Final Report

Flood Risk Mapping Consultancy for Pilot Areas in Ethiopia

submitted to

ENTRO

EASTERN NILE TECHNICAL REGIONAL OFFICE

by

RIVERSIDE

TROPICS CONSULTING ENGINEERS P.L.C

ሸበሌ ኮንሰልት ኃላፊነቱ የተወሰነ የግል ማኅበር
SHEBELLE CONSULT PLC *Development, Planning & Engineering Consultants*

July 2010

A report of Riverside Technology, inc. to the Eastern Nile Technical Regional Office

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

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. This multi-disciplinary study included topographic data collection and surveying, terrain modeling, hydrologic analysis, hydraulic modeling and analysis, flood hazard mapping, economic data collection and damage analysis, and vulnerability and risk assessment. The pilot areas considered were:

- Gumara River in the Fogera floodplain
- Ribb River in the Fogera floodplain
- Dirma River in the Dembiya floodplain
- Megech River in the Dembiya floodplain

Flood risk mapping can be an important aid to a community in taking action in the present to reduce future damages, in planning for flood preparedness and response, in developing infrastructure for reducing flood severity and flood damage, and in guiding development to avoid increased risk where hazard is frequent. An important aspect of this study was the development of models and procedures that could be applied using the data that were available. Because flood risk mapping relies on multiple data types and sources, and because some of those data represent detailed spatial characteristics for an extensive area, the quality and volume of data desired to support this study were not complete. Over time, data should become available through complimentary efforts on other studies that can be incorporated into subsequent updates to this study. Several useful outcomes of this study are highlighted here to serve as a reference to facilitate applying and taking advantage of them in subsequent related efforts. Important outcomes include the following:

- New cross section surveys in all four rivers in the pilot areas.
- Terrain models for the four river channels in the pilot areas and the Fogera and Dembiya floodplains – this terrain model integrates surveyed cross sections with a 90 meter DEM.
- A useful procedure for integrating a gridded DEM with channel survey data.
- Ground Control Points were setup that can be used in future surveying efforts.
- A frequency analysis for flows in the Dirma, Megech, Ribb and Gumara Rivers.
- A hydrologic model for the Dirma, Megech, Ribb, and Gumara River basins.
- Hydraulic models for the Dirma, Megech, Ribb, and Gumara rivers with geo-referenced cross sections – these models have many potential uses that are highlighted in the final section of the report.
- Flood hazard maps (extent, depth, velocity, and duration) – These maps are fairly straightforward to interpret and can be used for flood preparedness and response as well as for development planning
- Detailed asset geo-databases in both the Fogera and Dembiya plains, including structures, infrastructure, and agriculture
- Vulnerability and risk maps – These maps are more complicated than the hazard maps, but a study of them can reveal important relationships between flood frequency, flood extent, location of vulnerable infrastructure, and high-risk areas.
- Risk mapping procedure – Because all of the inputs to the risk maps are subject to change or refinement, it is important to have a procedure that can be followed to efficiently update risk maps and risk calculations in the future.

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. They include loss of agricultural productivity, including both opportunity as well as direct damage to crops in various stages of cultivation. They include direct damage to infrastructure, in addition to disruption of transportation and services, potentially affecting populations not directly touched by flood waters, and for extended periods of time, not limited to the period of inundation. 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. This study lays out a framework and specific tools for basic flood hazard and risk mapping and then applies those tools in two floodplains surrounding Lake Tana in Ethiopia. The method for estimating damage is indexed to depth, which means that the economic analysis must implicitly incorporate the other factors that influence the extent of damage in the depth-damage relation. This approach is consistent with the belief that if a basic analysis procedure is set forth, then resources can be allocated efficiently and predictably to undertake an initial flood hazard and risk mapping program at a regional level.

The desire on the part of public officials to characterize and quantify consequences of flooding is typically based on a responsibility to act in the public interest to reduce the undesirable consequences of flooding, and this must be done with limited resources on which there is no shortage of other claims. Risk assessment and risk mapping provide important information to aid in understanding the most vulnerable areas and to focus educational programs, policies, and other measures to achieve the greatest benefits. To be effective and sustainable, however, the approach to risk mapping and flood damage mitigation needs to proceed in a coordinated fashion to take advantage of and be consistent with related data development and management activities. An effective framework for risk assessment, therefore, should be flexible in permitting varying levels of detail and accuracy in the individual inputs, while allowing rapid updating of results based on the incorporation of updated or more detailed information as it is obtained or becomes available. This approach has at least two important benefits. One is that it can be widely deployed without detailed or expensive data collection efforts to obtain a preliminary assessment of hazard and risk. The second is that enhancements in the form of more detailed or accurate inputs can be easily incorporated as they become available, often as a result of parallel efforts that may be undertaken for other purposes.

Among the many items noted in the findings and recommendations of this report, one item that Riverside wishes to highlight is the potential value of the flood extent maps, in hard copy, PDF, or GIS layers. These maps convey the most basic information about the general vicinity in which flooding can be expected with varying frequencies. Local communities can make immediate use of these maps to identify areas of focus for flood protection, preparedness, warning, and future development guidelines. A flood extent map can be a valuable aid in communicating flood risk to local populations as part of education and outreach programs to encourage appropriate response. The vast geographical extent of the modeling and mapping effort and the limited resources available for the study has resulted in simplifications that produce inaccuracies. While these inaccuracies undoubtedly will invite some criticism of the products, Riverside believes that there is significant value in these initial flood maps and hopes that they can provide a useful baseline dataset that can be improved in subsequent studies.

1.0 INTRODUCTION / OVERVIEW

Riverside Technology, inc. (Riverside) and its partners, Tropic Consulting Engineers and Shebelle Consult, were contracted by the Eastern Nile Technical Regional Office (ENTRO) to perform a flood risk assessment for flood plains surrounding Lake Tana in Ethiopia. An Inception Report was prepared at the end of March 2009 describing initial data collection activities and an inception workshop conducted on March 2 and 4 of 2009. In July, 2009, Riverside prepared an Interim Report to provide a status update and share methods and initial results from the study. In addition, the report provided the basis for discussions with ENTRO regarding work performed to date, remaining work required to complete the study, and suggestions for the final report.

A final workshop was conducted in Bahir Dar on October 15 and 16, 2009. A Draft Final report was provided in advance of the workshops as a basis for discussion of the methodology and results. In addition, draft copies of risk maps (including maps of inundation, flood depth, velocity, vulnerability, and average annual risk) were provided for review and discussion. A training session was conducted following the workshop to provide hands-on practice using the tools and following the procedures that were applied in performing the study. This final report incorporates elements of the discussions that took place during the workshops and subsequent training, as well as the results of additional work that has been performed since the workshops to complete the study.

2.0 PROJECT BACKGROUND

Historically, the flow of the Blue Nile and its tributaries that flow into Lake Tana reaches maximum volume in the rainy season (from June to September), when it supplies two thirds of the water of the Nile proper. Flooding along the tributaries to Lake Tana is not uncommon, and such flooding has beneficial environmental effects because it is only during this time that erosion and transportation of the fertile silt occurs. Severe flooding along populated areas, however, can also have devastating effects on lives, livelihoods, and property. Infrastructure, agricultural land, and other resources at risk from floods can be vast, and include residential, commercial and industrial property, and public service infrastructure, including water supply and crops. The Eastern Nile region is particularly vulnerable to these frequent and damaging floods, causing significant loss of life and economic damages.

In Ethiopia recent floods have been particularly severe. The World Food Program reports that the 2006 Ethiopian floods in eastern and southern Ethiopia affected over 70,000 people, including 16,000 displaced, and over 600 dead. The summer 2007 floods were reported to be equally devastating, causing severe flooding in the regional states of Amhara and Gambella, affecting over 60,000 people and destroying farmlands, road, and homes.

Villager on the Blue Nile explaining the water level of a historical flood.

2.1 The Nile Basin Initiative

The Nile Basin Initiative (NBI) is a partnership of the riparian states of the Nile: Burundi, Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Rwanda, Sudan, Tanzania and Uganda (***Figure 2-1***). The NBI seeks to develop the river in a cooperative manner, share substantial socio-economic benefits, and promote regional peace and security. The NBI launched with a participatory dialogue process among the riparian that resulted in a shared vision: "to achieve sustainable socioeconomic development through the equitable utilization of, and benefit from, the common Nile basin water resources." The discourse also gave birth to a strategic action program to translate its vision into concrete activities and projects.

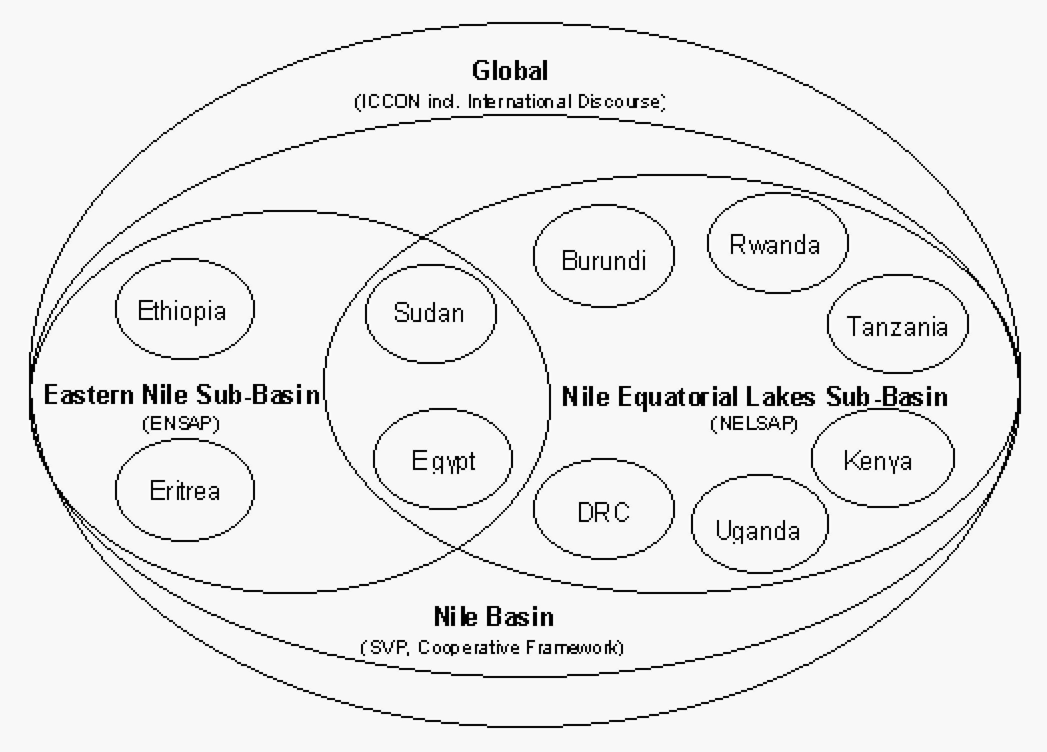


Figure 2-1: Nile Basin Initiative framework (NBI).

2.2 NBI's Strategic Action Program

The NBI's Strategic Action Program is made up of two complementary components: the basin-wide Shared Vision Program, to build confidence and capacity across the basin; and subsidiary action programs, to initiate concrete investment and action on the ground at sub-basin levels. The programs are reinforcing in nature. The Shared Vision Program lays the foundation for unlocking the development potential of the Nile by building regional institutions, capacity, and trust. This can be realized through the investment-oriented subsidiary action programs, currently under preparation in the Eastern Nile and the Nile Equatorial Lakes regions.

2.3 Eastern Nile Subsidiary Action Program (ENSAP)

The Eastern Nile region includes the countries of Egypt, Sudan and Ethiopia and encompasses the sub-basins of the Baro-Akobo-Sobat, the Blue Nile, the Tekezé-Setit-Atbarah, portions of the White Nile in

Sudan, and the Nile proper. The Eastern Nile countries are pursuing cooperative development at the sub-basin level through the investment-oriented Eastern Nile Subsidiary Action Program (ENSAP).

ENSAP seeks to realize the NBI shared vision for the Eastern Nile region, and is aimed at poverty reduction, economic growth, and the environmental degradation reversal throughout the region. Towards this end, the Eastern Nile countries have identified their first joint project, the Integrated Development of the Eastern Nile (IDEN). IDEN consists of a series of sub-projects addressing issues related to flood preparedness and early warning; power development and interconnection; irrigation and drainage; watershed management; multi-purpose water resources development; and modeling in the Eastern Nile.

IDEN projects are divided into fast-track projects and multi-purpose track projects. The fast-track projects consist of Flood Preparedness and Early Warning (FPEW), Eastern Nile Power Transmission Project, Eastern Nile Planning Model, Eastern Nile Irrigation and Drainage Project and Watershed Management whereas the multi-purpose track projects include the Eastern Nile Power Trade, Baro-Akobo-Sobat Multipurpose project and the Joint Multipurpose Project (JMP).

The Eastern Nile Technical Regional Office (ENTRO) is a technical regional body supporting the implementation of ENSAP. Established in 2002 and located in Addis Ababa, Ethiopia, ENTRO is responsible for providing administrative, financial management, and logistical support in the implementation and management of ENSAP. In general, ENTRO’s core functions are: ENSAP coordination and integration; project preparation; financial management; communications and outreach; training; monitoring and evaluation; information exchange; and serving as the secretariat for ENSAP organizations.

2.4 Flood Preparedness and Early Warning Project

The FPEW fast-track sub-project is among the seven projects identified within IDEN. The objective of the FPEW project is to reduce human suffering caused by frequent flooding while preserving the environmental benefits of floods. The project gives emphasis to flood risk management and non-structural approaches to managing the impacts of flood. The FPEW project enhances regional collaboration and improves national capacity in the mitigation, forecasting, warning, emergency preparedness, and response to floods in the Eastern Nile basin. Nested within these project components, and particularly key to flood preparedness and emergency response, is the Flood Risk Mapping for Pilot Areas Consultancy, which seeks to: (i) identify high-risk areas in the Tana Basin within Ethiopia, (ii) produce flood risk maps, and (iii) conduct flood risk assessments for the pilot areas within the Blue Nile Basin in Ethiopia. Identifying and mapping these flood prone areas, including locating the high-risk areas and the extent of flooding, will greatly enhance Ethiopia’s flood risk planning capacity and help Ethiopia develop enhanced flood mitigation measures. The approach and modeling described below will not only serve as a proof of concepts for developing flood risk maps for the pilot projects, but they can also be used in future development scenario studies. For example, model setups can later be easily modified by local experts to study the impacts of reservoir operations, preparedness for dam breaks, etc.

2.5 Project Location and Pilot Study Areas

There are several flood risk areas around Lake Tana. Two areas selected were the floodplains of the Fogera woredas and the floodplains of the Dembia woredas. These pilot reaches are shown in ***Figure 2-2***. These are the two largest flood risk areas and the two areas with the greatest flood impacts.

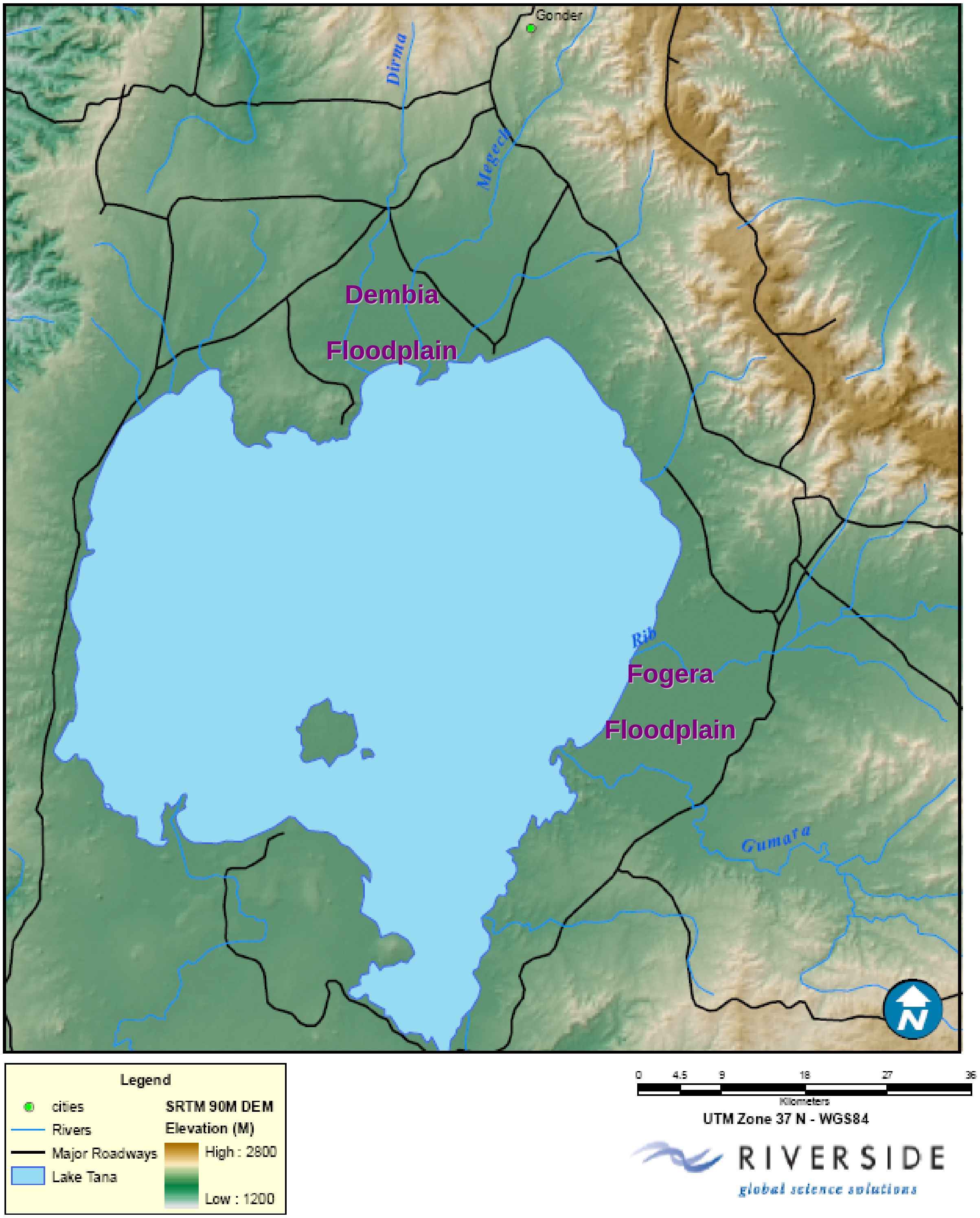


Figure 2-2: Lake Tana pilot study areas.

3.0 APPROACH & METHODOLOGY

Risk assessment and risk mapping provide important information to aid public officials in understanding the nature of flood risk, to identify the most vulnerable areas and to focus educational programs, policies, and other measures to achieve the greatest benefits in reducing the harmful effects of flooding. While a risk assessment and mapping program can be useful for any specific location, the benefits can be multiplied when a procedure can be defined and applied consistently at regional scales. Consistent application encourages efficient deployment and development of capacity in performing analyses, invites broader acceptance and use of maps and study results by public officials, and encourages development of standard datasets for input to future analyses to enhance accuracy of results and better decision making.

To be effective and sustainable, however, the approach to risk mapping and flood damage mitigation needs to proceed in a coordinated fashion to take advantage of and be consistent with available data and data formats. The framework for risk assessment should be flexible in permitting varying levels of detail and accuracy in the individual inputs, while allowing rapid updating of results based on the incorporation of updated or more detailed information as it is obtained or becomes available. This approach has at least two important benefits. One is that it can be widely deployed without detailed or expensive data collection efforts to obtain a preliminary assessment of hazard and risk. The second is that enhancements in the form of more detailed or accurate inputs can be easily incorporated as they become available, often as a result of parallel efforts that may be undertaken for other purposes. For example, as economic assessments and spatial infrastructure databases and surveys are undertaken as part of community development and management efforts, and as the potential benefits of accurate risk assessment are better understood, communities can facilitate the enhancement of risk assessment efforts by sharing valuable infrastructure and development data that would not have been feasible to obtain for flood risk assessment purposes alone.

A schematic of the conceptual design of the methodology for this study is shown in ***Figure 3-1***. The methodology for assessing flood risk involves the following main components:

- Data collection and field survey to characterize to provide input to terrain modeling and to define assets subject to damage, including agricultural areas, structures, and public infrastructure;

- Terrain modeling to develop a digital elevation model suitable for both extracting topographic data for the hydraulic model and for mapping the inundation that results from simulated hydraulic profiles;

- Hydrologic and hydraulic analysis and modeling to determine peak flow magnitudes and frequencies and associated hydraulic profiles;

- Flood hazard mapping to represent inundated area, depth and velocity for the various peak flows;

- Economic analysis to associate economic value with surveyed assets and to define a relationship between depth and damage for all assets subject to damage; and

- Vulnerability and risk mapping to convey the spatial nature of risk and to support the computation of expected annual damage.

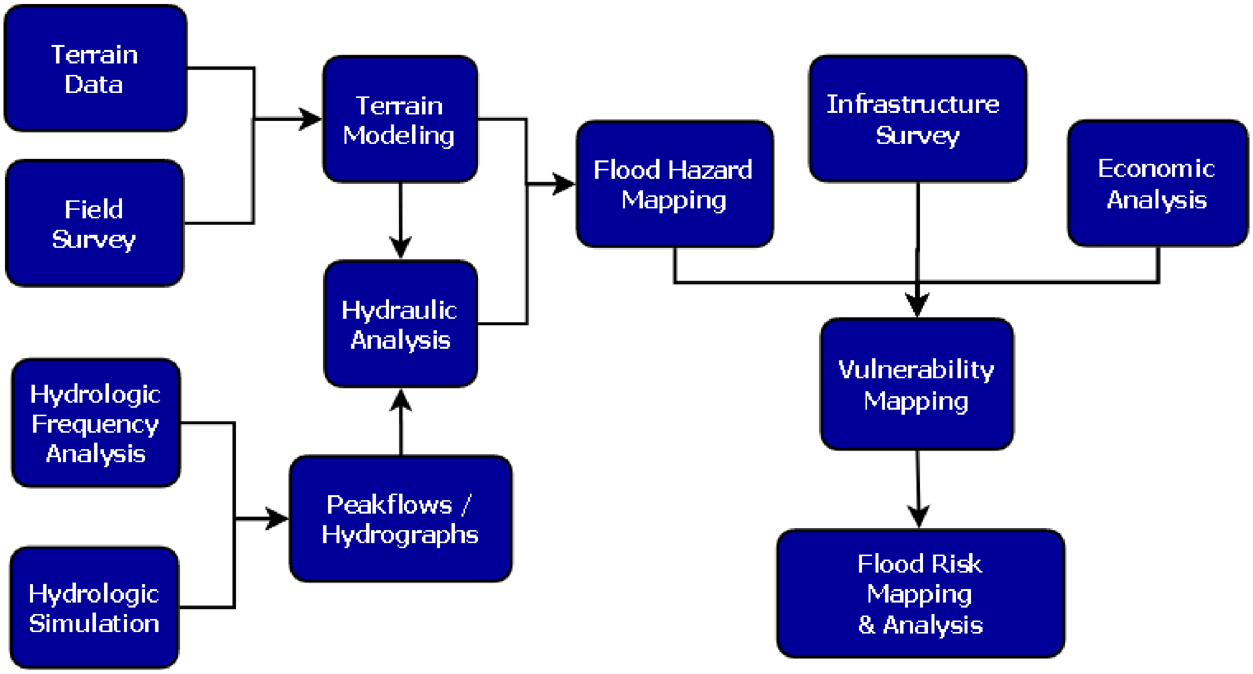


Figure 3-1: General approach for assessing flood risk.

3.1 Modeling Framework

The specific engineering software tools employed in this study were the US Army Corps of Engineer's Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HEC-HMS) to assist in developing frequency flows, the River Analysis System (HEC-RAS) program to perform one-dimensional steady flow analysis, the HEC-GeoRAS spatial pre-processor, the HEC-RASMapper post-processor, and ESRI's ArcGIS spatial data analysis software. These tools are internationally recognized, widely deployed and tested under many physiographic and development conditions. The HEC-HMS, HEC-RAS and HEC-GeoRAS tools are freely available, well supported and documented. In addition, these tools are known and used by the local professionals in the Eastern Nile region. These characteristics facilitated the use of these tools to collaborate with local partners and focus on the specific and unique challenges of flood risk mapping and the application of these tools to it, rather than on learning the tools for the first time. Riverside anticipates that the use of these tools also will facilitate effective technical transfer to planners and stakeholders in the region.

3.2 Workshops & Training

The Riverside team prepared presentations for and facilitated two ENTRO organized workshops and one training session; the first workshop took place after the inception report was submitted, and the second after the draft final report was submitted. The workshops and training were designed to build local capacity and to present the work done by the Riverside team. In addition, close coordination throughout the project was necessary in order to promote experience and capacity building of the project team.

3.2.1.1 First Flood Risk Mapping Workshop

The study team participated in an inception workshop in Bahir Dar, Ethiopia on Wednesday, February 25 and Thursday, February 26. The main objective of the workshop was to present the overall methodology of implementing this activity in terms of data, techniques, outputs, etc. On the first day, the Riverside team presented and discussed the flood risk mapping experiences of other countries/regions (including the challenges, limitations, and coping mechanism). On the second day, the Riverside team discussed in detail the methodology that would be applied in developing the flood risk maps and received input from stakeholders on important technical aspects of the project study area that should be considered in the execution of the work.

3.2.1.2 Second Flood Risk Mapping Workshop & Training

A final workshop was conducted in Bahir Dar on October 15 and 16, 2009. A Draft Final report was provided in advance of the workshops as a basis for discussion of the methodology and results. In addition, draft copies of risk maps (including maps of inundation, flood depth, velocity, vulnerability, and average annual risk) were provided for review and discussion. The objectives of the workshop were to present the results of the study, including a discussion and examples of the methodology that was followed, and to receive comments and feedback on the study and the draft report prior to completing the study. The draft agenda for the final workshop and a record of comments made by participants in the workshop is included in ***Appendix E***.

Several comments received during the workshop referred to topographic data collection. One concern was that a 30 meter DEM was available in the study area but a 90 meter DEM was used for the study area. As further addressed in chapter 4, the 30 meter DEM is based on new technology and the vertical accuracy is limited. The lack of vertical accuracy of the 30 meter DEM resulted in a poor fit with the field survey and would not increase the accuracy of the modeling effort as compared to the 90 meter DEM which had a much better correlation with the field survey. Another concern with regard to the topographic data collection was the location of the ground control points. Chapter 4 provides information on the standards used for the survey and ***Appendix B*** and ***C*** provide maps and locations of the established ground control points. These control points can be used to tie in future surveys to the existing data set or to expand the current set of ground control points.

Another concern was related to the extent of the flooding indicated on the floodmap. Flood plain areas lying between the main rivers in each floodplain were identified as flood prone areas based on historical information, but were not mapped as such on the floodmaps. This concern was addressed by performing additional surveying, expanding the hydraulic analysis to include the interior floodplain areas, and computing the runoff and hydraulic response that would contribute to these areas. Taking this into account expanded the representation of the inundated area for the Ribb River and the Fogera Floodplain as described in chapter 6.

In response to comments received during the second workshop it should be noted that the current model represents flood risk at a single point in time, while actual flood risk varies continuously and spatially. Not only do sediment loads in rivers reduce their capacity, but erosion and scour can realign the river completely, as recently happened with the Megech and Ribb Rivers. Although they represent only a point in time, the results of this study can be used to assess future changes in land use and land management. The models used in this study are also freely available online and can be updated with revised and additional data as it comes available. The models are setup in a way that stakeholders can modify parts of the modeling approach. As such it is reasonably easy to evaluate the difference of using for example the SCS curvenumber approach as opposed to a user defined hydrograph in the model. The information contained in the models would allow the user to analyze future events and compare them to the assumptions made in the report. Chapter 9 includes recommendations on actions that could reduce flood losses in the future.

The downstream boundary used for the river models is the water elevation in Lake Tana. Chapter 6 provides information on the impact of this boundary condition on the flooding levels in the floodplain and concludes that the impact of the boundary condition is limited to the area that would be flooded as a result of high lake levels, regardless of river conditions.

Uncertainties with regards to the data used in the model was brought up for several different data sources during the second workshop. Uncertainty in the input data clearly will result in uncertainty in the model results. The models are developed with available data and are defined in a way that if more reliable data becomes available it can be included in the model. Where limited data were available, reasonably conservative values were used to avoid under-estimating risk. Uncertainty can be reduced in future enhancements to this study using more accurate, high resolution terrain data and periodic surveying of river channels. Recommendations for these improvements are included in chapter 9.

In addition to the comments addressed above, the stakeholders present at the workshop provided valuable comments that are included and addressed throughout the report.

3.2.1.3 Local Partner Coordination

During the course of the project, Riverside and its partners recognized the need for closer cooperation to share specific expertise and to collaborate more closely in technical aspects of the study. For this purpose frequent meetings were required. The use of GoToMeeting® software for internet-based collaboration and sharing of desktop computing environments was employed for this purpose. These meetings provided direct training and collaboration opportunities for the team, with benefits similar to those that can be achieved in a co-located work environment. Examples of tasks that were conducted include:

- Jointly discussing hydraulic model results and pointing out on-screen expected versus mapped patterns of inundation that suggested the need for refinements to the hydraulic models;
- Illustrating on-screen ArcGIS sequences for performing complex tasks, and illustrating intermediate results that suggest subsequent processing steps;
- Giving prepared on-screen presentations to present general ideas that would guide a subsequent phase of work;
- Troubleshooting software and processing errors with help from experts at the remote location;
- Documenting meeting notes, decisions, and assignments on-screen during and at the conclusion of meetings to limit misunderstandings, clarify expectations, focus subsequent efforts and set the agenda for subsequent meetings.

During these meetings the team found occasional challenges with feedback, echoes, static, delayed responses, and periodic internet limitations, but learned that they could be frequently overcome through patience, obtaining better equipment, sharing equipment, using appropriate software controls for selective muting, and sometimes rescheduling the meeting for a later time. Riverside found, in general, that when users employ individual headsets and microphones for participation in the meetings the sound quality and response is generally better than telephone lines, cellular or otherwise.

3.3 Changes in Scope of Work or Approach

During the course of this project there have been instances where data availability, project needs, physiographic characteristics, or other circumstances were not consistent with assumptions at the beginning of the project and required adjustment in the focus of some element or the specific procedures that were planned. Significant changes to the scope of work or to important procedures are described below.

Riverside had originally planned to use the HEC Watershed Analysis Tool (WAT) as the modeling framework for the hydrologic, hydraulic and risk assessment tasks of this project. HEC-WAT is a program which organizes and streamlines model planning and development and provides an interface to manage the input and output of the individual HEC analysis tools. It is currently only available in a beta software release. In this release the documentation is not consistent with the user interface, there are some software instabilities and complex data requirements not consistent with the available data for this study.

For these reasons, and because the scope of work for this study could be satisfied by using the individual HEC tools independently, without the need to organize them using HEC-WAT, this tool was not employed. It is anticipated, however, that some of the tools used in this study may be beneficial in the future to assist in planning the development and management of the watershed to reduce the negative impacts of flooding. For this reason, we recommend that ENTRO consider it as a future option for improving capabilities in flood preparedness and flood damage mitigation.

During the final workshop in Bahir Dar recommendations for additional investigation and analysis were presented. Additional work items that were completed are described below.

- To better represent the flooding of the Ribb River, Riverside collected additional survey points in the abandoned Ribb channel and integrated the obtained cross sections with the previously developed terrain model to allow proper representation of the river channel in a hydraulic model and to provide an improved basis for hazard mapping in the vicinity of the river channel

- To better understand the flow patterns and assess a potential attenuation effect, the model previously developed was updated to allow for unsteady flow simulations. Flow hydrographs for both the upstream river basins as well as the local runoff from floodplain areas was taken from the hydrologic simulation model prepared previously. The inflow hydrographs were scaled as necessary to provide estimates based on the contributing areas to the rivers.

- Riverside and its partners created a high level infrastructure mapping of the Lake Tana region. In order to yield more reliable results for the vulnerability and risk analysis and for representing spatial trends in development and location of population centers, Riverside obtained high resolution satellite imagery collected from the GeoEye-1 satellite to develop a more detailed mapping of the infrastructure in the Lake Tana region.

4.0 SURVEY AND DATA COLLECTION

An inventory of the existing available topographic data was performed in order to identify data gaps and the need for additional field surveys and data collection. A full data inventory can be found in ***Appendix D***.

4.1 Flood History Recordation

An early process in the project was to perform a flood history recordation of the area in order to collect and assess information regarding known flood levels from past flood events in recent years, in addition to the various return period floods.

There are several flood risk areas around Lake Tana. Two areas selected were the floodplains of the Fogera woredas and the floodplains of the Dembia woredas. These pilot areas are shown in ***Figure 4-1*** and ***Figure 4-2***. These are the two largest flood risk areas and the two areas with the greatest flood impacts. The flood risk area of the Fogera floodplain also extends into the Libo Kemkem woreda to the north of the Fogera woreda (SMEC, 2006). The areas that are affected by flooding frequently are listed hereunder (SMEC, 2006).

Figure 4-1: Topographic map of the Fogera plain.

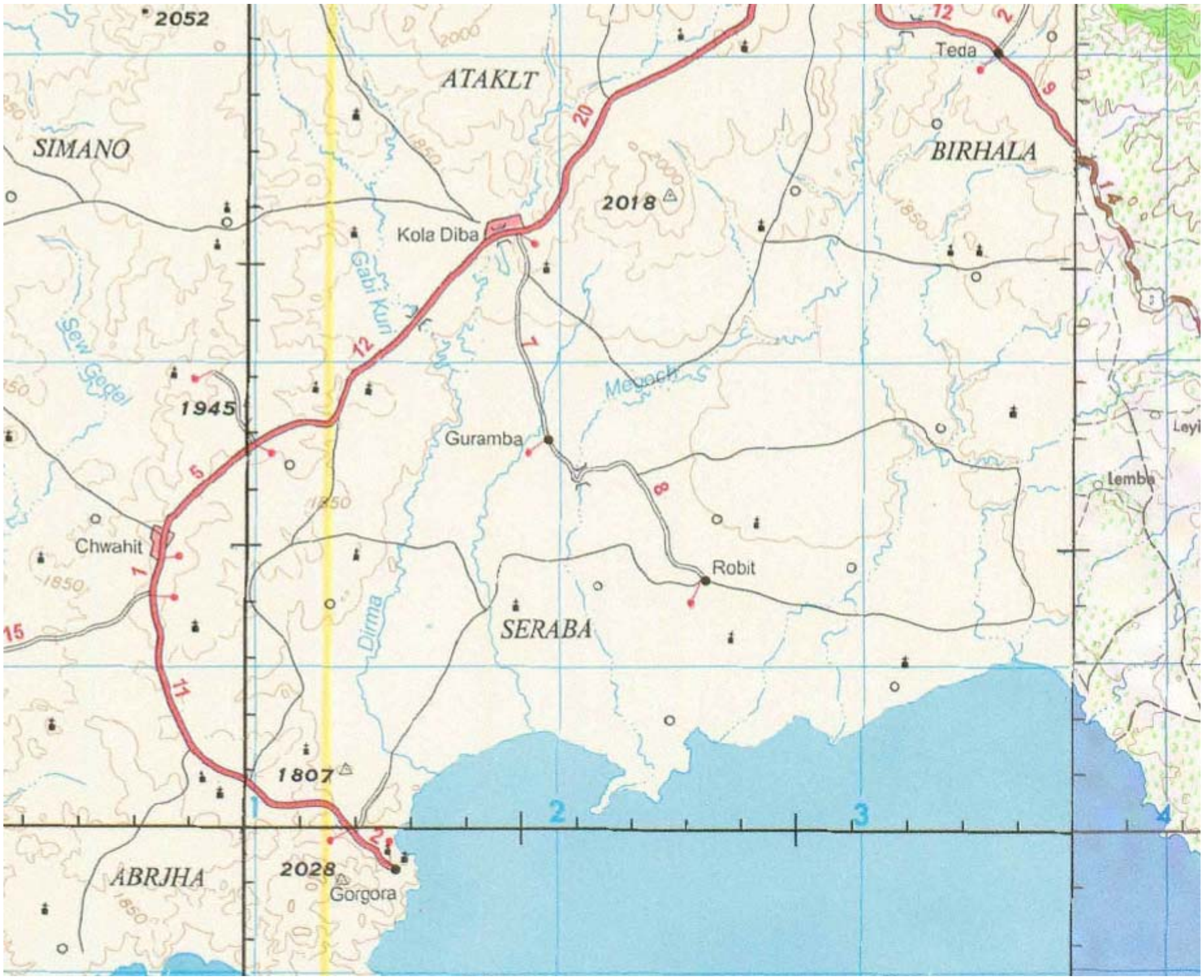


Figure 4-2: Topographic map of Dembia plain.

The Shana, Kuhar Mincheal, Abena Kokit, Wagtera, Kidist Hana, Nabega, and Shaga kebeles are most affected in Fogera Wereda, South Gondar Zone. Shana Tsion, Bambik, Gendassa, Tega Amba, Kaba, Tebaga, Bura and Agidana Kiring kebels are most devastated in Libo Kemkem Wereda, North Gondar Zone. In Debiya Woreda of North Gondar, the kebeles most affected are Tana Woyina Abo, Achera, Robit, Debir Zuriya Adisge, Arebiya Kesge Aba Libanes, Guramaamba Mikael. The total number of population affected could reach as high as 800,000.

4.1.1 Flood History

Very little information exists about the systematic documentation of flood history in the area. This report is based on an interview with local officials and references to existing local documents. The reports worth considering at this juncture are the Technical Background Paper on Flood Preparedness and Early Warning (SMEC, 2006), the Flood Report (ENTRO, 2006) and the Hydrological Study of Tana-Beles Subbasins (SMEC, 2008).

In the Abbay sub-basin, rural localities around Lake Tana are subjected to serious flooding, either from the lake or from tributary rivers in high runoff years (e.g. Rib, Gumera, Megech Rivers). The flooding causes serious hardship in virtually every year in particular localities.

Severe flooding has occurred in the Fogera floodplain and the Dembia floodplain. The causes of flooding are believed to be ponding of excess rainfall in floodplain depressions, rise of lake level and overflow of the rivers draining into the lake. According to Seid (2004), serious flooding also affected large numbers of people in 1964, 1988, 1993, 1994, and in 1995 when 44 people lost their lives. The flood of 1988 is worth citing at this point. It has caused a massive evacuation of the residents and damage to crops on the agricultural land.

Overflow from the Gumera and the Ribb Rivers resulted in flooding on 7 August 2006. Both Libo Kemkem and Fogera Woredas were affected. One person lost his life, 30,000 people were displaced, 45 houses were demolished and 2,478 domestic animals were swept away. Moreover, crops on 5,371 hectares of land were washed away.

Rising lake levels resulted in flooding on 30 August 2006. Twenty administrative units of seven Woredas surrounding Lake Tana were flooded in which more than 10,000 people were displaced.

September 2006 floods in Amhara Region affected about 100,000 people, displaced more than 37,000 people, and inundated more than 15,000 hectares of crop land (ENTRO, 2006). It was reported that 23 administrative units of seven woredas surrounding Lake Tana were affected with more than 10,000 people displaced and staying in temporary shelters. Some 13,000 individuals had been displaced due to the floods that hit three woredas of the South Gondar zone.

In the Fogera plains, floods killed three people, made 36,000 people homeless, inundated over 6,600 hectares of cropland, destroyed more than 320 beehives, damaged a school and several water points, spoiled stored seeds, and deposited large volume of gravel and sand on farmlands.

After the Tana outlet work (Chara Chara Dam) was built in 1997, rising of the Tana water level has been causing more intensive flooding of this area. Though previous designs of the weir ensured that historic flood levels would not be exceeded, it appears that actual construction of the weir did not conform to the original designs. Flood levels are also affecting the city of Bahir Dar which lies at the Southern shore of the lake. Since the reconstruction of the Chara Chara Dam in 1999, the lake levels in Lake Tana have been more regulated and flooding as a result of lake backwater has been reduced compared to the previous years.

4.1.1.1 Fogera Plain

In the Fogera plain, flooding occurs from the Gumera River near the southern end of the plain, and the Ribb 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 Gonder. Separated floodplains extend further up both rivers for many kilometers upstream of the highway. Inadequate cross-drainage through the highway embankment has aggravated upstream flooding in past years, but this has been partly corrected by recent addition of culverts.

The flooding in the northern part of the floodplain is primarily caused by bank overflow of the Ribb river and tributaries to the Ribb in the lower stretch of the river near Lake Tana. The inundation does not last long and most of the flood water drains back to the river in a period of days, as the water level in the river drops. Also, upstream of the bridge, the river regularly overflows, due to sedimentation in the river bed and obstruction caused by the bridge.

The flooding in the middle part of the floodplain is mainly caused by local rainfall and small local streams that end in depressions. Since this area does not have an outlet to the lake or to the larger rivers, the area remains inundated for a relatively long period. At times, floodwater from the Ribb in the northern zone or the Gumera in the southern zone may spill into the middle part of the floodplain.

Flooding in the southern part of the floodplain occurs primarily from the Gumera River as a result of overbank flow, which causes inundation in the vicinity of the river. The southern bank of the river is especially prone to flooding. However, at higher peak flows the northern bank is also observed to spill seasonally.

Korean consultants undertook flood frequency analysis and estimated the discharge conveyance capacity of the river channels downstream of the highway (EWRA, 1980). This study concluded that flooding of the adjoining floodplain would occur every year due to the low conveyance capacities. This conclusion is consistent with local reports. Flow velocities are impeded when floods coincide with high lake levels, contributing to sediment deposition. Flooding has been aggravated in the northern parts of the plain downstream of the highway by an avulsion of the Ribb River that took place *c*.1998 due to blockage of the old river channel. No clear or continuous channel connection to the lake has since developed, and field investigations by the SMEC Project Planning Team showed several new channels that now function during floods, but currently dissipate their flows in floodplain storage on both sides of the old river channel. The redistribution of flows caused by this development has aggravated flood depths and velocities in some places, and relieved them in others. Residents are still adjusting to the new conditions, and new channel development is likely to continue until a new river mouth is established.

4.1.1.2 Dembia Plain

In the Dembia plain, flooding occurs mostly on the lower part of the Megech and the Dirma Rivers. During high flows and high lake levels especially flooding occurs in areas near the lake due to overbank flow of the rivers in combination with the backwater effect of the lake. During high flows in the Dirma river water will flow in the overbanks and find its way to the Shenzli River, located in between the Megech and Drima River. In addition, during the field surveys frequent flooding due to sheet flow from higher areas was observed. Most of this type of flooding disappeared after one or two days.

Sediment deposition in very recent geological times has created a plain at the mouth of the Megech River. An avulsion that occurred *c*.1998 has caused an entirely new river course to develop over approximately the last 8 km to Lake Tana. The causes of the avulsion are similar to those in the Ribb River referred to above. The redistribution of flood flows has reduced the flood risk along the old river course, and dramatically increased the flood risk near the new river course, where inhabitants are still adapting to the new conditions of flood risk. In particular, the new main channel passes through and adjacent to the town of Robit, and severe flood impacts now occur there.

Reservoirs that are currently planned or under construction will limit the annual flooding in the floodplains. This will have a positive impact on the living conditions of people living in areas prone to flooding. However, there will be a negative impact on the recession agriculture that is based on receding flood waters in the floodplains.

4.2 Topographic Data Collection

Collection of topographic data was undertaken at the commencement of the project since it constitutes an essential part of the mapping process. The collected topographic data were developed previously for Ministry of Water Resources' irrigation projects around Lake Tana.

- In the Gumera region a topographic survey included the floodplain and the river. The topographic survey was conducted for the design of an irrigation dam and for laying out irrigation infrastructure. The raw survey data was delivered in an excel worksheet. The data included benchmarks. The total number of data points is roughly 33,000. The datum used is WGS_84. The data were generated in 2006.
- An aerial photo was generated for the purpose of preparing the topographic map of the Ribb irrigation command area. Hence, an orthophoto of the area was collected, as well as points generated from the same photo using photogrammetry techniques. The data were generated in 2008.
- An aerial photograph of the Dirma floodplain and elevation points generated from orthophotos were collected from the Ministry of Water Resources. The datum used is WGS_84. The data were generated in 2008.
- A topographic survey of the upper part of Megech River and floodplain was also conducted as part of the irrigation project. However, the survey does not extend to the lake.

In addition to the above survey data, 1:50 000 topographic maps were collected from the Ethiopian Mapping Agency.

4.3 Field Survey

A field survey was undertaken to collect detailed river cross section topographic data at selected points across the pilot rivers and across their confluences to Lake Tana. The data supports the hydraulic modeling and simulations of flows of the rivers for different flood scenarios. The scope of the ground survey assignment was prepared in detail and agreed upon by the joint consultants. The survey was undertaken by Shebelle Consult PLC (SCP) as part of the Riverside team.

A survey methodology was jointly prepared by Riverside, Tropics Consulting Engineers PLC (TCE), and SCP and with input from ENTRO for the purpose of a detailed river section survey in the pilot flood prone areas around Lake Tana. The survey methodology is included as ***Appendix A***. A layout of the proposed survey cross sections for each river was provided.

Figure 4-3 shows the proposed and actual cross section layout for the Ribb and Gumera Rivers. The figure shows the proposed cross sections along the old alignment of the Ribb River and the actual cross sections surveyed along the current alignment of the Ribb River. As part of the additional hydraulic analysis resulting from the final workshop, additional survey work was performed along the old alignment of the Ribb River to allow proper representation of the river channel in the hydraulic model and to provide an improved basis for hazard mapping in the vicinity of the river channel. ***Figure 4-4*** shows proposed and actual cross sections for the Dirm and Megech Rivers.

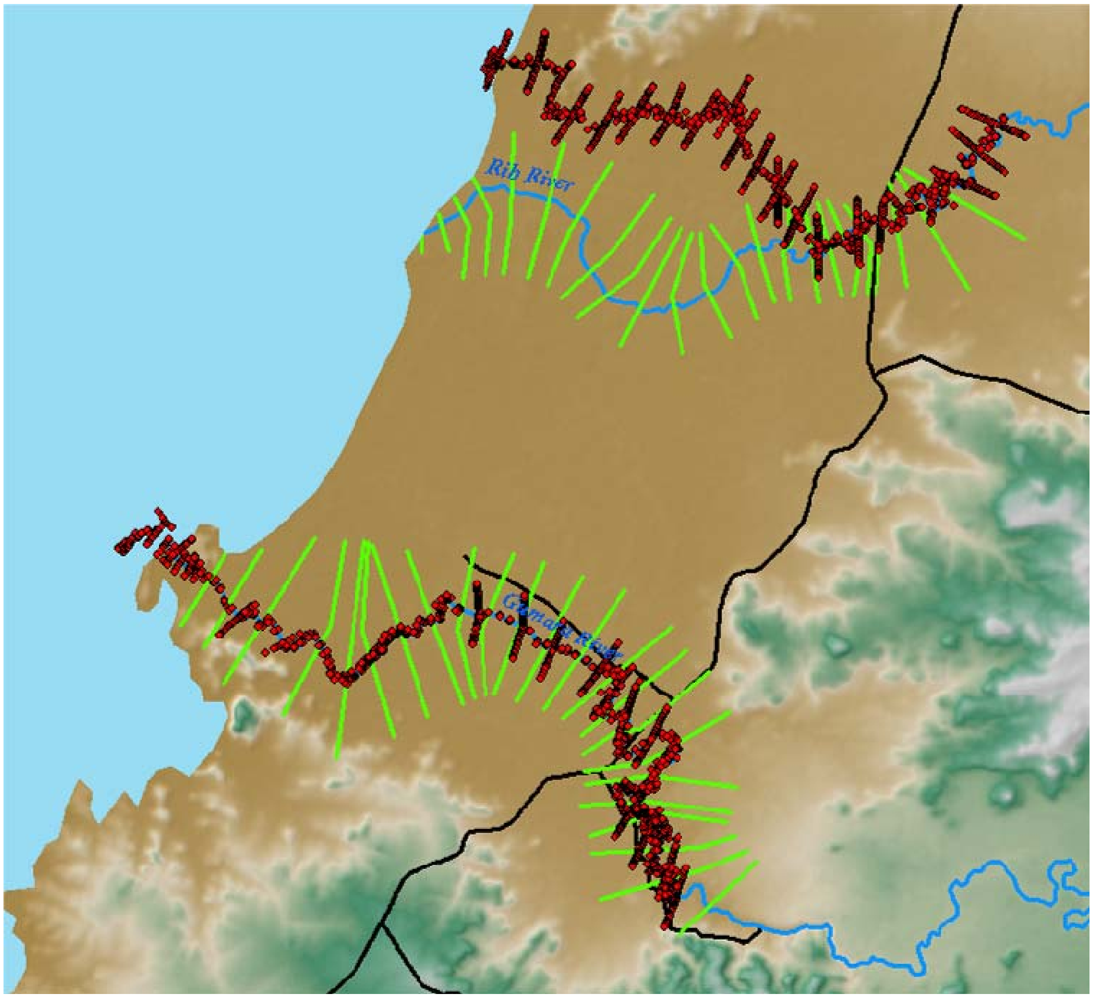


Figure 4-3: Proposed (green lines) and actual survey (red points) for the Gumara and Ribb Rivers.

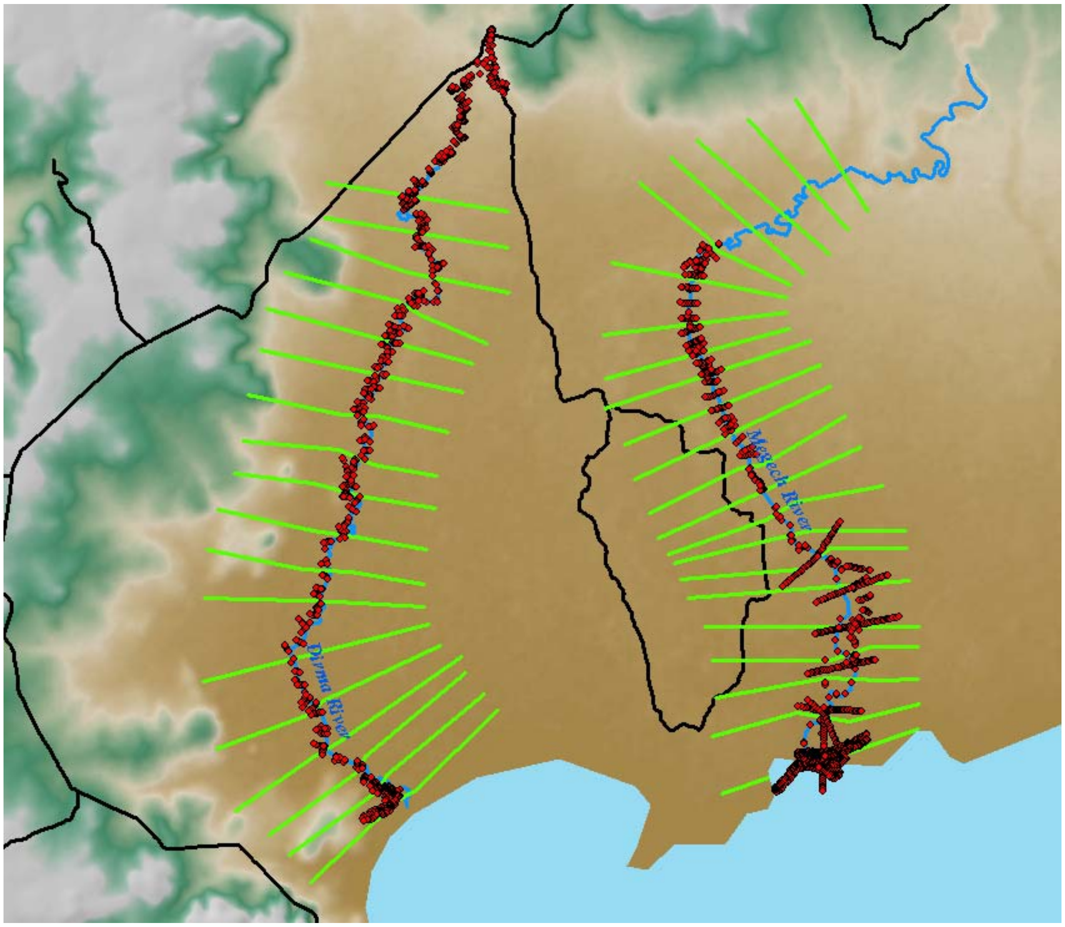


Figure 4-4: Proposed (green lines) and actual survey (red points) for the Dirma and Megech Rivers.

A paved highway circles Lake Tana from Bahir Dar to Gonder, enclosing the floodplains of the four rivers identified as flood prone, but generally maintaining a distance of 25 to 30 kilometers from the lake in the Fogera plain. Likewise, a main road encircling the Dembia plain maintains a distance of 16 kilometers from the lake near the Dirma and 2.5 kilometers from the lake near the Megech. During the inception workshop and subsequent field visits, reports from stakeholders and local population indicated that the flood prone areas were concentrated on the river reaches between the highway or main road and the lake shore. Indeed, the placement of these roads seems to coincide with high elevations of reduced susceptibility to flooding. Likewise, evaluation of the topography suggests that, even during extreme floods, the flow in the rivers will be confined to the main channels in upstream reaches of steep topographic relief, but could spill out of the channel and cause widespread flooding when it reached the floodplain. For this reason, the proposed cross sections include the complete river reaches from their intersection with the highway to the confluence with Lake Tana, in addition to extending upstream of the highway crossing several kilometers (5-6 kilometers for the Rib, Gumara and Megech and 1-2 kilometers for the Dirma) to assure adequate coverage for hydraulic modeling of affected areas.

The cross section layout and spacing was planned to balance available resources for the survey with the need for accurate representation of the river channels and flood plains. The goal of the survey was to assist in developing a digital terrain model suitable for extracting cross sections for hydraulic modeling and for flood hazard mapping based on simulated water surfaces. This was done by taking cross sections through the channel and extending into the flood plains at regular intervals of approximately 1 kilometer, while also taking additional survey points along the deepest section of river and river banks at closer intervals between cross sections. This approach permits a validation and adjustment of terrain models based on remotely sensed images for the flood plains, while permitting a more detailed description of the general channel shape, since the resolution of remotely sensed data cannot capture its detail. The cross section spacing was judged adequate to capture the variability of the channels based on observations during the field visit, and verified by the detailed field survey itself.

A Ground Control Point Establishment (GPS survey) was conducted from April 9-12, 2009. During this survey, the first GPS point at the national reference and its datum were identified. This national GPS point was then transferred to the pivot points around the rivers. In addition the site accessibility was evaluated and an overall socioeconomic assessment of the area was performed.

The detailed river cross section survey was carried out from April 28 to May 25, 2009 and is described in depth in ***Appendix B***. The survey team mobilized to the Dirma, Megech, Rib, and Gumera Rivers and conducted the ground surveys, orienting the effort from the respective control points. In addition, drainage structures found across the rivers, foot paths, settlements, trees, dykes, gauging stations along and near the river, etc., were surveyed.

The coordinate system and datum used for the area was UTM Zone 37N, WGS84. The vertical datum used was EGM96.

4.3.1 Established Ground Control Point

Observations at selected locations in the project pilot areas were conducted and permanent Ground Control Points (GCP) were established. The locations were selected based on relative locations, accessibility, convenience for conducting field tasks and the extent of the intended ground survey requirements. A Survey Grade Differential GPS was used to transfer the Ethiopian Mapping Agency (EMA) national ground reference/control point at Bahir Dar to the Ground Control Points (GCP). Two GCPs were established at each control station closer to each river. The progress was generally carried out in the northern direction.

Benchmarks and traverse stations were established later by referencing the CGP points using a Total Station. The detailed river cross section surveys were thus linked to the traverse stations. This was done first for the Megech River, next for the Ribb River, then for the Dirma River and finally for the Gumera River. The location of these ground control stations are presented in ***Appendix C***. These are also discussed under each river's sections in ***Appendix B***.

4.3.2 Benchmarks and Traverse Stations

All benchmarks alongside the rivers were established first by orienting the conventional ground survey along the two inter-visible GCPs project Control points by using Total Station. The bench marks were established to be inter-visible themselves, with the distance between any two bench marks varying from 250m to 950m. The number of traverse stations established for each river is discussed under each river's section in ***Appendix B***.

4.3.3 Cross Section Detail

Generally, detailed river cross section surveys were carried out for the channel at 300-450m intervals and for both the channel and the floodplain at one kilometer intervals along the river where appropriate and accessible. The river cross section surveys at one kilometer intervals extend about one kilometer to the left and to the right of the main channel banks. These cross sections were oriented perpendicular to the river section. In addition to the river cross sections, the water level at each cross section was recorded as per the prepared topographic survey methodology. A detailed discussion of the river cross section surveying is presented in ***Appendix B***.

While the proposed cross section locations were used as a guide, the actual cross section locations were taken based on accessibility and observation of river conditions in the field. During the GPS survey, the crew was able drive or walk far upstream in each of the rivers accompanied by local people to identify the sites where the rivers were observed to have been contained within the channel. Thus, knowing the area where the rivers do not breach out of the banks, and having visited the areas where flows were well contained, the width of the survey was limited so as not to expend effort in areas that are not subject to inundation. Geomorphic evidence, such as remains of grasses, leaves and high water marks on the side channels of the rivers in the reaches visited also suggested appropriate limits on the extent of the survey in upstream reaches.

Very few structures were encountered in the survey area (flood prone area) that would have a significant effect on the flow patterns, except the bridges at the main road crossing for each river. Full cross sections were surveyed at bridge sites, including the pier bottoms, top of head walls and road edge levels.

A culvert was found on the way to Wanzaye, far upstream of the Gumara highway bridge. The culvert invert level, culvert top level, road edge level and top of head wall over the culvert were surveyed. This culvert is believed to be the only culvert encountered in the surveyed area. Other structures including foot paths, transmission lines, huts, etc were surveyed as point data.

Dykes were also surveyed at intervals along the length the rivers, inasmuch as cross profiles of the river banks extend beyond the dykes. It is expected that the existing dykes will not serve as a permanent flood blockage owing to the fact that the materials are often silty sand and are not well compacted.

4.3.4 Topography and Soil

Generally, the topography of the entire study area around the Megech River, the Dirma River, the Ribb River, and the Gumera River is sufficiently flat. The soil is largely black cotton soil and the floodplains are also extensively farmed. The people cultivate fruits, vegetables and crops using water from these rivers. The Fogera Meda /Fogera floodplain is inundated by both Ribb and Gumera Rivers during the main river season.

4.3.5 Infrastructure and Vulnerable Structures

During the field visit, infrastructure was observed in the floodplain. The surveying team identified part of the infrastructure and incorporated these structures into the data.

The area is mainly agricultural land covered by various types of crops. Crops grown include increasing amounts of rice which appears to be very profitable for the farmers. The total area of recession cropping is approximately 17,500 ha, based on the agricultural land located in the flooded areas. Moreover, high voltage transmission lines, earthen roads, tukuls, and schools are some of the infrastructure prone to flooding.

4.3.6 Difficulties Encountered

There were difficulties encountered in performing the survey that should be noted for reference during subsequent surveys that may take place in preparation for specific investment projects in the floodplains.

The Ribb River meanders at a number of places, in addition to being wide and deep. Moreover the weather was foggy for about two days and hampered the surveying activities due to visibility problems.

The Gumera River is very wide, deep, and long. Due to dense vegetation along the banks of the river particularly downstream of Hode Gebeya, there were locations where it was not possible to target beyond the banks and into the floodplain. To overcome this the survey crew set up a number of instrument stations along a single axis and shifted some of the locations where floodplain cross sections were taken. Moreover, the Gumera River was very marshy near the lake, which accounted for one more week than planned to finish the survey.

A regional body has deployed excavators at some locations on the Gumera and Ribb Rivers, including near the bridge and communities, to dredge the silty-sand river bed material and dump it along the river banks to provide temporary protection against inundation of the communities during the rainy season. Although this has been a temporary flood coping mechanism in recent years in the area, it is difficult to see how dredging would result in a significant change to the river conveyance because the sediment load during the flood quickly replaces the dredged material. Likewise, the material deposited on the riverbanks is highly erodible and is not placed uniformly, so that breaches and washout of the embankment will result in little protection of the communities from large floods. For purposes of the flood risk mapping study, the most likely condition of the river channel that would coincide with the annual flood peak is that which is represented by the field survey cross sections with levees included in the terrain but not represented as confining the flow.

4.4 Terrain Data Development

Hydraulic modeling and flood mapping require an accurate digital elevation model (DEM) from which to extract cross sections and map the flood surface. The DEM must be of large enough extent to cover the possible limits of flooding as well as contain enough spatial detail within the river channel to enable accurate hydraulic modeling. These two needs present a dilemma when developing a single elevation model. The best way to create an accurate elevation model would be to use survey data, but this is cost prohibitive to cover such a large area. A second, more cost effective option would be to use available Digital Elevation Models (DEMs). These DEMs cover a wide extent but typically do not contain the needed spatial detail within the river channel.

Throughout this document the term DEM will be used to describe data that depicts the terrain surface. A DEM can be in a gridded raster format or a triangular irregular network (TIN). In the terrain development task the Riverside team has created a DEM in TIN format.

In order to create an elevation model that would accurately map the floodplain and hydraulics in the river channel, a multisource model was created. The field survey data has the highest level of detail and was used to represent the river channel. The 90 meter DEM was used to capture the floodplain.

4.4.1 Evaluation of 90 meter DEM

Differences exist between the 90 meter DEM and the elevations determined from the field survey. Potential sources of these differences include error in the DEM, error in the survey, and sampling differences between the two. The DEM represents the average elevation over a 90 meter grid cell, whereas a given survey point represents the elevation of a point no larger than the base of the survey rod. It is therefore possible to observe differences between the two data sources that do not imply error. It would not be surprising, for example, to observe a difference of plus one meter at one point and minus one meter at another point within the same 90 meter grid cell. ***Table 4-1*** presents the statistics associated with the differences between the two data sources. The count refers to the number of survey points used in the comparison. These observations do not include survey points within the river channel, where the DEM cannot represent the vertical relief and inclusion of the associated observations in the statistics would obscure the evaluation of differences in the floodplain.

Table 4-1: Differences between Survey and 90 m SRTM (Survey - SRTM, [m])

River	Count	Min	Max	Mean	Std. Dev.
Gumera	2312	-12.3	14.0	2.3	1.7
Ribb	1345	-17.6	18.4	1.9	1.6
Megech	1309	-2.8	5.1	0.5	1.0
Dirma	752	-2.0	14.8	1.8	2.6

4.4.2 Other data sources evaluated

There are a number of other sources of data for elevations in the floodplain, including contours in the Dirma derived from orthophotos, as well as previous land surveys in the Gumera. These other data sources often did not agree with the field survey data and there was no available reference information to reliably ascertain datums used in placing the existing contours and land surveys. In addition, these additional elevation data sources did not provide a complete and consistent coverage of the flood plain areas.

During the project, the United States NASA space agency and the government of Japan released a publicly available 30 meter Global Digital Elevation Model (GDEM). The DEM was created from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite imagery. Riverside has evaluated the potential for using this data in the final flood maps. The elevation values of the 30 meter ASTER DEM were compared with the elevation values from the 90 meter SRTM DEM and the survey points. Sample points were collected across the 30 meter and 90 meter DEMs. The difference between the sample elevation points was calculated. In most cases the values varied greatly. ***Table 4-2*** shows the statistics of the sample points for the Fogera plain and Dembia plain.

Table 4-2: Statistical comparison between ASTER and SRTM Elevation Values [m].

Floodplain	Min	Max	Mean	Standard Deviation
Fogera	**-31**	**102**	**7.35**	**5.35**
Dembia	**-73**	**51**	**1.27**	**9.17**

The statistics show that in some cases the elevation values vary greatly. The Fogera plain contains a mean elevation difference of 7.35 meters. While the Dembia plain has a much smaller mean difference at 1.27 and standard deviation of 9.17, indicating significant variability around this mean.

Riverside attempted to adjust the 30m ASTER DEM using these statistics to better match the SRTM and survey data. In the Fogera plain 7 meters was added to the base elevation of the 30m ASTER DEM and then used to build a TIN with the survey data using the procedure described in ***Section 4.4.3***. In the

Dembia plain the 30m ASTER DEM was used without adjustment to build a TIN with the survey data. In both flood plains the transition between the survey data and the 30m ASTER data was less than optimal. The variation in elevation and difference from SRTM and surveyed elevation values appears not to be constant and it was concluded that a uniform shift is ineffective. In both flood plains many anomalies were also discovered that could not be explained. The 30m ASTER data contains features with large topographic relief that seems unreasonable. Some examples include roadways that are up to 60 meters higher than the surrounding floodplain and other features that are simply inexplicable after reviewing topographic maps and aerial photography.

The documentation, which accompanies the 30m ASTER DEM, confirms Riverside's findings. The documentation states that the vertical accuracy is 20 m with 95% confidence and that some tiles have substantially better than 20 m accuracy and some tiles have substantially worse than 20 m vertical accuracy.

Extensive review and evaluation of these data sources led our team to conclude that the 90 m DEM data showed the greatest consistency, quality control, and agreement with the field survey data collected for this project.

4.4.3 Procedures for TIN Creation

A three step procedure was used to create a TIN with multi-resolution elevation models:

1. Create a TIN surface for the river channel from the survey data.

2. Extract elevation point data for the floodplain from the 90 meter SRTM gridded DEM.

3. Combine the river channel TIN surface with the elevation data from the 90 meter SRTM gridded DEM.

4.4.3.1 Creating a channel TIN

Processing the survey data and creating a TIN for each river channel was the first step in creating the multi-resolution elevation surface. The survey data consists of point locations with x, y, and z values and a classification code. Surveyed locations include river centerline, right and left water's edge, right and left bottom of bank, right and left top of bank, spot height, and other points of interest such as foot paths, wooden bridges, dykes, mud houses, and culverts. These survey points and associated elevations were used as inputs to create a preliminary TIN. ***Figure 4-5*** displays a preliminary TIN using only the survey points.

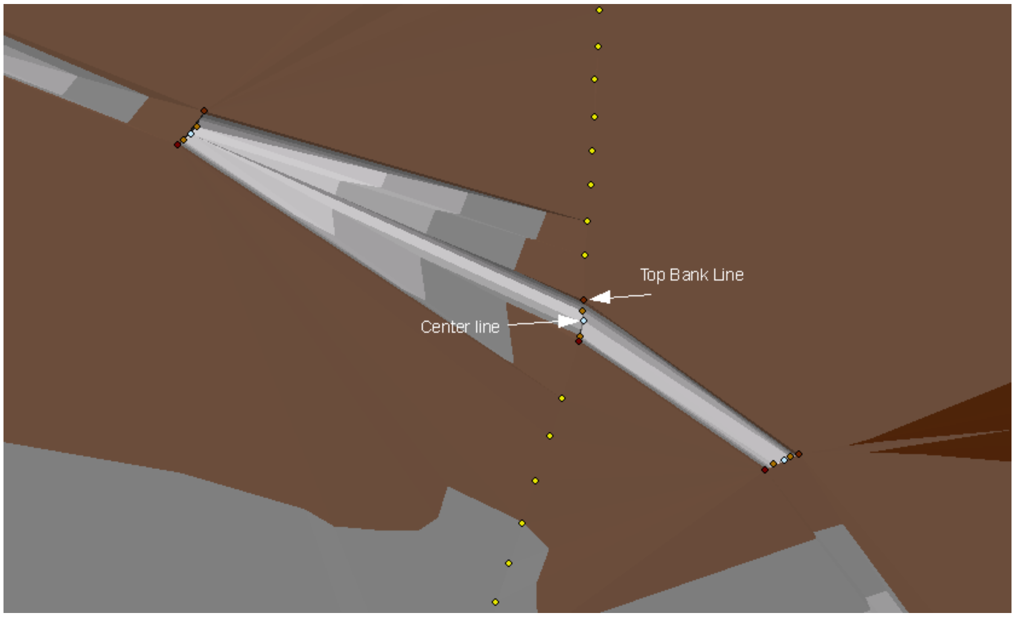


Figure 4-5: Preliminary TIN generated with the survey points.

The survey points were then further used to refine the TIN. The survey codes were used to identify and digitize stream centerlines and top of bank lines. The centerlines and bank lines were converted into 3D features and used as hard breaklines when forming the TIN. Breaklines maintain appropriate contouring by providing a known elevation. When the TIN is created, interpolation is not allowed to occur across breaklines. Using breaklines along the known river channel location preserved continuous channel topography. ***Figure 4-6*** shows the TIN with the breaklines.

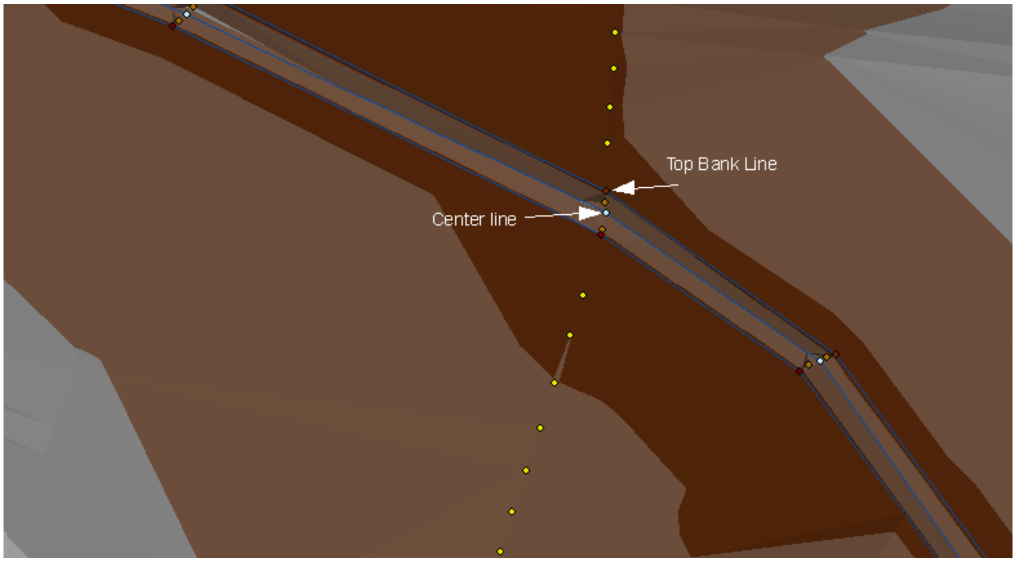


Figure 4-6: The TIN with the breaklines.

4.4.3.2 Extracting floodplain elevation data

A second step in creating the multi-resolution elevation model was to represent the floodplain area outside of the channel survey area. To create this surface, elevation points were extracted from the 90 meter SRTM DEM. Transects were set up at 90 meter intervals in the DEM. Sample points were then taken every 90 meters along each transect. These points were incorporated into the TIN surface as mass points.

4.4.3.3 Creating a combined channel and floodplain TIN

In order to create a single TIN surface, the results from the channel survey processing and the SRTM DEM processing were combined using ArcGIS 3D Analyst. When creating the single TIN, the survey points and SRTM transect points were used as mass points and the bank lines and stream centerline were used as hard breaklines. Building the TIN in this manner allowed for editing of the data inputs and quick rebuilding of the TIN. ***Figure 4-7*** displays the final TIN with the transect lines used to extract data from the 90 meter DEM.

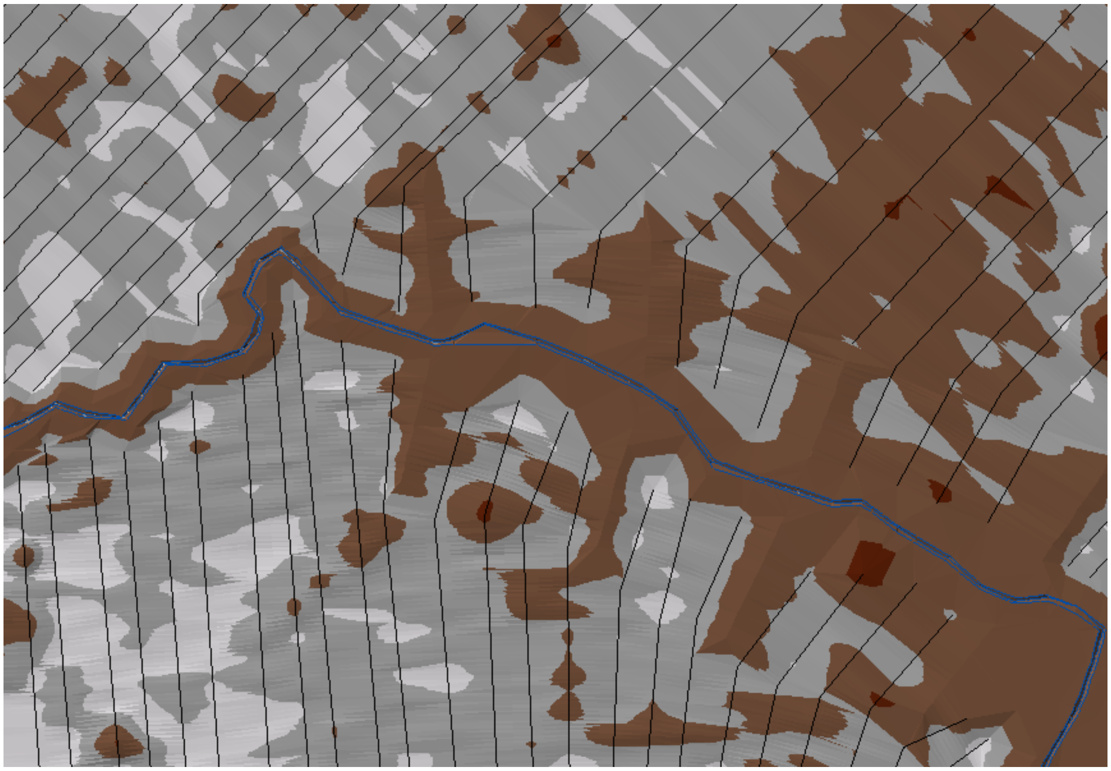


Figure 4-7: The final TIN with the transect lines.

In many cases there is additional stream alignment information available from satellite images that is complementary to the survey alignment, permitting interpolation of the stream banks and centerlines between surveyed cross sections. To take advantage of this information, additional top of bank and centerline points were interpolated and used as input for breaklines. ***Figure 4-8*** displays a location where top of bank points were interpolated to model a bend in the channel between surveyed cross sections. The green points are the actual survey points.

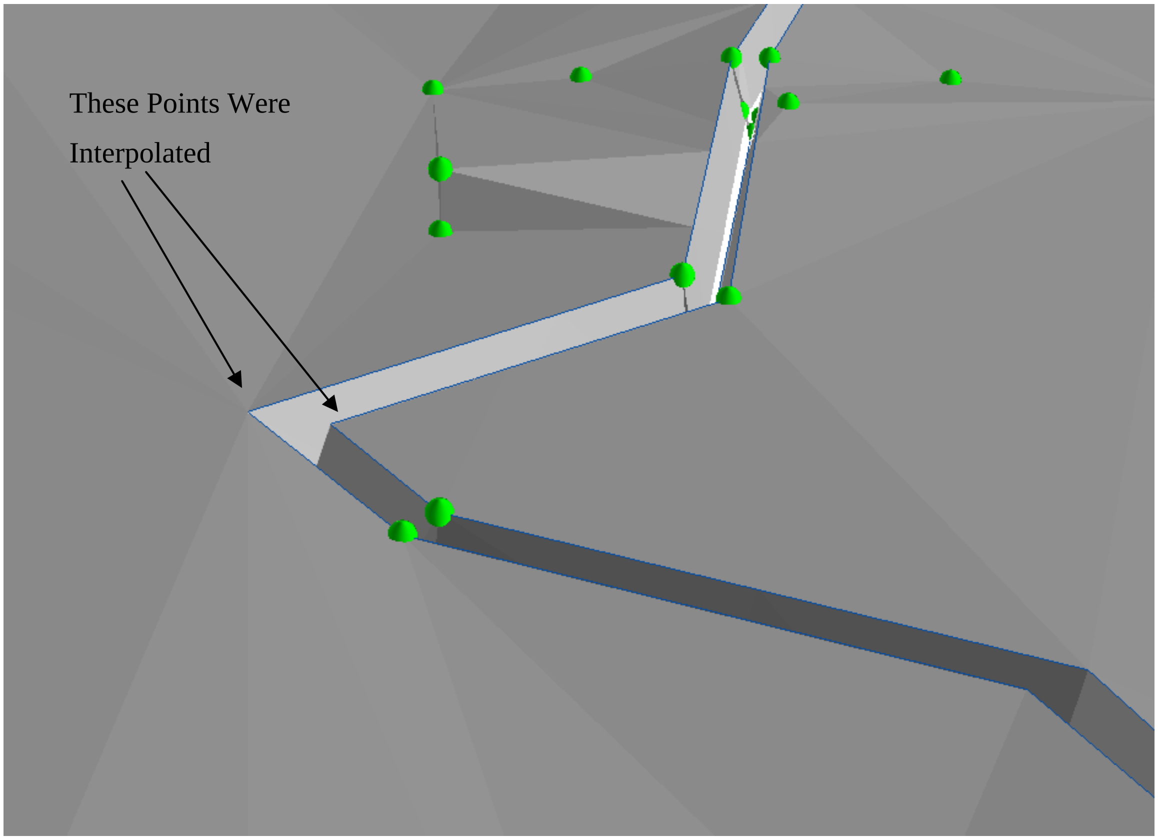


Figure 4-8: Interpolated channel bend

4.4.4 Quality Control Procedures

Quality control for cross-section survey and TIN creation consisted of two procedures. The first involved review of the survey points and bank line processing. The second involved manual review of the completed TIN.

A quality control check was performed on the survey data. Outliers in the elevation data (0 meters) were removed. Misplaced decimal points were corrected (i.e. 17975.362 corrected to 1797.5632). Bank lines and stream centerlines were reviewed to ensure that they connected true points along the bank and the bottom of the channel.

After the survey data were reviewed, a TIN was created with the survey data and reviewed in 3D using ArcGIS ArcScene and a vertical exaggeration of 10. This was a very useful tool for visually evaluating the terrain. Banks were inspected as well as peaks and holes that may be incorrect. If incorrect data were discovered in any step of the QA/QC process, the data were corrected and a new TIN was built. ArcGIS models were built to assist in the processing and TIN generation.

When the survey TIN was reviewed and complete it was combined with the digital elevation data from the flood plain to create a single TIN for the floodplain. This routine involved collecting sample points from the DEM for input as masspoints in the TIN. After the TIN was created it was again reviewed in ArcScene. Using ArcScene a slight bias or shift in the elevation was observed in the transition between the surveyed channels and the DEM floodplain. The difference in the survey data and DEM was calculated along the length of the channels. These differences were used to create a deviation surface TIN. The deviation surface was used to adjust the elevation of the DEM sample points around the survey. The new DEM sample points and survey data were then combined a final time to create the final TIN. The new TIN effectively removed the bias between the survey and DEM creating a smooth transition between the two datasets.

5.0 HYDROLOGIC MODELING

The purpose of the hydrologic analysis is to develop discharges for each river that are representative of peak flows for floods for a range of probabilities. A stream gage is present on three of the four rivers being modeled, permitting a frequency analysis of annual peak flows based on historical peak flow data. In the absence of accurate historical data, a hydrologic simulation may be performed to estimate flood flows based on simulated runoff from design storms representing rainfall at the corresponding frequencies. Because of uncertainty regarding the quality of the historic flow data, which is due largely to concerns about the quality of rating curves at the gage locations, stakeholders requested a basic hydrologic simulation as part of the hydrologic analysis. A subsequent decision to develop study results based on unsteady hydraulic routing required exclusive use of the hydrologic simulation results instead of frequency based discharges.

For this study, therefore, a hydrologic analysis of the four drainage basins of the Lake Tana region was performed to estimate the magnitude of peak floods corresponding to 2, 5, 10, 50 and 100 year return periods. The following two approaches were used:

1. A flood frequency analysis based on available historic data from hydro-meteorologic stations,

2. A rainfall-runoff model to compare against the derived flood flows from the frequency analysis, and to support unsteady hydraulic routing in the rivers.

Although a 2-year frequency flow was not included in the original scope of work, it represents a commonly occurring flow magnitude that local inhabitants would identify with and provides a valuable reference for understanding and interpreting the maps. Consequently, it is included in the analysis. In accordance with the overall project objectives of demonstrating a procedure for the generation of flood maps in the Lake Tana region, a simplified flood frequency analysis and rainfall runoff modeling were undertaken.

5.1 Lake Tana Region Hydrology

Ethiopia is generally characterized as residing in a tropical to sub-tropical climate, with the primary rainfall season typically occurring between the months of June to September. A secondary rainfall season usually occurs from February to May. The remaining months (October to January) tend to be the driest period. In general, the annual rainfall amount decreases as one moves to the northeast region of the country. The rainfall patterns over Ethiopia are driven by synoptic climatic mechanisms which tend to behave predictably over homogeneous regions. The main synoptic influences on the hydrometeorology in Ethiopia include the monsoon effects from the Indian and Atlantic Oceans, the impacts of the Inter-Tropical Convergence Zone seasonal movements (to the north during the summer months), and the influences of the low-level jet stream. During the main rainy season, precipitation amounts are strongly influenced by sea surface temperatures and the active jet stream movement northward (WWDSE 2007).

The project region around Lake Tana tends to be hydrometeorologically homogeneous with minor orographic impacts on precipitation evident near Debre Tabor in the east and Gish Abay in the south. A study by the Ethiopian Roads Authority (ERA 2002) characterizes the entire project region by a single set of Intensity Duration Frequency (IDF) curves.

5.2 Flood Frequency Analysis

A flood frequency analysis was performed to estimate flood flows for 2, 5, 10, 50 and 100 year recurrent intervals in the Gumara, Ribb, Megech and Dirma basins in the Lake Tana Region. ***Figure 5-1*** shows the location of these basins along with the hydro-meteorologic monitoring network. Available historic data from this network were reviewed and the hydrologic response observed at specific stations were analyzed to develop flood flows for the desired return periods.

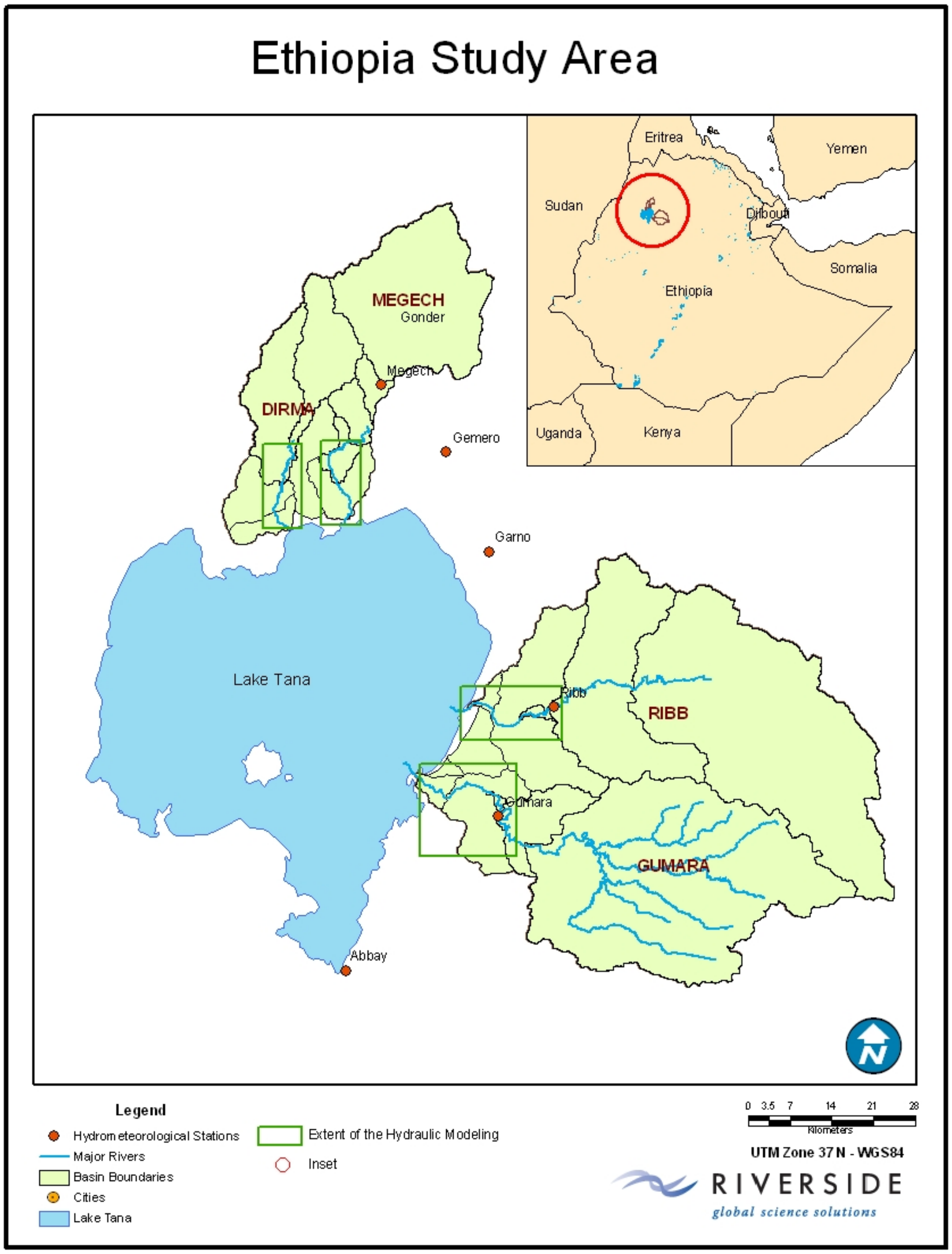


Figure 5-1: Investigated drainage basins and streamflow monitoring network.

Only a limited amount of continuous, daily streamflow data were available for the drainage basins of interest; however, these data do provide a sample of hydrologic response which is useful in characterizing the region. ***Appendix E*** shows annual hydrographs based on the available daily data for the Gumara, Ribb, and Megech streamflow stations.

For each station, the appendix includes three plots: the first plot is from the year within the available record that has the highest recorded discharges; the second plot is representative of an "average" hydrologic year; and, the third plot is from the year within the available record that has the lowest recorded annual high flows. From these streamflow plots, it is evident that the annual peak discharges in the region consistently occur during the mid- to late summer season. A large majority of the annual runoff volume occurs within this period (July – Sept). The variation in the level of Lake Tana also provides information that is useful in characterizing the regional hydrologic behavior. A plot of the complete available period of daily lake level stage is given in ***Figure 5-2***.

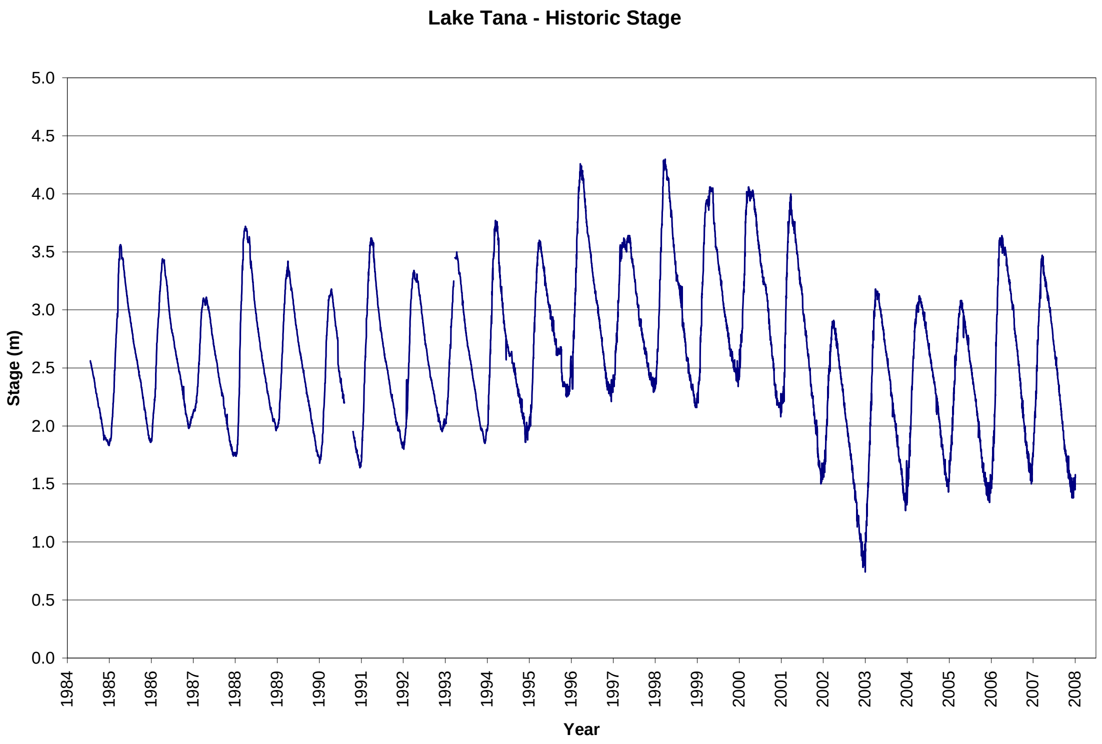


Figure 5-2: Historic Lake Tana level.

5.2.1 General Methodology

For the flood frequency analysis, the Log-Pearson Type III (LP3) distribution and the Extreme Value Type I (EVI) distribution were fitted to the available peak flow data at the Gumara, Ribb and Megech gages. A detailed description of the LP3 and EV1 distributions can be found in Chow et. al (1988). The US Geological Survey (USGS) computer program PeakFQ was used for the LP3 distribution statistical analysis. PeakFQ software together with its user manual are available at http://water.usgs.gov/software/PeakFQ/.

A different analysis was required for the Dirma basin, due to the lack of streamflow data to perform statistical analysis. The analysis for the Dirma basin is explained in ***Section 5.2.4*** of this document. Peak flow estimates were developed for the gaged areas of the basins. An additional analysis was performed to estimate the flows of ungaged areas within the floodplains downstream of the gage locations as described in ***Section 5.4*** of this document and ***Appendix M***.

5.2.2 Available Data Used in the Analysis

Historic daily peak streamflow data were available for seven (7) points in the Lake Tana region. Of these locations, four (4) are located within the drainage area which contributes to lake inflows. Three (3) of the available historic data points are located downstream of the lake outlet and their data do not necessarily reflect natural runoff behavior or hydrologic characteristics similar to the area of interest; therefore, these points were omitted from the analysis. Also available were data representing the historic peak lake levels of Lake Tana. These data are valuable for determining appropriate downstream boundary conditions for hydraulic model development. Analysis of the historic lake level data was, therefore, incorporated as part of this analysis. ***Table 5-1*** summarizes the available data used in the flood flow development/frequency analysis.

Table 5-1: Available data used in the flood flow development/frequency analysis.

POINT NAME	AVAILABLE HISTORIC PERIOD	NUMBER OF DAILY PEAKS AVAILABLE	NUMBER OF INSTANT. PEAKS AVAILABLE
Gumara near Bahir Dar	1959 – 2003	43	14
Ribb near Addis Zemen	1959 – 2003	42	18
Megech near Azezo	1980 – 2003	24	0
Gilgel Abbay near Merawi	1973 – 2003	31	7

The available data represent officially recorded daily and instantaneous peak values which presumably have already been through quality control procedures; therefore, the data were not altered from their original form. ***Figure 5-3*** shows a plot of the annual peak daily flow data available at the Gumara, Ribb and Megech gages. The year to year variability of the Gumara and Megech measurements is large. Also, measurements of the Ribb gage have a decreasing trend from about 1974 and the variability in flow discharge magnitudes is lower than the variability at the other two gages. It has been suggested that the rating curve used to estimate discharges from observed stages at the Ribb gage underestimates flows that exceed the channel banks.

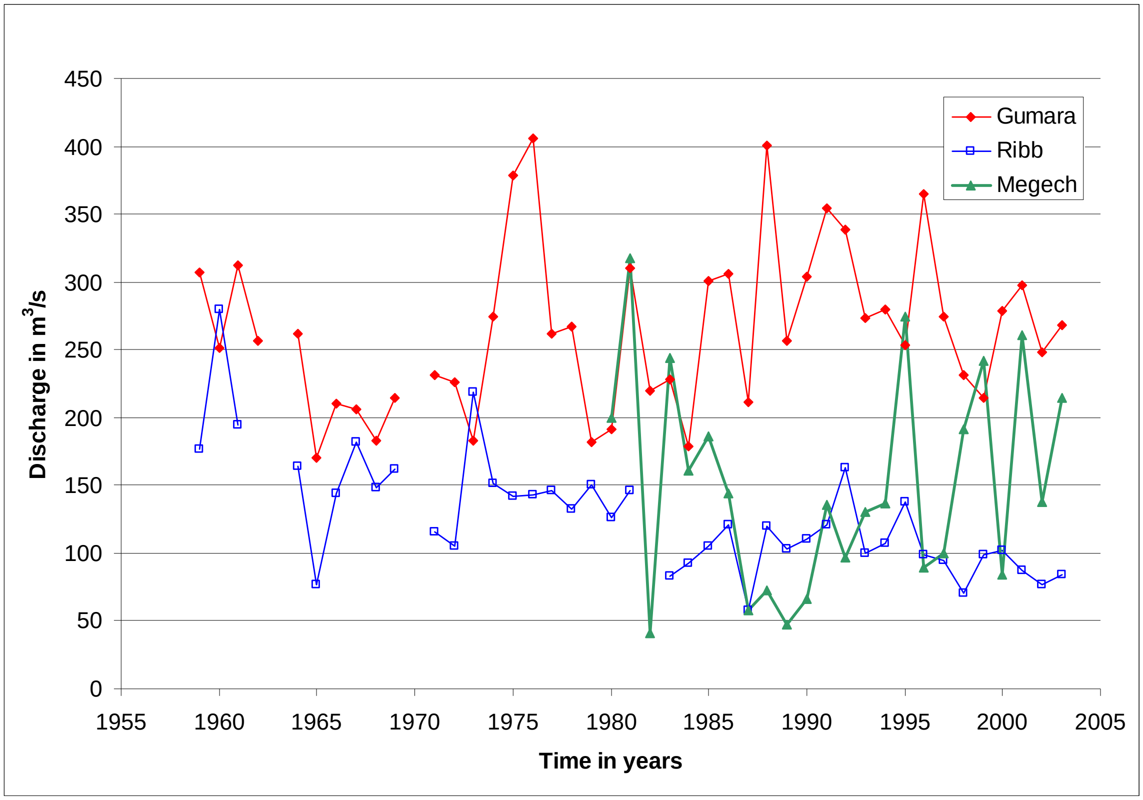


Figure 5-3: Daily peak streamflow data at Gumara, Ribb and Megech gage stations.

5.2.3 Required Data Adjustments

Because the overall project goal is to map the maximum inundation extents for flood events of various return periods, the input data for the flood frequency analysis should represent the instantaneous maximum streamflow. As seen in ***Table 5-1***, the bulk of the available data represents the peak daily average. For basins with times to peak of much less than 24 hours, the peak daily average is lower than the maximum instantaneous peak which occurred during that day. Therefore, to translate these daily averages into instantaneous peak values, the daily values were scaled upward by a peaking factor. In three cases (Gumara, Ribb, and Gilgel Abbay), peaking factors were determined by comparing the available instantaneous peak values to their corresponding daily average values. For each of these stations, the available peak daily average values were plotted against the calculated peaking factor to see if a relationship between the daily discharge magnitude and the peaking factor value was evident. These plots are given in ***Appendix G***. As seen on these plots, no clear relationships exist. Therefore, the average calculated peaking factor for each site was used to scale the daily average values (for years where instantaneous values were not available) so that they approximate instantaneous peaks. For the Megech, no instantaneous data were available; therefore, a peaking factor of 1.300 (the approximate average of the factors at the other sites) was used. ***Table 5-2*** shows the peaking factors which were calculated or estimated and used for each location. Final adjusted flow time series were plotted for the Gumara, Ribb and Megech stations and are included in ***Appendix G.***

Table 5-2: Calculated/estimated peaking factors.

POINT NAME	PEAKING FACTOR
Gumara near Bahir Dar	1.310
Ribb near Addis Zemen	1.296
Megech near Azezo	1.300
Gilgel Abbay near Merawi	1.324
Lake Tana Level	-

5.2.4 Flood Flow Estimates using Log Pearson Type III and Extreme Value Type I Distributions

The PeakFQ program was used to fit the LP3 distribution to the adjusted peak flow data for the Gumara, Ribb and Megech basins. Inputs to the program included the adjusted flow data and the station skewness. Preliminary results of the flood frequency analysis were developed from an estimate of a generalized skewness (arithmetic averaged of station skewness), because it has been found that a regional LP3 approach minimizes bias introduced by small samples (Bulletin #17, Interagency Advisory committee on Water Data, 1981). However, peak flow estimates generated from the station skewness differ only about 1.5% to 9.8% from the initial estimates. These differences were considered small compared to the degree of uncertainty introduced by a regional analysis based on only four stations. Consequently, sample skewness was used in the final analysis. ***Table 5-3*** lists the skewness of the stations.

Table 5-3: Sample skewness (sample data includes the peaking factor adjustemnet).

POINT NAME	SAMPLE SKEWNESS
Gumara near Bahir Dar	-0.044
Ribb near Addis Zemen	-0.068
Megech near Azezo	-0.391

Because streamflow data are not available for the Dirma basin, flood flows for the Dirma catchment were estimated by transposing the flood flows from the Megech basin as follows:

$$\frac{Q_{fDirma}}{Q_{fMegech}} = \left(\frac{A_{Dirma}}{A_{Megech}}\right)^{n}$$

Where Q_{fDirma} is the Dirma flow discharge for a given frequency of occurrence, $Q_{fMegech}$ is the Megech flow discharge for the same given frequency of occurrence, A_{Dirma} is the basin area of Dirma catchment, A_{Megech} is the basin area of Megech basin, and n is an exponent less than 1 (USGS 2000). Drainage area has been used in this analysis because it is highly correlated with flow discharge (Knighton 1998). Reported values of the exponent *n* are often between 0.6 and 0.9 (USGS 2000, Knighton 1998). Because there are not enough data to estimate the *n* value, an initial value of *n* = 0.8 was used and the resulting flows were verified with the results from the rainfall runoff model presented in ***Section 5.3.5***.

Megech and Dirma basins are adjacent catchments with similar land use and soil type characteristics (***Appendix J***). Additionally, both catchments are subject to the same meteorological regimes as confirmed by previous regional analysis performed by the Ethiopian Road Authority (ERA 2002) (See ***Figure 5-10*** in ***Section 5.3.2***). Consequently, the estimation of flood flows for the Dirma catchment based on Megech flood flow estmates is a reasonable approach. As pointed out before, Dirma basin does not have a streamflow gage. However, for analysis purposes a gage site was selected as the outlet of Subbasin 1 (***Figure 5-4***), where the terrain transitions from mountains to plains. ***Appendix H*** contains the output file from the PeakFQ program for the LP3 distribution.

The Extreme Value Type I (Gumbel) distribution also was fitted to the data and compared with the LP3 results. ***Table 5-4*** summarizes the flood flows from the statistical analysis using both the LP3 and the EV1 distributions. The flood estimates for the Dirma basin are developed using an *n* value of 0.8 and gaged areas of 513.6 km^2 and 57.8 km^2 for Megech and Dirma basins respectively.

Table 5-4: Flood flows estimates using LP3 and EVI distributions.

STATION NAME	**2-yr Peak (CMS)**	**5-yr Peak (CMS)**	**10-yr Peak (CMS)**	**50-yr Peak (CMS)**	**100-yr Peak (CMS)**
Gumara					
LP3	329	404	448	539	574
EVI	325	397	445	551	596
Ribb					
LP3	148	188	212	262	282
EVI	142	185	214	278	305
Megech					
LP3	177	278	346	491	550
EVI	180	270	330	461	516
Dirma					

LP3	69	108	135	191	214
EVI	70	105	128	179	201

Figure 5-4, Figure 5-5, Figure 5-6 and ***Figure 5-7*** include a comparison of the LP3, EV1 and the station data for each river. The station data were plotted using the Weibull plotting position formula (Chow et. al 1988).

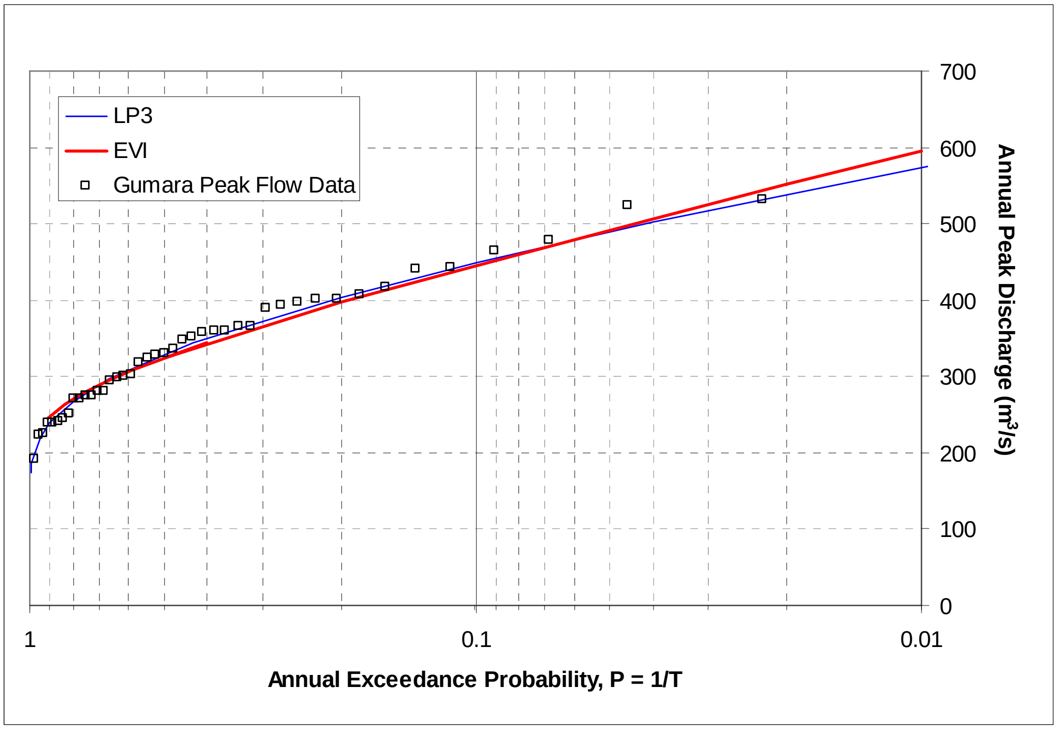


Figure 5-4: Gumara peak flow probability plot.

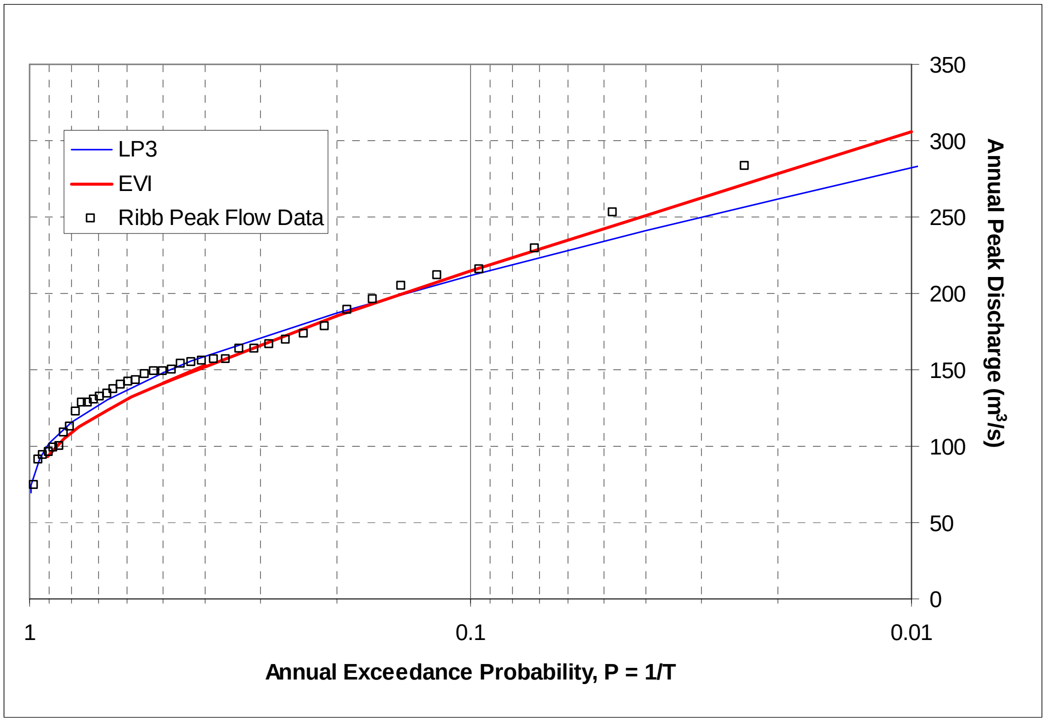


Figure 5-5: Ribb peak flow probability plot.

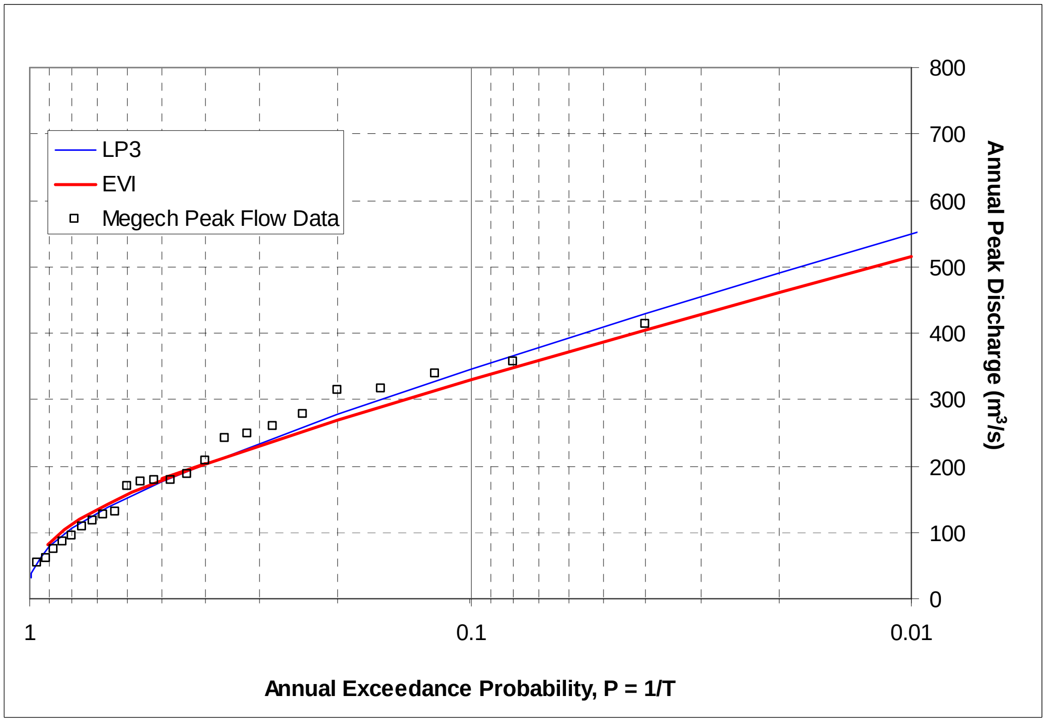


Figure 5-6: Megech peak flow probability flow.

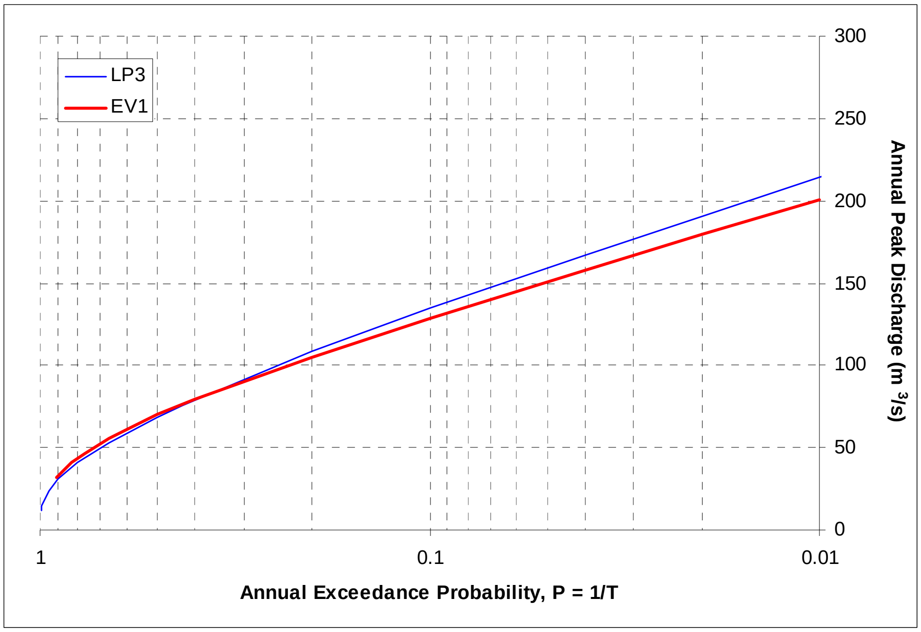


Figure 5-7: Dirma peak flow probability plot.

A inspection of the plots in ***Figure 5-4*** through ***Figure 5-7*** show that the LP3 distribution provides a good fit to the observed data for the Gumara and Megech gages, while the EVI distribution provides a better fit for the Ribb. For consistency in selection of a frequency distribution for the flood risk mapping, the LP3 distribution is used for all basins. Concerns regarding the representativeness of the historical peak flows for the Ribb, and to some extent for the Gumera, are addressed in the comparison with frequency flows estimated using hydrologic simulation.

5.2.5 Lake Level Estimates using Log Pearson Type III Distribution

The available Lake Tana water level data were also input into the PeakFQ program to fit a LP3 distribution and derive return period maximums. Because lake level varies slowly from day to day, no peaking factor adjustments are necessary. The sample skewness of the lake level data input into PeakFQ was 0.22911. Lake level estimates derived using both the LP3 and EV1 distributions are shown in ***Table 5-5***. Lake Tana level data were also analyzed and the results were found to be very similar between the two approaches.

Table 5-5: Lake level estimates ssing LP3 and EVI distributions.

Probability Distribution	**2-yr Peak (CMS)**	**5-yr Peak (CMS)**	**10-yr Peak (CMS)**	**50-yr Peak (CMS)**	**100-yr Peak (CMS)**
LP3	1787.22	1787.54	1787.73	1788.10	1788.24
EVI	1787.19	1787.51	1787.72	1788.19	1788.38

Note that the input data into PeakFQ for the Lake Tana level is the gage height scaled by a factor of 100. This was done to avoid rounding issues in the reported PeakFQ output. The values listed in ***Table 5-5*** have been adjusted to reflect the actual lake elevation (i.e., gage height plus the datum elevation). The datum elevation for the lake level gage was reported as being 1783.75 MASL. This value was used to translate the gage heights into lake elevation.

5.3 Rainfall-Runoff Response Model (HEC-HMS)

The Hydrologic Engineering Center Hydrologic Modeling System (HEC HMS) model was used to perform event-based rainfall runoff simulations for the Gumara, Ribb, Megech, and Dirma basins. In addition, two other basins located in between the Gumara and the Ribb watersheds (The Fogera Middle basin) and in between the Megech and Dirma watersheds (The Dembiya Middle basin) were modeled. The Fogera Middle basin was included in the Ribb basin schematics and is referred as Subbasin 5 and The Dembiya Middle basin was included in the Dirma basin schematics and is referred as Subbasin 5 as well. ***Appendix I*** includes the HEC-HMS schematics for all the basins.

Five different design storms corresponding to the 2, 5, 10, 50 and 100 year return periods were input into the model for simulation. Hydrologic simulations were carried out to verify the estimated flood flows from the flood frequency analysis and to support unsteady hydraulic modeling.

An assortment of different methods are available for the estimation of infiltration losses, transformation of excess precipitation into surface runoff, representation of baseflow contributions to subbasin outflows and simulation of routing flows in open channels. Based on data availability and on the primarily objectives of this modeling component of the project, the following methods were chosen:

Loss Rate Method: Soil Conservation Service (SCS) curve number

Transform Method: User-specified unit hydrograph

Baseflow Method: Constant monthly

Routing Method: Lag

Precipitation Method: Frequency Storm

5.3.1 GIS Data

The Gumara, Ribb, Megech and Dirma basins were subdivided into smaller Subbasins as shown in ***Figure 5-8*** and ***Figure 5-9***. Streamflow gage locations were used as outlets of Subbasin 1 in the Megech catchment and Subbasins 2 in the Gumara and Ribb basins. Subbasin areas were input into HEC HMS and are summarized in ***Table 5-6***. ***Appendix I*** contains the basin schematics with HEC HMS. Additionally, soil and landuse layers were used in GIS to estimate the inputs for the computation of water losses in the basins as described in subsequent sections. Soil and land use layers for each basin are included in ***Appendix J***.

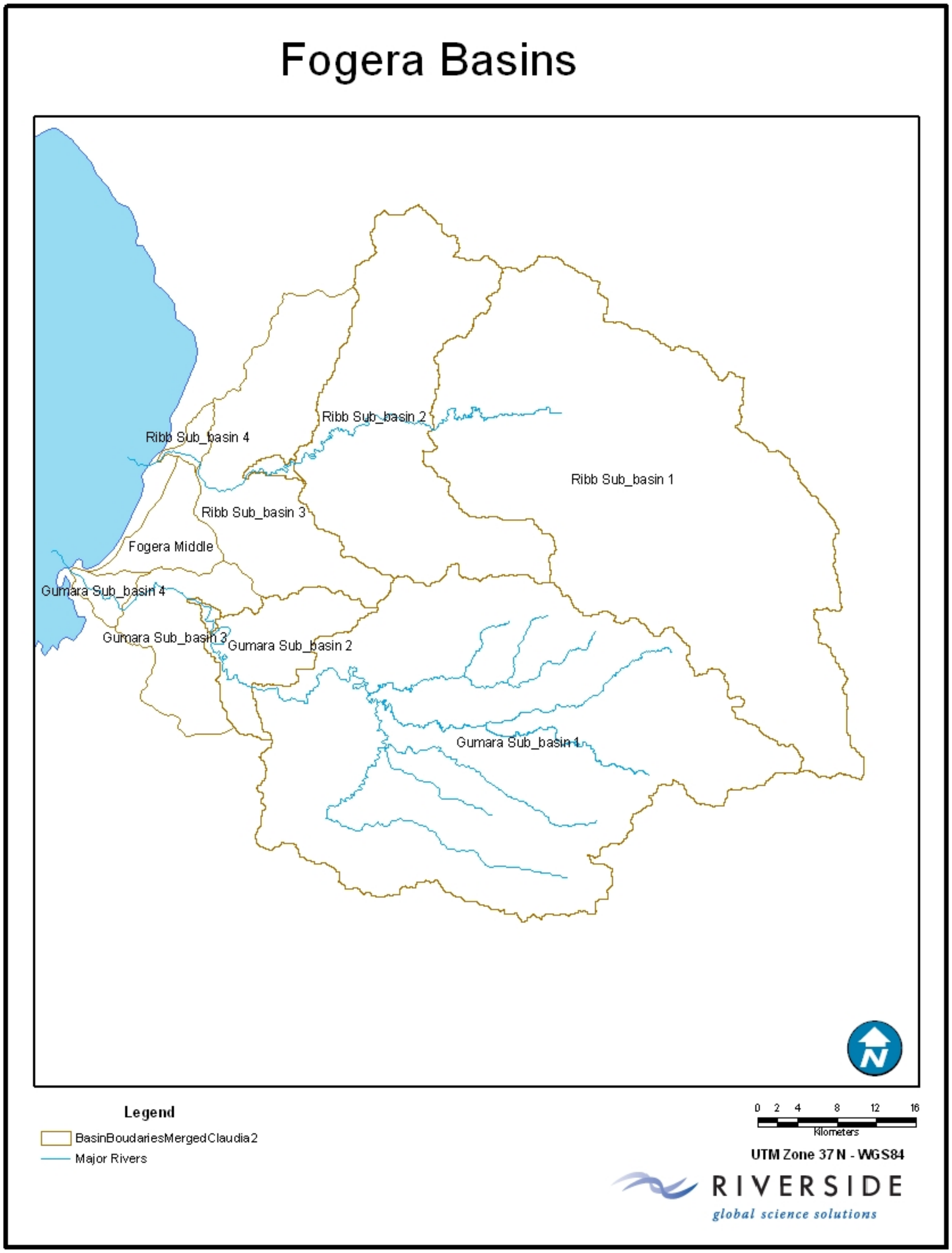


Figure 5-8: Map of the Gumara, Ribb and Fogera middle basins. Fogera middle corresponds to Subbasin 5 of the Ribb River basin schematics in HEC-HMS.

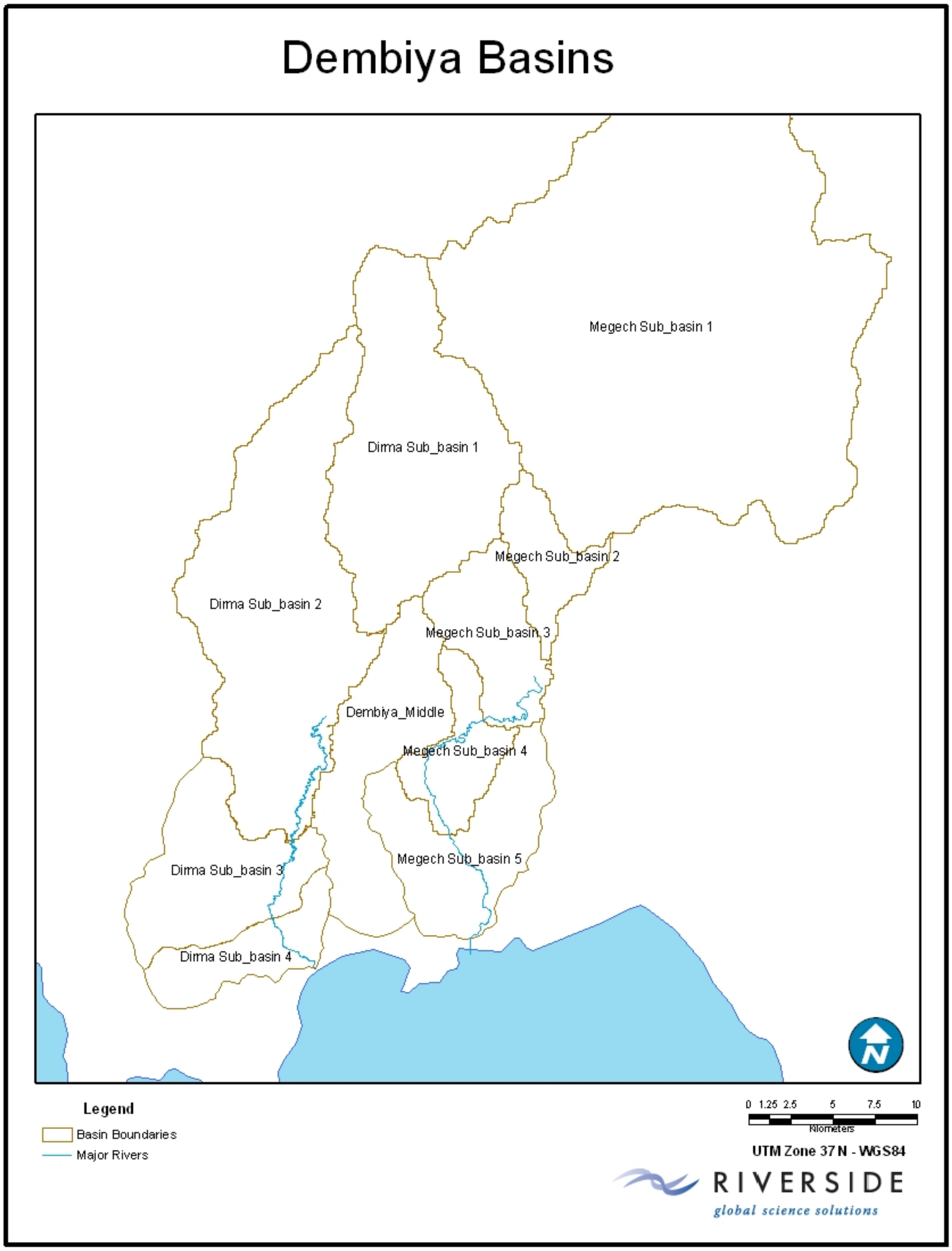


Figure 5-9: Map of the Dirma, Megech and Dembiya middle basins. Dembiya middle corresponds to Subbasin 5 of the Dirma River basin schematics in HEC-HMS.

Table 5-6: Basin areas in km^2.

Sub-basins	**Megech**	**Dirma**	**Ribb**	**Gumara**
1	514	158	1134	1236
2	31	197	491	118
3	48	77	313	143
4	35	37	15	24
5	73	81	70	-
Total Area	700	550	2023	1520

5.3.2 Meteorologic Model

HEC-HMS includes a meteorologic model that computes the precipitation input required for simulation. The *Frequency Storm* model was chosen to input precipitation depths for various durations and exceedance probabilities. It is recognized that the frequency of occurrence of simulated runoffs will not exactly correspond to the frequency of occurrence of the design storm input into the model due to the effect of antecedent moisture conditions and response characteristics of the basins. However, simulated peak flows will provide an estimate for comparison with the frequency analysis results developed from the streamflow data at the gages.

Intensity-Duration-Frequency (IDF) curves have been developed by the Ethiopian Roads Authority (ERA) for different hydrologic regions with similar rainfall patterns (ERA 2002). Curves for rainfall durations from 15 to 120 minutes were available for each region. The IDF curves for Region A2 (***Figure 5-10***), which includes the Gumara, Ribb, Fogera Middle, Megech, Dirma and Dembiya Middle basins, were used as inputs for the HMS model. Since rainfall events generally last more than 2 hours during the raining season, the IDF curves were extended to include 24 hour intensity duration frequency data available from the Ribb Dam Hydrological Study and the Megech Dam Final Feasibility Study developed by Water Works Design & Supervision Enterprise (WWDSE 2007 and 2008). HEC HMS requires 3, 6 and 12 hours depth duration data as well. Consequently, these values were visually interpolated in between the available 2 hour and 24 hour data (***Figure 5-11*** and ***Figure 5-12***). ***Table 5-7*** and ***Table 5-8*** summarize the depth-duration-frequency values input into the model. HMS produces a hyetograph based on these data. The storm duration was 24 hours and the intensity position was chosen to occur at 50% of the storm duration. This means the intensity peaked at 12 hours, such that half of the rainfall volume falls in the first 12 hours and the other half in the last 12 hours. Although the model allows for the intensity positions to occur from 25% to 75% of the storm duration, there was not available information to justify using a different intensity position.

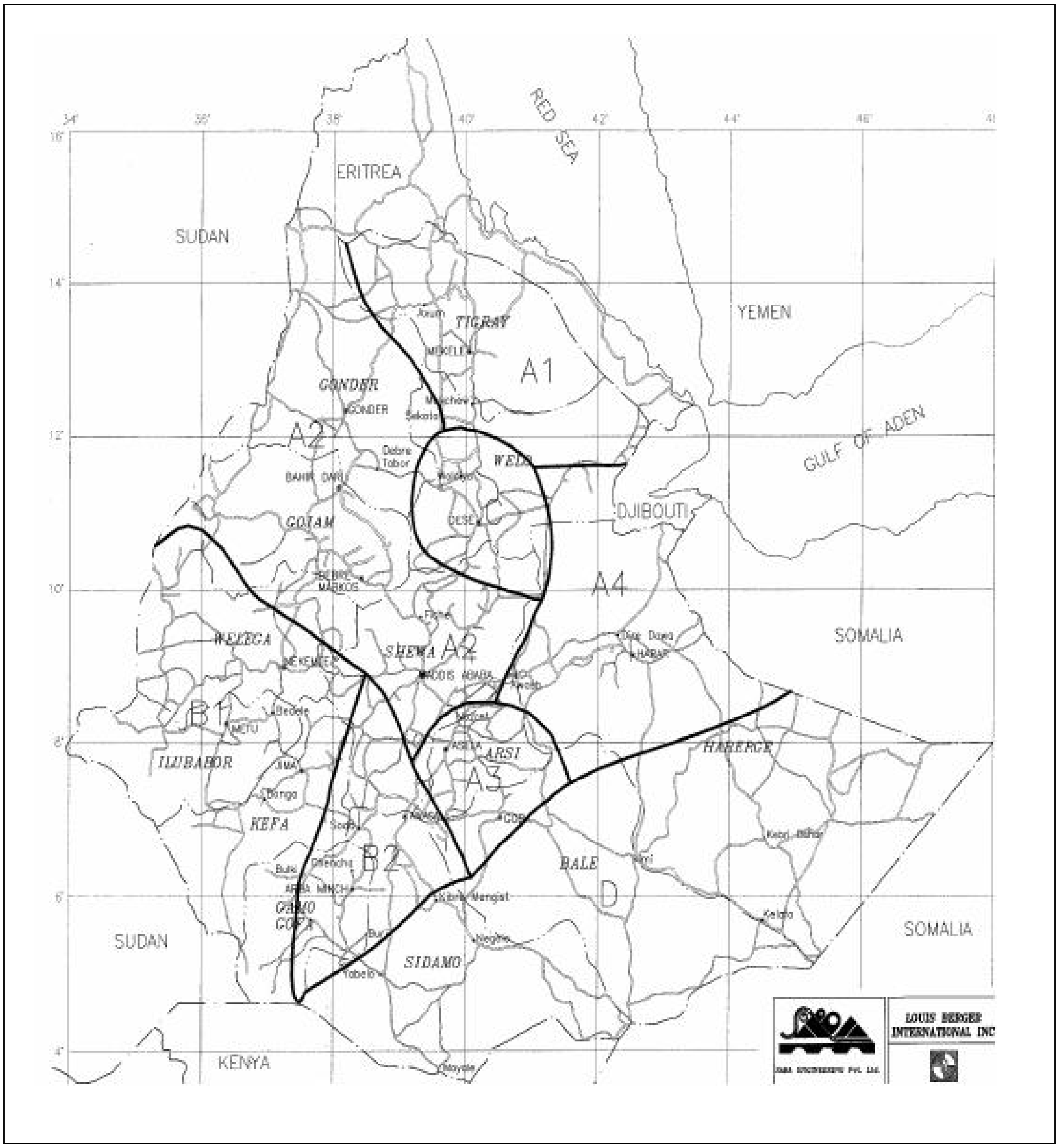


Figure 5-10: Hydrologic regions in Ethiopia with similar rainfall patterns. The Gumara, Ribb, Megech and Dirma basins are located into Region A2.

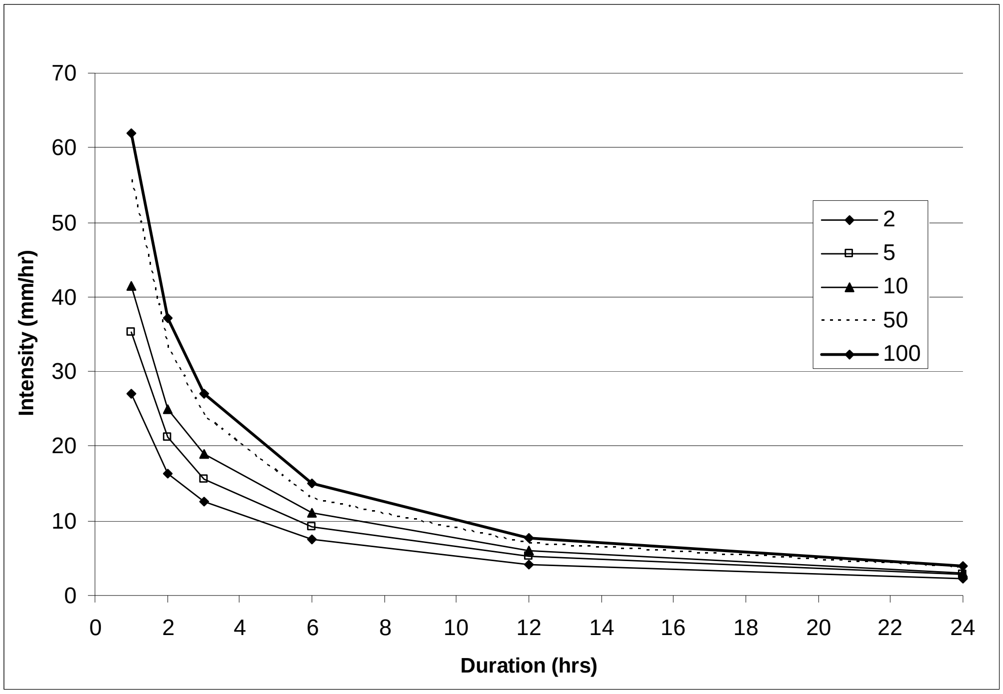


Figure 5-11: Intensity Duration Curves for Ribb and Gumara basins. 24-hour intensity duration frequency values reported by WWDSE, 2007.

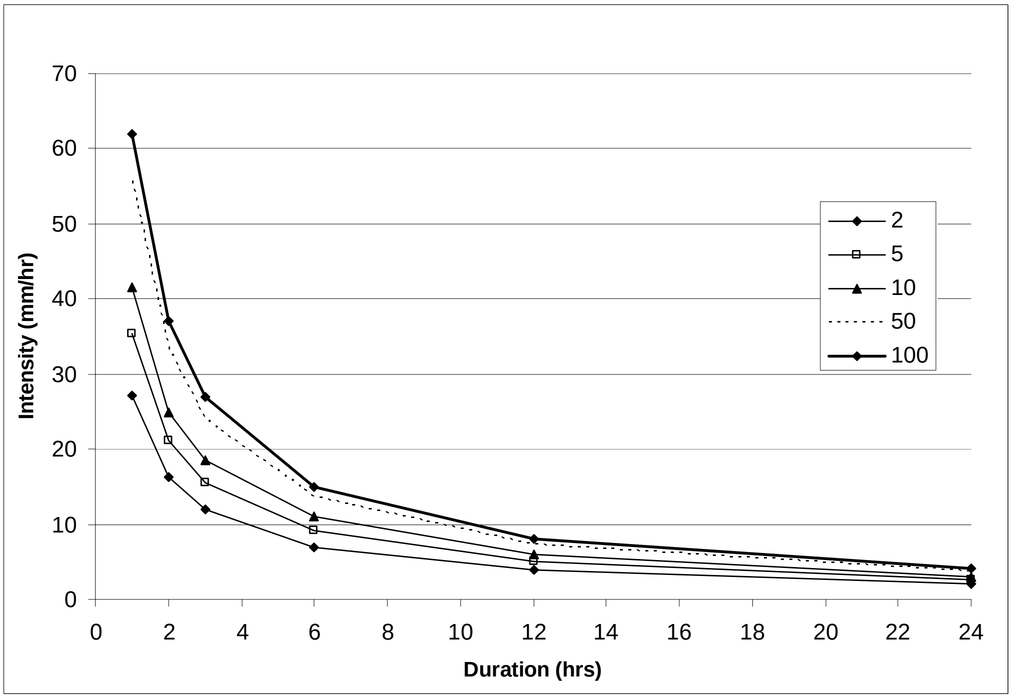


Figure 5-12: Intensity Duration Curves for Megech and Dirma basins. 24-hour intensity duration frequency values reported by WWDSE, 2007.

Table 5-7: Depth-Duration-Frequency data for Ribb and Gumara basins input into HEC-HMS.

		Frequency in yrs				
		2	5	10	50	100
Duration in hrs	1	27.1	35.3	41.5	55.8	62.0
	2	32.6	42.4	49.8	66.8	74.2
	3	37.5	46.5	57.0	72.0	81.0
	6	45.0	55.5	66.0	78.0	90.0
	12	50.4	63.0	72.0	84.0	93.0
	24	51.8	67.6	74.0	88.0	93.9

Table 5-8: Depth-Duration-Frequency data for Megech and Dirma basins input into HEC-HMS.

		Frequency in yrs				
		2	5	10	50	100
Duration in hrs	1	27.1	35.3	41.5	55.8	62.0
	2	32.6	42.4	49.8	66.8	74.2
	3	36.0	46.5	55.5	72.0	81.0
	6	42.0	55.5	66.0	82.2	90.0
	12	46.8	60.0	72.0	88.5	96.0
	24	48.0	64.0	73.0	91.0	99.0

5.3.3 Basin Model

The basin model within HEC-HMS computes outflows from the meteorologic data by subtracting losses, transforming excess rainfall and adding baseflow. Consequently, a *Loss Method*, a *Transform Method* and a *Baseflow Method* were chosen for the simulations.

5.3.3.1 Loss Method

The *SCS Curve Number Loss* method was chosen to model the losses in the subbasins in HEC-HMS. This method implements the curve number methodology to compute the incremental infiltration volume for each time interval. It requires a composite curve number and percent imperviousness for each subbasin.

Initial Abstractions, I_a, are not required for the method but were used in the model. The initial abstraction represents the amount of water that is lost before water starts to runoff. These values were obtained as a function of the determined curve number, CN, for the subbasin as seen in ***Equation 5-1***and ***Equation 5-2*** (ERA 2002, Chow et. al 1988).

Equation 5-1:

$$I_a = 0.2S \text{ , in inches, where}$$

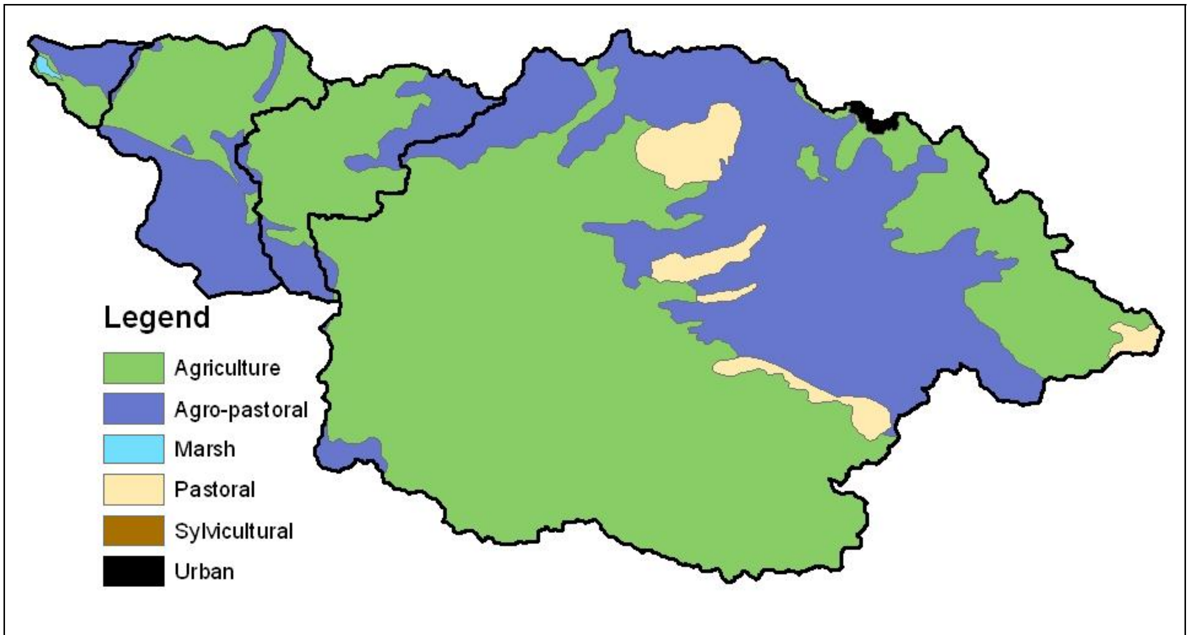
Equation 5-2:

$$S = 1000 / CN - 10$$

A composite curve number for each subbasin is required for this loss method. The curve number was determined from soil group and landuse combinations from GIS layers for each subbasin. Composite curve numbers for different Hydrologic Soil Groups from soils and landuse cover types were found in the Drainage Design Manual developed by the Ethiopian Road Authority (ERA 2002). Landuse for all subbasins was primarily agricultural, agro-pastoral, and pastoral. In agricultural areas, straight row cropping was assumed for the cover type. In subbasins where small portions of landuse were classified as urban, it was assumed this was equivalent to the Farms – buildings, lanes, driveways, and surrounding lots cover type description.

Soils located in the basin but not explicitly in the Drainage Design Manual were assigned Hydrologic Soil Group classifications of similar soils. Specifically, some types of Fluvisols, Luvisols and Vertisols not found in the Manual were assigned to Hydrologic Soil Groups B, B/C. and D respectively. Leptosols, a gravelly type soil common to mountainous regions, were not found in the Manual at all and were predominant in the headwater basins of Megech and Dirma. Although leptosols have qualities of very pervious soils, these soils are very shallow, found over hard rock and susceptible to water logging (FAO World Reference Base for Soil Resources available at http://www.fao.org/docrep/W8594E/W8594E00.htm). For this reason, when determining the Curve Number for leptosols, some weight was given to Hydrologic Soil Group A with more weight given to the most impervious soils located in these basins (C, D).

Any impervious area is defined separately in the method; no loss calculations are carried out over this area. Because urban landuse was included in the curve number generation for the models, all impervious area was set to 0%. Landuse and soil layers for the Gumara Basin are included in ***Figure 5-13***. ***Appendix J*** contains the landuse and soil layers of the other modeled basins. ***Table 5-9*** shows all subbasin inputs into the model for the SCS Curve Number Loss method.



Gumara Land Use

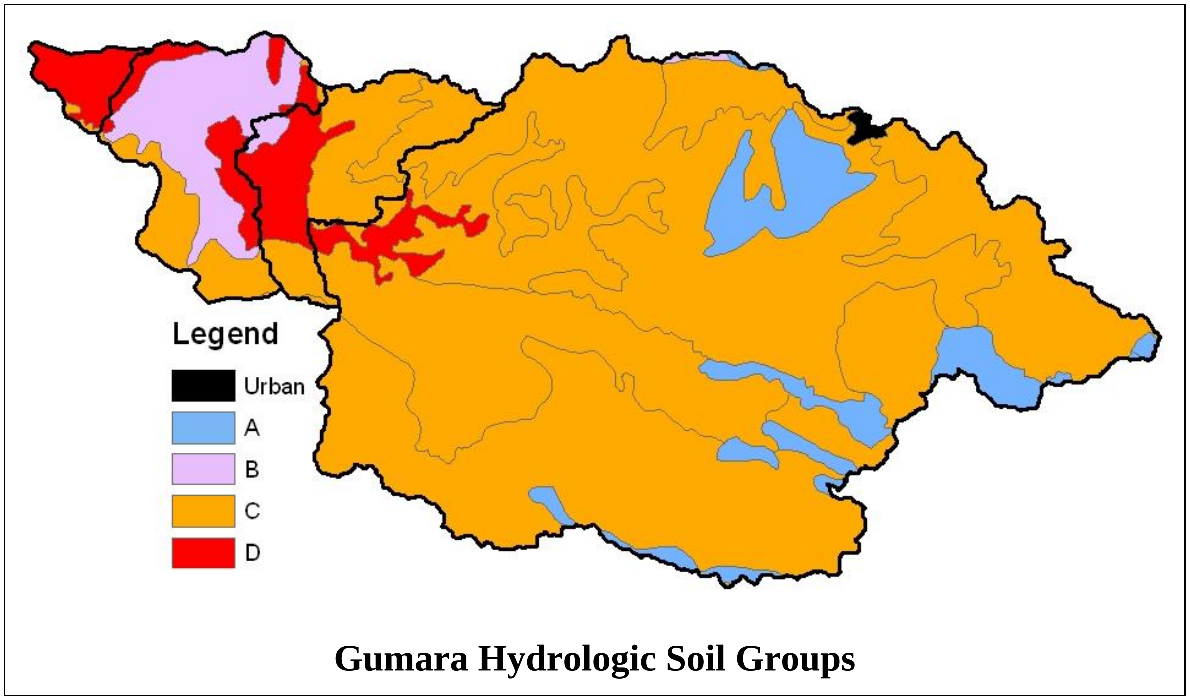


Figure 5-13: Landuse and soil layers for the Gumara Basin.

Table 5-9: SCS curve number loss method inputs.

	Predominant Soil Group	**I_a mm**	**CN**	**Impervious %**
Gumara				
Subbasin1	C	11.2	81.9	0
Subbasin2	C	11.2	82	0
Subbasin3	B	14.1	78.3	0
Subbasin4	D	6.0	89.4	0
Ribb				
	Predominant Soil Group	**I_a mm**	**CN**	**Impervious %**
Subbasin1	A/B	20.3	71.5	0
Subbasin2	B	17.8	74.1	0

Subbasin3	B	14.4	77.9	0
Subbasin4	B	11.1	82.1	0
Subbasin5	D	5.8	89.5	0
Megech				
	Predominant Soil Group	**I_a mm**	**CN**	**Impervious %**
Subbasin1	A	12.8	85.7	0
Subbasin2	D	7.4	87.3	0
Subbasin3	D	12.3	80.5	0
Subbasin4	D	5.1	90.9	0
Subbasin5	D	6.2	89.2	0
Dirma				
	Predominant Soil Group	**I_a mm**	**CN**	**Impervious %**
Subbasin1	A/B	11.7	84.3	0
Subbasin2	D	6.7	90.1	0
Subbasin3	D	5.0	91.0	0
Subbasin4	D	11.4	81.7	0
Subbasin5	D	6.0	89.5	0

5.3.3.2 Transform Method

HEC-HMS computes the surface runoff using a Transform Method. A *User-specified Unit Hydrograph Transform* method was chosen. GIS synthetic unit hydrographs (UH) were developed for each Subbasin and input into the model. The required data to perform the GIS UH derivation method include a DEM of the basins, basin delineation polygon files, flow accumulation and flow direction grids, basin areas, and estimates of hydraulic radius and roughness coefficients (n_0) at the outlet of the basins. Mean channel velocities, channel widths and discharges were obtained from the hydraulic modeling of the basins to estimate the hydraulic radius. DEM data consisted of the 90-meter SRTM grids.

The ArcGIS program was used to compute the unit hydrographs. Isochrones of zones of equal travel time to the outlets for each basin were computed. Time-discharge histograms associated with each basin were generated assuming a uniform depth of water of 1 mm on each cell of the DEM. The total discharge produced on each zone within the isochrones was then translated to the outlet using the associated travel time. The resulting time-discharge histograms represented instantaneous unit hydrographs. These unit hydrographs were then routed in order to account for the storage and delays that occur in the basins. Reservoir routing coefficients were initially estimated as the ratio of the outflow rate given by the peak discharge of the hydrograph and the storage given by the area under the unit hydrograph or volume to be displaced after the peak.

The instantaneous unit hydrographs were then converted to 1-hour unit hydrographs with 1-hour ordinates for use in the hydrologic simulations. Routing coefficients of 720 minutes (12 hours) in the Gumara and Ribb basins and 360 minutes (6 hours) in the Dirma and Megech basins were selected for the subbasins located in the plains around Lake Tana where larger storage and flow delays are expected to occur. For the headwater basins, 540 minutes (9 hours) in the Gumara and Ribb basins and 180 minutes (3 hours) in the Dirma and Megech basins were estimated. The UH for the Fogera Middle basin was estimated by scaling the developed UH for Subbasin 4 of Ribb by area and using a routing coefficient of 12 hours. The UH for the Dembiya Middle basin was estimated by scaling the developed UH for Subbasin 2 of Dirma by area and using a routing coefficient of 6 hours. These two subbasins were chosen based on their similarities in location, landuse, and hydrological soil group characteristics to the Fogera and Dembiya Middle basins. ***Figure 5-14*** through ***Figure 5-17*** show the developed unit hydrograph for the Gumara Basin. ***Appendix K*** contains the unit hydrographs for all other basins.

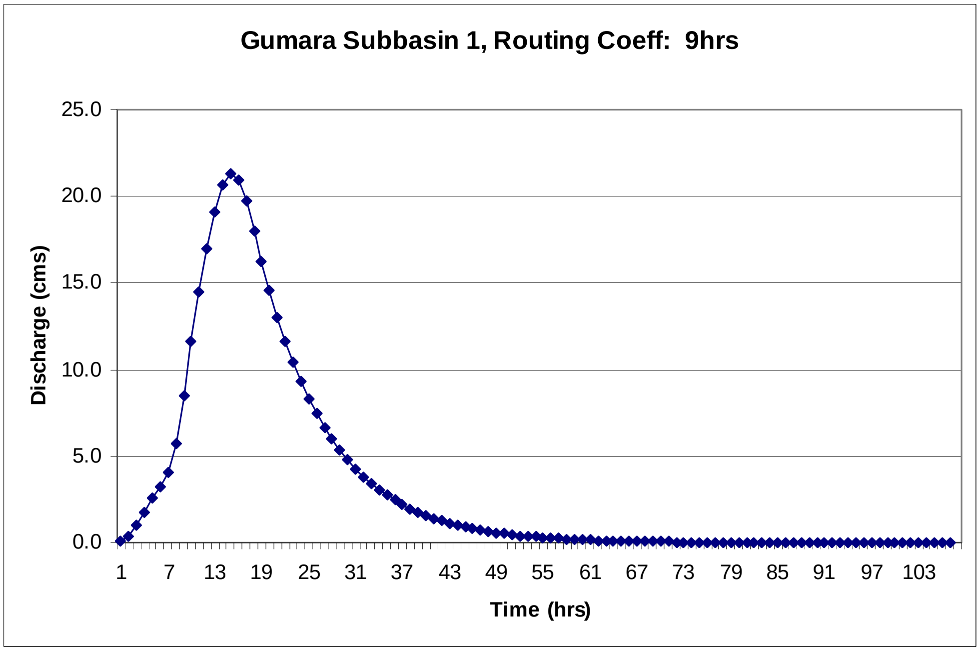


Figure 5-14: Unit hydrograph for Gumara Subbasin 1.

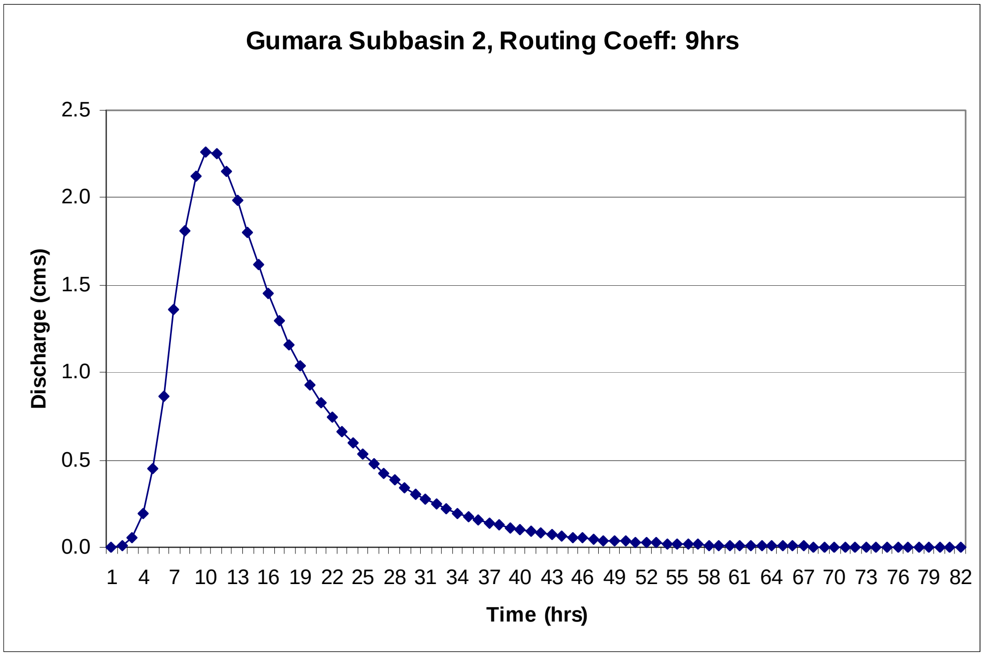


Figure 5-15: Unit hydrograph for Gumara Subbasin 2.

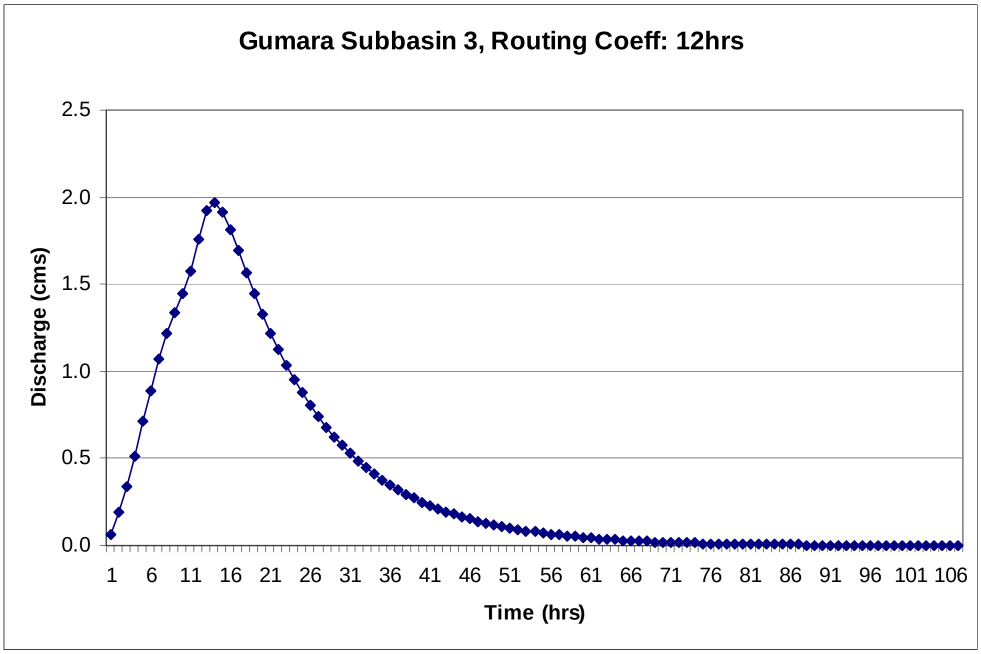


Figure 5-16: Unit hydrograph for Gumara Subbasin 3.

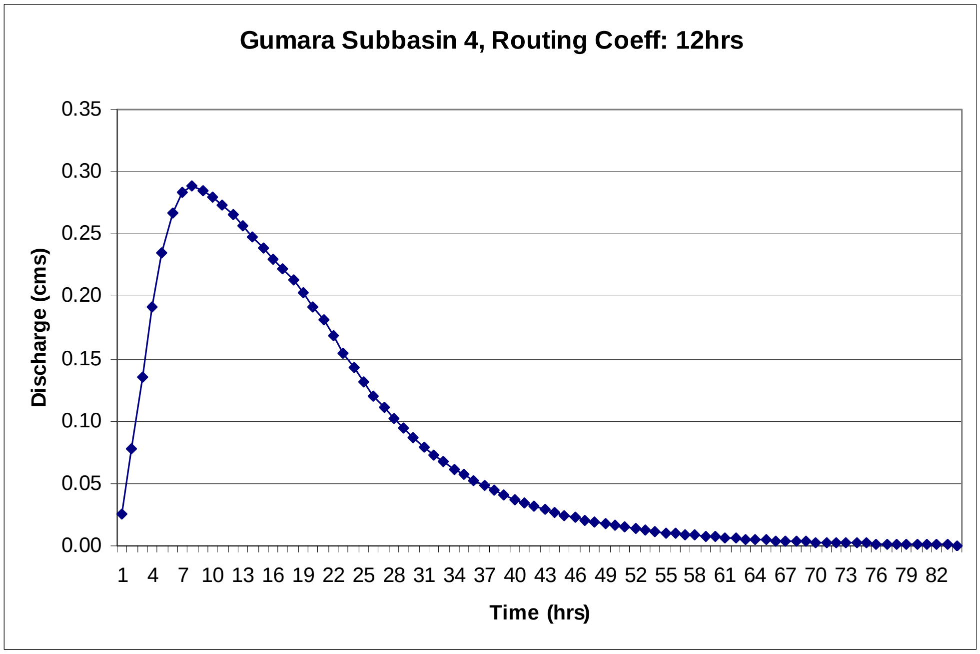


Figure 5-17: Unit hydrograph for Gumara Subbasin 4.

5.3.3.3 Baseflow Method

The *Constant Monthly Baseflow* method was chosen to model the baseflow in the subbasins in HEC-HMS. This method represents baseflow as a constant that is allowed to vary by month. It requires a local baseflow for each subbasin in the model on a monthly basis. The user-defined baseflow is added to the direct runoff computed for each subbasin at each time step of the simulation.

Monthly baseflow values were estimated empirically for each basin using measurements of stream flow within the basins. For the Gumara, Ribb, and Megech basins, daily stream flow data from wet years between 1985 and 2008 were selected. A wet year was defined as a year where the stream flow had peaks greater than 300, 120, and 250 m^3/s for the three basins, respectively. These years were averaged to determine the average daily flow for wet years in the basin to which a monthly baseflow curve was fit. ***Figure 5-18*** shows the averaged daily flow for wet years with the averaged monthly baseflow for the Gumara gage. Similar plots for Ribb and Megech gages are included in ***Appendix L***.

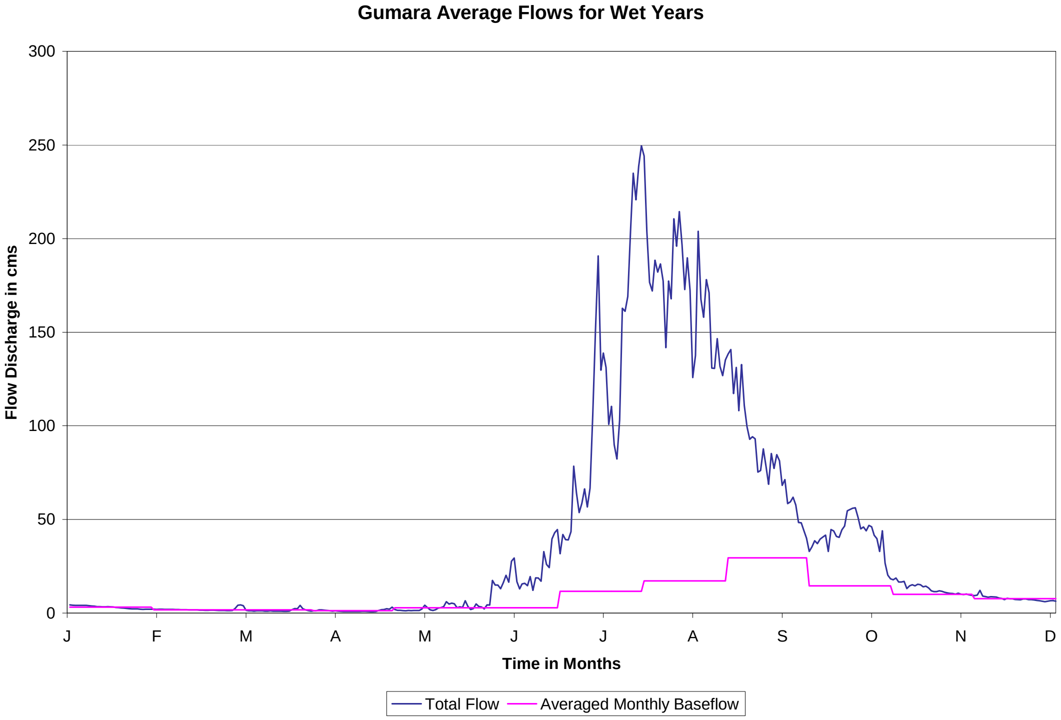


Figure 5-18: Gumara Daily Average streamflow and Monthly Average Baseflow.

To develop the monthly baseflow curve, the averaged daily total flow was converted to monthly averages. In months when the total flow was comprised of predominately baseflow, the baseflow curve was set equal to the monthly average. During the period when stream flow is dominated by direct runoff, the baseflow curve was equal to a portion of the total flow. The baseflow curve was set to peak at roughly one month after the peak of the total flow. The area under the monthly baseflow curve was limited so that baseflow volume was equal to approximately 20% of the total flow volume while runoff is contributing to the stream flow. ***Figure 5-19*** shows the averaged total flows with the monthly baseflow curves for Gumara. Similar plots for the Ribb and Megech basins are included in ***Appendix L***. ***Table 5-10*** through ***Table 5-13*** summarize the monthly baseflow values input into the model.

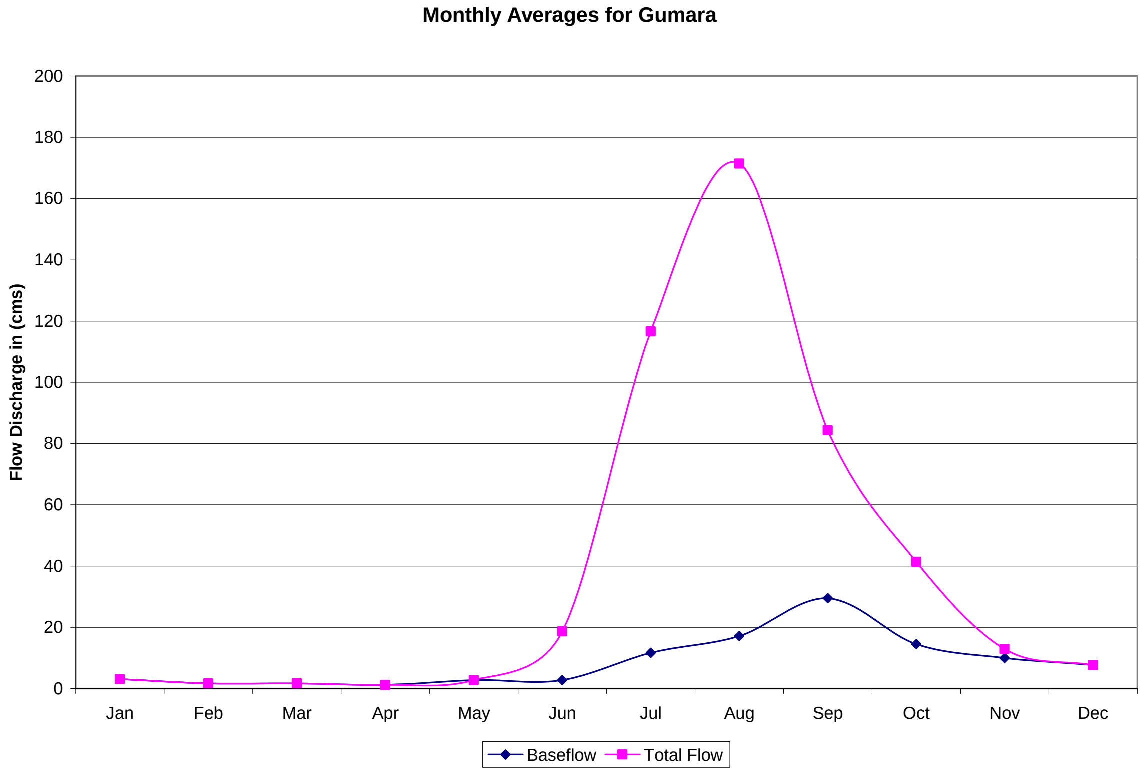


Figure 5-19: Gumara Constant Monthly Baseflow Curve.

Table 5-10: Monthly baseflow values for Gumara.

	Monthly Baseflow (m^3/s)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Subbasin 1	2.83	1.55	1.55	1.12	2.53	2.55	10.61	15.6	26.86	13.18	9.1	7
Subbasin 2	0.28	0.15	0.15	0.11	0.25	0.25	1.05	1.54	2.66	1.3	0.9	0.69
Subbasin 3	0.33	0.18	0.18	0.13	0.29	0.29	1.23	1.81	3.11	1.53	1.05	0.81
Subbasin 4	0.05	0.03	0.03	0.02	0.05	0.05	0.21	0.3	0.52	0.25	0.18	0.14

Table 5-11: Monthly baseflow values for Ribb.

	Monthly Baseflow (m^3/s)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Subbasin 1	0.23	0.12	0.08	0.13	0.28	0.29	1.84	6.47	9.97	4.20	1.05	0.64
Subbasin 2	0.10	0.05	0.03	0.06	0.12	0.12	0.79	2.77	4.27	1.80	0.45	0.28
Subbasin 3	0.06	0.03	0.02	0.04	0.08	0.08	0.51	1.78	2.74	1.15	0.29	0.18
Subbasin 4	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.09	0.14	0.06	0.02	0.01
Subbasin 5	0.17	0.10	0.10	0.06	0.17	0.17	0.71	1.01	1.76	0.85	0.61	0.47

Table 5-12: Monthly baseflow values for Megech.

	Monthly Baseflow (m^3/s)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Subbasin 1	1.64	1.65	1.60	1.36	1.31	1.35	1.46	2.82	4.37	2.47	1.76	1.20
Subbasin 2	0.10	0.10	0.10	0.08	0.08	0.08	0.09	0.17	0.26	0.15	0.11	0.07
Subbasin 3	0.16	0.16	0.15	0.13	0.12	0.13	0.14	0.27	0.41	0.23	0.17	0.11
Subbasin 4	0.11	0.11	0.11	0.09	0.09	0.09	0.10	0.20	0.30	0.17	0.12	0.08
Subbasin 5	0.23	0.23	0.23	0.19	0.19	0.19	0.21	0.40	0.62	0.35	0.25	0.17

Table 5-13: Monthly baseflow values for Dirma.

	Monthly Baseflow (m^3/s)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Subbasin 1	0.50	0.51	0.49	0.42	0.40	0.41	0.45	0.87	1.34	0.76	0.54	0.37
Subbasin 2	0.63	0.63	0.62	0.52	0.50	0.52	0.56	1.08	1.68	0.95	0.68	0.46
Subbasin 3	0.25	0.25	0.24	0.20	0.20	0.20	0.22	0.42	0.65	0.37	0.26	0.18
Subbasin 4	0.12	0.12	0.11	0.10	0.09	0.10	0.10	0.20	0.31	0.18	0.13	0.09
Subbasin 5	0.26	0.26	0.25	0.22	0.21	0.21	0.23	0.45	0.69	0.39	0.28	0.19

5.3.4 Reach Model

5.3.4.1 Routing Method

The *Lag Method* was chosen as the routing method to translate the flood waves from the upstream basins to the downstream basins. This method does not account for attenuation of the peaks and for diffusive processes. However, attenuation of the peaks is expected to occur and was modeled and accounted for in the developed unit hydrographs. The only input parameter for the *Lag Method* is the lag time in minutes. River reaches were measured using GIS and mean velocities in the rivers were estimated from the hydraulic modeling using HEC-RAS. Then, mean travel times were estimated and are included in ***Table 5-14***.

Table 5-14: Lag times in minutes for Gumara, Ribb, Megech and Dirma basins.

Reach	**Gumara**		
	Length (km)	**Mean V (m/s)**	**T_{lag} (min)**
1	15	1.4	180
2	15	1.4	180
3	10	1.4	120

Reach	**Ribb**		
	Length (km)	**Mean V (m/s)**	**T_{lag} (min)**
1	22	2	180
2	14	2	120
3	7	2	60

Reach	**Megech**		
	Length (km)	**Mean V (m/s)**	**T_{lag} (min)**
1	7	1	120
2	11	1	180
3	14	1	240
4	7	1	120

Reach	**Dirma**		
	Length (km)	**Mean V (m/s)**	**T_{lag} (min)**
1	18	1	300
2	7	1	120
3	4	1	60

5.3.5 HEC-HMS Results and Discussion

HEC-HMS was run using the 2, 5, 10, 50 and 100 yr design storms with a one hour time step for a total of six days. Based on the inspection of daily streamflow data, it was concluded that generally the largest flows occur in the month of August. Consequently, the simulation dates were set in August and the August monthly baseflow values were used in the simulations. ***Table 5-15*** through ***Table 5-18*** summarize the results from the model. Cumulative peak flow values at the outlet of each subbasin are listed together with the discharge volumes at the outlet of the gaged subbasins and the outlet of each river basin. Output hydrographs for the 100 year return period at the gage site of each basin are included in ***Figure 5-20*** through ***Figure 5-23***.

Table 5-15: HEC-HMS results for Gumara basin.

	Cumulative Q_{HMS} at Subbasins				Volume in 10^3 m^3	
Return Period (T) in years	1	2 (Gage)	3	4 (Outlet)	2 (Gage)	4 (Outlet)
2	221	236	247	425	22,123	24,640
5	393	422	446	452	37,619	41,908
10	557	592	622	628	45,148	50,312
50	756	803	845	853	59,246	66,064
100	864	914	963	973	65,127	72,693

Table 5-16: HEC-HMS results for Ribb basin.

	Cumulative Q_{HMS} at Subbasins					Volume in 10^3 m^3	
Return Period (T) in years	1	2 (Gage)	3	4 (Outlet)	5 (Fogera Middle)	2 (Gage)	4 (Outlet)
2	71	113	153	155	20	10,618	13,903
5	211	325	422	425	36	24,657	31,658
10	268	411	530	534	42	29,100	37,204
50	400	612	782	786	53	41,876	53,064
100	478	729	928	934	59	47,408	59,899

Table 5-17: HEC-HMS results for Megech basin.

	Cumulative Q_{HMS} at Subbasins					**Volume in 10^3 m^3**	
Return Period (T) in years	**1 (Gage)**	**2**	**3**	**4**	**5 (Outlet)**	**1 (Gage)**	**5 (Outlet)**
2	99	103	105	108	115	5,005	8,135
5	229	236	241	246	260	10,169	15,773
10	330	338	344	349	365	13,587	20,709
50	500	510	520	527	550	20,072	29,950
100	579	591	601	609	637	23,010	34,101

Table 5-18: HEC-HMS results for Dirma basin.

	Cumulative Q_{HMS} at Subbasins					**Volume in 10^3 m^3**	
Return Period (T) in years	**1 (Gage)**	**2**	**3**	**4 (Outlet)**	**5 (Dembiya Middle)**	**1 (Gage)**	**4 (Outlet)**
2	40	91	104	107	26	1,712	7,332
5	88	181	2205	211	47	3,403	13,336
10	125	246	275	285	61	4,505	17,057
50	188	353	397	411	85	6,576	23,849
100	217	403	452	468	95	7,508	26,851

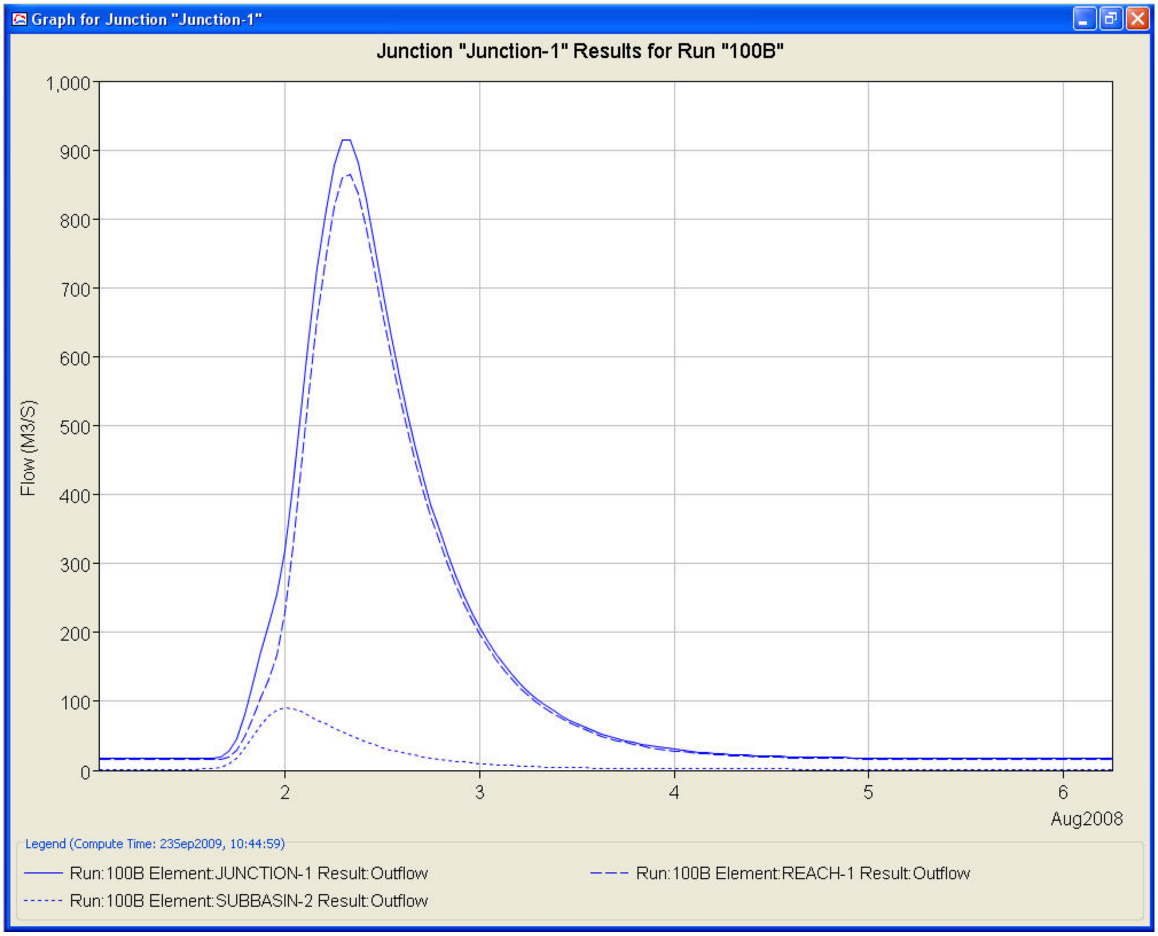


Figure 5-20: Gumara gage hydrographs for the 100-yr event. Dotted line corresponds to Subbasin 2 local flows. Dash line corresponds to Subbasin 1 contribution (upstream contribution). Solid line represents the total flow at the gage.

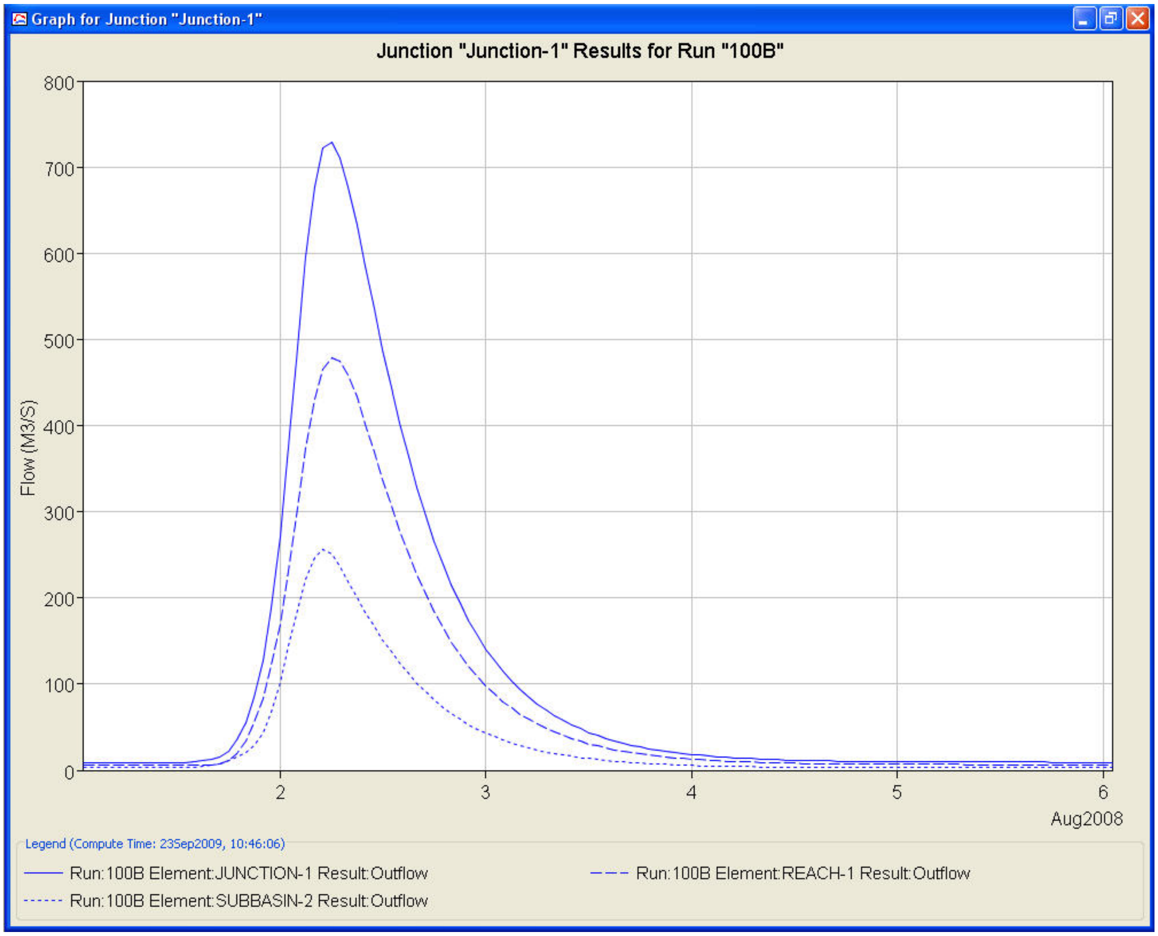


Figure 5-21: Ribb gage site hydrographs for the 100-yr event. Dotted line corresponds to Subbasin 2 local flows. Dash line corresponds to Subbasin 1 contribution (upstream contribution). Solid line represents the total flow at the gage.

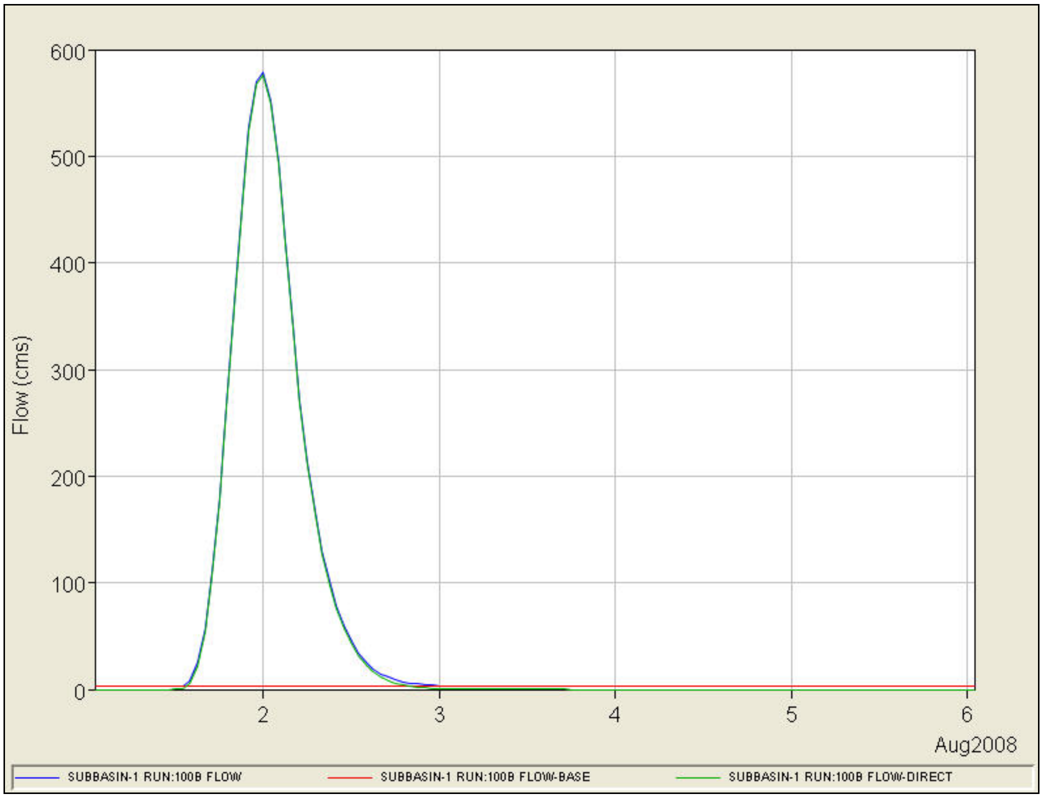


Figure 5-22: Megech gage hydrographs for the 100 yr rainfall event.

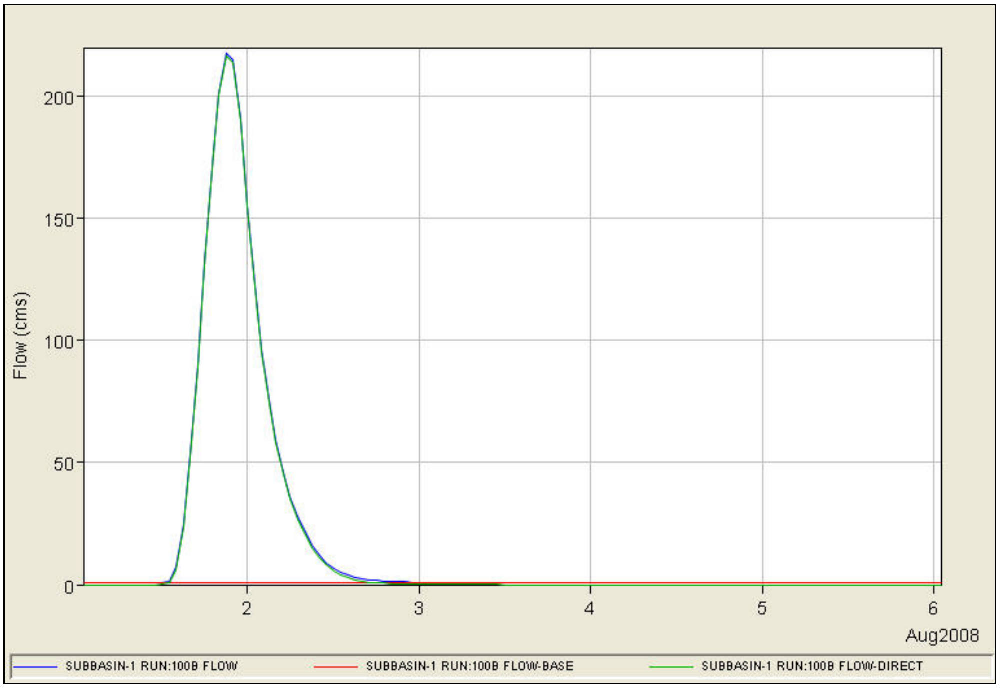


Figure 5-23: Dirma gage site hydrographs for the 100 yr rainfall event.

The two most upstream Subbasins in Gumara, upstream from the gage site, represent 89% of the total area and generate about 90% of the total flow volume at the outlet. The peak flows at the gage site are about 94% of the peak flows at the outlet. High discharge volume from the gaged area is likely due to the large contributing area to the outlet and to the impervious nature of the soils as indicated by the large Curve Numbers and low initial abstractions of these subbasins.

Subbasin areas upstream from the gage site at the Ribb River represent about 65% of the total area and produce 79% of the total flow volume at the outlet. Peak flows at the gage site are on average about 76% of the peak flows at the outlet. The gaged area of the Ribb basin has more pervious soils than the gaged area of the Gumara basin as shown by their lower Curve Numbers and larger initial abstractions.

The gaged area of the Ribb basin is 118% of the gaged area in the Gumara basin. For the 100-yr flow event, the discharge volume at the Ribb gage is about 70% of the volume at the gage site on the Gumara and the peak flow at the Ribb gage (729 m^3/s) is about 80% of the peak flow at Gumara gage (914 m^3/s). At the outlet, the discharge volume of the Ribb is 80% of the total discharge volume of Gumara but the 100-yr peak flow at the Ribb (934 m^3/s) is only about 4% lower than the peak flow of the Gumara (973 m^3/s). Even though the 100 year peak flows are almost the same, the total volumes are different. This similarity in peak flows is due to the unit hydrographs used in the simulations.

The gaged area in the Megech represents 73% of the total basin area and produces on average 65% of the total discharge volume of the entire basin. Peak flows at the gage site are on average 89% of the peak flows at the outlet.

The Dirma basin is the smallest of all basins. Its area is about 67% of the Megech area. The Dirma basin does not have a gage. However, for analysis purposes a gaged site was chosen at the outlet of Subbasin 1, which comprises the mountainous terrain of the catchment. Subbasin 1 covers 34% of the total basin area and produces on average 26% of the total discharge volume of the basin. Peak flows at Subbasin 1 are about 43% of the outlet peak flows.

The Megech and Dirma have similar Curve Numbers and initial abstractions. However, their differences in basin areas account for the differences in discharge volumes. Dirma volumes at the outlet are about 83% of the total discharge volume produced at Megech. Peak flows at the outlet of Dirma basin are on average 80% of the peak flow magnitudes at the outlet of Megech.

5.4 Comparison of Flood Frequency Analysis and Rainfall-Runoff Model Results

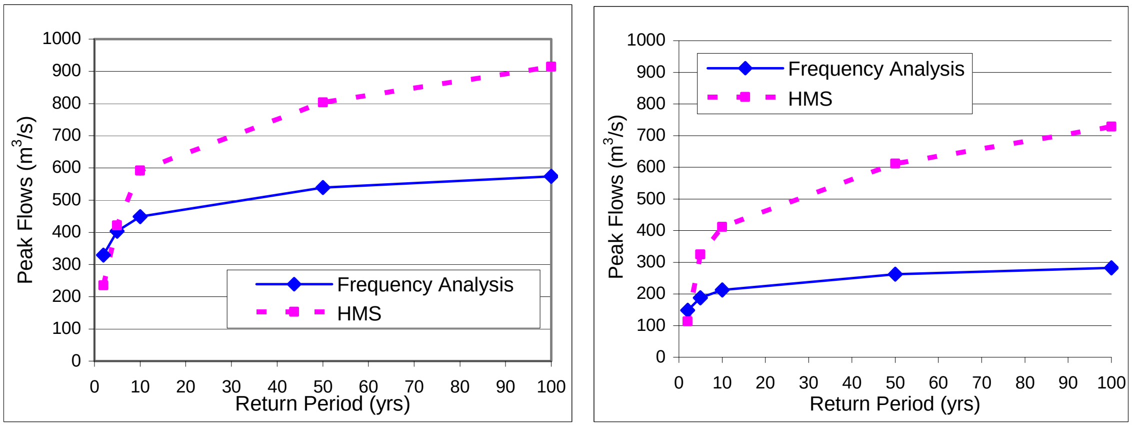
Table 5-19 summarizes the results from both methods at the gage locations. ***Figure 5-24*** shows a graphical representation of these results.

Table 5-19: Peak Flow Estimates for all Basins from the Frequency Analysis (FA) and from HEC-HMS (HMS).

STATION NAME	2-yr Peak (CMS)	5-yr Peak (CMS)	10-yr Peak (CMS)	50-yr Peak (CMS)	100-yr Peak (CMS)

Gumara (gaged area = 1354 km^2)					
FA	329	404	448	539	574
HMS	236	422	592	803	914
Ribb (gaged area = 1625 km^2)					
FA	148	188	212	262	282
HMS	113	325	411	612	729
Megech (gaged area = 514 km^2)					
FA	177	278	346	491	550
HMS	99	229	330	500	579
Dirma (gaged area = 158 km^2)					
FA	69	108	135	191	214
HMS	40	88	125	188	217

Gumara **Ribb**



Megech **Dirma**

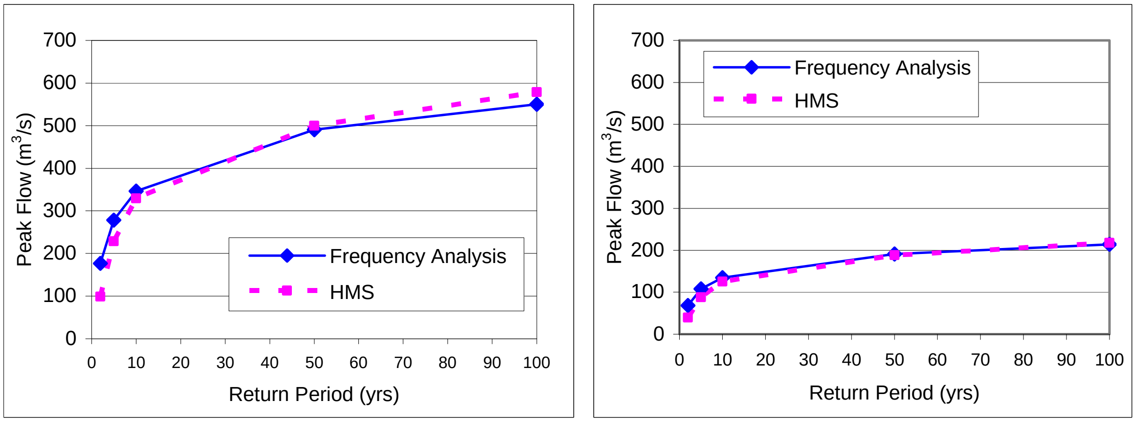


Figure 5-24: Comparison of the Frequency Analysis and the HEC-HMS Peak Flow Results for the Gumara, Ribb, Megech and Dirma Basins.

Peak flow estimates at the gage sites from the frequency analysis and rainfall-runoff model are comparable for the Megech and Dirma basins. Moreover, the exponent *n* = 0.8 used in the frequency analysis to transpose the Megech flows to the Dirma basin appears to have been a reasonable estimate as confirmed by the similarity between the results from flood frequency and HEC-HMS analyses. It may also be noted that the hydrologic simulation results generally compare well among basins in relation to the drainage areas of each of the basins.

However, estimates from HEC-HMS for the Ribb and Gumara gage sites are larger than the flood frequency analysis results. This difference is significant, with the hydrologic simulation producing an estimate for the 100 year frequency event that is 59% greater in the Gumera and 159% greater in the Rib. This is consistent with concerns that have been noted that the Ribb River has much lower observed discharge despite its large catchment size compared to Megech and Gumara. It has been documented that the rating curves of the Ribb and Gumara rivers are not reliable for peak flows since sedimentation and flooding of the river and floodplains have caused major problems in the stage-discharge relationships (Wale 2008). It is possible that the rating curves used to estimate discharge from observed stages for the

Ribb and Gumera rivers is extrapolated in such a way that it underestimates flows that exceed the channel banks at the gaging sites. This would significantly bias the frequency analysis of peak flows. Consequently, real peak flows might be greater than the reported values at the gage and HEC-HMS results might be better estimates of flood peaks. For this reason flood peaks based on the HEC-HMS hydrologic simulation are considered more reliable. They are also more conservative than the frequency analysis results and were thus chosen as the peak flows for subsequent steps in the risk analysis. Moreover, following the final workshop in Bahir Dar the scope of this assignment was expanded to include unsteady hydraulic modeling of the flood events and associated inundation. This required the use of the HEC-HMS simulation results for all of the pilot areas as inputs to the unsteady hydraulic models.

During previous stages of the assignment the frequency based flows were used as the basis for a steady flow analysis of inundation extent and risk. Because the frequency analysis provided peak flow estimates only at the gage locations, a methodology was required to estimate additional local flows that would contribute to peak discharges downstream of the gage locations. Because the frequency based flows are no longer used as the basis for the remainder of the study, this method is not described here, but it is included as ***Appendix M***.

6.0 HYDRAULIC MODELING

6.1 Methodology/Analysis Procedures

For hydraulic modeling, the Hydrologic Engineering Center River Analysis System (HEC-RAS) program was used to perform both one-dimensional steady flow and one-dimensional unsteady flow analysis. The unsteady flow analysis was added at the request of stakeholders to determine the effects of storage in the basin on the inundation extents and to evaluate the duration of flooding. The HEC-RAS models were set up to provide the channel width and floodplain bed elevations for study reaches. The four rivers tributary to Lake Tana used the lake as the downstream boundary condition, with an evaluation of appropriate lake levels corresponding to various return period flows for the tributaries. RAS-Mapper was used to predict inundation extents and water surface elevations, including information on depths and velocities that enable identification of flood hazard areas for floods up to and including the 100-year return flood event

6.2 HEC-RAS and HEC-GeoRAS Overview

HEC-RAS is a hydraulic model that can perform one-dimensional steady flow and unsteady flow modeling. Its popularity is based on its ease of use and many features designed to support flood plain analysis. HEC-RAS is tightly coupled with geospatial pre- and post-processor HEC-GeoRAS allowing for digitizing of the channel geometry from a terrain model for import into HEC-RAS as well as an iterative process during calibration using the flood inundation mapping (***Figure 6-1***). The HEC-RAS / HEC-GeoRAS system has the ability to rapidly compute water surface profiles for several different characterizations of the system under study. Modifications can be made to channel geometry and flow data, and plans formulated by selecting a particular geometry and/or flow file. This enables comparisons between existing and future channel and flow conditions to be made, and is typically used to assess the impact of engineered structures such as bridges or levees designed to reduce flood risk. Secondly, optional capabilities in HEC-RAS allow for mixed flow regime calculations. HEC-RAS provides the means to generate predictions of flow velocity in the channel and across the floodplain under flood conditions and will thus produce useful hazard data for this risk assessment.

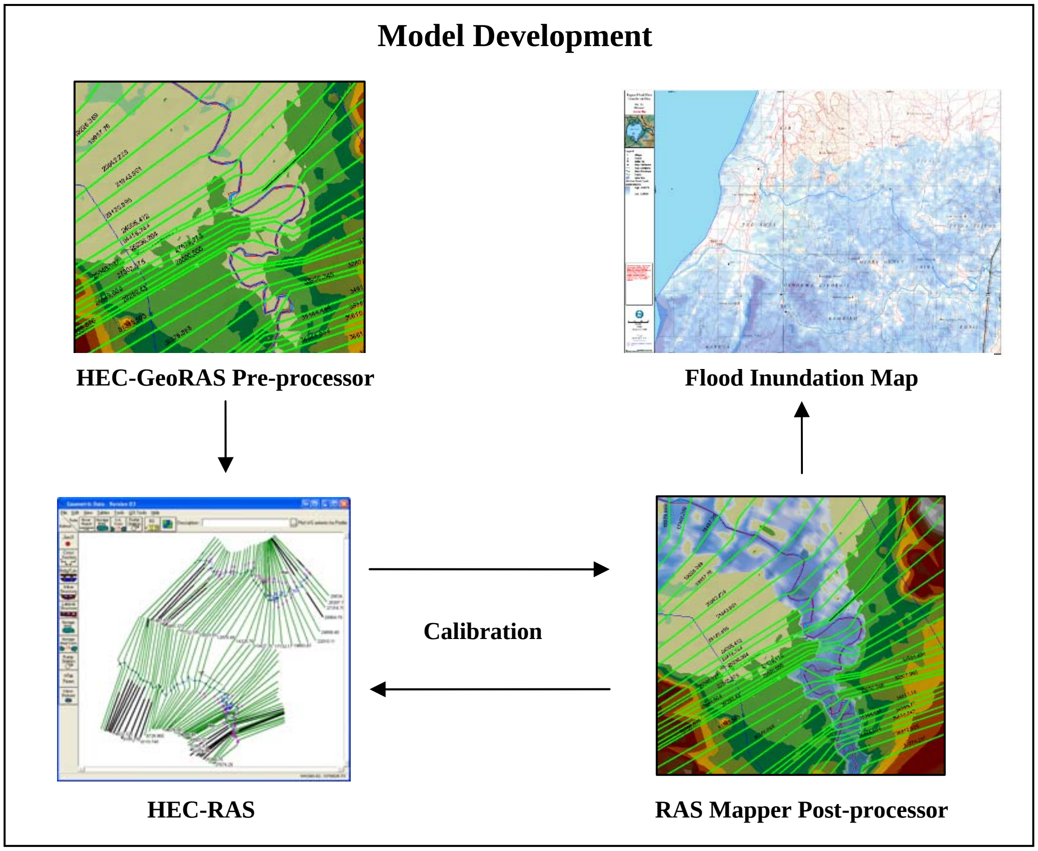


Figure 6-1: Illustration of HEC-RAS / HEC-GeoRAS model development and calibration procedure

6.3 One-Dimensional Hydraulic Model Considerations

One of the main challenges of hydraulic modeling in the Lake Tana floodplains is that many areas of the floodplain adjacent to the rivers are at or near elevations within the upper part of the channel, so that overflows from the channel could conceivably overflow and fill the depressions, and potentially convey flow through the floodplain. Actual filling and/or active flow in these areas, however, depends on the availability of a hydraulic connection to the river and an active flow path between cross sections in the floodplain or overbanks. Moreover, the hydraulic behavior of the flow in the floodplains is complex and its representation using a one-dimensional flow model will result in simplifications that may be significant.

While a two dimensional flow model could theoretically improve the accuracy of the hydraulic modeling and resulting flood hazard mapping in the floodplains, there are important considerations that have led to the selection of the one-dimensional HEC-RAS model.

- One of the project goals is to develop and provide training on approaches that can be extended reasonably to other areas of the country using local technical resources.

- The selected HEC modeling tools are available without licensing costs and are well integrated for both flood hazard mapping and risk analysis.

- Two dimensional modeling will not be required in many (perhaps the majority) of other locations in Ethiopia where hazard mapping and risk analysis are most needed.

- The potential advantages of a two dimensional model in addressing the concerns noted above may be limited by the resolution of the DEM, whereas simplifications in the one-dimensional model permit user judgment to be used to overcome some of these limitations (such as permitting active flow where flow paths are likely, even though they are not explicitly evident at a 90 meter (or even a 30 meter) grid resolution.

In summary, Riverside believes that the selected tools represent an effective combination for establishing consistent procedures that have the best chance for a successful national implementation. Specific modeling approaches for representing the complex flow noted above are discussed in following sections.

6.4 Hydraulic Model Development

As described in ***Section 2.5***, four tributaries to Lake Tana were included in the hydraulic analysis, the Rib, Gumera, Dirma, and Megech. The Ribb and Gumera rivers share the Fogera floodplain, and the Dirma and the Megech share the Dembia floodplain. The upstream extents of the modeled reaches were estimated at locations where the historical flows would not overflow the channel banks and create significant flooding. These upstream extents were determined as discussed in ***Section 4.3*** and verified during the field survey. The hydraulic modeling also verified the selection of the upstream reaches.

6.4.1 Geometric Data

The geometry input files for the HEC-RAS models were created using a combination of ArcGIS and HEC-GeoRAS. The river centerline, bank lines, flow paths, levee alignments, and cross sections were digitized in HEC-GeoRAS (***Figure 6-2***). The river centerline was digitized to match the channel centerline as indicated by the field survey. The bank lines represent the point where the river is considered "out of bank" and the river is flowing onto its floodplain. In addition, these lines determine the change in Manning's n roughness coefficients in the hydraulic model and may be adjusted in the model itself. The channel bank lines were also digitized using the field survey as a reference. Three flow path lines were setup in HEC-GeoRAS to represent the direction of flow within the channel banks and in the left and right flood plains. These lines also determine the cross section stationing as well as the right and left overbank distances between cross sections. Finally the cross sections were oriented perpendicular to the flow, and located to represent areas in the reach where physical changes occur.

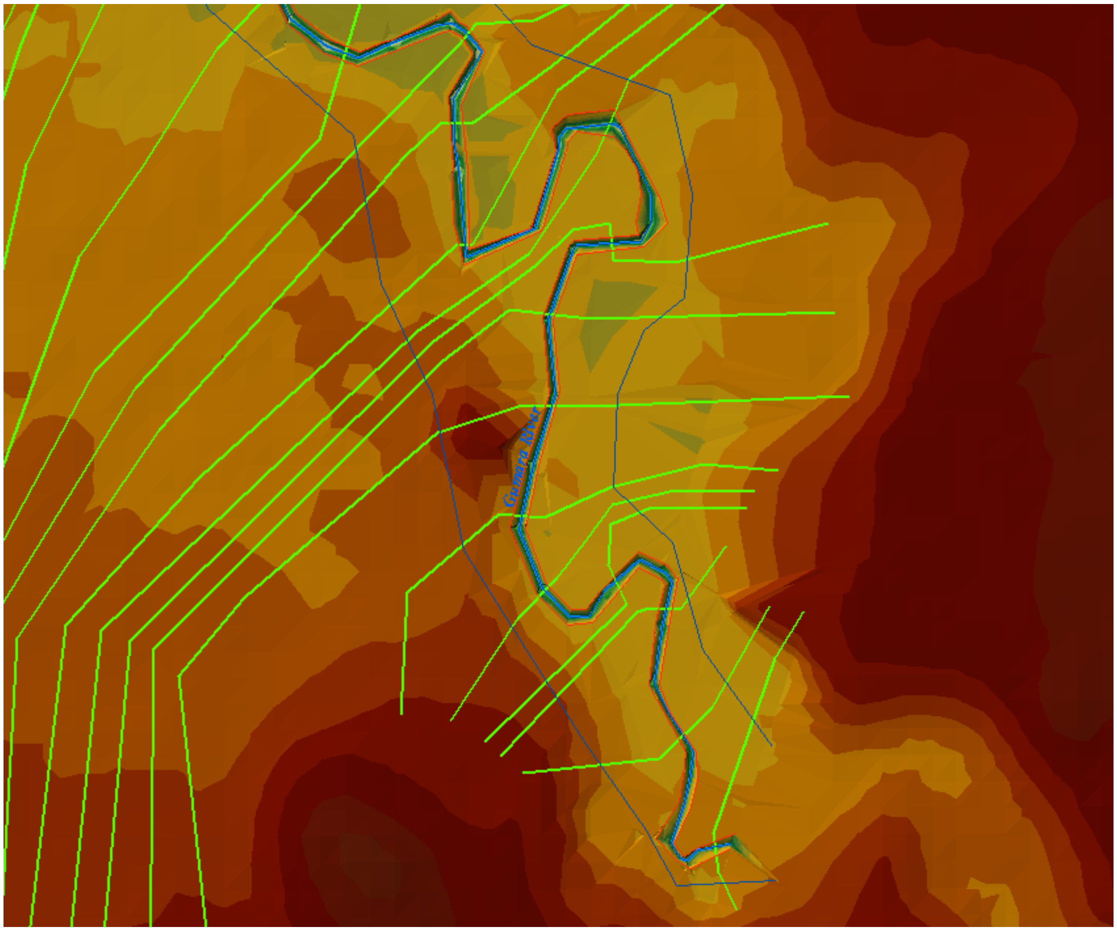
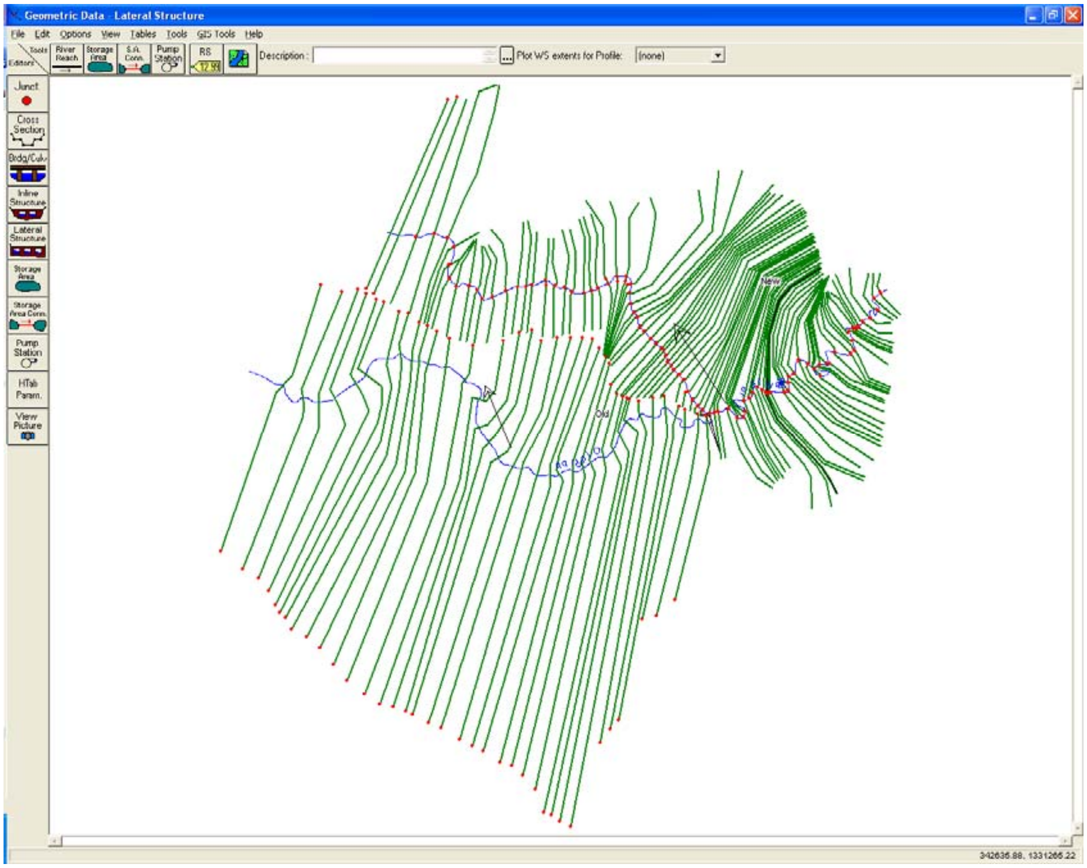


Figure 6-2: Example digitization of river features in HEC-GeoRAS. River centerline (light blue), bank lines (red), flow paths (dark blue), and cross sections (green).

Once the digitization process was complete, the HEC-GeoRAS data was imported into HEC-RAS. The transition between the pre-processor and the hydraulic model is smooth and results in a visual representation of the model identical to that created in the pre-processor. A sample plan view of the Ribb River and Gumera River streamline, bank points, and cross sections is displayed in ***Figure 6-3***. The geometric data were reviewed in HEC-RAS and initial bank stations were adjusted as necessary. Downstream reach lengths were verified by measuring the distances in ArcGIS.



Plot WS extents for Profile: (none)

Figure 6-3: Sample plan view of Ribb River cross sections in HEC-RAS.

For both the Fogera and Dembia flood plains an attempt was made to identify appropriate flow paths that would be expected in the portions of each floodplain that are at an extended distance from the rivers, and to draw the cross sections in such a way that they would be perpendicular to the flow, should it extend that far. The ultimate intent was to lay out the cross sections in such a way that the water surface across the width of the cross section could be expected to be at the same elevation, as this assumption would be enforced in the hydraulic model.

6.4.1.1 Fogera Plain

The Ribb River model is comprised of two separate reaches connected by a lateral structure. The main reach in the model reflects the current Ribb River and is 30 km long and contains 90 cross sections with an average distance of 330 m between cross sections. The second reach reflects the old alignment of the Ribb and is 21 kilometer long and contains 36 cross sections with an average distance of 580 meters between cross sections. The second reach was added in order to be able to model the interception of run-off by the old Ribb River as well as to represent overflow from the Main Ribb River into the old alignment of the river during high flow conditions. Both reaches were connected by a lateral structure that represented the existing ground between the two reaches.

The Gumera River model reach is 37 km long and contains 118 cross sections with an average distance between cross sections of 320 m. The cross sections for this river are laid out as shown in ***Figure 6-4***.

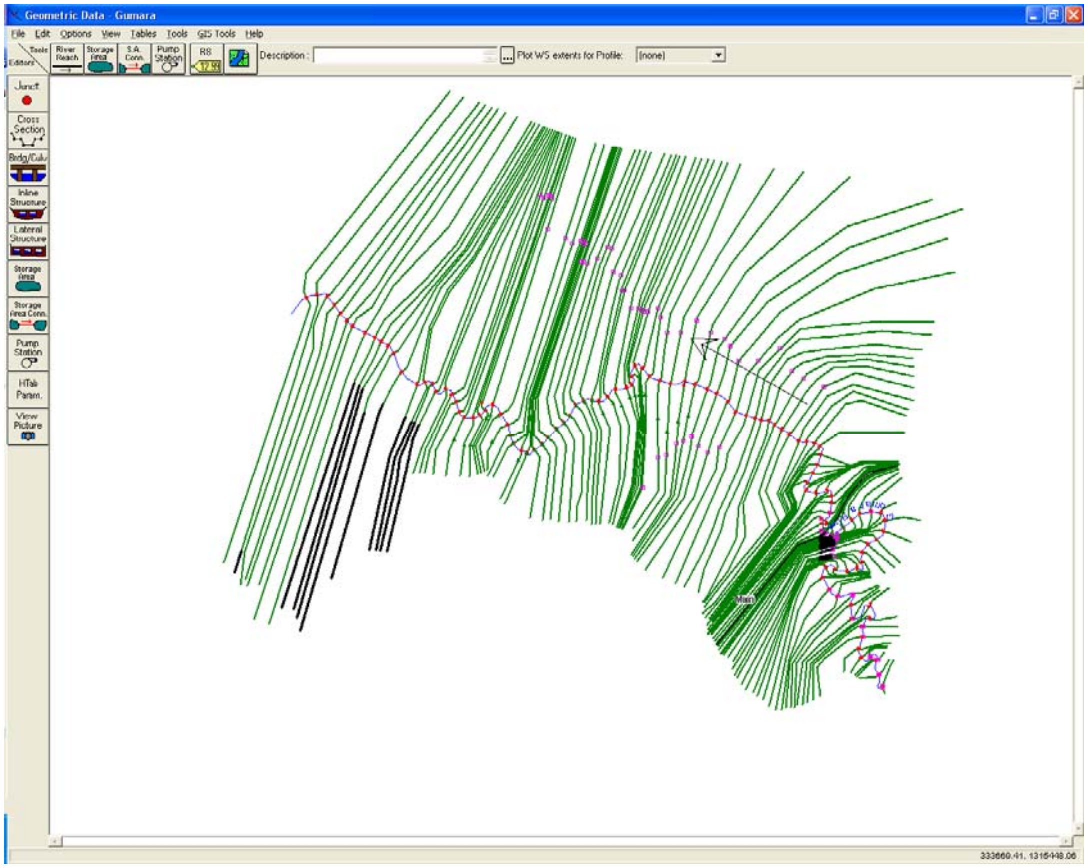


Figure 6-4: Sample plan view of Gumera River cross sections in HEC-RAS.

6.4.1.2 Dembia Plain

The Dirma River model reach is 32 km long, contains 225 cross sections with an average distance between cross sections of 142 m. The Megech River model reach is 15 km long, contains 68 cross sections with an average distance between cross sections of 220 m. As the modeling proceeded, it became evident that the central portion of the Dembia plain is drained by a separate channel that originates within the plain and has a small drainage area, but which is potentially inundated by flow from the Dirma River. A separate hydraulic model reach was defined for this intermediate area with lateral connections to the Dirma river to receive high flows from the Dirma floodplain in several locations. The geometry for this channel was based on the DEM, as there was no direct field survey of this area. Separate modeling of this reach permitted a representation of the extension of the Dirma flows into the wider floodplain without requiring the elevations in the two floodplain areas to be the same. The cross sections for these rivers were laid out as shown in ***Figure 6-5***.

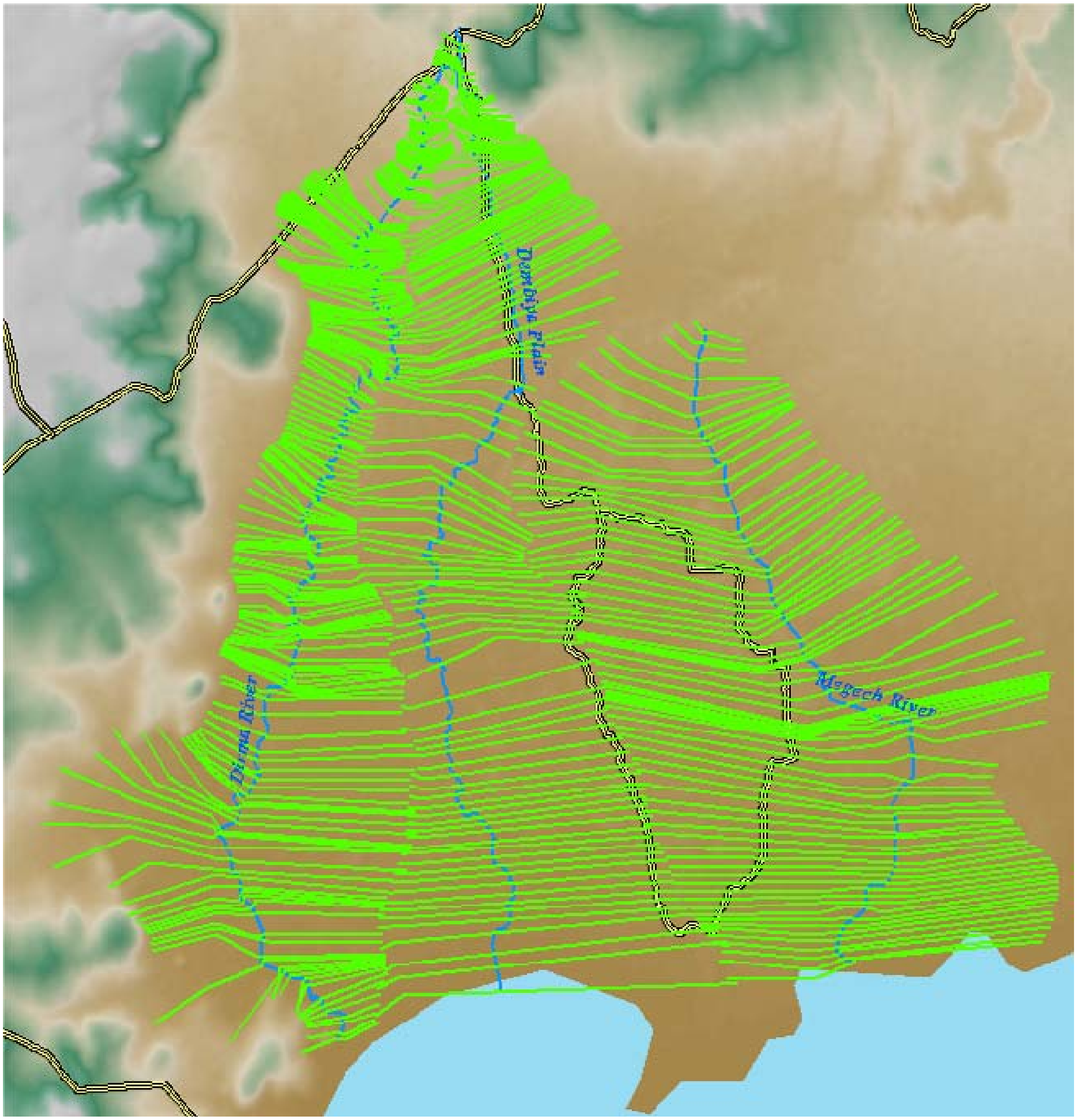


Figure 6-5: Dembia plain HEC-RAS model layout.

6.4.2 Ineffective Flow Areas, Levees and Blocked Obstructions

By default, the HEC-RAS program will assume all areas of the cross section are active flow areas and that they have velocities greater than zero. Elevated potions of the channel will split the flow and the model will convey flow downstream in all portions of the cross section that lie below the water surface. A combination of ineffective flow, levees and blocked obstructions can be used to restrict flow to the effective flow areas of the cross section for both left and right flood plains.

Ineffective flow areas represent areas of ponding with zero velocity in the downstream direction. ***Figure 6-6*** illustrates a sample ineffective flow area in a sample reach. When an area is defined in HEC-RAS as ineffective, the velocity is set to zero and flow is not conveyed downstream. However, the ineffective flow area is included in storage calculations. In HEC-RAS the ineffective flow area is defined by elevation and stations defined along the cross-section from the left bank to right bank (***Figure 6-7***). The ineffective flow elevation can be set arbitrarily high so that the area never conveys flow. Alternately, the ineffective flow elevation can be set lower. Once the water surface reaches the set elevation the total area becomes active and conveys flow downstream. A third option allows for a combination of active and ineffective flow in the overbanks. This is achieved by setting the ineffective flow area to permanent. In this scenario conveyance in the ineffective area will always be zero, but any flow above the set elevation will be active and convey flow downstream, effectively going over the top of the ineffective flow area.

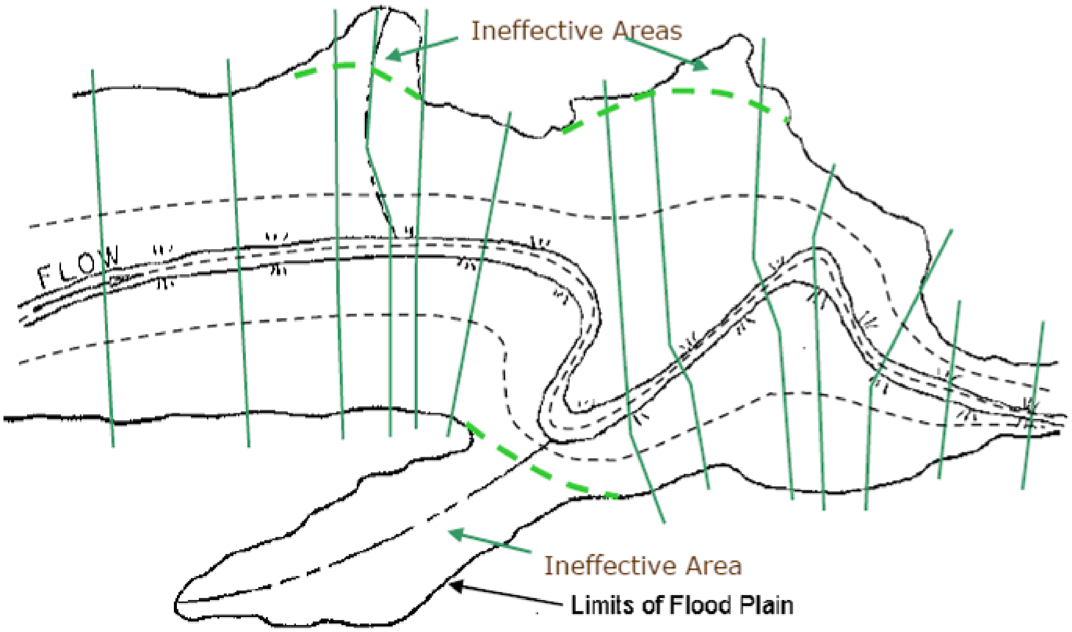


Figure 6-6: Example of ineffective flow areas in a floodplain (HEC-RAS Reference Manual).

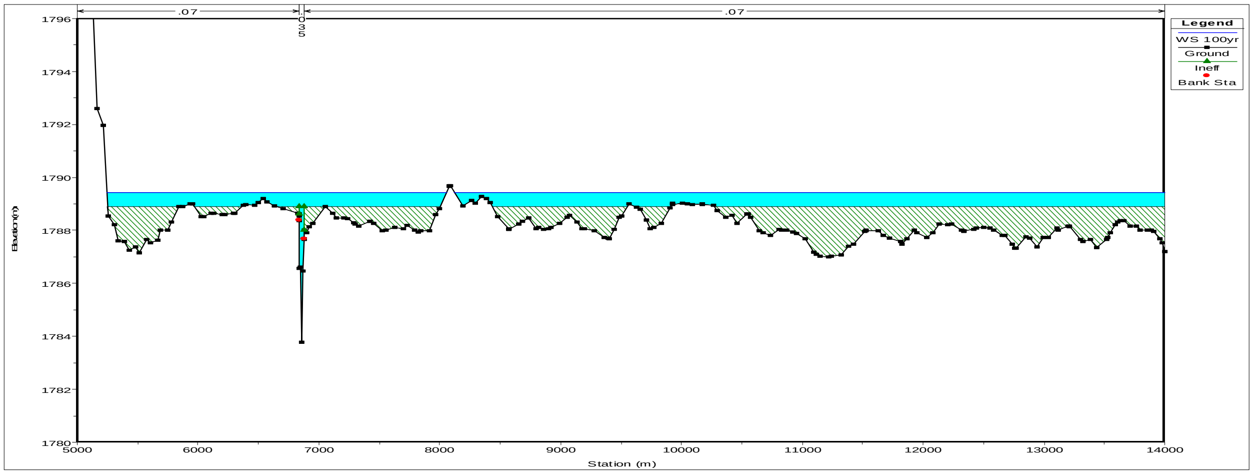


Figure 6-7: Example ineffective flow area in HEC-RAS (green diagonal lines).

In HEC-RAS water is assumed to flow in all areas of a cross section by default. Levees confine flow within a location until the water surface elevation is greater than the levee height and then the levee is considered overtopped and water may flow beyond the levee. ***Figure 6-8*** illustrates a default cross section where flow is considered active in all areas of the cross section. In reality, flow would not be able to reach areas in the left and right bank (stations below 1200 m and above 2200 m). ***Figure 6-9*** illustrates the flow constrained to a location by a left and right levee. It should be noted that the levees defined in this plot are set to ground elevation so that there are no changes to the cross section geometry by the addition of levees.

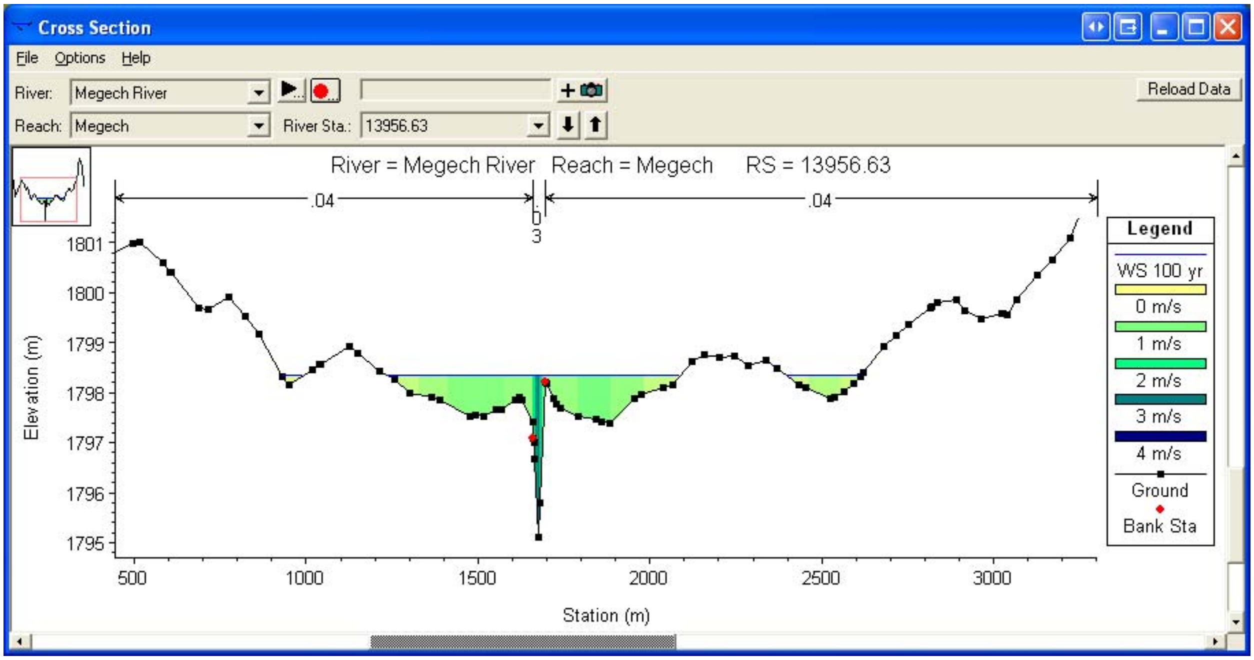
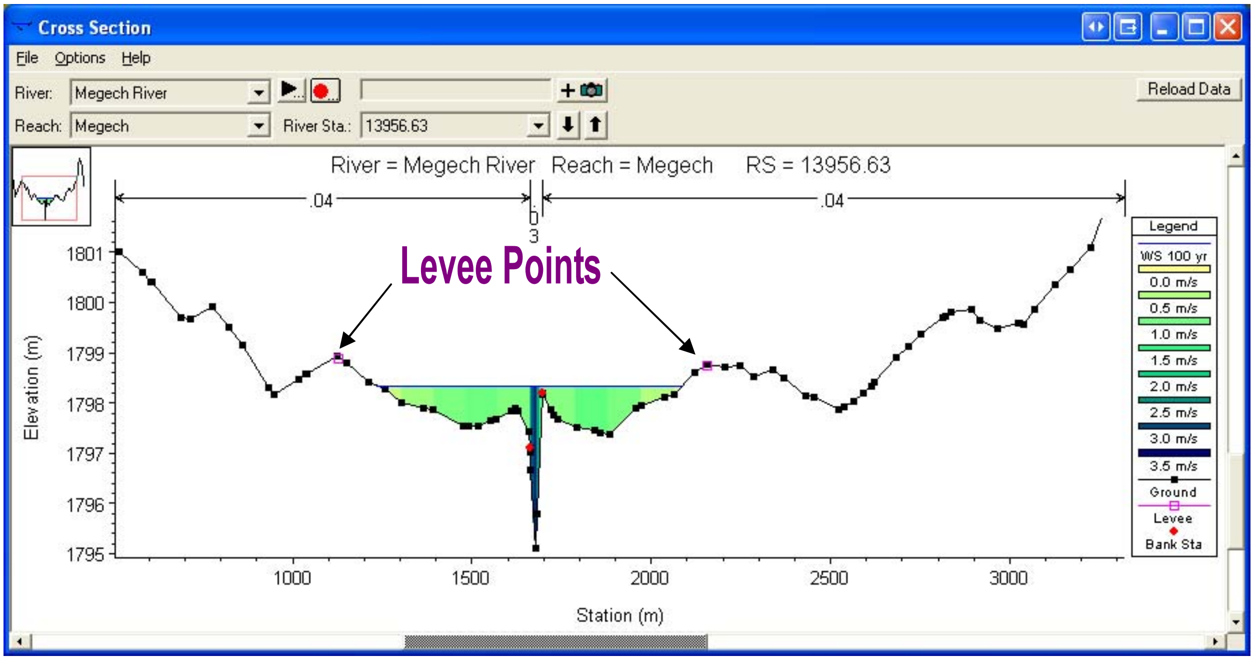


Figure 6-8: Sample cross section plot illustrating flow in all areas of the cross section.



River: Megech River

Reach: Megech

River Sta.: 13956.63

Figure 6-9: Sample cross section plot illustrating flow constrained within the levee points.

A levee is designated in HEC-RAS by a station and elevation point for each levee. The model allows one left bank and one right bank levee per cross section. Unlike ineffective flow areas which include its area in storage calculations, a levee will reduce the area of the cross section as long as the water surface elevation remains below the elevation of the levee.

Blocked obstructions allow the user to define areas of the cross section that will be permanently devoid of flow. This is useful when a levee designation may represent constraints for one flow profile but not another. ***Figure 6-10*** illustrates the use of both a levee and a blocked obstruction to represent inactive flow areas. Both a 100-yr and 2-yr flow are represented by blue lines, the levees are represented by pink squares and the blocked obstruction is represented by the shaded black area. For the 2-yr flow, the flow is constrained to the channel and the left overbank area. The right bank levee keeps flow out of the right overbank area. The 100-yr flow overtops the right bank levee and floods the right overbank area. There is inundation in adjacent overbank area and the section between stations 2500 m and 3300 m. Although not obvious from this figure, this far right inundation is accurate because the upstream cross section conveys the flow downstream. The blocked obstruction keeps flow out of the area located in station 3700 m and above which is separated by high points in the flood plain and therefore would not convey flow. Blocked obstructions are designated by two pairs of station/elevation points per obstruction. HEC-RAS allows multiple blocked obstructions per cross section. The blocked obstruction also reduces the area of the cross section.

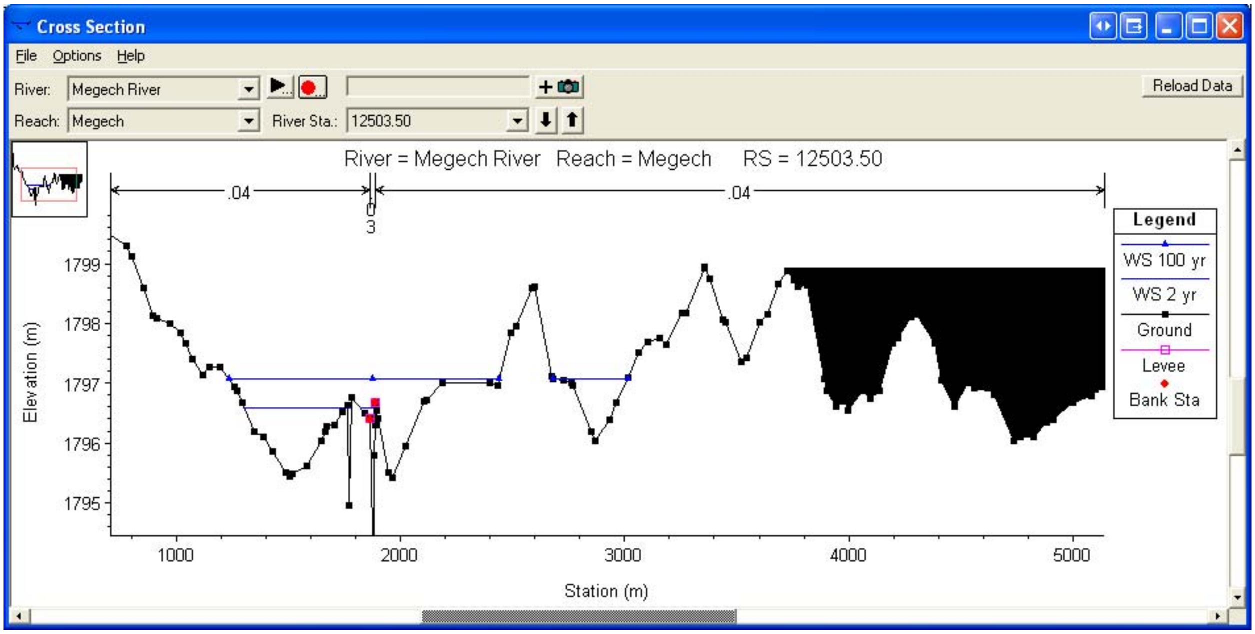
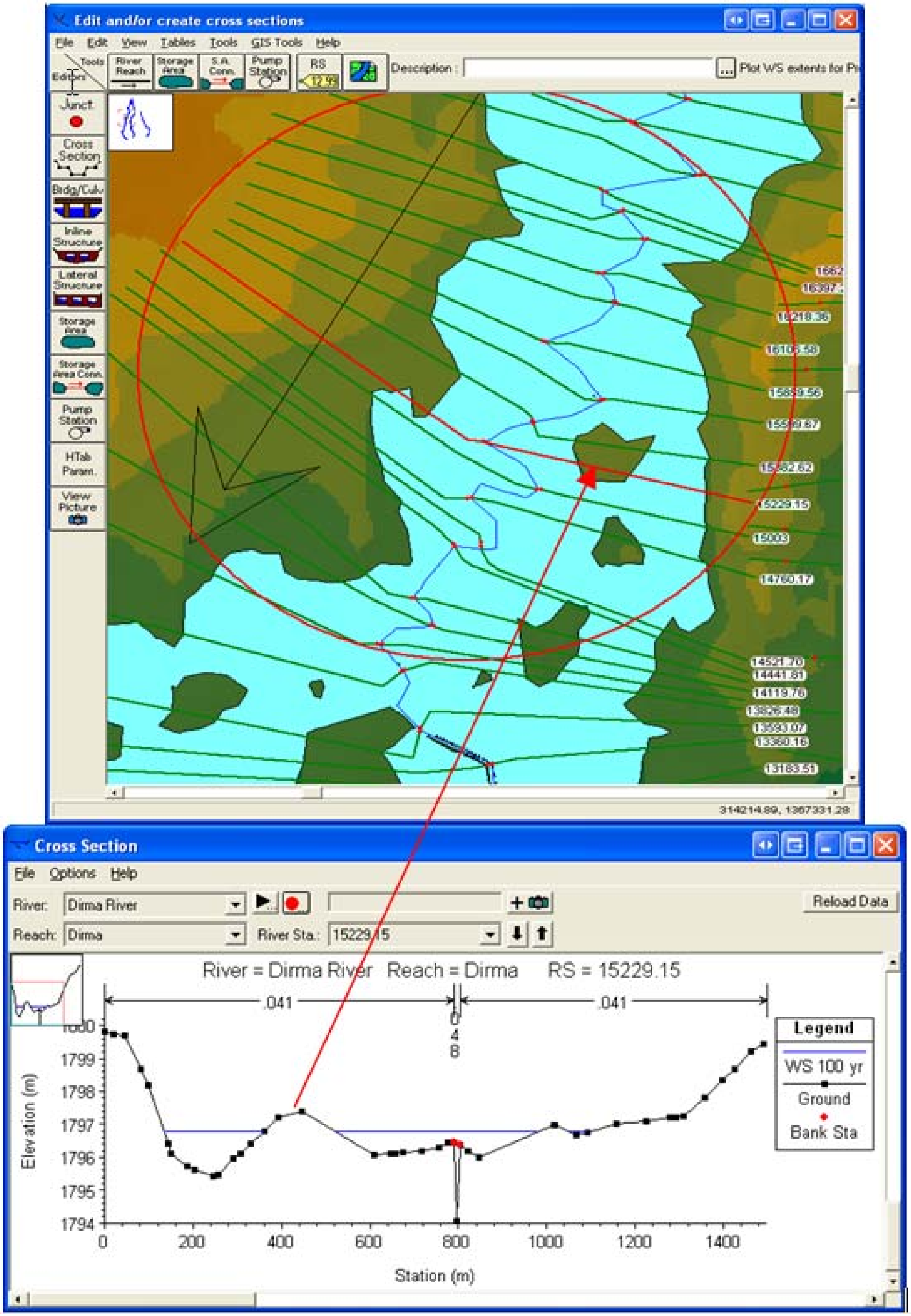


Figure 6-10: Sample cross section plot illustrating constrained flow with levees and blocked obstruction.

As noted previously, one of the main challenges of hydraulic modeling in the Lake Tana floodplains is to accurately represent the conveyance of water and the extent of inundation through hydraulic connections with the river channel. In many cases there is a direct and continuous connection between the river and the floodplains. In other cases there is an interruption in the water surface. For the flow to access the floodplain beyond a high point in the topography, it must be accessible to the main channel or another area of the floodplain from either an upstream or a downstream cross section. This can best be determined through an iterative process of simulating the flow, generating an inundation map, and then adjusting hydraulic constraints in the model to limit or extend flow to areas that can be observed to be hydraulically connected. ***Figure 6-11*** and ***Figure 6-12*** show the relationship between cross sections and inundated area for connected flow and disconnected flow areas, and demonstrate how the inundation map can provide guidance on placement of hydraulic model constraints. The hydraulic modeler uses judgment to define levees (flow does not enter the flood plain until it exceeds the height of the levee), flow blockage (areas where flow/inundation is not simulated), and ineffective flow (areas that may be inundated but do not contribute to conveyance in the river system). This judgment is not only based on the information contained in the 90 meter DEM, but also relies on field observations and information provided during visits and meetings. This process was an important component of the hydraulic modeling.

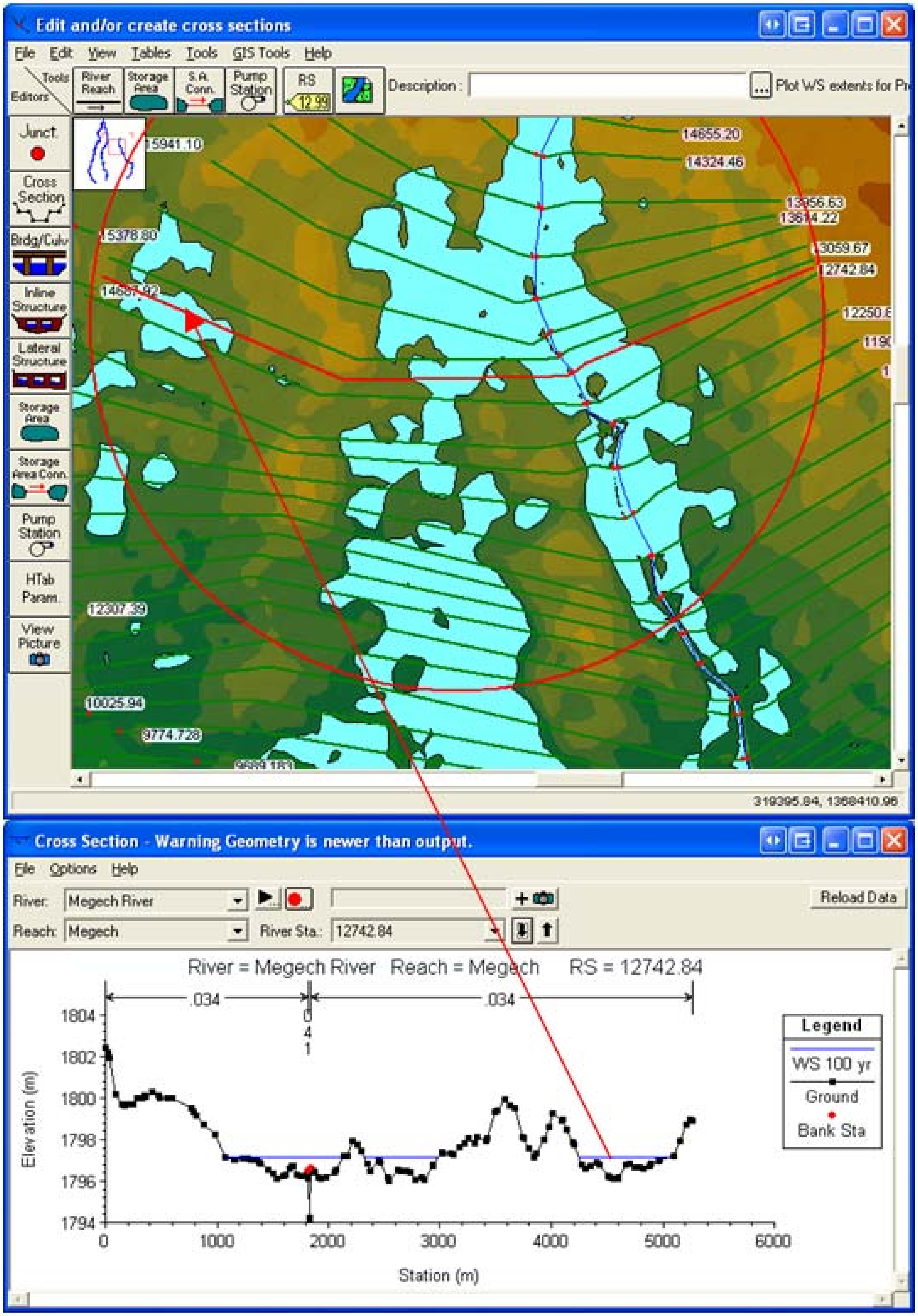


River: Dirma River

Reach: Dirma

River Sta.: 15229.15

Figure 6-11: Example of hydraulic connectivity from an upstream cross section which is not apparent from the cross section alone.



Edit and/or create cross sections

Cross Section - Warning Geometry is newer than output.

River: Megech River

Reach: Megech

River Sta.: 12742.84

Figure 6-12: Example of a section that is not connected to the river channel.

6.4.3 Hydraulic Structures

Two bridges are located in the hydraulic model areas of the Fogera Plain. One bridge is located on the Ribb River and one bridge is locate on the Gumara River. Both bridges are on the road connecting Woreta and Bahir Dar. The bridge parameters were determined based on the results of the field survey and the elevation model was used to extend the bridge out into the floodplain.

In addition to the two bridges, the Dirma river model contains two lateral structures and the Ribb River model contains one lateral structure. The lateral structures were used in the model to simulate the flow of water into the overbanks and cross into adjacent subbasins. The location of the lateral structures was determined based on low spots in the terrain and the height of the lateral structure was set to match the terrain elevation.

6.4.4 Manning's "n" values

Manning's n values were estimated using both field survey photos (***Figure 6-13*** through ***Figure 6-20***) and a method outlined in USGS Water Supply Paper 2339 (Arcement and Schneider, 1989). For sand channels this method estimates a base value related to grain size and then applies adjustments for additional factors affecting channel and floodplain roughness. The method uses the following equation developed by Cowan (1956) to estimate a channel Manning's n value.

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m$$

where:

n_b = a base value of n for a straight, uniform, smooth channel in natural materials

n_1 = a correction factor for the effect of surface irregularities

n_2 = a value for variations in shape and size of the channel cross section

n_3 = a value for obstructions

n_4 = a value for vegetation and flow conditions

m = a correction factor for meandering of the channel

A base value of 0.012 was used for both the Dembyia and the Fogera reaches. This value corresponds to a sandy channel with a grain size of 0.2mm. Adjustments were made to the Megech assuming a moderately eroded channel, with large and small cross sections alternating occasionally, negligible obstructions, a small amount of vegetation and a fairly straight channel. Similar adjustment values were used for the Dirma; assuming mildly eroded channels, less cross sectional variability than the Megech, minor obstructions, and a small amount of vegetation, but more than the Megech. It was also assumed that the Dirma had a higher degree of meandering than the Megech. A channel Manning's n of 0.034 was used for the Megech, and 0.035 was used for the Dirma.

In the Fogera plain, separate Manning's n values were estimated for the upper sections and lower sections of the study reaches. When comparing the upper and lower reaches, field photos indicated that the upper sections had more eroded banks, more vegetation and a higher degree of meandering. A value of 0.033 was used in the upper reach of the Gumara, and 0.037 was used in the upper reach of the Rib. In the middle and lower reaches, a value of 0.03 was used in both the Gumara and the Rib. According to Chow (1959) a Manning's n value of 0.037 would be valid for clean winding channel with some pools and shoals. For the middle and lower reaches which are clean, straight, with no rifts or deep pools Chow recommends an upper value of 0.03.

A similar equation was used to estimate Manning's n values for the floodplain.

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m$$

where:

n_b = a base value of n for the floodplains natural bare surface

n_1 = a correction factor for the effect of surface irregularities in the floodplain

n_2 = a value for variations in shape and size of the floodplain cross section, assumed to equal 0.0

n_3 = a value for obstructions on the floodplain

n_4 = a value for vegetation on the floodplain

m = a correction factor for sinuosity of the floodplain, equal to 1.0

A floodplain Manning's n of 0.041 was used for both the Megech and the Dirma. This value assumes a few rises and dips in the floodplain, a few scattered obstructions and a medium amount of vegetation. In the upper reach of the Ribb a higher value of 0.043 was used due to areas of more dense vegetation. For the lower floodplain of the Ribb, a value of 0.041 was used. In floodplain areas of the Gumera with more trees a value of 0.07 was used, and for the remainer of the Gumera floodplain a value of 0.040 was used. These values are also similar to those recommended by Chow (1959). According to Chow, a floodplain with mature field crops would have an average value of 0.04, while a floodplain with medium to dense brush would have a value of 0.07.

Figure 6-13: Photo of upstream Megech River.

Figure 6-14: Photo of downstream Megech River.

Figure 6-15: Photo of upstream Dirma River.

Figure 6-16: Photo of downstream Dirma River.

Figure 6-17: Photo of the upstream section of Gumara, showing eroding banks and vegetation.

Figure 6-18: Photo of the downstream section of Gumara, showing clean channel with less vegetation.

Figure 6-19: Photo of the upstream section of Ribb, showing eroding banks and vegetation.

Figure 6-20: Photo of the downstream section of Ribb, showing clean channel with less vegetation.

6.4.5 Boundary Conditions

6.4.5.1 Steady Hydraulic Model

Peak flow data for 2, 5, 10, 50, and 100 year discharges were used for the steady flow analysis (***Section 5.0***). The Lake Tana water surface elevations were used as the downstream boundary conditions using lake levels with return periods corresponding to the various return period flows, as discussed in the hydrologic modeling section. It is noted that the use of a low frequency boundary condition, such as the 100 year water level, combined with the 100 year flow, might be an unrealistic combination of probabilities that would over-estimate flood depths and inundation. The frequency of inundation, however, occurs regardless of the source (be it high lake level or river flooding), so the overestimation depends on the magnitude of the backwater effect of the lake *upstream* of the direct impact of the lake level on floodplain inundation. An analysis of water surface profiles for both high and low lake levels in each of the rivers indicated that the effect is not significant (***Figure 6-21*** through ***Figure 6-24***). By the time peak flows reach the area of influence of the lake in the channel and floodplain, the flow has spread sufficiently to exhibit large flow areas and low velocities. These conditions do not lend themselves to extended upstream backwater effects from the lake beyond the direct influence of the high water levels.

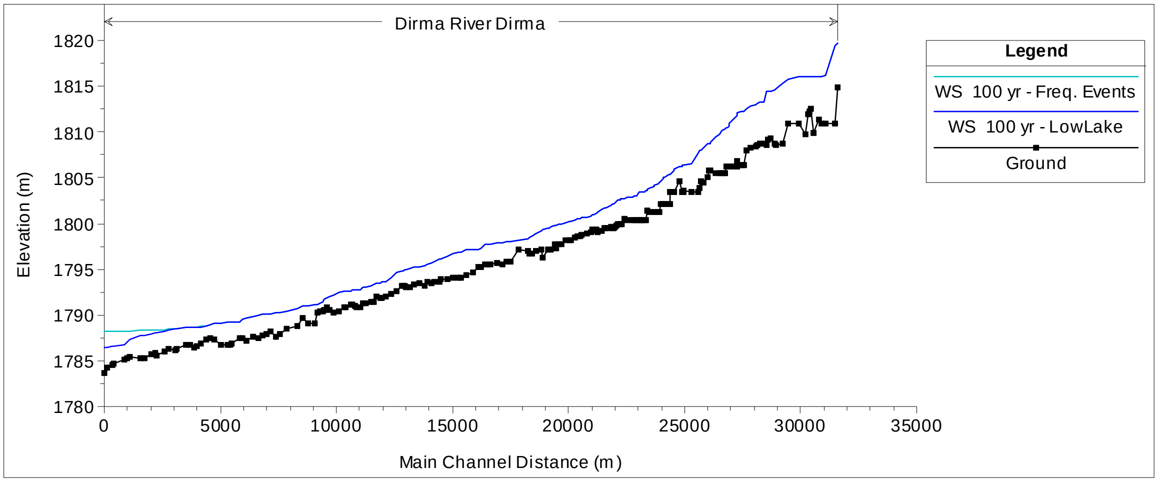


Figure 6-21: Simulation using the 100-year lake level compared with the lowest historical peak lake level (1786.5 m) for the downstream boundary of the Dirma River.

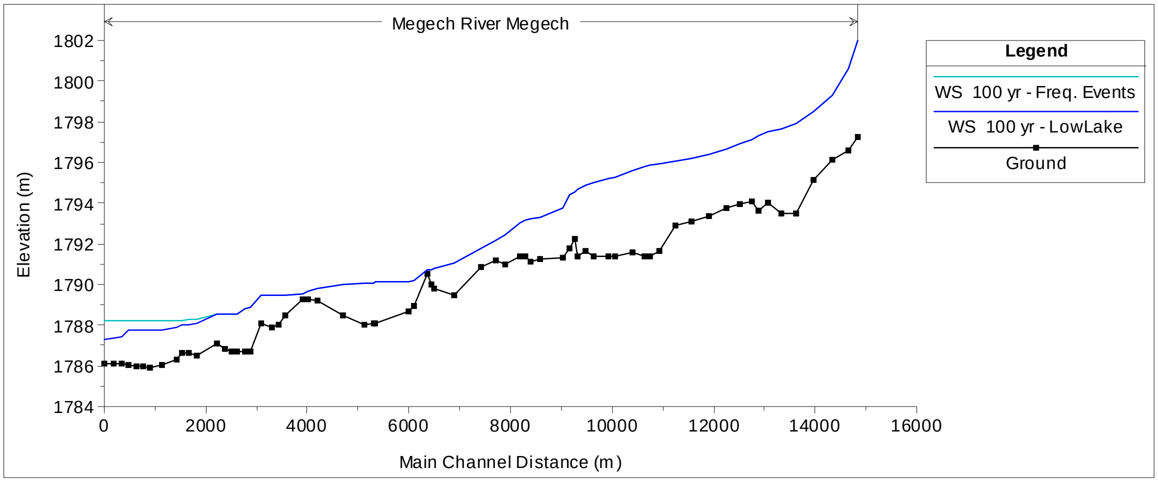


Figure 6-22: Simulation using the 100-year lake level compared with the lowest historical peak lake level (1786.5 m) for the downstream boundary of the Megech River.

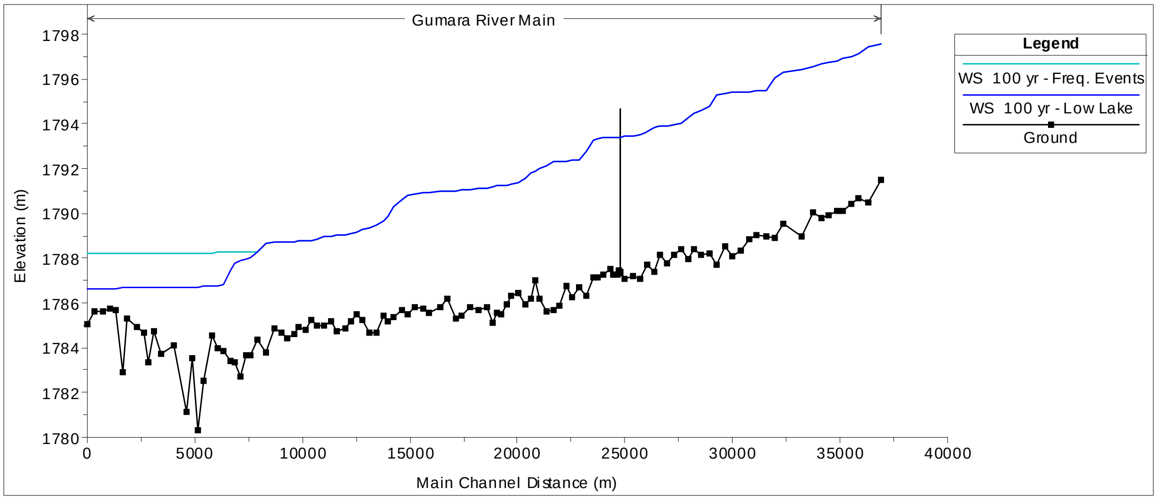


Figure 6-23: Simulation using the 100-year lake level compared with the lowest historical peak lake level (1786.5 m) for the downstream boundary of the Gumara River.

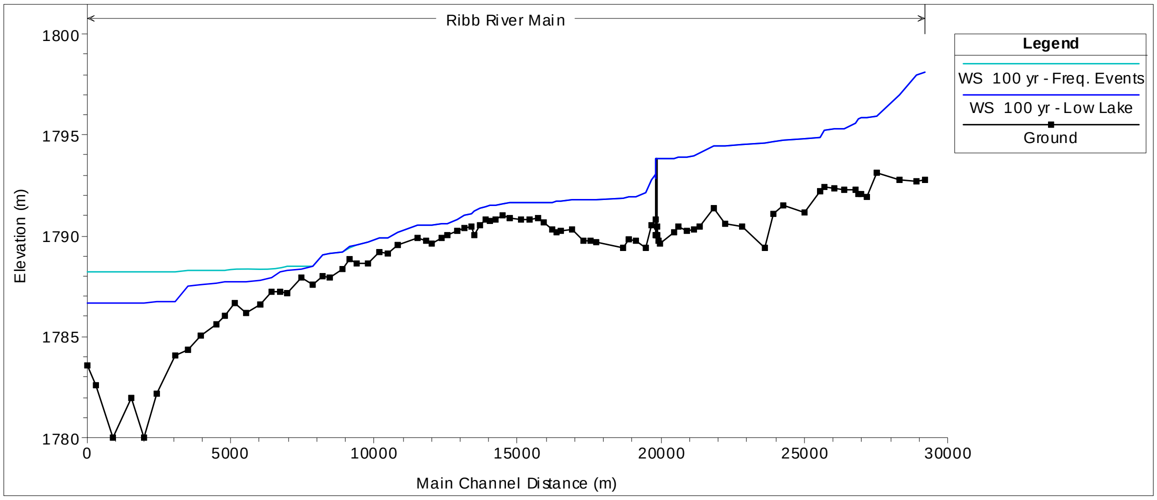


Figure 6-24: Simulation using the 100-year lake level compared with the lowest historical peak lake level (1786.5 m) for the downstream boundary of the Rbb River.

In the Ribb and Gumara Rivers, an alternate hydraulic simulation also was performed using the frequency flows determined from hydrologic simulation instead of the frequency analysis based on historical gage data. As discussed in the hydrologic modeling section, these flows are significantly higher, representing flow frequencies that might be expected if more reliable rating curves were employed in developing the historical discharge estimates.

6.4.5.2 Unsteady Hydraulic Model

For the unsteady state model the flow hydrographs from HEC-HMS for the individual subbasins were used as inflow and lateral inflow into the model. The downstream boundary condition was the lake level as described in the steady state model boundaries. Due to the short duration of the rainfall event and the minimal water level variations that could be expected in the lake over this time period, the water level was considered constant for the duration of the event.

6.5 Model Evaluation

During a workshop meeting stakeholders indicated that the modeled flood extents for the Ribb River in the Fogera plain did not include the Nabega region that lies between the Ribb and Gumera Rivers. In order to include this area, it was necessary to update the model to include an additional river following the old alignment of the Ribb River, with inflows derived from local runoff from the interior basins between the two main rivers, and with additional inflow derived from overflows from the main Ribb channel under high flow conditions. The overflow point was defined at the location where the old and new channels diverge.

The model results for the flood extents for the Gumera and Ribb rivers were evaluated during a field visit in October 2009, when the study team traveled through portions of the flood plains and reviewed evidence of flooded areas from the 2009 flood season in relation to model predictions regarding maximum flooding extents for the 2-year event. Observations were consistent with expectations in relation to anticipated flood depths and extents from the flood mapping. Development patterns were observed to be in general agreement with expectations, based on the mapping, with very little permanent and high value development within the 2-year floodplain, and increasing development toward the 100-

year floodplain boundaries, where recent serious flooding is less likely to be present in the memory of the population and has less influence on the selection of location for development. Older development was likewise observed to be outside of the 100-year floodplain reflecting historical development patterns associated with permanent, high-value enduring construction in the absence of significant land development pressure. Although these observations are not a precise measure of the accuracy of the hydrologic analysis or the hydraulic modeling, they confirm that the predicted flood extents are reasonable and are in fact useful in guiding subsequent development efforts without resorting to trial-and-error development in the floodplain with its attendant costs and impacts on affected population.

6.6 Hydraulic Model Results

The hydraulic modeling indicated very similar flood elevations and extents for the steady and unsteady hydraulic models. The unsteady model simulates the attenuation of peak flows, but the resulting reduction in peak flow is not large in percentage terms perhaps because total hydrograph volumes are large enough to fill storage areas on the rising limb, leaving only modest incremental volume to store and attenuate peak flows. Moreover, because of the large flooded area, differences in peak water level are even less noticeable than differences in peak flows between the steady and unsteady models. These differences suggest that, for purposes of future flood risk assessment and mapping, uncertainties associated with the simplifications required for steady modeling are not large. However, whereas the steady model appears to provide reasonable estimates of flood depths and velocities, the results from the unsteady models are useful in assessing the duration of flooding at multiple locations within the floodplain.

6.6.1 Dembiya Floodplain

The model results for the Dirma River show that during a 2-year flood water starts to cross from the Dirma Basin into the Dembiya middle basin (Shenzli River). During larger flood events significant amounts of water flow into the Dembiya middle basin. This flood water, in combination with local runoff from the middle basin results in large inundated areas in the Dembiya floodplain. Figure 6-25 is a typical cross section for the Dirma River, showing the water levels during the 2 year flood, which included some inundation in low areas adjacent to the river, and the water levels for the 100-year flood, which results in significant flooding in the floodplain. Figure 6-26 shows the profile for the 100-year flood in the Dirma River.

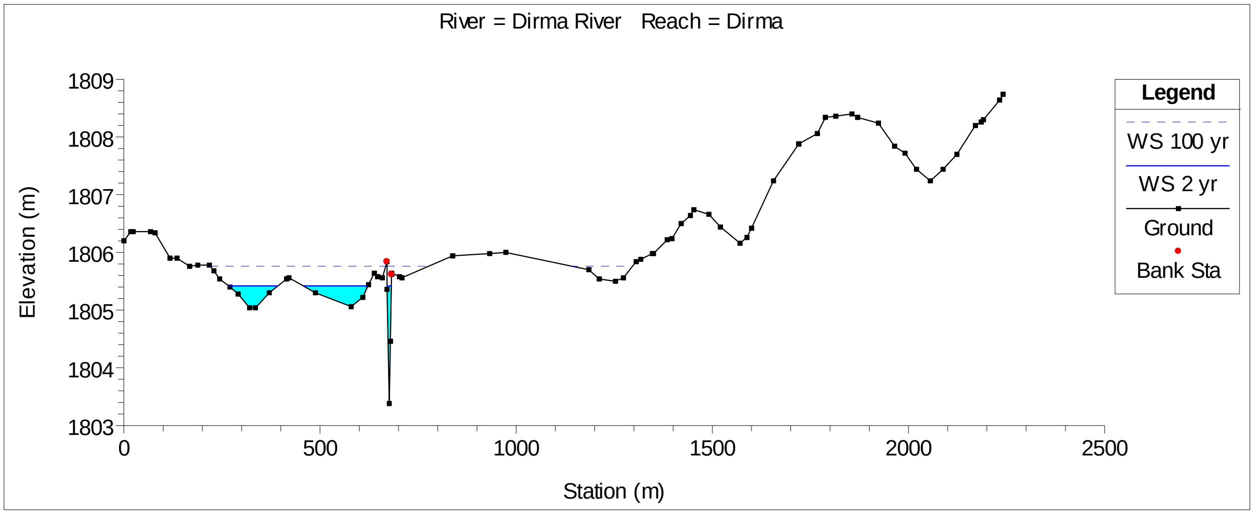


Figure 6-25: Typical cross section for the Dirma River showing the 2 and 100 year water levels.

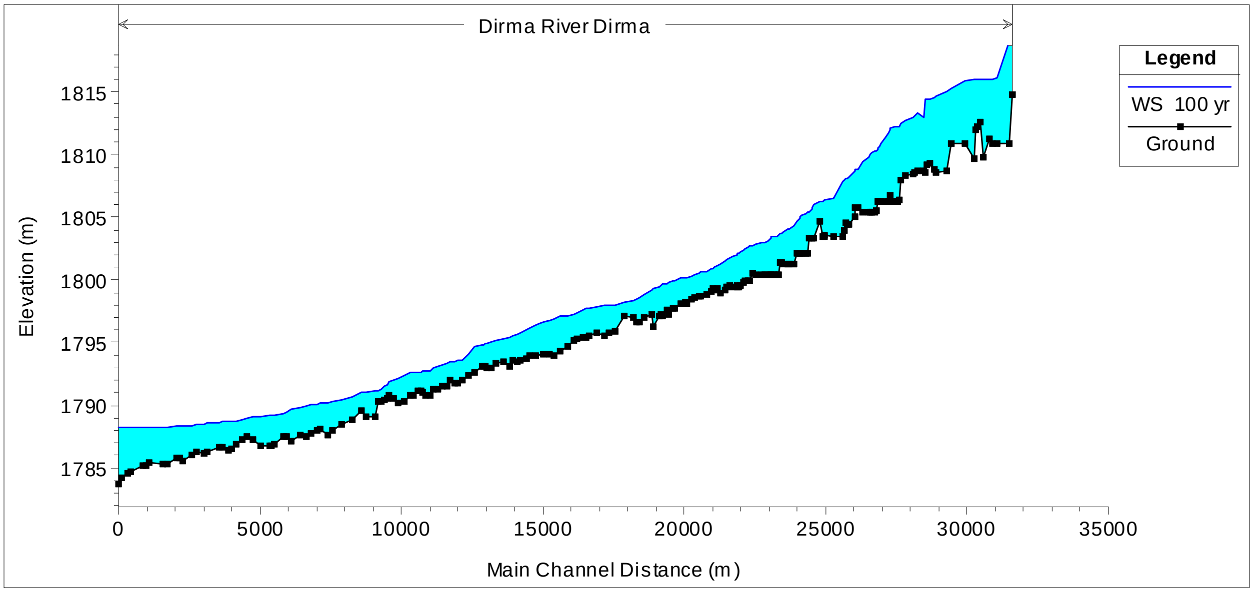


Figure 6-26: Profile plot for the Dirma River for the 100 year flow.

The modeling results for the Megech River show that flood waters not only follow the Megech River towards lake Tana, but also use a flow path west of the River. Figure 6-27 shows a typical cross section indicating both these flow paths. This cross section also shows that during the 2-year flood some minor flooding alongside the river and western flow path should be expected, whereas during the 100-year flood, significant portions of the floodplain are inundated in both the eastern (left) and western (right) floodplains. Figure 6-28 shows the profile for the 100-year flow in the Megech river.

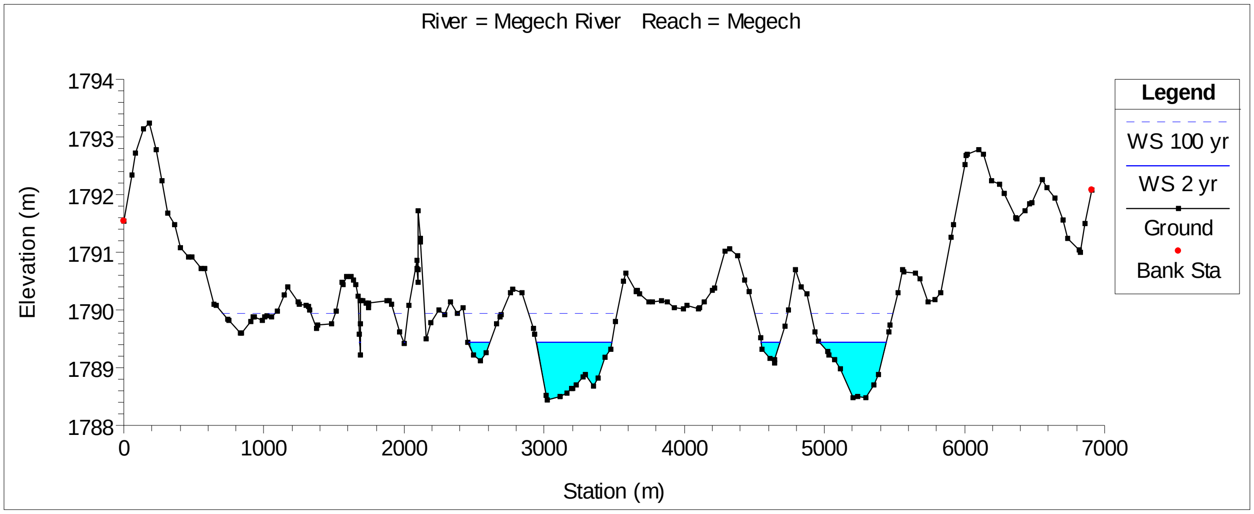


Figure 6-27: Typical cross section for the Megech River showing the 2 and 100 year water levels.

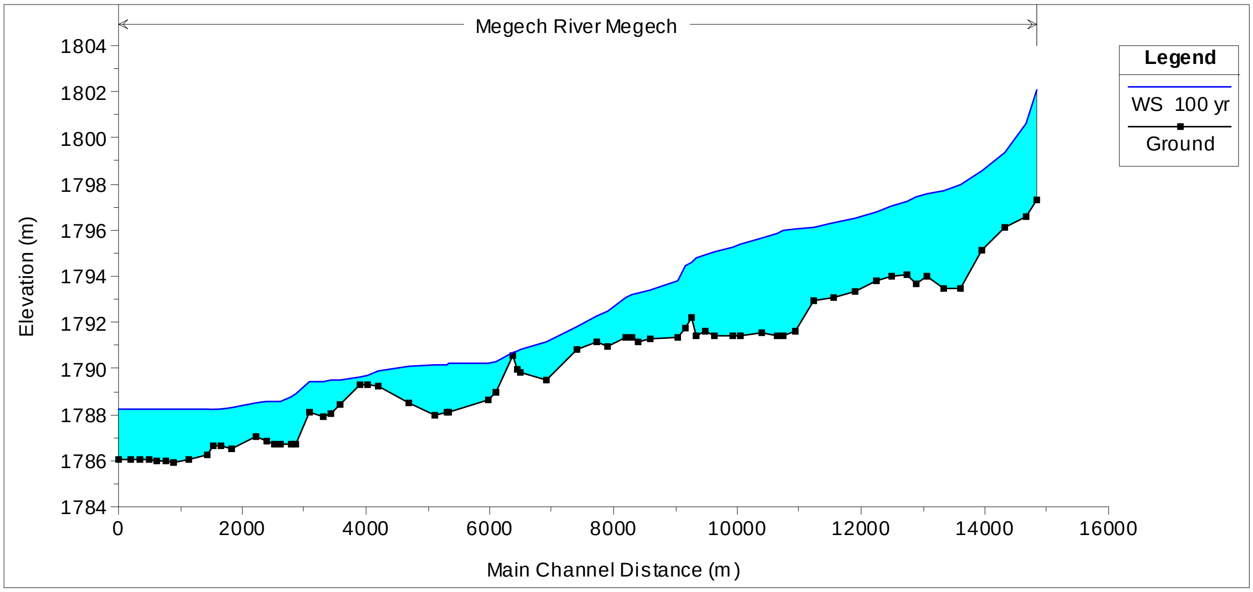
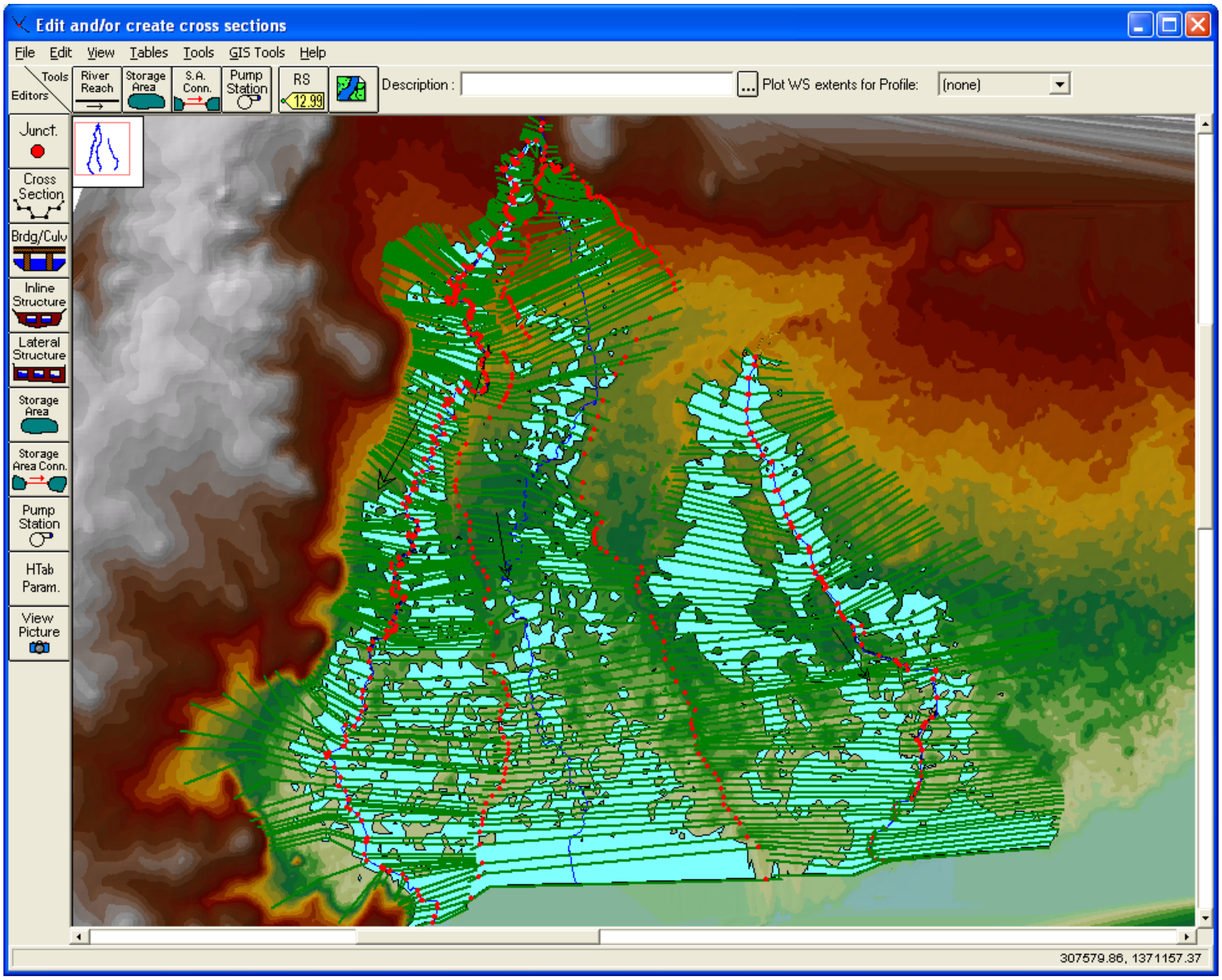


Figure 6-28: Profile plot for the Megech River for the 100 year flow.

There are several location in the profile where the channel bottom is elevated and depths are shallow. In these cases there is often a substantial alternate flow path that permits a large portion of the water to pass the section without staying in the main channel. These areas may also represent future points of departure for re-alignment of the channel. Figure 6-29 shows the Dembiya floodplain with the extents of the 100-year flooding in both the Megech and Dirma River. The figure clearly shows the two flow paths used by the Megech River to reach lake Tana as well as the flooding in the middle Dembiya subbasin caused by overflow from waters from the Dirma River.



Description :

Plot WS extents for Profile: (none)

307579.86, 1371157.37

Figure 6-29: Plan view of the extent of flooding for the Dirma and Megech Rivers for the 100 year flow.

6.6.2 Fogera Floodplain

Inundation maps of the Gumera River indicate that flooding is expected in the overbanks relatively close to the river. Velocities in the overbank are relatively slow in most locations but are as high as 2 meter per second in some steeper areas of the floodplain, possibly resulting in some erosion in these areas. During the 100 year flood, velocities in the channel can be over 4 meter per second. At these velocities, scour of the riverbed and banks should be expected. Figure 6-30 shows a typical cross section of the Gumara River. This cross section also shows that during the 2-year flow the inundation area is extensive, but flooding depths in most locations are limited to approximately half a meter. During the 100-year flow, some additional areas are flooded, and the flooding depth in certain areas is in excess of two and a half meters. Figure 6-31 shows the profile of the Gumara River during the 100-year flow. The uniformly large flow depth suggests that the channel should remain relatively stable and is unlikely to experience a major re-alignment that would result in abandonment a large length of the channel.

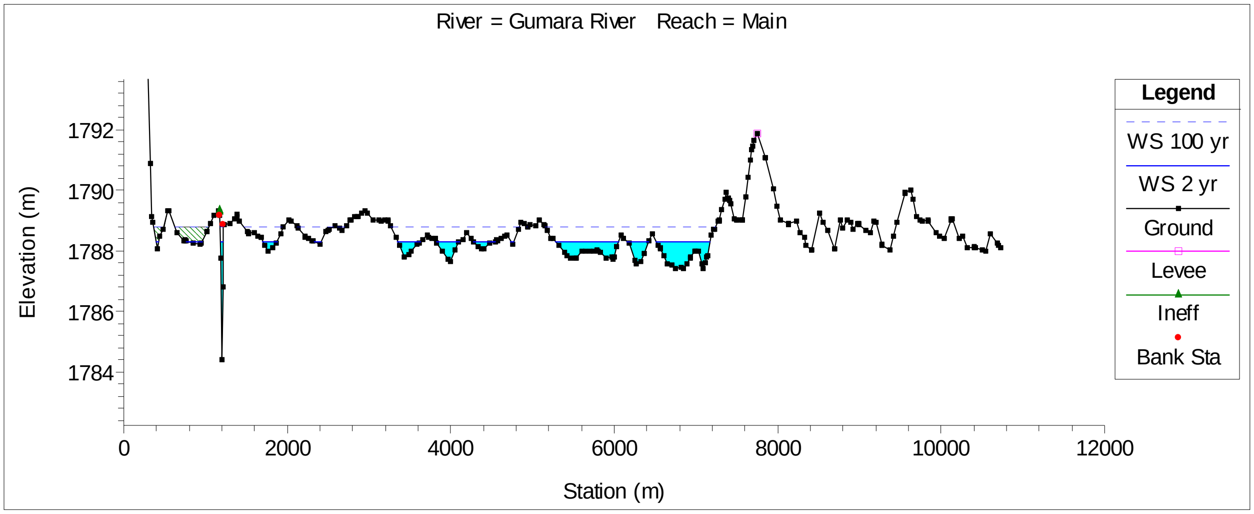


Figure 6-30: Typical cross section for the Megech River showing the 2 and 100 year water levels.

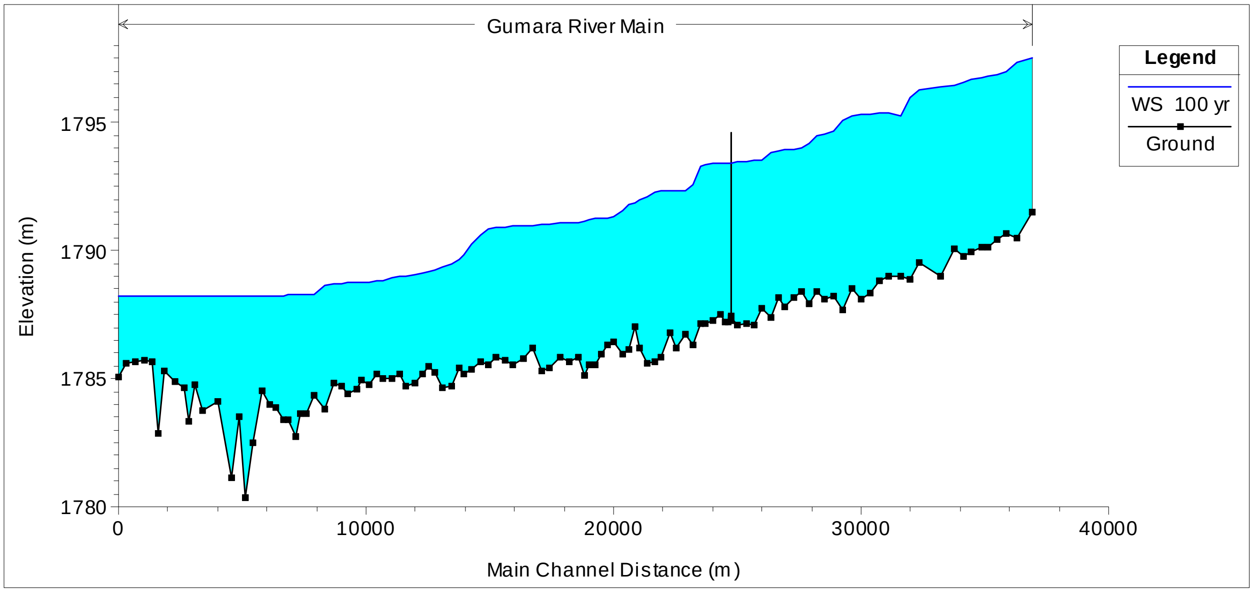


Figure 6-31: Profile plot for the Gumara River for the 100 year flow.

The inundation maps of the Ribb River indicate significant flooding along the alignment of the current Ribb River even during an event with a recurrence interval of 2 years. For most natural rivers the 2 year flow would be approximately the bank full flow. These results match earlier observations and studies that flooding of the overbanks of the Ribb River should be expected every year. The 100-year outflow of the Ribb River is more than six times larger than the 2-year flow but the difference in water elevation between the 2-year and the 100-year flow is on average considerably less than a meter. The largest differences are observed at the upstream end of the reach as well as the downstream end under the influence of the lake levels. Due to the flat terrain, the floodwaters spread considerably, resulting in large inundated areas. The results show that flow velocities in the Ribb River floodplains are less than 2 meter per second, with lower velocities in the southern floodplain. In addition to riverine flooding, local runoff is also considered a major source of flooding in the subbasins located downstream of the highway. To predict detailed flooding caused by local runoff, the use of advanced two dimensional models, combined with a DEM with a resolution far more detailed that the available 90 meter DEM would be required. The use of advanced and proprietary models in combination with expensive, detailed data is well beyond the objective of this assignment, which has as one of its purposes establishing procedures that can be extended and repeated by local engineers with access to freely available tools and datasets. For the low lying areas in the Ribb floodplain, a connection with the Ribb River was assumed, eventhough the 90 meter DEM did not indicate a direct connection with the Ribb River. Based on observation during flood events, the results of the model are considered reasonable.

Figure 6-32 shows a typical cross section for the Ribb River in the Fogera floodplain. The location of the river can be identified by the bank stations at approximate station of 1400 meter. The cross section clearly indicates that runoff from within this subbasin will be collected in the low spots on either side of the river, resulting in flooding in these areas. The cross section also shows that during flows larger than the 2-year flow, water from the Ribb River will overtop the left bank and aggravate the flooding in the low areas as a result of local rainfall. During flows as large as or larger than the 100 year flow, water from the Ribb River is also likely to overtop the right bank and aggravate the flooding in the low spot to the north of the river in this location.

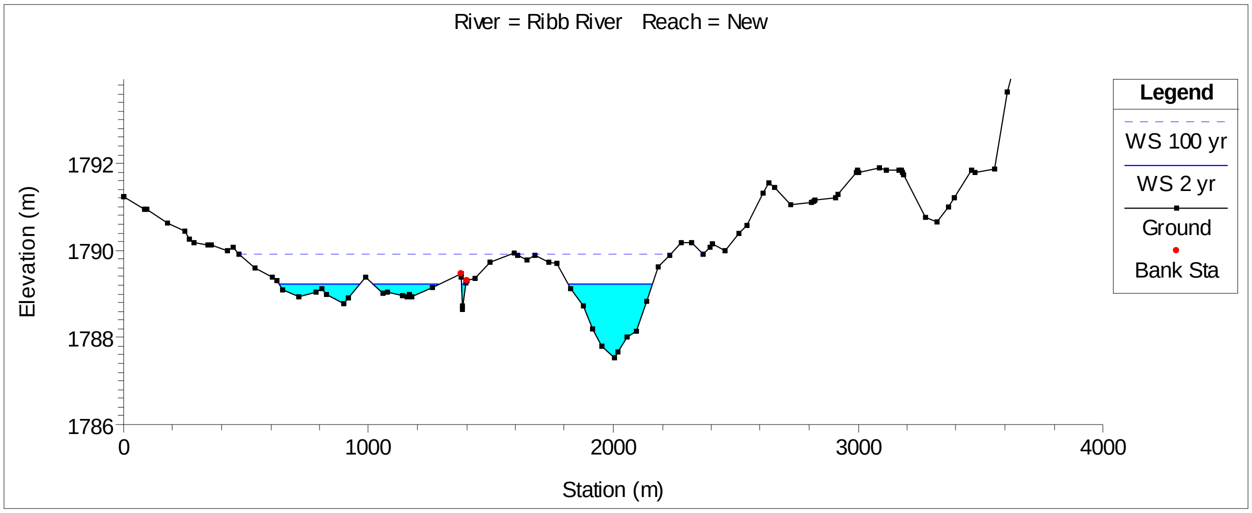


Figure 6-32: Typical cross section for the Megech River showing the 2 and 100 year water levels.

Flooding was also prevalent around the previous alignment of the Ribb River. The flooding is not only caused by local runoff intercepted by the old riverbed, but during high flows in the new Ribb River channel, water will flow over the banks into the old alignment, resulting in additional flooding beyond what would have been expected from local runoff alone.

Figure 6-33 shows the profile of the Ribb River during the 100-year flood. The profile shows the lateral structure used to connect the Ribb River to its old alignment at approximately 16 kilometers upstream from the mouth of the Ribb River. ***Figure 6-34*** shows the water profile for the 100-year flow in the old alignment of the Ribb River.

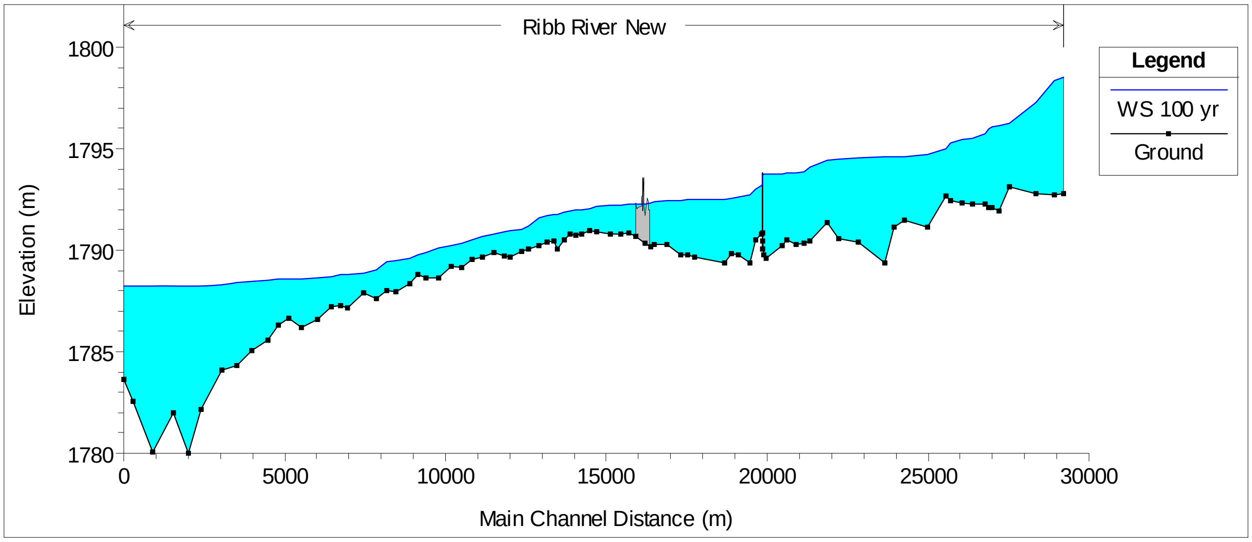


Figure 6-33: Profile plot for the Ribb River for the 100 year flow.

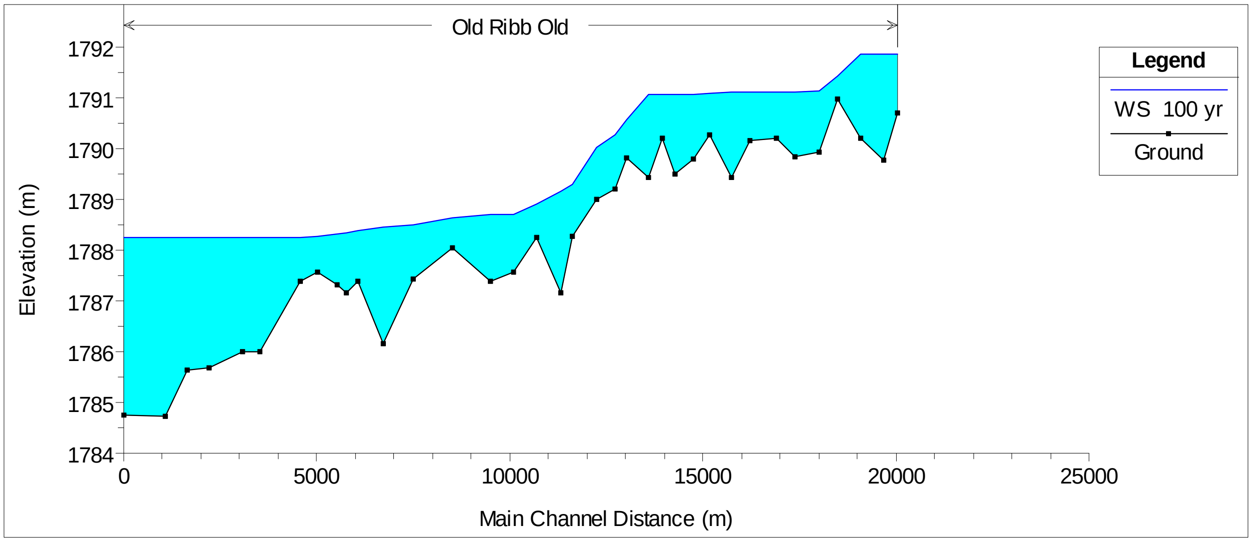


Figure 6-34: Profile plot for the Ribb River for the 100 year flow.

Analysis of the results of the steady and unsteady models for the Ribb River show that the maximum difference in water elevation for the 100-year flow is less than 10 centimeters and the average difference between the models is less than one centimeter. These differences are well within the uncertainty of the model and therefore the results can be considered the same for the Ribb River. ***Figure 6-35*** shows the profile plot of the Ribb River for the 100 year flows for both modeling approaches. As can been seen from the graphs, the differences between the results are not significant. ***Figure 6-36*** shows the flood extend during the 100-year flow in both the Ribb and Gumara River.

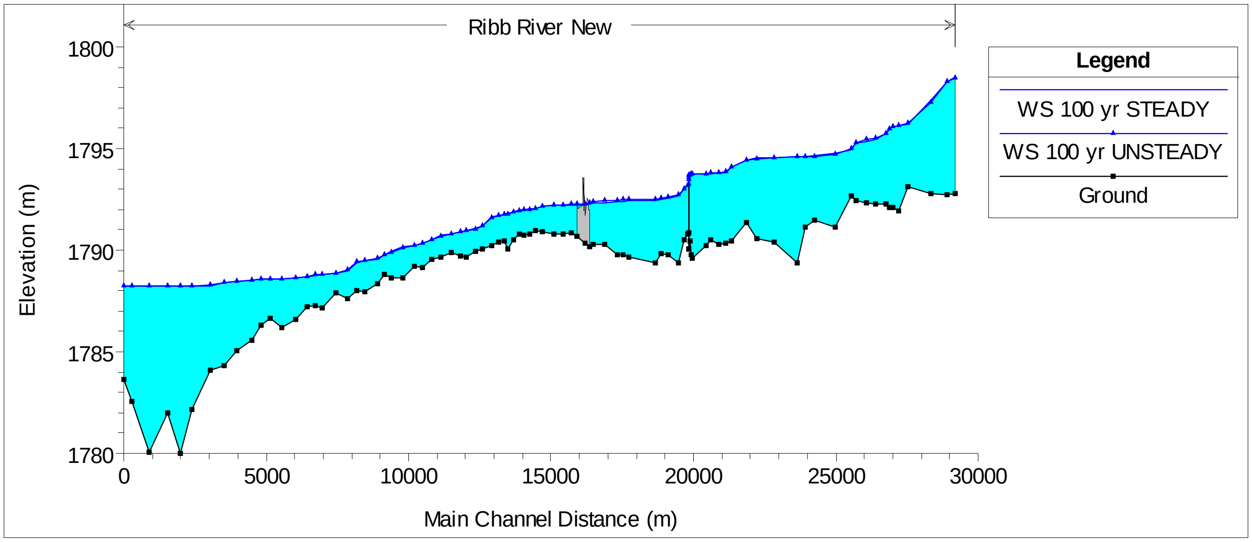


Figure 6-35: Profile plot for the Ribb River for the 100 year flow both steady and unsteady simulation.

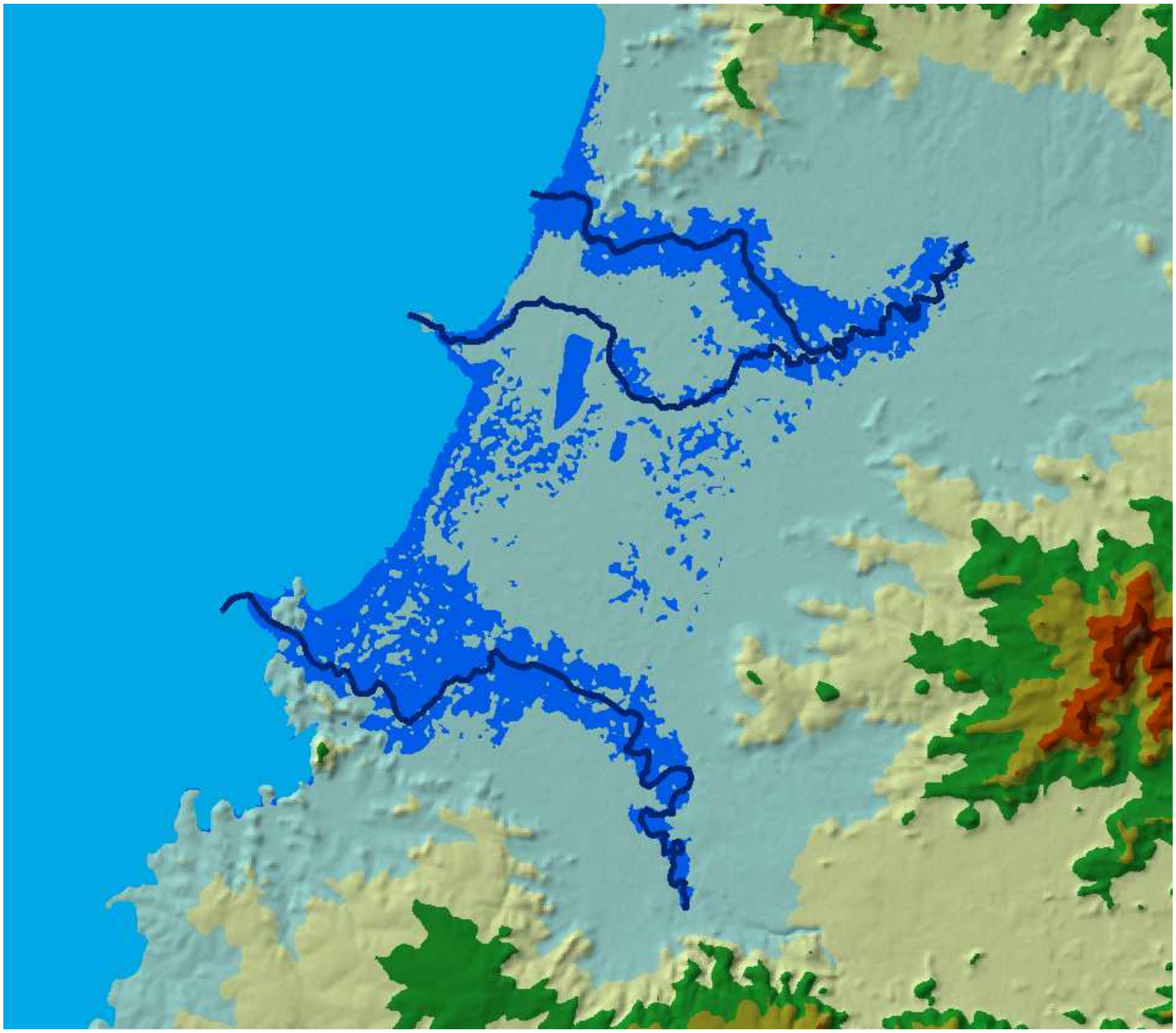


Figure 6-36: Plan view of the extent of flooding for the Gumara and Ribb Rivers for the 100 year flow.

7.0 FLOOD RISK ASSESSMENT

A central objective of this project is the development of *Flood Risk Maps* to convey flood risk in spatial terms that permit the formulation of responses that reduce that risk, as opposed to simply reducing flooding. It is especially important to differentiate between flood hazard and flood risk in the Lake Tana region where flooding is accompanied by the deposition of sediment upon which the population relies for agricultural production. Mapping of risk provides insight to the evaluation of alternative measures that can be employed to reduce it.

Risk incorporates the concepts of hazard and vulnerability. In quantitative terms, annualized risk can be estimated as the product of probability of occurrence of the flood and the actual consequence, combined over all scenarios. Given a flood frequency curve, a rating curve, and a depth-damage curve, it is possible to compute a damage-probability curve, as shown in ***Figure 7-1***. The damage probability curve can then be numerically integrated to estimate the expected annual damages, thus quantifying risk.

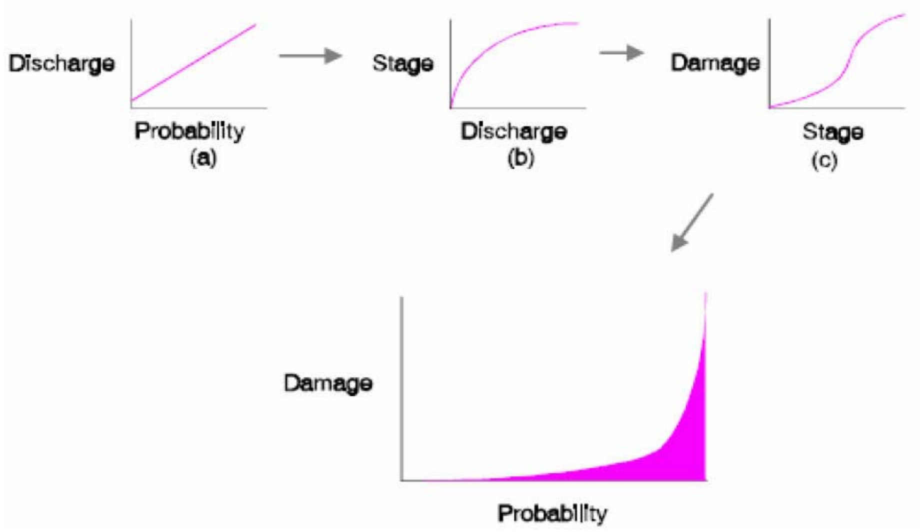


Figure 7-1: Transformation for traditional expected annual damage computation (from USACE)

The process of flood risk mapping can be used both as a tool in evaluating risk and as an alternate means of developing a damage probability curve for determining average annual damage. The central elements of the process are:

- Flood hazard mapping based on hydraulic model output, in which not only the extent of inundation but also the depth of inundation for a flood of a given probability is estimated in a spatially distributed manner across the flood prone area. This process is repeated for multiple events of varying probability (or return period or frequency);
- Identification of vulnerable assets subject to damage from the effects of flooding, including buildings, transportation and other infrastructure, and active agricultural production, including their location;
- Development of local depth-damage functions for the identified assets; and
- Vulnerability mapping, or the spatial computation of expected damage for each flood event by computing damage for discreet assets based on flood depth and the appropriate depth-damage curve.

- Risk mapping, or the spatial integration of expected damage for each event with event probabilities to yield a grid of expected annual damages.

The total of the distributed damage for each event will yield a damage probability curve, which can be integrated to compute total average annual damage (and should equal the total of the grid of expected annual damages).

7.1 Flood Hazard Mapping (HEC-RAS Mapper)

A key feature of the HEC-RAS and HEC-RAS Mapper tools is the ability to pass geo-referenced simulated water surface elevation information to the GIS to permit inundation mapping. This process was used in an iterative fashion as part of the hydraulic modeling to visualize inundated areas and hydraulic connectivity to the channel, as described previously. As part of this process, exported water surface elevations are assigned to the entire width of an associated cross section in the GIS, which represents the same cross section from the hydraulic model. A water surface is then interpolated between adjacent cross sections. This surface is intersected with the terrain model to obtain a polygon layer of inundated area, as well as a depth grid, as shown in ***Figure 7-2***, indicating depth of inundation at any point in the inundated area. Both of these layers describe components of the hazard.

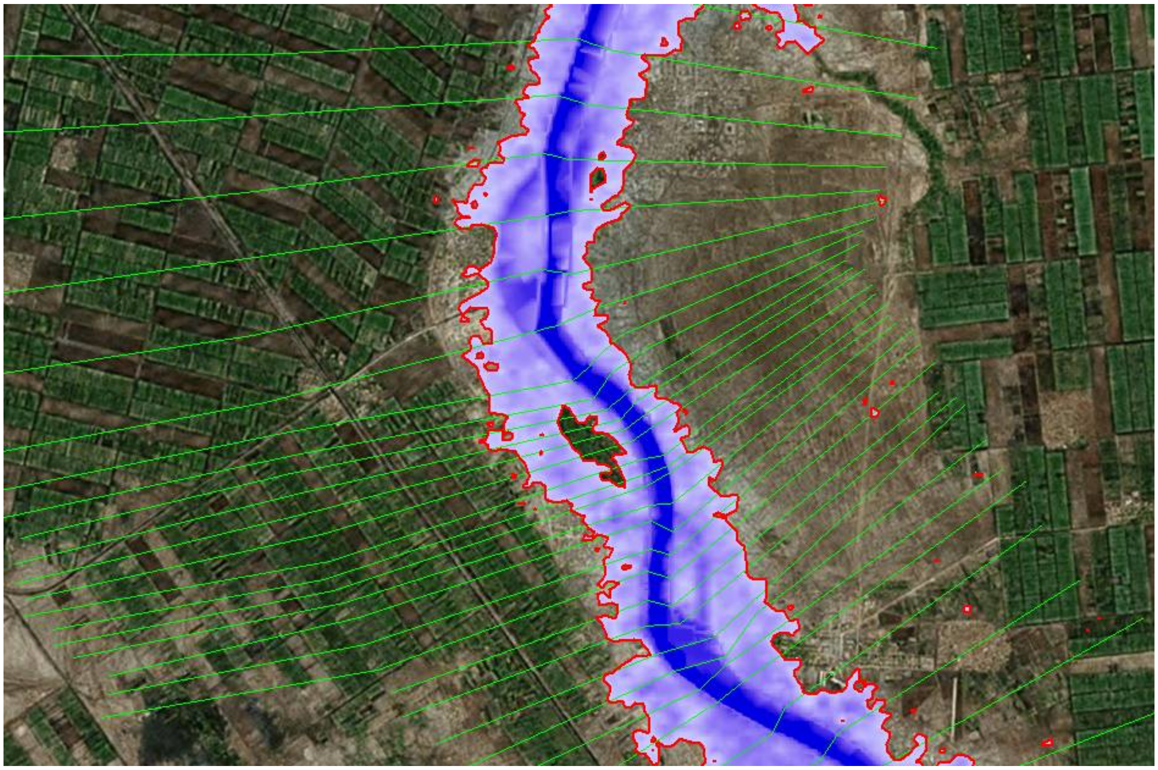


Figure 7-2: Development of inundation extent (red outline) and depth (blue gradients).

Another component of hazard is the velocity associated with the peak discharge. HEC-RAS simulates the variation in velocity across a given section. This velocity distribution can also be exported to the GIS, where a velocity surface can be interpolated between the cross sections to create a velocity grid. It is important to note that the velocity grid is only an interpolation based on simulations at each cross section in they hydraulic model. Therefore, topographic variations in the terrain model that are not represented in the hydraulic model definition or that occur in between cross sections in the model will not be reflected in the velocity grid. Areas within the velocity grid that coincide with areas outside the inundation extents will be clipped so that no velocity information is implied where there is no water, as shown in ***Figure 7-3***. The velocity grid can therefore be viewed as providing guidance on local velocities to be expected, with the assumed flow direction being from upstream to downstream cross section.

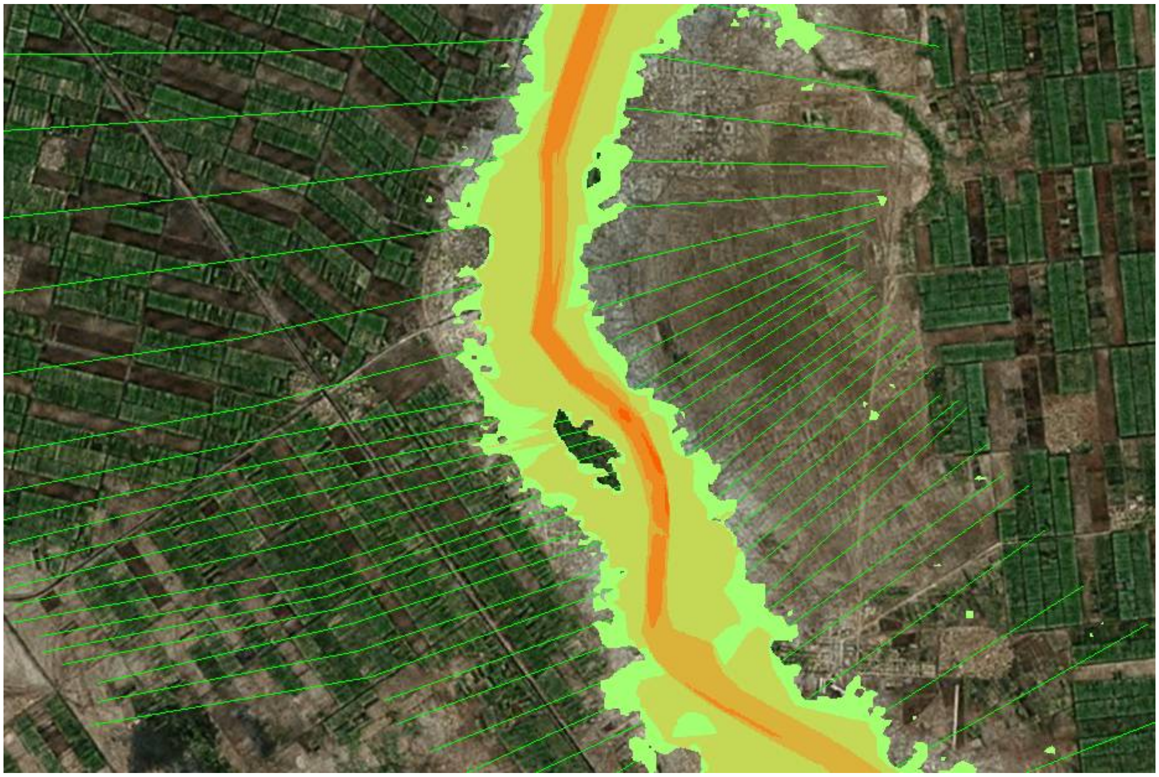


Figure 7-3: Development of velocity grid

In performing these steps, linkages between pre-processed cross-sections and post-processed water surface elevation predictions in HEC-RAS Mapper are achieved spatially, with the initial cross-sections providing the location ‘anchor’. Thus pre-processing enables optimal site selection and deployment of cross-sections for hydraulic modeling, but also transparency when linking post-processed flood inundation results back to the hydraulic model.

7.2 Identifying Vulnerable Assets

Vulnerability to flooding at a point or for a specific structure or asset can be represented by a depth vs. damage curve for that structure or asset. The vulnerability of agricultural land (which may vary seasonally) can be described by a curve of depth vs. damage per unit area. The spatial representation of vulnerability to a given flood level, however, depends not on a single depth at a point but on the interaction of the varying depths across a floodplain with the specific assets that are impacted. It requires spatial identification and classification of vulnerable assets, development of depth-damage functions for each type of asset, and intersection of the hazard (the depth grid) with the location of vulnerable assets and their associated damage functions to identify the spatial distribution of damages. The following sections describe the identification and classification of vulnerable assets, including infrastructure (roads), agriculture, and structures.

Delineation of the different structures, infrastructure and agriculture was based on visual interpretation and automated classification of remotely sensed data. The structures were manually digitized in ArcGIS ArcMap using high resolution GeoEye-1 satellite imagery. The infrastructure (roads) was digitized in ArcMap from georeferenced topographic maps. The agriculture was classified with an unsupervised classification using Landsat 5 imagery in ERDAS Imagine.

Structures were digitized in the Dembia and Fogera plains through satellite image interpretation. The risk analysis geodatabase was used for digitizing. The geodatabase includes different structure types. Through image interpretation, structures were digitized for wood/mud huts with thatched roof, wood/mud huts with iron roof, schools, and churches. The structures were digitized as points representing the center of each structure.

The infrastructure was digitized from locally obtained, georeferenced topo maps. The roads were also digitized into the risk analysis geodatabase. Two types of roads were digitized: unpaved trails, and paved roads.

Agriculture was classified for the Fogera and Dembia plains using Landsat 5 imagery. An unsupervised classification with 50 classes was performed. Traditional ground truth data was not available for the floodplain. However, information on the distribution and area of agriculture in the different woretas was available. This information was used to merge and name the 50 classes from the unsupervised classification. While this classification is by no means perfect, Riverside feels that reasonable representation of the agriculture has been achieved.

All vector layers were digitized and coded under a GIS framework. The final GIS products were transformed to Universal Transverse Mercator "UTM" projection, WGS84 Spheroid. The main layers created include agriculture, infrastructure and structures.

7.3 Depth-Damage Relations

The following general procedure was used to develop the depth-damage relations. They were defined in a slightly different manner for transportation infrastructure, structures, and agricultural areas. In all cases the relationship was divided into assignment of value to assets and definition of the depth-damage relationship in terms of the percent of value lost due to flooding of a given depth.

1. Estimate values of structure classes, crops, and transportation infrastructure using local knowledge, survey estimates and expert judgment;

2. For structures, estimate value of structure contents for each structure class. This can be a value for each structure or a value per unit area for a neighborhood of structures of the same class;

3. For transportation infrastructure, estimate replacement value. This is specified as a value per unit length;

4. For agriculture, estimate value of lost production as a value per unit area for each agricultural class.

5. Estimate damage to structures, transportation infrastructure, and crops due to flooding to various water depths at the site, using a depth versus percent damage function for the various classes in each asset type.

Asset values and damage curves were developed for each type of asset in the geographic database. ***Figure 7-4***, ***Figure 7-5***, and ***Figure 7-6*** show examples of damage functions for the three different asset types: structures, infrastructure, and agriculture.

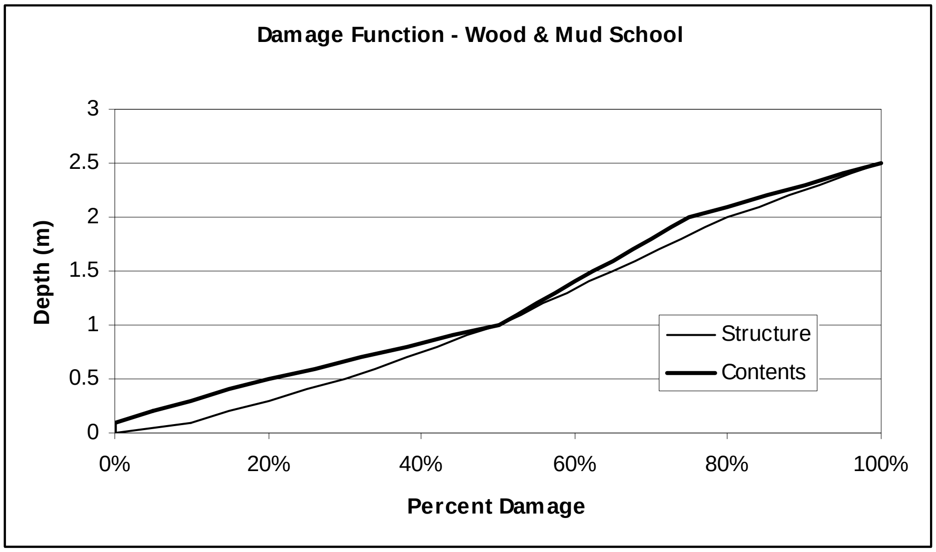


Figure 7-4: Damage curve: structure asset type

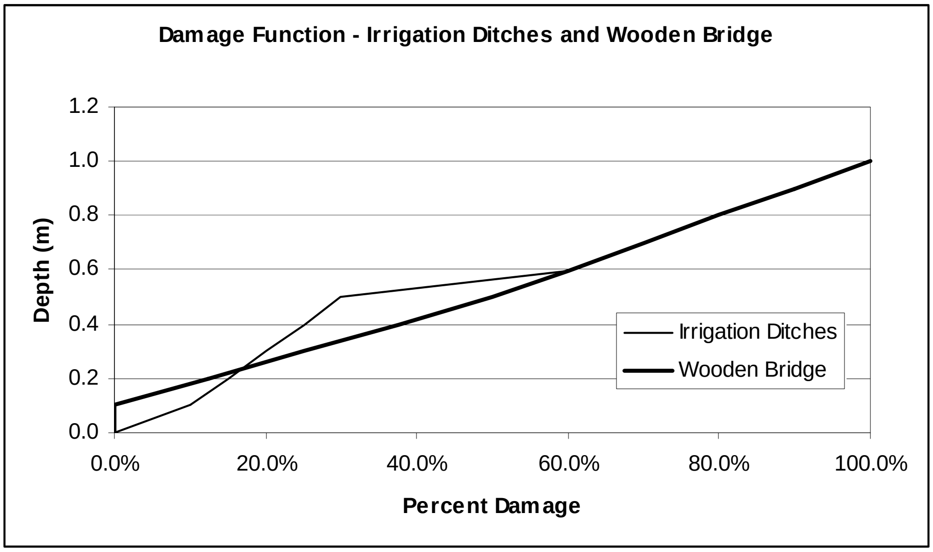


Figure 7-5: Damage curve: infrastructure asset type

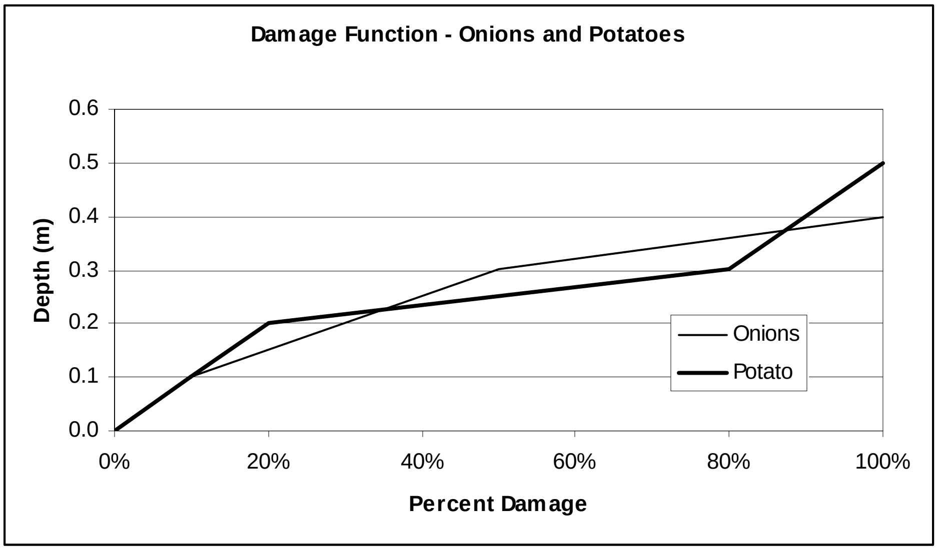


Figure 7-6: Damage curve: agricultural asset type

7.4 Vulnerability Mapping

The vulnerability mapping is conceptually simple, although it can be complex to implement. It involves GIS processing to intersect the flood depth layer for a given frequency event with each of the asset elements in the spatial database, identifying the associated damage from the damage curves, and creating a raster or grid representing the combined damage from all asset elements within each grid cell. This process is repeated for each frequency event in the analysis. An ArcGIS model was set up to perform the vulnerability analysis in a repeatable and standardized manner. The standardized model and database can be updated to refine the values and can be translated to other areas. ***Figure 7-7*** illustrates the complexity of the ArcGIS model required for the analysis. One of the chief difficulties in the model is identifying and extracting areal and linear features for each grid cell and computing the associated length or area within the grid cell prior to computing the damage from the damage curve. The model has three branches to compute the vulnerability individually for structures, roads, and agriculture plots. ***Figure 7-8*** shows a section of a vulnerability map for the Gumera River in the Fogera plain. The red and orange cells represent higher vulnerability than the green and lighter color cells.

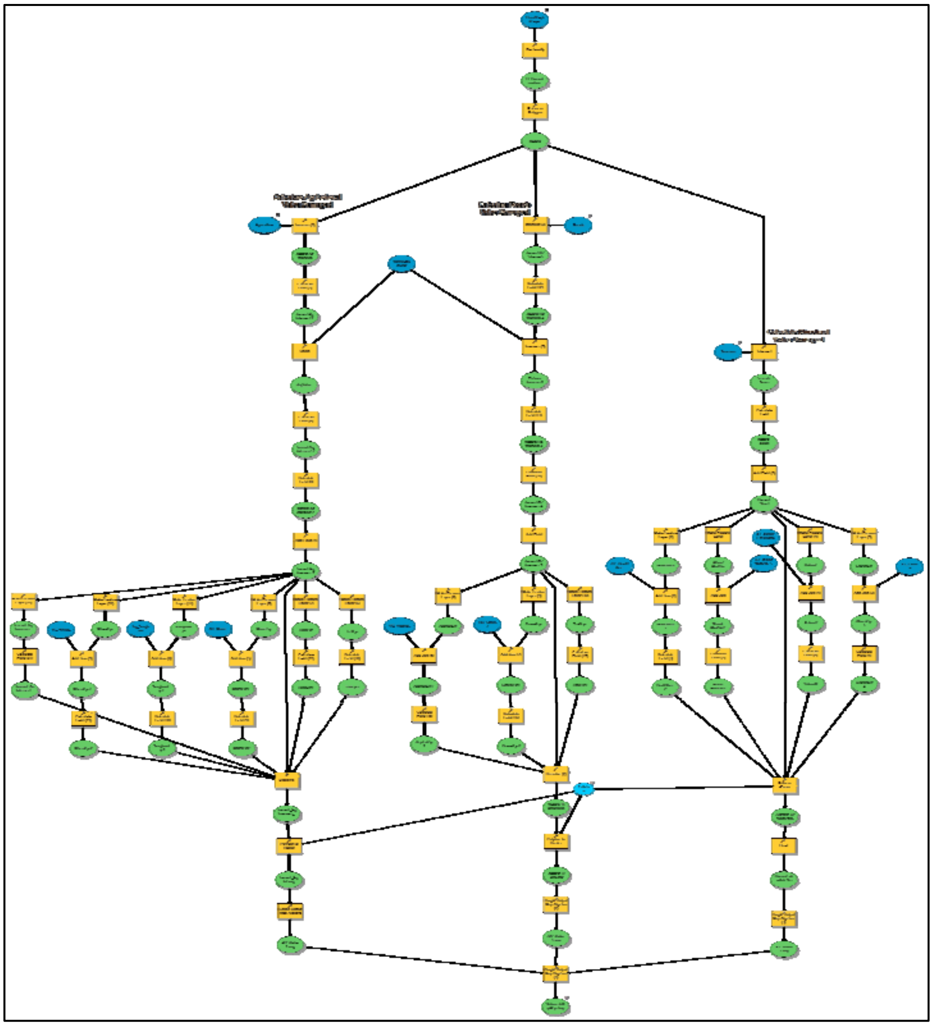


Figure 7-7: ArcGIS vulnerability model

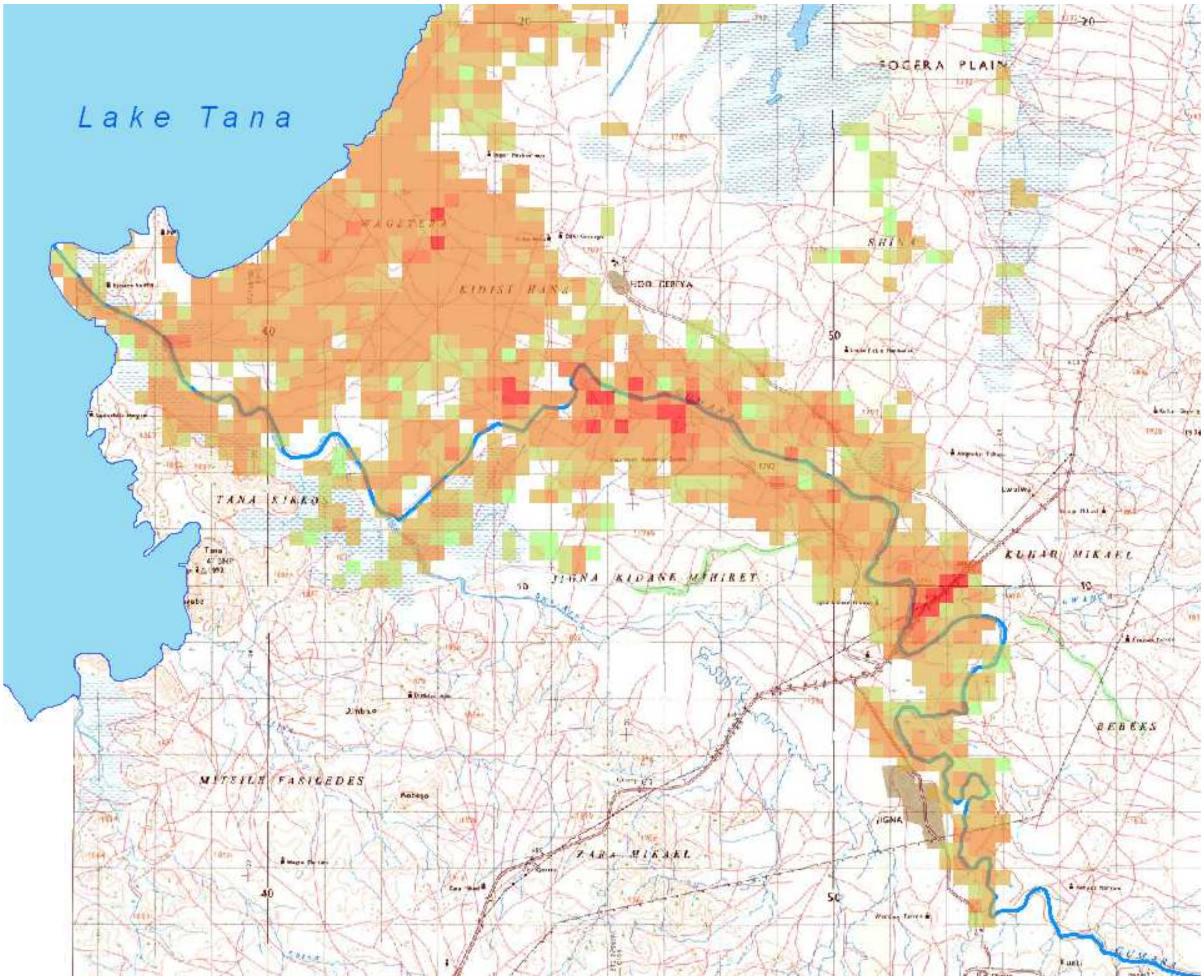


Figure 7-8: Section of the 100 yr vulnerability map for the Gumara River

The resulting maps represent the spatial distribution of damage that would be expected from a flood of the magnitude represented by that frequency event. The values of all of the grid cells can be combined to indicate the total damage that would be expected. The expected damage for the different recurrence intervals are summarized in table 7-1.

Table 7-1: Vulnerability Assessment for each pilot area. Damages are in millions of dollars.

	Return period (year)				
Location	**2**	**5**	**10**	**50**	**100**
Dembiya	$1.0	$1.6	$1.8	$2.4	$2.6
Fogera Plain	$3.2	$4.8	$5.5	$7.0	$7.7
Total	$4.2	$6.4	$7.3	$9.4	$10.3

7.5 Risk Mapping and Assessment

A damage probability curve was constructed from the estimated damages caused by the events with probabilities of annual occurrence of 0.5, 0.2, 0.1, 0.02, and 0.01 (corresponding to the events of 2, 5, 10, 50, and 100 year return periods). A total of five damage-probability pairs of points were used to define the damage probability curve, using the total damage values computed in the previous step. The annualized risk was computed as the area under this curve. The curve was broken up in slices to compute the area as the product of the damage and the range of probability associated to it. For example, the 50 year return period damage was associated to a probability range of 0.045, which was computed as the difference of the average of the probabilities between the 10 and 50 years (0.06) and the average of the probabilities between the 50 and 100 years (0.015). For the 2 year probability range, it was assumed that at a probability of 100% the damage was zero. For return periods greater than 100 years, the damage associated with the 100 year event was assumed, so that the 100 year probability range represented by the 100 year event extended to the limit of zero probability. The sum of the products of the floodplain damages and the probability ranges provided the annualized risk. A total annualized damage of 4.2 million dollars was computed for the two pilot areas.

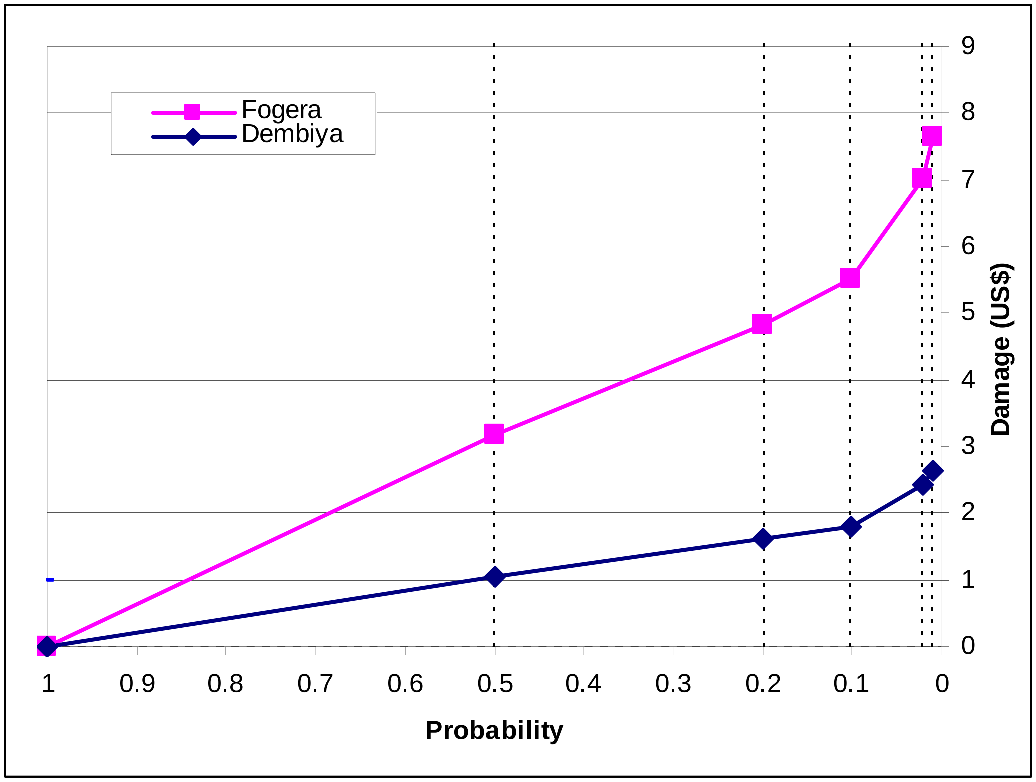


Figure 7-9: Damage probability curve for pilot areas

Table 7-2: Total annualized risk in millions of dollars for each pilot area

Location	Annual Risk (Million US$)

Dembiya Plain	$1.1
Fogera Plain	$3.2
Total	$4.2

A similar procedure was performed in the GIS environment to develop an annualized risk map. For each vulnerability map, each grid cell was multiplied by the probability range computed from the damage-probability curve to produce a partial damage grid representing the annualized damage for each probability range. The damage grids for each probability range were then combined to produce the average annual damage grid, which is the annualized risk map.

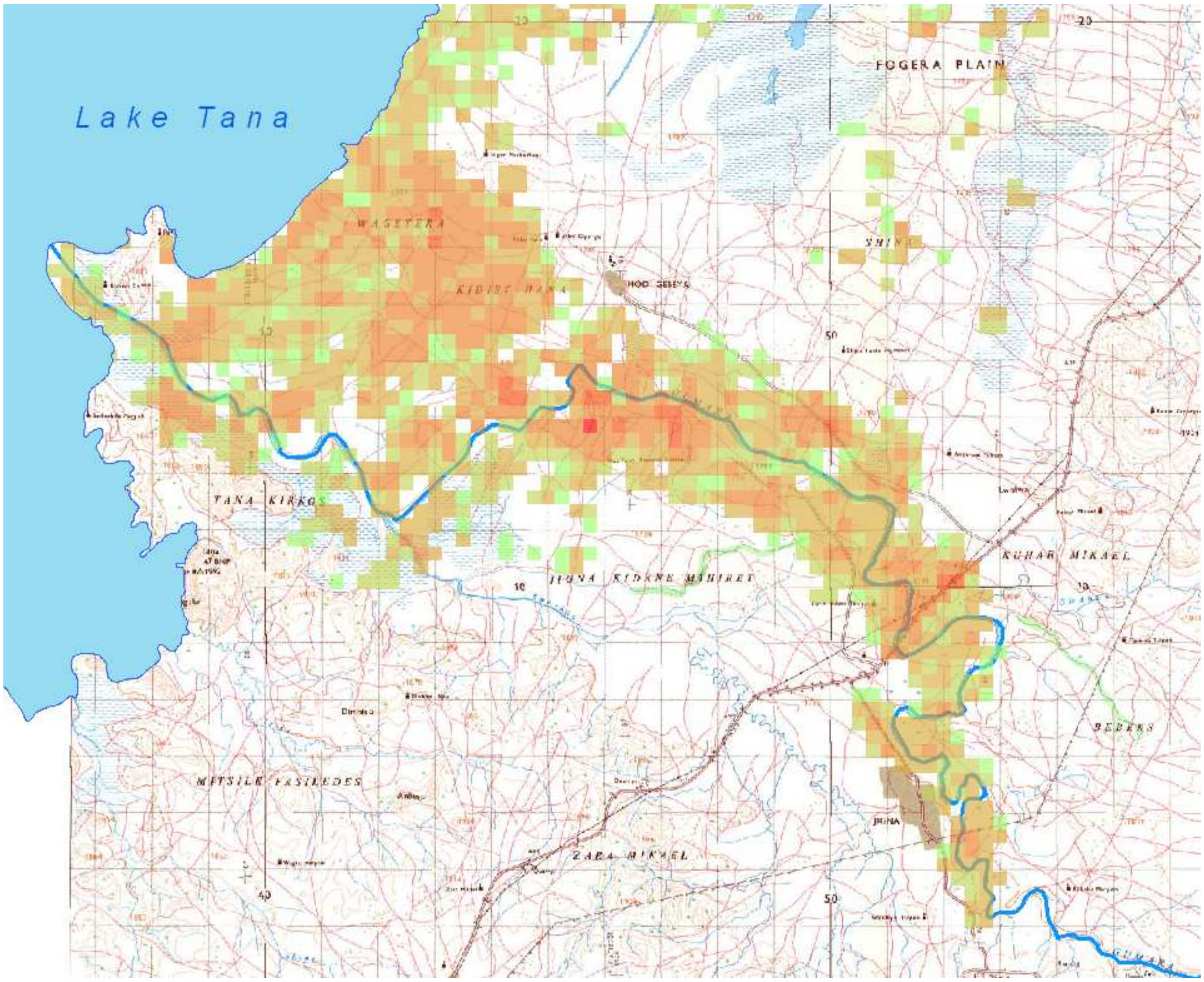


Figure 7-10: Section of the Risk Map for the Gumara River

The final flood hazard, vulnerability, and risk maps are provided digitally as outlined in ***Section 8.4***.

There are several cautions that should be noted when studying the risk and vulnerability maps. First, the agricultural land use layers include areas that may be described as recession agriculture, in which crops are planted at the edge of the water following the flood season, taking advantage of the soil moisture that remains as the flood waters recede. Because there is a large amount of land that is exposed over the course of the recession from fall through early summer, this land use constitutes a significant agricultural production area that is theoretically subject to damage from flooding. In the risk model, this area is included in computing damages for all return period floods, although it is likely that harvesting may be complete before seasonal inundation occurs in these areas. This approach may result in an overestimation of the damages associated with agricultural land in the frequently inundated zone of the floodplain. These damages have been retained in the analysis so that they will not be eliminated from consideration in evaluating flood damages or potential benefits from flood management measures.

A second caution is that sedimentation and erosion during large storm events could realign the rivers, as previously occurred for the Megech and Ribb Rivers. As a result of the realignment of a river, areas currently indicated as low risk and vulnerability could see an increased risk, whereas areas close to the old alignment of the river would likely see a reduction in risk and vulnerability. In spite of these inherent limitations in the risk mapping methodology, the resulting maps contain useful information that should be beneficial in targeting flood protection measures to maximize the flood damage reduction benefits associated with flood mitigation investment.

8.0 DELIVERABLES

In accordance with the deliverables identified in the inception report, Riverside and the local project team have delivered to ENTRO the following:

8.1 Inception report

The inception report was submitted to ENTRO after the first flood risk mapping workshop. The report included an appraisal of the required data and provided a detailed methodology for all activities required to complete the study. The inception report also included the work plan for completing the study and defined the deliverables and the delivery schedule.

8.2 Draft Final Report

A draft version of the final document was submitted to ENTRO and discussed during the second workshop. The report contained a thorough conclusion of the work completed and recommendations for application of the information. The purpose of the Draft Final Report was to invite feedback and comments on the findings documented in the report.

8.3 Final Report (this document)

The final report for this project incorporates the information provided in the draft final report and the comments and suggestions provided by the client and stakeholders. This report contains:

- Executive Summary of project findings
- Background information
- The approach and methodology used for this project, including the changes and additions to work scope and deliverables agreed upon during the course of the study
- Development of the terrain model and data collection
- Details of all hydrologic and hydraulic modeling and analyses, including discussion of the results
- Results of the flood risk assessment
- An overview of all project deliverables
- All study findings, conclusions and recommendations

8.4 Data/Information

A significant component of the value of the Flood Risk Mapping Study is found in the digital models and datasets that were developed as part of the project. To facilitate the application of the large amount of digital data developed, Riverside is providing to ENTRO a disk containing the following data:

- HEC-HMS hydrologic models

- HEC-RAS Hydraulic models, including both the steady and unsteady models

- Economic assessment spreadsheets

- Principal GIS layers used in the study, including:
    - Survey data
    - Final terrain model
    - Infrastructure/asset layers
    - GeoRAS cross sections
    - Flood extents
    - Flood depths
    - Flow velocity
    - Duration of flooding
    - Vulnerability
    - Risk

- ArcGIS Model Builder models used for vulnerability and risk mapping

- Digital maps published in PDF format, including the following types of maps:
    - Flood Inundation Extents (all frequencies on a single map)
    - Flood Inundation Depth (each frequency on a separate map)
    - Peak Flow Velocity (each frequency on a separate map)
    - Flood Inundation Duration(each frequency on a separate map)
    - Vulnerability (each frequency on a separate map)
    - Risk (a single map integrates all frequencies)

    The Dembia plain is covered by two maps sheets, and the Fogera plain is covered by five map sheets. An index maps is provided for the Dembia plain and another for the Fogera plain.

- Final workshop presentations

9.0 FINDINGS & RECOMMENDATIONS

Flood risk mapping can be an important aid to a community in taking action in the present to reduce future damages, in planning for flood preparedness and response, in developing infrastructure for reducing flood severity and flood damage, and in guiding development to avoid increased risk where hazard is frequent. An important aspect of this study was the development of models and procedures that could be applied using the data that were available. Because flood risk mapping relies on multiple data types and sources, and because some of those data represent detailed spatial characteristics for an extensive area, the quality and volume of data desired for a study of this nature are often not available. Over time, however, data often become available through complimentary efforts on other studies that can be incorporated into subsequent updates. The following discussion highlights findings of this study, including limitations of the study results and their application, together with recommendations for interpreting the results or for improving them in the future.

9.1 Useful outcomes

There are several useful outcomes of the study that should be highlighted to serve as a reference to facilitate applying and taking advantage of them in subsequent related efforts. Important outcomes include the following:

- New cross section surveys in all four rivers in the pilot areas.
- Terrain models for the four river channels in the pilot area and the Fogera and Dembiya floodplains – this terrain model integrates surveyed cross sections with a 90 meter DEM.
- A useful procedure for integrating a gridded DEM with channel survey data.
- Ground Control Points were setup that can be used in future surveying efforts.
- A frequency analysis for flows in the Dirma, Megech, Ribb, and Gumera Rivers.
- A hydrologic model for the Dirma, Megech, Ribb, and Gumara River basins.
- Hydraulic models for the Dirma, Megech, Ribb, and Gumara rivers with geo-referenced cross sections – these models have many potential uses that are highlighted in the final section of the report.
- Flood hazard maps (extent, depth, velocity, and duration) – These maps are fairly straightforward to interpret and can be used for flood preparedness and response as well as for development planning
- Detailed asset geo-databases in the Fogera and Dembiya plains, including structures, infrastructure, and agriculture
- Vulnerability and risk maps – These maps are more complicated than the hazard maps, but a study of them can reveal important relationships between flood frequency, flood extent, location of vulnerable infrastructure, and high-risk areas.
- Risk mapping procedure – Because all of the inputs to the risk maps are subject to change or refinement, it is important to have a procedure that can be followed to efficiently update risk maps and risk calculations in the future.

9.2 Limitations and Potential Enhancements

Various limitations in the scope of the study and available data likewise limit the outputs. Many of these limitations can be overcome by establishing a program of flood risk assessment and management that systematically updates study inputs and procedures using improved data and detailed modeling. Specific limitations and potential enhancements are described below.

9.2.1 Programmatic Issues

The integration of tools and techniques developed in this study to map flood hazard and risk in the Lake Tana region has been conceptualized with the idea of having a repeatable procedure that could be used in other parts of the Eastern Nile region. Not only does this study lay out a repeatable procedure for flood hazard and risk mapping, it also identified the limitations on the available data and in the results. To deal with the data limitations and allow for a broader implementation of flood hazard and risk mapping, it may be helpful to define multiple levels of standards corresponding to different levels of accuracy and detail for each of the components of the process. A first set of flood hazard and risk maps could be developed for many areas based on the currently available data. The risk identified at this initial level can be used to prioritize the locations were additional and more detailed data will be obtained to reduce the uncertainty in the flood hazard maps. Subsequent improvements in detail and accuracy to further raise the level of the studies will be an ongoing program based on the risks identified in previous studies as well as on improvements in data collection and availability and improvements in modeling software and professional capacity.

9.2.2 Survey and Terrain Modeling

Detailed topographic information is essential for accurate floodplain modeling. Detailed terrain models of the floodplain could be obtained by Light Detection And Ranging (LIDAR) surveys. These surveys should be performed during dry periods to maximize the extent of the surveyed floodplain area. The cost of the LIDAR survey will likely not be justified by the needs of floodplain mapping alone, but the information obtained from the survey can be shared with multiple administrative or government programs, justifying the cost by sharing the benefits.

9.2.3 Hydrology

In addition to the improvements in the survey and terrain modeling, improved hydrologic information would greatly increase the reliability of the flood mapping. A first step in improving the hydrologic information for the area is to perform a study of the rating curves on the Ribb and Gumara rivers to increase the confidence in the observations which are used for hydrologic frequency analysis. An initial study could be undertaken based on the hydraulic models developed for this study.

In addition to updated rating curves at the existing Ribb and Gumara river, the gages might be relocated and improved to avoid the effects of significant overbank flow, as well as limit the impact of sedimentation and scour on the rating curve used at the gage locations. This information could be used to optimize the frequency analysis as well as to calibrate the hydrologic model.

Additional stream gage and new rainfall gages would allow for a better understanding of the hydrology in the Lake Tana area and allow for a more detailed and accurate hydrologic model. The additional rainfall gages would also permit refinements to the Intensity-Duration-Frequency curves from the Ethiopian Roads Authority to represent more variation in the region and to be applicable in smaller geographic areas.

9.2.4 Hydraulic Modeling

The results of the hydraulic modeling depend on many key variables that can be closely estimated, but calibration of these parameters is required to obtain reliable results. The model would benefit from additional monitoring at key locations through a planned monitoring program to allow for a thorough calibration of the model.

Sediment transport and scour are ongoing processes in all four rivers modeled as part of this study. Scour or sediment deposition can have a significant impact on the hydraulic behavior of the river and the floodplain. The ground control points set as part of this study can be used to perform periodic surveying of river channels to capture morphologic changes and update hydraulic modeling accordingly. To better understand the impact of the sediment, it is recommended to perform a sediment study of the watersheds to characterize variability in channel morphology and floodplains due to sediment supply from the erosion of the upland areas of the basins.

9.2.5 Risk

The attachment of economic value to land use types and the assignment of depth-damage relationships was performed at a very large scale. The risk model permits individual parcels and infrastructure elements to have unique values and damage relationships defined. If individual communities desire more detailed or accurate local assessment of risk, more detailed local surveys of the value of assets can be performed and the results can be populated in the infrastructure database. Updated risk assessment and mapping can then be performed using the refined database.

There are numerous indirect impacts of flooding that have real economic and social consequences. Indirect impacts are those that are not associated with contact with floodwaters but that are attributable to damages or loss of service due to flooding. A washed out bridge represents a direct impact from flooding, while the loss of transportation access is an indirect impact, even though its economic consequences may be greater than the value or replacement cost of the bridge. Likewise, loss of a school has both a direct economic cost (replacement of the structure and contents) as well as an indirect consequence in terms of loss of educational opportunity for students. The procedures used in this study do not consider indirect impacts, although the general vulnerability formulation suggests that any secondary impact could be handled in the same way as direct impacts, by assigning a numerical value to an asset and then describing the loss of that value as a function of flood depth.

The current risk mapping methodology does not consider seasonality of cropping patterns, but rather associates the agricultural database and damage characterization with cropping patterns that would be in effect at the typical time of the peak of the rivers in the pilot areas. If planners are concerned about relative damages associated with flooding that comes either earlier or later than normal, a procedure would be required to represent the probability of flooding at times other than the accepted flood season, and the agricultural state of the land at those times, and perform a supplemental risk assessment.

The resolution of the depth grid used for vulnerability mapping results in some inaccuracies in damage computation where steep slopes exist in the topography. The grid size is a limitation imposed by computer hardware and software coupled with the large extent of the area that was mapped. Separate studies of individual pilot areas using more detailed topography, infrastructure layers, and damage relationships could reduce these inaccuracies.

It would be helpful if a National Infrastructure Mapping/Spatial Database could be developed and maintained that could be used for these types of studies in the future, as well as for a wide variety of other purposes.

9.3 General Application

The following list of recommendations represents a general list of activities that could be taken either to make use of the information developed as a part of this study or to enhance the accessibility of the information.

- An internet-based map service could be implemented to allow electronic versions of maps to be accessed by anyone with internet access. The maps could be made available as electronic versions of paper maps or as a database of feature layers that could be viewed with an internet based map server such as Google Earth.
- The maps can be studied for use in emergency response
- The maps can be used to guide development policy, i.e. to restrict types of development within the floodplain or to establish economic policies to encourage responsible development.
- The flood boundary maps can be used to identify areas of focus for subsequent data collection and refinement of results.
- Vulnerability and risk maps can be studied to improve understanding of locus of expected damages due to flooding.
- The maps can be published and disseminated for review by local population
- Population in areas of high flood hazard could be encouraged/educated regarding flood resistant construction materials and methods consistent with hazard (frequency of depth, velocity hazards)
- The hydraulic model can be used as part of analyses for the design of flood protection works (embankments)
- The hydraulic model can be used to evaluate increasing stages resulting from development and encroachment on the river.
- Alternate uses for infrastructure mapping products can be found that will encourage a shared approach for maintaining and improving the database.

9.4 Operational Forecast System Development

A project is ongoing to implement forecasting capability around Lake Tana using the models developed as part of this study. Though not part of the scope of this study, it would be possible to develop an integrated flood hazard mapping tool with the hydraulic model for real-time flood hazard mapping. This would also require some form of dissemination in order to be useful.

The HEC-RAS model can be operated in real-time by posting input data to the HEC-DSS time series database, performing simulations, and then reading resulting data from the database. The HEC has developed the Corps Water Management System (CWMS), which is a pre and post processing environment to facilitate use of its models in real-time forecast mode. The CWMS integrates the modeling of hydrologic, hydraulic, reservoir, and economic damage assessment models with a complete data collection and management system using an Oracle database. The Real Time System (RTS) is a more basic version of CWMS that does not include the Oracle database. One of these systems might be considered in the future as a possible operational environment for forecasting in Ethiopia.

This real time information could be used to provide inundation warning and allow people to evacuate the area ahead in advance of flooding, possibly reducing losses during the flood. The short lead time in the rivers feeding Lake Tana would likely require a fully automated system, including rain gages in the upstream subbasins to allow enough time for people to evacuate based on knowledge of imminent flooding.

9.5 Capacity Development

Riverside recommends that additional training beyond the training that was conducted as part of this study be coupled with a specific objective for development of some enhancement of the study results. For example, an enhancement could be taken on as a training project involving updates to the terrain model and hydraulic model followed by updating all subsequent maps. Because the full process involves repetitive processing, participants in the exercise would gain useful practice in performing all of the processing steps of the study with only minor additional data collection required.

It is noted that multi-disciplinary capabilities are required to complete the full analysis and that a team of individuals with complementary background in hydraulics, terrain modeling, economic evaluation, and map processing would be required to successfully complete the exercise, as well as to build risk mapping capacity in an organization.

9.6 Presentation

Among the many items noted above, one item that Riverside wishes to highlight is the potential value of the flood extent maps, in hard copy, PDF, or GIS layers. These maps convey the most basic information about the general vicinity in which flooding can be expected with varying frequencies. Local communities can make immediate use of these maps to identify areas of focus for flood protection, preparedness, warning, and future development guidelines. A flood extent map can be a valuable aid in communicating flood risk to local populations as part of education and outreach programs to encourage appropriate response. The vast geographical extent of the modeling and mapping effort with the limited resources available for the study has resulted in simplifications that result in inaccuracies that are obvious when the maps are viewed at large scale with a satellite photo background, as will be possible with the products that are being provided. While these inaccuracies undoubtedly will invite some criticism of the products, Riverside believes that there is significant value in these initial flood maps and hopes that they can provide a useful baseline dataset for improvement in subsequent studies.

The significant amount of map-based information generated for this study is not always easily accessible using hardcopy maps. An internet based map service would permit flexible selection of many combinations of layers for investigative purposes and would make the full complement of maps available to a broader audience for review and understanding.

10.0 REFERENCES

Arcement, G.J., Schneider, V. R., *Guide for selecting Manning's roughness coefficients for natural channels and flood plains*. Denver, CO.: U.S. Geological Survey, 1989.

Chow, V.T., D.R. Maidment, and L.W. Mays (1988). *Applied Hydrology*. McGraw-Hill, Inc.

Chow, V.T., 1959, *Open-channel hydraulics*, New York, McGraw- Hill Book Co., 680 p.

Cowan, W.L., 1956, *Estimating hydraulic roughness coefficients: Agricultural Engineering*, v. 37, no. 7, p. 473-475.

Ethiopia Road Authority (2202). *Drainage Design Manual*

Interagency Advisory Committee on Water Data. *Guidelines for Determining Flood Flow Frequency: Bulletin #17B of the Hydrology Subcommittee*, United States Geological Survey, 1981.

Knighton, D. (1998) *Fluvial Forms and Processes. A New Perspective.* Arnold Publishers.

USGS (2000). *Flood-Frequency Prediction Methods for Unregulated Streams of Tennessee*. *Water-Resources Investigations Report03-4176.* Prepared in cooperation with the Tennessee Department of Transportation.

Wale, A. *Hydrological Balance of Lake Tana, Upper Blue Nile Basin, Ethiopia*. Masters Thesis, International Institute for Geo-information Science and Earth Observation, Enschede, The Netherlands, 2008.

WWDSE (2008). *Megech Dam Project, Final Feasibility Report, Hydrological Investigation*. Prepared for Ministry of Water Resources, Ethiopia.

WWDSE (2007). *Ribb Dam Hydrological Study, Draft Final Report*. Prepared for Ministry of Water Resources, Ethiopia.

A. TOPOGRAPHIC SURVEY METHODOLOGY

This methodology of topographic survey was developed by ***Riverside Technology*** *in collaboration with* ***Tropics****,* ***Shebelle*** *and* ***Civil Engineering Department of Addis Ababa University*** *and submitted to ENTRO 2 April 2009. As indicated in the Final Inception Report - Flood Risk Mapping Consultancy for Pilot Areas in Ethiopia, the topographic data, particularly cross section data of the main rivers in the pilot study area will be developed. This methodology provides specifications that will be understood and followed by the parties involved. Also the methodology provides instructions and guidelines for the survey team.*

Background

During the studies for the Tana Beles Project, in the late 1980's, a considerable amount of map production was undertaken. These maps were produced from aerial photographs (scales 1:50,000 and 1:20,000) and from ground surveys. Those maps, relevant to the present study are the 1: 50,000 maps of Ethiopian Mapping Agency (EMA). The specific quad sheets for Megech and Dirma Rivers are 1237-C2, 1237-A4, 1237-B3 and for Ribb River: 1137-B1, 1237-D3, 1237-D4 and 1137-B2. These maps shall be made available by the Ministry of Water Resources. The availability of these maps shall greatly reduce the extent of additional mapping required to support the present study.

In addition to these maps, The availability of recent (2008) topographic map (with 0.5m vertical interval) produced through the World Bank supported irrigation project which covers part of the Fogera and Dembia plain adjacent to Lake Tana and the WWDSE topographic survey for the upper Megech irrigation area shall be assessed.

The above maps are all hard copies, but the availability of other maps (30m x 30m) and (90m x 90 m) resolutions digital elevation Models (DEM) will be used to cut cross-sections that extend to the flood plains. Cross-sections can be extracted using HEC-GEORAS by overlaying the stream lines (hopefully there is some kind of shapefiles) on the DEM. The cross-sections that are obtained from these data would have less detailed channel characteristics and also would not have the channel bottom elevations.

Objectives

The main objective of this survey is to supplement the river cross-section data by obtaining detailed survey at selected points along the rivers which coincide with the automatically derived cross-section cuts. The location of the survey points will be roughly indicated on the map that will be provided to the survey team. The river cross-sections that are generated from this survey project are critical components of the hydrodynamic modeling as well as flood inundation mapping of the study area. In order to accomplish this objective, the following methodology (guideline) is provided.

Field Work

Survey Instruments

The additional survey work at Project Area shall be carried out by a survey team from Shebelle under the direction of the Lead Consultant, Riverside. Prior to starting work, the team members shall be given on-site instruction on instrument work and good surveying practice by the Engineers. The team is expected to be equipped with the following:

- 4 No. Topcon CTS-201 D electronic total station or similar,
- Ancillary equipment comprising tripods, retro-prisms, detail poles, leveling change plates.

Acoustic Doppler Current Profiler (ADCP) and flow trackers could be deployed for measuring flow velocity and taking additional bathymetry as a cross-check. The equipment are available at Addis Ababa University (AAU). The AAU team shall deploy these equipment.

Survey Methods

Controls, Vertical and Horizontal References

Control surveys shall be carried out as required at the sites by closed loop theodolite traversing. Semi-permanent stations shall be established at key locations around the sites. These stations shall comprise a mark painted on rock or a steel reinforcing bar driven into the ground and then surrounded with concrete. Horizontal and vertical control will be established to a local grid system by incorporating the stations in a closed 3D traverse. The horizontal angle, vertical angle and slope distance between adjacent stations will be measured by the electronic total station. To ensure accuracy, each angle will be measured twice on each theodolite face and the mean result used in calculation. Slope distances will be measured both ways. Any angular closing errors will be distributed equally among the measured angles prior to calculation of co-ordinates.

Small level misclosures shall be distributed between survey stations in proportion to the lengths of the measured distances. In no case shall the angular misclosure be greater than 20" or the vertical misclosure greater than 50 mm.

From each of the traverse stations, local topographical features will be surveyed by bearing and distance to provide x, y, z co-ordinates for each point surveyed.

Local bench mark for Gumara River shall be taken on the bridge guide rail. Later that elevation will be connected to the National grid/ Chara Chara weir elevation.

Horizontal control shall be established approximately using a hand-held GPS instrument to estimate the local UTM co-ordinates of a station.

What to Survey and Document

In addition to compliance to the control standards described above, the survey project shall gather and document data as specified in the flowing 10 points.

1. Cross-section survey shall be carried out at 1 kilometre interval except in cases described in #2. The sections shall be proposed on 1:50,000 topographic maps. The Universal Transverse Mercator (**UTM**) coordinates for the intersection between the cross-sections lines and the river centre line shall be prepared by measuring from the maps, this will be useful to locate the axis vector on the ground to conduct the surveying. The sections shall be taken perpendicular to the flow direction.

2. The 1km spacing is quite sufficient, however take additional surveys at

   a. hydraulic structure (for example, bridges, dikes)

   b. sites that are easily accessible such as pedestrian road crossing the river. This helps to identify future addition of observation sites.

   c. at current observation sites (gauging sites).

3. The cross-section survey shall be taken in 1m horizontal interval across the main channel and 5-50 m horizontal interval (depending on variation in elevation and also limited to accessibility) outside the riverbanks. The survey shall extend to about 1km to the flood plain from both left and right river banks. Unique topographic features such as abrupt change of elevation shall be recorded regardless of the distances set in between two consecutives target points.

4. Digital photos of the cross-sections shall be taken using a high resolution camera for the purpose of judging the roughness coefficient for the both the main channel and the flood plain. USGS Water Supply Paper 1849 shall be used as a plausible reference for estimating the roughness coefficients. Each photo shall be related to the site by having consecutive pictures of cross-section as survey proceeds from downstream to upstream. Setting up the time correctly and noting the date and time on survey recorded can help to relate cross-section pictures to surveyed data.

5. Naming of cross-sections (River Stations). River stations shall be named with using the first letter of the name of the river and the river distance from the most downstream point. For example for Megech River that ends in the lake, river stations shall be named as M0, M1, M2, M3…etc for 0km, 1km, 2km, 3km distance upstream of the lake. For stations within a 1km distance, decimal points shall be used. For example, due to conditions described in #2, if there is a need to add a station in the midpoint between 2 km and 3 km of the Megech River, the new river station shall be named as M2.5.

6. For each cross-section, survey and record coordinates shall be made from left bank to right bank. Left and Right bank are designated by looking towards flow direction.

7. In each cross-section, the left and right river bank limits shall be indicated as LB and RB, respectively. These are the approximate limits of the bankfull flow.

8. The water surface elevation during the survey period shall be recorded.

9. For each cross-section, high water marks related to historical floods could be noted, if there is any information available from any marks on structures or from locals.

10. At each river station, two additional current water level elevations shall be measured: one at 200 m upstream and another at 200 m downstream from the station.

11. In addition to detailed cross-section survey to be taken at 1km interval, thalweg line (approximately centre line of the river bed), left and right end of the river bed, left and right overbank top elevations (in total 5 points across a river), with spacing of 200 m shall be surveyed.

Expected Results

Upon completion of the day's work, data shall be downloaded to laptop computers. Raw data shall be filed in a separate folder. The raw survey data shall be plotted using mapping software such as

TERRAMODEL contour maps. Cross sections at the surveyed sections will be generated, checked and if need be shall be checked or resurveyed the next morning.

B. DETAIL SURVEY OF RIVER CROSS SECTIONS

B.1 First Ground Control Point

The first ground control point was set up at Bahir Dar at the national reference point located 700m to the right alongside the road from Bahir Dar to Adet. This control is found on out crop rock which is schematically presented in the ***Figure B-1*** below.

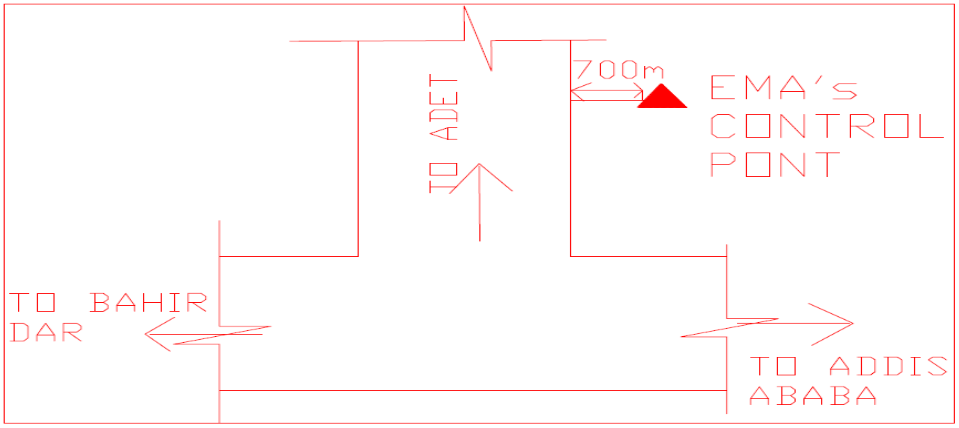


Figure B-1: Schematic Established GCP locations-EMA.

B.2 The Megech River Reach

B.2.1 Location and Accessibility

The new Megech River course is accessible from Kola Diba located at some 35 km southwest from Gondar Airport through all weather roads. Robit Village is located alongside the Megech River and is about 17.5 km southeast from Kola Diba and 7 km upstream from Lake Tana. The survey crew camped and mobilized from Robit Village and conducted the detail surveying for the Megech River.

B.2.2 The River Morphology

During the rainy season in 1999, the Megech River has changed its course and follows a new course to Lake Tana. The new course of the Megech River is more than 14km in length and passes through the Robit village, mainly along the right side of the village. The old Megech is stretched dry for about 15 km upstream of Lake Tana to where it meets the new Megech course. The old Megech is situated to the right of the new Megech looking in the downstream direction. ***Figure B-2*** shows this course in orange color.

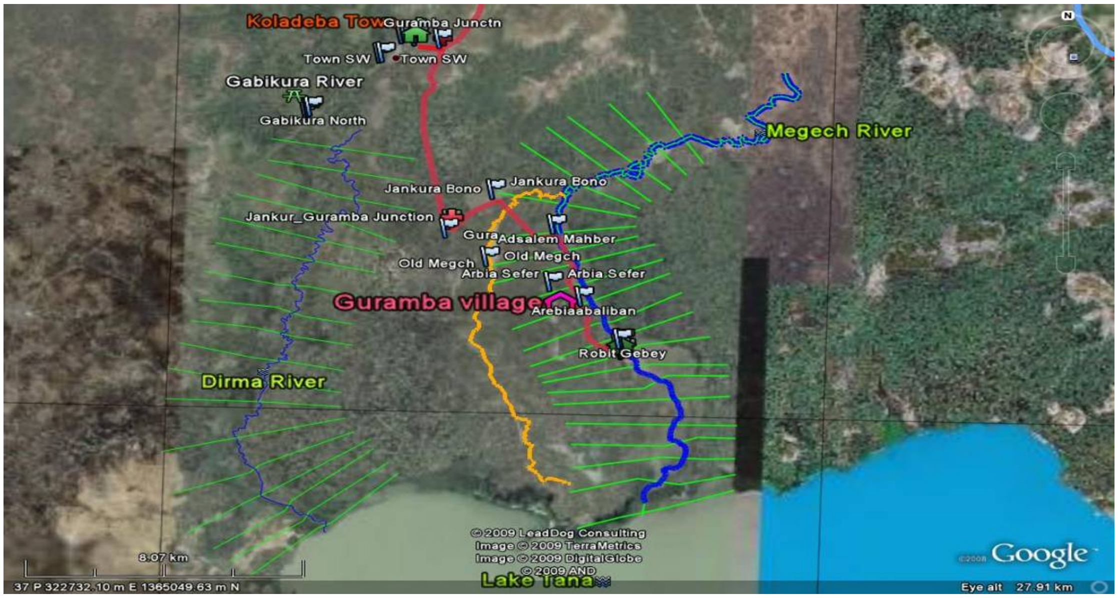


Figure B-2: Megech & Dirma Rivers survey cross-sections.

B.2.3 Establishment of GCPs, Benchmarks and/or Traverse Stations

The ground Control Points (FR14 & FR15) for surveying the Megech River were established within the Zengi Robit School compound where it can be properly protected by guards. The school is about 16 km south from Kola Diba town along the track through Guramba village.

The first control is located on the concrete water tanker and the other control is set on wooden remains. Both are centered, hammered, and painted in red. The location and coordinates of these points are as indicated below in ***Table B-1***.

Table B-1: Megech River Established GCPs.

Easting	Northing	Ortho Height	Site Description	ID
324673.89m	1362815.935m	1792.242	Robit school	FR14
324723.461m	1362861.702m	1792.253	Robit school East	FR15

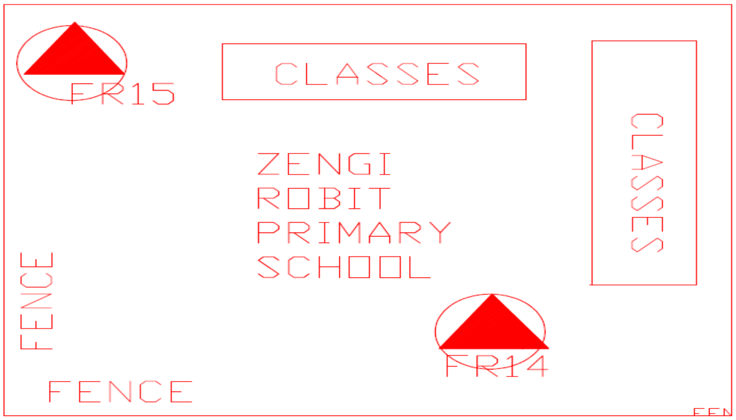


Figure B-3: Schematic Established GCP locations-Megech.

Figure B-3 shows the location of the GCP's in relationship to the classrooms and fence of the Zengi Robit School. The two GCP's established at the School were used to survey the Megech River in upstream and downstream direction using the traverse method during the second mission. Detailed information on the GCP's is presented in ***Appendix C***.

B.2.4 Megech River Detail Cross-Section Survey

The detail cross section survey was carried out on the new Megech and further past the junction to old Megech where the river opens up in to relatively flatter terrain. The river has had very low flow and at water depths at some places were as low as 20cm whereas other places the river was dry. At certain locations the river was 6m deep. During the rainy season, however, the water overtops the banks of the river and inundates nearly half of the villagers as reported by the locals. Lake Tana is the downstream boundary of the survey whereas the upstream extent of survey extends further upwards where the river open up in to relatively falter terrain.

A Total of 90 river cross sections were shot at approximately 300-450m intervals and at every kilometer upstream from Lake Tana. Each station of was designated by the 1st letter of the rivers name followed by the distance in km from lake Tana (M0, M0.3, M0.7, M1, M1.3, …, M15). The cross sections were surveyed starting from Lake Tana and extending upstream where the river opens up in to the flood plains.

At each section/station, the left and right bank bottom levels, left and right bank top levels, side channels, river bed level and water level were surveyed. In addition, at about every kilometer along the river, the cross section survey was extended further out into the flood plain for about 1km to the left and right beyond the river channel.

Moreover at the beginning, a conventional topographic survey was performed on about 48ha of land adjacent to Lake Tana where the Megech River enters into the lake. The Lake Tana water levels were recorded as part of this survey.

A closer river cross-section picture with a reasonably higher pixel have also been take at the cross-section where ground survey have been conducted.

B.2.5 Structure/Infrastructure Survey

Dyke:

About 2km downstream of the Robit Village, there exists a 150m long flood protection dyke. The top levels of the dyke along the Megech River was taken and coded as "Dyke" in the data. The bottoms of the dyke flushes out down at the river's natural ground level.

Foot Paths:

The foot paths found around the river were also traced and marked as "FOOT PATH".

Settlements:

There are sparse settlements with mud houses coded as "CHK". Trees exist across various points in the reaches.

Gaging stations:

There is no gauging station on the Megech River through the extent of the conducted ground survey.

B.3 The Dirma River

B.3.1 Location and Accessibility

The Dirma River is located southwest to Gondar. It is accessible up to Kola Diba, which is 35 Km from Gondar Airport through all weather roads. The River is situated a few kilometers west to the Megech River. The survey crew camped and mobilized at Kola Diba Town to conduct the detailed survey for the Dirma River. From Kola Diba down towards Lake Tana, it was accessible only on foot. The crew had to leave through Gorgora upon completion

B.3.2 The River Morphology

The Dirma River is relatively wide and shallow compared to the Megech River.

B.3.3 Establishment of GCPs, Benchmarks and/or Traverse Stations

The ground control points for the Dirma River were established on out crop rocks on the left and right side of the Gabi Kura Bridge on the way to Choit from Kola Diba. The points are centered and painted in red. Gabikura River itself flows in to the Dirma River about 6 km away from Kola Diba town. The location and coordinates of these points are indicated below in ***Table B-2*** and also shown in ***Figure B-4*** below. Two more GPS points were also established within the Kola Diba TVTE school compound.

Table B-2: Dirma River Established GCPs.

Easting	Northing	Ortho Height	Site Description	ID
315346.155	1371488.305	1807.233	Gabikura south	FR16
315458.034	1371644.308	1808.25	Gabikura North	FR17
318442.529	1374300.404	1843.335	Kola Diba TVTE schol	FR12
318441.562	1374300.362	1843.362	Kola Diba TVTE schol	FR13

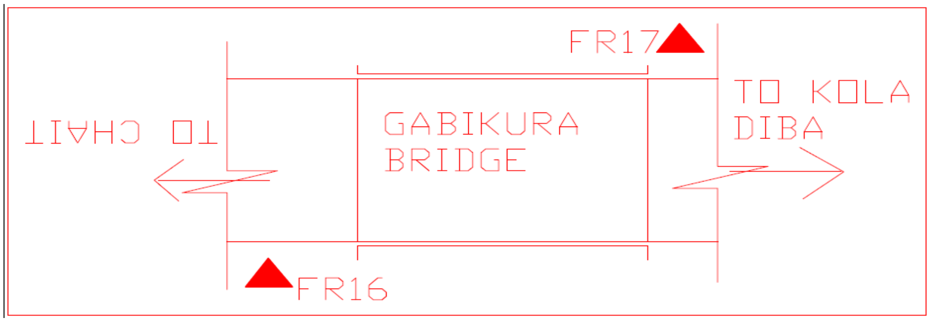


Figure B-4: Schematic Established GCP locations-Dirma.

The GCP's established at Gabi Kura and at Kola Diba TVTE school were used to run a traverse survey downstream to Lake Tana and upstream the Dirma River during the second mission by using total stations.

B.3.4 Dirma River Detail Cross-Section Survey

The Dirma River was also almost dry, shallow, and flat except that there was some depth of water under the bridge at Kola Diba Town. The depth varies from place to place the highest being 5m and the lowest being 80cm. At about 2km downstream of the bridge the water was just stagnant. Near and around the lake it was still dry. During the major rainy season, the water overtops the banks of the river and inundates the farmlands. The downstream boundary of the survey is Lake Tana.

Total number of 183 river cross sections at every 300-450m interval and at every kilometer which have been designated by stations as D0, D0.3, D0.7,D1, D1.3, …, D32, were surveyed, starting from the river confluence to Lake Tana, all the way upstream where the river opens up in to the flood plain..

At each section/station, left and right bank bottom levels, left and right bank top levels, side channels, river bed level and water level were taken. In addition, at about every kilometer along the river, the cross section survey was extended further out into the flood plain for about 1km to the left and right beyond the river channel..

Moreover at the beginning, a conventional topographic survey was performed on about 2ha of land adjacent to Lake Tana where the Dirma River enters into the lake. The Lake Tana water levels were recorded as part of this survey.

A closer river cross-section picture with a reasonably higher pixel has also been taken at the cross-section where ground survey has been conducted.

B.3.5 Structure/infrastructure survey

Bridges:

In addition to the Gabi Kura Bridge there is a wooden bridge called “Kento” at about 3 km downstream.

The levels of bridge pier’s bottom was taken. The top of the head walls over the bridge were also taken These are coded as ”PILLARS” and “HW” respectively in the data for the Dirma.

Settlements:

There are generally sparse settlements with mud houses and small huts (Gojo) coded as “CHK” and “TUKUL” respectively. Trees across various points in the reaches were also noted and coded as TREE.

Gauging stations:

There is no gauging station on the Dirma River within the reach length of the project survey extents.

B.4 The Ribb River

Location and Accessibility: The Ribb River is located about 610 km Northwest from Addis Ababa. The terrain is flat and the local people sometimes call it Fogera Meda. For surveying the Ribb and the Gumera rivers the survey crew camped at Woreta Town. Woreta is 13km away from Gumera Bridge and 12km away from the Ribb Bridge. The Ribb River is accessible downstream for about 20km and upstream of the bridge for about 5km.

B.4.1 The River Morphology

The Ribb River is a large river that is very wide and deep. Especially near Lake Tana, the river becomes very large. At about 3 km upstream of Lake Tana the river has changed its course over the past years. Despite the width and depth of the river, there are some place where there is no water in the river. The deepest observed depth was 13m.

B.4.2 Establishment of GCPs, Benchmarks, and/or Traverse Stations

The ground control points for surveying the Ribb River were established on the out crop rock near the Ribb Bridge on the top left side of the river. The points are centered, hammered, and painted in red. These control points were mainly used to cover the whole upstream and downstream works. The location and coordinates of these points are as indicated in ***Table B-3***, and are shown in ***Figure B-5*** below.

Table B-3: Ribb River Established GCPs.

Easting	Northing	Ortho Height	Site Description	ID
359708.12	1326139.2	1794.556	Ribb river left GSTN	FRM8
359675.297	1326076.666	1794.316	Ribb River near road	FRM9

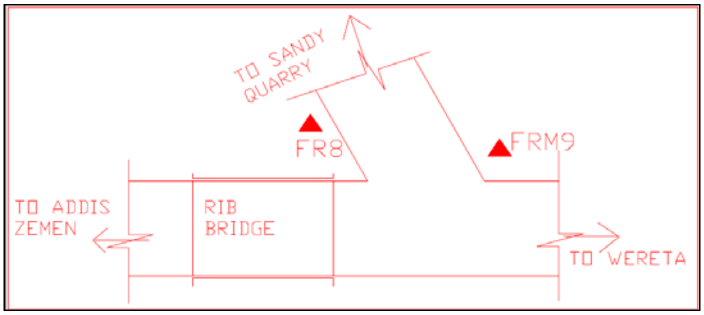


Figure B-5: Schematic Established GCP locations-Rib.

These Ground Control points established at Ribb Bridge area were used to run a traverse downstream to lake level and further upstream along the Ribb River.

B.4.3 The Ribb River Detail Cross-Section Survey

Despite the depth of the Ribb River,it was possible to measure the depth at the deepest point with the help of local people. Closer to Lake Tana, however, it wasn’t always possible to determine the deepest point of the river due to the width of the river. The detail survey was done from lake Tana to approximately 5Km upstream of the bridge.

A total number of 163 river cross sections at every 300-450m interval and at every kilometer which have been designated by stations, R0, R0.3, R0.7,R1, R1.3, …, R29, were surveyed starting from the river confluence with Lake Tana towards upstream the upstream boundary.

At each section/station, left and right bank bottom levels, left and right bank top levels, side channels, river bed level and water revel were taken. In addition, at about every kilometer along the river, the cross section survey was extended further out into the flood plain for about 1km to the left and right beyond the river channel..

Moreover at the beginning, a conventional topographic survey was performed on about 2ha of land adjacent to Lake Tana where the Ribb River enters into the lake. The Lake Tana water levels were recorded as part of this survey.

A closer river cross-section picture with a reasonably higher pixel have also been take at the cross-section where ground survey have been conducted.

B.4.4 Structure/infrastructure Survey

Bridge:

The Ribb Bridge is the only bridge across the Ribb River. The bottom levels of the bridge piers were taken (coded “PILLARS”). The top of the head wall over the bridge were also taken which are coded as “HW”. The road edge levels over the bridge were also recorded and coded as “RE”.

Dyke:

For about 5km downstream of the Ribb Bridge, the top level of the dyke along the Ribb River was taken all the way down at every 300m interval along the river. The bottoms of the dyke flushes out down at the river’s natural ground level

Electric Poles:

High voltage electric poles about 3 km upstream of the bridge were noted as “EP”.

Settlements:

Tukuls (small huts) built along the river and foot paths were also traced.

Gauging stations:

There is a gauging station on the Ribb River upstream of the bridge.

B.5 The Gumera River

B.5.1 Location and Accessibility

The Gumera River is located about 600km from Addis. It was accessible downstream of the bridge after 2-3km distance. It is accessible upstream of the bridge up to Wanzaye Village. The crew camped at Woreta Town which is 13km away from Gumera Bridge and 12km away from The Ribb Bridge.

B.5.2 The River Morphology

The Gumera River is the largest river of all four rivers surveyed as part of this project. The Gumera River appears to be a very stable channel when it comes to channel migration.

B.5.3 Establishment of GCPs, Benchmarks, and/or Traverse Stations

The first ground Control Points for surveying the Gumera River is established on the Gumera Brige near to the right wing wall and another one some 257 m away from the bridge at a gauging station on a buried metal. The points are centered, hammered, and painted in red. These control points were mainly used to cover the whole upstream and downstream works up to Hud Gebeya. The location and coordinates of these points are as indicated in ***Table B-4*** and ***Figure B-6*** shown below.

Table B-4: Gumera River Established GCPs-Bridge.

Easting	Northing	Ortho Height	Site Description	ID
351275.533	1309054.495	1795.298	GUMERA BRIDGE	FRM2
351531.47	1309050.308	1793.704	GOMARA GAUGING ST	FRM3

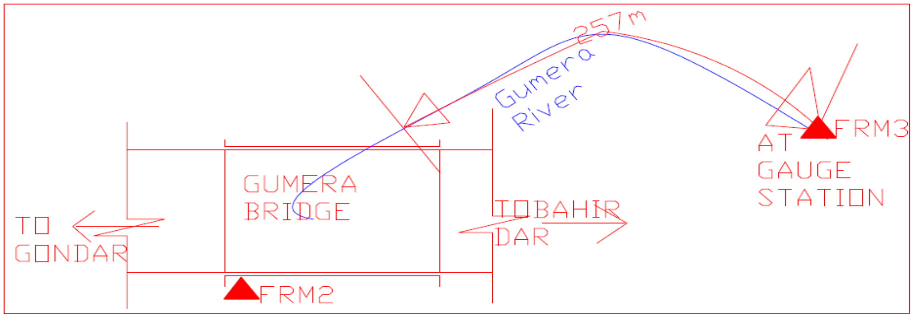


Figure B-6: Schematic Established GCP locations-Gumera Bridge.

Additional GCP's were installed in the Hud Gebeya village. The Hud Gebeya village is 9km to the left of the junction with the main road from the Gumera Bridge towards Gondor accessible by dry weather roads. The junction is located approximately 5 km along the main road from the Gumera Bridge towards Gondar. Two GCP's were established in the village, one of them on the corner of the water tank and the other on wood remains near Ato Teklu and Ato Muhabaw Belay House. This town has no power as it is located far from Woreta but has telephone and water facilities. These controls were used to run a traverse survey down from Hud Gebeya to Lake Tana. The location of the GCP's are shown in ***Table B-5*** and ***Figure B-7*** below.

Table B-5: Gumera River Established GCPs-Eastern.

Easting	Northing	Ortho Height	Site Description	ID
346497.167	1315417.278	1790.02	Hod Gebeya West	FRM4
346525.182	1315585.022	1789.8	HOD GEBYA East	FRM5

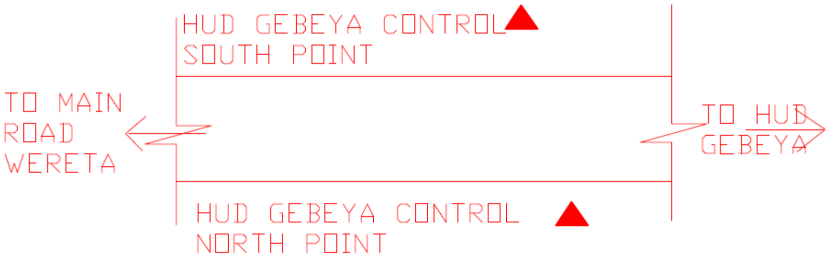


Figure B-7: Schematic Established GCP locations-Gumera Eastern.

Additional GCP's were located in the Gigna Mender village. The Gigna Mender village is located about 6 km to the right from the main road from Bahir Dar to Gondar on the road that leads to Wanzaye Village. Yimer Meda junction is found on the way on the right side of the way to Wanzaye where there is a quarry site. Wanzaye has full access to electricity, water, and telephone and thus two control points are established for the Gumera upstream works near to Wanazaye. The first point is found on out crop rock near to the quarry site at the road edge -good for transferring more points from it. The second point is on the field known as Wediyae. Both points are centered and painted in red. These data and illustration are shown in ***Table B-6*** and in ***Figure B-8*** below.

Table B-6: Gumera River Established GCPs-Western.

Easting	Northing	Ortho Height	Site Description	ID
352857.548	1303414.023	1832.718	Yimer meda junction	FRM6
352791.953	1304043.027	1813.005	Gedam Geregera Gumar	FRM7

Figure B-8: Established GCP locations-Gumera Western.

The above controls were thus used to run a traverse survey both upstream and downstream of the Gumera Bridge during the second mission.

B.5.4 Gumera River Detail Cross-Section Survey

A detailed survey was performed for both upstream of the bridge and downstream to Lake Tana. The height difference between top of bank and bottom of bank were large and it wasn't always possible to cross the river from one side to the other and thus we had to use locals to swim across the water and measure the depth of the water.

Total number of 155 river cross sections at every 300-450m interval and at every kilometer which have been designated as stations, G0, G0.3, G0.7, G1, G1.3, …, G37, were surveyed starting from the river confluence with Lake Tana to the upstream survey boundary.

A conventional topographic survey was performed on about 2.3ha of land adjacent to Lake Tana where the Gumara River enters into the lake. The Lake Tana water levels were recorded as part of this survey.

A closer river cross-section picture with a reasonably higher pixel have also been take at the cross-section where ground survey have been conducted.

B.5.5 Structure/Infrastructure

Bridge:

The Gumera Bridge is the only bridge across the Gumera River. The levels bridge pier bottoms were taken (coded “PILLARS”). The top of the head wall over the bridge were taken (coded “HW”). The road edge levels over the bridge were also recorded and coded as “RE”.

Culvert:

One culvert was found on the road to Wanzaye. The invert, top of pipe, road crest elevation, and the top elevation of the head wall were taken. Where the rivers turns around closer to the main road, the road level was also taken.

Dyke:

Approximately 1km downstream of Hud Gebeya, a dyke of about 1200m long was surveyed along the Gumera River. The top level of the dyke was taken at about every 300m interval along the river. The bottom of the dyke flushes out down at the bank top level of the river.

Ditch:

A ditch of about 280 m long was found along the Wanzaye road which was also traced.

Settlements:

There were local mud-houses built alongside the river at three places downstream of the Hud Gebeya. These were designated as “CHK.” There were also several Tukuls built along the river at different places.

Trees:

There are dense trees downstream of Hud Gebeaya alongside the river for more than 12 km.

Electric Poles:

About 11 high voltage electric poles were noted passing over the river and closer to road.

Gauging stations:

There is a gauging station on the Gumera River 257 m upstream of the highway bridge.

C. ESTABLISHED GROUND CONTROL POINTS

Table C-1: Established GCPs

Easting	Northing	Ortho Height	Site Description	ID
474317.099	998745.737	2452.967	Addis	ADIS
324150.129	1278375.026	1801.89	Bahir Dar Town	BDTW
334499.155	1379927.293	1940.015	Teda police station	FM12
350558.878	1355514.57	1933.72	Enfranz high school	FM10
342865.881	1369228.185	1926.92	Maksegit Total	FR11
318442.529	1374300.404	1843.335	Kola Diba TVTE schol	FR12
318441.562	1374300.362	1843.362	Kola Diba TVTE schol	FR13
324673.89	1362815.935	1792.242	Robit school	FR14
324723.461	1362861.702	1792.253	Robit school East	FR15
315346.155	1371488.305	1807.233	Gabikura south	FR16
315458.034	1371644.308	1808.25	Gabikura North	FR17
343129.959	1302833.284	1935.713	HAMUSIT	FRM1
351275.533	1309054.495	1795.298	GUMERA BRIDGE	FRM2
351531.47	1309050.308	1793.704	GOMARA GAUGING ST	FRM3
346497.167	1315417.278	1790.02	Hod Gebeya West	FRM4
346525.182	1315585.022	1789.8	HOD GEBYA East	FRM5
352857.548	1303414.023	1832.718	Yimer meda junction	FRM6
352791.953	1304043.027	1813.005	Gedam Geregera Gumar	FRM7
359708.12	1326139.2	1794.556	Ribb river left GSTN	FRM8
359675.297	1326076.666	1794.316	Ribb River near road	FRM9
367334.606	1135987.49	2429.371	Debre Markos	TWQ3

Table C-2: GCPs established earlier in April to connect to the national grid with the help of survey grade differential GPS.

COMPONENT					
East	**North**	**Ortho Height**		ID	
474317.099	998745.737	2452.967	Addis	ADIS	PLAN
324150.129	1278375.026	1801.89	Bahir Dar Town	BDTW	324150.129,1278375.026,1801.89
334499.155	1379927.293	1940.015	Teda police station	FM12	334499.155,1379927.293,1940.015
350558.878	1355514.57	1933.72	Enfranz high school	FM10	350558.878,1355514.57,1933.72
342865.881	1369228.185	1926.92	Maksegit Total	FR11	342865.881,1369228.185,1926.92
318442.529	1374300.404	1843.335	Kola Diba TVTE schol	FR12	318442.529,1374300.404,1843.335
318441.562	1374300.362	1843.362	*Kola Diba TVTE schol*	FR13	318441.562,1374300.362,1843.362
324673.89	1362815.935	1792.242	*Robit school*	FR14	324673.89,1362815.935,1792.242
324723.461	1362861.702	1792.253	*Robit school East*	FR15	324723.461,1362861.702,1792.253
315346.155	1371488.305	1807.233	*Gabikura south*	FR16	315346.155,1371488.305,1807.233
315458.034	1371644.308	1808.25	*Gabikura North*	FR17	315458.034,1371644.308,1808.25
343129.959	1302833.284	1935.713	*HAMUSIT*	FRM1	343129.959,1302833.284,1935.713
351275.533	1309054.495	1795.298	*GUMARA BRIDGE*	FRM2	351275.533,1309054.495,1795.298
351531.47	1309050.308	1793.704	*GOMARA GAUGING ST*	FRM3	351531.47,1309050.308,1793.704
346497.167	1315417.278	1790.02	*Hod Gebeya West*	FRM4	346497.167,1315417.278,1790.02
346525.182	1315585.022	1789.8	*HOD GEBYA East*	FRM5	346525.182,1315585.022,1789.8
352857.548	1303414.023	1832.718	*Yimer meda junction*	FRM6	352857.548,1303414.023,1832.718
352791.953	1304043.027	1813.005	*Gedam Geregera Gumar*	FRM7	352791.953,1304043.027,1813.005
359708.12	1326139.2	1794.556	*Rib river left GSTN*	FRM8	359708.12,1326139.2,1794.556
359675.297	1326076.666	1794.316	*Rib River near road*	FRM9	359675.297,1326076.666,1794.316
367334.606	1135987.49	2429.371	*Debre Markos*	TWQ3	
Coordinate system		**Datum**		**Projection**	
Name :	UTM/WGS 84/UTM zone 37N~12	**Name :**	WGS 84	**Projection Class :**	Transverse_Mercator
Type :	Projected	**Ellipsoid Name :**	WGS 84	**latitude_of_origin**	0° 00' 00.00000"N
Unit name :	Meters	**Semi-major Axis :**	6378137.000 m	**central_meridian**	39° 00' 00.00000"E
Meters per unit :	1	**Inverse Flattening :**	298.2572236	**scale_factor**	0.9996
Vertical datum :	EGM96	**DX to WGS84 :**	0.0000 m	**false_easting**	500000.000 m
Vertical unit :	Meters	**DY to WGS84 :**	0.0000 m	**false_northing**	0.000 m
Meters per unit :	1	**DY to WGS84 :**	0.0000 m		
		RX to WGS84 :	0.000000 "		
		RY to WGS84 :	0.000000 "		
		RZ to WGS84 :	0.000000 "		
		ppm to WGS84 :	0		

D. DATA INVENTORY

(This list contains data obtained through One System Inventory and is currently available at ENTRO. This list only includes major data and not the full exhaustive list of the archives.)

Time Series Data

This section contains the following data sets:

- Time series data of stream flow records from river gauging stations
- Time series data of rainfall records
- Time series data of evaporation records
- Time series data of temperature records
- Time series data of humidity records
- Time series data of atmospheric pressure records
- Time series data of irrigation demands
- Time series data of sediment measurements
- Time series data of water quality measurements

The presentation of the available data set is provided below, grouped by sub-basin in which the river or canal is located. Name of the measuring station and time span of data record available is also indicated in the tables.

Stream Flow Records

Table D-1: River Flow Records for Stations in Blue Nile Sub-basin

River/Canal	Station	Time of Record	Time Step	Remark
Dinder	Giwasi	(1992-2000)	10 days	Sudan
Rahad inflow	El-Hawata	(1950-2000)	10 days	Sudan
Blue Nile	Roseries	(1950-2001)	10 days	Sudan
Blue Nile	Sennar Dam	(1950-2002)	10 days	Sudan
Abbay	Border	(1980-2000)	Monthly record	Ethiopia
Abbay	Near Bahir Dar	(1980-2000)	Monthly record	Ethiopia
Abbay	Near Kessie	(1980-2000)	Monthly record	Ethiopia
Abbay	Jema	(1980-2000)	Monthly record	Ethiopia
Aleltu	Near Nedjo	(1980-2000)	Monthly record	Ethiopia
Angar	Near Nekemete	(1980-2000)	Monthly record	Ethiopia
Birr	Birr	(1980-2000)	Monthly record	Ethiopia

River/Canal	Station	Time of Record	Time Step	Remark
Blue Nile	Eddeim Station	(1980-2000)	Monthly record	Sudan
Blue Nile	Roseries Station	(1980-2000)	Monthly record	Sudan
Blue Nile	Sennar Station	(1980-2000)	Monthly record	Sudan
Blue Nile	Khartoum Station	(1980-2000)	Monthly record	Sudan
Blue Nile	Wad Madani	(1980-2000)	Monthly record	Sudan
Bogena	Bogena	(1980-2000)	Monthly record	Ethiopia
Dabana	Near Abasina	(1980-2000)	Monthly record	Ethiopia
Dabus	Near Assosa	(1980-2000)	Monthly record	Ethiopia
Debis	Near Guder	(1980-2000)	Monthly record	Ethiopia
Diddessa	Near Arjo	(1980-2000)	Monthly record	Ethiopia
Dinder	Giwasi	(1980-2000)	Monthly record	Sudan
Dura	Near Metekel	(1980-2000)	Monthly record	Ethiopia
Muger	Near Chancho	(1980-2000)	Monthly record	Ethiopia
Rahad	El-Hawata	(1980-2000)	Monthly record	Sudan

Rainfall Data Records

Table D-2: Rainfall Records for Stations in Blue Nile Sub-basin

Description	Duration	Remark
Rainfall records at Addis Zemen Station	1980-2000	Incomplete for the years 1983, 1991, 1992, 1993, 1997, 1999
Rainfall records at Agaro Station	1980-2000	Incomplete for the years 1980, 1981, 1982, 1983, 1984, 1990, 1991, 1994, 1995, 1999
Rainfall records at Alem Ketema Station	1980-200	Incomplete for the years 1990, 1991, 1998
Rainfall records at Ambo Station	1984-200	All data are incomplete except for the year 2000

Description	**Duration**	**Remark**
Rainfall records at Bahir Dar Synoptic Station	1980-2000	Incomplete for the years 1991, 1998
Rainfall records at Chagni Station	1980-1992 &1998-2000	Incomplete for the years 1983, 1984, 1990, 1991, 1992, 1998
Rainfall records at Dabat station Station	1988-2000	All data are incomplete
Rainfall records at Debark Station	1980-1989 &1992-200	Incomplete for the years 1982, 1983, 1984, 1985, 1986, 1987, 1988, 1989, 1992, 1993, 1996, 1998
Rainfall records at Debre Birhan Station	1982-2000	Incomplete for the years 1982, 1983, 1990, 1994, 1995, 1997
Rainfall records at Debre Markos Station	1980-2000	Incomplete for the year 1991
Rainfall records at Debre Tabor Station	1980-200	Incomplete for the years 1986, 1989, 1990, 1991
Rainfall records at Dejen Station	1980-2000	Incomplete for the years 1982, 1983, 1986, 1990, 1999
Rainfall records at Ebinat Station	1980-1984 &1997-200	All data are incomplete except for the years 1980, 1984
Rainfall records at Fiche Station	1980-2000	Incomplete for the years 1980, 1982, 1983, 1984, 1988
Rainfall records at Finote Selam Station	1980-1997	Incomplete for the years 1980, 1983, 1985, 1986, 1990, 1991, 1992, 1993
Rainfall records at Gedo Station	1980-2000	Incomplete for the years 1990, 1991, 1992, 1993, 1994, 1995, 1997, 1999, 2000
Rainfall records at Gondar Station	1980-2000	Incomplete for the years 1991, 2000
Rainfall records at Humera Station	1980-1988 &1996-2000	Incomplete for the year 1980, 1984, 1987, 1988, 1996, 1997, 1998, 2000

Description	Duration	Remark
Rainfall records at Kunzela Station	1980-1990	All data are incomplete except the years 1981, 1984
Rainfall records at Mehal Meda Station	1980-2000	Incomplete for the years 1990, 1991
Rainfall records at Mekane Selam Station		
Rainfall records at Merawi Station	1981-1995	Incomplete for the years 1981, 1982, 1983, 1990, 1991, 1992, 1993, 1994
Rainfall records at Metema Station	1987-1989 &1994-2000	All data are incomplete except for the year 2000
Rainfall records at Motta Station	1980-2000	Incomplete for the years 1982, 1983, 1990, 1991, 2000
Rainfall records at Nefas Mewcha Station	1986-2000	Incomplete for the years 1986, 1989, 1990, 1991, 1994
Rainfall records at Pawe Station	1987-2000	Incomplete for the years 1990, 1991
Rainfall records at Wegel Tena Station	1980-1989 & 1992-2000	Incomplete for the years 1982, 1983, 1988, 1989, 1992, 1993, 1996, 1997
Sennar Station Monthly Rainfall in mm	1980-2000	Complete
Khartoum Station Monthly Rainfall in mm	1980-2001	Complete

Evaporation Records

Table D-3: Evaporation Records for Stations in Blue Nile Sub-basin

Station	Duration	Remark
Agaro	1986-1994	Incomplete data for the year 1994
Ambo	1983,1986-1991, 1993, 1999, 2000	All data are incomplete except for years 1987, 1993

Station	Duration	Remark
Chagni	1980-1988 & 1998-2000	Incomplete data for the year 1988, 1998
Debre Markos	1980-1982 & 1985-1999	Incomplete data for the years 1980, 1981, 1982, 1986, 1989, 1990, 1991, 1992, 1995, 1999
Finote Selam	1982-1988	Incomplete data for the years 1984, 1985, 1986, 1988
Motta	1990-1993 & 1998-2000	Incomplete data for the years 1990, 1991, 1993, 2000
Alem Ketema	1989-2000	Incomplete data for the years 1990, 1991, 1998, 1999
Bahir Dar Synoptic	1997-2000	Complete for all years
Debre Birhan	1985-1990	Incomplete data for the year 1990
Fiche	1997-2000	Complete for all years
Mehal Meda	1997-2000	Complete for all years
Gondar	1980-1985 & 1997-2000	Incomplete data for the year 1980, 1981, 1997, 2000
El-Damazin	1990-2000	Complete for all years
Sennar Station	1990-2000	Complete for all years
Khartoum Station	1990-2000	Complete for all years

Relative Humidity

Table D-4: Relative Humidity Records for Stations in Main Nile Sub-basin

Station	Duration	Remark
Rosetta	Monthly Average()	Egypt
Damietta	Monthly Average()	Egypt
Damnhour	Monthly Average()	Egypt

Station	Duration	Remark
El-Mansoura	Monthly Average()	Egypt
Tanta	Monthly Average()	Egypt
Quesna	Monthly Average()	Egypt
Cairo	Monthly Average()	Egypt
Giza	Monthly Average()	Egypt
Bni Sweef	Monthly Average()	Egypt
Minya	Monthly Average()	Egypt
Asyut	Monthly Average()	Egypt
Sohag	Monthly Average()	Egypt
Kena	Monthly Average()	Egypt
Luxor	Monthly Average()	Egypt
Aswan	Monthly Average()	Egypt

Air Temperature

Table D-5: Air Temperature Records for Stations in Main Nile Sub-basin

Station	Duration	Remark
Rosetta	Monthly Average()	Egypt
Damietta	Monthly Average()	Egypt
Damnhour	Monthly Average()	Egypt
El-Mansoura	Monthly Average()	Egypt
Tanta	Monthly Average()	Egypt
Quesna	Monthly Average()	Egypt
Cairo	Monthly Average()	Egypt
Giza	Monthly Average()	Egypt

Station	Duration	Remark
Bni Sweef	Monthly Average()	Egypt
Minya	Monthly Average()	Egypt
Asyut	Monthly Average()	Egypt
Sohag	Monthly Average()	Egypt
Kena	Monthly Average()	Egypt
Luxor	Monthly Average()	Egypt
Aswan	Monthly Average()	Egypt

Atmospheric Pressure

Table D-6: Atmospheric Pressure Records for Stations in Main Nile Sub-basin

Station	Duration	Remark
Rosetta	Monthly Average()	Egypt
Damietta	Monthly Average()	Egypt
Damnhour	Monthly Average()	Egypt
El-Mansoura	Monthly Average()	Egypt
Tanta	Monthly Average()	Egypt
Quesna	Monthly Average()	Egypt
Cairo	Monthly Average()	Egypt
Giza	Monthly Average()	Egypt
Bni Sweef	Monthly Average()	Egypt
Minya	Monthly Average()	Egypt
Asyut	Monthly Average()	Egypt
Sohag	Monthly Average()	Egypt
Kena	Monthly Average()	Egypt

Luxor	Monthly Average()	Egypt
Aswan	Monthly Average()	Egypt

Irrigation Demand

Table D-7: Future and Current Irrigation Demand/Abstraction at Nodes in Blue Nile Sub-basin

Location	River /Canal	Time Step	Remark
Gezira/Managil Irrigation	Blue Nile	Total 10 days	Sudan
Pump Irrigation Demand D/S Sennar (Sennar- Khartoum)	Blue Nile	Total 10 days	Sudan
Pumps Irrigation Demand D/S Sennar(Sennar- Khartoum)	Blue Nile	Total 10 days	Sudan
Future Pump Irrigation Demand U/S Sennar	Blue Nile	Total 10 days	Sudan
Pumps Future Irrigation Demand U/S Sennar	Blue Nile	Total 10 days	Sudan

Table D-8: Future and Current Irrigation Demand/Abstraction at Nodes in Main Nile Sub-basin

Location	River /Canal	Time Step	Remark
Demand (Hasanab-Dongola)	Main Nile	Total 10 days	Sudan
Future Demand (Hasanab-Dongola)	Main Nile	Total 10 days	Sudan
Future Irrigation Demand (Khartoum-Hasanab)	Main Nile	Total 10 days	Sudan
Irrigation Demand (Khartoum-Hasanab)	Main Nile	Total 10 days	Sudan

Geographic Information Systems (GIS) Data Set

In this section available GIS Spatial Data Sets are listed. Primarily, the data is grouped by country and then by source.

GIS Data of Ethiopia

The major source of GIS data sets are shown in the table below. The following tables list available data sets from each source.

Table D-9: GIS Data from the Ministry of Water Resources

Data Set	Data Type
All rivers and streams in Abbay river basin	ESRI Shapefile
Climatic zone	ESRI Shapefile
Farming zone	ESRI Shapefile
Lakes and impoundments boundary	ESRI Shapefile
Land cover map	ESRI Shapefile
Land use map	ESRI Shapefile
Main rivers with names assigned	ESRI Shapefile
Major road	ESRI Shapefile
Dry and wet all road network	ESRI Shapefile
Soil map	ESRI Shapefile
Digital contour map 1:25000 map scale	ESRI Shapefile
Vector file showing extent of Abbay river basin	ESRI Shapefile
Lakes and reservoirs in Abbay river basin	ESRI Shapefile
Potential irrigation sites as identified in the master plan	ESRI Shapefile
Major rivers in the Abbay river basin	ESRI Shapefile
Identified dam sites in Abbay river basin	ESRI Shapefile
Existing dam site location	ESRI Shapefile
Boundary of Abbay river basin	ESRI Shapefile

Table D-10: GIS Data from the Ministry of Agriculture

Data Set	Data Type
Soil erosion hazard map	Shapefile
Agro-ecology map	Shapefile

Soil erosion hazard map Universal Transverse Mercator (UTM)	Shapefile
Vegetation cover map	Shapefile
Vegetation cover map UTM	Shapefile
Spatial soil depth map UTM	Shapefile
Major soil group	Shapefile
Soil loss	Shapefile

Table D-11: GIS Data of International Livestock Research Institute (ILRI)

Data Set	Data Type
Digital terrain model (DTM)	ESRI grid
DTM in UTM	Shapefile
Eco-forest map	Shapefile
Lakes and water bodies	Shapefile
River network	Shapefile
National park	Shapefile
Wet land	Shapefile
Major road network	Shapefile

Table D-12: GIS Data of Ethiopian Development Research Institute (EDRI)

Data Set	Data Type
Digital elevation model 90 meter resolution	Shapefile
Agro-ecology zone	Shapefile
Annual rainfall	ESRI grid
Spatial rainfall for the month January	ESRI grid
Spatial rainfall for the month February	ESRI grid

Data Set	**Data Type**
Spatial rainfall for the month March	ESRI grid
Spatial rainfall for the month April	ESRI grid
Spatial rainfall for the month May	ESRI grid
Spatial rainfall for the month June	ESRI grid
Spatial rainfall for the month July	ESRI grid
Spatial rainfall for the month August	ESRI grid
Spatial rainfall for the month September	ESRI grid
Spatial rainfall for the month October	ESRI grid
Spatial rainfall for the month November	ESRI grid
Spatial rainfall for the month December	ESRI grid
Shaded relief map	ESRI grid
Slope map	ESRI grid

GIS Data Of Woody Biomass By Region

Table D-13: Data for the following regions: Amhara, Gambela, Tigray, Benishangul-Gumuz, Oromia, and Southern Nations, Nationalities, and People's Regional State (SNNPRS)

Data Set	**Data Type**
All-weather roads	Shapefile
Dry weather roads	
Foot paths	
Altitude zone	Shapefile
Lake and impoundments	Shapefile
Contour	Shapefile
Land forms	Shapefile

Data Set	Data Type
Soil depth	Shapefile
Ecology zone	Shapefile
Forest system	Shapefile
Geomorphology	Shapefile
Rainfall isoheight	Shapefile
Lakes	Shapefile
Land cover	Shapefile
Crop suitability	Shapefile
Risk crop	Shapefile
Major rivers	Shapefile
Parks	Shapefile
Rainfall isoheight	Shapefile
Soil map	Shapefile
Temperature zone	Shapefile
Tributary rivers	Shapefile

Table D-14: National GIS Data for Ethiopia

Data Set	Data Type
Agro-climatic zone	ESRI Shapefile
Agro-ecology zone	ESRI Shapefile
Digital elevation model (DEM) 90 meter	ESRI Shapefile
Soil map from Food and Agricultural Organization (FAO)	ESRI Shapefile
Annual rainfall	ESRI Shapefile
Spatial rainfall January	ESRI Shapefile

Data Set	**Data Type**
Spatial rainfall February	ESRI Shapefile
Spatial rainfall March	ESRI Shapefile
Spatial rainfall April	ESRI Shapefile
Spatial rainfall May	ESRI Shapefile
Spatial rainfall June	ESRI Shapefile
Spatial rainfall July	ESRI Shapefile
Spatial rainfall August	ESRI Shapefile
Spatial rainfall September	ESRI Shapefile
Spatial rainfall October	ESRI Shapefile
Spatial rainfall November	ESRI Shapefile
Spatial rainfall December	ESRI Shapefile
All lakes and water bodies In Ethiopia	ESRI Shapefile
Livestock maps	ESRI Shapefile
Road maps	ESRI Shapefile
Major towns	ESRI Shapefile
Spatial minimum monthly temperature for January	ESRI grid
Spatial minimum monthly temperature for February	ESRI grid
Spatial minimum monthly temperature for March	ESRI grid
Spatial minimum monthly temperature for April	ESRI grid
Spatial minimum monthly temperature for May	ESRI grid
Spatial minimum monthly temperature for June	ESRI grid
Spatial minimum monthly temperature for July	ESRI grid
Spatial minimum monthly temperature for August	ESRI grid

Data Set	**Data Type**
Spatial minimum monthly temperature for September	ESRI grid
Spatial minimum monthly temperature for October	ESRI grid
Spatial minimum monthly temperature for November	ESRI grid
Spatial minimum monthly temperature for December	ESRI grid
Spatial maximum monthly temperature for January	ESRI grid
Spatial maximum monthly temperature for February	ESRI grid
Spatial maximum monthly temperature for March	ESRI grid
Spatial maximum monthly temperature for April	ESRI grid
Spatial maximum monthly temperature for May	ESRI grid
Spatial maximum monthly temperature for June	ESRI grid
Spatial maximum monthly temperature for July	ESRI grid
Spatial maximum monthly temperature for August	ESRI grid
Spatial maximum monthly temperature for September	ESRI grid
Spatial maximum monthly temperature for October	ESRI grid
Spatial maximum monthly temperature for November	ESRI grid
Spatial maximum monthly temperature for December	ESRI grid
Spatial agricultural wheat production map	Shapefile
Cattle density	Shapefile
Sheep density	Shapefile
Frost maps	Shapefile
Administrative division	Shapefile
Hospital distribution by woreda	Shapefile
Health center by woreda	Shapefile

Data Set	Data Type
Dry climate zone	Shapefile
Wet climate zone	Shapefile
Land cover	Shapefile
Land use	Shapefile
Parks	Shapefile
Wetlands	Shapefile
Soil	Shapefile
Geology	Shapefile
Major towns	Shapefile
Cities	Shapefile
Populated places	Shapefile

Table D-15: GIS Data of Sudan

Data Set Description	Data Type
Administrative divisions	ESRI Shapefile
Population distribution land scan	ESRI Shapefile
Third level sub-basin division	ESRI Shapefile
Geology	ESRI Shapefile
Road networks	ESRI Shapefile
Major towns	ESRI Shapefile
Populated places and landmarks	ESRI Shapefile
Digital elevation model	ESRI Shapefile
Land cover	ESRI Shapefile

Data Set Description	**Data Type**
Land use	ESRI Shapefile
Dams and barrages	ESRI Shapefile
Soil group	ESRI Shapefile
Land forms	ESRI Shapefile
Relief maps	ESRI Shapefile
Spatial precipitation	ESRI Shapefile
Spatial evaporation	ESRI Shapefile
Forest cover	ESRI Shapefile
Wetlands	ESRI Shapefile
Sudan boundary	ESRI Shapefile
Locations of flow gauging stations	ESRI Shapefile
Locations of meteorological stations	ESRI Shapefile
River network	ESRI Shapefile
Agricultural maps	ESRI Shapefile
Bare areas	ESRI Shapefile
Range lands	ESRI Shapefile
Urban areas	ESRI Shapefile
Water bodies	ESRI Shapefile
Woody	ESRI Shapefile

Table D-16: GIS Data of Entire Eastern Nile Basin from Various Sources

ID	**Data Set Description**	**Data Type**	**Source**
1	Digital elevation model (90 meter)	ESRI grid file	Internet Global Data Set
2	Administrative boundaries	ESRI Shapefile	

ID	Data Set Description	Data Type	Source
3	Road networks	ESRI Shapefile	
4	Population densities	ESRI Grid file	
5	Cities	ESRI Shapefile	
6	Major towns populated places and land marks	ESRI Shapefile	
7	Water bodies	ESRI Shapefile	
8	Rivers and Streams	ESRI Shapefile	
9	Drainage pattern	ESRI Shapefile	
13	Vegetation cover	ESRI Shapefile	FAO
14	Soil map	ESRI Shapefile	FAO
15	Land use / land cover	ESRI grid file	US Geological Survey (USGS)
16	Spatial rainfall map	ESRI grid file	OSI Synthesis
17	Spatial evaporation map	ESRI grid file	OSI Synthesis
18	Spatial humidity map	ESRI grid file	OSI Synthesis
19	Spatial temperature map	ESRI grid file	OSI Synthesis
20	River flow schematic	JPG file	OSI Synthesis
21	Landsat Enhanced Thematic Mapper (ETM) imagery	MrSID format	Internet Global Data Set
22	Geology	ESRI Shapefile	Internet Global Data Set
23	Landforms	ESRI Shapefile	Internet Global Data Set
24	Normalized Differential Vegetation Index (NDVI) maps	ESRI Grid file	Internet Global Data Set
25	Locations of river gauging stations	ESRI Shapefile	

ID	Data Set Description	Data Type	Source
26	Locations of met stations	ESRI Shapefile	

Table D-17: Published Maps

Map Description
Highest monthly values of recorded for air temperature July
Highest monthly values of recorded for air temperature October
Highest monthly values of recorded for air temperature December
Mean monthly amount of precipitation June
Mean monthly amount of precipitation October
Mean monthly amount of precipitation December
Mean amount of daily relative humidity July
Mean amount of daily relative humidity October
Mean amount of daily relative humidity December
Soil map of Egypt
Map of Wadi Halfa
Map of Cairo
Map of Nile Delta

E. FINAL WORKSHOP

ENTRO
EASTERN NILE TECHNICAL REGIONAL OFFICE

DRAFT AGENDA FOR FINAL FLOOD RISK MAPPING INCEPTION WORKSHOP

BAHIR DAR, ETHIOPIA

DAY ONE - October 15, 2009

TIME	AGENDA ITEM	ISSUES FOR CONSIDERATION/DISCUSSION
8:30-9:00	**Introductions**	
9:00-10:30	**Study Background, Objectives** **Overall Approach** Methodology Study team Status of project	
10:30-Lunch	**Topographic Survey** Proposed/final survey locations Methods **Terrain Model Development** Source DEM Channel topography definition Integration with DEM	90 vs. 30 meter DEM quality Scale, resolution, consistency
1:00-2:00	**Hydrologic Frequency Analysis** Frequency distributions Results	Reliability of source data
2:00-3:00	**Hydrologic Simulation** Inputs and assumptions Results Frequency analysis comparison	
3:00-5:00	**Hydraulic Model Development** Cross section extraction Roughness coefficients Evaluation of flow paths and extents **Hydraulic Model Results** Frequency profiles Extent of flooding	Terrain/Cross section representation Roughness sensitivity Downstream boundary sensitivity DEM resolution and flow path identification Unsteady flow considerations Areas of confined flow, floodplain flow, and significant impact

*A break will be taken in the morning, for lunch, and in the afternoon

ENTRO
EASTERN NILE TECHNICAL REGIONAL OFFICE

DRAFT AGENDA FOR FINAL FLOOD RISK MAPPING INCEPTION WORKSHOP

BAHIR DAR, ETHIOPIA

DAY ONE - October 15, 2009

TIME	AGENDA ITEM	ISSUES FOR CONSIDERATION/DISCUSSION
8:30 – 9:00	**Review, informal discussions**	
9:00-10:30	**Flood Hazard mapping**	Interpreting hazard maps; limitations of velocity mapping
10:30-Lunch	**Infrastructure/Asset Mapping** Structures Transportation infrastructure Agriculture	
1:00-3:00	**Risk Assessment** Economic analysis Vulnerability mapping Risk Mapping	Damage as a function of depth only Sources of uncertainty
3:00-4:30	**Recommendations** **Deliverables** Final report notes Maps Models Software	Details of Maps: • Hardcopy and digital formats • use of multi-color overlays • Scales • Background Topographic Maps • Infrastructure representation
4:30-5:00	**Workshop Conclusion**	Present and respond to comments and issues raised during the workshop; Review plans for project completion

*A break will be taken in the morning, for lunch, and in the afternoon

Meeting Description: ENTRO Flood Risk Mapping Workshop, Bahir Dar, Ethiopia

Project: ENTRO-FRM Ethiopia

Date: 2009-10-15,16 ***Time:*** All Day

Location/meeting type: Papyrus Hotel, Bahir Dar, Ethiopia

Participants

Riverside, Tropics, Shebelle, ENTRO, MOWR, ORDR, AAU, others

Agenda

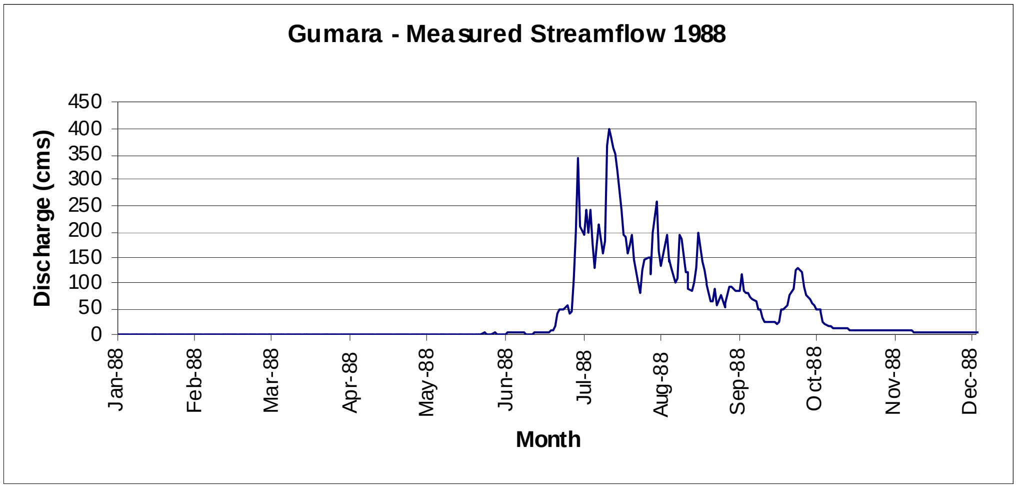
Notes

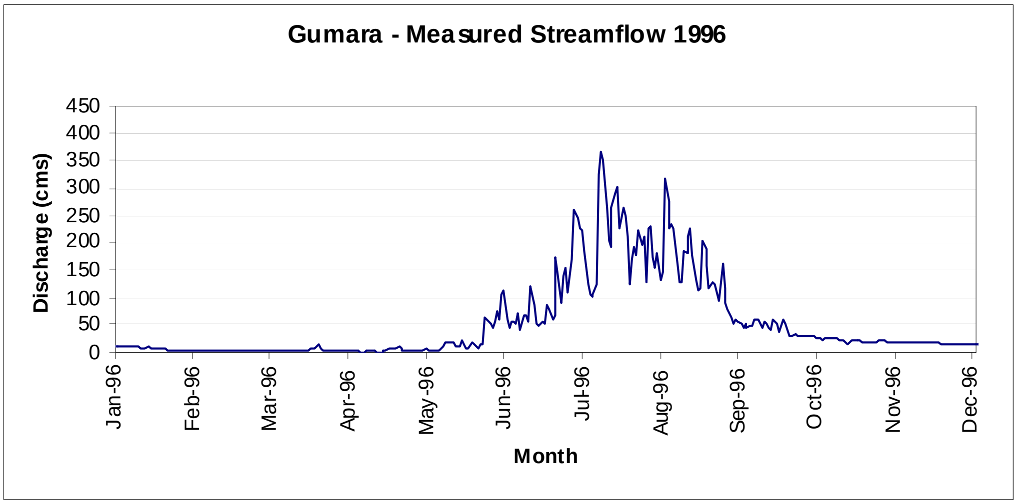
1. Participants noted that it seems that if a 30 meter DEM is available, it should be better than a 90 meter DEM. We note that currently available 30 meter DEM for the Lake Tana region is a new product derived from new technologies. It has not been adequately quality assured, and in fact exhibits many errors that make its use unacceptable for this project at the present time. The 90 meter DEM has been shown to have good correlation with ground survey data and has been further manipulated to conform to ground survey observations.
2. Land use and land management can have important impacts on hydrologic response, include sediment load of streams as well as the response time of the basins. Neither the frequency analysis nor the hydrologic simulation model explicitly incorporate land management practices, although planned or actual land management could be represented in subsequent hydrologic simulation by applying hydrologic judgment to the analysis.
3. Control points and benchmarks that were established or identified during the field survey need to be clearly documented and presented in the report, including a map on which the locations are identified. Complete survey data should be made available.
4. Dykes identified during the survey are often byproducts of dredging operations in a channel that are meant primarily to increase channel conveyance capacity and have the secondary effect of containing the river flow until their capacity is exceeded. This should be properly considered in the study.
5. MOWR has cross section information at gaging stations obtained during the flow measurement that could be compared with the survey performed for this study. Availability of control point information from this study should permit subsequent surveys to be able to tie these cross sections (as well as the gaging station datum) directly to the study survey and the resulting hydraulic model.
6. It will be important to record in the report the standards that were applied to the survey for this study, how they relate to the adjustment of the DEM, and how future surveys can be related to this survey.
7. The contours on 1:50,000 scale maps contain information that could be compared with the DEM.
8. Showing the proposed survey locations together with the actual survey points highlights potential differences in expectation between the hydraulic modeling team and the survey team. It also documents the realities of the execution of the project and may be helpful for planning subsequent efforts.
9. The flood history section of the report contains some information regarding the principal causes of flooding around Lake Tana that needs to be corrected.
10. It would be helpful if the report described lessons learned from the survey.
11. Local regional experts are an important source knowledge and experience in the study area.
12. The figures (numbers) related to damage and consequences of floods found in the flood history section of the report should be consistent with those maintained by local authorities.

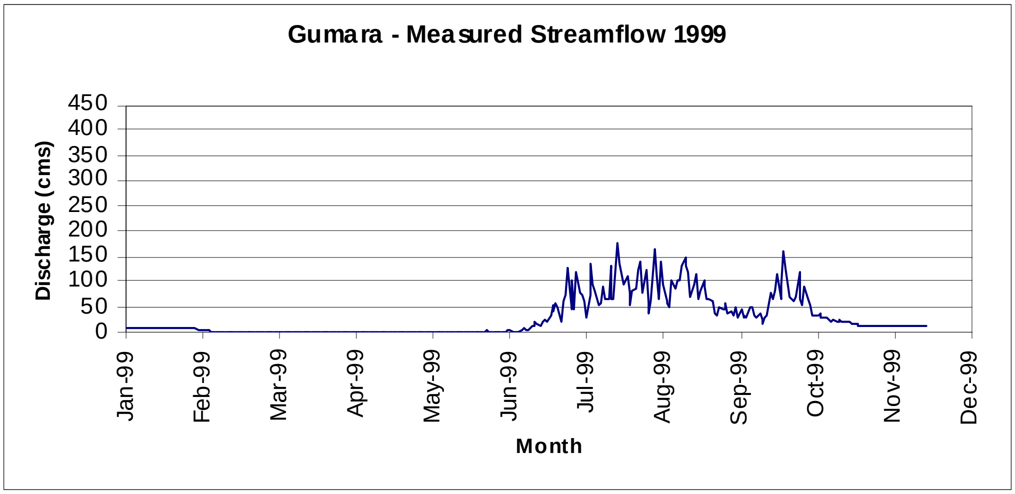
13. The background section of the report would benefit from including more reference to the local context of the Lake Tana region.
14. The hydrologic model may benefit by applying a larger areal reduction factor for precipitation for the larger catchments (Gumera and Rib). It would be interesting to compare hydrologic model response using the SCS unit hydrograph method.
15. Intensity-Duration-Frequency curves that were taken from the ERA may be conservative.
16. Reported figures for the area at each gage are not consistent with previous reported values. The area reported for the Rib appears incorrect.
17. The characterization of floods for this study has focused on peak flows. It has been observed that volume (as represented in the shape of the runoff hydrograph) also can be a factor in determining flood damage. The hydrologic simulation model developed for this study may be a valuable tool in further enhancing the understanding of the nature and consequences of floods in the region and individually for each river. This may include analysis of runoff simulated from historic precipitation in addition to the frequency based design storms used in this study.
18. The uncertainties and lack of confidence that have been reported regarding the streamflow data invite a response and recommendations about how to improve the data.
19. It is challenging (and perhaps a weakness of the study) that we are developing results based on inputs drawn from a variety of data sources whose purposes differ from one another, as well as differing from the purposes of our study.
20. Regarding the correlation between frequency flows and frequency lake levels, it would at least be helpful to describe the limits of lake level impact based on the hydraulic model results.
21. Lake level trends will be changing in the future as a function of downstream hydropower development and upstream reservoir construction, so lake level frequency needs to be understood in that context.
22. It would be interesting to see the temporal trends that are observed in flood frequency and severity over the past several decades. This study attempts to describe the current flood risk, as a “snapshot” in time, using a methodology that allows updating of this estimate based on future conditions. As a result, this study has reviewed reported trends, but does not contain information that actively adds to that narrative.
23. The downstream boundary might be defined at a corresponding frequency level as an upper bound, or at an average annual level for the month during which people are most affected.
24. In addition to direct economic damages, there are secondary economic impacts as well as social and environmental impacts that can be very significant. These were not considered in the study, but methods could be developed to add these characteristics to the analysis.
25. The methodology allows for infrastructure to be updated based on available areal photos or other sources of infrastructure information. This would improve the economic analysis basis, which is the 1:50,000 scale maps.
26. GIS maps available from WaterWatch might have been useful for this study. The GIS layers that we were able to obtain were of value for general review but did not contain data of a form that could be used directly in the analysis.
27. Are the damages a lower bound or upper bound?
28. Population data are available by Kebele – various approaches for spatial representation and analysis
29. What about animals? Impact of loss of agricultural production on animal food supply and health.
30. Need to add additional kebele boundaries
31. Central floodplain inundation not shown on map. Three sources of flooding – lake, local runoff, river overflows. Various ways to represent, some simple, some complex.
32. Community planning is a vital follow-on piece.
33. Potential uses include planning and operations

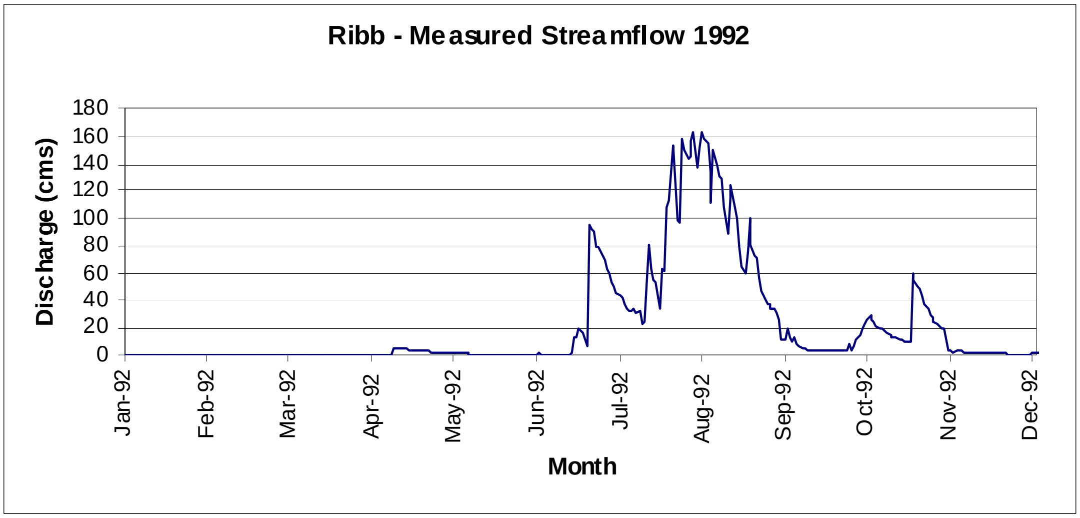
34. Dams, watershed management programs, and irrigation projects will have impacts.
35. Maps could prioritize evacuation
36. Impact of a hypothetical dam failure should be evaluated.
37. Consolidate similar comments
38. The weir at the outlet of Lake Tana needs to be tied to the control points

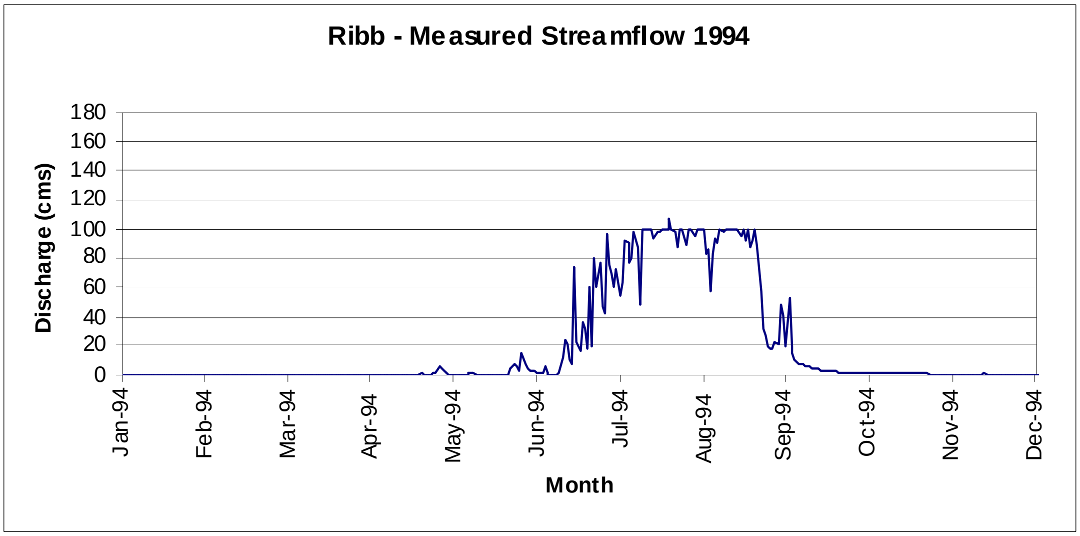
F. EXAMPLE ANNUAL HYDROGRAPHS

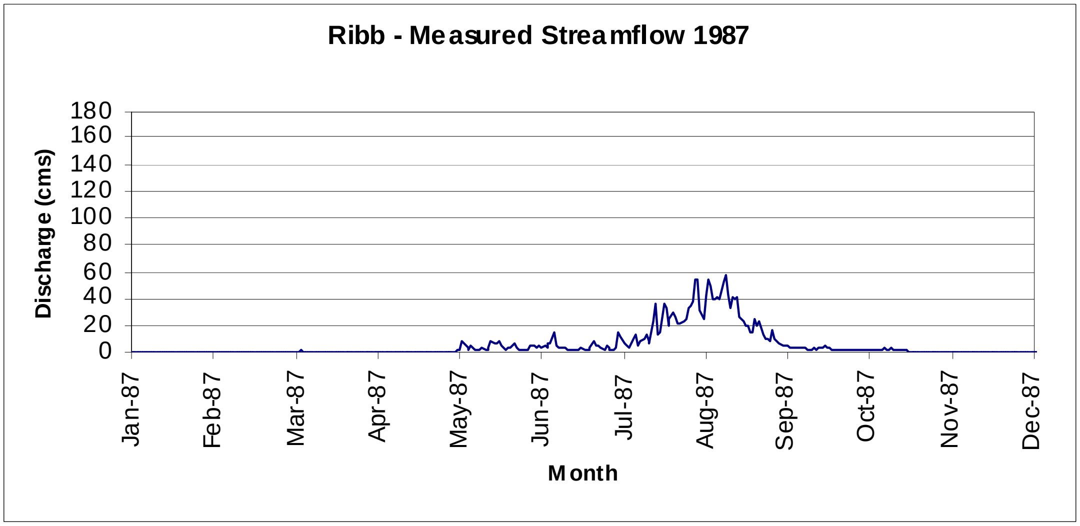


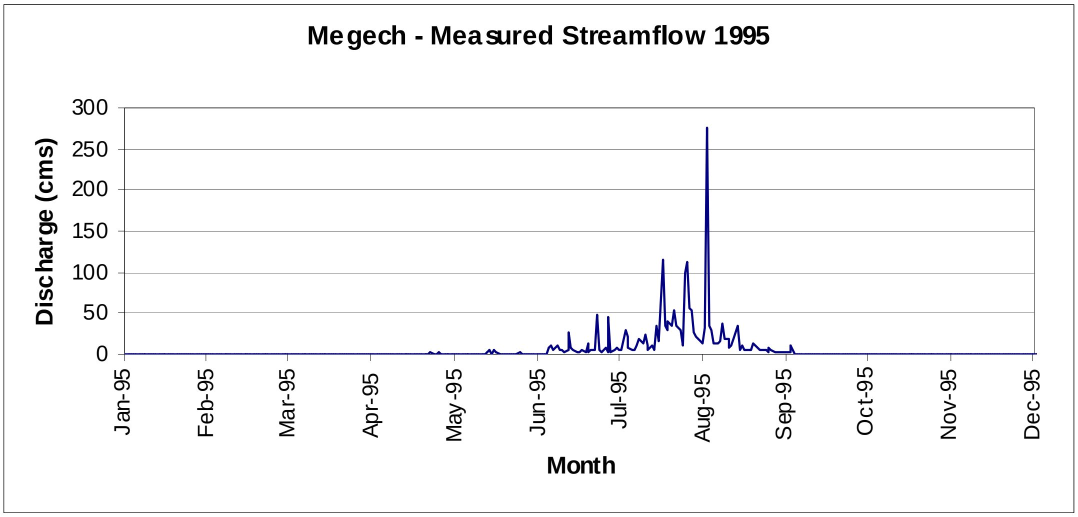


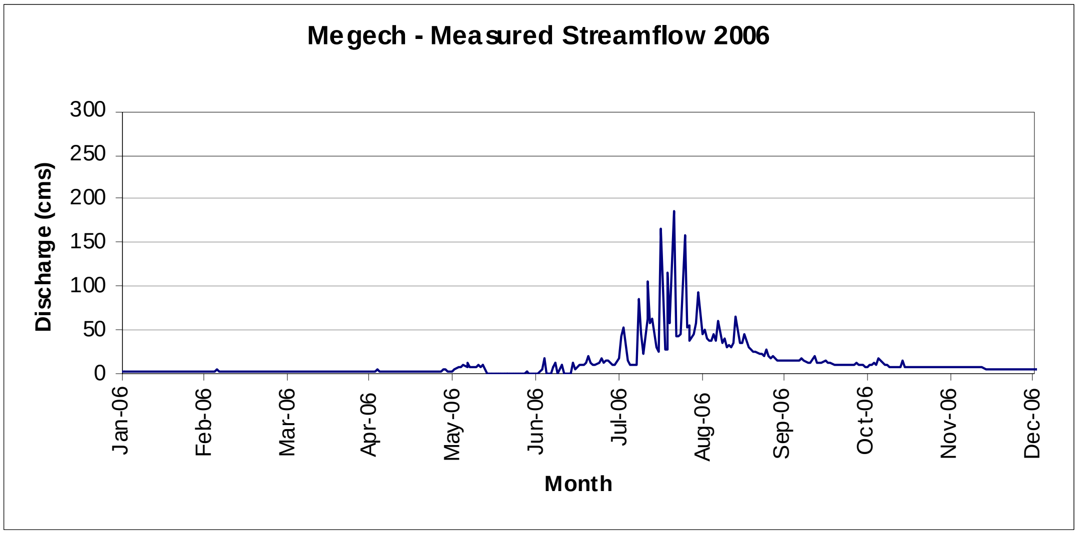


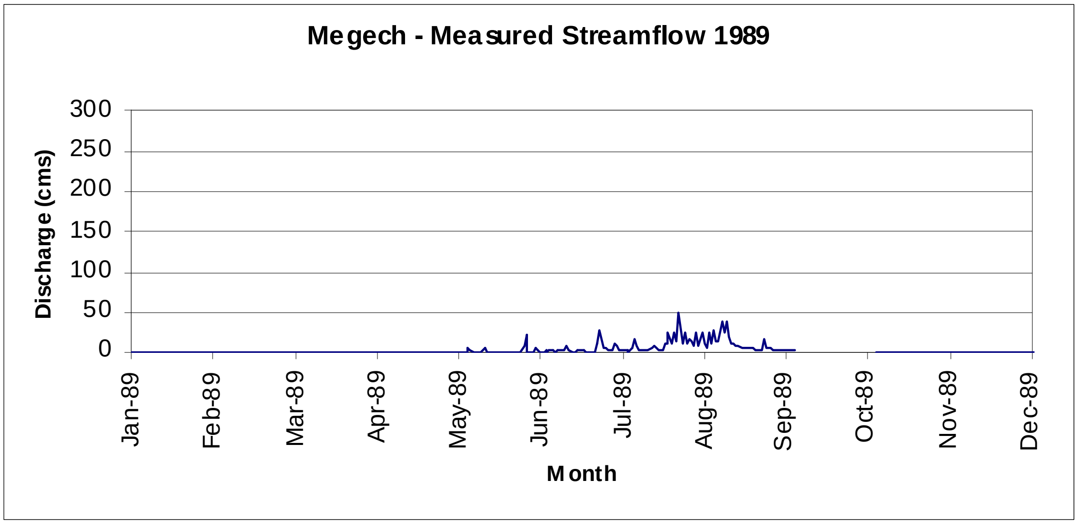

Ribb - Measured Streamflow 1992
Discharge (cms)
180
160
140
120
100
80
60
40
20
0
Jan-92
Feb-92
Mar-92
Apr-92
May-92
Jun-92
Jul-92
Aug-92
Sep-92
Oct-92
Nov-92
Dec-92
Month


Ribb - Measured Streamflow 1994
Discharge (cms)
180
160
140
120
100
80
60
40
20
0
Jan-94
Feb-94
Mar-94
Apr-94
May-94
Jun-94
Jul-94
Aug-94
Sep-94
Oct-94
Nov-94
Dec-94
Month

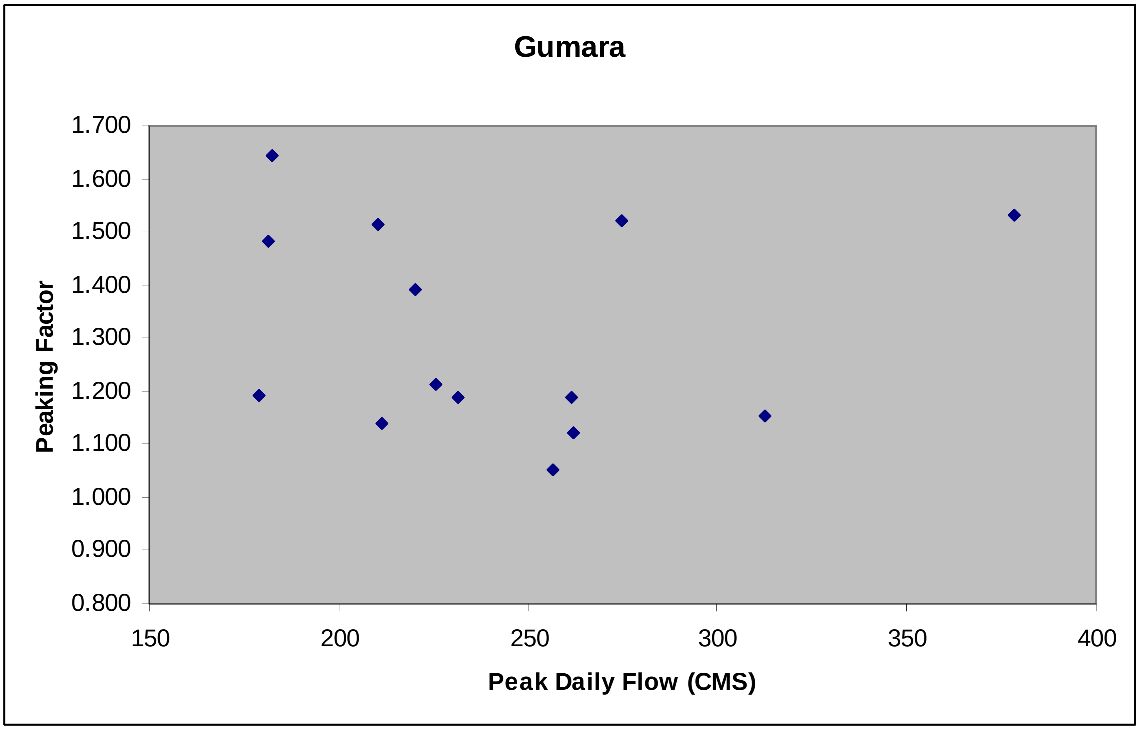

Ribb - Measured Streamflow 1987
Discharge (cms)
180
160
140
120
100
80
60
40
20
0
Jan-87
Feb-87
Mar-87
Apr-87
May-87
Jun-87
Jul-87
Aug-87
Sep-87
Oct-87
Nov-87
Dec-87
Month

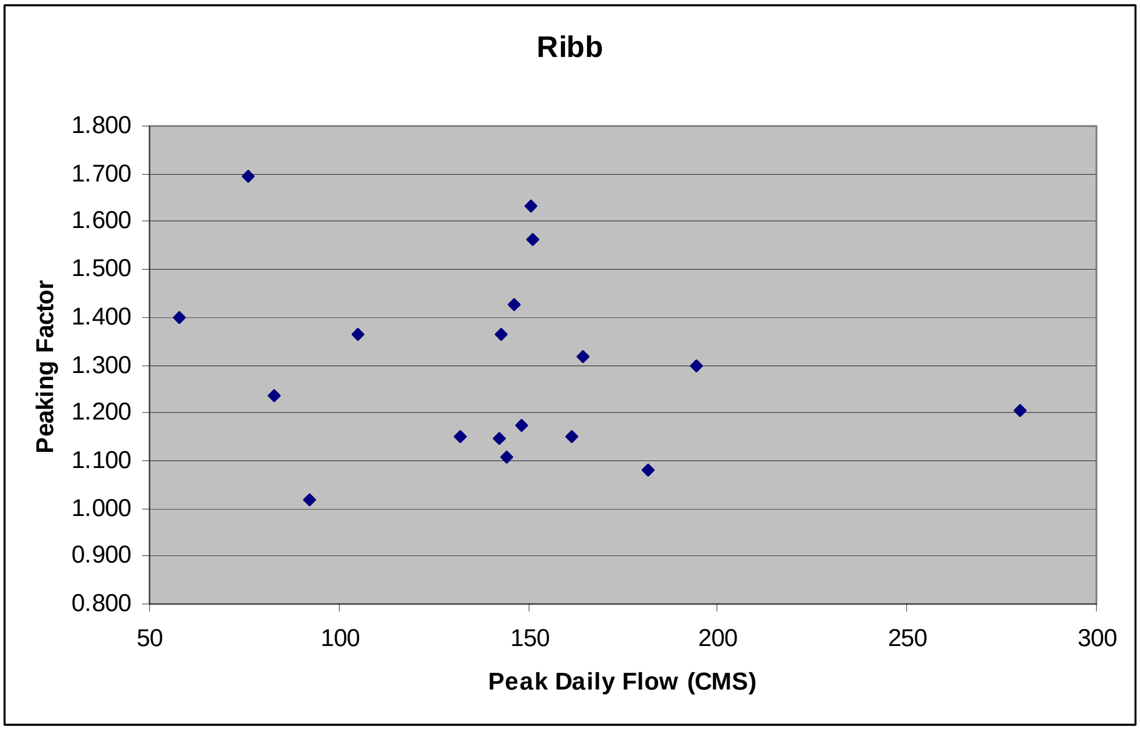

Megech - Measured Streamflow 1995
Discharge (cms)
300
250
200
150
100
50
0
Jan-95
Feb-95
Mar-95
Apr-95
May-95
Jun-95
Jul-95
Aug-95
Sep-95
Oct-95
Nov-95
Dec-95
Month

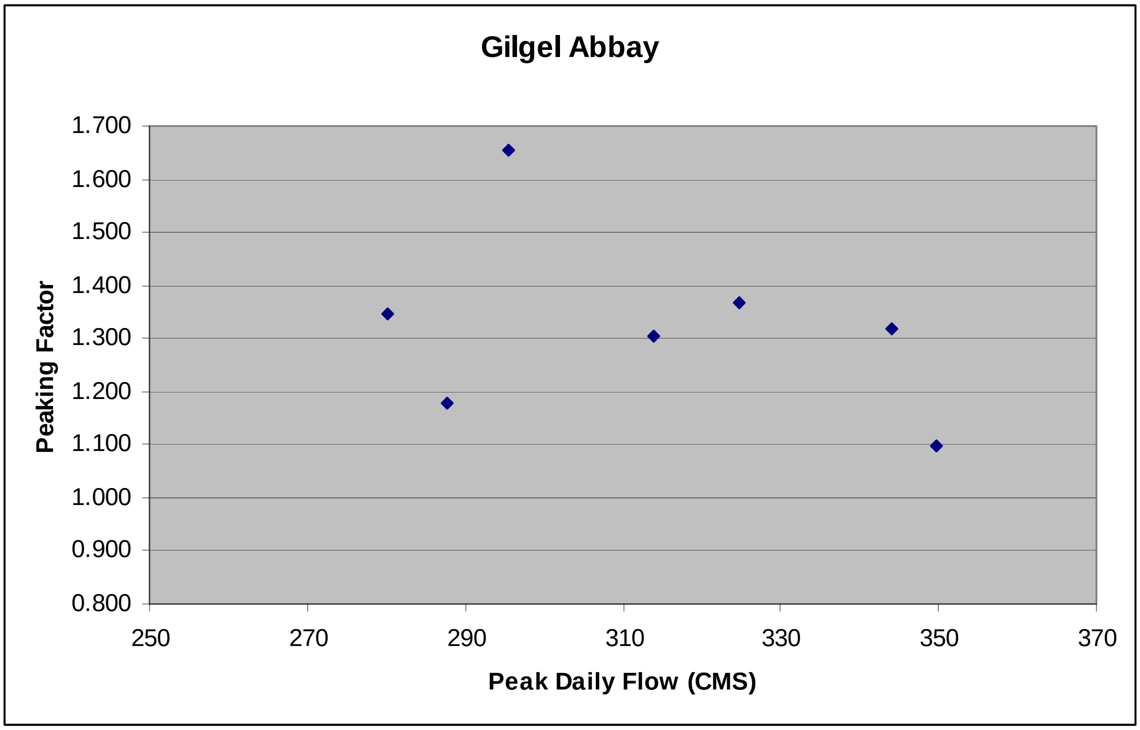

Megech - Measured Streamflow 2006
Discharge (cms)
300
250
200
150
100
50
0
Jan-06
Feb-06
Mar-06
Apr-06
May-06
Jun-06
Jul-06
Aug-06
Sep-06
Oct-06
Nov-06
Dec-06
Month

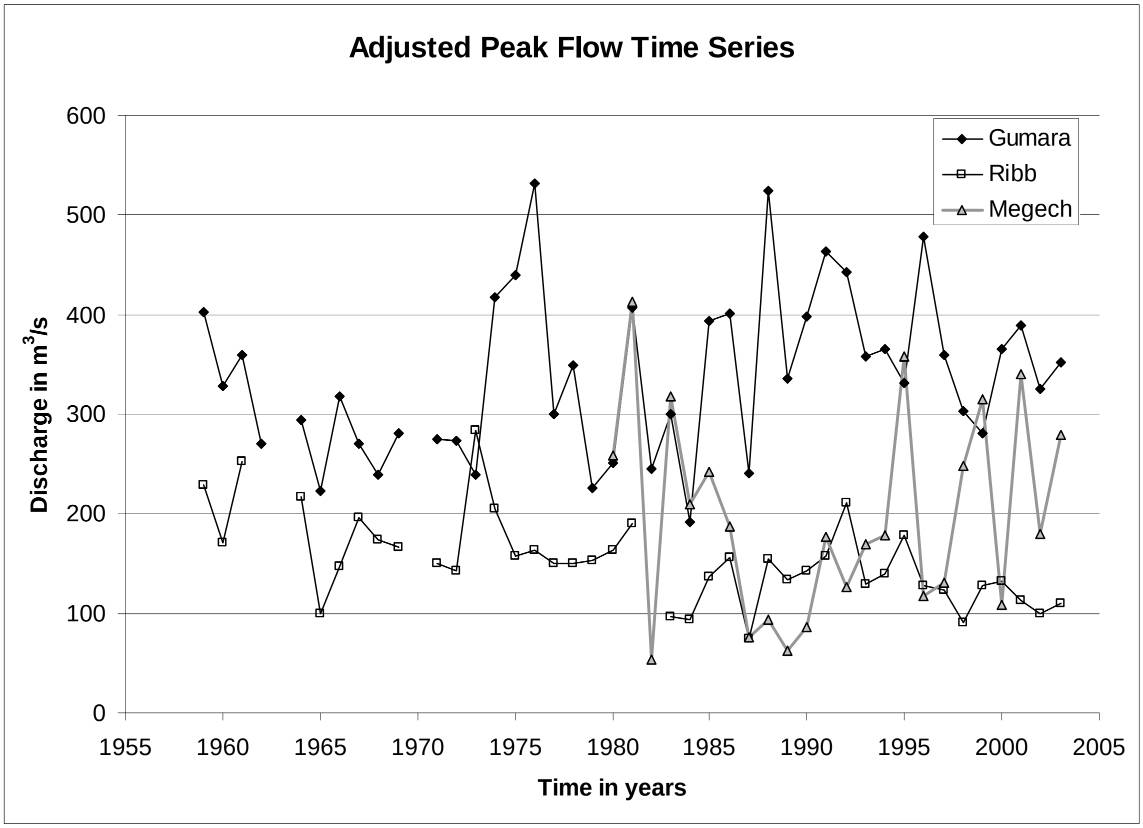

Megech - Measured Streamflow 1989
Discharge (cms)
300
250
200
150
100
50
0
Jan-89
Feb-89
Mar-89
Apr-89
May-89
Jun-89
Jul-89
Aug-89
Sep-89
Oct-89
Nov-89
Dec-89
Month

G. PEAKING FACTOR PLOTS AND FINAL ADJUSTED PEAK FLOW TIME SERIES






Gilgel Abbay
Peaking Factor
1.700
1.600
1.500
1.400
1.300
1.200
1.100
1.000
0.900
0.800
250
270
290
310
330
350
370
Peak Daily Flow (CMS)


Adjusted Peak Flow Time Series
Discharge in m^3/s
600
500
400
300
200
100
0
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Time in years
Gumara
Ribb
Megech

H. PEAKFQ OUTPUT FILE

```
   Program PeakFq           U.  S.  GEOLOGICAL SURVEY             Seq.000.000

  Ver.  5.2            Annual peak flow frequency analysis      Run Date / Time
  11/01/2007          following Bulletin 17-B Guidelines       09/24/2009 11:11

                         --- PROCESSING OPTIONS ---

                      Plot option         = Graphics device
                      Basin char output   = None
                      Print option        = Yes
                      Debug print         = No
                      Input peaks listing = Long
                      Input peaks format  = WATSTORE peak file

                      Input files used:
                         peaks (ascii)  - C:\DOCUMENTS AND SETTINGS\CAL\MY
DOCUMENTS\ETHIOPIA\PEAKFQ\FLOWSATGAGES.INP
                         specifications - PKFQWPSF.TMP
                      Output file(s):
                         main - C:\DOCUMENTS AND SETTINGS\CAL\MY
DOCUMENTS\ETHIOPIA\PEAKFQ\FLOWSATGAGES.PRT


  Program PeakFq           U.  S.  GEOLOGICAL SURVEY             Seq.001.001
  Ver.  5.2            Annual peak flow frequency analysis      Run Date / Time
  11/01/2007          following Bulletin 17-B Guidelines       09/24/2009 11:11

                   Station - 00111007  MEGECH RIVER NR AZEZO


                     I N P U T   D A T A   S U M M A R Y

                Number of peaks in record            =       24
                Peaks not used in analysis           =        0
                Systematic peaks in analysis         =       24
                Historic peaks in analysis           =        0
                Years of historic record             =        0
                Generalized skew                     =   -0.023
                     Standard error                  =    0.550
                     Mean Square error               =    0.303
                Skew option                          = STATION SKEW
                Gage base discharge                  =      0.0
                User supplied high outlier threshold =   --
                User supplied low outlier criterion  =   --
                Plotting position parameter          =     0.00



  *********  NOTICE  --  Preliminary machine computations.        *********
  *********  User responsible for assessment and interpretation.  *********

    WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                   0.0
    WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.             41.0
    WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.       705.3
   *WCF151I-17B WEIGHTED SKEW REPLACED BY USER OPTION.    -0.228    -0.391  -1
1


  Program PeakFq           U.  S.  GEOLOGICAL SURVEY             Seq.001.002
  Ver.  5.2            Annual peak flow frequency analysis      Run Date / Time
  11/01/2007          following Bulletin 17-B Guidelines       09/24/2009 11:11
```

```
                   Station - 00111007  MEGECH RIVER NR AZEZO


           ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                        FLOOD BASE                   LOGARITHMIC
                  ----------------------  -------------------------------
                             EXCEEDANCE                 STANDARD
                   DISCHARGE PROBABILITY    MEAN    DEVIATION    SKEW
                  -------------------------------------------------------
 SYSTEMATIC RECORD       0.0     1.0000     2.2306     0.2504     -0.391
 BULL.17B ESTIMATE       0.0     1.0000     2.2306     0.2504     -0.391



    ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

      ANNUAL                              'EXPECTED   95-PCT CONFIDENCE LIMITS
   EXCEEDANCE     BULL.17B    SYSTEMATIC PROBABILITY'  FOR BULL.  17B ESTIMATES
   PROBABILITY    ESTIMATE      RECORD     ESTIMATE        LOWER        UPPER

      0.9950         31.2         31.2         24.8         17.3         45.4
      0.9900         37.8         37.8         31.8         22.2         53.2
      0.9500         62.0         62.0         57.6         42.0         80.8
      0.9000         79.6         79.6         76.2         57.4        100.4
      0.8000        106.2        106.2        103.9         81.6        130.2
      0.6667        137.0        137.0        135.8        109.9        166.3
      0.5000        176.6        176.6        176.6        144.9        216.1
      0.4292        195.3        195.3        195.9        160.8        241.3
      0.2000        278.4        278.4        283.2        226.6        363.8
      0.1000        346.1        346.1        357.1        276.0        474.4
      0.0400        430.1        430.1        453.3        333.8        622.3
      0.0200        490.9        490.9        527.0        373.9        735.7
      0.0100        550.0        550.0        602.1        411.9        850.5
      0.0050        607.8        607.8        679.2        448.2        966.5
      0.0020        682.3        682.3        784.3        493.9       1121.0
1

  Program PeakFq           U.  S.  GEOLOGICAL SURVEY             Seq.001.003
  Ver.  5.2          Annual peak flow frequency analysis       Run Date / Time
  11/01/2007        following Bulletin 17-B Guidelines       09/24/2009 11:11

                   Station - 00111007  MEGECH RIVER NR AZEZO


                       I N P U T   D A T A   L I S T I N G


     WATER YEAR    DISCHARGE   CODES      WATER YEAR    DISCHARGE   CODES

        1980          259.0                    1992          126.0
        1981          413.0                    1993          169.0
        1982           54.0                    1994          178.0
        1983          317.0                    1995          357.0
        1984          209.0                    1996          117.0
        1985          242.0                    1997          130.0
        1986          187.0                    1998          248.0
        1987           75.0                    1999          315.0
        1988           94.0                    2000          109.0
```

```
        1989          62.0                    2001          339.0
        1990          86.0                    2002          179.0
        1991         177.0                    2003          279.0


        Explanation of peak discharge qualification codes

       PeakFQ    NWIS
        CODE     CODE   DEFINITION

          D        3    Dam failure, non-recurrent flow anomaly
          G        8    Discharge greater than stated value
          X       3+8   Both of the above
          L        4    Discharge less than stated value
          K      6 OR C Known effect of regulation or urbanization
          H        7    Historic peak

          -  Minus-flagged discharge -- Not used in computation
                -8888.0 -- No discharge value given
          -  Minus-flagged water year -- Historic peak used in computation



1


  Program PeakFq           U.  S.  GEOLOGICAL SURVEY            Seq.001.004
  Ver.  5.2             Annual peak flow frequency analysis      Run Date / Time
  11/01/2007           following Bulletin 17-B Guidelines       09/24/2009 11:11

                    Station - 00111007  MEGECH RIVER NR AZEZO


   EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

      WATER          RANKED       SYSTEMATIC      BULL.17B
       YEAR        DISCHARGE        RECORD        ESTIMATE

       1981          413.0         0.0400         0.0400
       1995          357.0         0.0800         0.0800
       2001          339.0         0.1200         0.1200
       1983          317.0         0.1600         0.1600
       1999          315.0         0.2000         0.2000
       2003          279.0         0.2400         0.2400
       1980          259.0         0.2800         0.2800
       1998          248.0         0.3200         0.3200
       1985          242.0         0.3600         0.3600
       1984          209.0         0.4000         0.4000
       1986          187.0         0.4400         0.4400
       2002          179.0         0.4800         0.4800
       1994          178.0         0.5200         0.5200
       1991          177.0         0.5600         0.5600
       1993          169.0         0.6000         0.6000
       1997          130.0         0.6400         0.6400
       1992          126.0         0.6800         0.6800
       1996          117.0         0.7200         0.7200
       2000          109.0         0.7600         0.7600
       1988           94.0         0.8000         0.8000
       1990           86.0         0.8400         0.8400
       1987           75.0         0.8800         0.8800
       1989           62.0         0.9200         0.9200
```

```
       1982           54.0         0.9600         0.9600
1


  Program PeakFq           U.  S.  GEOLOGICAL SURVEY             Seq.002.001
  Ver.  5.2            Annual peak flow frequency analysis      Run Date / Time
  11/01/2007          following Bulletin 17-B Guidelines       09/24/2009 11:11

                 Station - 00111005  RIBB RIVER NR ADDIS ZEMEN


                     I N P U T   D A T A   S U M M A R Y

                Number of peaks in record            =        41
                Peaks not used in analysis           =         0
                Systematic peaks in analysis         =        41
                Historic peaks in analysis           =         0
                Years of historic record             =         0
                Generalized skew                     =    -0.023
                     Standard error                  =     0.550
                     Mean Square error               =     0.303
                Skew option                          = STATION SKEW
                Gage base discharge                  =       0.0
                User supplied high outlier threshold =    --
                User supplied low outlier criterion  =    --
                Plotting position parameter          =      0.00



  *********  NOTICE  --  Preliminary machine computations.        *********
  *********  User responsible for assessment and interpretation.  *********

    WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                    0.0
    WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.              68.5
    WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.        317.4
   *WCF151I-17B WEIGHTED SKEW REPLACED BY USER OPTION.    -0.054    -0.068  -1
1


  Program PeakFq           U.  S.  GEOLOGICAL SURVEY             Seq.002.002
  Ver.  5.2            Annual peak flow frequency analysis      Run Date / Time
  11/01/2007          following Bulletin 17-B Guidelines       09/24/2009 11:11

                 Station - 00111005  RIBB RIVER NR ADDIS ZEMEN


           ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                        FLOOD BASE                   LOGARITHMIC
                  ----------------------  --------------------------------
                             EXCEEDANCE                STANDARD
                   DISCHARGE PROBABILITY     MEAN     DEVIATION     SKEW
                  --------------------------------------------------------
 SYSTEMATIC RECORD       0.0     1.0000     2.1686      0.1237     -0.068
 BULL.17B ESTIMATE       0.0     1.0000     2.1686      0.1237     -0.068



    ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

      ANNUAL                              'EXPECTED   95-PCT CONFIDENCE LIMITS
```

```
   EXCEEDANCE     BULL.17B    SYSTEMATIC PROBABILITY'  FOR BULL.  17B ESTIMATES
   PROBABILITY     ESTIMATE      RECORD     ESTIMATE       LOWER        UPPER

      0.9950         69.5         69.5         66.2         57.6         79.6
      0.9900         74.9         74.9         72.1         63.1         84.9
      0.9500         91.8         91.8         90.2         80.3        101.5
      0.9000        102.2        102.2        101.0         91.1        111.7
      0.8000        116.1        116.1        115.5        105.5        125.7
      0.6667        130.8        130.8        130.5        120.5        140.8
      0.5000        147.9        147.9        147.9        137.3        159.4
      0.4292        155.6        155.6        155.7        144.6        168.1
      0.2000        187.6        187.6        188.6        173.3        206.4
      0.1000        212.0        212.0        214.2        193.9        237.6
      0.0400        241.2        241.2        245.7        217.7        276.5
      0.0200        261.9        261.9        268.8        234.1        305.1
      0.0100        282.0        282.0        291.8        249.8        333.2
      0.0050        301.6        301.6        315.0        264.8        361.2
      0.0020        327.0        327.0        346.1        284.0        398.1
1


  Program PeakFq           U.  S.  GEOLOGICAL SURVEY            Seq.002.003
  Ver.  5.2            Annual peak flow frequency analysis      Run Date / Time
  11/01/2007          following Bulletin 17-B Guidelines       09/24/2009 11:11

                 Station - 00111005  RIBB RIVER NR ADDIS ZEMEN


                       I N P U T   D A T A   L I S T I N G


     WATER YEAR    DISCHARGE   CODES      WATER YEAR    DISCHARGE   CODES

        1959          229.0                  1984            94.0
        1960          170.0                  1985           137.0
        1961          253.0                  1986           156.0
        1964          216.0                  1987            75.0
        1965           99.0                  1988           155.0
        1966          147.0                  1989           134.0
        1967          196.0                  1990           142.0
        1968          174.0                  1991           157.0
        1969          167.0                  1992           212.0
        1971          150.0                  1993           130.0
        1972          143.0                  1994           140.0
        1973          283.0                  1995           178.0
        1974          205.0                  1996           128.0
        1975          157.0                  1997           123.0
        1976          164.0                  1998            91.0
        1977          149.0                  1999           128.0
        1978          149.0                  2000           132.0
        1979          154.0                  2001           113.0
        1980          164.0                  2002           100.0
        1981          189.0                  2003           109.0
        1983           96.0


        Explanation of peak discharge qualification codes

       PeakFq    NWIS
        CODE     CODE   DEFINITION
```

```
          D        3    Dam failure, non-recurrent flow anomaly
          G        8    Discharge greater than stated value
          X       3+8   Both of the above
          L        4    Discharge less than stated value
          K      6 OR C  Known effect of regulation or urbanization
          H        7    Historic peak

          -  Minus-flagged discharge -- Not used in computation
                -8888.0 -- No discharge value given
          -  Minus-flagged water year -- Historic peak used in computation



1


  Program PeakFq            U.  S.  GEOLOGICAL SURVEY             Seq.002.004
  Ver.  5.2             Annual peak flow frequency analysis      Run Date / Time
  11/01/2007           following Bulletin 17-B Guidelines       09/24/2009 11:11

                 Station - 00111005  RIBB RIVER NR ADDIS ZEMEN


   EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

      WATER          RANKED       SYSTEMATIC      BULL.17B
       YEAR        DISCHARGE        RECORD        ESTIMATE

       1973           283.0          0.0238         0.0238
       1961           253.0          0.0476         0.0476
       1959           229.0          0.0714         0.0714
       1964           216.0          0.0952         0.0952
       1992           212.0          0.1190         0.1190
       1974           205.0          0.1429         0.1429
       1967           196.0          0.1667         0.1667
       1981           189.0          0.1905         0.1905
       1995           178.0          0.2143         0.2143
       1968           174.0          0.2381         0.2381
       1960           170.0          0.2619         0.2619
       1969           167.0          0.2857         0.2857
       1976           164.0          0.3095         0.3095
       1980           164.0          0.3333         0.3333
       1975           157.0          0.3571         0.3571
       1991           157.0          0.3810         0.3810
       1986           156.0          0.4048         0.4048
       1988           155.0          0.4286         0.4286
       1979           154.0          0.4524         0.4524
       1971           150.0          0.4762         0.4762
       1977           149.0          0.5000         0.5000
       1978           149.0          0.5238         0.5238
       1966           147.0          0.5476         0.5476
       1972           143.0          0.5714         0.5714
       1990           142.0          0.5952         0.5952
       1994           140.0          0.6190         0.6190
       1985           137.0          0.6429         0.6429
       1989           134.0          0.6667         0.6667
       2000           132.0          0.6905         0.6905
       1993           130.0          0.7143         0.7143
       1996           128.0          0.7381         0.7381
       1999           128.0          0.7619         0.7619
       1997           123.0          0.7857         0.7857
```

```
       2001          113.0         0.8095         0.8095
       2003          109.0         0.8333         0.8333
       2002          100.0         0.8571         0.8571
       1965           99.0         0.8810         0.8810
       1983           96.0         0.9048         0.9048
       1984           94.0         0.9286         0.9286
       1998           91.0         0.9524         0.9524
       1987           75.0         0.9762         0.9762
1


  Program PeakFq           U.  S.  GEOLOGICAL SURVEY             Seq.003.001
  Ver.  5.2            Annual peak flow frequency analysis      Run Date / Time
  11/01/2007          following Bulletin 17-B Guidelines       09/24/2009 11:11

                 Station - 00111006  GUMARA RIVER NR BAHIR DAR


                     I N P U T   D A T A   S U M M A R Y

                Number of peaks in record            =       43
                Peaks not used in analysis           =        0
                Systematic peaks in analysis         =       43
                Historic peaks in analysis           =        0
                Years of historic record             =        0
                Generalized skew                     =   -0.023
                     Standard error                  =    0.550
                     Mean Square error               =    0.303
                Skew option                          = STATION SKEW
                Gage base discharge                  =      0.0
                User supplied high outlier threshold =   --
                User supplied low outlier criterion  =   --
                Plotting position parameter          =     0.00



  *********  NOTICE  --  Preliminary machine computations.        *********
  *********  User responsible for assessment and interpretation.  *********

    WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                   0.0
    WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.            169.8
    WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.       635.6
   *WCF151I-17B WEIGHTED SKEW REPLACED BY USER OPTION.    -0.038    -0.044  -1
1


  Program PeakFq           U.  S.  GEOLOGICAL SURVEY             Seq.003.002
  Ver.  5.2            Annual peak flow frequency analysis      Run Date / Time
  11/01/2007          following Bulletin 17-B Guidelines       09/24/2009 11:11

                 Station - 00111006  GUMARA RIVER NR BAHIR DAR


           ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                        FLOOD BASE                   LOGARITHMIC
                  ----------------------  -------------------------------
                             EXCEEDANCE                STANDARD
                   DISCHARGE PROBABILITY     MEAN     DEVIATION     SKEW
                  -------------------------------------------------------
 SYSTEMATIC RECORD       0.0     1.0000     2.5166      0.1057     -0.044
```

```
 BULL.17B ESTIMATE       0.0      1.0000      2.5166      0.1057     -0.044



    ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

      ANNUAL                                'EXPECTED   95-PCT CONFIDENCE LIMITS
   EXCEEDANCE     BULL.17B     SYSTEMATIC PROBABILITY'  FOR BULL.  17B ESTIMATES
   PROBABILITY    ESTIMATE        RECORD     ESTIMATE        LOWER         UPPER

      0.9950        173.7         173.7        167.1        148.8         194.4
      0.9900        185.0         185.0        179.5        160.4         205.3
      0.9500        219.5         219.5        216.4        196.5         238.6
      0.9000        240.2         240.2        238.1        218.3         258.8
      0.8000        267.8         267.8        266.6        247.3         286.1
      0.6667        296.3         296.3        295.7        276.7         315.1
      0.5000        329.1         329.1        329.1        309.3         350.3
      0.4292        343.7         343.7        344.0        323.3         366.5
      0.2000        403.5         403.5        405.3        377.7         437.0
      0.1000        448.3         448.3        452.2        416.2         493.1
      0.0400        501.3         501.3        509.1        460.0         561.9
      0.0200        538.6         538.6        550.3        490.1         611.7
      0.0100        574.3         574.3        590.8        518.5         660.2
      0.0050        609.0         609.0        631.3        545.7         708.1
      0.0020        653.6         653.6        685.2        580.3         770.7
1

  Program PeakFq           U.  S.  GEOLOGICAL SURVEY             Seq.003.003
  Ver.  5.2            Annual peak flow frequency analysis      Run Date / Time
  11/01/2007          following Bulletin 17-B Guidelines      09/24/2009 11:11

                 Station - 00111006  GUMARA RIVER NR BAHIR DAR

                            I N P U T   D A T A   L I S T I N G

     WATER YEAR    DISCHARGE   CODES      WATER YEAR    DISCHARGE   CODES

        1959         402.0                   1983         299.0
        1960         329.0                   1984         191.0
        1961         360.0                   1985         393.0
        1962         270.0                   1986         401.0
        1964         294.0                   1987         241.0
        1965         223.0                   1988         524.0
        1966         318.0                   1989         336.0
        1967         271.0                   1990         398.0
        1968         239.0                   1991         464.0
        1969         281.0                   1992         443.0
        1971         275.0                   1993         357.0
        1972         274.0                   1994         366.0
        1973         240.0                   1995         331.0
        1974         418.0                   1996         478.0
        1975         440.0                   1997         360.0
        1976         532.0                   1998         303.0
        1977         300.0                   1999         281.0
        1978         349.0                   2000         365.0
        1979         225.0                   2001         389.0
        1980         251.0                   2002         325.0
        1981         407.0                   2003         352.0
```

```
        1982          245.0


        Explanation of peak discharge qualification codes

       PeakFQ    NWIS
        CODE     CODE   DEFINITION

          D        3    Dam failure, non-recurrent flow anomaly
          G        8    Discharge greater than stated value
          X       3+8   Both of the above
          L        4    Discharge less than stated value
          K     6 OR C  Known effect of regulation or urbanization
          H        7    Historic peak

          -  Minus-flagged discharge -- Not used in computation
                -8888.0 -- No discharge value given
          -  Minus-flagged water year -- Historic peak used in computation



1


  Program PeakFq            U.  S.  GEOLOGICAL SURVEY             Seq.003.004
  Ver.  5.2             Annual peak flow frequency analysis      Run Date / Time
  11/01/2007           following Bulletin 17-B Guidelines       09/24/2009 11:11

                 Station - 00111006  GUMARA RIVER NR BAHIR DAR


   EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

      WATER         RANKED       SYSTEMATIC      BULL.17B
       YEAR        DISCHARGE       RECORD        ESTIMATE

       1976          532.0         0.0227         0.0227
       1988          524.0         0.0455         0.0455
       1996          478.0         0.0682         0.0682
       1991          464.0         0.0909         0.0909
       1992          443.0         0.1136         0.1136
       1975          440.0         0.1364         0.1364
       1974          418.0         0.1591         0.1591
       1981          407.0         0.1818         0.1818
       1959          402.0         0.2045         0.2045
       1986          401.0         0.2273         0.2273
       1990          398.0         0.2500         0.2500
       1985          393.0         0.2727         0.2727
       2001          389.0         0.2955         0.2955
       1994          366.0         0.3182         0.3182
       2000          365.0         0.3409         0.3409
       1961          360.0         0.3636         0.3636
       1997          360.0         0.3864         0.3864
       1993          357.0         0.4091         0.4091
       2003          352.0         0.4318         0.4318
       1978          349.0         0.4545         0.4545
       1989          336.0         0.4773         0.4773
       1995          331.0         0.5000         0.5000
       1960          329.0         0.5227         0.5227
       2002          325.0         0.5455         0.5455
       1966          318.0         0.5682         0.5682
```

```
      1998          303.0         0.5909         0.5909
      1977          300.0         0.6136         0.6136
      1983          299.0         0.6364         0.6364
      1964          294.0         0.6591         0.6591
      1969          281.0         0.6818         0.6818
      1999          281.0         0.7045         0.7045
      1971          275.0         0.7273         0.7273
      1972          274.0         0.7500         0.7500
      1967          271.0         0.7727         0.7727
      1962          270.0         0.7955         0.7955
      1980          251.0         0.8182         0.8182
      1982          245.0         0.8409         0.8409
      1987          241.0         0.8636         0.8636
      1973          240.0         0.8864         0.8864
      1968          239.0         0.9091         0.9091
      1979          225.0         0.9318         0.9318
      1965          223.0         0.9545         0.9545
      1984          191.0         0.9773         0.9773
1


  Program PeakFq          U.  S.  GEOLOGICAL SURVEY            Seq.004.001
  Ver.  5.2             Annual peak flow frequency analysis      Run Date / Time
  11/01/2007           following Bulletin 17-B Guidelines       09/24/2009 11:11

                       Station - 99999999  LAKE TANA LEVEL


                      I N P U T   D A T A   S U M M A R Y

                Number of peaks in record            =       40
                Peaks not used in analysis           =        0
                Systematic peaks in analysis         =       40
                Historic peaks in analysis           =        0
                Years of historic record             =        0
                Generalized skew                     =    0.229
                     Standard error                  =    0.550
                     Mean Square error               =    0.303
                Skew option                          = STATION SKEW
                Gage base discharge                  =      0.0
                User supplied high outlier threshold =   --
                User supplied low outlier criterion  =   --
                Plotting position parameter          =     0.00



  *********  NOTICE  --  Preliminary machine computations.        *********
  *********  User responsible for assessment and interpretation.  *********

    WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                    0.0
    WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.             264.6
    WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.        457.7
   *WCF151I-17B WEIGHTED SKEW REPLACED BY USER OPTION.     0.229     0.229  -1
1


  Program PeakFq          U.  S.  GEOLOGICAL SURVEY            Seq.004.002
  Ver.  5.2             Annual peak flow frequency analysis      Run Date / Time
  11/01/2007           following Bulletin 17-B Guidelines       09/24/2009 11:11

                       Station - 99999999  LAKE TANA LEVEL
```

```
          ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                        FLOOD BASE                LOGARITHMIC
                  ----------------------  -------------------------------
                            EXCEEDANCE              STANDARD
                   DISCHARGE PROBABILITY     MEAN    DEVIATION     SKEW
                  -------------------------------------------------------
 SYSTEMATIC RECORD       0.0      1.0000     2.5416      0.0444      0.229
 BULL.17B ESTIMATE       0.0      1.0000     2.5416      0.0444      0.229


    ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

      ANNUAL                                'EXPECTED   95-PCT CONFIDENCE LIMITS
   EXCEEDANCE     BULL.17B    SYSTEMATIC PROBABILITY'  FOR BULL.  17B ESTIMATES
   PROBABILITY    ESTIMATE       RECORD      ESTIMATE        LOWER         UPPER

      0.9950        273.4        273.4        269.7        256.9        286.1
      0.9900        279.2        279.2        276.1        263.4        291.3
      0.9500        296.2        296.2        294.6        282.6        306.9
      0.9000        306.1        306.1        305.1        293.8        316.1
      0.8000        319.0        319.0        318.4        308.1        328.3
      0.6667        332.0        332.0        331.7        322.1        341.0
      0.5000        346.7        346.7        346.7        337.4        356.1
      0.4292        353.1        353.1        353.2        343.8        363.0
      0.2000        378.8        378.8        379.6        368.1        392.1
      0.1000        397.6        397.6        399.3        384.9        414.7
      0.0400        419.4        419.4        422.8        403.7        441.7
      0.0200        434.6        434.6        439.7        416.4        460.9
      0.0100        449.0        449.0        456.1        428.4        479.3
      0.0050        462.8        462.8        472.4        439.8        497.2
      0.0020        480.5        480.5        494.0        454.2        520.3
1

  Program PeakFq           U. S.  GEOLOGICAL SURVEY             Seq.004.003
  Ver.  5.2              Annual peak flow frequency analysis      Run Date / Time
  11/01/2007            following Bulletin 17-B Guidelines      09/24/2009 11:11

                        Station - 99999999  LAKE TANA LEVEL


                         I N P U T   D A T A   L I S T I N G


     WATER YEAR    DISCHARGE   CODES      WATER YEAR    DISCHARGE   CODES

        1961          382.0                  1983          296.0
        1962          377.0                  1984          304.0
        1964          402.0                  1985          356.0
        1966          330.0                  1986          344.0
        1967          362.0                  1987          311.0
        1968          348.0                  1988          372.0
        1969          341.0                  1989          342.0
        1970          322.0                  1990          318.0
        1971          338.0                  1992          334.0
        1972          285.0                  1993          350.0
        1973          317.0                  1994          377.0
```

```
        1974          364.0                      1995          360.0
        1975          389.0                      1996          426.0
        1976          356.0                      1997          364.0
        1977          345.0                      1998          430.0
        1978          338.0                      1999          406.0
        1979          320.0                      2000          406.0
        1980          326.0                      2001          400.0
        1981          330.0                      2002          305.0
        1982          301.0                      2003          318.0


        Explanation of peak discharge qualification codes

       PeakFQ    NWIS
        CODE     CODE   DEFINITION

          D        3    Dam failure, non-recurrent flow anomaly
          G        8    Discharge greater than stated value
          X       3+8   Both of the above
          L        4    Discharge less than stated value
          K     6 OR C  Known effect of regulation or urbanization
          H        7    Historic peak

          -  Minus-flagged discharge -- Not used in computation
                -8888.0 -- No discharge value given
          -  Minus-flagged water year -- Historic peak used in computation



1


  Program PeakFq           U.  S.  GEOLOGICAL SURVEY            Seq.004.004
  Ver.  5.2               Annual peak flow frequency analysis      Run Date / Time
  11/01/2007             following Bulletin 17-B Guidelines      09/24/2009 11:11

                         Station - 99999999  LAKE TANA LEVEL


   EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

      WATER          RANKED       SYSTEMATIC       BULL.17B
       YEAR        DISCHARGE        RECORD         ESTIMATE

       1998          430.0         0.0244          0.0244
       1996          426.0         0.0488          0.0488
       1999          406.0         0.0732          0.0732
       2000          406.0         0.0976          0.0976
       1964          402.0         0.1220          0.1220
       2001          400.0         0.1463          0.1463
       1975          389.0         0.1707          0.1707
       1961          382.0         0.1951          0.1951
       1962          377.0         0.2195          0.2195
       1994          377.0         0.2439          0.2439
       1988          372.0         0.2683          0.2683
       1974          364.0         0.2927          0.2927
       1997          364.0         0.3171          0.3171
       1967          362.0         0.3415          0.3415
       1995          360.0         0.3659          0.3659
       1976          356.0         0.3902          0.3902
       1985          356.0         0.4146          0.4146
```

```
       1993          350.0         0.4390         0.4390
       1968          348.0         0.4634         0.4634
       1977          345.0         0.4878         0.4878
       1986          344.0         0.5122         0.5122
       1989          342.0         0.5366         0.5366
       1969          341.0         0.5610         0.5610
       1971          338.0         0.5854         0.5854
       1978          338.0         0.6098         0.6098
       1992          334.0         0.6341         0.6341
       1966          330.0         0.6585         0.6585
       1981          330.0         0.6829         0.6829
       1980          326.0         0.7073         0.7073
       1970          322.0         0.7317         0.7317
       1979          320.0         0.7561         0.7561
       1990          318.0         0.7805         0.7805
       2003          318.0         0.8049         0.8049
       1973          317.0         0.8293         0.8293
       1987          311.0         0.8537         0.8537
       2002          305.0         0.8780         0.8780
       1984          304.0         0.9024         0.9024
       1982          301.0         0.9268         0.9268
       1983          296.0         0.9512         0.9512
       1972          285.0         0.9756         0.9756
1


 End PeakFQ analysis.
   Stations processed :       4
   Number of errors   :       0
   Stations skipped   :       0
   Station years      :     148
```

I. BASIN SCHEMATICS WITHIN HEC-HMS

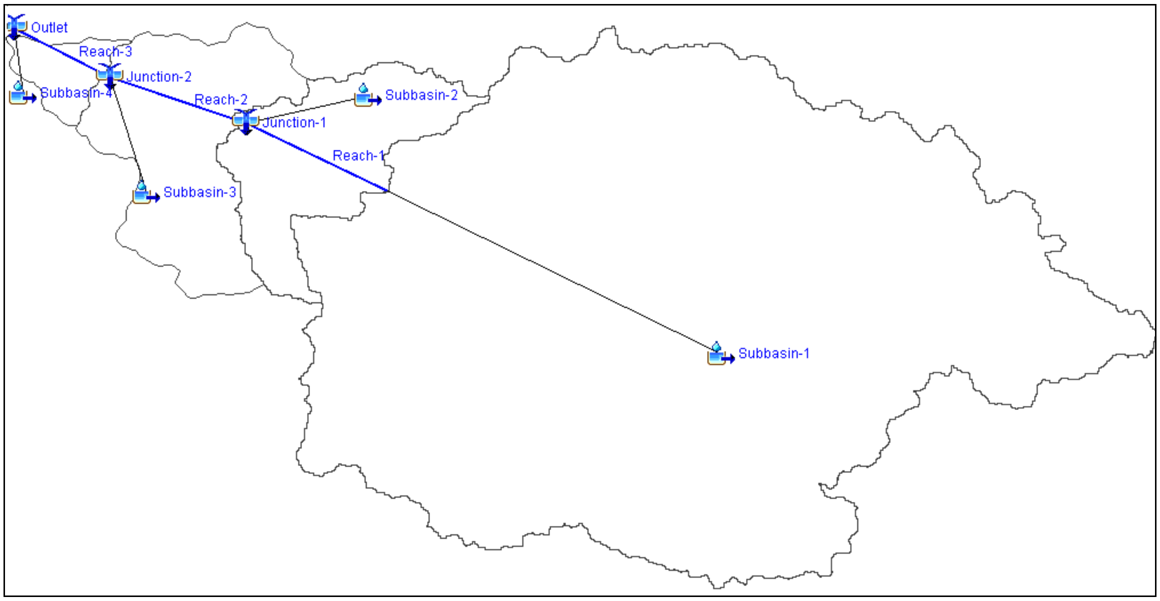


Figure I-1: Gumara HEC-HMS schematic.

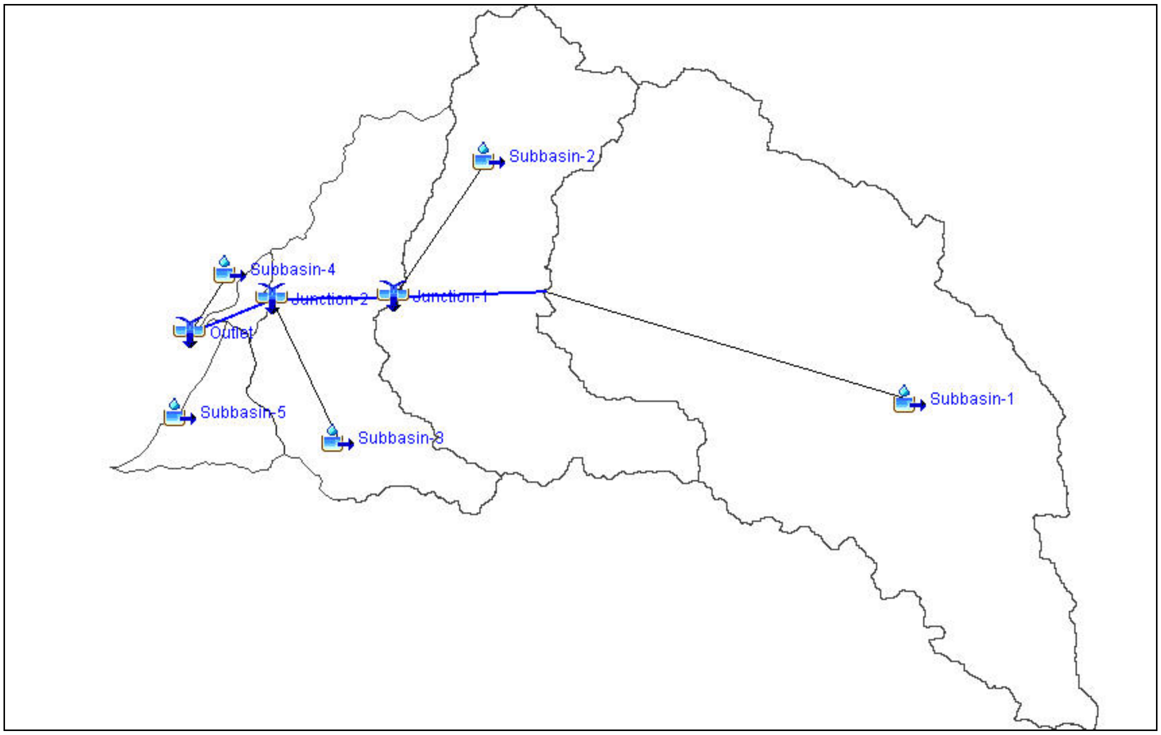


Figure I-2: Ribb HEC-HMS schematic. Subbasin 5 corresponds to the middle basin located in between the Ribb and Gumara basins.

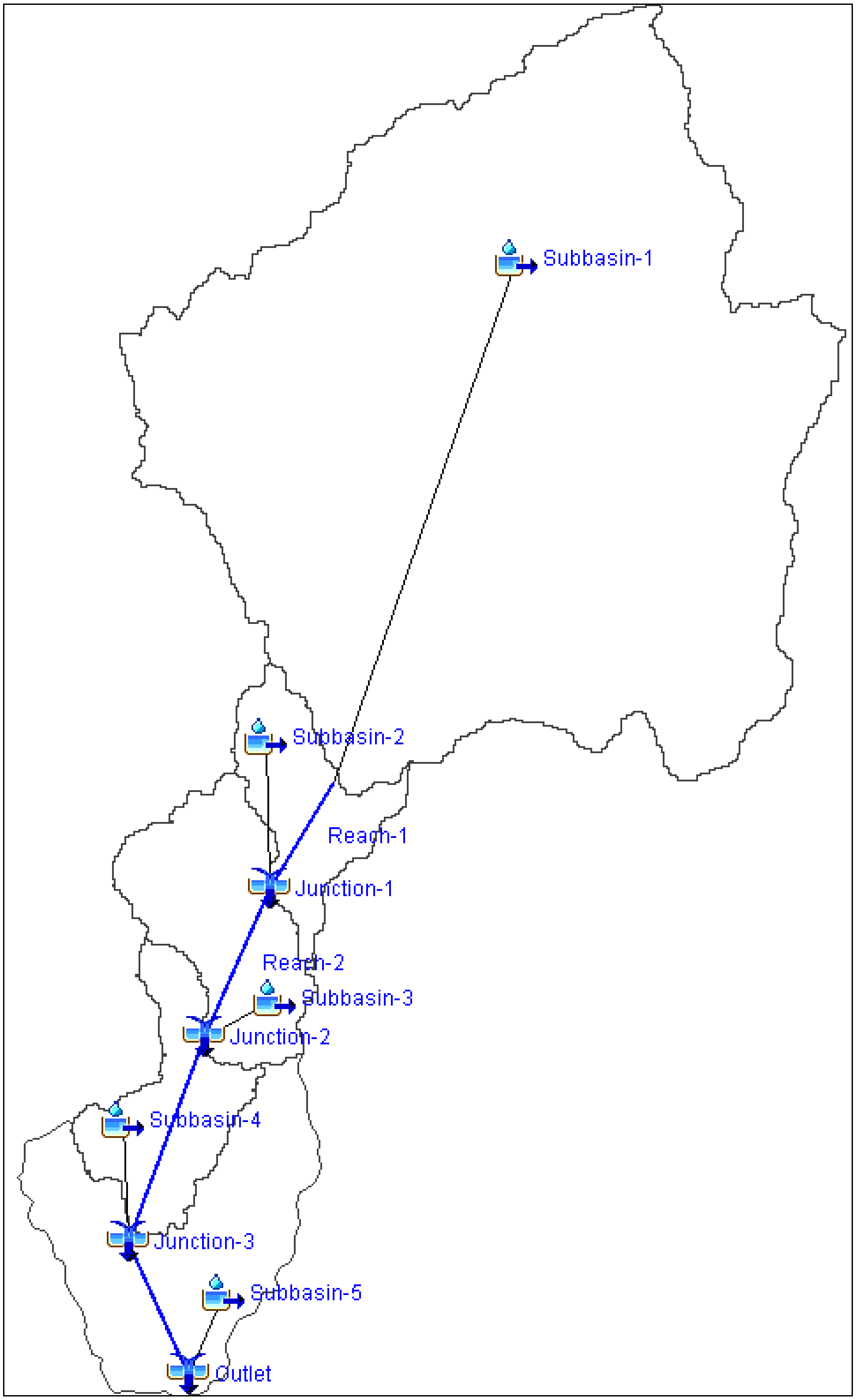


Figure I-3: Megech HEC-HMS schematic.

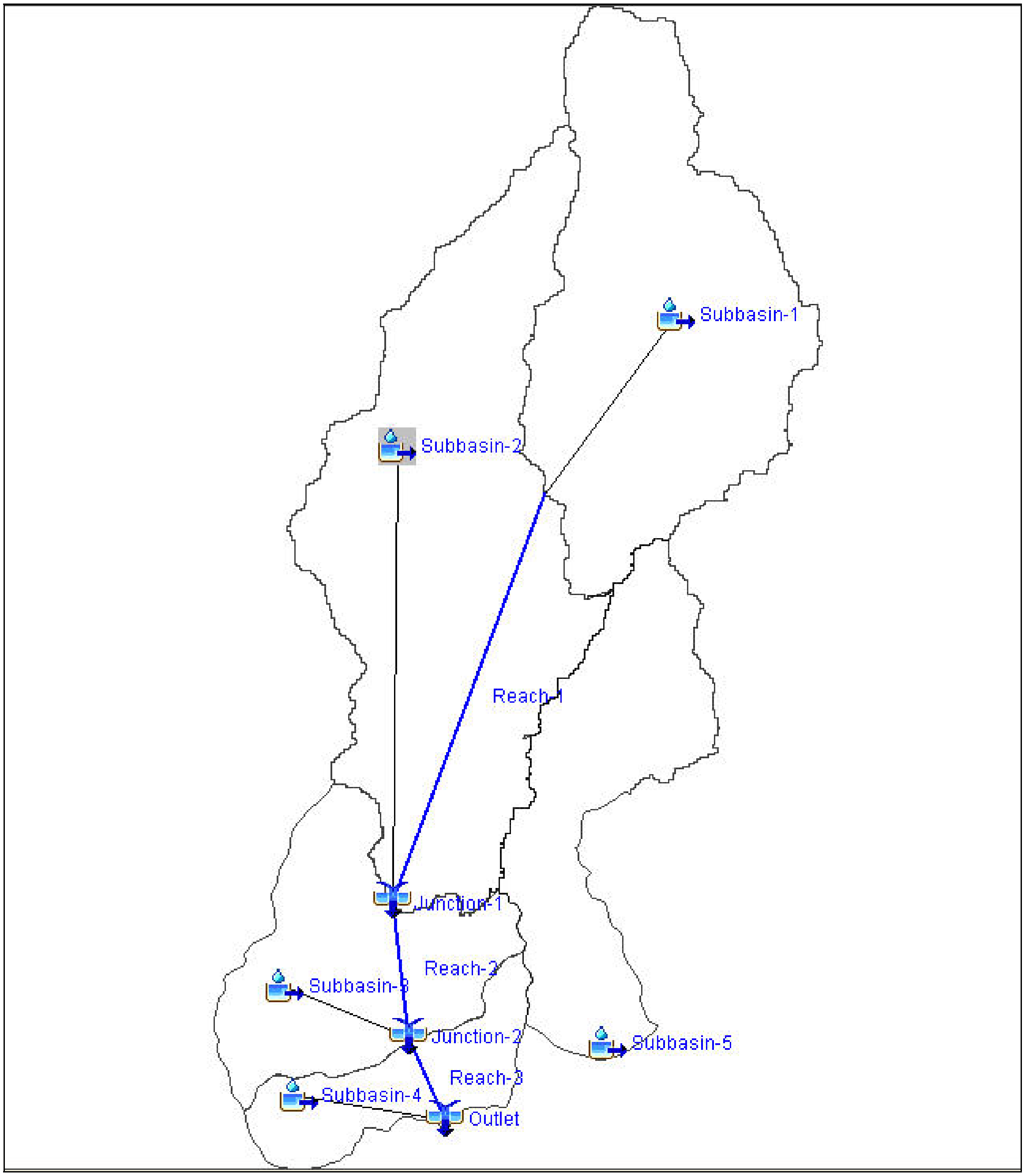


Figure I-4: Dirma HEC-HMS schematic.

J. LANDUSE AND HYDROLOGIC SOIL GROUPS

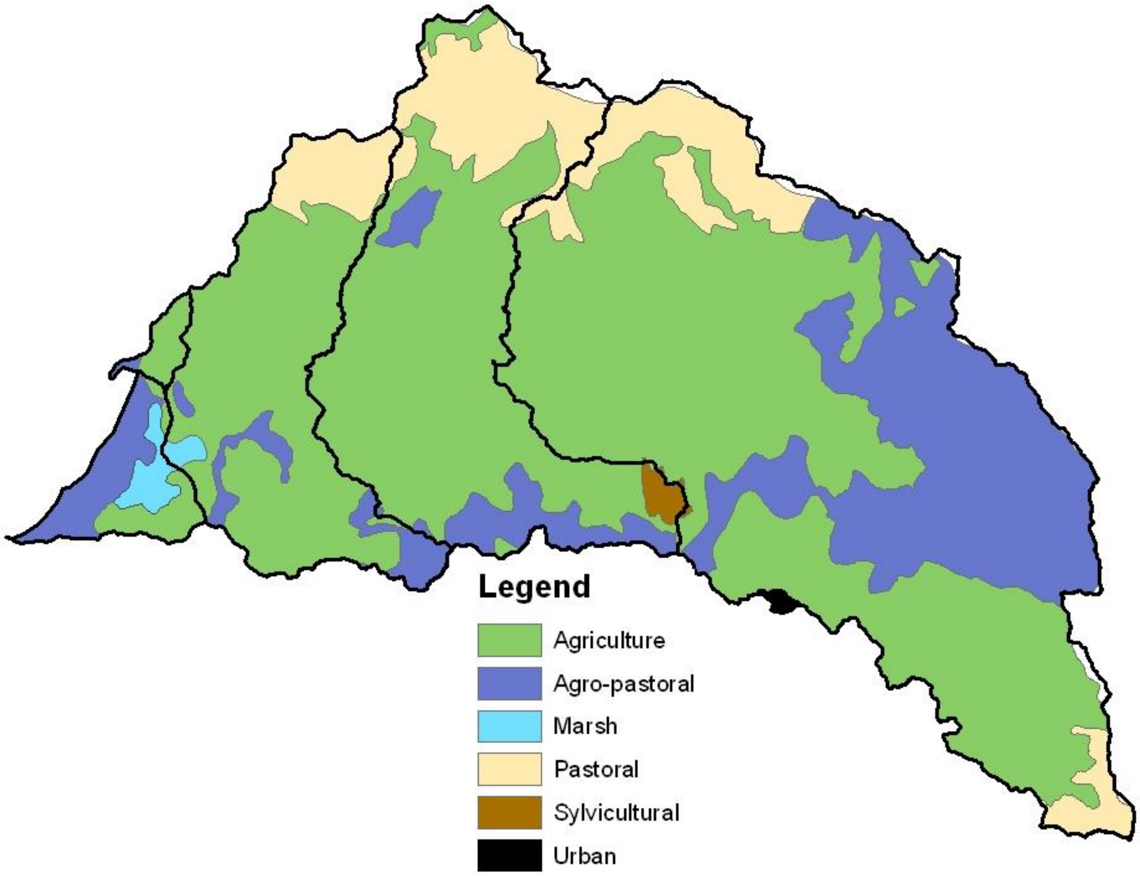


Figure J-1: Landuse for the Ribb basin including the Fogera Middle basin.

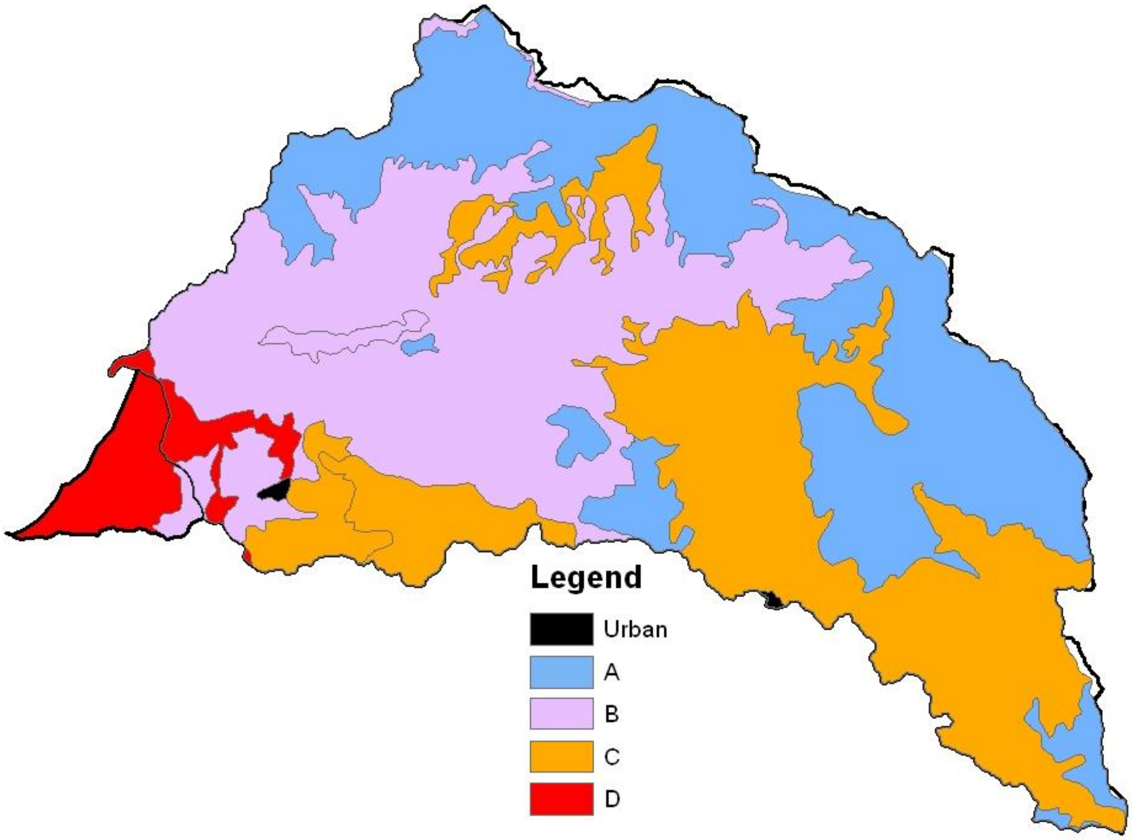


Figure J-2: Hydrologic Soil Groups for the Ribb basin including the Fogera Middle basin.

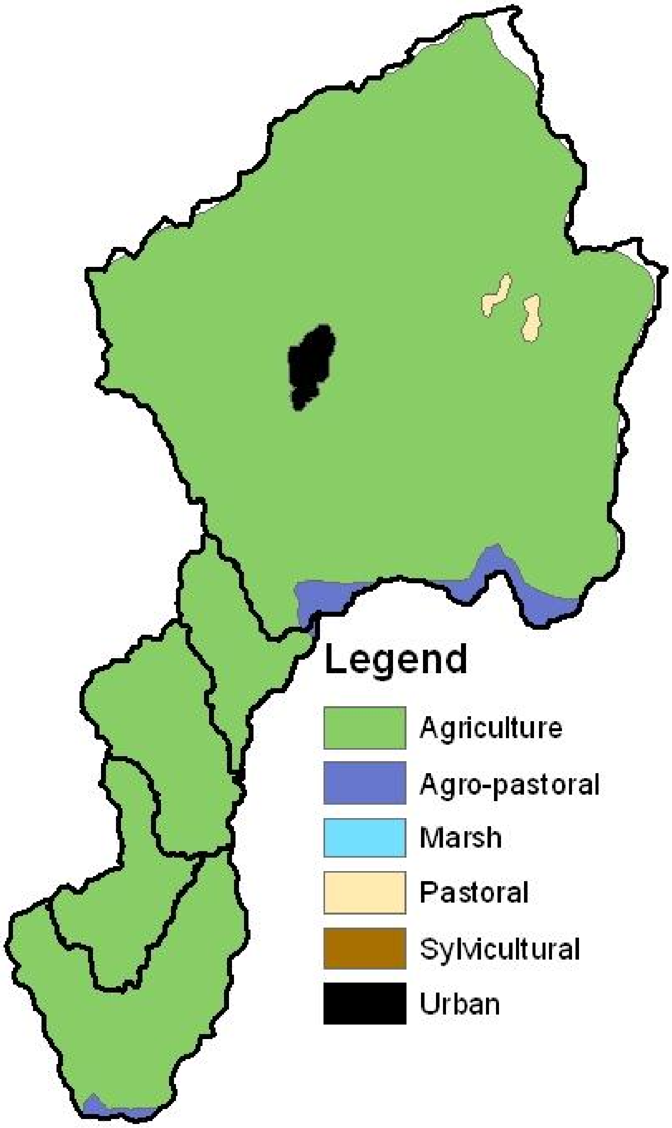


Figure J-3: Landuse for the Megech basin.

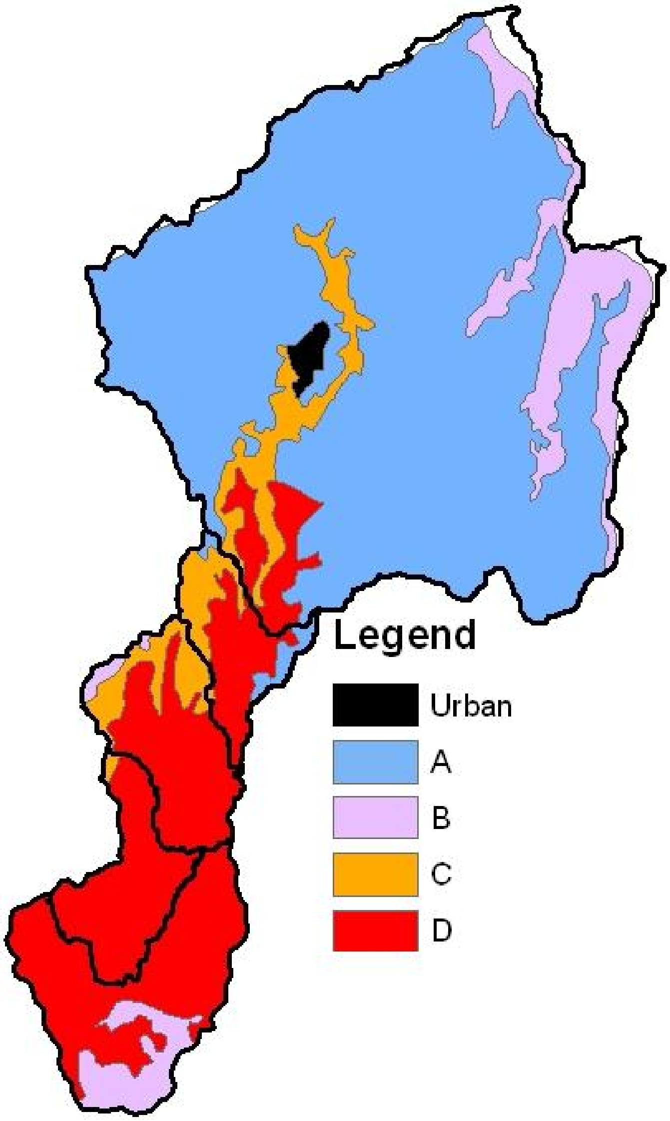


Figure J-4: Hydrologic soil groups for the Megech basin.

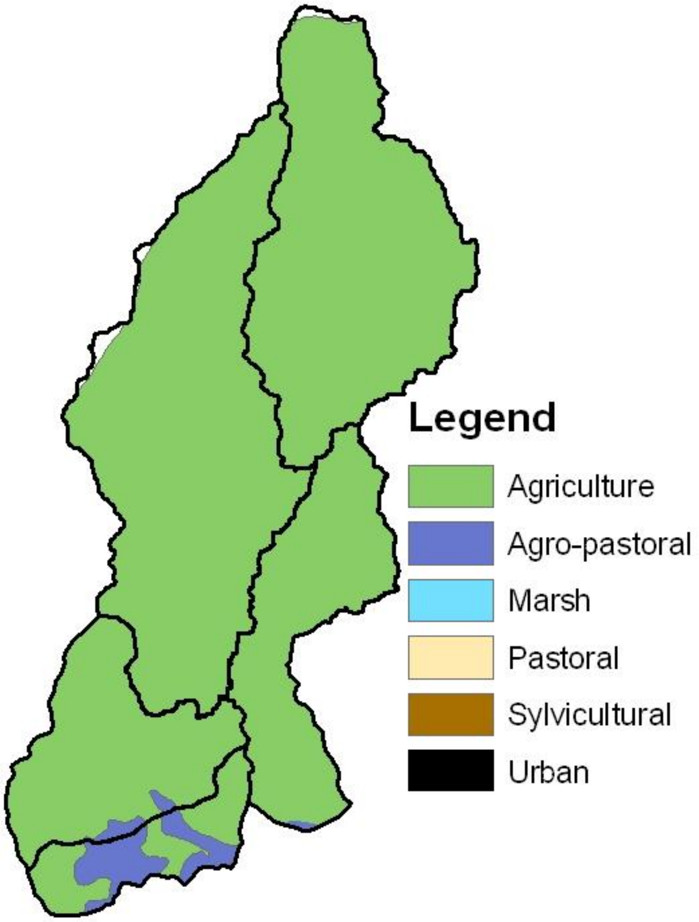


Figure J-5: Landuse for the Dirma basin including the Dembiya Middle basin.

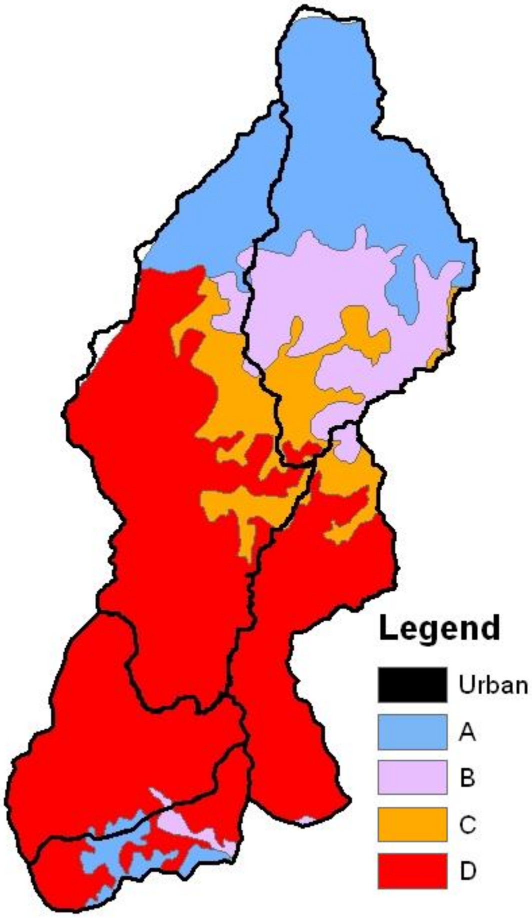


Figure J-6: Hydrologic soil groups for the Dirma basin including the Dembiya Middle basin.

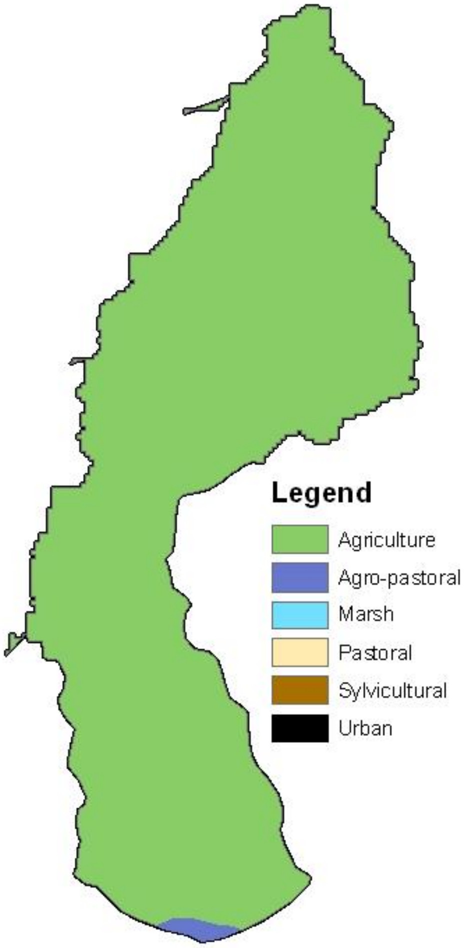


Figure J-7: Landuse for the basin between Dirma and Megech basins.

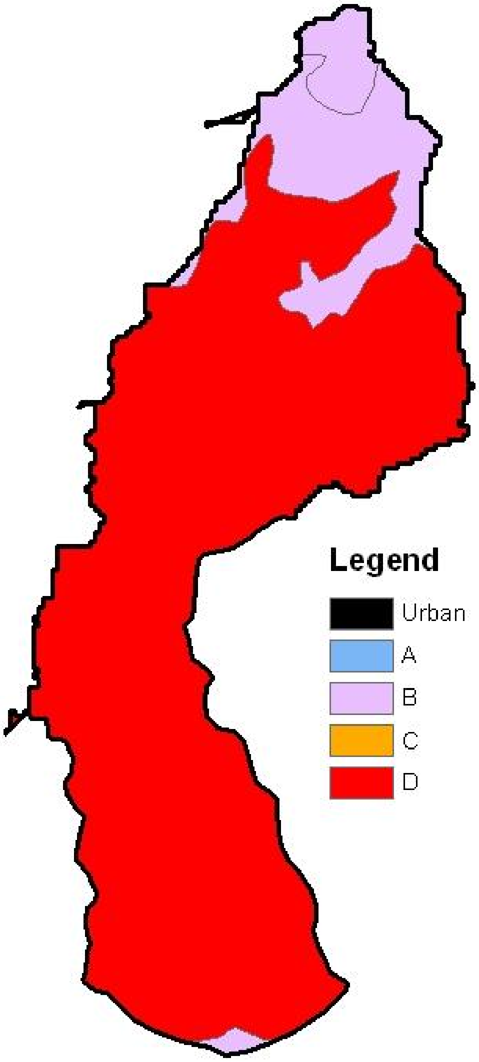
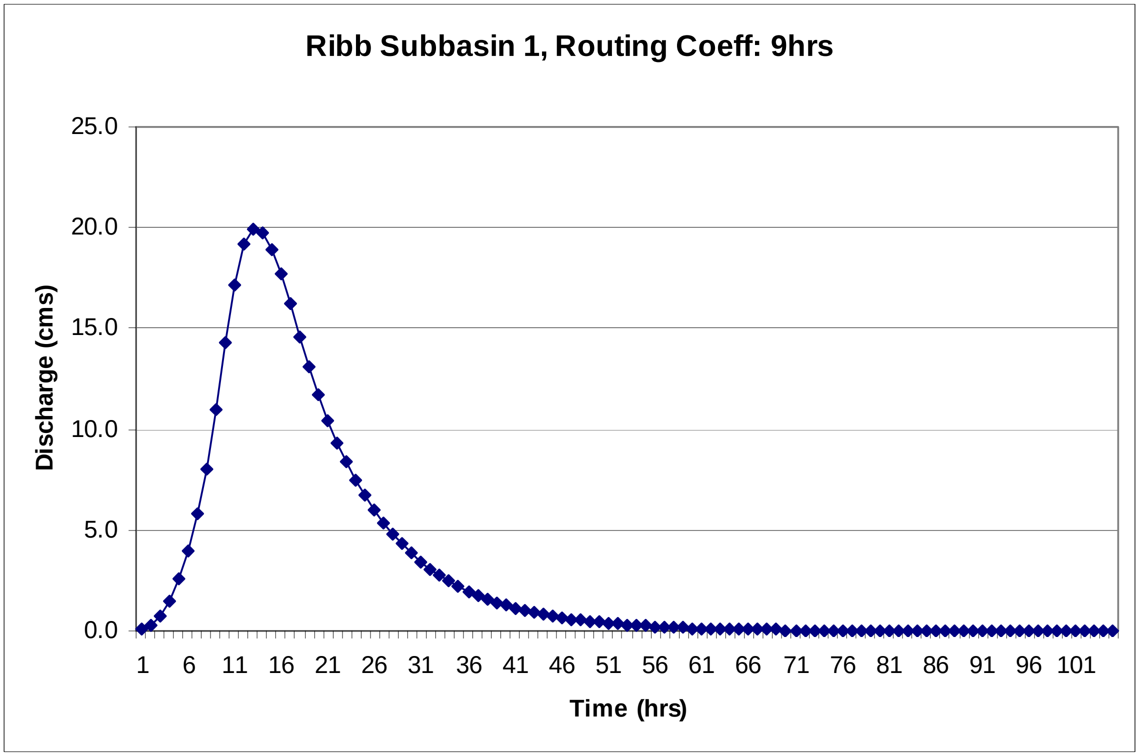
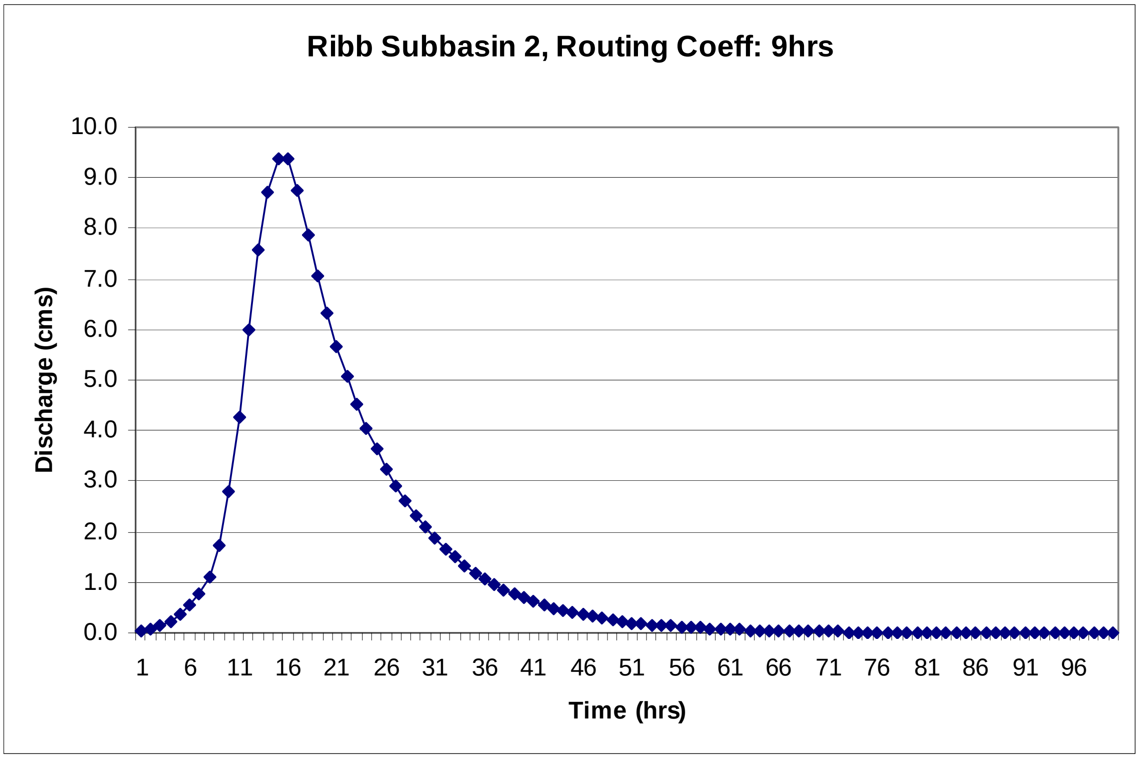
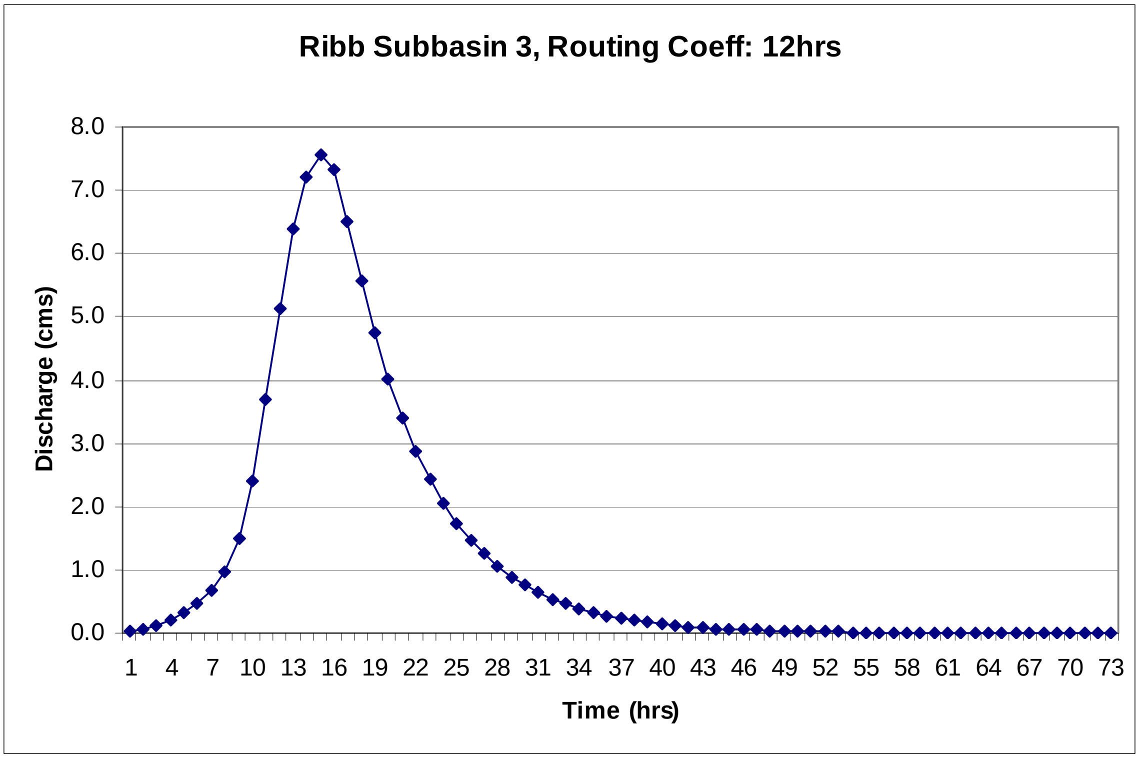


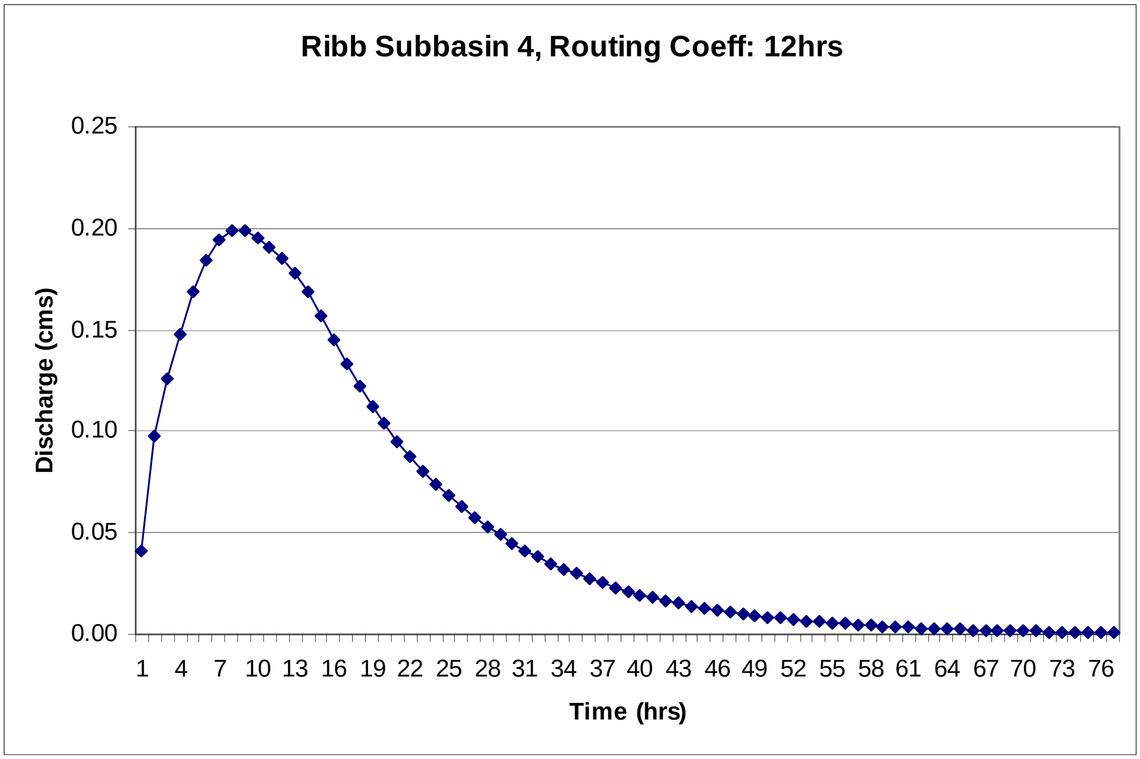
Figure J-8: Hydrologic soil groups for the basin between Dirma and Megech basins.

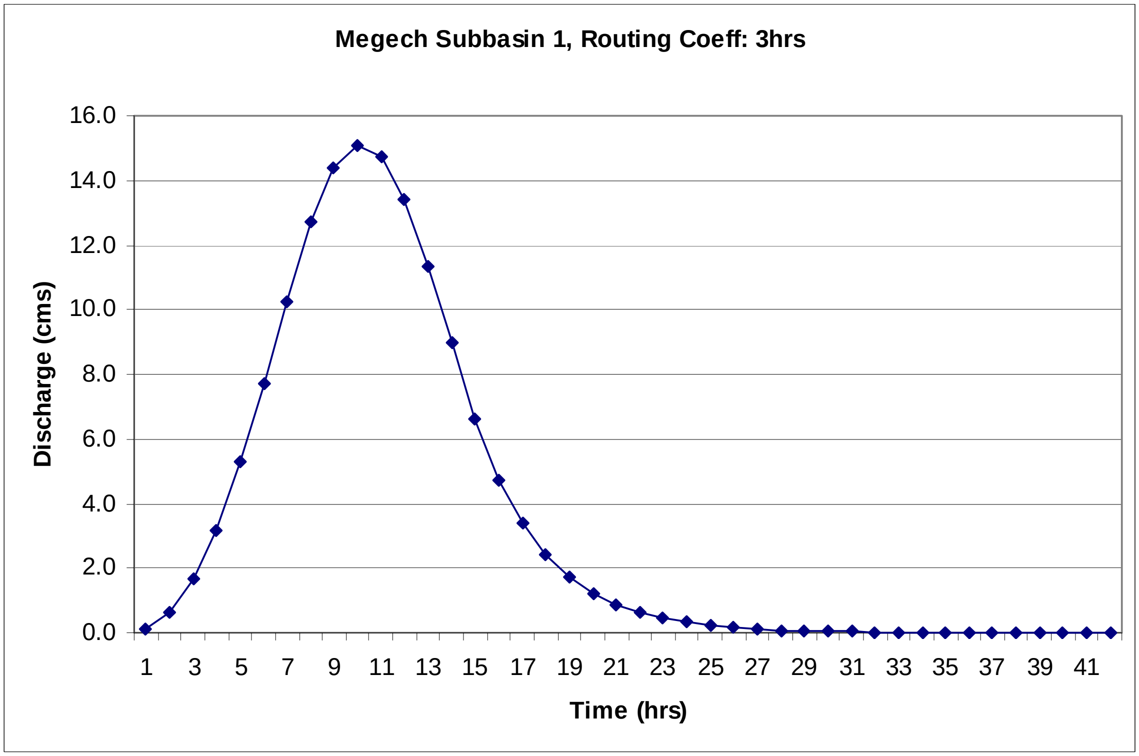
K. UNIT HYDROGRAPHS

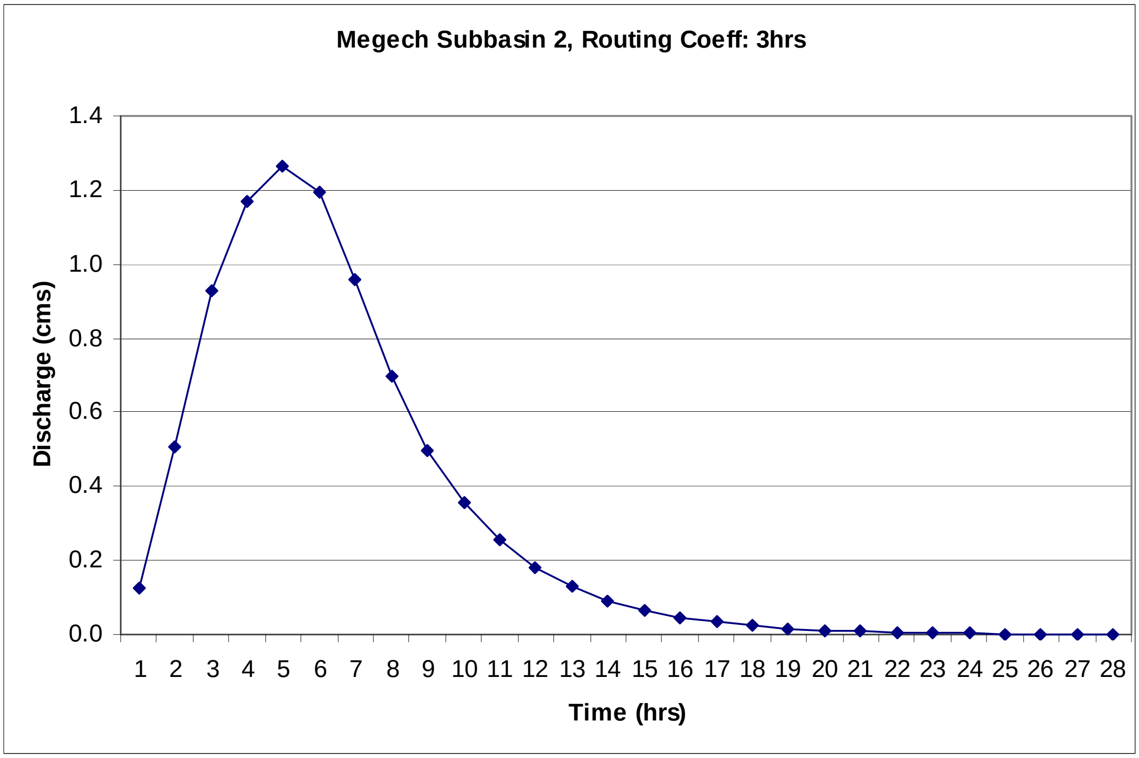


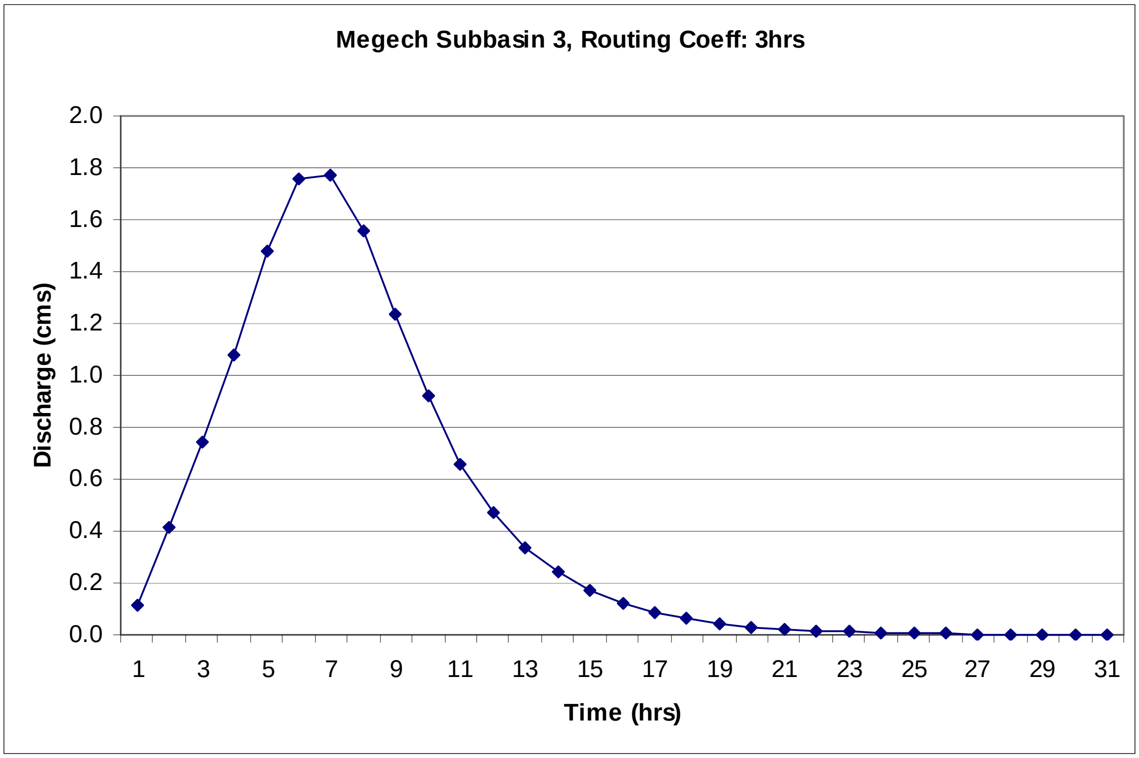


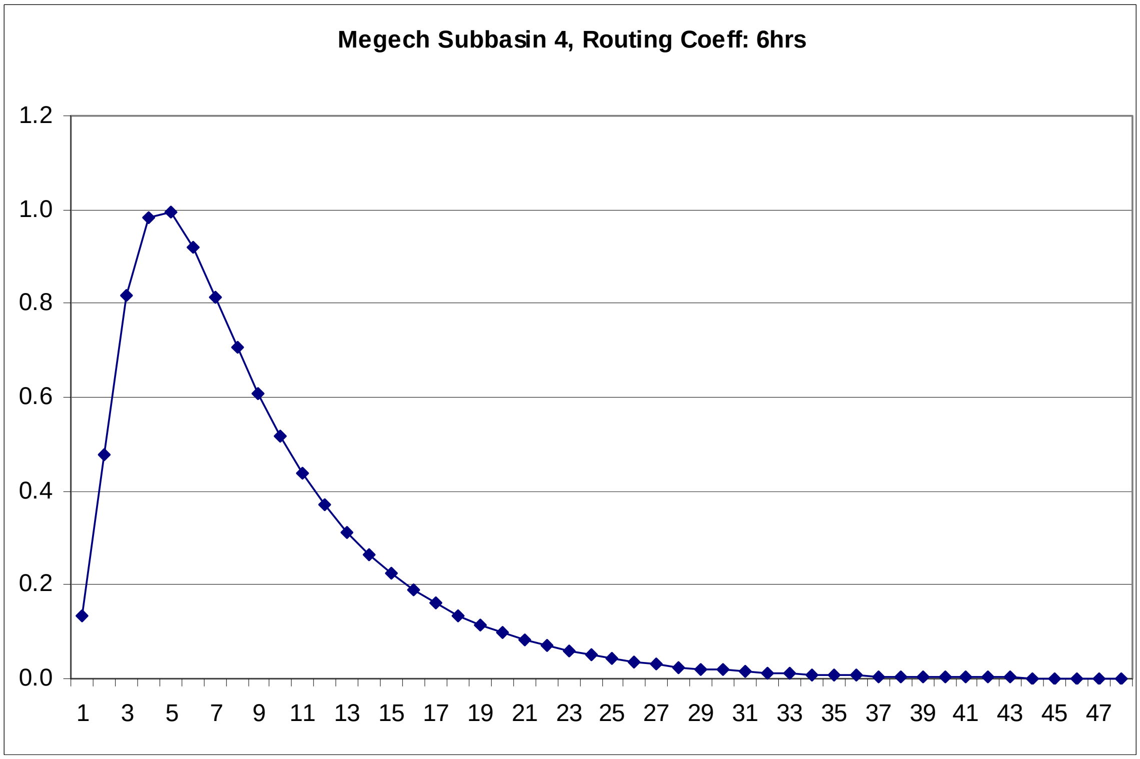

Ribb Subbasin 3, Routing Coeff: 12hrs
Discharge (cms)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1
4
7
10
13
16
19
22
25
28
31
34
37
40
43
46
49
52
55
58
61
64
67
70
73
Time (hrs)

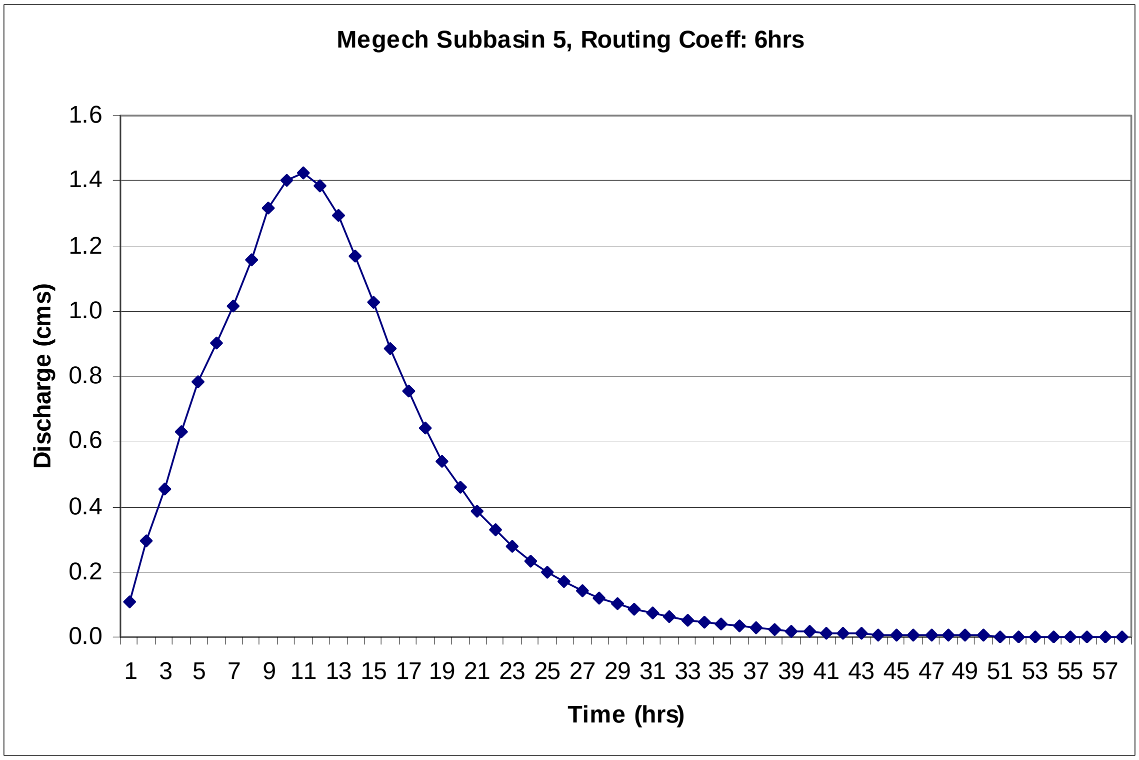

Ribb Subbasin 4, Routing Coeff: 12hrs
Discharge (cms)
0.25
0.20
0.15
0.10
0.05
0.00
1
4
7
10
13
16
19
22
25
28
31
34
37
40
43
46
49
52
55
58
61
64
67
70
73
76
Time (hrs)

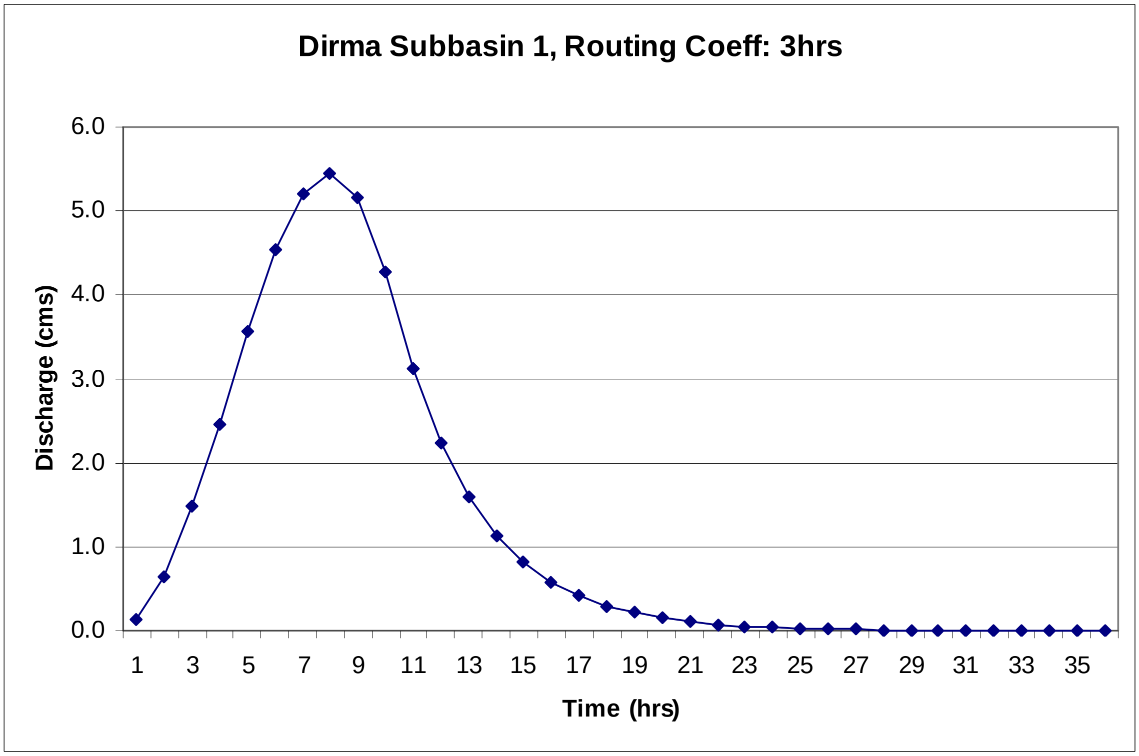

Megech Subbasin 1, Routing Coeff: 3hrs
Discharge (cms)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
Time (hrs)

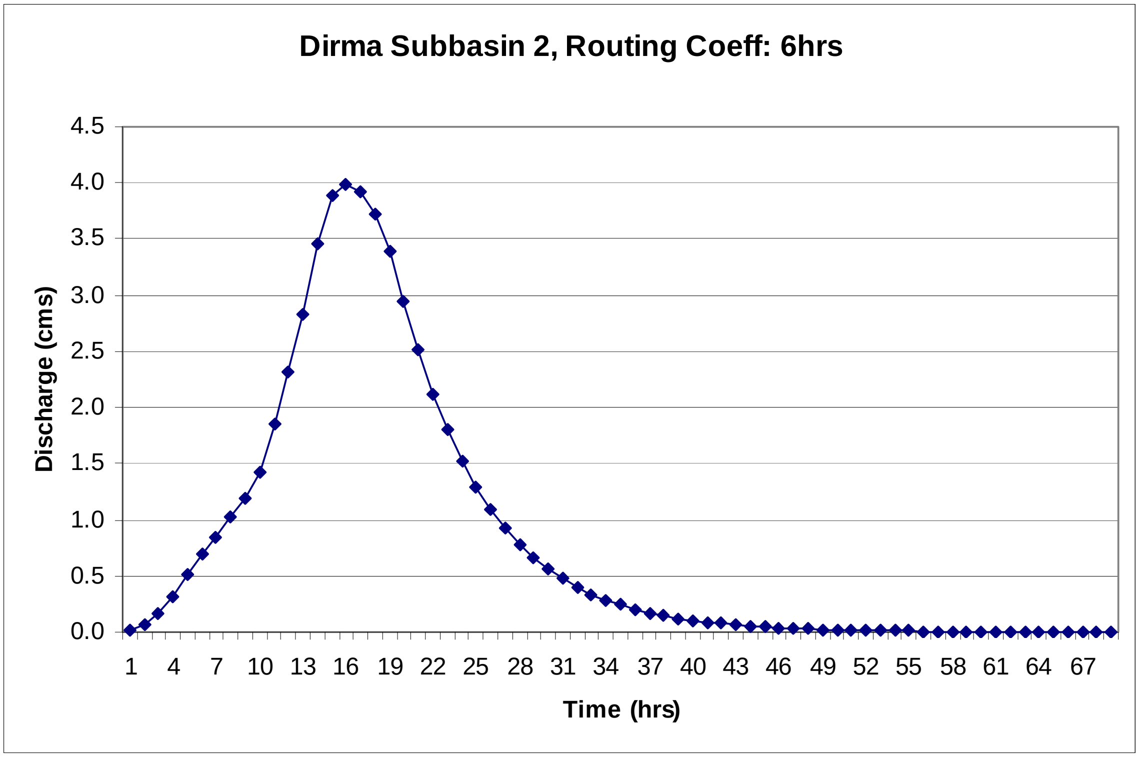

Megech Subbasin 2, Routing Coeff: 3hrs
Discharge (cms)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
Time (hrs)

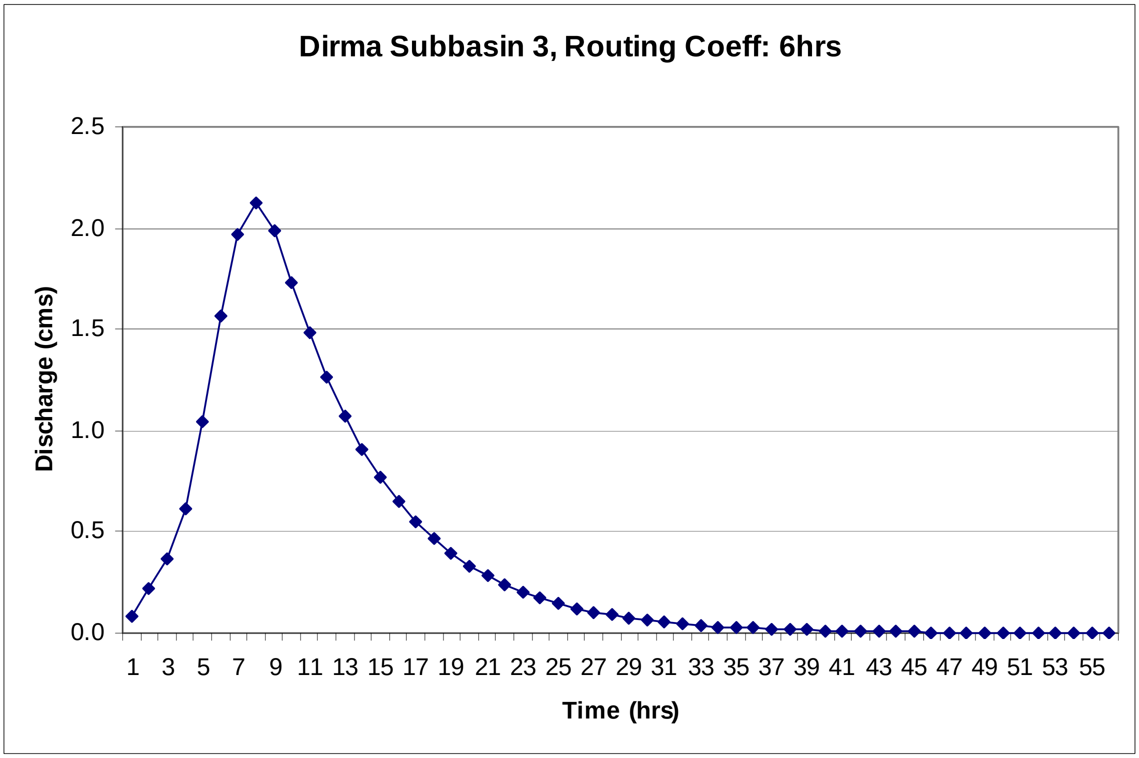

Megech Subbasin 3, Routing Coeff: 3hrs
Discharge (cms)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
Time (hrs)

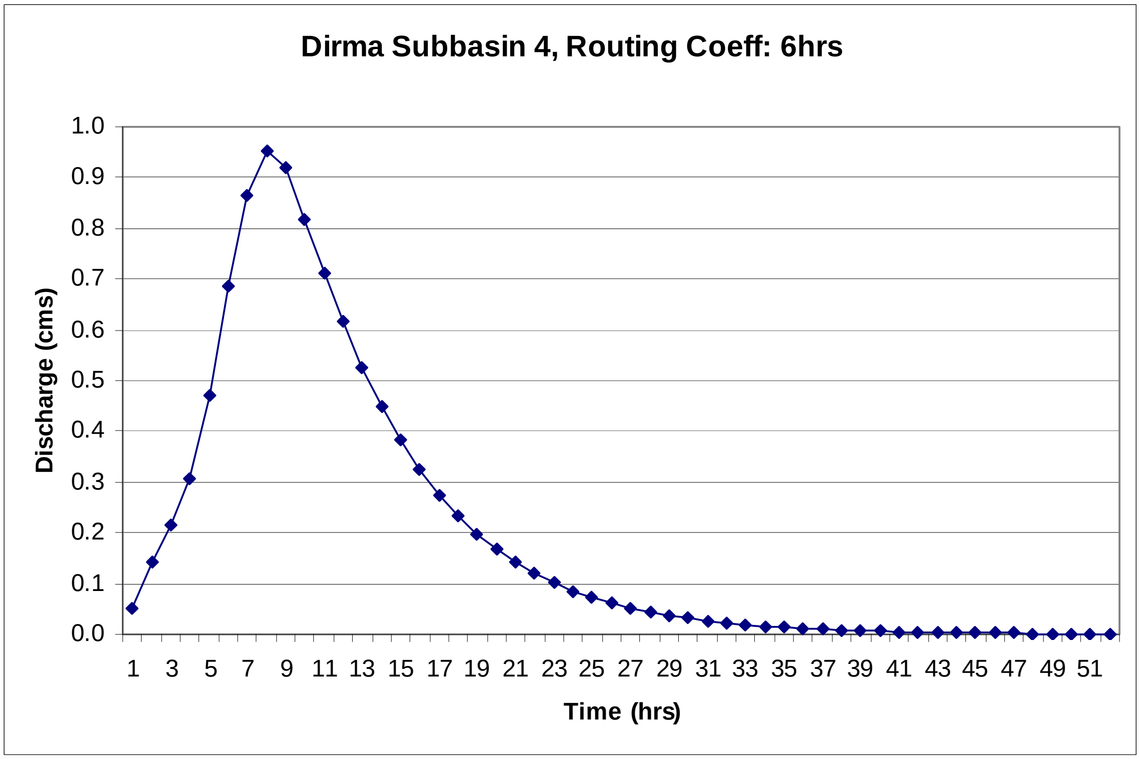

Megech Subbasin 4, Routing Coeff: 6hrs
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
43
45
47

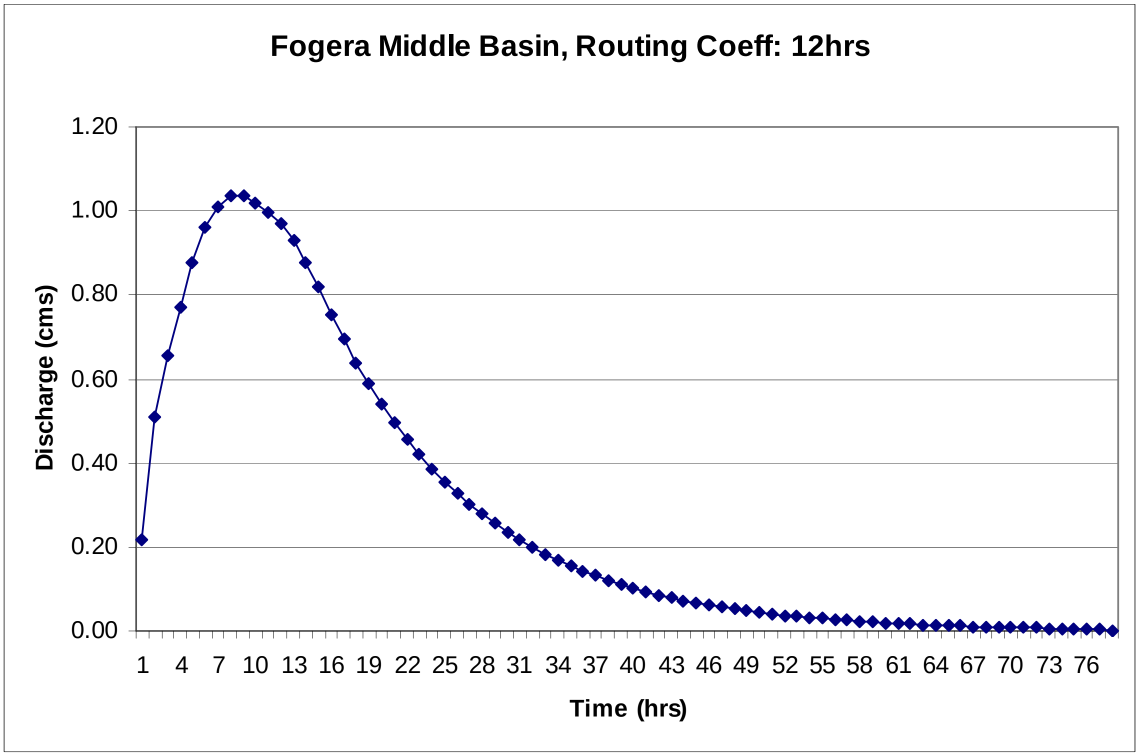

Megech Subbasin 5, Routing Coeff: 6hrs
Discharge (cms)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57
Time (hrs)

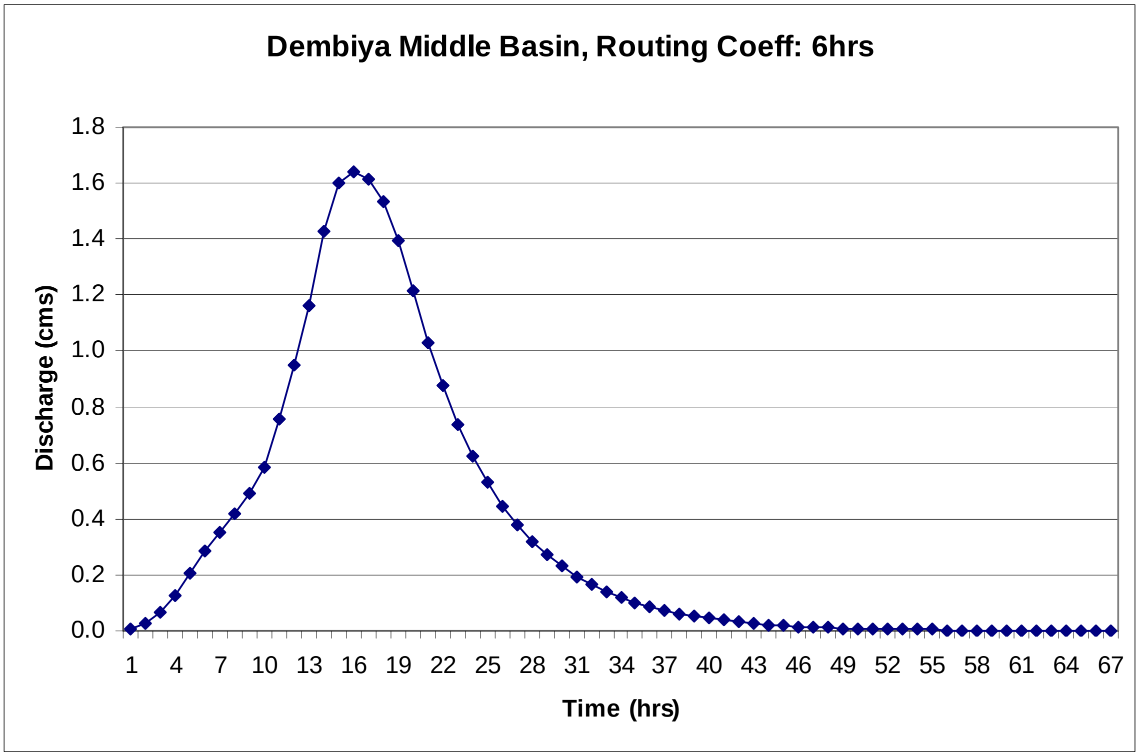

Dirma Subbasin 1, Routing Coeff: 3hrs
Discharge (cms)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
Time (hrs)


Dirma Subbasin 2, Routing Coeff: 6hrs
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Discharge (cms)
1
4
7
10
13
16
19
22
25
28
31
34
37
40
43
46
49
52
55
58
61
64
67
Time (hrs)


Dirma Subbasin 3, Routing Coeff: 6hrs
2.5
2.0
1.5
1.0
0.5
0.0
Discharge (cms)
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
43
45
47
49
51
53
55
Time (hrs)


Dirma Subbasin 4, Routing Coeff: 6hrs
Discharge (cms)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51
Time (hrs)


Fogera Middle Basin, Routing Coeff: 12hrs
Discharge (cms)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58 61 64 67 70 73 76
Time (hrs)


Dembiya Middle Basin, Routing Coeff: 6hrs
Discharge (cms)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
4
7
10
13
16
19
22
25
28
31
34
37
40
43
46
49
52
55
58
61
64
67
Time (hrs)

L. BASEFLOW PLOTS

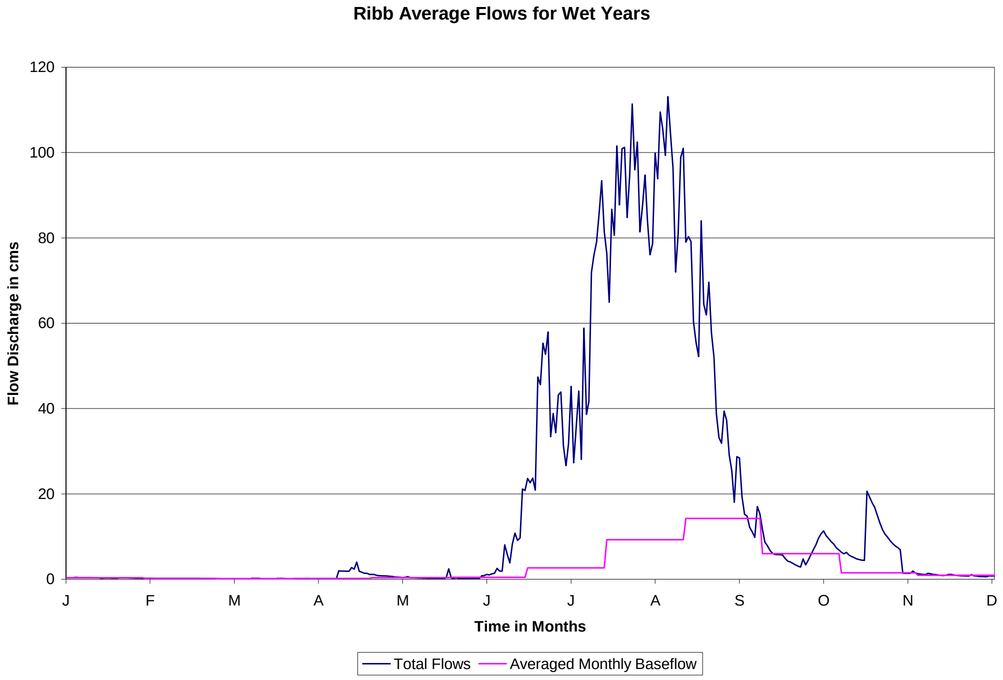


Figure L-1: Ribb daily average streamflows and monthly averages of baseflows.

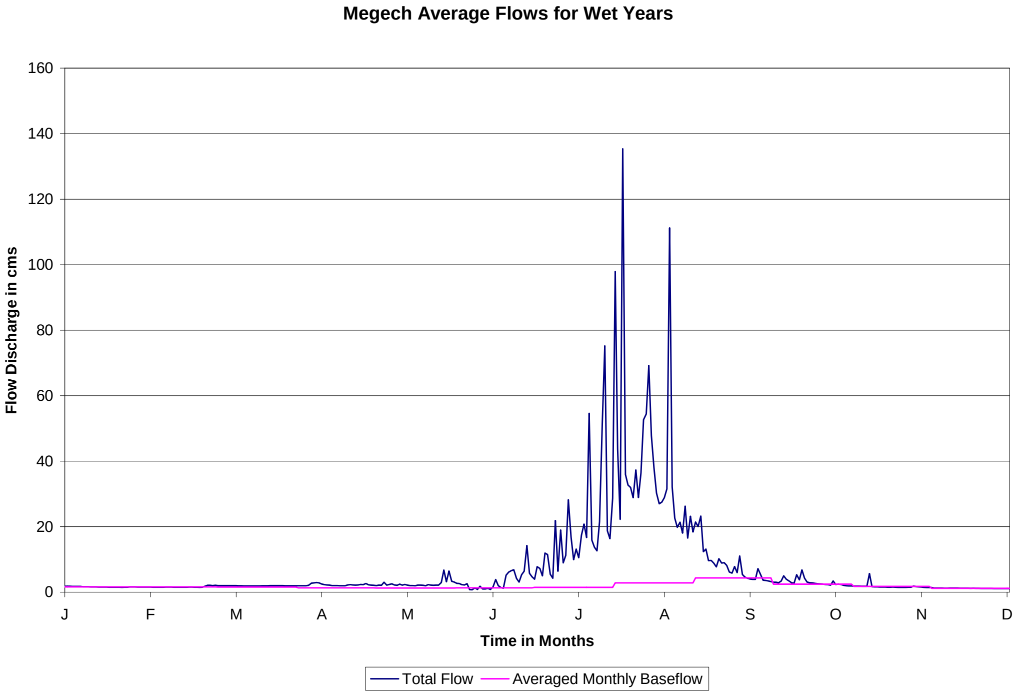


Figure L-2: Megech daily average streamflows and monthly averages of baseflows.

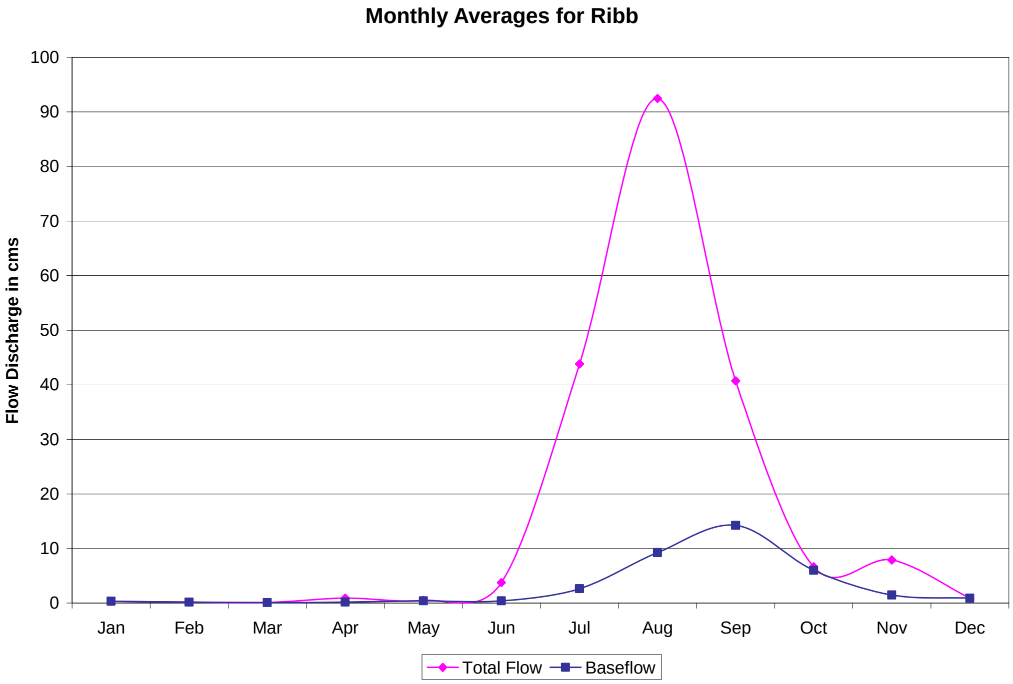


Figure L-3: Ribb constant monthly baseflow curve.

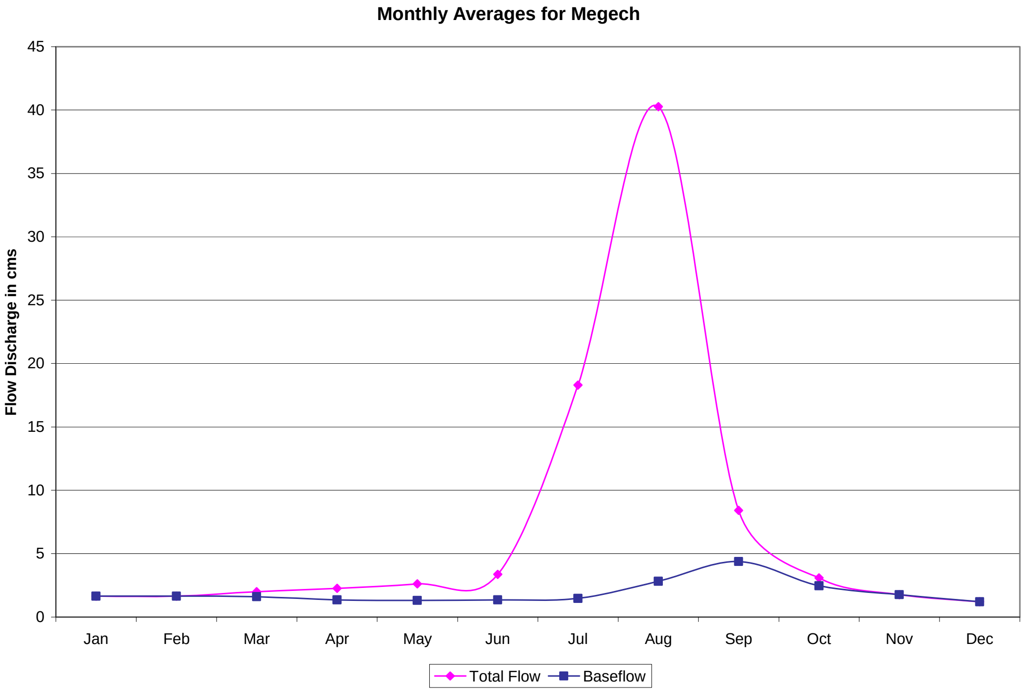


Figure L-4: Megech constant monthly baseflow curve.

M. FLOOD FLOW ESTIMATES OF UNGAGED DRAINAGE AREAS

Estimates of incremental flows downstream of the gage sites on each basin were computed based on the results from the flood frequency analysis using the LP3 distribution and the rainfall-runoff model. These incremental lateral flows to simulate flow change locations in the hydraulic models representing additional lateral flows from local runoff.

The incremental flows were computed as follows:

$$Q_{d/s\_increment} = Q_{fGage} * \frac{Q_{HMSd/s}}{Q_{HMSGage}} - Q_{fGage}$$

Where $Q_{d/s\_increment}$ is the flow at the outlet of an ungaged subbasin, Q_{fGage} is the estimated flow at the gage from the frequency analysis, $Q_{HMSd/s}$ is the estimated flow from HEC-HMS at the outlet of the ungaged downstream subbasin, and $Q_{HMSGage}$ is the estimated flow at the gage from HEC-HMS. To compute the local lateral flows, that is, the local contribution for each subbasin downstream of the gage, the difference between the flow of the downstream subbasin and the immediate upstream subbasin was calculated. The final results are reported in Table M-1, Table M-2, Table M-3, and Table M-4.

During floods, flows from Dembiya Middle basin interact with flows from Dirma basin. HEC-HMS flow rates from Dembiya Middle basin that coincide with the peak flows at the outlet of Dirma Subbasin 2 were input into HEC-RAS model and are listed in Table M-5. Similarly, HEC-HMS flow rates from Fogera Middle basin that coincide with the peak flow of the outlet of Ribb basin were used in HEC-RAS and are listed in Table M-5 as well. These flow rates are for the 100-year return period event.

Table M-1: Flow rates in m^3/s for the ungaged areas of Gumara basin.

Gumara Basin			$Q_{HMSd/s}$		**Cumulative Lateral Flows ($Q_{d/s\_increment}$)**		**Local Lateral Flows**	
T (yrs)	Q_{fGage}	$Q_{HMSGage}$ **Subbasin 2**	Q_{HMS} **Subbasin 3**	Q_{HMS} **Subbasin 4**	Q_3 **increment**	Q_4 **increment Outlet**	**Subbasin 3**	**Subbasin 4**
2	329	236	247	251	16	21	16	4.6
5	404	422	446	452	24	29	24	5.7
10	448	592	622	628	23	28	23	4.9
50	539	803	845	853	28	33	28	5.6
100	574	914	963	973	31	37	31	6.0

Table M-2: Flow rates in m^3/s for the ungaged areas of Ribb basin.

Ribb Basin			$Q_{HMSd/s}$		**Cumulative Lateral Flows ($Q_{d/s\_increment}$)**		**Local Lateral Flows**	
T (yrs)	Q_{fGage}	$Q_{HMSGage}$ **Subbasin 2**	Q_{HMS} **Subbasin 3**	Q_{HMS} **Subbasin 4**	Q_3 **increment**	Q_4 **increment Outlet**	**Subbasin 3**	**Subbasin 4**
2	148	113	153	155	53	55	53	1.7
5	188	325	422	425	56	58	56	1.7
10	212	411	530	534	61	63	61	1.9
50	262	612	782	786	73	75	73	2.1
100	282	729	928	934	77	79	77	2.0

Table M-3: Flow rates in m^3/s for the ungaged areas of Megech basin.

Megech Basin			$Q_{HMSd/s}$ at Subbasins				Cumulative Lateral Flows ($Q_{d/s\_increment}$)				Local Lateral Flows at Subbasins			
T (yrs)	Q_{fGage}	$Q_{HMSGage}$ Subbasin 1	2	3	4	5	Q_2 increment	Q_3 increment	Q_4 increment	Q_5 increment Outlet	2	3	4	5
2	176.6	98.9	102.6	105.2	107.8	115.3	7	11	16	29	7	4.6	4.6	13.4
5	278.4	228.5	235.6	241.4	246	259.6	9	16	21	38	9	7.1	5.6	16.6
10	346.1	329.7	337.6	343.9	349.1	365.2	8	15	20	37	8	6.6	5.5	16.9
50	490.9	499.6	510.4	519.7	526.8	550.3	11	20	27	50	11	9.1	7.0	23.1
100	550	578.7	590.8	601.4	609.3	636.7	11	22	29	55	11	10.1	7.5	26.0

Table M-4: Flow rates in m^3/s for the ungaged areas of Dirma basin.

Dirma Basin			$Q_{HMSd/s}$			Cumulative Lateral Flows ($Q_{d/s\_increment}$)			Local Lateral Flows		
T	Q_{fGage}	$Q_{HMSGage}$ Subbasin 2	Q_{HMS} Subbasin 2	Q_{HMS} Subbasin 3	Q_{HMS} Subbasin 4	Q_2 increment	Q_3 increment	Q_4 increment Outlet	Subbasin 2	Subbasin 3	Subbasin 4
2	69	40	91	104	107	87	110	115	87	24	5
5	108	88	181	205	211	114	143	151	114	30	8
10	135	125	246	275	285	130	161	171	130	31	10
50	191	188	353	397	411	168	212	226	168	45	14
100	214	217	403	452	468	182	231	246	182	49	15

Table M-5: Lateral Flow Contributions from the Fogera Middle and Dembiya Middle Basins to the Ribb/Gumara and Dirma Basins respectively.

T (yrs)	$Q_{FogeraMiddle}$ at time of peak flow of Ribb Outlet	$Q_{DembiyaMiddle}$ at time of peak flow of Subbasin 2 Outlet
2	12.9	23.8
5	23	43.9
10	27.2	57.6
50	34.7	80.5
100	37.1	80.9