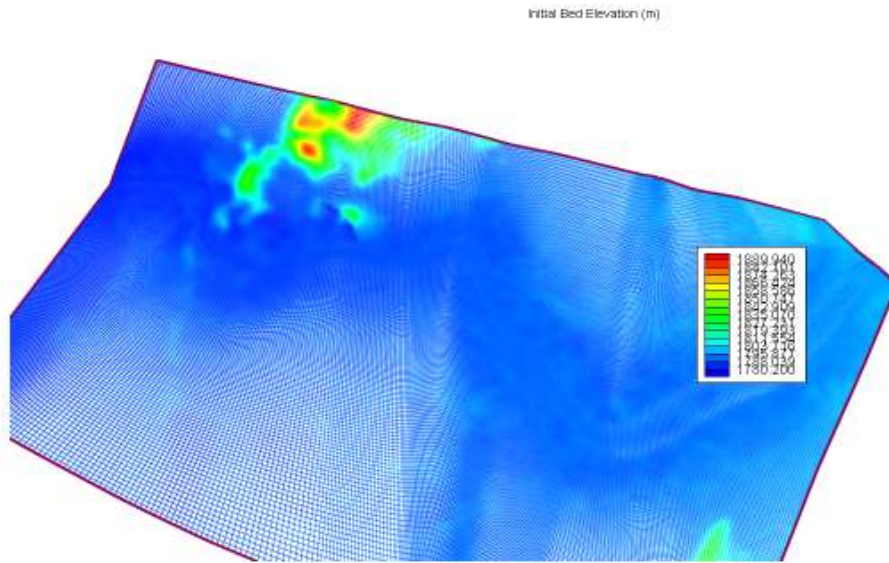


Figure 3-13 Mesh with interpolated bed elevation values

### **3.4 Boundary and initial conditions**

The hydrodynamic model uses the essential boundary conditions, velocity vectors are specified along inlet(s), outlet(s) and wall boundaries and water surface elevation are needed to be specified along the computational domain. Three boundary types, inlet, outlet and solid walls are of the most importance, and they are discussed separately.

#### **3.4.1 Inlet Boundary**

##### **3.4.1.1 Steady State Simulation**

###### **Specifying Total Discharge**

For simulation the river the velocities at the inlet cross sections are to be specified. This can be specify either the discharge per unit width,  $q_i$  at each node across the inlet cross-section, or the total discharge,  $Q$  which is distributed automatically in the inlet sections as unit discharges. In both cases, the unit discharge is then converted to the velocity components along the cross-section. In our case a total discharge corresponding to 100 years return period flood and peak discharge for august 2006 is specified along the inlet as an inlet boundary.

##### **3.4.1.2 Unsteady state simulation**

###### **The discharge hydrograph**

When unsteady flow is studied, the discharge at the inlet is specified a function of time. The hydrograph for this kind of simulation was developed using the rainfall –runoff model called HEC-HMS. The discharge hydrograph corresponding to different return period flood is specified at the inlet of the hydraulic model.

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

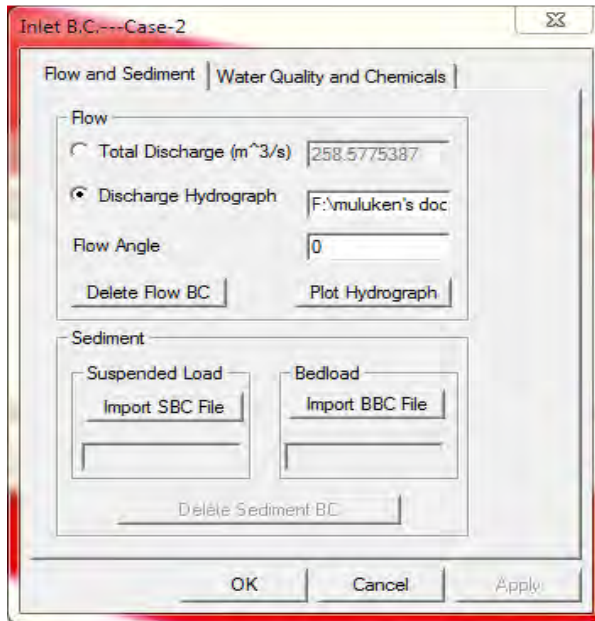


Figure 3-14 Inlet boundary condition

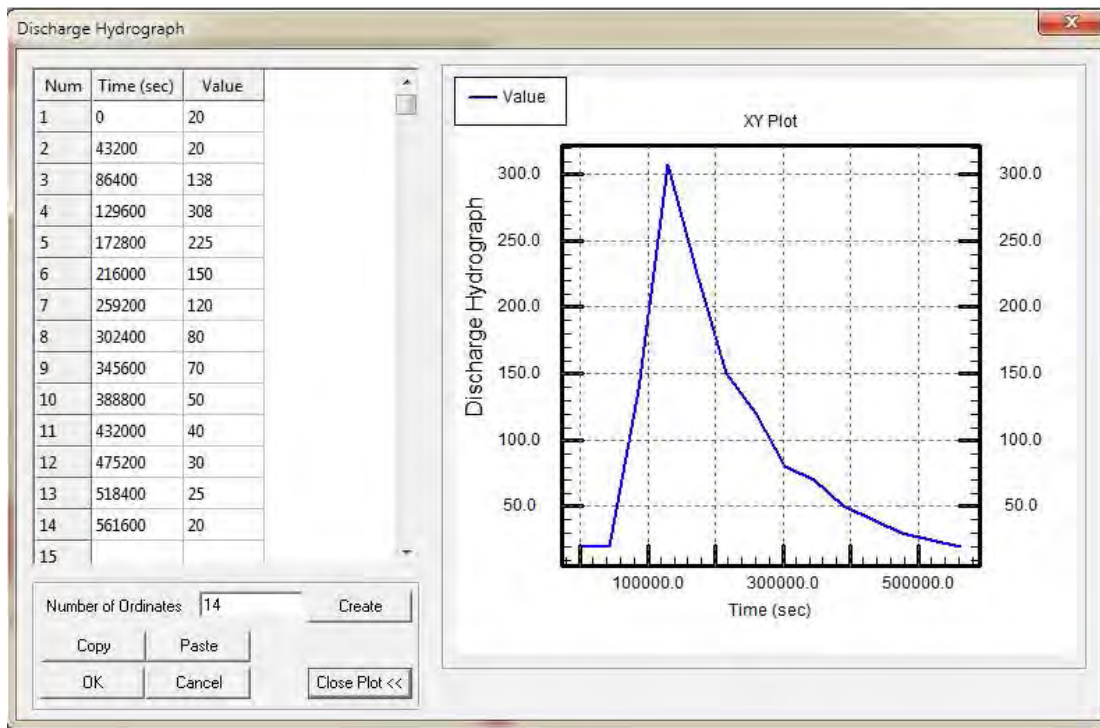


Figure 3-15 the discharge hydrograph at the inlet for 100 year return period

### 3.4.2 Outlet Boundary

#### Constant water surface elevation

For all applications seeking for steady state solutions, the water surface elevation along the outlet section are usually set to be a constant value across the section, that is

$$\eta = \text{constant}$$

The water level of Lake Tana, which is collected twice a day at a gauge, located in Bahir Dar at 11°35'' N and 37°22'' E, is selected for outlet boundary. An average value of 1788 m ASL is taken for our analysis.

### 3.5 Initial Conditions

Initial values for all the flow variables  $u$ ,  $v$ , and  $\eta$  are necessary for starting a simulation. The CCHE2D model can either assign values to these variables or use previous solution as the initial condition depending on how the simulation is started.

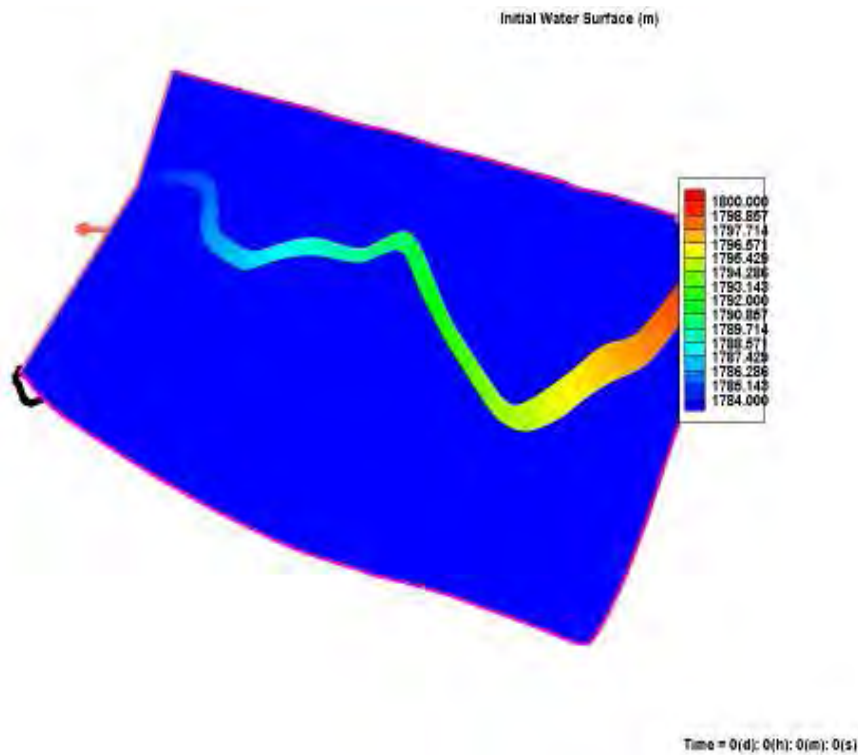


Figure 3-16 initial water surface level

### 3.6 Surface roughness

Surface roughness values as required by the model have been derived from land use map of the floodplain and from the properties of river bed material. The land use type which is dominant is cultivated area and the river bed material is dominantly clay. The river bed consists of sedimented clay particles and causes much less friction to flow as compared to the floodplain. To setup the model a manning roughness coefficient value of 0.03 for floodplain and 0.02 for river bed is used.

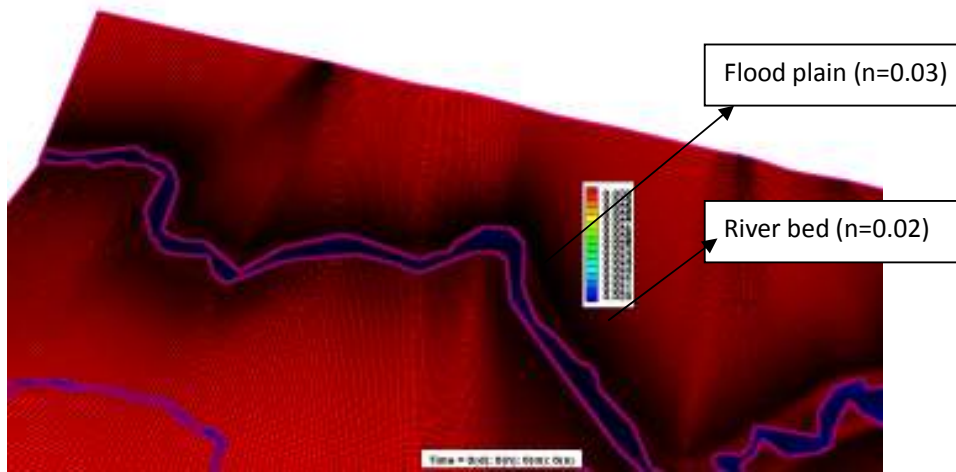


Figure 3-17 initial water surface level

### Parameter setting

The flow parameters consist of Simulation parameters, Bed Roughness parameters and advanced parameters

Simulation Parameters, the parameters are divided into five groups

#### ***In group Time Step,***

*Simulation time* (s): the total time period in seconds of the simulation. In case of steady flow, this time should be sufficient so that a steady solution could be achieved

*Time step* (s): the step for time marching of the simulation.

***In group Time Step for Output,*** you can set the step intervals to output results into the Intermediate File, the History File, and for the Monitor Points, and set the step intervals for screen outputs indicating Convergence process.

#### ***In group Turbulence,*** there are three Turbulence Model Options

For Parabolic Eddy Viscosity Model and Mixing Length Model, you can set the Turbulence viscosity coefficient. This coefficient serves as a multiplier, i.e., a value of 10 means that the

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

turbulent viscosity is 10 times that computed from the selected turbulence model. Although normally it equals 1, this coefficient has been tested in a range of [0.1, 1000].

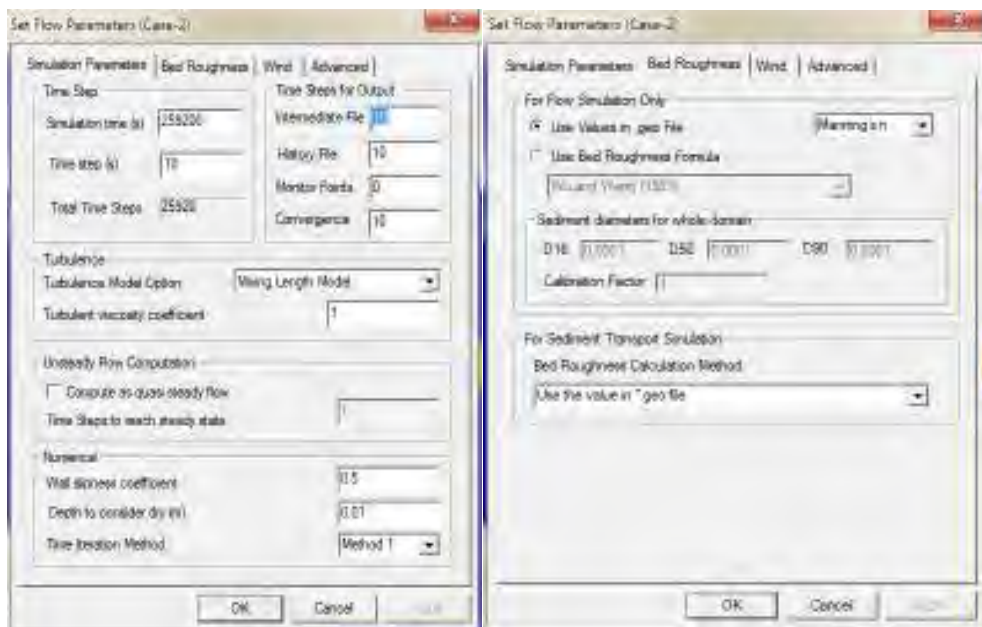
***In group Unsteady Flow Computation***, you can choose to compute as quasi-steady flow instead of the real unsteady flow.

### ***In group Numerical***,

**Wall slippness coefficient:** It is used to specify the wall boundary condition at no-flow boundaries. A value of 0.0 means no slip condition and a value of 1.0 means total slip, i.e., tangential velocity at no flow boundaries is allowed. A value between 0.0 and 1.0 would mean partial slip. A value greater than 1.0 signals the application of log-law. The log-law boundary condition allows partial slip; however, the shear stress is accurately predicted.

***Depths to consider dry (m):*** It is used to determine the wet and dry nodes. The minimum water depth above it used to consider a node to be wet, while the water depth below that value would make a node dry.

***Time Iteration Method:*** This parameter provides information about the number of internal iterations per time step. The Method 1, Method 2 and Method 3 mean small, medium, and large number of iterations per time step. The actual number is set by the computational model. The value should be based on the time step size, i.e., if the time step size is large the iteration control flag should be set to a higher value.



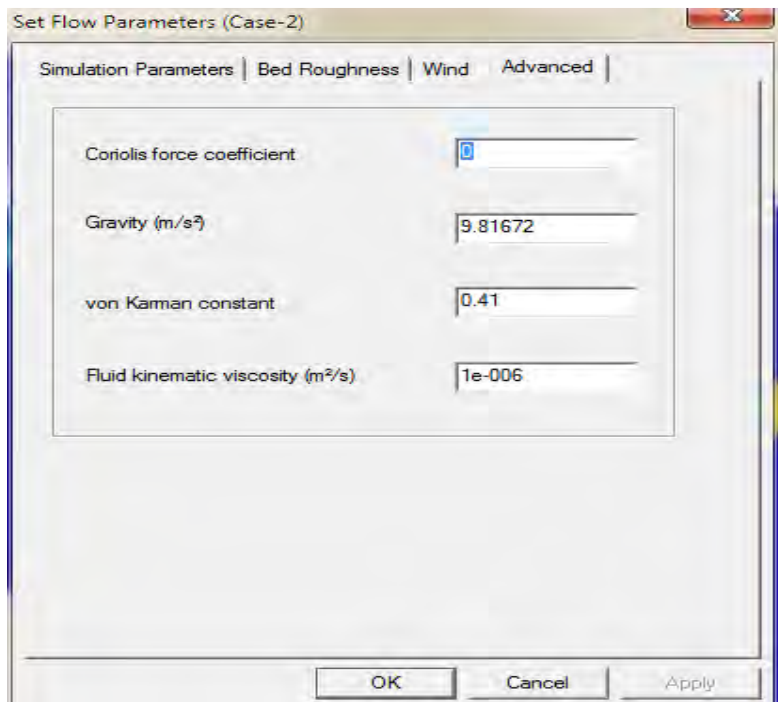
**A: simulation parameters**

**b: bed roughness**

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

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In page **Advanced**, there are four parameters, namely, *Coriolis force coefficient*, *gravitational acceleration*, *von Karman constant* and *kinematic viscosity of fluid*, with default values that suffice for most cases.



### C: Advanced parameters

Figure 3-18 parameter



### 4 Model Results and Discussion

Numerical model is developed under certain assumptions; the results should be reliable if the simulated flow satisfies these assumptions. However, the natural is always complicated; these assumptions could never be satisfied one hundred percent.

#### 4.1 VALIDATION

In order to assess the accuracy of the terrain model and floodplain map, they must be validated against independent data sources.

##### 4.1.1 Comparison of simulated inundation

It is very important to evaluate the model for its capability in predicting the flooding.

###### 4.1.1.1 MODIS flood map

Flood inundation maps for the study area are available from the dart mouth flood observatory (DFO). For this study the MODIS rapid response inundation map 3 of the August 2006 flooding in Lake Tana is obtained from the DFO archive and is referred to as the master index of rapid response inundation maps 2006 and 2008 glide number FL- 2006-000123-SDN. This map was acquired under no cloud cover. The Figure below shows the inundation map of the flooding in August 14 (in dark) and August 19 (in gray) 2006 obtained from DFO. For the purpose of GIS analysis with the simulated results the inundation map is geo referenced.

For the purpose of comparison with MODIS inundation the rib river reach is divided into two flooding zones. the first zone is the area in the upstream reach of the river in which flooding is mainly governed by the rib river flow discharge and the second zone is the area in the middle and lower reach of the river where flow is governed by the river ,the lake and flow from the surrounding catchment. As a result, the first zone is considered for the purpose of comparison with MODIS inundation map.

The inundation created by case 1 simulation is compared against the MODIS inundation map. The simulated flooding extent in the comparison zone is 10 km<sup>2</sup> and extends 4 and 3 km from right and left bank respectively. On the contrary the extent in MODIS inundation map is 29.6km<sup>2</sup> and extends 6 and 5 km from right and left bank respectively. The comparison results indicate that 34 % of the MODIS flooding extent is explained by the flood extent simulated from the flow of the rib river.

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

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The flood map obtained from MODIS inundation map is much larger than the model simulation. This difference can be from the following possible reasons.

- i. MODIS inundation map may over estimate the flooding extent just by reporting some wetted surface as a flood area
- ii. The effect of rainfall on the flood plain is not modelled. Usually flood plain area is characterized by low infiltration rate ( $< 5\text{mm/day}$ ). Therefore, this produces significant flooding due to direct rainfall.
- iii. The contribution of ungauged flows to the flooding is not modelled due to lack of data and complexity of the analysis.

Although the model simulation is able to predict the flooding accurately, there might be some miss- much when we compare it with other real time data due to the complexity of the nature. However, the difference could be acceptable regarding the possible results stated and the complexity of modelling nature accurately.

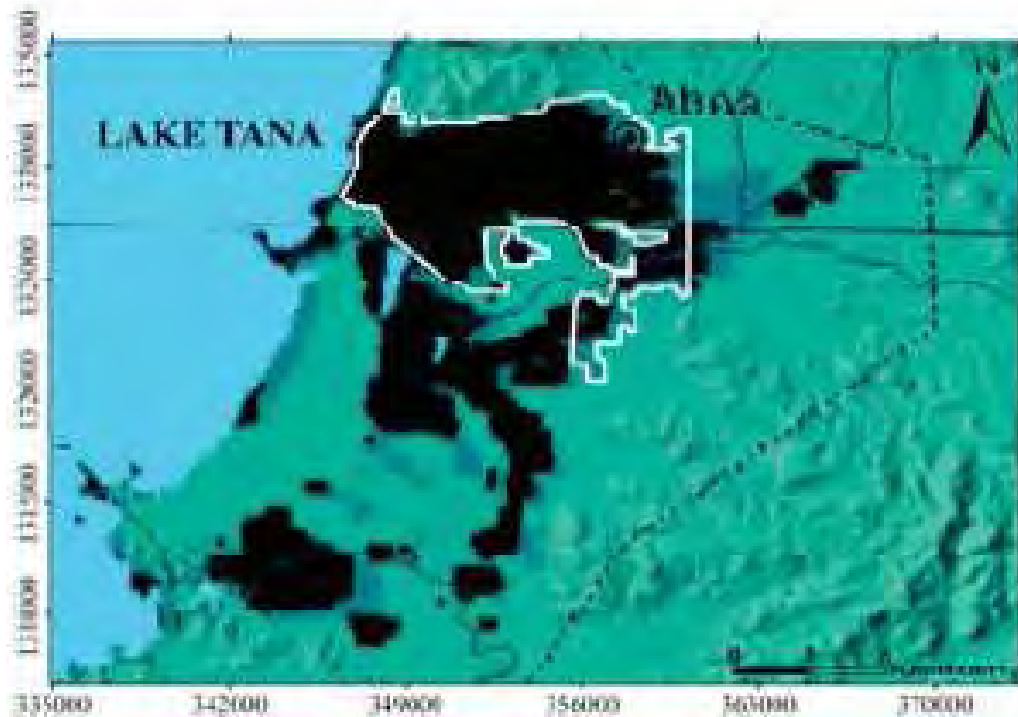


Figure 4-1 geo referenced Lake Tana rapid response inundation map (Dartmouth flood observatory, 2006)

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

### 4.1.1.2 Comparison of the model result with other model results

A similar study was conducted by Zelalem Abera on the rib river using HEC-RAS, a hydraulic model developed by the Hydrologic Engineering Centre (HEC) of the U.S. Army Corps of Engineers. Although, the model has some basic difference from the model I use it can be used in the case of limitation of verification data.

The results of the HEC-RAS model by Zelalem for A 100 Years flood for the different land use types is shown on the figure below.

Table 4-1 Land use in risk and respective flood depth (100 year flood)( Zelalem 2011)

Land use	Depth of flood	% covered	Area (km <sup>2</sup> )
Agricultural	0-0.4	32.30	6.4
	0.4-0.8	37.62	7.45
	0.8-1.4	18.08	3.6
	1.4-2.4	9.23	1.8
	2.4-6.2	2.77	0.5
<b>Total</b>		<b>100</b>	<b>19.8</b>
Agro-pastoral	0-0.4	23.2	0.55
	0.4-0.8	38.8	0.92
	0.8-1.4	30.5	0.73
	1.4-2.4	3.70	0.088
	2.4-6.2	3.80	0.09
<b>Total</b>		<b>100</b>	<b>2.385</b>
River	0-0.4	0	0
	0.4-0.8	57.9	0.18
	0.8-1.4	32.5	0.102
	1.4-2.4	0	0
	2.4-6.2	9.6	0.03
<b>Total</b>		<b>100</b>	<b>0.315</b>

A comparison has done on the flood simulation results of the 100 years return flood. As it is shown in the Figure 4.2 and Figure 4.3 below, there exists similar general trend. For instance, for 100 year storm event, the HEC-RAS result shows depth of the flood ranges from 0m-6.24m and the flood extent also stretches to about 4km having 2km from each side. Similarly, CCHE2D results reveals the flooding has a depth lower than 6 m which extends 4 KM and 3 KM outside right bank and the left bank of the main river respectively. In addition, both

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

models results shows most of the catchment area has a flood depth less than 1M and higher flood depths of 6M shares only 0.03% of the total flooded area.

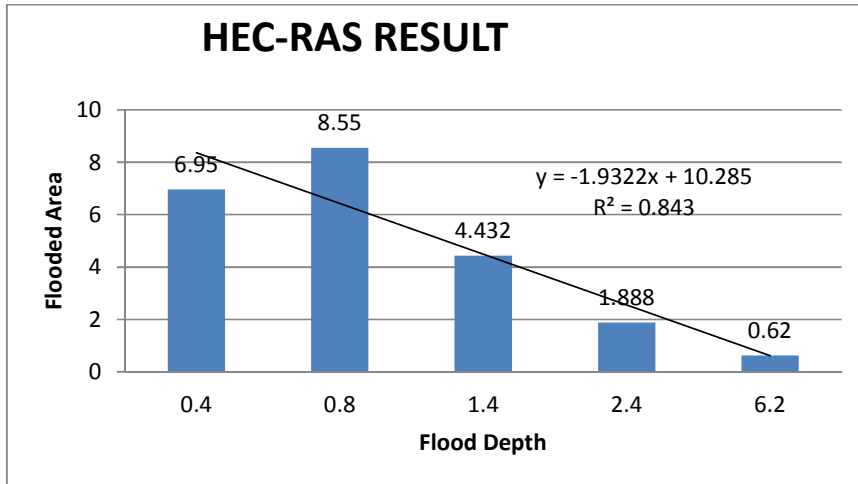


Figure 4-2 HEC-RAS output of 100 year flood

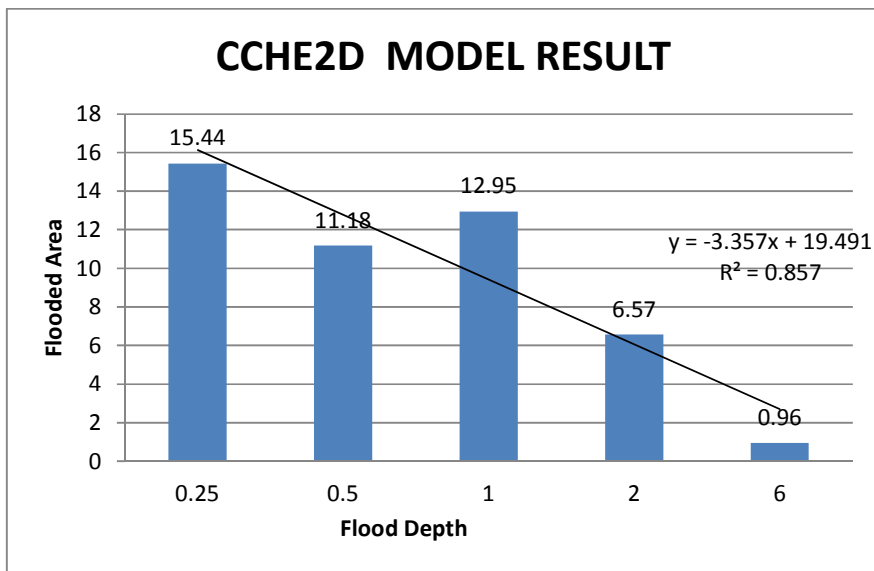


Figure 4-3 CCHE2D output of 100 year flood

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

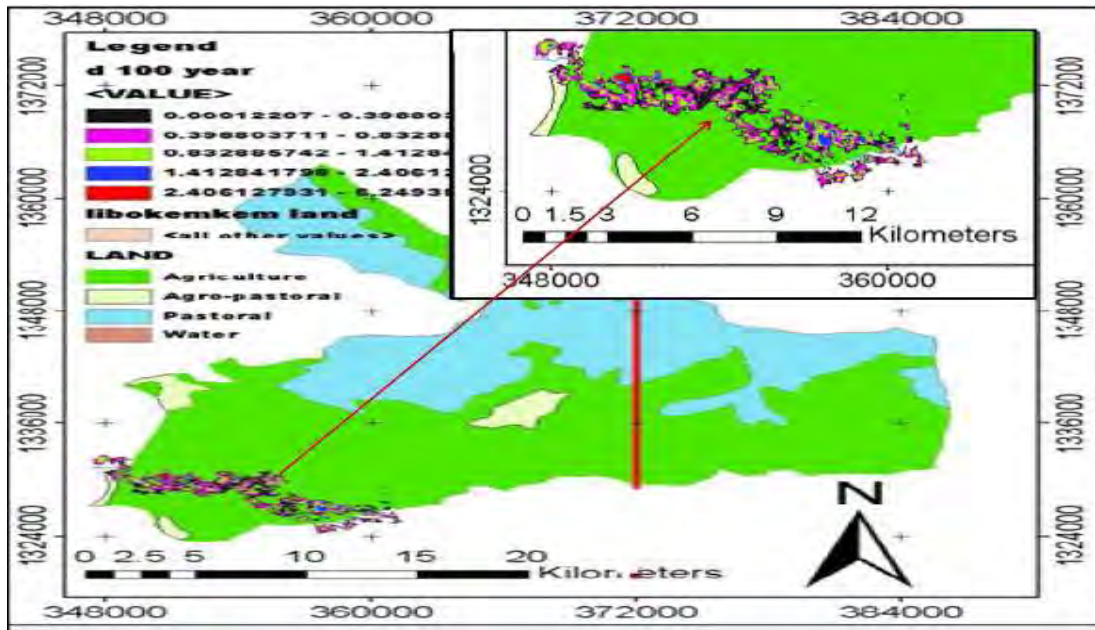


Figure 4-4 Risk map of the Libo Kemkem and Fogera Woreda by 100 year flood( (Zelalem 2011)

According to Zelalem’s risk map, most flood depths are in range of 0.4m-0.8m which covers 38% of the total flood extent. The next highest portion is covered by 0m-0.4m which is about 32%. Other flood depths 0.8m-1.4m, 1.4m-2.4m and 2.4-6.2m takes in decreasing proportion. Similarly, the CCHE2D model results about 32% of the area have depth less than 0.25m And around 50% of the area has depth between 0.5m and 1m. This suggests the results of the models have nearly the same tend with small deviation.

However, the total area of flooding developed by each model differs significantly, the total area of inundation for the CCHE2D model is around 50km<sup>2</sup> but it is only around 25 km<sup>2</sup> which is almost half of the flooding expressed by the CCHE2D model. This may be due to model makeup variation as The HEC-RAS is a one dimensional model and CCHE2D is a two dimensional model. Usually One dimensional approach is computationally efficient but it lacks the simulation of transverse dynamics of flood wave, it doesn’t represent floodplain storage, topography is discretized as a cross section rather than a surface and the orientation of the cross section is defined subjectively

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

### 4.2 Simulated flood extent, level, depth and velocity

Maps of flood extent, level, depth and velocity are developed using 100 years return periods flood. The figure below shows the inundation created by case 2 simulation for the 100 year return period flood. This period flood has the inundation area of 47.13km<sup>2</sup> while the simulated flood extent has flood depths less than 5.88m. The depth between 5.88m and 2m is located along the river channel and on the pond which is located south of the rib river. However, the depths below 2m exist largely on the flood plain which extend 4km and 3 km outside right bank and the left bank of the main river respectively. The simulated water level ranges between 1798.42m ASL at the upstream and 1788m ASL at the downstream end of the main river. The simulation result indicates much of the flooding occur in the middle part of the river where the flow behaviour is mainly dominated by the inflow from the rib river. The flooding in the downstream part of the river is mainly dominated by the lake water level and the ungauged catchments of the neighbouring area which.

Another important magnitude for flood analysis is the velocity of flow. The simulated velocity of the rib river varies significantly from the centre of the channel where it is between 5.8m/s and 1.5m/s to the flood plain where it exhibits nearly tranquil state as it is shown in the fig below.

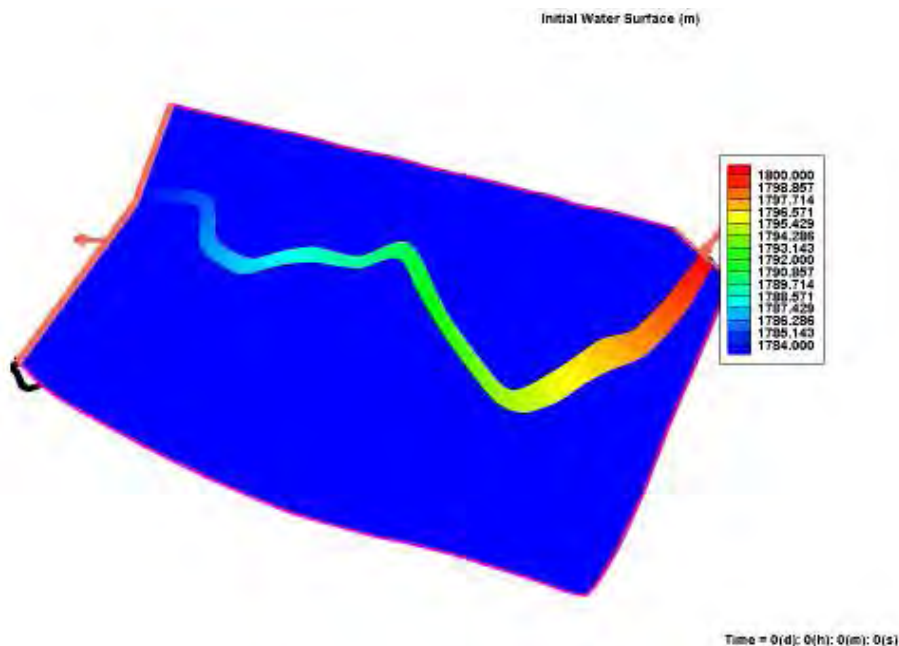


Figure 4-5 initial water surface

# 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

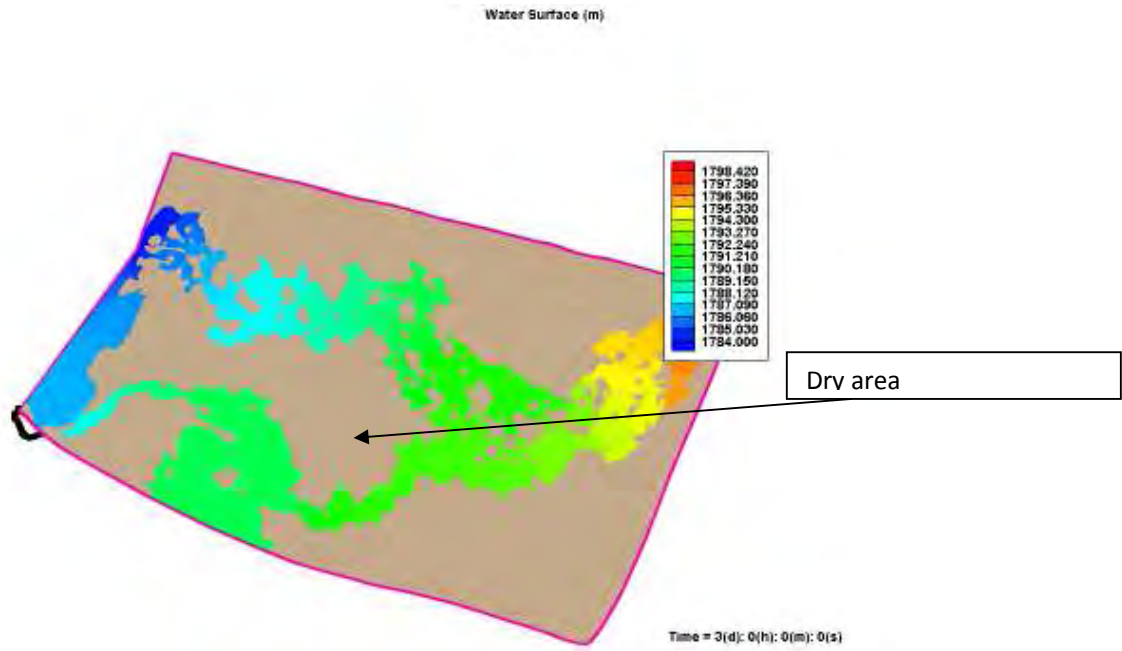


Figure 4-6 water surface for 100 year return flood

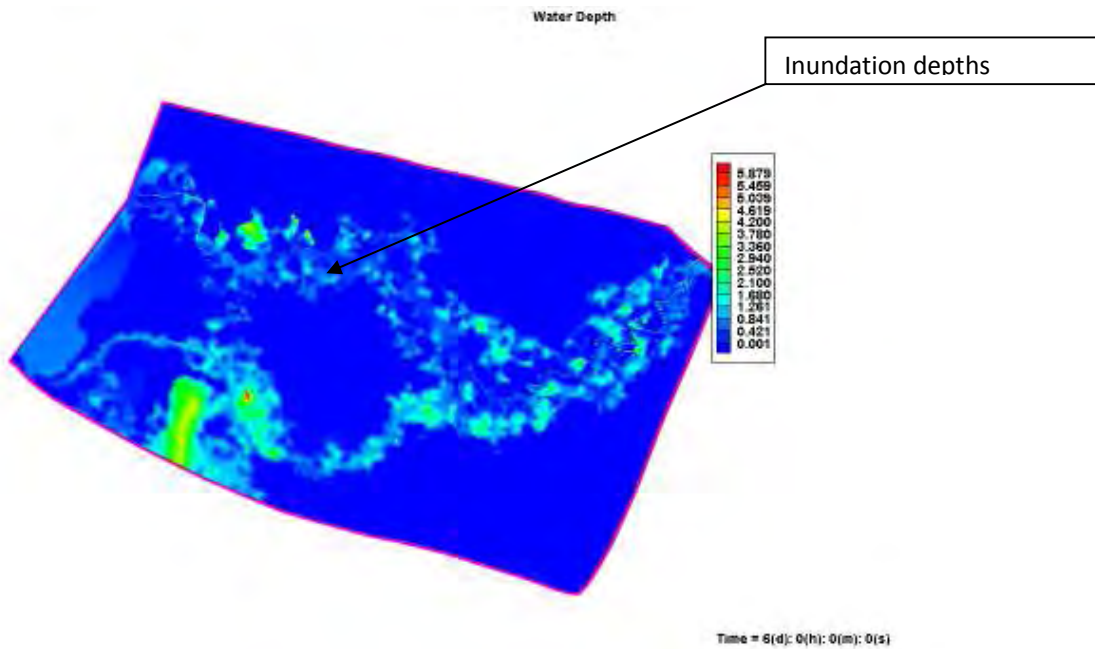


Figure 4-7 inundation depth of the flooded area

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

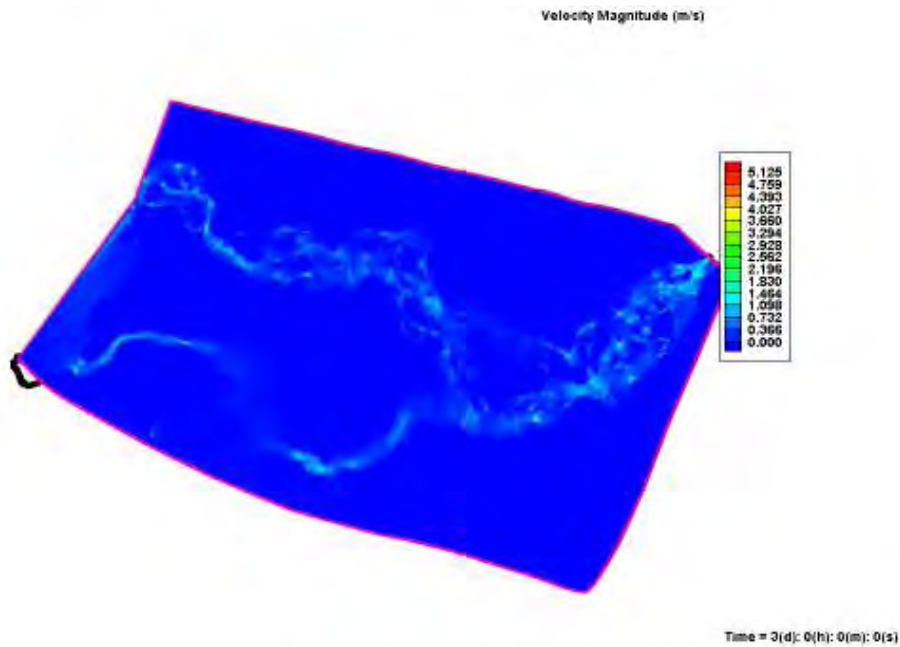


Figure 4-8 flow velocity of the flood

Table 4-2 summary of inundation extent, flood depth and flood velocity

flood characteristics	100 year return flood	
Flooding extent (Km <sup>2</sup> )		47.13
Max-flood depth (M)	M	Km <sup>2</sup>
	<0.25	15.44
	0.25_0.5	11.18
	0.5_1	12.95
	1_2	6.57
	>2	0.96
Max-flood velocity (M\S)	M\S	Km <sup>2</sup>
	<0.25	27.30
	0.25_0.5	9.31
	0.5_1	3.92
	1_2	0.25
	>2	0.006

### 4.3 Flood hazard, Vulnerability and risk Analysis

*Flood Hazard map*- is a representation of areas subject to flooding, together with probability of occurrence. The figure below shows Flood hazard map for the fogera plain with the probability of 1% occurrence. *Vulnerability* – a measure of how easily damaged the elements in flood prone areas are as a function of the magnitude or depth of flooding. The vulnerability maps for the flood areas were prepared by intersecting the land use map of the floodplains with the flood area polygon for each of the flood event being modeled. This depicts the vulnerability aspect of the flood risk in the particular area in terms of the presence or the absence of flooding of a particular return period as a binary model. Most of the areas around the flood plain are cultivated land with less proportion of agro-pastoral, marsh and pastoral. 85-90% of the flood inundated areas are covered by agricultural land. The remaining 10-15% is covered by agro-pastoral near inlet to Lake Tana. *Risk* - the product of hazard and vulnerability.

Water Level (m)	Velocity (m/s)		
	0.5	1.0	1.0
1.0	High	High	Very High
0.5	Moderate	High	High
0.5	low	Moderate	High

Figure 4-9 Flood hazard classification based on water depth and velocity (frame work for flood event management)

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

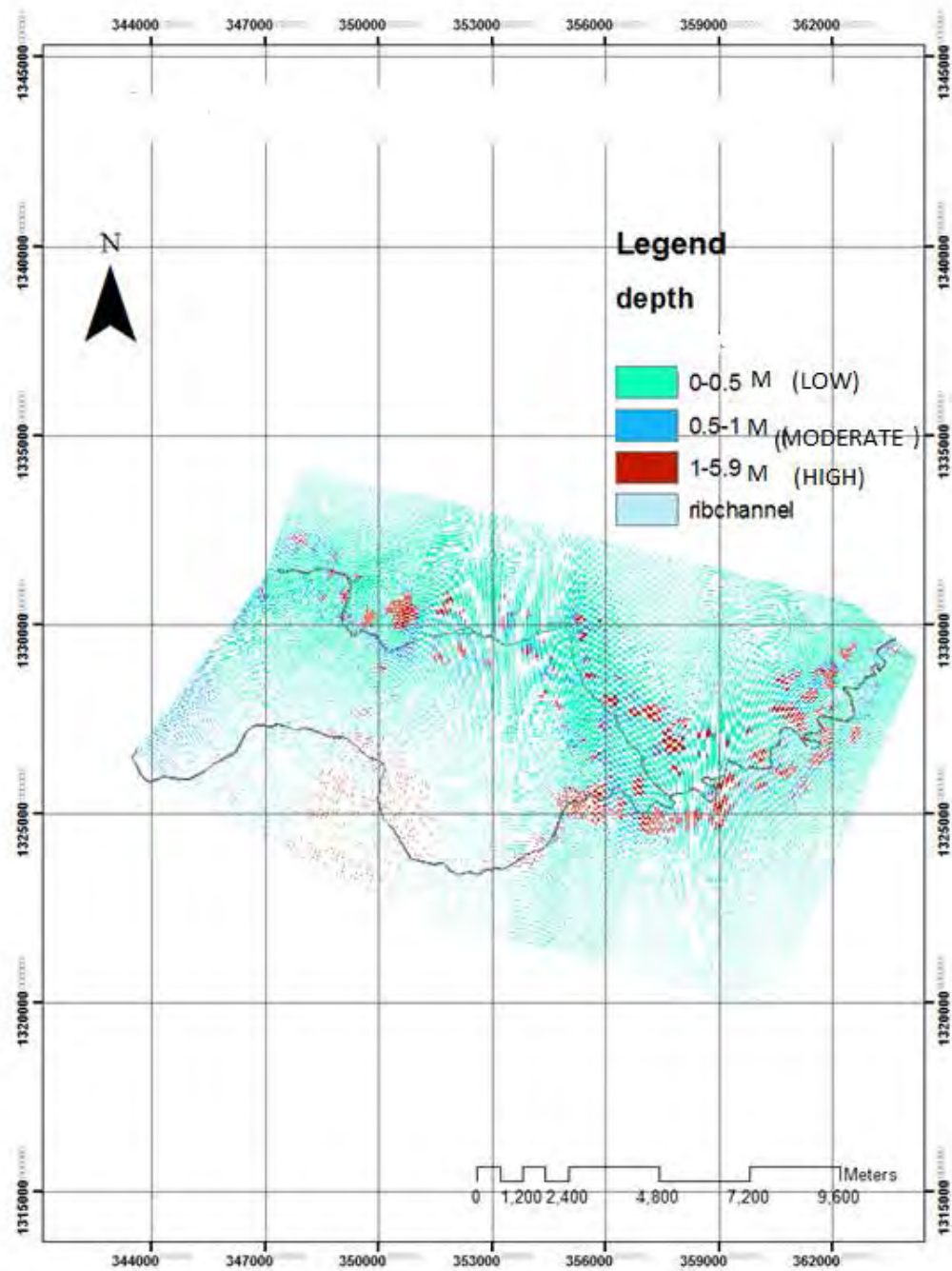


Figure 4-10 Hazard map based on depth

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

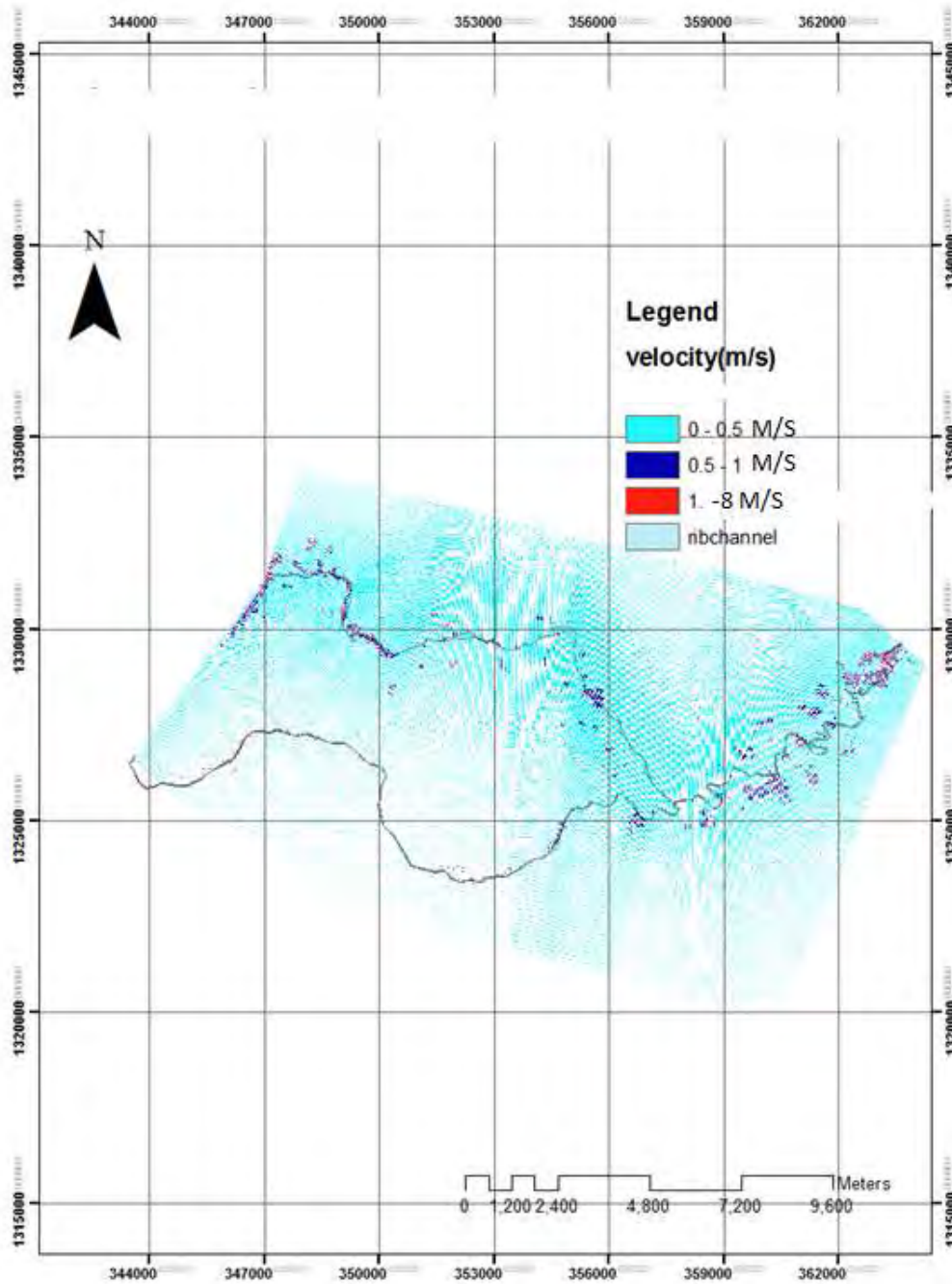


Figure 4-11 Hazard map based on velocity

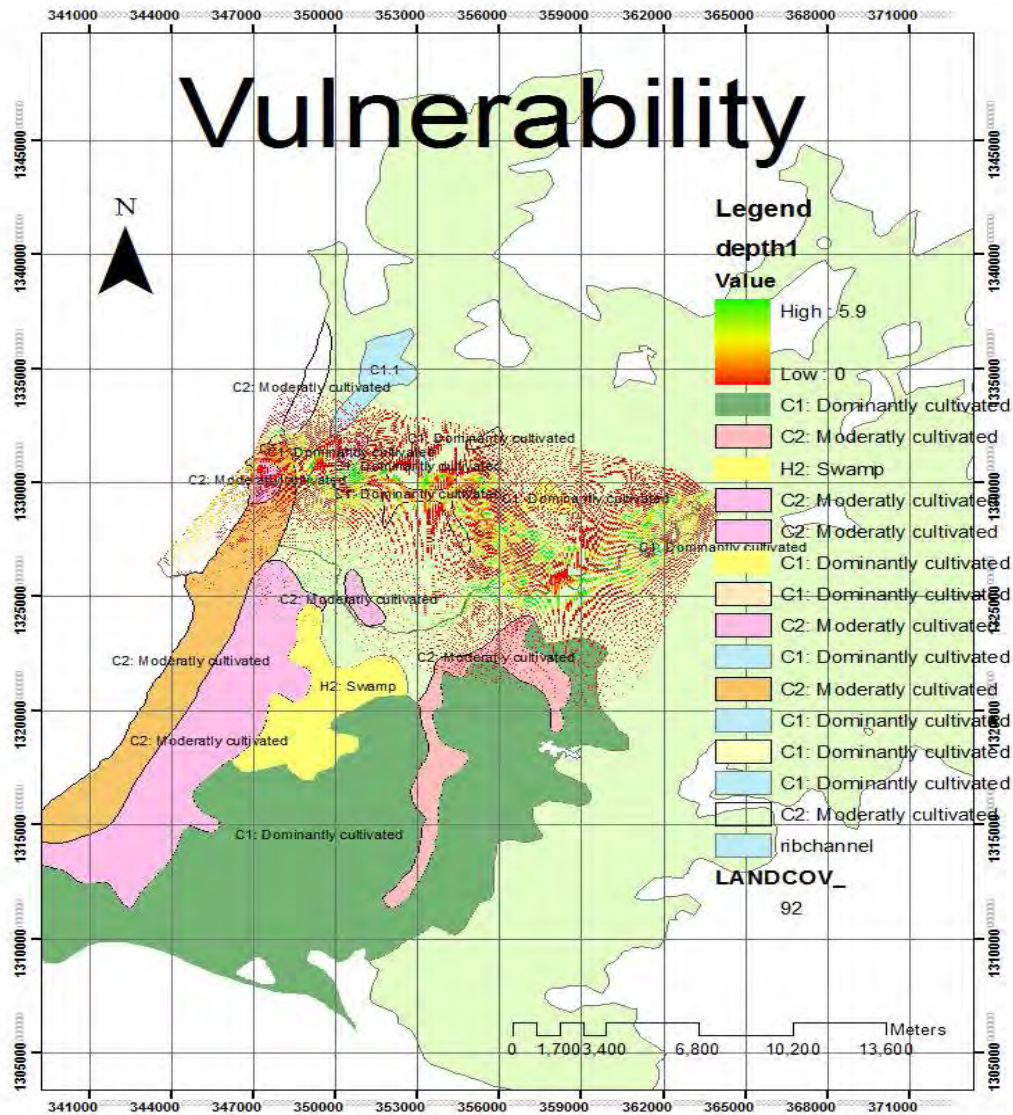


Figure 4-12 Vulnerability map

### 5 CONCLUSION AND RECOMMENDATION

#### 5.1 Conclusion

The flood from the rib river, which is usually formed by out banking of the river channel, is causing direct damage to property and structures, as well as disruption of economic activity and displacement of affected population and the loss of agricultural productivity in the Fogera plain.

This study presents a systematic approach in the preparation of flood map of vulnerability and risk with the application of hydrodynamic models and GIS. The major tools/models used in this method are two-dimensional hydrodynamic model CCHE2D and ArcGIS for spatial data processing. 2D hydrodynamic models are remarkable tool for flood modelling due to the various benefits: 2D models are able to provide important variables for flood risk analysis, such as water depth, velocity and discharge at every point in the domain, Outputs are easy to mapping, Less assumptions than 1D Models and Models take into account the change of features and structures on the surface, The higher the DEM resolution and enough Topographic data, the more accurate the flood map is. Topographic analysis using GIS and field survey data has a greater efficiency to represent terrain nature exactly. The automated floodplain mapping and analysis using these tools provide more Efficient, effective and standardized results and saves time and resources.

The simulated flood characteristics shows that large flooding is observed in the middle reach of the river where many people displaces in August 2006 flooding. In addition, the simulation revealed that large flooding occurs at the right bank as compared to the left bank.

The study also made the assessment of flood hazards with relation to the return period of floods and their water depth. The examination of the flood water depth shows that most of the areas under flooding have water depth less than 1.5m with most of the depths range from 0-1.4m. The presentation of results in GIS provide a new perspective to the modelled data and this approach can facilitate a transition from a flood hazard model based on the field investigation to a knowledge-based model that can be related to flood intensity. The assessment of the vulnerability due to the flooding was made with regard to the land use pattern in the flood areas. The assessment of the flood area indicates that a large percentage (more than 78 %) of vulnerable area lies in flood plain area i.e. agricultural land followed by agro-pastoral and river comprising 18.7% and 3.3% respectively.

Flooding in Fogera is devastating even with a one year storm (E.g. 2006 flooding). Based on the flow simulation results of this research the decision makers should consider structural

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

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measures such as construction dike along the river which would prevent the flooding caused by over banking. Resettlement measures should also be considered for high risk areas.

Hydrologic data are central to flood plain analysis. Availability of hourly time series Data increases the model reliability. Additional cross sections are used in the areas where the river makes Meandering in order to avoid errors during interpolation.

### **5.2 Recommendations**

Dealing with flooding is the difficult task as it needs different data as input; it involves complex process and it requires advanced technology. Usually the accuracy and reliability of researches related to flood are directly affected and enhanced with the data available. This study was conducted under major constraint of limited data availability. Therefore, the following recommendations on are made for the further studies in the future.

- **Topographical Data:** For modelling flows, topographic data should be of high resolution and available enough so that the topography of the floodplains could be properly represented.

- **Flow data:** Most of flooding occurs within hours. Therefore, Availability of hourly time series data increases the model reliability and the daily series is essential to analyse the extreme event.

- **Up-to-date DEM:** should be adapted for high accuracy in representation of the study area. Since the river morphology of Rib is changing with time, frequent conduction of the channel should be accurately known.

- **Inundation data** this data are very important for calibrating and verifying the model results. Therefore data on inundation extent, depth and velocity should be taken during flooding season.

- **Effect of ungauged catchment flow on the flooding:** for accurate modelling of the flooding the effects of the ungauged flows is significant. Therefore future studies should consider on incorporating this flows.

- **Accuracy of results:** in order to increase the accuracy of results it is better increase the number of the computation nodes by reducing the spacing between them and decrease the cell size when converting the channel and flood plain TIN to grid.

- **Use of hydraulic models:** hydrodynamic models can also be used to simulate other natural and human made phenomena. For instance, they can be used to simulate dam break analysis which allows the environmentalist and the planners to oversee the dam consequences and to take per measurements like resettlement of the settled people downstream of the dam.

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### ANNEXES

#### **Appendix A: Double Mass Curve of Stations Near Ribb**

## 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

year	Debretabor	Woreta	Gonder	Bahir dar	Addis zemen	average
1992	3.71	3.1	2.05	3.9	2.94	3.14
1993	4.31	3.9	2.9	4.52	3.5	3.826
1994	4.92	3.6	3.4	4.06	3.04	3.804
1995	4.3	3.6	2.92	4.06	3.04	3.584
1996	4	3.57	2.91	4.04	3.03	3.51
1997	5.5	2.5	3.46	3.31	2	3.354
1998	4.17	4.17	2.97	3.89	1.86	3.412
1999	4.55	4.22	2.99	4.04	3.35	3.83
2000	4.61	3.9	3.26	4.29	4.36	4.084
2001	3.7	3.1	2.95	4.27	1.96	3.196
2002	4.13	3.1	2.67	4.1	3.68	3.536
2003	4.2	3.46	2.25	4.51	3.23	3.53
2004	4.13	3.35	2.75	3.64	3.18	3.41
2005	4.3	3.8	3.18	4.11	3.35	3.748
2006	4.3	4.15	3.26	4.06	3.96	3.946

Table A1: Mean annual precipitation of stations

Debretabor	Woreta	Gonder	Bahir dar	Addis Zemen	cumm aver
3.71	3.1	2.05	3.9	2.94	3.14
8.02	7	4.95	8.42	6.44	6.966
12.94	10.6	8.35	12.48	9.48	10.77
17.24	14.2	11.27	16.54	12.52	14.354
21.24	17.77	14.18	20.58	15.55	17.864
26.74	20.27	17.64	23.89	17.55	21.218
30.91	24.44	20.61	27.78	19.41	24.63
35.46	28.66	23.6	31.82	22.76	28.46
40.07	32.56	26.86	36.11	27.12	32.544
43.77	35.66	29.81	40.38	29.08	35.74
47.9	38.76	32.48	44.48	32.76	39.276
52.1	42.22	34.73	48.99	35.99	42.806
56.23	45.57	37.48	52.63	39.17	46.216
60.53	49.37	40.66	56.74	42.52	49.964
64.83	53.52	43.92	60.8	46.48	53.91

Table A2: Cumulative mean annual of the stations

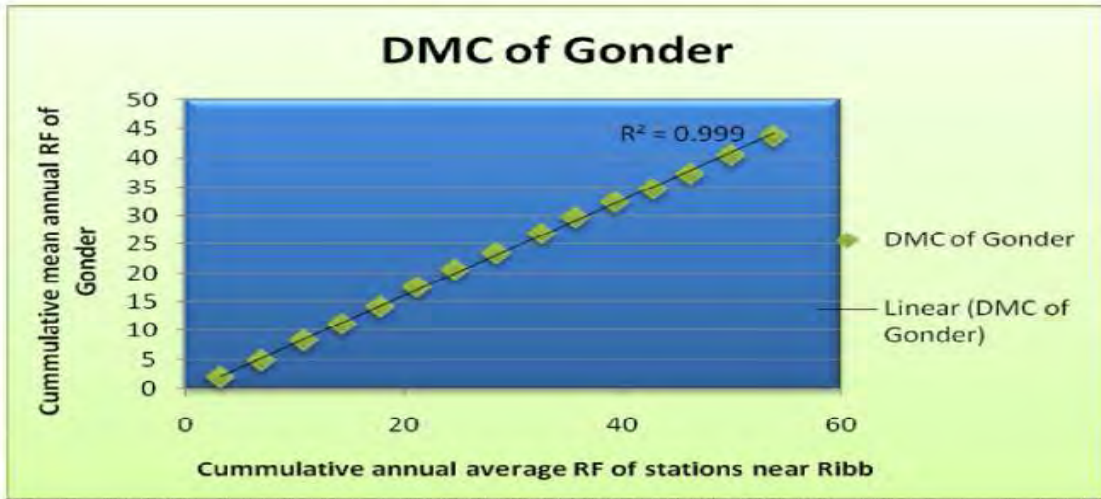


Fig A1: DMC of Gonder

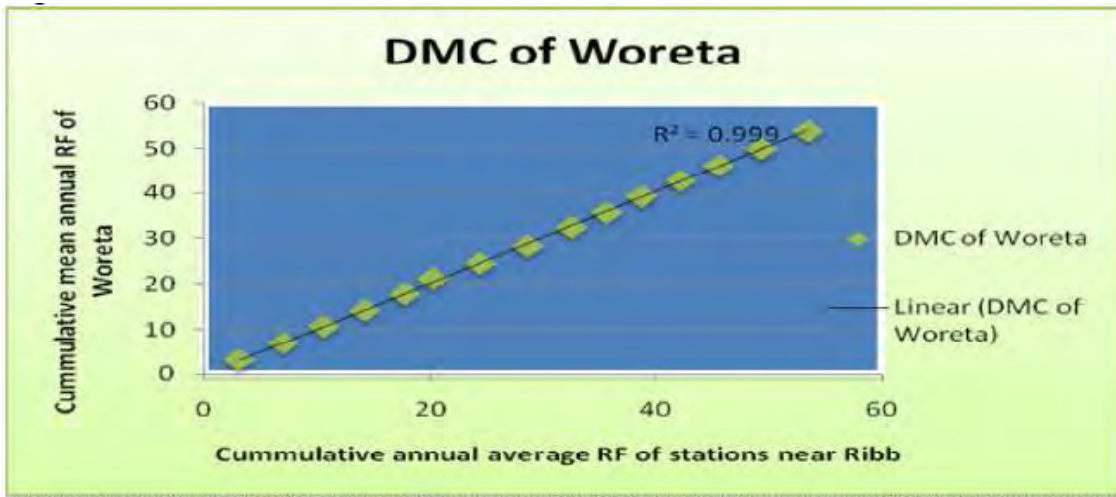


Fig A2: DMC of Woreta

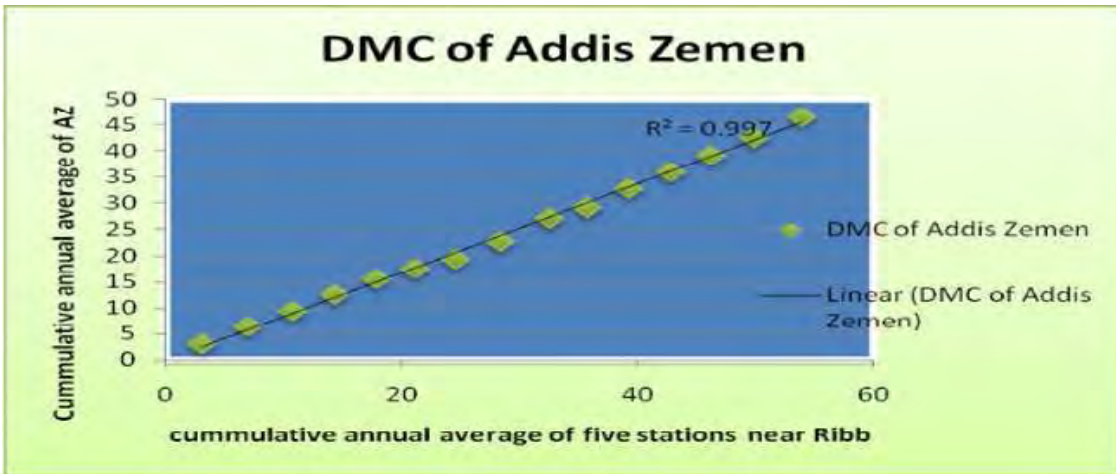


Fig A3: DMC of Addis Zemen

## Appendix B: HEC-HMS outputs

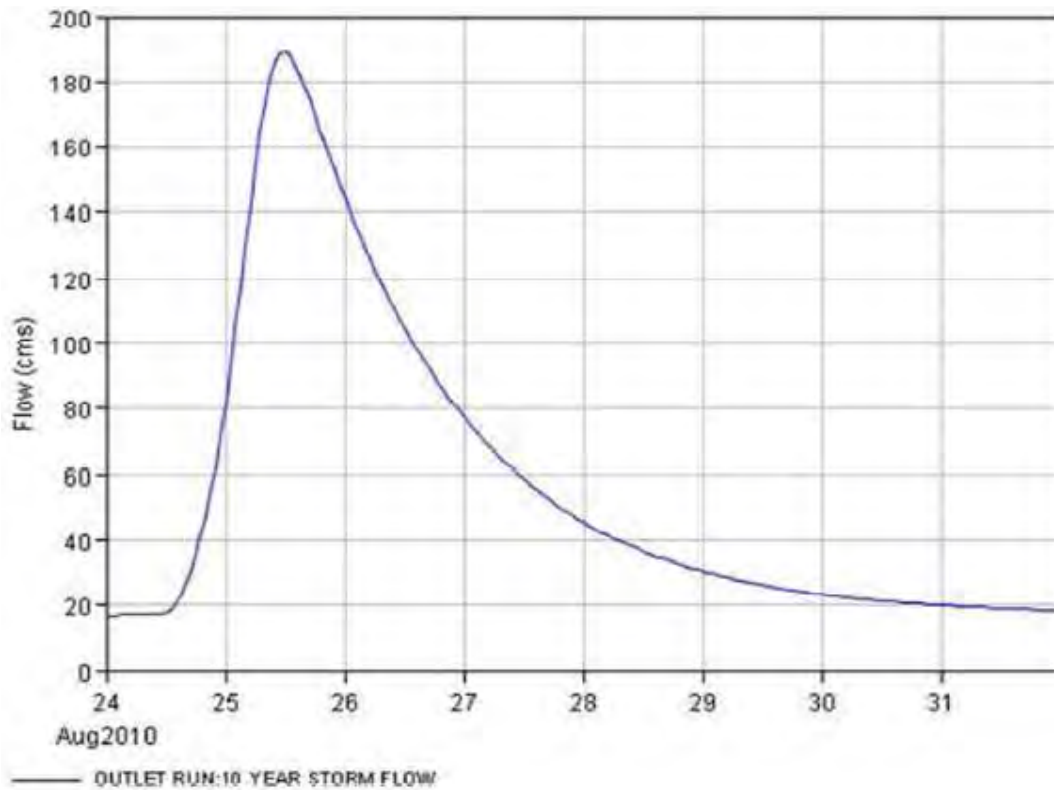


Fig B1: 10 year storm flow hydrograph

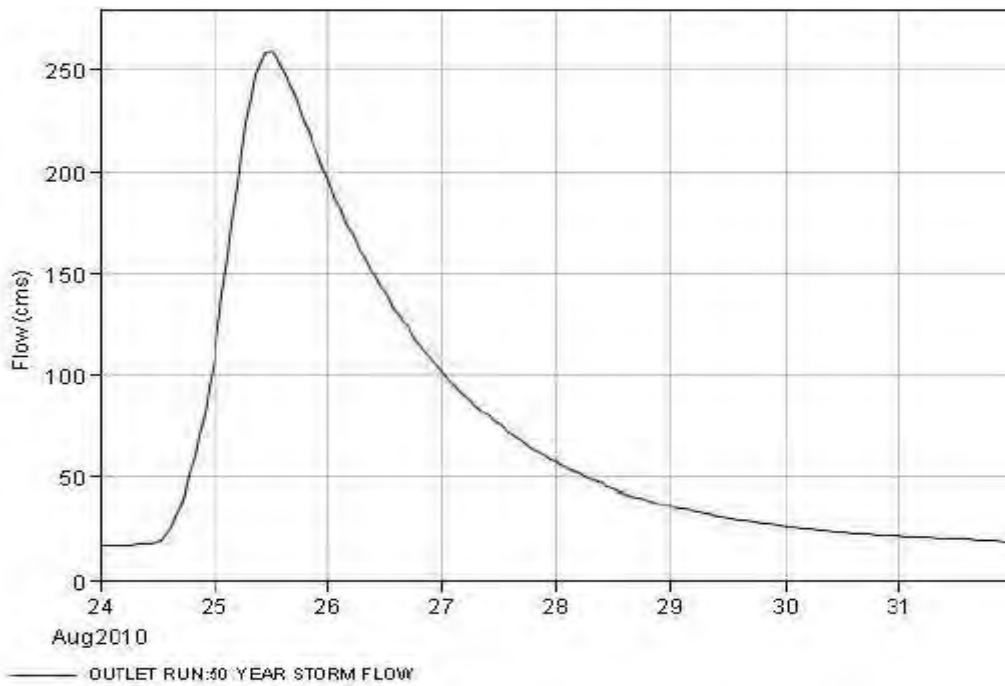


Fig B2: 50 year storm flow hydrograph

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### Appendix C: Rib flow data

Table A1: Rib Annual maximum flow data

<u>Year</u>	<u>Annual Maximum ,Q (m3/s)</u>	<u>Year</u>	<u>Annual Maximum ,Q (m3/s)</u>
1959	176.411	1984	92.085
1960	279.928	1985	105.581
1961	194.595	1986	120.48
1962	77.722	1987	57.796
1963	149.325	1988	119.52
1964	164.366	1989	103.542
1965	76.269	1990	109.924
1966	144.13	1991	121.17
1967	181.533	1992	163.249
1968	148.375	1993	99.93
1969	161.409	1994	99.468
		1995	137.676
1971	115.705	1996	98.588
1972	104.962	1997	94.544
1973	218.692	1998	70.214
1974	151.266	1999	98.977
1975	142.252	2000	101.795
1976	142.774	2001	86.915
1977	146.457	2002	77.117
1978	132.029	2003	84.411
1979	150.727	2004	84.91
1980	126.493	2005	90.818
1981	146.191	2006	94.224
1983	83.053		



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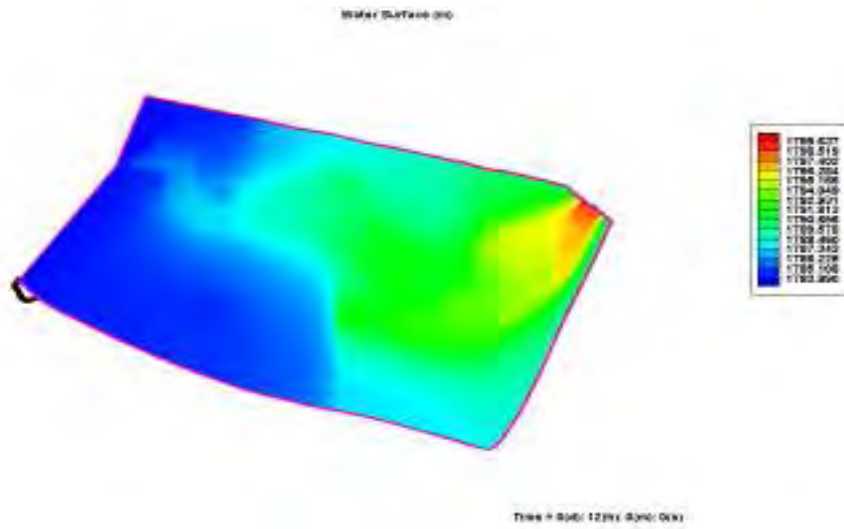


Figure 0-1 Water surface elevation after 12 h

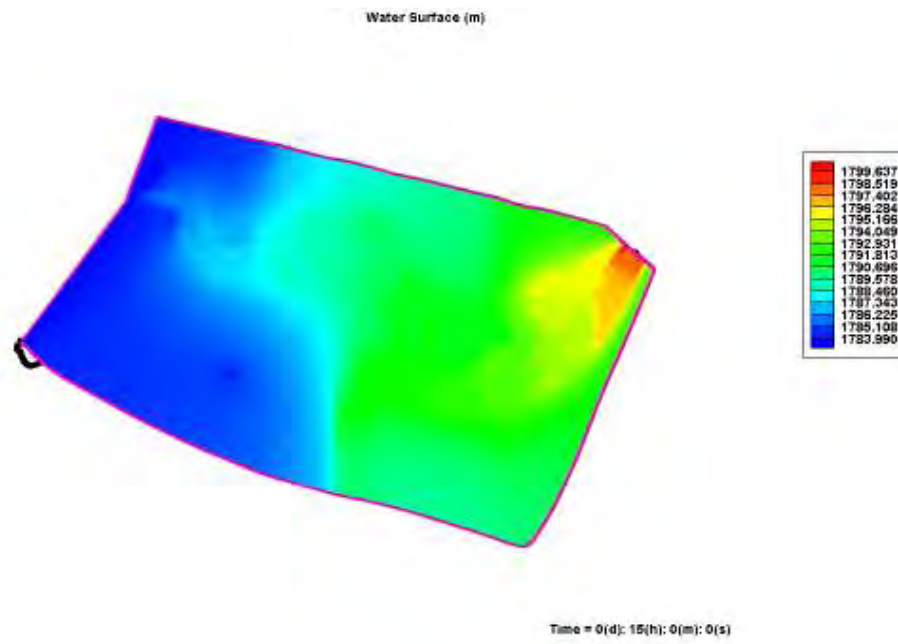


Figure 0-2 Water surface elevation after 15h

# 2D HYDRODYNAMIC MODELLING OF THE RIB RIVER

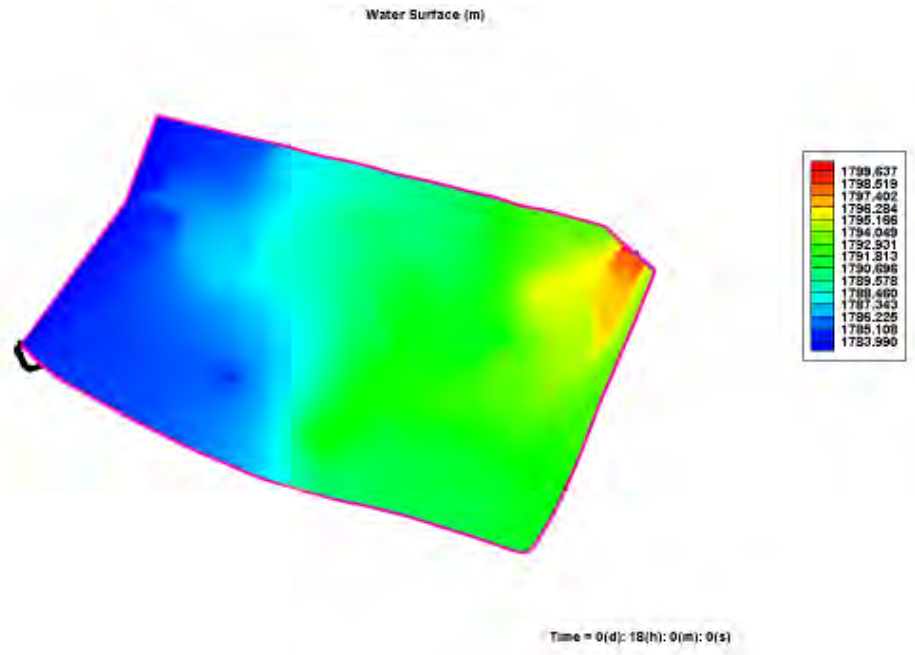


Figure0-3 Water surface elevation after 12 h

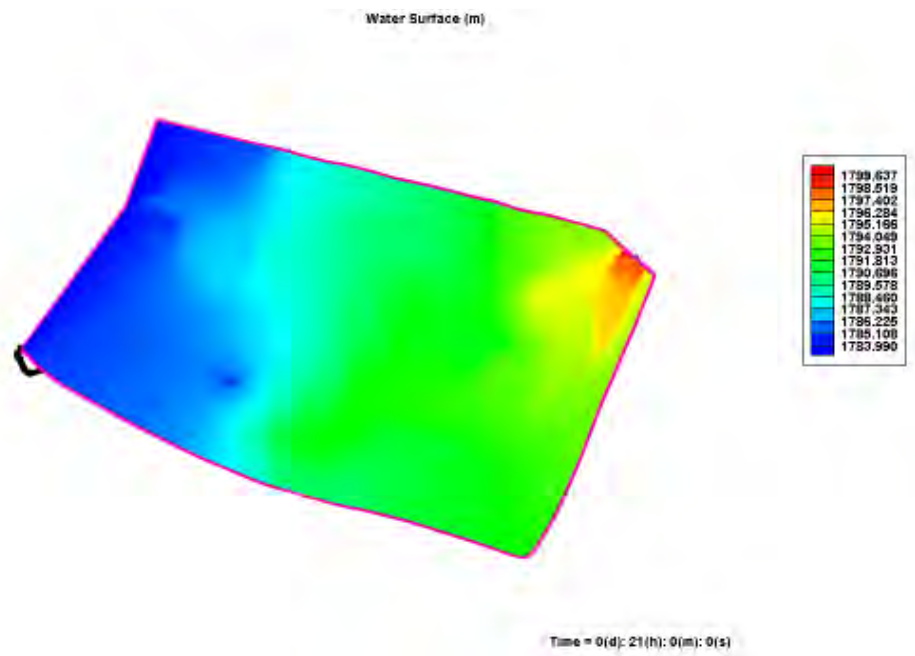


Figure 0-4 Water surface elevation after 12 h

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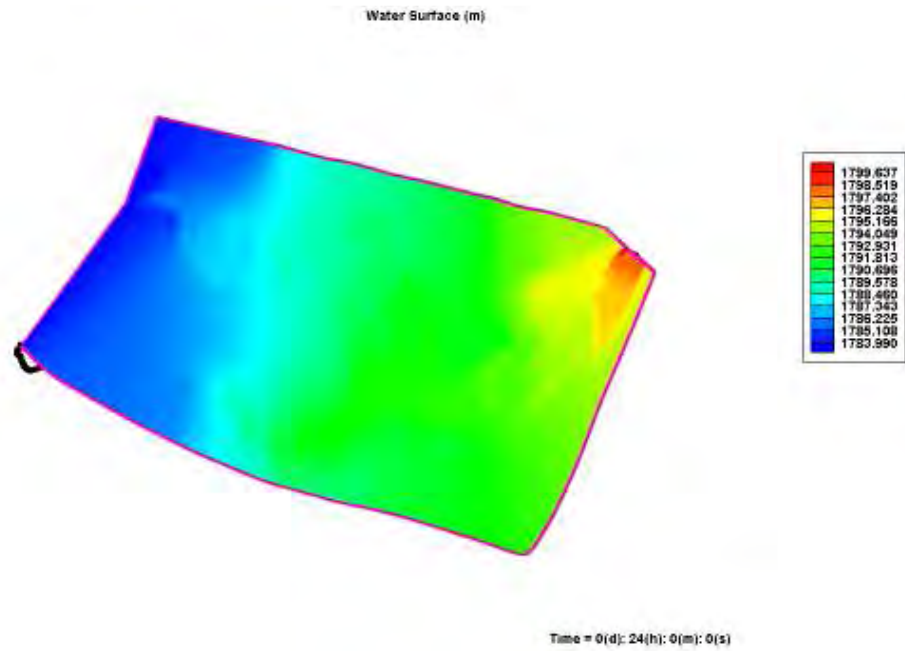


Figure 0-5 Water surface elevation after 12 h