Final Report

Flood Risk Mapping Consultancy for Pilot Areas in Sudan

submitted to

ENTRO

EASTERN NILE TECHNICAL REGIONAL OFFICE

by

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and

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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., in cooperation with its partner, UNESCO Chair in Water Resources, has completed a flood risk mapping study for pilot areas along the Blue Nile River in Sudan. 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:

- Khartoum City, covering part of Khartoum City along the Blue Nile and the proposed development area at Soba
- Hasahisa Region and Wad Medani at the River Rahad junction
- Singa City
- Roseires Dam

Although the study focused on several pilot areas in the data collection, hydraulic modeling, and risk assessment, the hydraulic model and resulting hazard assessment was performed for the entire length of the Blue Nile in Sudan, and results are available in the digital datasets beyond the pilot areas for which detailed map sheets have been produced.

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 pilot areas along the Blue Nile.
- Terrain models for the channel and floodplain of the Blue Nile – this terrain model integrates surveyed cross sections from multiple sources with a 90 meter DEM.
- A useful procedure for integrating a gridded DEM with channel survey data.
- A frequency analysis for the Blue Nile in Sudan.
- Blue Nile hydraulic model with geo-referenced cross sections – this model has many potential 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 along the Blue Nile in Sudan, 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 floodwaters, and for extended periods, 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 floodwaters, and potential disruption associated with re-alignment of rivers following major floods.

The desire on the part of public officials to characterize and quantify these consequences 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 incorporated easily 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.

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 that are obvious when the maps are viewed at a 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 that can be improved in subsequent studies.

1.0 INTRODUCTION / OVERVIEW

Riverside Technology, inc. (Riverside) and its partner, UNESCO Chair in Water Resources, were contracted by the Eastern Nile Technical Regional Office (ENTRO) to perform a flood risk assessment for pilot areas of the Blue Nile River in Sudan. An Inception Report was prepared at the end of March 2009 describing initial data collection activities as well as an inception workshop that was 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 Khartoum on October 12 and 13, 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 reaches maximum volume in the rainy season (from June to September), and it supplies two thirds of the water of the Nile proper. Flooding along the Blue Nile 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 Sudan, recent floods have been particularly severe. In August 2007, after suffering many devastating floods over the previous decade, Sudan experienced its worst flood in living memory. Al Jazeera Television Broadcasting (August 25, 2007) reported that this event left hundreds of thousands of people homeless and short of food with more than 30,000 homes and many crops and animals being swept away. The most devastating impact was reported to be the inundation of 40,000 ha of agricultural land and complete destruction of more than 650 wells, leaving many without livelihoods. The Sudan Tribune (September 5, 2007) reported the death toll from the flood as 122, and that the U.N. agency Office for the Coordination of Humanitarian Affairs had estimated the flooding had left 200,000 people homeless, and had destroyed roads, schools, and access to safe drinking water. The flood was reported by many news agencies to have reached levels in Khartoum higher than in both 1988 and 1946, previously the worst floods to hit Sudan in the last century.

Figure 2-1: Villager 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**.** 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.

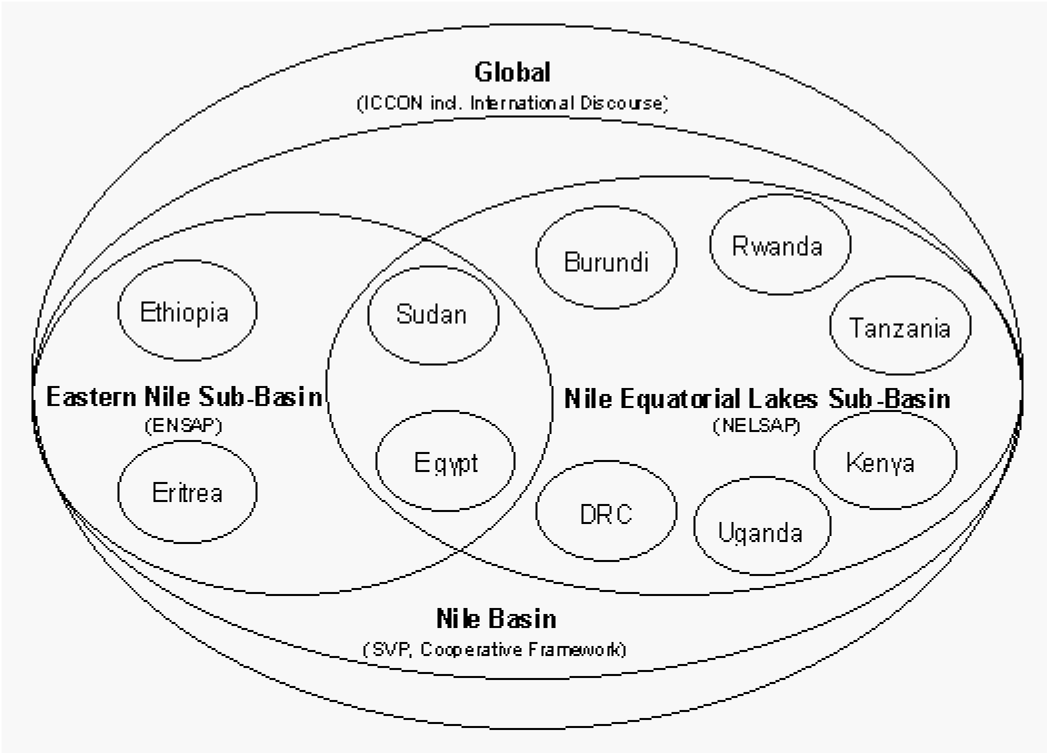


Figure 2-2: Nile Basin Initiative framework (NBI).

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 Blue Nile within Sudan, (ii) produce flood risk maps, and (iii) conduct flood risk assessments for the pilot areas within the Blue Nile Basin in Sudan. ENTRO has determined that identifying and mapping these flood prone areas, including locating the high-risk areas and the extent of flooding, will greatly enhance Sudan's flood risk planning capacity and help Sudan develop enhanced flood mitigation measures. The approach and modeling conducted and described below not only serves as a proof of concepts for developing flood risk maps for the pilot projects, but can also be used in future development scenario studies.

2.5 Project Location and Pilot Study Areas

The project study area, shown in ***Figure 2-3***, is the Blue Nile River extending from the Ethiopia-Sudan border to the Confluence of the Blue Nile with the White Nile in Khartoum, Sudan. Within this study area are five pilot study reaches as follows:

- Khartoum City, covering part of Khartoum City along the Blue Nile and the proposed development area at Soba
- Hasahisa Region and Wad Medani at the River Rahad junction
- Singa City
- Roseires Dam

1.

2. The pilot areas were selected as locations at which more detailed field surveys would be obtained to supplement the existing data for improved hydraulic modeling and where detailed risk assessment would be performed. The initial list of proposed pilot reaches identified during the inception phase of the project suggested selecting either the River Rahad junction or the River Dinder junction. The River Rahad junction was selected because of better data availability, and the Hasahisa region was also added.

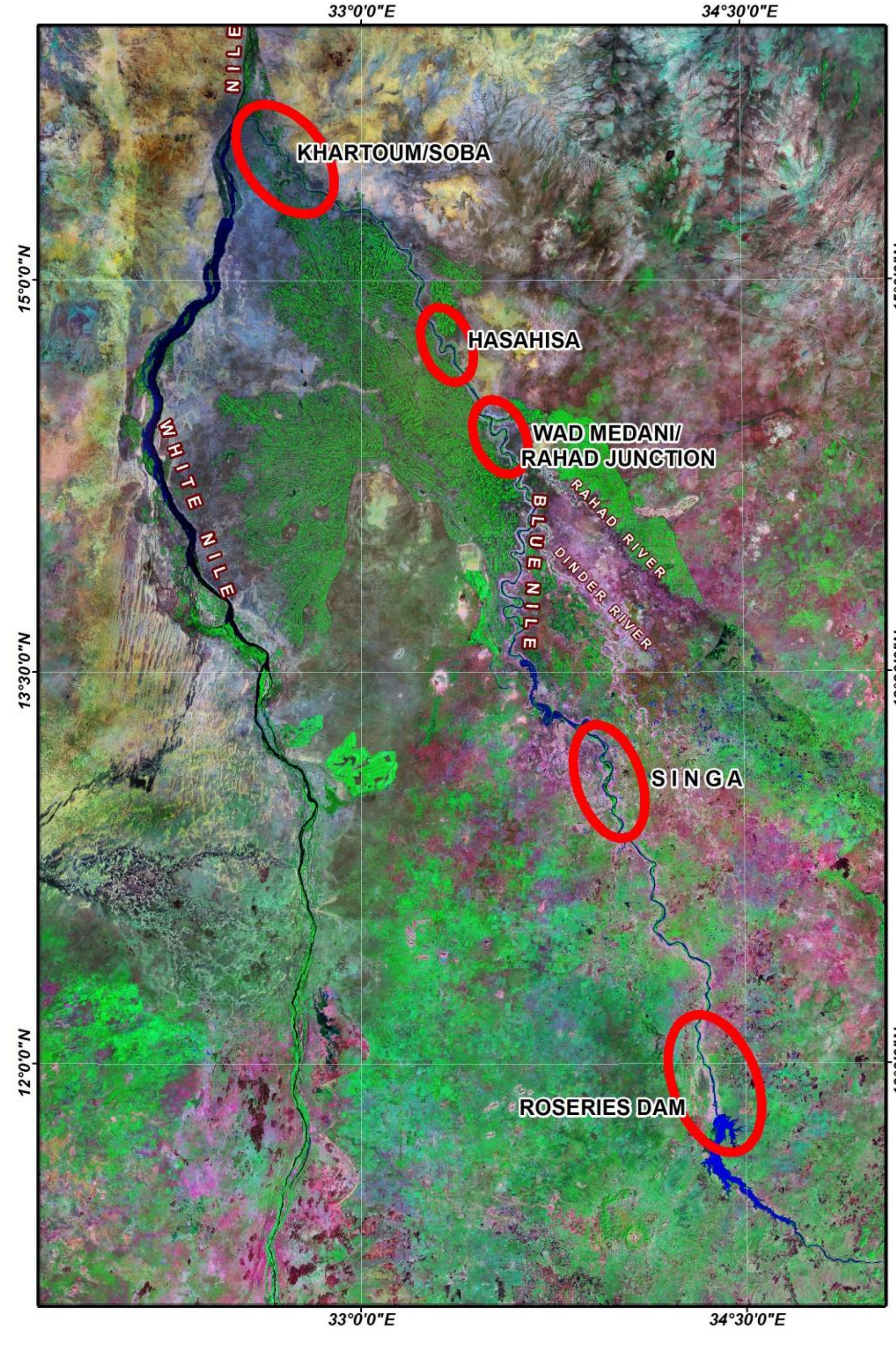


Figure 2-3: Pilot study areas in Sudan

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 is shown in ***Figure 3-1***. The methodology for assessing flood risk involves the following main components:

- Data collection and field survey 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 analysis to determine peak flow magnitudes and frequencies;
- Hydraulic modeling to determine hydraulic profiles associated with frequency-based flows;
- 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.

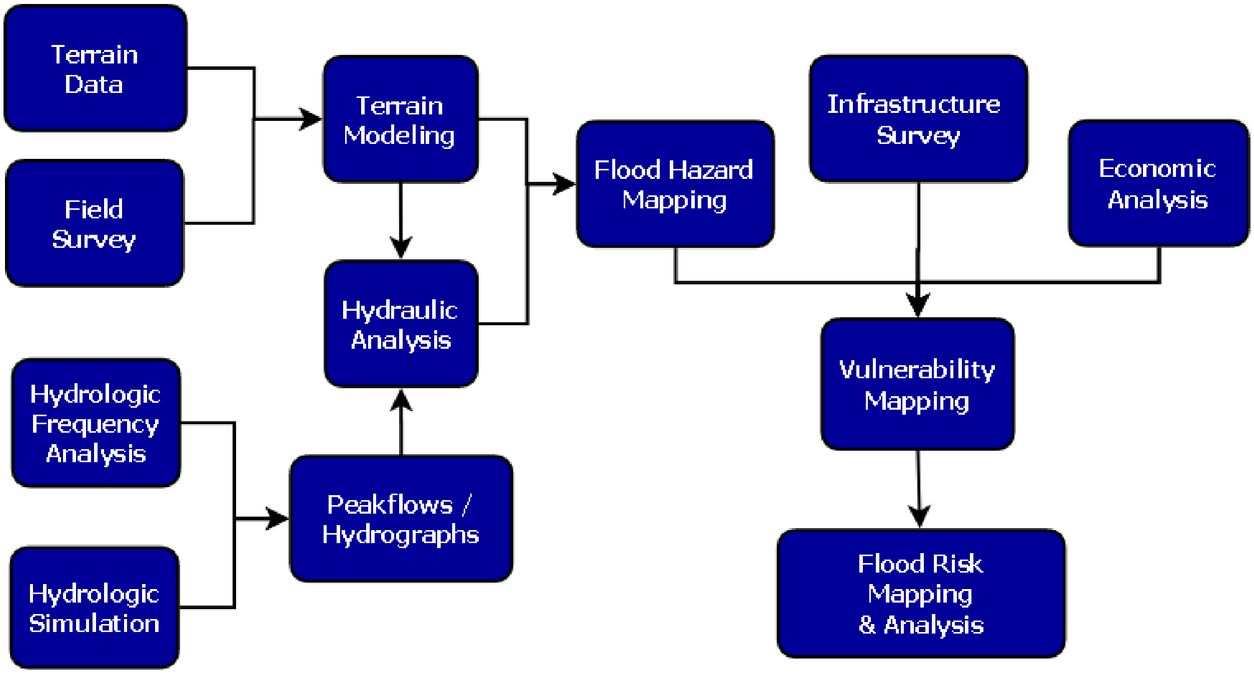


Figure 3-1: General approach for assessing flood risk

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) River Analysis System (HEC-RAS) program to perform one-dimensional flow analysis, the HEC-GeoRAS spatial pre- and 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-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 First Flood Risk Mapping Workshop

The Riverside/UNESCO-CWR team participated in an inception workshop in Khartoum, Sudan on Monday, March 2 and Wednesday, March 4. The main objective of the Khartoum 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 mechanisms). 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 to be considered in the execution of the work.

3.2.2 Second Flood Risk Mapping Workshop & Training

A final workshop was conducted in Khartoum on October 12 and 13, 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 is included in ***Appendix A***. A record of comments made by participants in the workshop is included in ***Appendix B***.

A training session was conducted in Addis Ababa, Ethiopia on October 19-22, 2009 to provide hands-on practice using the tools and following the procedures that were applied in performing the study. Topics included hydrologic modeling using HEC-HMS, terrain modeling in ArcGIS, hydraulic modeling using HEC-RAS and Geo-RAS and vulnerability and risk mapping using ArcGIS. The exercises were organized to allow participants to proceed at their own paces and to explore features of the software while proceeding through the steps of flood risk assessment and mapping. Multiple versions of many of the training datasets were prepared representing various stages of completion so that participants would have a consistent set of files for work on subsequent training tasks. It became clear during the training that the complexity of the tasks combined with the multi-disciplinary nature of the topics made it challenging for participants individually to perform all of the tasks involved in the flood risk mapping procedure. Prior experience with the individual software tools was noted to be essential and multi-disciplinary teams were most effective in performing the complete set of tasks. This would hold true for subsequent ongoing training efforts, and reflects the reality that a multi-disciplinary team was organized to perform the study documented in this report, and that no single individual possessed the composite skills necessary to perform all of the tasks embodied in the study.

3.2.3 Local Partner Coordination

During the course of the project, Riverside and UNESCO-CWR 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 (several times per week at certain stages of the study) 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 that organizes and streamlines model planning and development and provides an interface to manage the input and output of the individual HEC analysis tools. At the time of this study, it was only available in a beta software release. In that release, the documentation was not consistent with the user interface and there were some software instabilities and complex data requirements that were 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 second workshop in Khartoum, recommendations for unsteady flow analyses were proposed to study the effects of attenuation of peak flows and to assess the duration of flooding in the primary areas of risk due to flooding. Another anticipated benefit of the unsteady flow model was the ability to apply it for unsteady modeling of flows in a real-time forecasting system. In response, an unsteady flow modeling component was included as an additional component of the study.

4.0 SURVEY AND DATA COLLECTION

4.1 Flood History

Sudan experienced very severe flooding in 1878, 1946, and 1988 and most recently in 2003, 2006 and 2007. Flash flood and riverine flood impacts include loss of crops, cattle, agricultural machinery, loss of houses and properties, displacement of large communities, deterioration of health conditions and disruption of social life (SMEC, 2006). In 1998, heavy rains and floods occurred in 18 of Sudan's 26 States affecting over one million people. The states most affected were White Nile, Kassala, Gadaref, Sennar, Khartoum, and North Kodofan (SMEC, 2006). Flooding of 2006 in Khartoum exceeded flood levels recorded in 1988, one of the heavier floods previously experienced in the Sudan (SMEC, 2006).

4.2 Topographic 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. A full data inventory was included in the project inception report. The following data were collected and processed:

4.2.1 1992 Field Survey Data for the Blue Nile River

Data used in the configuration of the Flood Early Warning System (FEWS) developed for the River Nile in 1992 were retrieved. A total of 87 field-surveyed cross-sections for the Blue Nile from Roseires Reservoir to Khartoum were available from this system. The cross-sectional data were available in distance-elevation format for each cross-section. As such, there was limited information with which to locate the specific cross sections geographically on a map for subsequent integration with other data sources for the development of a terrain model, for hydraulic modeling, and for inundation mapping.

In order to use these cross-sectional data for the study, it was necessary to geo-reference the location of each cross section. First, the location of the most upstream cross-section just downstream for Roseires Reservoir was plotted. Then the remaining cross sections were located along the centerline of the river according to the available distance between adjacent cross sections. A discrepancy of about 7 km between the total reach length based on the GIS and the total reach length described by the cross section spacing was found for the 545 km river reach. This error was equally distributed among the 87 sections resulting in an adjustment of about 12.9 meters per kilometer in the horizontal alignment of the cross-sections. The plotted cross-sections were geo-referenced using the approach outlined in ***Appendix A***.

4.2.2 2007 Bathymetric Survey for the 25 Km Blue Nile River Reach between Khartoum and Bagair

A recent bathymetric survey was performed by the Dam Implementation Unit (Sudan) in association with Ministry of Irrigation and Water Resources (MOIWR Sudan). This survey covers a 25 km reach between Khartoum and Bagair and is a very dense bathymetric survey collected at an interval of 100 m. The available data are in distance-water depth format for each cross-section. The data were geo-referenced using the same approach outlined in the previous section. Almost no error or shift was encountered because of the large amount of cross sections and the short distance between cross-sections.

4.2.3 2007 Bathymetric Survey for Roseires Reservoir

A bathymetric survey was performed by the Dam Implementation Unit in association with MOIWR for Roseires Reservoir. The survey covers a reach of about 110 km upstream of Roseires Reservoir with geo-referenced data. The data were pre-screened to check for the right datum projection (WGS-UTM84) and a number of referenced points were utilized to verify the accuracy of the data.

4.3 Field Survey

After collecting and analyzing the available topographic data, a field survey was performed to supplement the available data and verify the accuracy of existing river cross-sections. The survey at each river cross-section was tied to a control point of known elevation. For the purpose of consistency, the Elevation Datum was chosen to be a MOIWR reference datum because all the previous cross-section surveys were based on MOIWR elevation data. There is a vertical shift of 3 meters between the survey datum and MOIWR datum.

The availability of benchmarks along the Blue Nile is limited and most of the benchmarks described in the National Survey Department Handbook are either unavailable or destroyed. Based on this fact, more reliance were given to known control points such as flow gauging stations and hydraulic structures including pumping stations or irrigation features in close proximity of the river. A total of 42 additional river cross-sections along the Blue Nile River were surveyed. The additional cross sections were at a closer spacing and extended further into the floodplain than previous surveys. The selection of the additional surveying sites included the pilot areas outlined in ***Section 2.5*** as well as 13 select locations along the Blue Nile that corresponded with known control points. The locations of the field-surveyed cross-section were chosen based on proximity to control points of known elevation, they were distributed throughout the reach for comparison with historical cross sections, and they were taken with a higher density in pilot areas. ***Figure 4-1*** highlights the locations and layout of the additional river cross sections and ***Appendix D*** provides details of the collected field surveyed data.

4.4 Topography and Soils

The landforms of the Blue Nile have predominant characteristics resulting from a combination of fluvial erosion and constructive action forming flood plains. The flood plains are formed once the river attains a graded position. A classification of the topographic characterization of reaches along the Blue Nile is detailed in ***Table 4-1***.

Table 4-1: Topographic characterization of reaches along the Blue Nile

Reach	Length	Description
Ethiopia to Roseires Dam	107 km	Incised in rock and shows a minimum of lateral erosion and deposition with very minor flood plains.
Roseires to Singa	203 km	Drops 24 m and has a meandering nature in a clay plain characterized by lateral erosion and deposition, forming flood plains on the inner curves and bank erosion in the outer curves.
Singa to Sennar	90 km	Meandering channel characterized by pronounced shifting from west to the east with many remnants of ox-bow lakes and abandoned channels.
Sennar to Hag Abdalla	108 km	Characterized by many bends and ox-bow lakes at shorter distances. In this portion, the Dinder River joins the Blue Nile.
Sennar to Wad Medani	66 km	Characterized by many meanders and severe gully erosion forming Kerib land on both banks. The Rahad River joins the Blue Nile at Wad Medani.
Wad Medani to Hasahisa	47 km	Characterized by moderate meandering and both towns are located in pronounced bends.
Hasahisa to Khartoum	157 km	Characterized by wider meander bends.

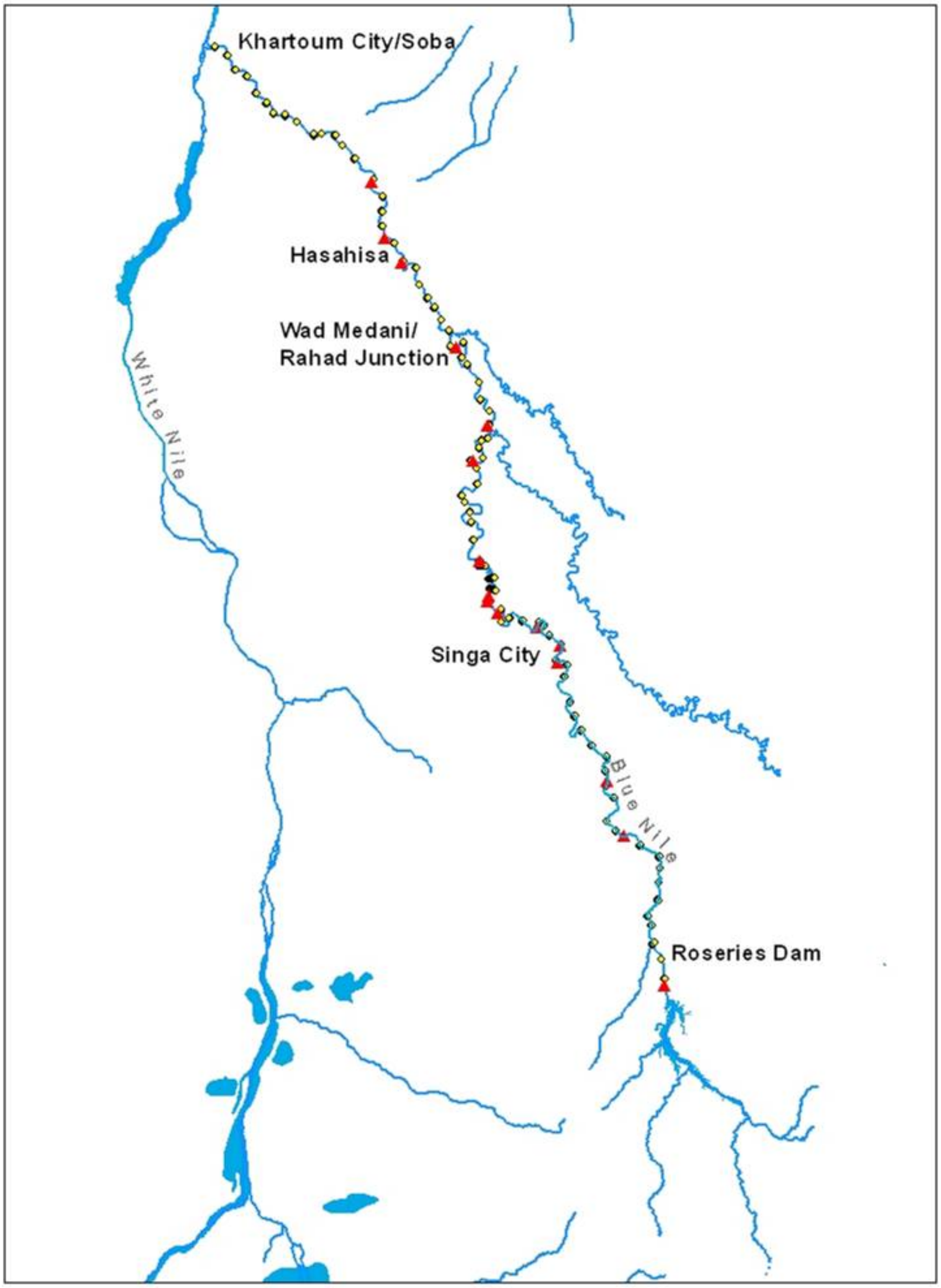


Figure 4-1: Layout of original cross-sections (yellow) and surveyed locations (red)

The general topography and soils of the flood plains of the Blue Nile can be classified into five geomorphic units: Recent Terrace, Upper Terrace, Sand Bars, Abandoned Channels, Ox-bow Lake, and Central Clay Plain. ***Table 4-2*** lists these classifications and their associated description.

Table 4-2: Geomorphic units of the Blue Nile

Geomorphic Unit	Description
Recent Terrace	The recent terraces are narrow strips along the Blue Nile. The topography is almost flat. The soils are mainly silt loam (Entisols). The recent terraces are narrow strips that appear at lower levels with the sand bars. The recent terraces are sown with vegetables and, together with the sand bars are subject to complete disappearance as a result of high flows.
Upper Terrace	The upper terraces occupy higher positions up the recent terraces with vertical slope. It varies in its extent with almost flat to gently undulating. The soils are mainly silty clay loam (Entisols). The upper terraces are about 2 meters above the low water level. These terraces include agricultural activities such as horticulture (Citrus, Mangoes, Guava, and Bananas) and fodder (Alf Alfa and Abu Sabein). The land use is irrigated agriculture pumped by gas or electric pumps. Diary and chicken farms are also located in the upper terraces. The vegetables are also grown in these terraces near large towns.
Sand Bar	The sand bars occur on the inner curves adjacent to the recent terrace. The topography is gentle slope to slightly undulating. The soils are sand to loamy sand (Entisols).
Abandoned Channel	The abandoned channels occur as elongated concave shape along the Blue Nile. The topography is generally sloping concave. The soils are generally expansive clays more than 60 % clay (Vertisols). The sunt (Acacia nilotica) occur mainly in abandoned flood channels. On the elevated areas, they are planted with Banana plantations.
Ox-bow Lake	The ox-bow lake has a semi circular shape occurring near the Blue Nile. The soils are mainly expansive clays with less that 60 % clay (Vertisols).
Central Clay Plain	These have flat topography with steep slopes to the Blue Nile. The soils are clay with high clay percentage (Vertisols). These clay plains have no relation with the present flood plains of the Blue Nile. They occur on high positions of about 5 to 6 meters above the low water level in the Blue Nile. There are two kinds of agricultural activities, irrigated and rain fed agriculture. All major irrigated agricultural schemes and the rain fed schemes are located on the clay plains. The main irrigated crops are cotton, sorghum, wheat, groundnuts, sugar cane, and vegetables. The main crops under rain fed agriculture are sorghum and sesame. All these crops are of high value but are seldom subjected to flooding.

The flood plains of the Blue Nile are entrenched in the central clay plain where irrigated and rain fed agriculture are practiced. There are degraded lands between the flood plains and clay plains. These lands are severely dissected as kerib land exposing the $CaCO_3$ substratum or with the top fertile soil eroded to expose rocky land, khors, or jebels and their pediments and bare land. None of those parcels are shown as being under any land use, with no associated economical value and no associated damage.

4.5 Infrastructure and Vulnerable Structures

As part of the 2009 field surveyed, land use and infrastructure data were collected. These data are documented in ***Appendix D***. Land used in flood prone areas includes fodder, vegetable and fruit farms, chicken farms, residential development, government offices, and public service centers such as schools, religious centers, markets, and recreational facilities. Flood control structures such as earth embankments along the river were also identified. From all the sites surveyed, it appears that the land cover for the Medani and Singa areas consists mainly of buildings. The other sites are mainly covered by agricultural land.

A field visit was conducted on both banks from Khartoum to Soba and Khartoum to El Alfun to verify the identification of crops. Conversations with farmers were carried out about the damage of floods, crop production, and prices. A detailed description of the agriculture classification and economic analysis can be found in ***Section 7.0***.

5.0 TERRAIN DEVELOPMENT

Hydraulic modeling and flood mapping require an accurate digital elevation model (DEM) from which to extract cross-sections for modeling and onto which the flood surface can be mapped. 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 because available DEMs that cover the required area typically do not have the required resolution to represent the river channel (and rarely include the shape of the channel beneath the water surface), while most river surveys do not extend far enough into the floodplain to represent the area that would be flooded by extreme events. An effective option for meeting both requirements of the terrain model is to combine detailed survey data within the channel with an available DEM for the floodplain area.

A 90-meter resolution DEM is available from the Shuttle Radar Topography Mission (SRTM). This dataset has been widely used, tested, and quality controlled. Its availability for the entire floodplain of the Blue Nile makes it a good primary data source for a study of such extensive scope. During the study, 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 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. Sample points were collected across the 30-meter and 90-meter DEMs. The difference between the sample elevation points was calculated and in most cases revealed a large error. 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. Visual inspection of the terrain revealed numerous anomalous features, such as deep depressions and large peaks that are not found in the 90-meter dataset and that are of a larger scale than the resolution of either DEM. This led the study 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.

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). For the terrain development task, the Riverside team created a DEM in TIN format.

5.1 TIN Creation

The accuracy of the hydraulic modeling and flood mapping depends on the underlying topographic data. The terrain should have sufficient detail to ensure the quality of the hydraulic modeling and should cover enough area to map properly the extent of floodwaters. 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 while the 90-meter DEM was used to capture the floodplain.

For the Blue Nile, the spacing of surveyed cross sections results in reaches of river with meanders and bends that are not represented by the geo-referenced cross sections but that are visible on satellite images. The satellite images permit the identification of areas where the 90-meter DEM is valid, in contrast with areas that are covered by water where the general shape of surveyed cross sections would be a better representation of the underlying bathymetry than the DEM. To accommodate an interest in using the satellite imagery to enhance the quality of the terrain model that would be developed, and to do so within the constraints of a study such as this, where terrain development is only one component of study with a large spatial extent, a procedure was developed to utilize the facility of the hydraulic model for interpolating cross sections as a means to enhance the quality of the final terrain model that would be used for flood hazard mapping and risk analysis.

A multi-step procedure was used to create a TIN from multiple sources of elevation data. The following steps were used:

3. Generate a TIN in ArcGIS using the survey data exclusively (no DEM data for the floodplain). The TIN generation is an automated GIS process that generates a preliminary TIN whose exclusive purpose is to incorporate the survey data into a surface for extraction into HEC-RAS.
4. Digitize the centerline and bank lines of the river from satellite imagery. This step adds additional information about river alignment and meandering that is not available in the reaches between surveyed cross sections.
5. Delineate cross sections in GeoRAS/ArcGIS that correspond to surveyed cross section locations, but that are confined within the bank lines drawn in step 2
6. Extract the cross sections, bank lines, and river centerline to RAS. This step provides HEC-RAS with all of the original cross section data in a geo-referenced form.
7. Interpolate additional cross sections at 100-meter spacing between surveyed cross sections, following the river centerline, and export the cross sections to GeoRAS/ArcGIS. In many sections of the river, the surveyed cross section spacing was greater than 6 kilometers, so this step resulted in the addition of more than 60 interpolated cross sections between each surveyed cross section. In areas with surveyed cross sections that are spaced more closely than 100 meters (such as most of Khartoum), no interpolation is performed.
8. Delineate breaklines in ArcGIS at the centerline and at previously defined bank lines with elevations defined by surveyed and interpolated cross sections.
9. Extract elevation point data for the floodplain from the 90-meter SRTM gridded DEM.
10. Generate a multi-source TIN surface by combining the breaklines and cross section data points with elevation data from the 90 meter SRTM gridded DEM using ArcGIS 3D Analyst.

The resulting TIN can be used for extracting cross sections that extend into the floodplain, as well as for mapping flood hazard using results from a hydraulic model. ***Figure 5-1*** illustrates the final surface, together with the source DEM and cross sections for a portion of the Blue Nile.

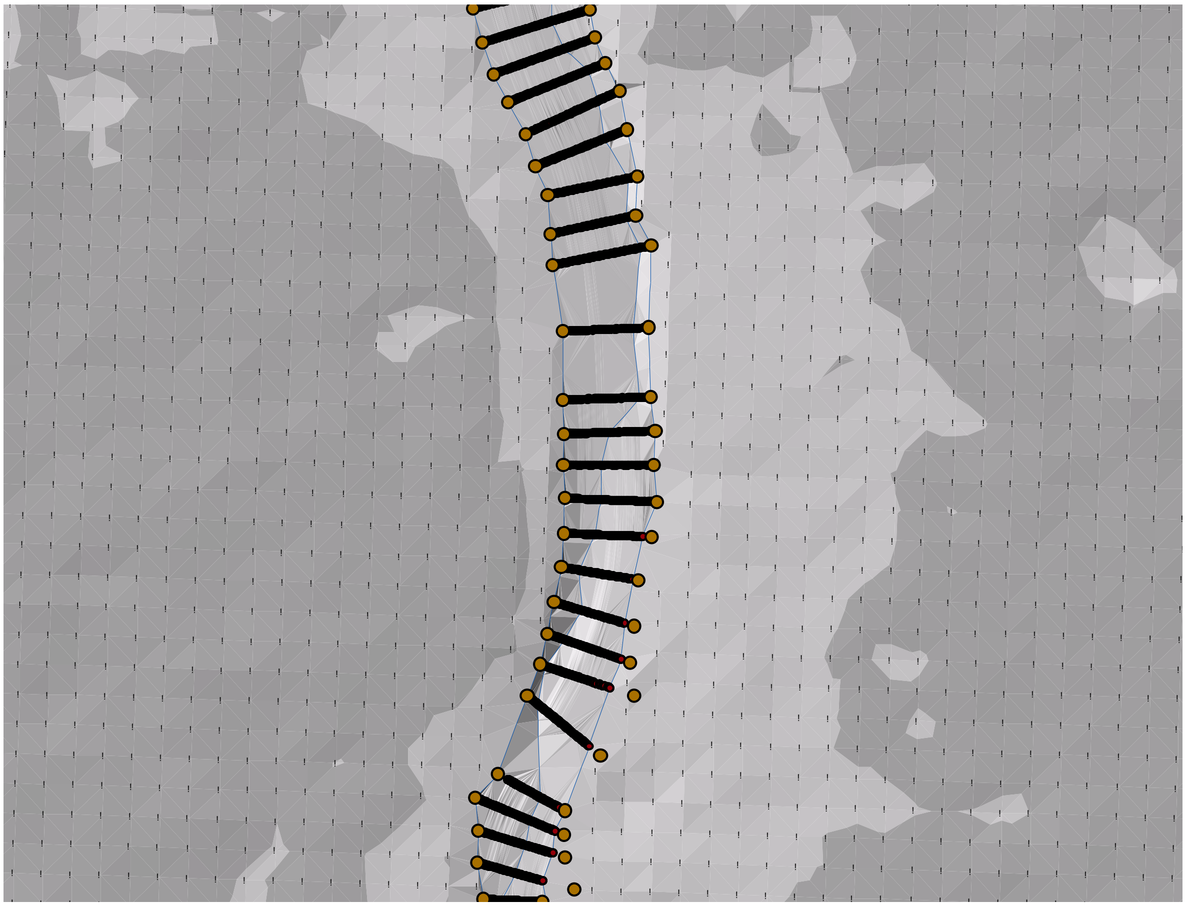


Figure 5-1: Source DEM and Channel Survey used to create final TIN for a portion of the Blue Nile

The interpolation of the TIN points from the breaklines between cross sections results in some generalization of the cross section into a triangular shape between cross sections in the final TIN. This aspect of the TIN does not impact the hydraulic model, which considers only the specific cross section shapes, and it does not impact the flood extent mapping because the effect is seen only within the low-flow channel. The effect is seen, however in the flood depth maps.

The final TIN was used as the basis for extracting cross sections for the hydraulic model, and subsequently in mapping the flood hazard and computing vulnerability.

6.0 HYDROLOGIC MODELING

6.1 Flood Frequency Analysis

The purpose of the hydrologic analysis was to develop discharges that are representative of peak flows for floods for a range of probabilities. The overall scope of this project, with a focus on the integration of tools and techniques from multiple disciplines into a repeatable, adaptable procedure for flood hazard and flood risk mapping, did not warrant nor permit an exhaustive hydrologic analysis.

For this study, therefore, a hydrologic analysis of stream gages along the Blue Nile in Sudan was performed to estimate the magnitude of peak floods corresponding to 2, 5, 10, 50 and 100 year return periods. 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 along the Blue Nile, a basic flood frequency analysis was undertaken.

6.1.1 General Methodology

A flood frequency analysis was performed to estimate the magnitude of the flood flows corresponding to recurrence intervals of 2, 5, 10, 50, and 100 years. The peak flow data extracted from the daily streamflow records described in Section 2.3 were analyzed to identify the underlying statistical distribution. Of the six gage stations analyzed, four of the stations are located along the Blue Nile (Eddiem, Rosaries, Sennar, and Khartoum), while the other two are located on tributaries of the Blue Nile. By the time the river reaches the Eddiem gage in Sudan, it is large enough that annual peak runoff events typically occur over the course of several days. Consequently, significant differences between the daily peak flows and instantaneous peak flows are not expected, and a frequency analysis using daily peak flows was considered adequate.

6.1.2 Available Data Used in the Analysis

The Blue Nile within Sudan territory is gauged at several control points. Records start as early as the beginning of the 20th century. ***Figure 6-1*** shows the location of the stations along the Blue Nile and within the entire Nile system. The Ministry of Irrigation and Water Resources (MOIWR) is the sole authority for collecting, processing, and archiving the flow data. Data used in this study were provided by MOIWR. Time-series records for six key stations along the Blue Nile River and its tributaries were collected. These stations are:

- Eddiem gauging station along the Blue Nile river system at the Sudan-Ethiopia border
- Roseires Station, just downstream of Roseires Reservoir along the Blue Nile River
- Sennar station, just downstream of Sennar Reservoir along the Blue Nile River
- Khartoum Station, just upstream of the confluence with the White Nile along the Blue Nile River system
- Gwaisi station along the Dinder River (Tributary of the Blue Nile).
- Hawata station along the Rahad River (Tributary of the Blue Nile).

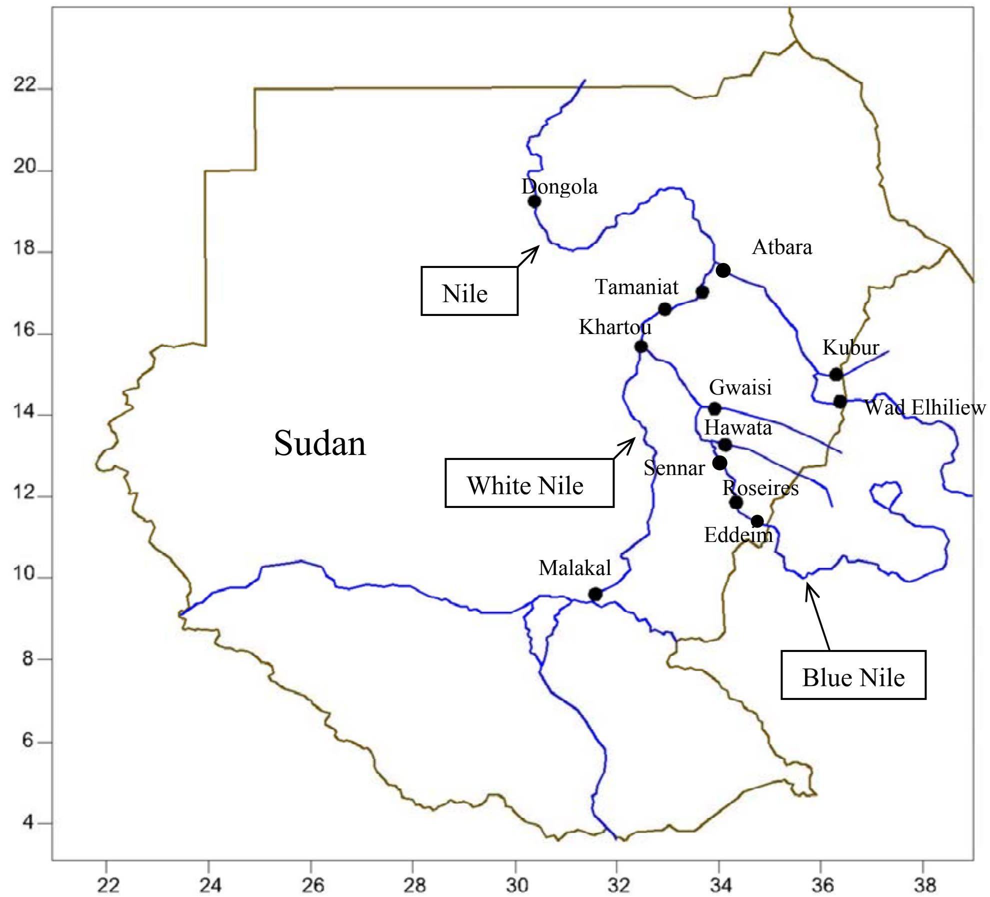


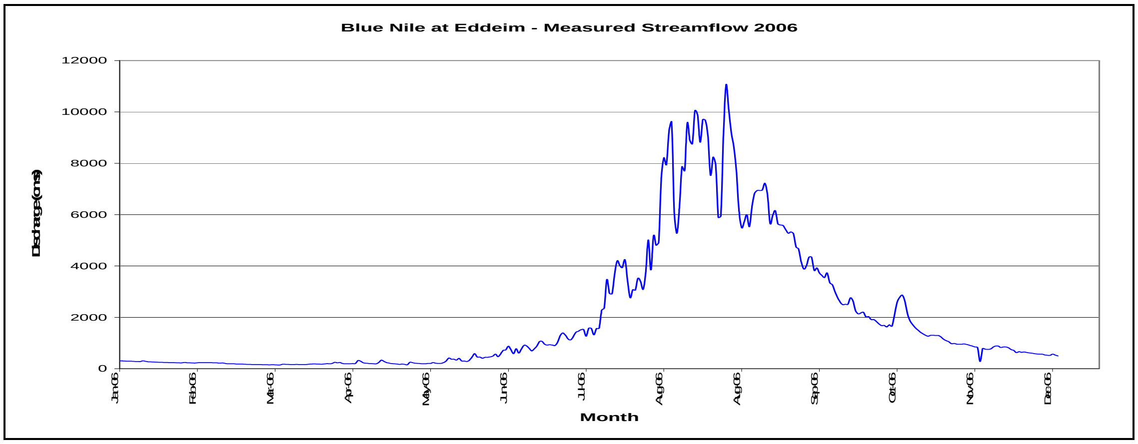
Figure 6-1: Locations of streamflow gages within the Nile Basin in Sudan

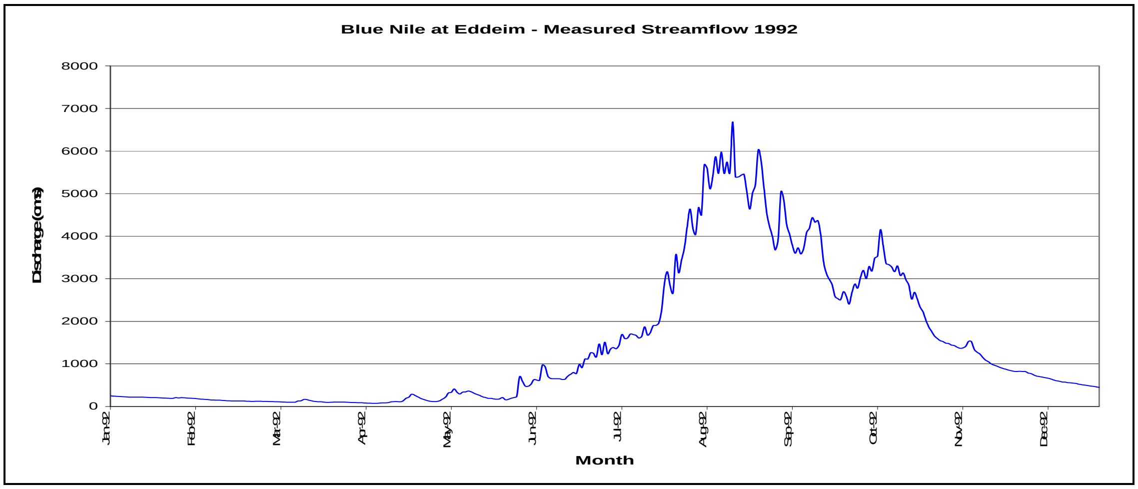
These data are available in daily format and the annual maximum daily flow series for each station were extracted from the raw data to perform a flood frequency analysis. ***Table 6-1*** lists the period of record and maximum streamflow values reported at the six selected stations.

Table 6-1: Period of record and maximum streamflow data at the six selected sites.

Station Name	Period of Record	Maximum Flow (Cumecs)
Eddiem	1965-2007	11052.68 in (2006)
Roseires	1967-2007	9384.14 in (2001)
Sennar	1968-2007	9699.07 in (2006)
Khartoum	1965-2007	11057.97 in (1975)
Hawata	1972-2006	205.73 in (1981)
Gwaisi	1972-2006	1064.01 in (1975)

Figure 6-2 through ***Figure 6-6*** show plots of annual hydrographs at Eddiem, Khartoum, and Sennar in the Blue Nile River and at Dinder and Rahad Rivers. Plots of high, medium, and low flow years are represented for each station. A consistent pattern can be observed within the basin with annual peak discharges occurring from about June to October. The large majority of the annual runoff occurs within this period mostly caused by heavy rains from the summer monsoons.





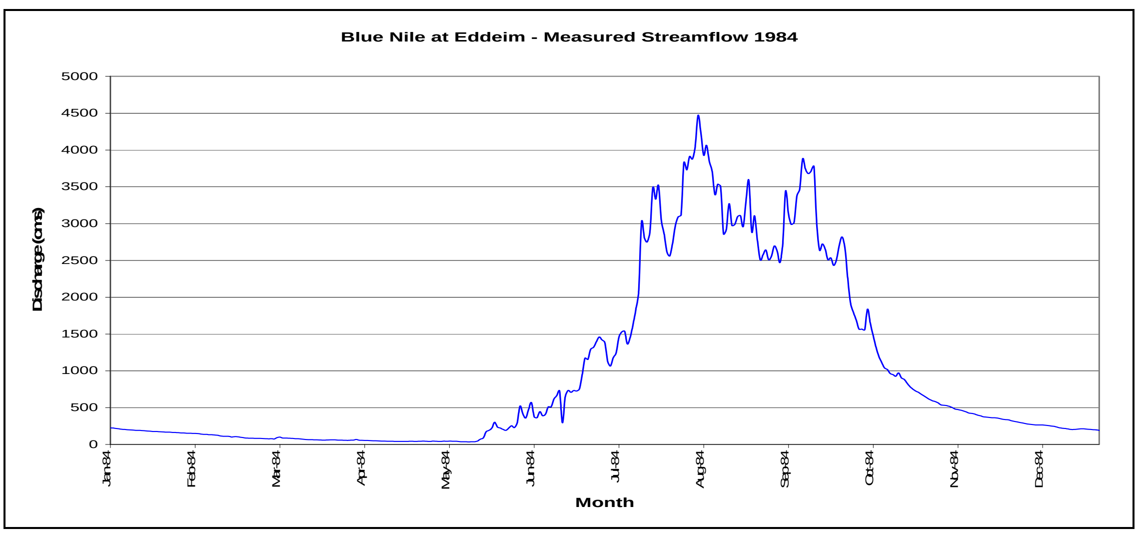
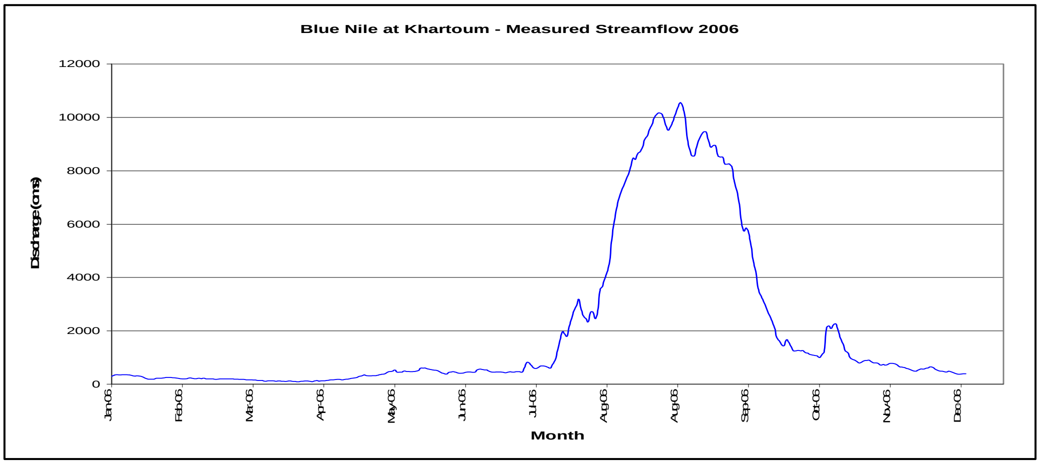
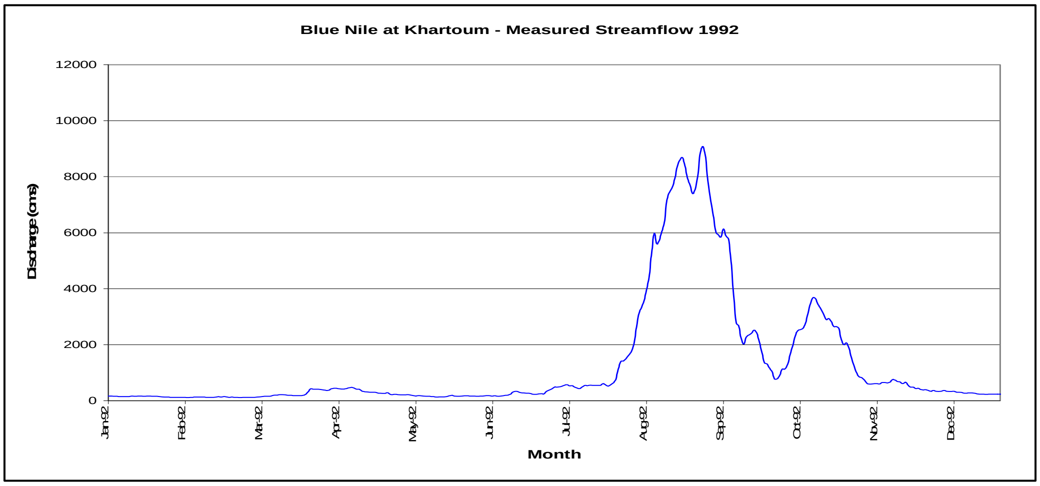


Figure 6-2: Annual flow hydrographs at Blue Nile at Eddiem for a high flow year (2006), a medium flow year (1992) and a low flow year (1984).





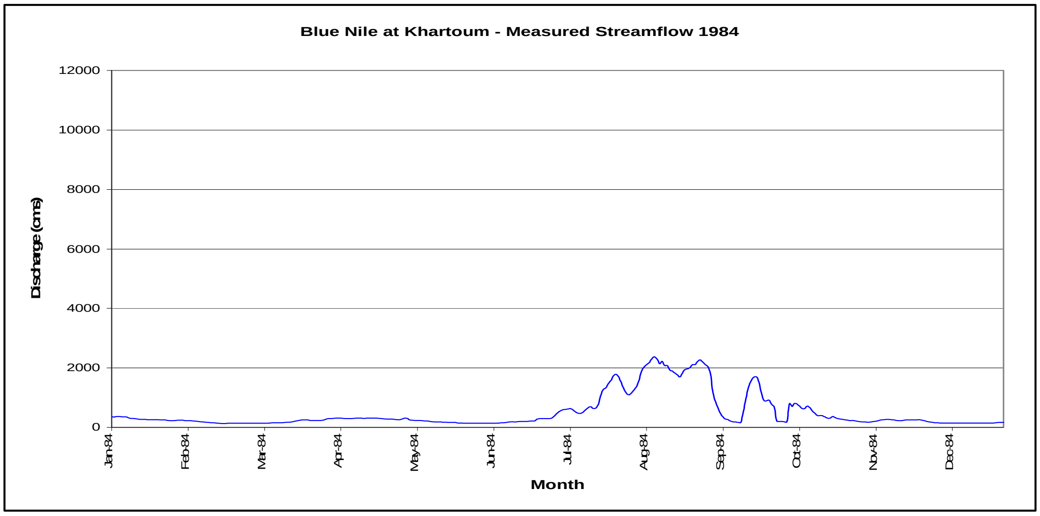


Figure 6-3: Annual flow hydrographs at Blue Nile at Khartoum for a high flow year (2006), a medium flow year (1992) and a low flow year (1984).

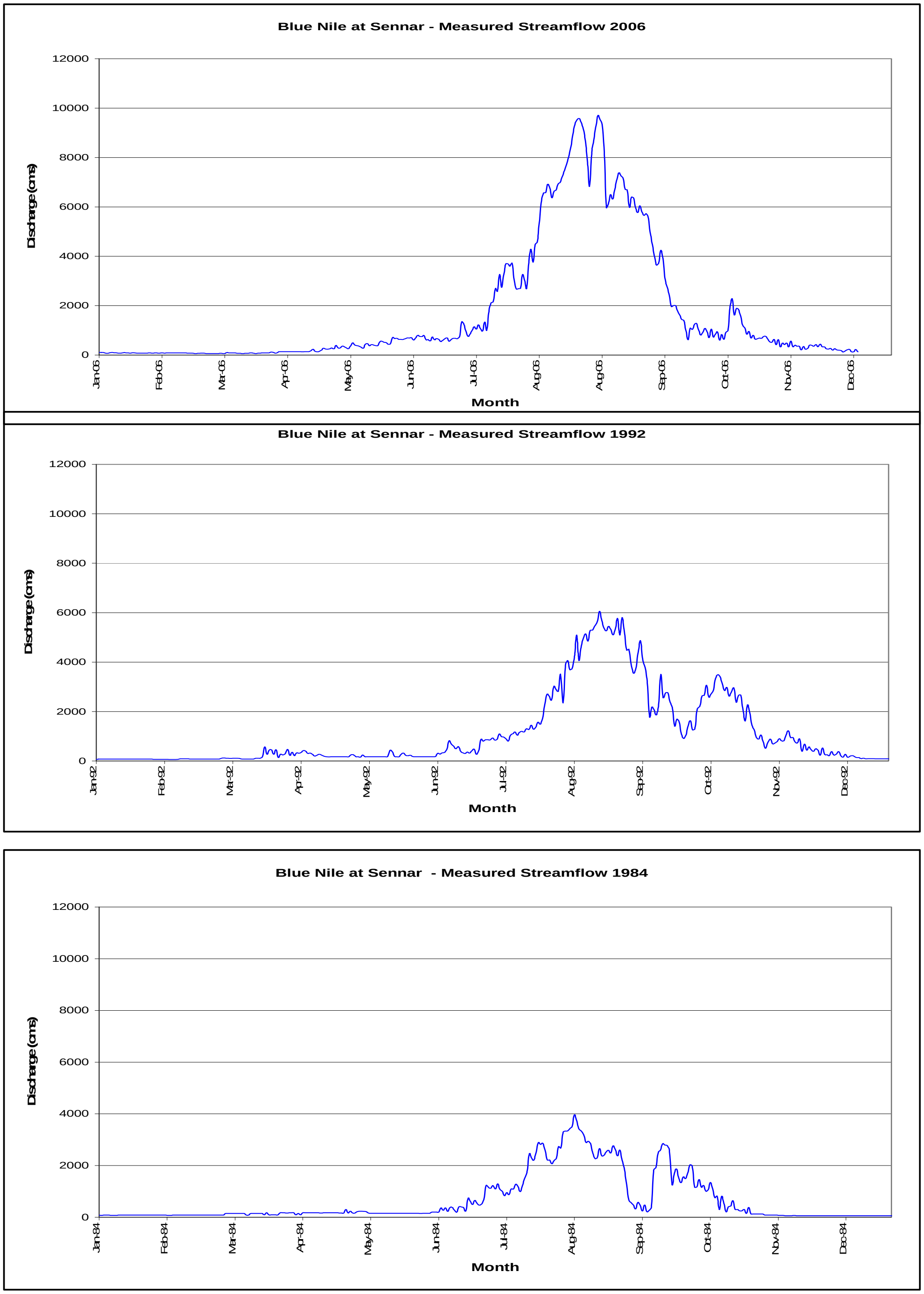


Figure 6-4: Annual flow hydrographs at Blue Nile at Sennar for a high flow year (2006), a medium flow year (1992) and a low flow year (1984).

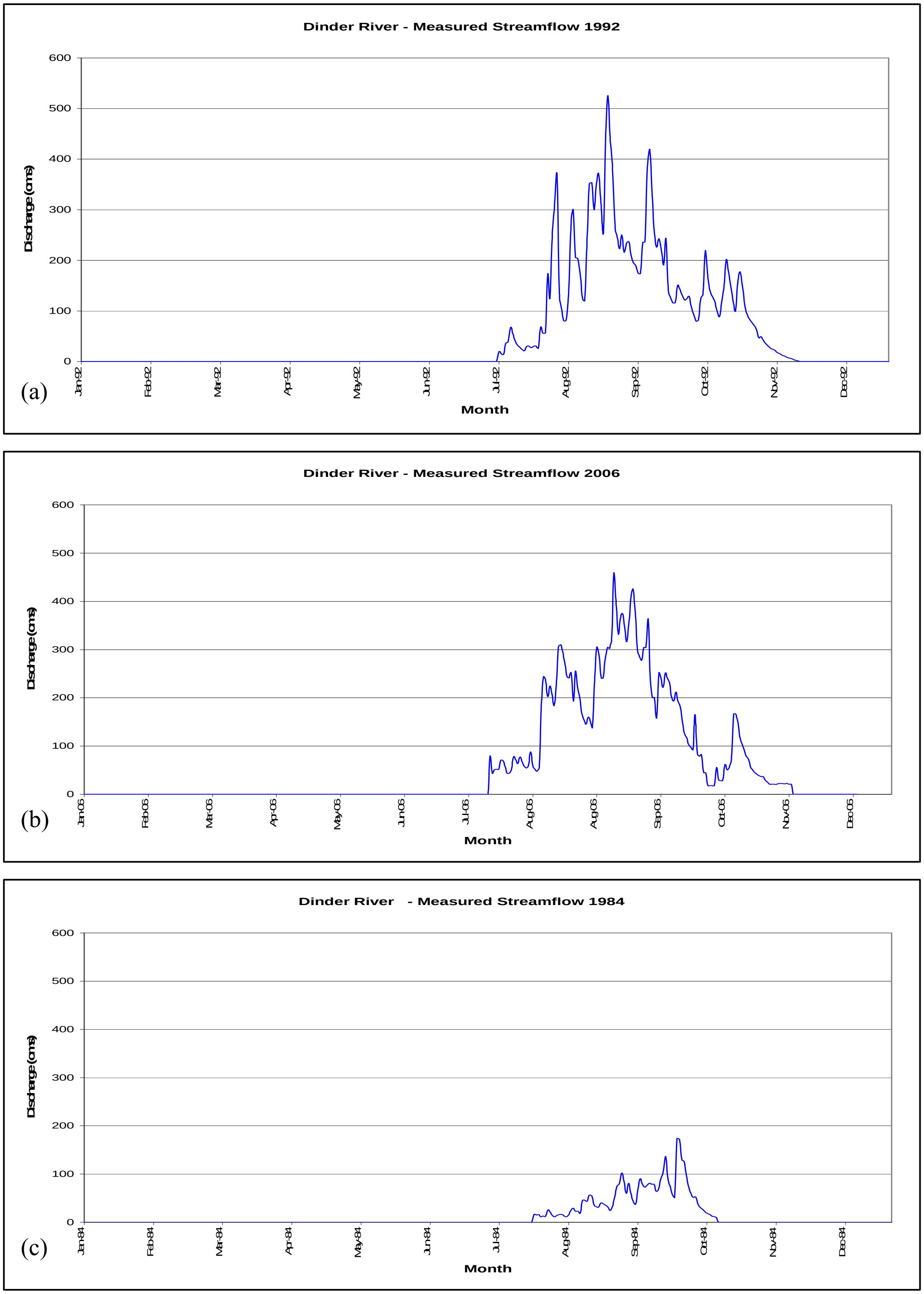


Figure 6-5: Annual flow hydrographs at Dinder River for a high flow year (2006), a medium flow year (1992) and a low flow year (1984).

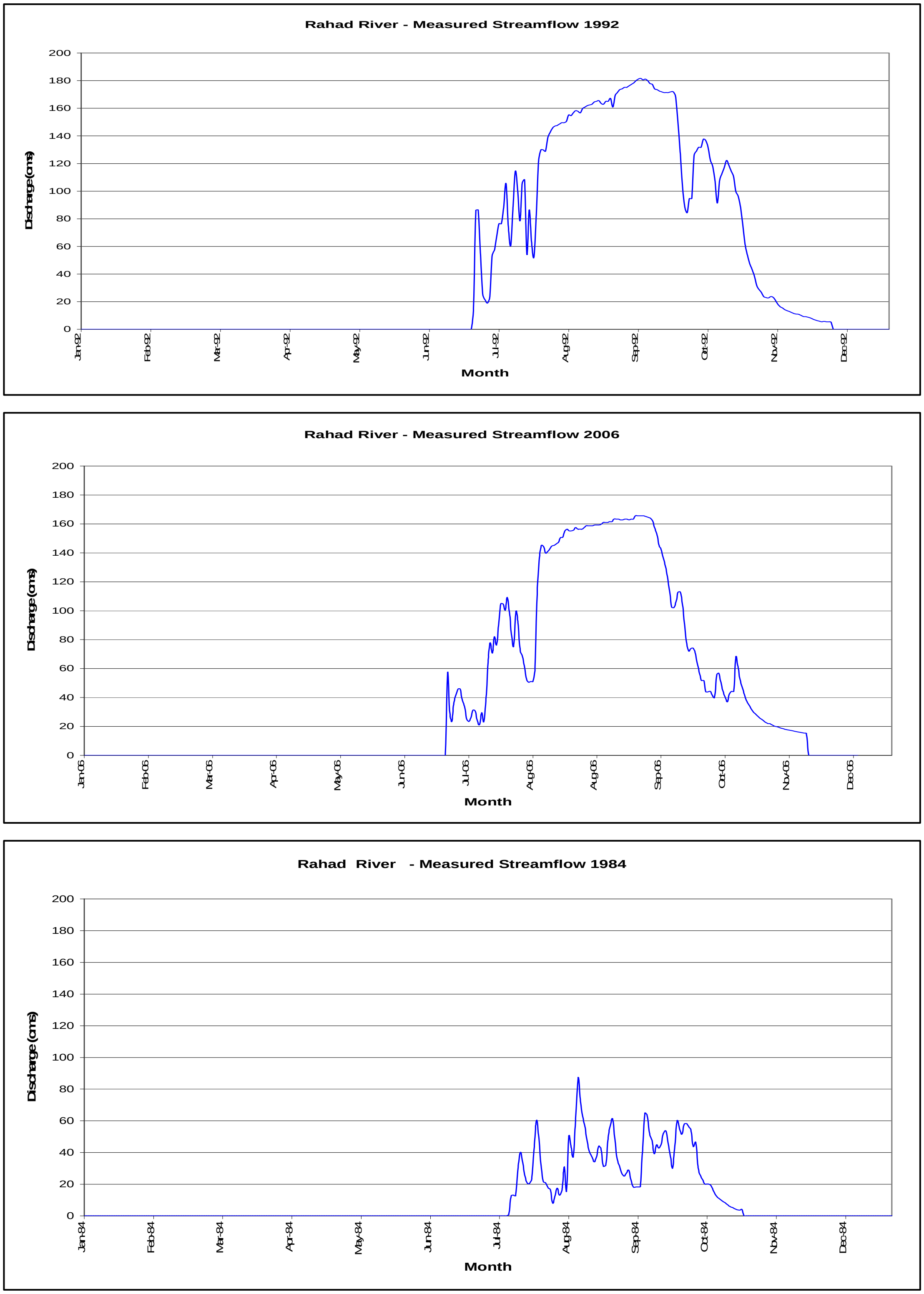


Figure 6-6: Annual flow hydrographs at Rahad River for a high flow year (2006), a medium flow year (1992) and a low flow year (1984).

Table 6-2 summarizes the sample statistics for the six streamflow gages considered in this study. The Log Pearson Type 3 (LP3) and Extreme Value Type 1 (EV1) statistical distributions were tested and their parameters were estimated using the method of moments. ***Appendix D*** summarizes in detail the equations used in this analysis.

Table 6-2: Sample moments from the streamflow data at six gage stations.

Station Name	Sample Moments			
	Sample Size, n	Mean	Standard Deviation	Skewness
Khartoum	43	7563.46	1795.90	-0.23
Sennar	40	6801.69	1431.58	-0.38
Roseires	40	6941.16	1645.08	-1.13
Eddiem	38	7658.10	1648.86	+0.36
Dinder	35	516.44	185.91	+0.42
Rahad	35	165.91	20.77	-1.43

6.1.3 Results

The Log Pearson Type 3 and Extreme Value Type 1 probability distributions were fitted through the data and the results were compared against the observed values. The probability distributions utilized for the flood frequency analysis are summarized in ***Appendix E***. ***Table 6-3*** shows the estimated quantiles for selected return periods using the candidate distributions for the six selected stations.

Table 6-3: Estimated Quantiles at different return periods using different distributions for six gage stations.

STATION NAME	2-yr Peak (CMS)	5-yr Peak (CMS)	10-yr Peak (CMS)	50-yr Peak (CMS)	100-yr Peak (CMS)
Khartoum					
LP3	7930	9140	9517	9830	9865
EVI	7918	8865	9888	12139	13090
Sennar					
LP3	6950	8106	8594	9237	9400
EVI	6607	7853	8677	10493	11260
Roseires					
LP3	7674	8058	8065	8410	8796
EVI	6717	8149	9097	11182	12064
Eddeim					
LP3	7510	9035	9935	11700	12386
EVI	7434	8880	9838	11947	12838
Dinder/Gwaisi					
LP3	517	685	766	885	919
EVI	491	657	766	1007	1109
Rahad/Hawata					
LP3	174	181	182	182	183
EVI	163	182	194	221	232

Plots of Peak Flow (Q) versus Return Period (T) produced by the Log Pearson type 3 distribution for all stations are presented in ***Figure 6-7***. The results for Hawata and Gweisi stations of the Rahad and Dinder Rivers are significantly smaller, because they are tributaries of the Blue Nile and their local catchments are smaller. Overall, as the return period increases the variation in peak flow among stations increases. The Eddiem station gave the highest flow peaks because the flow at this station is a natural unregulated flow. Downstream from Roseires peaks are reduced due to reservoir regulation and abstractions. The Khartoum station reflects contributions from Rahad and Dinder and hence it shows a tendency of higher flows than Roseires and Sennar.

Quantiles at Eddiem stations were selected for the hydraulic model as being representative for the entire downstream reach, although they are somewhat conservative for locations in the middle reaches. The LP3 distribution is a commonly used distribution for the analysis of annual peak floods. The LP3 and EV1 results for Eddiem station are very similar, as show in ***Figure 6-8***. Therefore, flows from the LP3 distribution were chosen for input to the hydraulic model at Eddiem. The 2, 5, 10, 50, and 100-year return period flows used for the hydraulic modeling are 7510 m^3/s, 9035 m^3/s, 9935 m^3/s, 11700 m^3/s, and 12386 m^3/s, respectively.

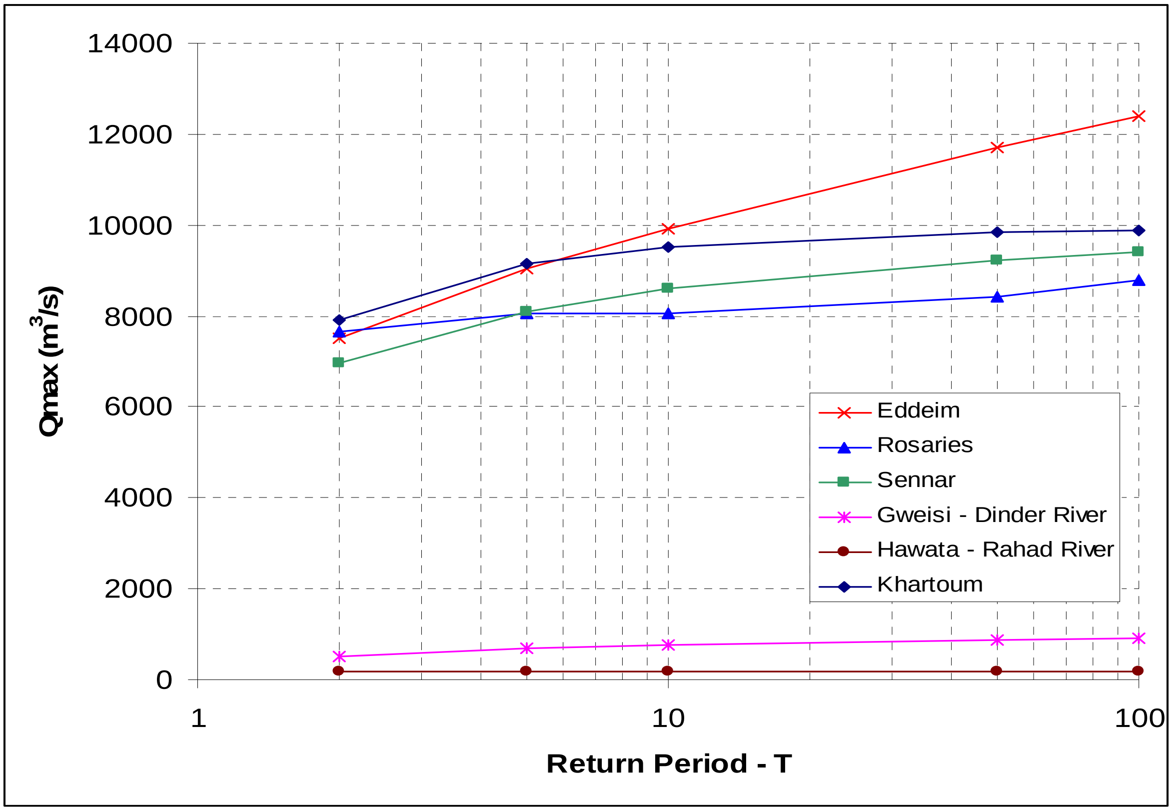


Figure 6-7: Q-T relationships based on LP3 distribution.

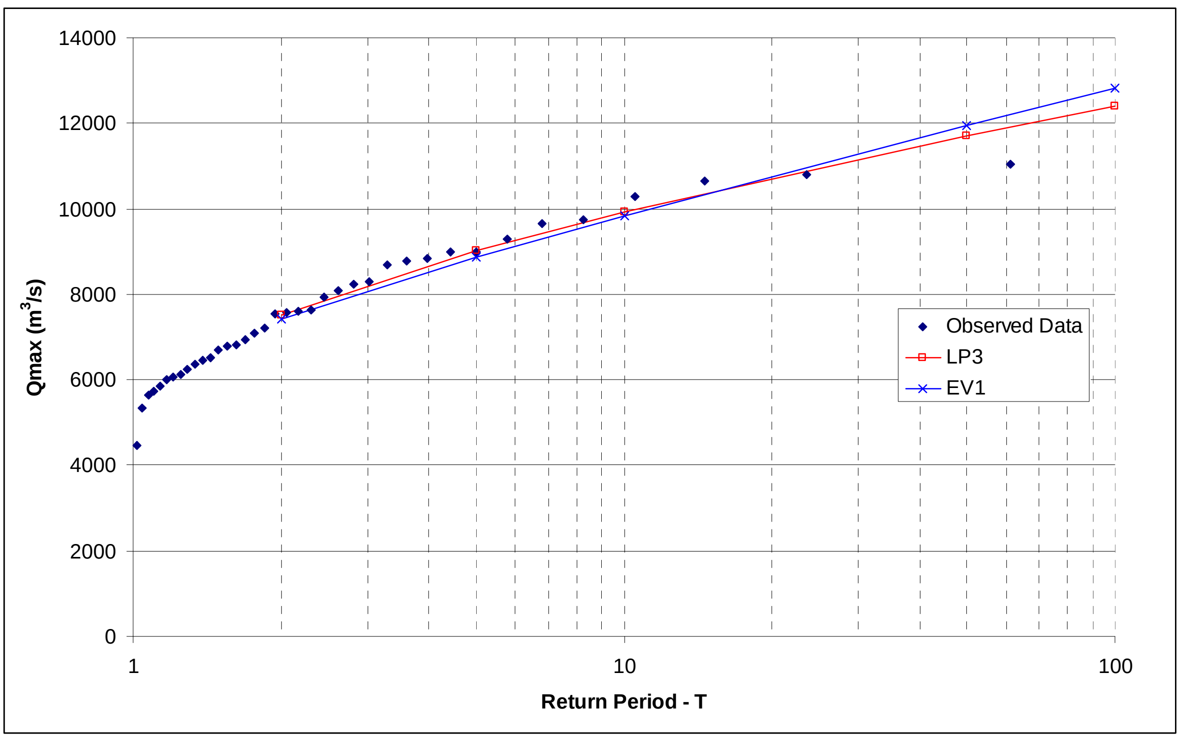


Figure 6-8: Comparison of observed data and LP3 and EV1 probability distributions at Eddiem station.

7.0 HYDRAULIC MODELING

The hydrologic analysis described in ***Section 1.0*** defines peak flood discharges that can be expected at varying return periods or frequencies. Hydraulic modeling is employed to estimate hydraulic characteristics of the flow in the river channel that would result from passing the discharge from each return period event through the river channel. The characteristics of importance for the flood risk mapping study include water surface elevation, flow depth, and flow velocity.

7.1 Methodology/Analysis Procedures

For hydraulic modeling, the Hydrologic Engineering Center River Analysis System (HEC-RAS) program was used to perform one-dimensional flow analysis. 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. The HEC-RAS / HEC-GeoRAS system has the ability to compute rapidly 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 thus produces useful hazard data for the risk assessment.

The HEC-GeoRAS tool was used to extract river geometry to the HEC-RAS model, including cross sections, river centerlines, and bank lines. The predicted inundation extent and water surface elevations, including information on depths that enable identification of flood hazard areas for floods up to and including the 100-year return flood event, were developed and output to HEC-GeoRAS for hazard mapping.

Modeling for frequency events is typically performed using a series of steady flows representing the peak flow for each return period. Because of the length of reach under study (More than 700 kilometers), and because of an interest in understanding the expected duration of flooding due to peak flows, an unsteady analysis also was performed to supplement the information derived from the steady flow analysis.

7.2 Hydraulic Model Development

7.2.1 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, and cross sections were digitized in HEC-GeoRAS. The river centerline was digitized to match the channel centerline as indicated by the field survey, supplemented by reference to satellite imagery. The bank lines represent the point where the river is considered "out of bank" and the river is accessing its floodplain for active flow. 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.

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 (***Figure 7-1***).

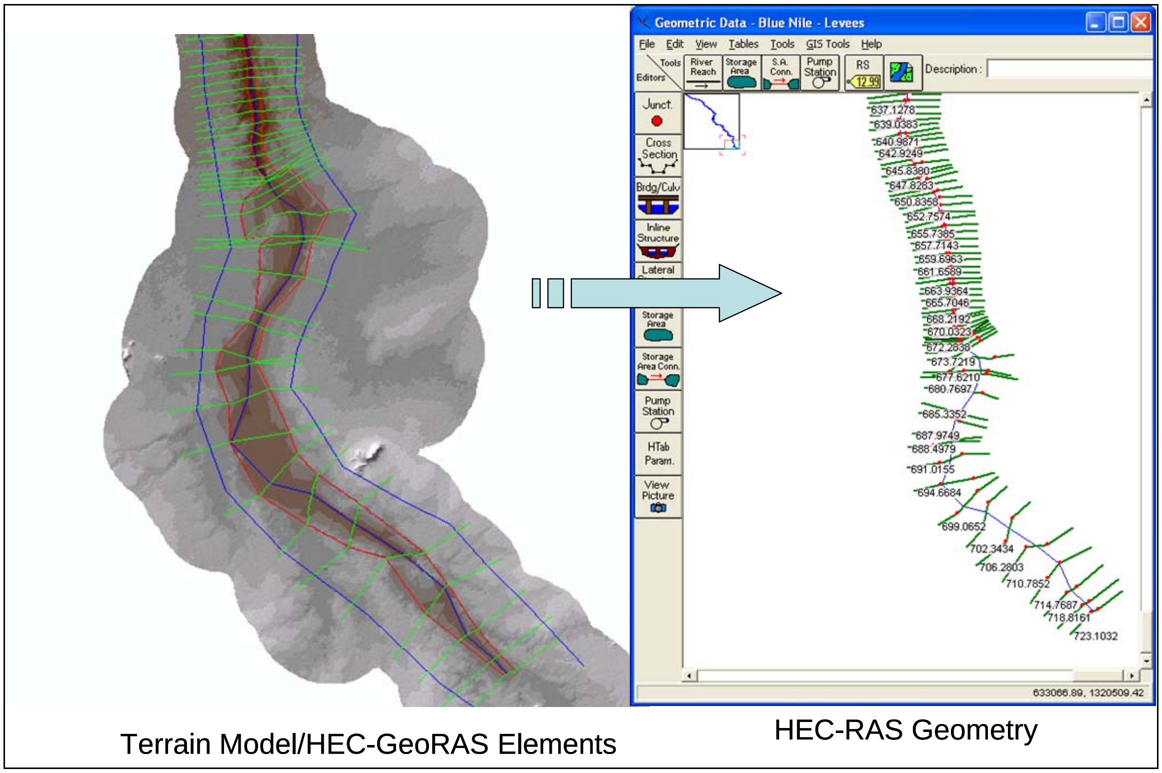


Figure 7-1: Illustration of HEC-GeoRAS/HEC-RAS model development

One of the main challenges of hydraulic modeling in areas with broad floodplains adjacent to rivers 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 a floodplain area 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 7-2*** and ***Figure 7-3*** show examples of the relationship between cross sections and inundated area for connected flow and disconnected flow areas, and demonstrate how inundation mapping 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).

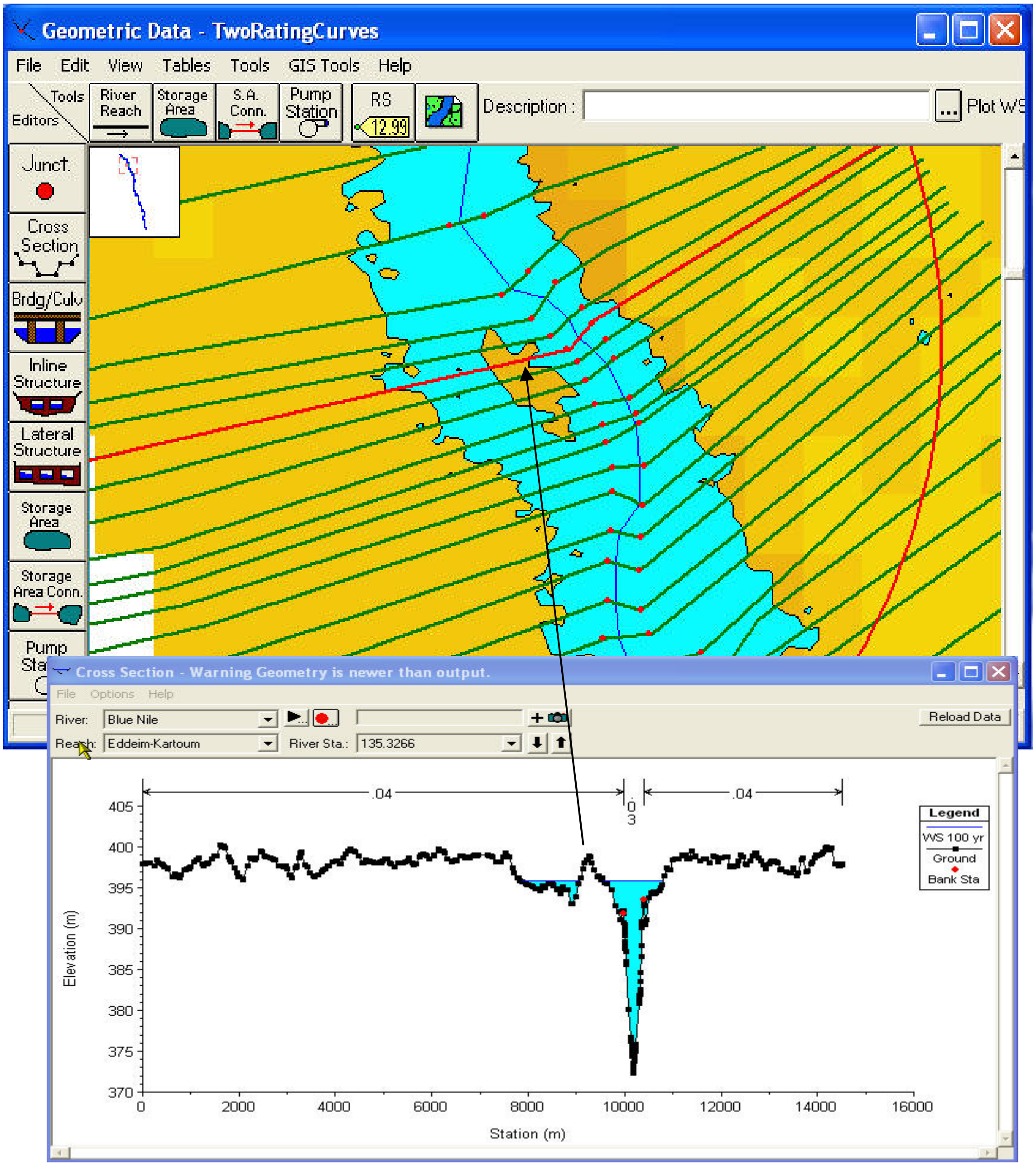


Figure 7-2: Example of hydraulic connectivity

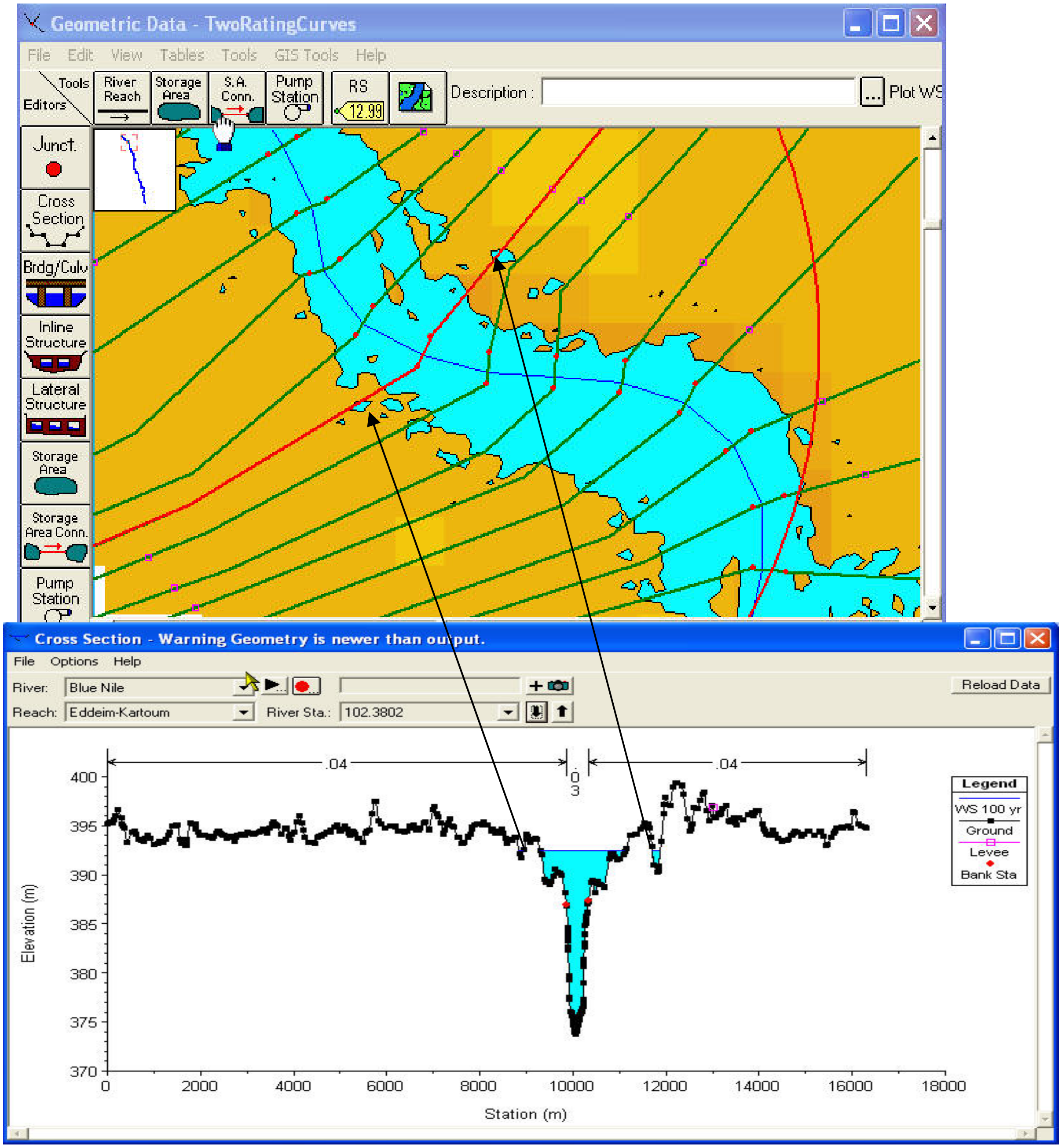


Figure 7-3: Example of a lack of hydraulic connectivity

In the river reach between Khartoum and the Hasahisa pilot area, the flow was constrained between levees that were defined in the left and right banks in the model. ***Figure 7-4*** illustrates the flow constrained to a location by a left and right levee. Flow would not be able to reach areas in the left and right sides of the channel at about stations 4000 and 15000, respectively. The levees, as defined in this case, are used as modeling tools to limit the flow to those parts of the terrain to which the river has access.

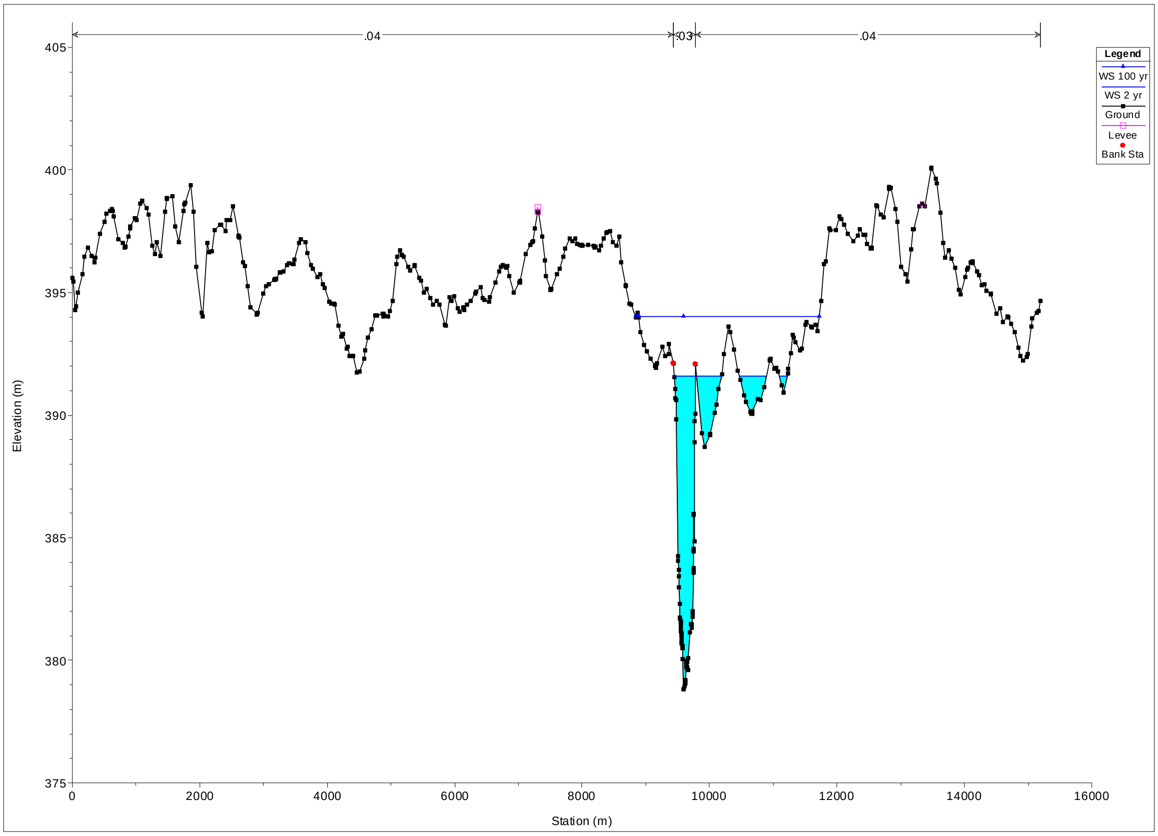


Figure 7-4: Cross section plot illustrating flow constrained within the levee points

7.2.2 Hydraulic Structures

There are two dams within the reach under study. Roseires Dam is the most upstream dam located about 550 km South East of Khartoum City, and Sennar Dam located about half way between Khartoum City and Roseires Dam. The operation of these dams has an effect on the flow regime of the Blue Nile. During high flows, the spillway and outlet works are fully open to allow the flood peak to pass and flush the sediment that gets trapped behind the dam to reduce siltation. The effect of these dams has been considered under both the steady and unsteady conditions.

7.2.2.1 Roseires Dam

Roseires Dam has gated spillway and deep sluices. The spillway has seven gates, each 10 m wide by 13.0 m high, located at level 463.70. The deep sluices consist of five gates, each 6 m wide by 11.5 m high, located at level 435.5.

In modeling the effect of the Roseires Dam, a single rating curve was developed to prescribe the total releases through the spillway and the sluice gates at different pool elevations in the reservoir. This curve corresponds to the fully open position of the gates and is shown in ***Figure 7-5***, together with the spillway and sluice gate curves. To avoid instability in the model, the total rating curve was modified to release low flows at higher pool elevations in the reservoir. To incorporate this information into the model, a rating curve boundary condition was used at the river station that corresponds to the location of Roseires Dam (station 671.804), such that the model computes the elevation at that particular station according to the rating curve.

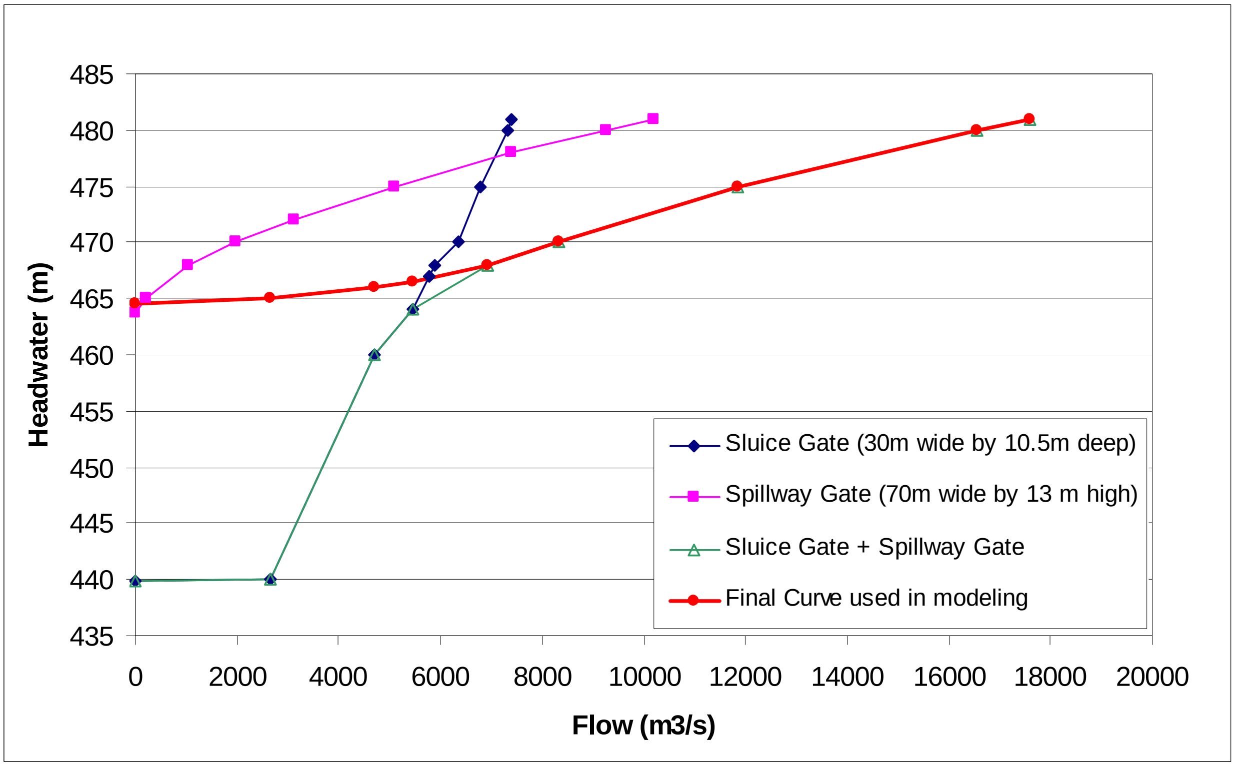


Figure 7-5: Roseires Dam rating curves.

7.2.2.2 Sennar Dam

Sennar Dam is constructed with a gated spillway, deep sluices, and gates for Irrigation of the Gezira and Managil irrigation schemes. The spillway has 72 working gates, each 5 m wide by 3.4 m high, located at level 413.80. The deep sluices have 80 gates each 2 m wide by 8.4 m high located at level 404.2, while the Gezira and Managil have a total of 25 gates 3m by 5m each.

Here also the total releases were simulated with a single rating curve that accounts for the releases through the fully open spillway, deep sluices and irrigation canal. ***Figure 7-6*** shows the rating curve used in the model together with the rating curve for each one of the hydraulic structures. The total rating curve was incorporated into the model as a boundary condition at the river station where Sennar Dam is located (station 379).

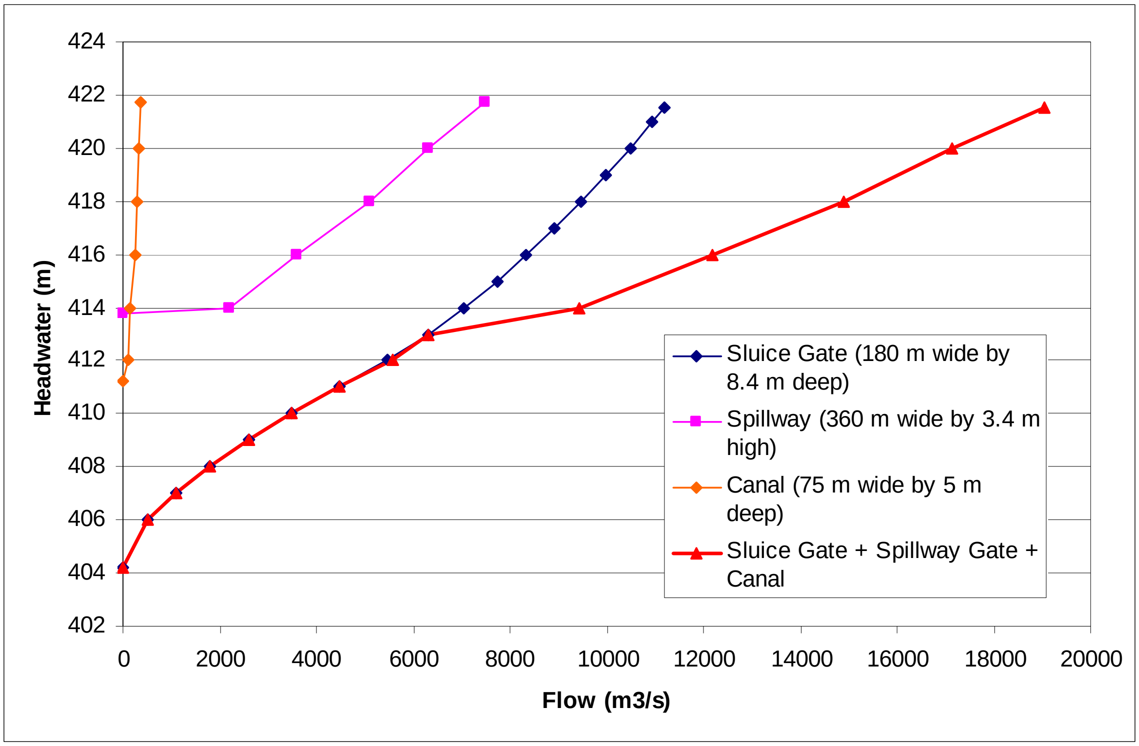


Figure 7-6: Sennar Dam rating curves.

7.2.3 Manning's "n" values

Manning's roughness coefficient (*n*) is an important parameter of the hydraulic model that represents the resistance to flow in the river and overbanks or floodplain. There is no exact method for selecting the *n* value, but guidelines can be followed for selecting n values based on channel conditions. The river reach was divided into the following reaches for estimating n values: Eddiem- Roseires reach, Roseires-Sennar reach, Sennar-Medani reach, Medani-Alnuba, and Alnuba- Khartoum reach. The characteristics and land use in each of these reaches was obtained from satellite imagery as well as during the field survey.

The reach between Eddiem and Roseires (represented in the photo in ***Figure 7-7***) is characterized by farming activities and light brush. Chow (1959) recommends a range of n value between 0.035 and 0.06 for these reaches. A value of 0.045 was selected for the flood plain and a value of 0.040 was used for the channel. Both the channel and the flood plain in this reach are affected by the backwater of Roseires Dam.

Figure 7-7: Eddiem- Roseires reach.

The reach between Roseires and Sennar (***Figure 7-8***) is characterized by clay plain soil and rain-fed agriculture with a meandering river, and is dominated by horticultural activities (banana plantations, Mangos, Gwafa and citrus). A value of 0.03 to 0.05 was cited in the literature for field crops. In this study, a value of 0.030 was used for the channel and 0.050 for the flood plain. For Sennar Dam Reservoir, the same n values as for the Eddiem to Roseires reach was used.

Figure 7-8: Roseires-Sennar reach.

The reach between Sennar and Medani (***Figure 7-9***) is characterized by light brush, dark clay agriculture activities, grazing lands and some trees. Selected n value for the reach ranged from 0.030 to 0.060 and varied throughout the reach.

Figure 7-9: Sennar-Medani reach.

The reach between Medani and Alnuba (***Figure 7-10***) is characterized by a meandering channel with vertical accretion and formation of terraces, cultivation of fodder, and with sunut forest. n values from the literature for these conditions range from 0.03 to 0.05. A value of 030 was used in the channel and 0.040 in the floodplain for this reach.

Figure 7-10: Medani-Alnuba reach.

The reach between Alnuba and Khartoum is to some extent urbanized; therefore, a value of 0.055 was used in the floodplain, with 0.030 in the channel.

An evaluation of the sensitivity of simulated water levels to the Manning's roughness coefficient was conducted. Manning's n values were varied by plus/minus 0.005 at all locations in the steady model to investigate the resulting changes in water surface elevation. ***Table 7-1*** summarizes the differences in water surface elevation at representative stations (indicated in parenthesis) of the pilot areas. The most sensitive reach appears to be the area just below Roseires Dam. The selected variation in n values is larger than the anticipated error in the selection of the parameter values, so that the maximum error in the simulation results should be less than the values shown in the table, perhaps by about half. It is also noteworthy that in the reaches where water level is the most sensitive to n value, the difference in extent of flooding is the least, because the flow is generally confined to the channel.

Table 7-1: Differences in Water Surface Elevation in meters (WSE (n ± 0.005) - WSE(n)). Cross section stations are in parenthesis.

Pilot Area Name	2-yr	5-yr	10-yr	50-yr	100-yr
Roseires (km 665.7046)					
n + 0.005	0.93	0.98	0.98	1.01	1.02
n - 0.005	-1.08	-1.12	-1.15	-1.19	-1.19
Singa City (km 465.9027)					
n + 0.005	0.76	0.79	0.79	0.78	0.77
n - 0.005	-0.86	-0.89	-0.92	-0.92	-0.92
Wad Medani/Rahad Junction (km 203.4645)					
n + 0.005	0.82	0.77	0.76	0.74	0.74
n - 0.005	-1.02	-0.96	-0.93	-0.88	-0.88
Hasahisa (km 146.3298)					
n + 0.005	0.67	0.65	0.63	0.64	0.62
n - 0.005	-0.82	-0.78	-0.76	-0.74	-0.74
Khartoum City (km 20.9653)					
n + 0.005	0.68	0.67	0.62	0.53	0.50
n - 0.005	-0.80	-0.77	-0.78	-0.64	-0.64
Average - Entire Model					
n + 0.005	0.73	0.73	0.71	0.70	0.69
n - 0.005	-0.88	-0.86	-0.86	-0.82	-0.82

7.2.4 Boundary Conditions

Boundary conditions are required in the hydraulic model to define characteristics of the river system that influence the model simulation but that occur outside of the boundaries of the model. Sub-critical, steady flow hydraulic models are often formulated by specifying constant discharge as an upstream boundary and river stage or elevation as a downstream boundary. The downstream stage is determined as a function of discharge, with higher discharges being associated with higher stages. If multiple discharges are to be modeled, or an unsteady hydrograph is to be simulated, the model needs to dynamically compute the downstream boundary as a function of stage, and a stage-discharge rating is entered directly in the model. Another option is to allow the model to determine a rating curve by specifying what is known as normal depth based on the downstream cross-section shape and a known downstream slope.

Early in the study, a linear-shaped rating curve was obtained from the Ministry of Irrigation and Water Resources, which seemed to represent stages reasonably at peak annual flow levels. In an effort to provide a more realistic rating curve whose shape would be more representative of typical non-linear rating curves, the normal depth boundary option was selected in HEC-RAS, using a slope for the downstream reach of 0.00012. This slope was estimated based on the longitudinal profile of the riverbed upstream and downstream of Khartoum. The Blue Nile between Sennar Dam and Khartoum City and the White Nile upstream of the confluence have average slopes of about 0.0001. The Main Nile downstream of the confluence in Khartoum has an average slope of 0.00015 (Waterbury, 1979). The resulting rating curve was generally consistent with the linear relationship provided previously, although it resulted in a slight increase in depth for the 2-year flow and a decrease in depth for the 100-year flow in the vicinity of Khartoum. The sensitivity of model stages to the downstream boundary is only evident within the first 15 kilometers upstream of the boundary. A comparison of the rating curve used early in the study and the new rating curve used in the model are shown in ***Figure 7-11***.

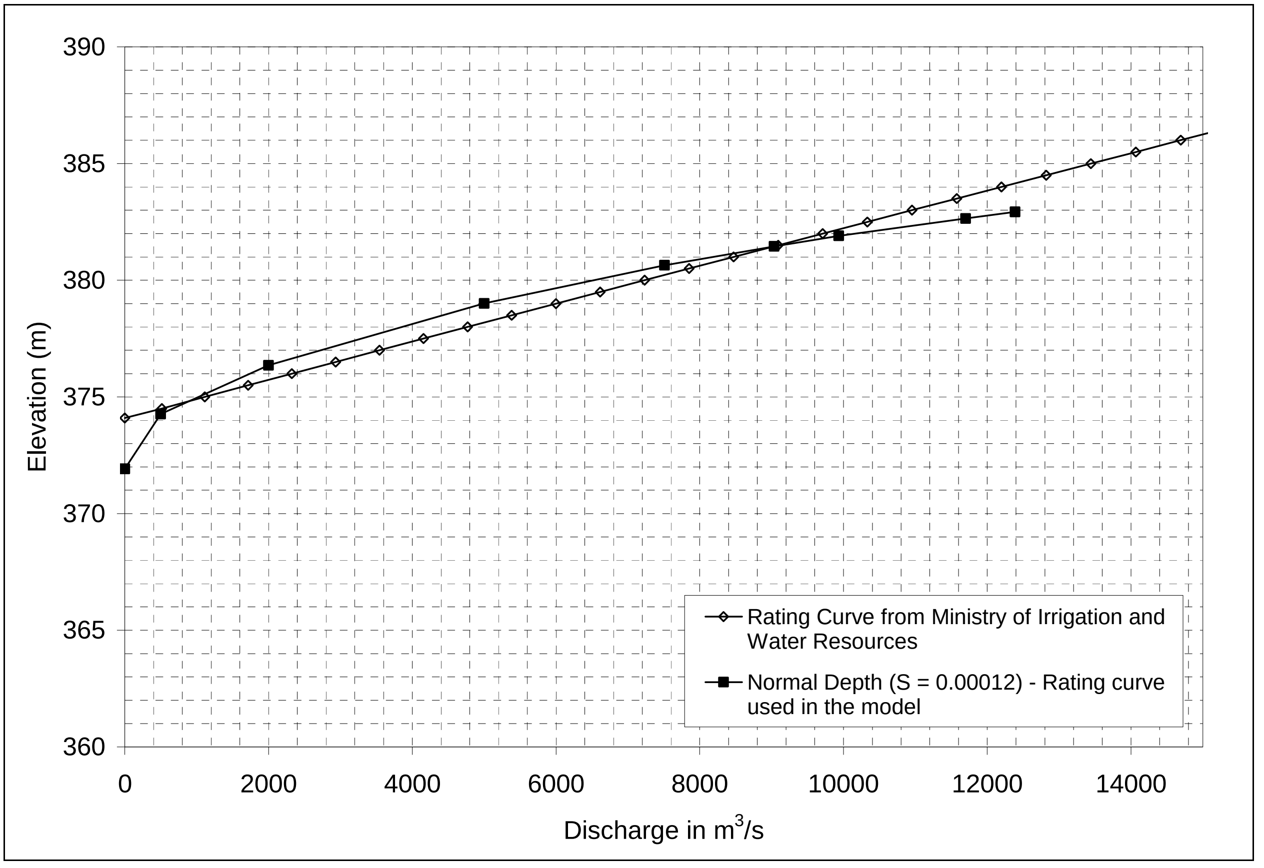


Figure 7-11: Comparison of a preliminary rating curve and normal depth rating

The upstream boundary for the steady model for each frequency event was the discharge determined from the hydrologic analysis. For the unsteady model, it was a time series representing the 2006 discharge hydrograph, scaled such that the peak would correspond to the peak discharge for the flow frequency being considered.

7.3 Model Evaluation

During a field visit in October 2009, the study team monitored a GPS that showed current position together with the 100-year flood boundary, which permitted a visual inspection of development, land use, and terrain in comparison to model predictions regarding maximum flooding extents. Observations of terrain and soil types in and adjacent to the floodplain 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.

7.4 Hydraulic Model Results

7.4.1 Steady State Model

The steady state analysis is consistent with expectations that the Blue Nile has a well-established channel that is generally able to contain large flows, including the 100-year flow in some locations. In other locations, the river overflows its banks and floods surrounding areas for flows at and above the 10-year return period level. The two-year flow is generally contained within the banks of the river. There is a tendency toward increased spreading of the flow into the floodplain in the downstream portions of the reach. ***Figure 7-12*** shows the longitudinal profile of the Blue Nile and the water surface profiles for the two and the 100-year return period events. The 5, 10, and 50-year water surface profiles fall in between the 2- and the 100-year profiles. The location of pilot areas is indicated in this plot. The differences in water surface elevation between the two profiles average 2.5 meters. This change in water surface elevation does not produce major changes in flood extent in the upper reaches of the river. ***Figure 7-13*** shows a cross section representative of Roseires pilot area downstream from Roseires Dam. The 2 and 100-year water surfaces are shown on the plot. It can be observed that the extent of flooding is about the same between the two flows. The extent of flooding increases in the downstream direction as the floodplain widens. ***Figure 7-14*** illustrates a cross section representative of the Wad Medani/Rahad Junction pilot area. This plot shows less difference in depth, but significant differences in water surface extent between the 2- and the 100-year events. The mean channel and floodplain velocities for the 2- and 100-year events are listed in ***Table 7-2*** . Higher velocities are found in the main channel as expected. Overflow areas are shallower and produce lover velocities.

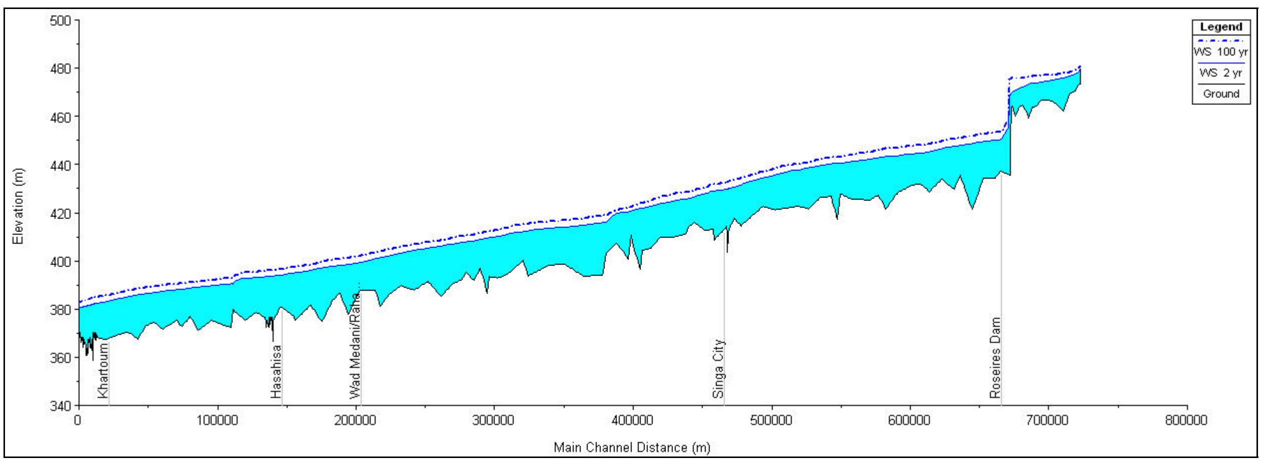


Figure 7-12: Water surface profile of the 2- and the 100-year events

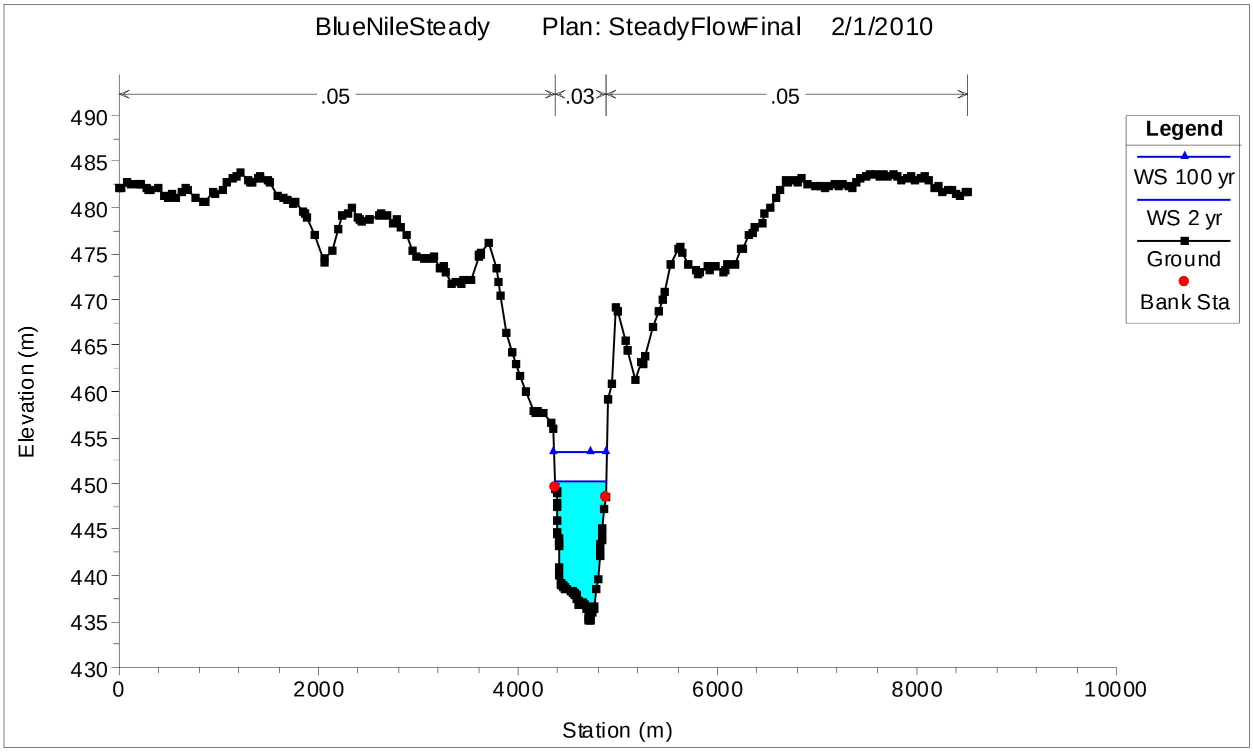


Figure 7-13: Typical cross section, Roseires pilot area

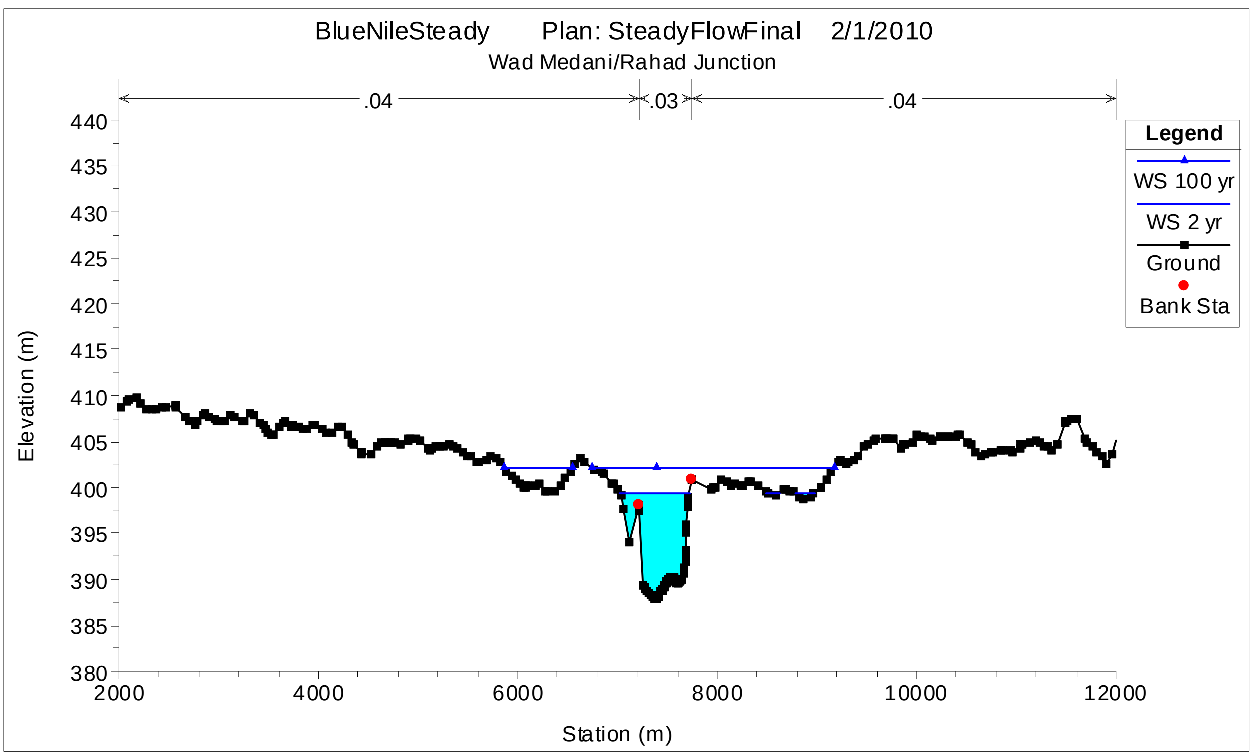


Figure 7-14: Typical cross section, Wad Medani /Rahad Junction pilot area

Table 7-2: Mean channel and floodplain velocities for the 2 and 100 year events for the four pilot areas.

	Velocity in m/s			
	2-year		100-year	
Location	Channel	Floodplain	Channel	Floodplain
Khartoum City	1.6	0.3	2.0	0.3
Hasahisa-Wad Medani/Rahad Junction	1.5	0.3	1.7	0.4
Singa	1.8	0.3	2.2	0.4
Roseires Dam	1.4	0.2	1.7	0.3

7.4.2 Unsteady Flow Model

The primarily objective of the unsteady flow modeling was to improve the assessment of the inundation hazard by estimating the attenuation of peak flows and characterizing the duration of flooding. Unsteady flow modeling requires an input hydrograph as the upstream boundary condition. The 2006 flood season hydrograph at Eddiem gage was selected as representative of high flow years, and hydrograph ordinates were scaled to the 2, 5, 10, 50, and 100-year flood magnitudes such that the peak of the hydrographs matched the peak flow magnitude of the flood frequency events. These hydrographs were input into the HEC-RAS model to perform unsteady flow simulations. ***Figure 7-15*** shows the five flow hydrographs input into the model.

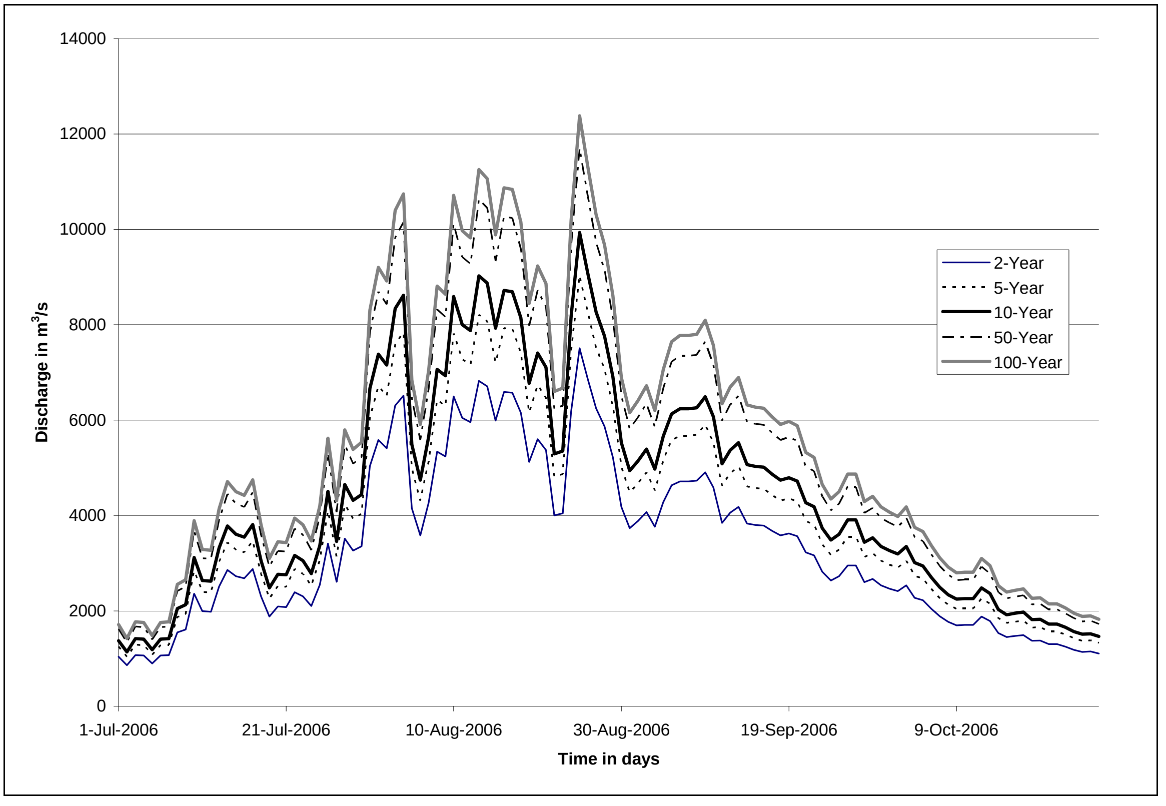


Figure 7-15: Flow hydrographs input into the unsteady model.

This flood season hydrograph includes a typical seasonal rise and fall in baseflow onto which individual peak runoff events are added. In 2006, the peak event of the season occurs near the end of August, and is of short enough duration that some attenuation of the peak may be anticipated as the flood passes from

Eddiem to Khartoum. The hydraulic model simulates an average attenuation of the flood peak of 16% for all the flood levels. The timing of the peak between Eddiem and Khartoum is offset by six to seven days for all flood events. A comparison of the total volume represented by the four-month hydrograph with the total volume of water in storage in the channel when the peak flow is occurring in the middle of the reach indicates that for all events the channel stores about 10 percent of the total seasonal volume. This accounts for the capacity of the channel to attenuate peak flows. ***Table 7-2*** summarizes the flood peak magnitude at the upstream end (inlet) and downstream end (outlet) of the study reach, as well as the travel time of the largest flood peak and a comparison of the volume of the channel when the peak is at the middle of the reach and the volume of the hydrograph. ***Figure 7-16*** and ***Figure 7-17*** illustrate the travel time and attenuation simulated in the unsteady model for the 100-year and 2-year events, respectively.

Table 7-3: Summary of results from the unsteady model.

Return Period	Station	Max Q	% change in peak (*)	Time at Max	Travel Time in days	Volume when Peak @ Middle reach (1000 m^3)	Hydrograph Volume (1000 m^3)
2	Inlet	7510		25-Aug-07			
	Outlet	6375	15.1	31-Aug-07	6	3,635,213	34,192,090
5	Inlet	9035		25-Aug-07			
	Outlet	7615	15.7	1-Sep-07	7	4,193,803	41,135,224
10	Inlet	9935		25-Aug-07			
	Outlet	8418	15.3	1-Sep-07	7	4,526,267	45,232,812
50	Inlet	11700		25-Aug-07			
	Outlet	9830	16.0	1-Sep-07	7	5,237,515	53,268,636
100	Inlet	12386		25-Aug-07			
	Outlet	10318	16.7	1-Sep-07	7	5,504,185	56,391,908

It was observed by participants at the Eastern Nile Flood Forum in Nazareth, Ethiopia in January 2010, that travel time between Eddiem and Khartoum has been observed on occasion to be about three days. It should be noted that the offset in timing reported above for the hydraulic simulation is the offset of the peak flow, which includes the effects of both travel time and attenuation, and is larger than would be expected for travel time alone. In fact, the difference in timing of the initial rise of the hydrograph at the beginning of the season is simulated in the hydraulic model to be closer to three days. Finally, the observed peak flow in Khartoum in 2006 did in fact occur about seven days after the peak was observed at Eddiem, as illustrated in ***Figure 7-18***.

The reduction in peak discharge attributable to attenuation of the peak flows is not sufficient to warrant a change in the steady state hydraulic model, which uses the peak flows from the frequency analysis at Eddiem for the entire reach of the Blue Nile. This is because the reduction in peak is not as significant in the upper reaches of the river and the flood extents are less sensitive there, and the reduction in peak in Khartoum is offset by additional inflows from the Rahad and Dinder rivers in Khartoum, as is evident in the frequency analysis of peak flows there.

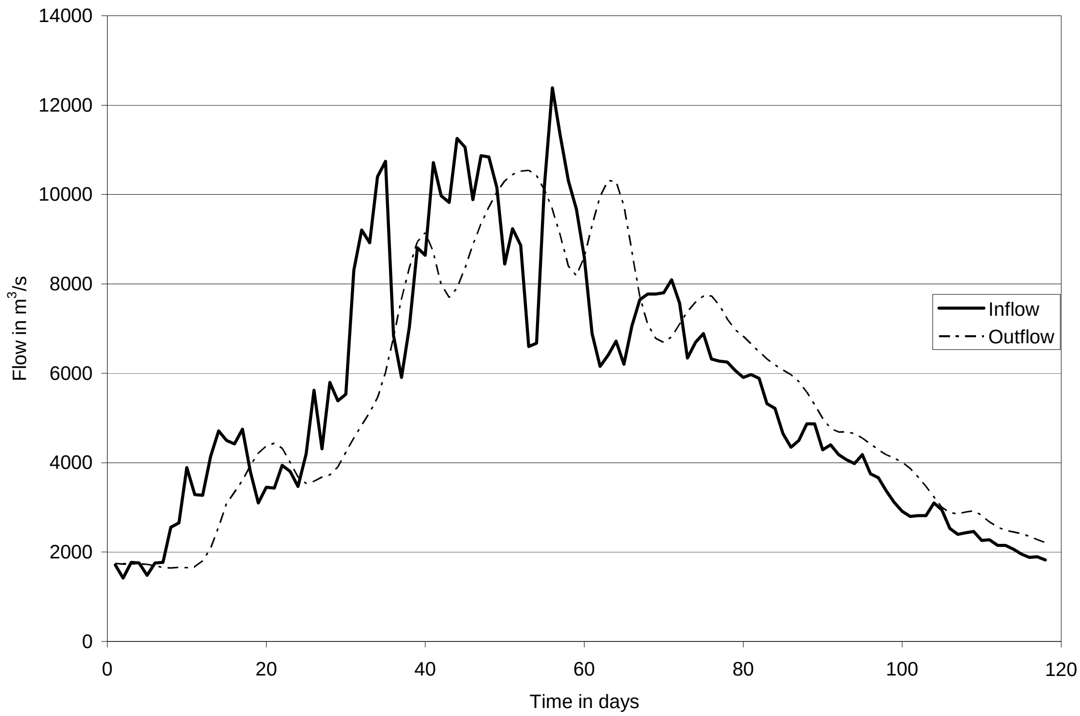


Figure 7-16: 100-year return period inflow and outflow hydrographs

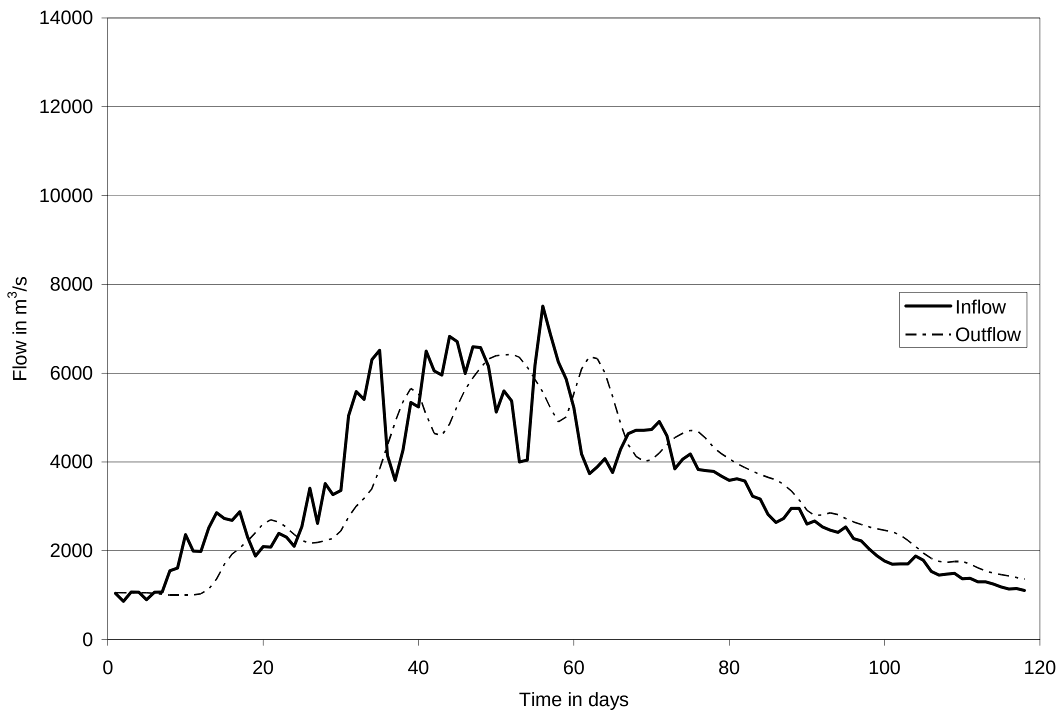


Figure 7-17: 2-year return period inflow and outflow hydrographs

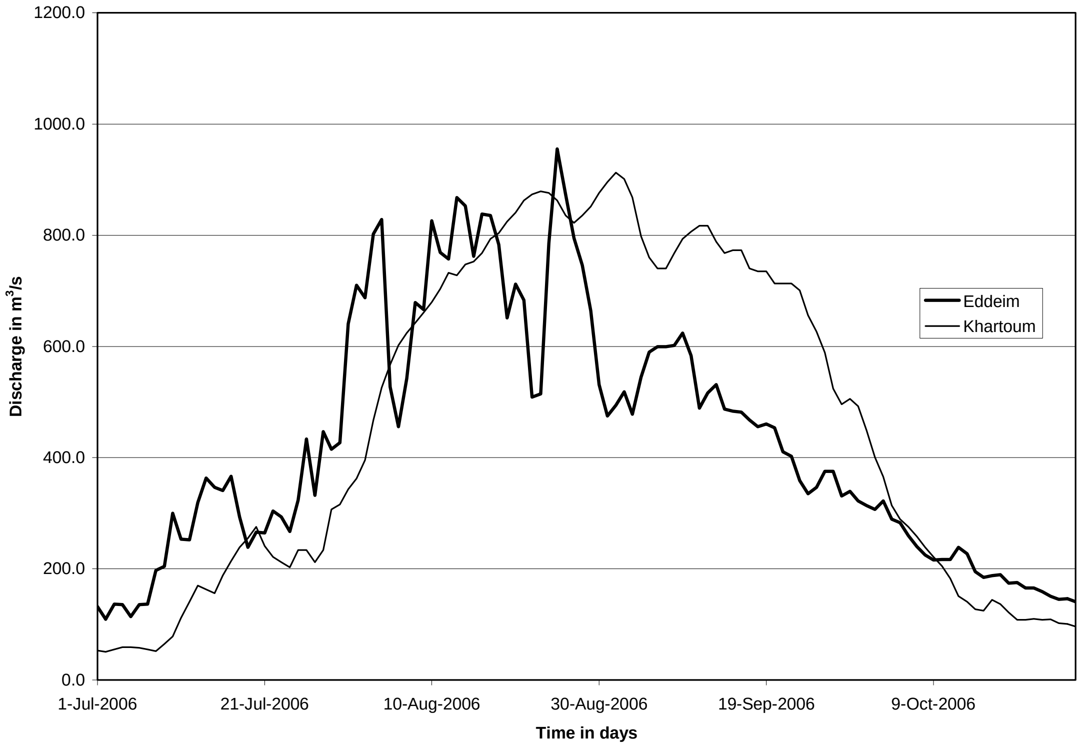


Figure 7-18: Observed flow hydrograph at Eddiem and Khartoum.

Another important result of the unsteady flow analysis is the ability to analyze duration of flooding. The unsteady flow model computes water surface elevation for each cross section in the model at each time step in the simulation. Although the process is time-consuming and computationally intensive, duration of flooding can be computed over a grid representing the floodplain using the following steps:

1. Run the unsteady hydraulic model simulation for a given frequency event using the inflow hydrograph for the associated frequency and saving the water surface profile at each cross section at a daily time step.
2. Export all water surface profiles to HEC-GeoRAS.
3. Generate an inundation extent grid for each day of the flood season.
4. Use the GIS to count the number of days that each grid cell is inundated and record the result in a new grid. This grid represents the duration of flooding for each grid cell in the flood impact area.

The principal question of interest in the present analysis is the impact of duration of flooding on damages and on the impacted population. For purposes of the impacted population, reference to duration of flooding maps can provide guidance on when displaced populations might be able to return to their homes after the commencement of flooding of a given frequency. ***Figure 7-19*** illustrates the relationship between the flooded area and the duration of flooding. The lines in the figure depict the number of hectares that are flooded for more than the number of days shown on the horizontal axis. For example, from the graph, it can be seen that about half of the total area inundated by the 5-year flood can be expected to see flood waters recede within 30 days of being inundated, and less than a third of the impacted area will be inundated for more than 60 days. It may also be noted that the area that is inundated for more than 60 days is approximately the same between the 5- and 100-year events, but for durations less than 60 days there is significantly more area inundated by the 100-year event.

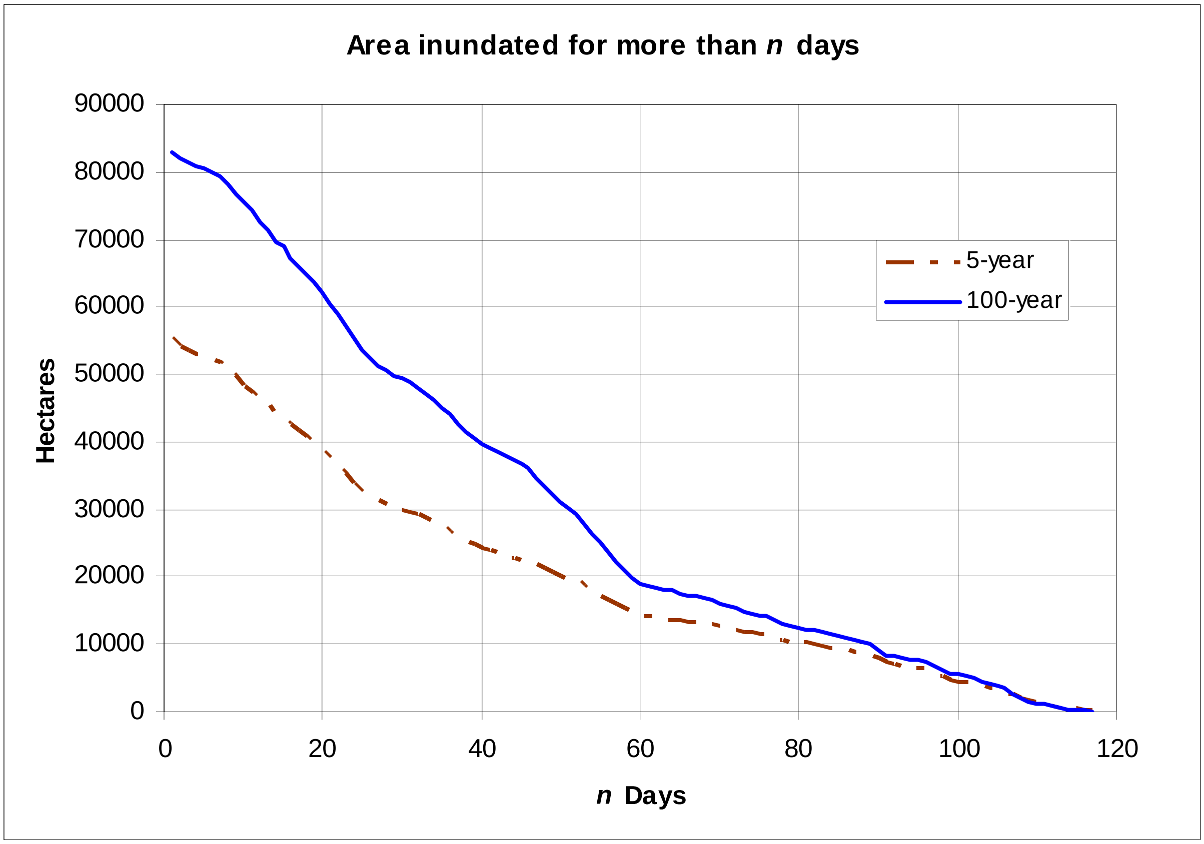


Figure 7-19: Area and Duration of Flooding Relationships, 5-year and 100-year Events

It is somewhat complicated to incorporate duration of flooding directly into the depth-damage relationship that is commonly used for computing flood damages. A simplified approach can be seen to be acceptable, however, by considering the strong relationship between peak flood depth and duration of flooding. ***Figure 7-20*** below shows the correlation between depth and duration for the reach below Sennar Dam for the 100-year event. As the flood hydrograph recedes, the last areas to flood in a given region will be the first to recede as the water level in the river declines, and also will correspond to those areas that experienced the lowest flood depths. In this way, depth of flooding can be seen to be a strong indicator of duration of flooding, and the economic analysis that estimates depth damage curves in a given region can implicitly consider the anticipated duration of flooding associated with a given depth. This approach is especially effective because in the relatively subjective economic analysis it is common for the economist to have difficulty separating the concept of damage as a function of depth from the implied duration of flooding, especially in the minds of local inhabitants that might be consulted as part of the evaluation. To fully benefit from this approach in future studies, it would be necessary to develop both depth and duration maps for use by an economist prior to the economic analysis.

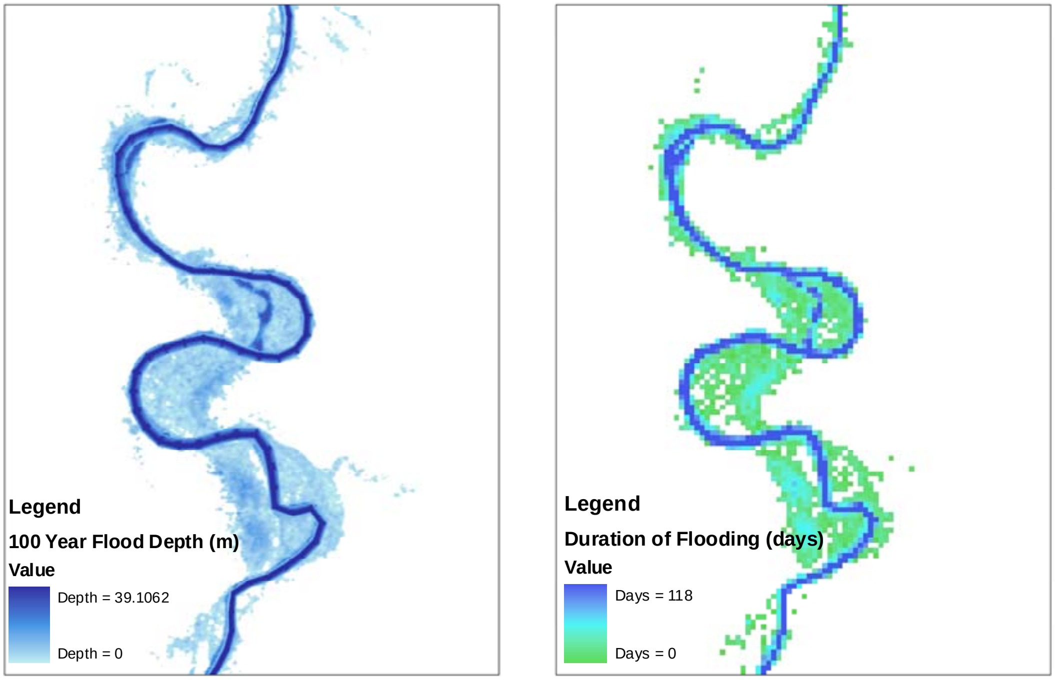


Figure 7-20: Comparison of Depth and Duration of Flooding Downstream of Sennar, 100-year event

8.0 FLOOD RISK ASSESSMENT

A central objective of this project was 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 floodplain of the Blue Nile in Sudan, where direct intervention to reduce flood magnitude through storage may be both infeasible and unsustainable or may impose unacceptable downstream consequences. 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 8-1***. The damage probability curve can then be numerically integrated to estimate the expected annual damages, thus quantifying risk.

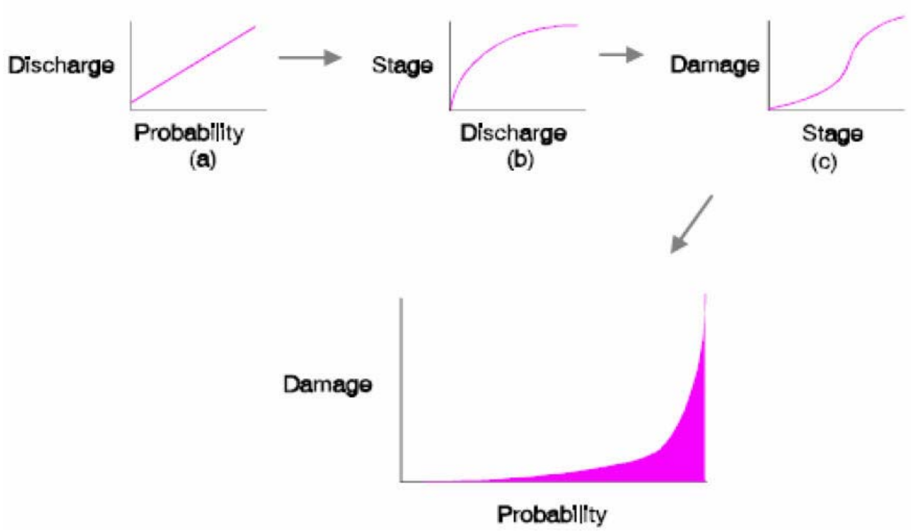


Figure 8-1: Transformation for traditional expected annual damage computation (from USACE)

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 its 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).

8.1 Flood Hazard Mapping (HEC-GeoRAS)

A key feature of the HEC-RAS and HEC-GeoRAS 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 8-2***, indicating depth of inundation at any point in the inundated area. Both of these layers describe components of the hazard.

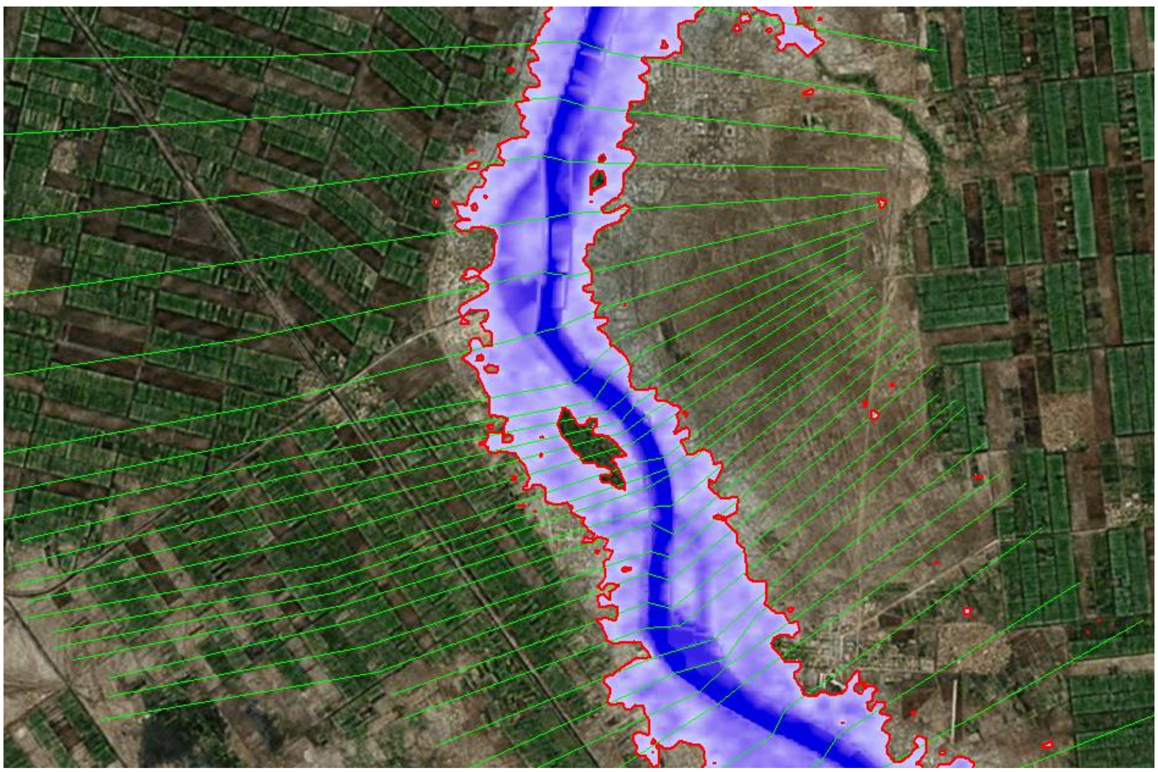


Figure 8-2: Development of inundation extent (red outline) and depth (blue gradients).

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 the 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 8-3***. The velocity grid can be viewed as providing guidance on local velocities to be expected, with the assumed flow direction being from upstream to downstream cross section.

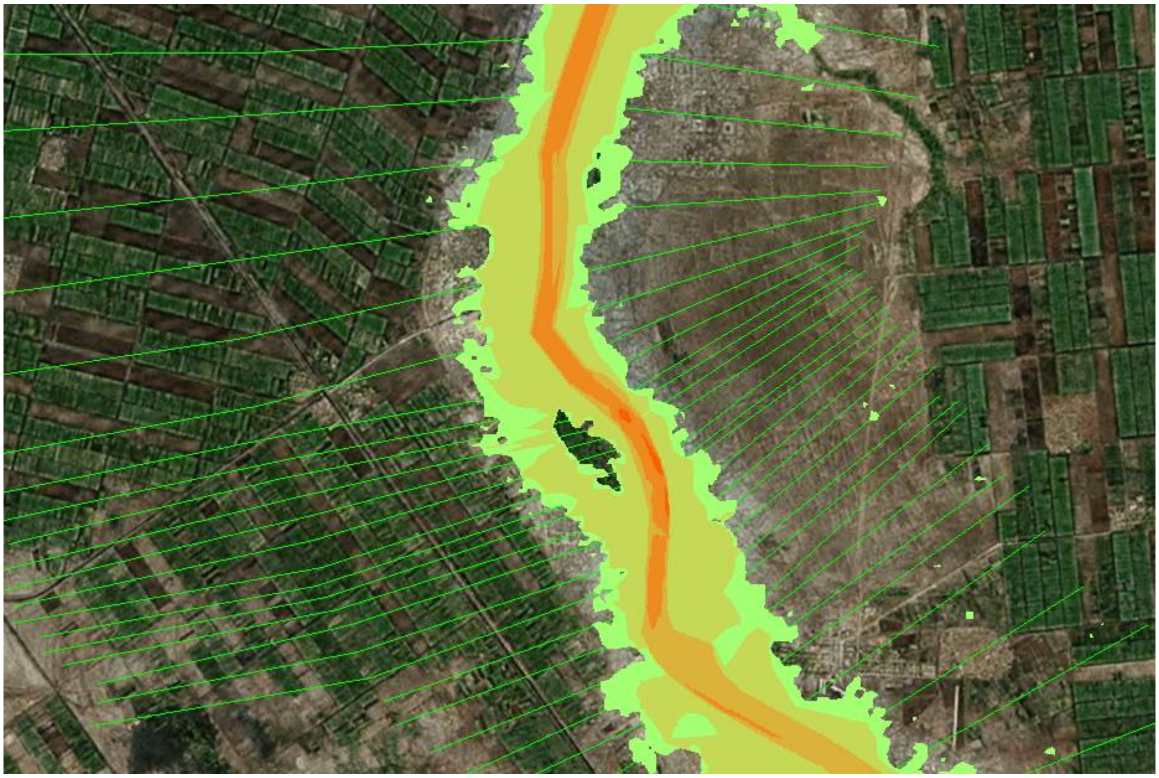


Figure 8-3: Development of velocity grid

In performing these steps, linkages between pre-processed cross-sections and post-processed water surface elevation predictions in HEC-GeoRAS 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.

8.2 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, infrastructures, and agriculture was based on visual interpretation of remotely sensed data, Sudan survey topographic sheets, field checks, and consulting local references. The Satellite data used include mosaics of Landsat7 ETM$^+$ images and mosaics of downloaded Google Earth geo-referenced images. Digital and scanned geo-referenced Sudan Survey topographic sheets of scales 1:100 000 and 1: 250 000 were used to identify different localities, towns, and villages.

All vector layers were digitized and coded under a GIS framework. The final GIS products were transformed to a Universal Transverse Mercator "UTM" projection, WGS84 Spheroid. The main created layers include agriculture, infrastructure, and structure. The extent of the mapped area covers about 3Km off the Blue Nile River banks on both sides. The total length of the reach mapped is about 730Km. The degree to which the area under investigation was mapped depended largely on the availability of high-resolution satellite images. About 600Km were mapped to a scale of 1:20 000. The Sennar - Medani reach was mapped to a scale of 1:100 000 because of the lack of high-resolution satellite data. Where high resolution satellite data were not available, structures could not be distinguished and were not digitized.

The infrastructure layer was classified into highways, paved, and dirt roads.

The delineated structures included the following major classes:

- Residential areas classes (A+, A, B, C and D)
- Service classes (Hospitals, Schools, Universities, Mosques & Churches, Cemeteries, Hotels and Police station)
- Public Utilities classes (Stadiums, Power and water supply stations)
- Commercial areas classes (Market and Banks)

The agriculture layer described the following major classes:

- Horticulture classes (Citrus, Mangos and Guava)
- Vegetables class
- Fodders class
- Forests classes (Sunt, trees, Safsaf trees, and wood)
- Activities on clay plains classes (Agricultural schemes of Gezira, Blue Nile, Sugar cane, Kenaf, Kenana Research Station, and Sorghum)
- Lands between the flood plain and clay plain classes (Khor, Eroded Land, Kerib Land, Rocky land, Jebal and pediment, and Bare land)
- Remnants of the flood plain classes (Ox-bow Lake, Abandoned channel, Depressions, and Sand bar)
- Other Activities classes (Brick factory, Chicken Sheds, and Dairy farm)

The types of horticultural trees and annual crops are identified by element and physiographic methods. The element method depends on tone, texture, and size of the field parceling. The texture is used to classify citrus from mangoes, guava, and bananas. The citrus (grapefruits, lemons, and orange) trees have the same spacing (7x7 meters) with small leaf crowns giving a similar dotted texture. Thus, it is difficult to differentiate the grapefruit, lemon, and orange. In this case, there are two reflections from the citrus and soils. The spacing of mangoes is 10 x10 meters with a large crown cover giving a closed canopy. Thus, the reflection is only from the crown and does not include the soil. The vegetables are sown in small parcels, while fodder (Alfalfa and Abu Sabein) is sown in large elongated parcels. The physiographic positions are used to differentiate Sunt forests (Acacia nilotica) in the abandoned channels from banana plantation on the upper parts, depending on reflection and texture. Safsaf trees grow naturally along the banks and form a biological protection from bank erosion. They can be distinguished by their position.

The sheds for diary and chicken farms were recognized by tone and shape. The sandy bars were recognized by the white tone shape and their physiographic position.

All the irrigated schemes (GZS, BNS, Sugc, KRS, KNFS) were recognized by their geographic locations, the size of parceling and reflections of the different crops depending on their crowns, the alignments of canals, and the size of the parcels. The Sorghum (sog) under rain fed agriculture is distinguished by the regular parceling without canals and irregular parceling for undemarcated agriculture while the traditional agriculture has small parceling around villages.

8.3 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. The general steps are:

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 8-4***, ***Figure 8-5***, and ***Figure 8-6*** show examples of damage functions for the three different asset types: structures, infrastructure, and agriculture.

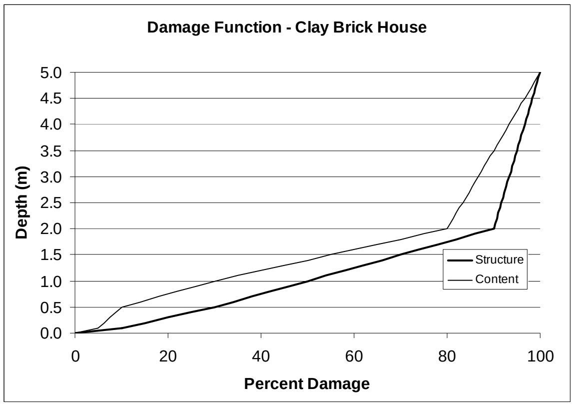


Figure 8-4: Damage curve: structure asset type

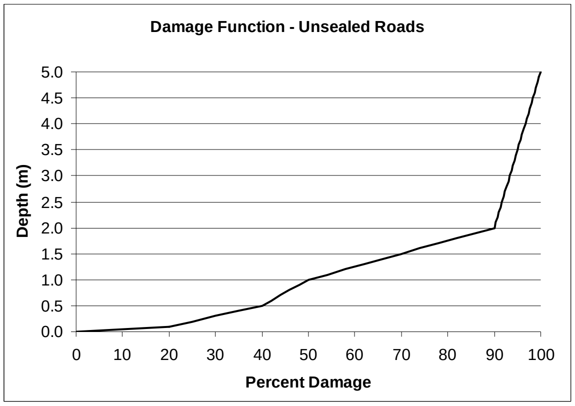


Figure 8-5: Damage curve: infrastructure asset type

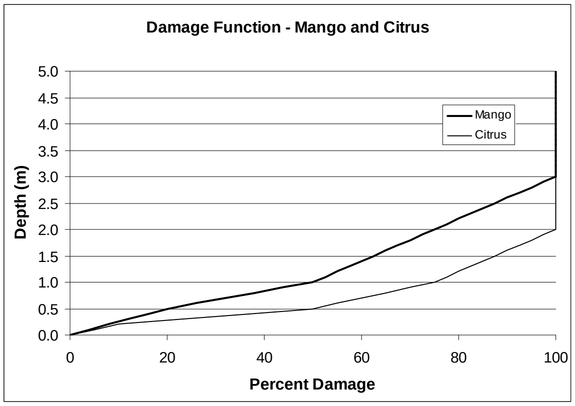


Figure 8-6: Damage curve: agricultural asset type

8.4 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 8-7*** 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 to structures, roads, and agriculture plots. ***Figure 8-8*** shows a section of the vulnerability map at Khartoum City. The red and orange cells represent higher vulnerability than the green and lighter color cells.

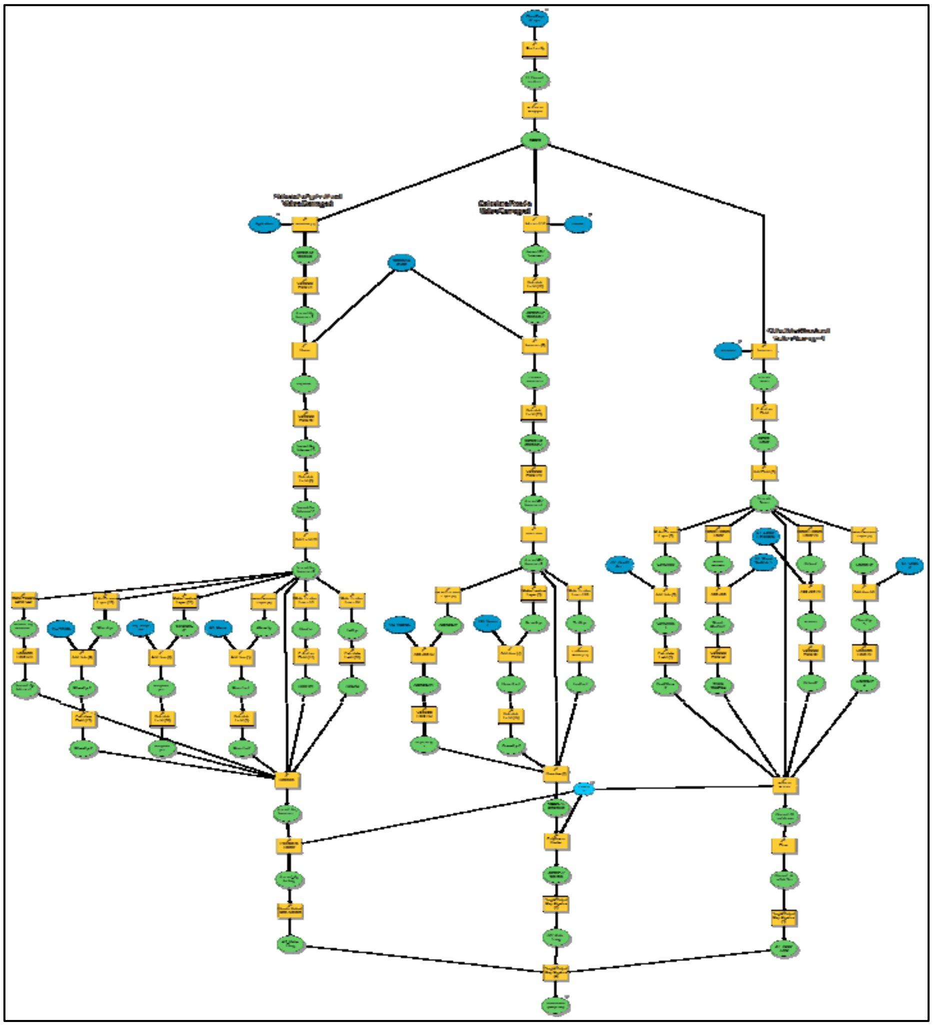


Figure 8-7: ArcGIS vulnerability model.

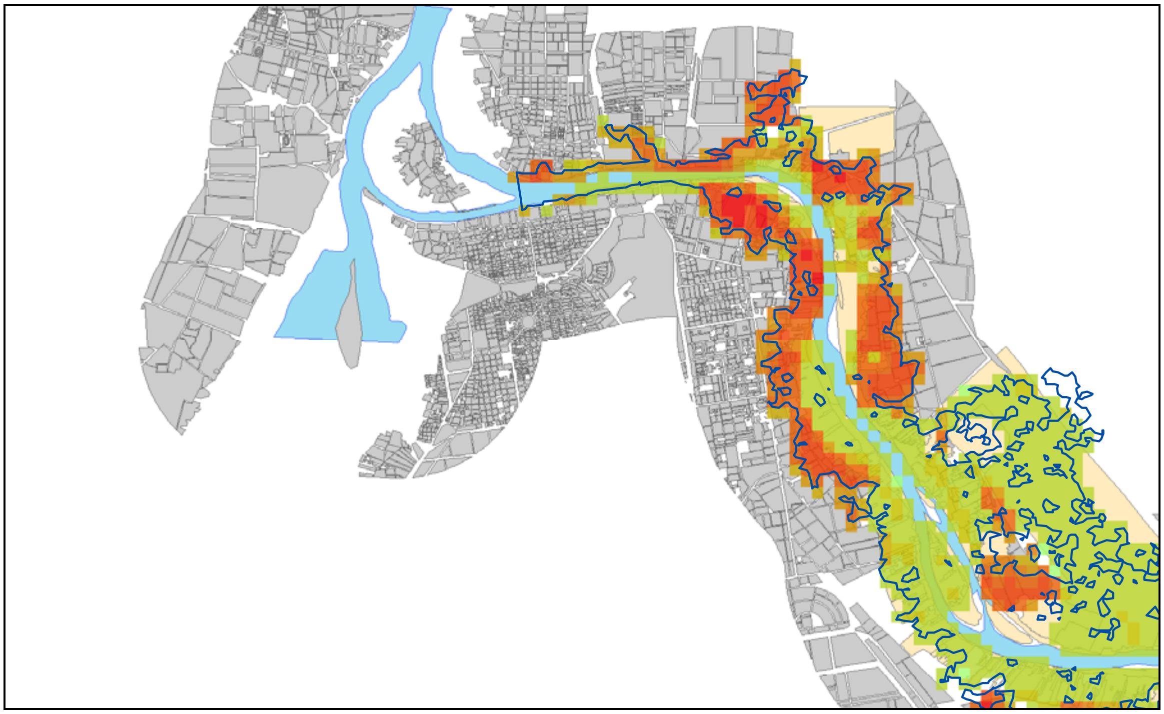


Figure 8-8: Section of the 100 yr vulnerability map at Khartoum City

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. ***Table 8-1*** lists the vulnerability assessment by pilot area for each return period. The damage resulting from the 2-year event, which seems high, is mostly due to the flooding of agricultural lands, specifically mangos, citrus, and bananas in the three pilot areas upstream from Khartoum City.

Table 8-1: Vulnerability Assessment for each pilot area. Damages are in millions of dollars.

	Return Periods				
Location	**2**	**5**	**10**	**50**	**100**
Khartoum/Soba	204	628	1,177	2,749	3,444
Hasahisa-Wad Medani/Rahad Junction	326	669	957	1,689	2,023
Singa	14	37	57	118	150
Roseries Dam	4	5	6	8	9
Total	550	1,344	2,207	4,614	5,726

8.5 Risk Mapping and Assessment

The risk mapping involves the integration of the results from the hazard and vulnerability maps. A damage probability curve was constructed from the estimated damages caused by the events with probabilities of 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 from the vulnerability maps. The annualized risk was computed as the area under this curve. The curve was divided into slices to compute the area as the product of the damage and the range of probability associated with 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 % (corresponding to 1-year return period) 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 $ 974 million was computed for the four pilot areas. ***Figure 8-9*** shows the damage probability curves for all pilot areas. ***Table 8-2*** lists the computed damages and the total annualized damage for each pilot area. In terms of total damages, it appears that Khartoum is more resilient than Hasahisa/Wad Medani for higher probability events, while the reverse is true for lower probability events. Perhaps this is due to the presence of more low-lying agricultural area at Hasahisa and higher value development at slightly higher elevations in Khartoum.

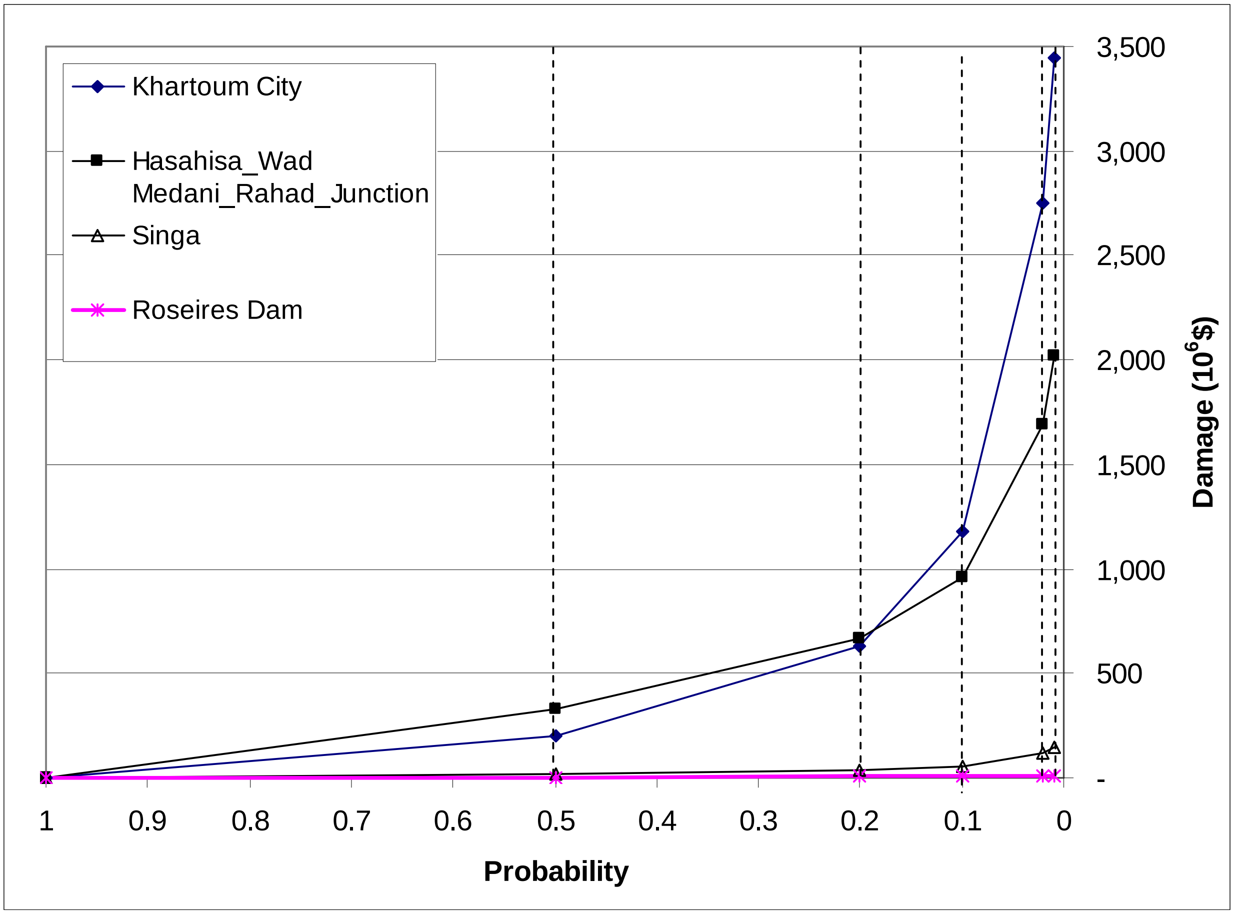


Figure 8-9: Damage probability curve for pilot areas

Table 8-2: Computed damages and total annualized risk in millions of dollars for each pilot area

	Return Periods					
Location	**2**	**5**	**10**	**50**	**100**	**Risk ($ 10^6)**
Khartoum/Soba	204	628	1,177	2,749	3,444	488
Hasahisa-Wad Medani/Rahad Junction	326	669	957	1,689	2,023	457
Singa	14	37	57	118	150	26
Roseries Dam	4	5	6	8	9	4
Total	550	1,344	2,207	4,614	5,726	974

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 8-10*** shows a section of the annualized risk map in Khartoum City. The intensity of cell colors is slightly subdued compared to the 100-year vulnerability maps due to the reduction in cell values obtained when the damages are multiplied by the low probability of the 100-year event.

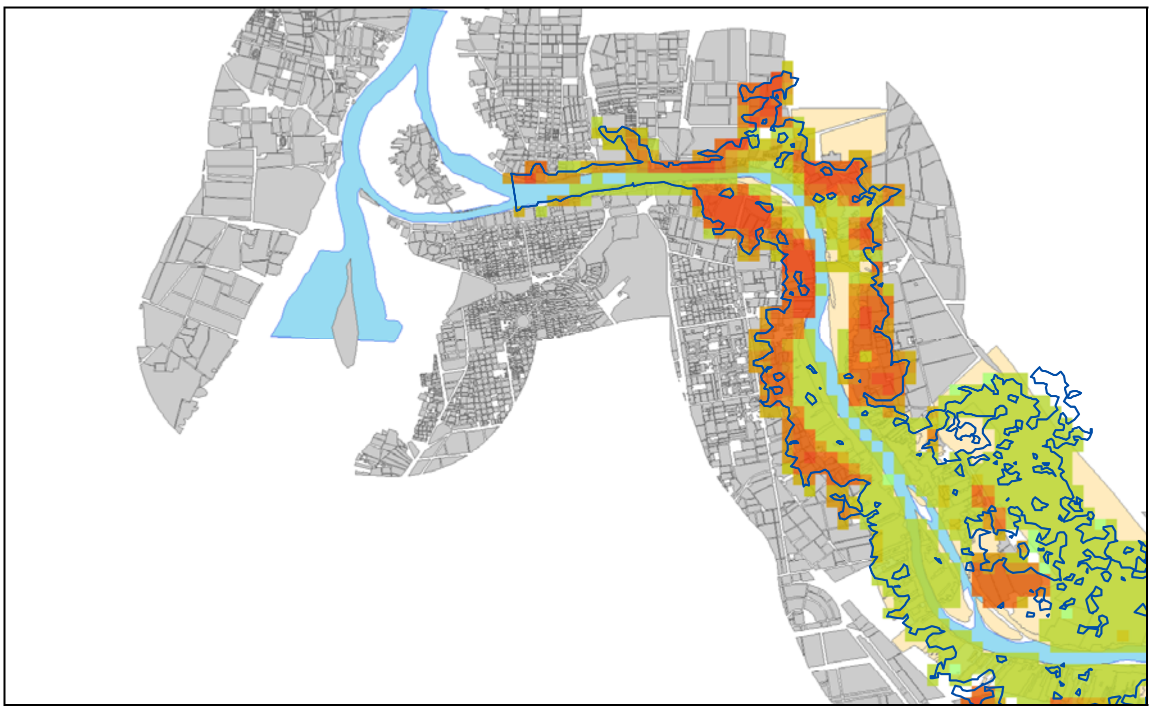


Figure 8-10: Section of the Risk Map at Khartoum City

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

9.0 DELIVERABLES

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 DVDs containing the following data:

- 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 (x 5)
  - Flood depths (x 5)
  - Flow velocity (x 5)
  - Duration of flooding (x 5)
  - Vulnerability (x 5)
  - Risk

- ArcGIS Model Builder models used for vulnerability and risk mapping

- Digital maps published in PDF format (described in ***Appendix F***)

- Final workshop presentations

10.0 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.

Among the many items noted below, 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.

10.1 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 pilot areas along the Blue Nile
- Terrain models for channel and floodplain of the Blue Nile – this terrain model integrates surveyed cross sections from multiple sources with a 90 meter DEM.
- A useful procedure for integrating a gridded DEM with channel survey data
- A frequency analysis for the Blue Nile in Sudan
- Blue Nile hydraulic model with geo-referenced cross sections – this model has many potential uses as described below
- Flood hazard maps (extent, depth velocity) – These maps are fairly straightforward to interpret and can be used for flood preparedness and response as well as for planning development
- Detailed asset geo-databases along the Blue Nile in Sudan, 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.

10.2 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.

10.2.1 Survey and Terrain Modeling

River surveying was limited to specific pilot reaches of the Blue Nile. Floodplain areas were characterized using a 90-meter DEM. The river is subject to continuous changes in channel geometry due to its high sediment load. Opportunities to improve the terrain modeling include the following:

- Obtain Light Detection And Ranging (LIDAR) surveys in order to improve the quality of the terrain models by producing highly detailed DEMs. These should be performed during dry periods. It is likely that these surveys would require support from multiple administrative or government programs to justify the cost by sharing the benefits.
- Establish a program of periodic surveying of river channels to capture morphologic changes and update the terrain model accordingly.
- Extend the cross section interpolation approach to include more manual processing interpolated cross section data using satellite imagery to improve consistency in representing the river banks

It should be noted that due to the size of the reach being modeled, any higher resolution elevation models might exceed the current processing capacity of common desktop computing environments in some of the risk mapping steps. This might require subdividing the geographic area for terrain processing and hazard and risk mapping.

10.2.2 Hydraulic Modeling

Model results in Khartoum are sensitive to the downstream boundary condition, about which there is some uncertainty. The uncertainty could be reduced by extending the model 30 to 50 kilometers downstream using representative cross sections. This would establish more reliable water levels in Khartoum. About 20 kilometers of the White Nile upstream of the confluence could be modeled as a tributary, with constant discharge equal to the average White Nile flow at the time of the Blue Nile flood. This would improve both the steady and unsteady versions of the model.

The model could be expanded with additional tributaries and local runoff to represent areas subject to damage from flash floods. To effectively integrate this in the flood risk-mapping program would require assessment of various frequency events on the tributaries with prevailing discharges in the main river as the tributary boundary condition.

The hydraulic modeling would benefit from additional verification at key locations through a planned monitoring program. To be effective it would be necessary to measure stage and discharge at various flow levels at several locations distributed throughout the river reach to be able to calibrate model roughness parameters.

It might be useful 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.

10.2.3 Risk Assessment

Although hazard mapping was performed for the entire reach of the Blue Nile from Eddiem to Khartoum, Risk Assessment was performed only for the four regions that encompass the pilot areas. The process of performing the vulnerability mapping and calculation was computationally intensive, even when limited to the pilot areas, and subdividing the analysis into separate areas. With additional time and resources, additional risk mapping could be provided for the remaining areas of the Blue Nile where asset mapping is complete.

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 represent impacts 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. This 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 Blue Nile flood. 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. Riverside suggests that at the present time the other areas of potential enhancement of these results would produce more benefits in relation to the associated effort than an attempt to address varying seasonality of cropping patterns, given the general regular nature of the Blue Nile flood.

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.

10.2.4 Program Development

The integration of tools and techniques developed in this study to map flood hazard and risk along the Blue Nile in Sudan as been conceptualized with the idea of having a repeatable procedure that could be used in other parts of the Eastern Nile region. For a broader implementation of flood hazard and risk mapping, it may be helpful to define three 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 at a basic level of standards, with subsequent improvements in detail and accuracy to raise the studies to medium or high levels based on the initial risk identified and improvements in data availability and professional capacity.

10.3 General Application

The following list of recommendations represents a general list of activities that could be taken either 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.

10.4 Operational Forecast System Development

A project is ongoing to implement forecasting capability for the Blue Nile in Sudan using the models developed as part of this study. Though not part of the scope of this study, there are several items that may warrant consideration in the development and enhancement of a forecast system based on the hydraulic model and associated tools that were a part of this study. These are listed briefly below:

An unsteady flow version of the hydraulic model was developed as part of this study. It models Roseires and Sennar dams using an internal rating curve boundary that reflects the operation of the gates fully open as is the case during the peak of the Blue Nile flood. For the model to accurately simulate attenuation and backwater from the dams, they would need to be represented as in-line structures with time-dependent gates, and a time series of gate openings would be required as part of the input to the model. This type of operation of the model could be implemented after the forecast system operators have gained some experience with the model and are ready to increase the complexity of its operation.

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 pre and post processing environments to facilitate use of its models in real-time forecast environments. The Corps Water Management System (CWMS) integrates a modeling environment for 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 Sudan.

10.5 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, the enhancement identified under the first paragraph in section 10.2.2 Hydraulic Modeling could be taken on as a training project with enhancement 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. Another potential enhancement that would work well as a training example would be some research into the value of development in a high hazard area and modifying the parcel database to reflect the updated values.

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 truly build risk mapping capacity in an organization.

11.0 REFERENCES

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SMEC (2006) Project Preparation, Eastern Nile Flood Preparedness & Early Warning Report. December 2006.

Waterbury, J. 1979. *Hydropolitics of the Nile Valley*. Syracuse University Press. 1979.

APPENDIX A FINAL WORKSHOP AGENDA

ENTRO
EASTERN NILE TECHNICAL REGIONAL OFFICE

DRAFT AGENDA FOR FINAL FLOOD RISK MAPPING INCEPTION WORKSHOP

KHARTOUM, SUDAN

DAY ONE - October 12, 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** Existing data Additional survey locations **Terrain Model Development** Source DEM Channel topography definition Integration with DEM	90 vs. 30 meter DEM quality Residual errors in the channel Reservoir representation
1:00-2:30	**Hydrologic Frequency Analysis** Frequency distributions Results and evaluation	
2:30-5:00	**Hydraulic Model Development** Cross section extraction Roughness coefficients Reservoirs (internal boundary) 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 Reservoir behavior Inundation representation for reservoir areas Areas of confined flow, floodplain flow 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

KHARTOUM, SUDAN

DAY TWO - October 13, 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 (velocity, duration were not included)
3:00-4:30	**Recommendations** **Deliverables** Report finalization	Details of Maps: • Which ones to print 10 paper copies of • Acceptability of multi-color overlays • Scales • Background Topographic Maps • Infrastructure representation • Areas selected for detail
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

APPENDIX B PARTICIPANT COMMENTS AT FINAL WORKSHOP

Following is a compilation of comments from final workshop. These comments and associated responses were reviewed and discussed interactively by the consultant and the participants at the conclusion of the workshop.

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 the 30-meter DEM 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.
2. It would be interesting to model actual floods in addition to frequency based flood events in the hydraulic model.
3. The consultant will include the associated discharge on the flood hazard maps.
4. Roughness coefficients have been studied by researchers in the past and the selected values are consistent with previous findings. Variations will be simulated to appreciate a potential range of impact on water levels
5. Regarding the agricultural mapping – if the land use is changing over time, then are multiple satellite images needed to characterize the land use? For this study the land use for purposes of damage calculation are taken as the use at the time of the peak of the flood, and seasonal variations were not included in the methodology.
6. A large percentage of the data collection was verified during a field visit based on local knowledge of people involved in the project and interviews with knowledgeable people.
7. There is concern about the validity of results over time, with development and land use change. These things require continuous updating of data inputs. This may be facilitated using remote sensing techniques.
8. Landcover mapping can sometimes be accomplished in a more efficient manner by using a supervised classification.
9. The stakeholders will have access to the soil and land use information that has been collected.
10. Duration of flooding was not considered explicitly in the methodology for estimating damages; however it is implicit in the damage functions, which are related to actual damages that have been observed from actual events.
11. The products developed could be used in future studies of health impacts of flooding, such as malaria. This would require the development of a methodology similar to what was done for economic risk.
12. There needs to be education/training in the communities in connection with delivery of the maps.
13. The velocity grids might find application in evaluation of transmission and diffusion of point source pollution.
14. The stakeholders are hoping for specific recommendations from the consultant about high risk areas where development restrictions might be advisable.
15. It would be interesting to verify the hydraulic model using a historical event using the historical downstream boundary condition.
16. It will be important for the Ministry to be able to take ownership of the datasets delivered as part of this project. On-going training may be required.
17. Consultant will include a review of the GoToMeetings in the report.

APPENDIX C METHODOLOGY FOR GEO-REFERENCING FIELD SURVEYED DATA

The following steps outlined the procedure to geo-reference the field data and is illustrated in ***Figure C-1***.

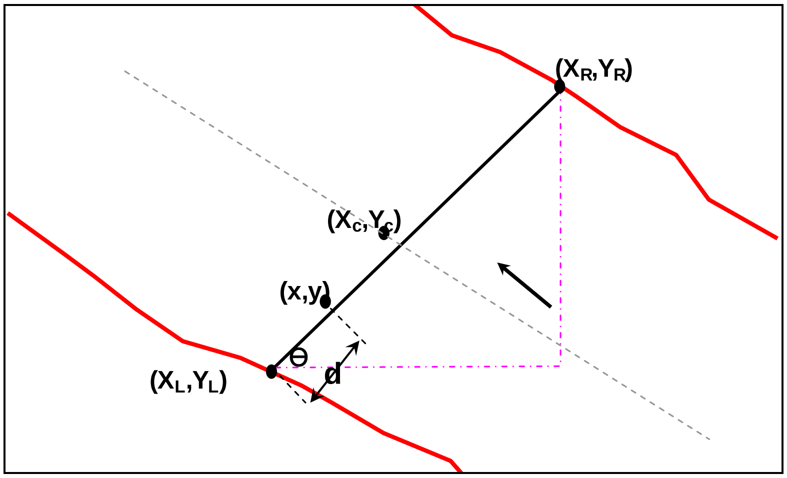

Figure C- 1: Procedure to geo-referencing field surveyed data.

1. Knowing the coordinates of the centerline point of the cross-section along the river reach (X_c,Y_c), a Cutline is drawn perpendicular to the centerline of the river reach (This step is performed within ARC-GIS 9.2).
2. With the aid of information obtained from the raw surveyed data (total width of the river section surveyed is known – d), establish the left coordinates (X_L,Y_L) of the cross-section and right coordinates (X_R,Y_R) of the cross-section in a way that the distance between left point and right point shall be equal to total width of the surveyed section as given in the raw surveyed data (This step is performed within ARC-GIS 9.2) .
3. Having determined the coordinates at left point and right point (see sketch below), the coordinates at each intermediate point are given as follows:

$$Sin\theta = \frac{(Y_R - Y_L)}{\sqrt{(X_R - X_L)^2 + (Y_R - Y_L)^2}} \qquad Cos\theta = \frac{(X_R - X_L)}{\sqrt{(X_R - X_L)^2 + (Y_R - Y_L)^2}}$$

$$x = X_L + dCos\theta$$

$$y = Y_L + dSin\theta$$

Table C- 1 contains an example of the geo-reference results for a cross section in the Blue Nile River at Sennar-Wad Elhadad Reach.

Table C- 1: Geo-reference results for cross section A-1 in the Blue Nile River at Sennar-Wad Elhadad Reach.

CROSS-SECTION : A1
DATE : 02.10.1991
GAUGE STATIONS : SENNAR-WAD ELHADAD

X_L	567765.000	Y_L	1499064.220
X_R	567980.000	Y_R	1499338.100

Dist.	357.7526
Sin Θ	0.786775
Cos Θ	0.617239

Row Data				Geo-Refrenced Cross-section Data		
(METRES)		DEPTHS	Red. Level	x	y	z
-66	0	7.141	412.14477	567765.1	1499064.22	412.144771
-64	2	7.056	412.05977	567766.3	1499065.80	412.059771
-38	28	5.91	410.91377	567782.4	1499086.25	410.913771
-22	44	4.782	409.78577	567792.3	1499098.84	409.785771
-6	60	2.507	407.51077	567802.1	1499111.43	407.510771
-4	62	1.859	406.86277	567803.4	1499113.00	406.862771
0	66	0	405.00377	567805.9	1499116.15	405.003771
5	71	-5.2	399.80377	567808.9	1499120.08	399.803771
10	81	-5.55	399.45377	567815.1	1499127.95	399.453771
20	91	-6.05	398.95377	567821.3	1499135.82	398.953771
30	101	-6.4	398.60377	567827.5	1499143.69	398.603771
40	111	-6.45	398.55377	567833.6	1499151.55	398.553771
50	121	-6.5	398.50377	567839.8	1499159.42	398.503771
60	131	-6.55	398.45377	567846	1499167.29	398.453771
70	141	-6.8	398.20377	567852.1	1499175.16	398.203771
80	151	-7.2	397.80377	567858.3	1499183.03	397.803771
90	161	-7.75	397.25377	567864.5	1499190.89	397.253771
100	171	-8.1	396.90377	567870.7	1499198.76	396.903771
110	181	-8.5	396.50377	567876.8	1499206.63	396.503771
120	191	-8.95	396.05377	567883	1499214.50	396.053771
130	201	-9.45	395.55377	567889.2	1499222.36	395.553771
140	211	-9.5	395.50377	567895.4	1499230.23	395.503771
150	221	-9.5	395.50377	567901.5	1499238.10	395.503771
160	231	-9.8	395.20377	567907.7	1499245.97	395.203771
170	241	-10.3	394.70377	567913.9	1499253.83	394.703771
180	251	-11.1	393.90377	567920	1499261.70	393.903771
190	261	-10.3	394.70377	567926.2	1499269.57	394.703771
200	271	-9	396.00377	567932.4	1499277.44	396.003771
210	281	-5.85	399.15377	567938.6	1499285.31	399.153771
220	291	-5.8	399.20377	567944.7	1499293.17	399.203771
230	301	-4	401.00377	567950.9	1499301.04	401.003771
240	311	-0.7	404.30377	567957.1	1499308.91	404.303771
2	313	0	405.00377	567958.3	1499310.48	405.003771
4	317	1.899	406.90277	567960.8	1499313.63	406.902771
7	320	2.792	407.79577	567962.6	1499315.99	407.795771
11	324	5.279	410.28277	567965.1	1499319.14	410.282771
15	328	5.885	410.88877	567967.6	1499322.28	410.888771
19	332	6.493	411.49677	567970	1499325.43	411.496771
35	348	7.655	412.65877	567979.9	1499338.02	412.658771

APPENDIX D DETAILS OF 2009 FIELD SURVEYS

The survey was conducted from May 4 through May 11, 2009. The following equipment was used in the survey:

- GPS ECHO-sounder
- Automatic Level
- GPS Navigator
- Gauging Staff and Level recorder and Boat.

The survey team consists of the following:

- Team Lead/Civil Engineer
- Land Surveyor
- Land use specialist
- Bathymetric Surveyor
- 2 Labors and Boat driver

The details of the 2009 field surveys are provided in connection with this report in the following files:

- Dinder Pilot Area.pdf
- Hasaheisa.pdf
- Medani to Khartoum.pdf
- Near Roseires.pdf
- Singa Pilot Area.pdf
- Singa to Sennar.pdf
- Wad Medani Cross Section.pdf

The above files are compressed in the file “Appendix B 2009FieldSurvey.zip”.

APPENDIX E FLOOD FREQUENCY ANALYSIS

The probability distributions utilized for the flood frequency analysis are summarized below.

EV1 (Gumbel) Distribution

The EV1 Gumbel distribution is a two-parameter distribution. It is also referred to as double exponential and/or Gumbel distribution. Its form arises from consideration of the statistical properties of sample extreme values. It was first introduced in hydrology by Gumbel. It has the form:

$$f(x) = \frac{1}{\alpha} e^{-\frac{(x-u)}{\alpha} - e^{-\frac{(x-u)}{\alpha}}} \text{ and } F(x) = e^{-e^{-\frac{(x-u)}{\alpha}}}$$

or $g(y) = e^{-y-e^{-y}}$ and $G(y) = e^{-e^{-y}}$

Although y may vary from $-\infty$ to $+\infty$, the practical range is -2 to +6. The distribution is skewed to the right (positively skewed). The practical range for x is $u - 2\alpha$ to $u + 6\alpha$.

The value of x and y that have the same values of probability G(y) = F(x) satisfies:

$y = (x-u)/\alpha \Rightarrow x = u + \alpha y$

The value of y, which has return period T, satisfies the equation:

$1 – G(y) = 1/T$

$G(y) = 1 – 1/T$ or

$$e^{-e^{-y}} = 1 - 1/T$$

This gives $y_T = -\ln(-\ln(1-1/T))$ where y_T denotes value of y for a return period T

Moments: $E(x) = E(u + \alpha y) = u + \alpha E(y) = u + 0.5772\alpha$

$Var(x) = Var(u + \alpha y) = \alpha^2 var(y) = \alpha^2\pi^2/6$

Skewness x = skewness y = 1.14 (dimensionless)

Values of X that has a return period T satisfies: $1 – F(x) = 1/T$

Or $F(x) = e^{-e^{-\frac{(x-u)}{\alpha}}} = 1 - \frac{1}{T}$

Taking logarithms twice and rearranging yields:

$$X_T = u + \alpha\left[-\ln\left(-\ln\left(1-\frac{1}{T}\right)\right)\right]$$

But the term in brackets is y_T therefore

$x_T = u + \alpha y_T$

Log Pearson Type 3

The traditional hydrological method of dealing with Log Pearson Type 3 distribution is to transform the data by Z = lnx. Z is the Pearson Type 3 variate with three parameters. A more general approach is to consider $Z = \ln(x - x_0)$ as a three parameter Person Type 3, x then having a four parameter distribution.

Letting the location, scale and shape parameters of the Z variate be z_0, λ and η respectively, the distribution function is:

$$\phi(z) = \frac{(z - z_0)^{\eta-1} e^{-\left(\frac{z-z_0}{\lambda}\right)}}{\lambda^{\eta}\Gamma(\eta)}$$

If z = lnx then the density function of x is $f(x) = \phi(z(x))\left|\frac{dx}{dz}\right| = \frac{(\ln x - z_0)^{\eta-1} e^{-\left(\frac{\ln x - z_0}{\lambda}\right)}}{x\lambda^{\eta}\Gamma(\eta)}$

A quantile is easily computed if the parameters are specified as z_0, λ and η, the log domain parameters. The corresponding quantile y in a reduced gamma distribution with parameter η is found using tables. Then: $z_T = z_0 + \lambda y_T$ is the corresponding quantile in the Pearson type 3 distribution and the corresponding Log Pearson Type 3 variate is $x_T = \exp(z_T)$ or $x_T = x_0 + \exp(z_T)$ in the 4 parameter case.

It is customary to define the Pearson Type 3 in the log domain only because simple expressions relating the log domain parameters with the moments in the x domain are not available.

APPENDIX F FINAL FLOOD INUNDATION MAPS

The final flood hazard and risk maps are provided in electronically in connection with this report. An index map is provided (BlueNileFloodRiskIndexMap.pdf) to locate the detail maps along the Blue Nile. The detail maps use the following naming convention:

<Map number><Map Type Identifier><Frequency Flow Profile>.pdf

Where <*Map number*> refers to detail map number from the index map, <*Map Type Identifier*> refers to a map type as indicated in ***Table F- 1***, and <*Frequency Flow Profile*> refers to the associated frequency flow for the individual map. For risk maps and flood extent maps no frequency flow profile is identified because these maps incorporate all frequency flow profiles. 22 Map sheets were laid out on the index map for the entire length of the Blue Nile in Sudan, but only 9 detail maps associated with the selected pilot areas have been prepared. The map numbers, therefore, are not continuous, but rather include only map sheets 3, 9, 10, 15, 16, 17 20, 21, and 22.

Example filename: 03d002.pdf

Map Location Number = 03 (map sheet 3)

Map Type Identifier = d (Depth Grid)

Frequency Flow Profile (padded with zeros) = 002 (2 year frequency flow)

Example filename: 06a100.pdf

Map Location Number = 15 (map sheet 15)

Map Type Identifier = a (Vulnerability Map)

Frequency Flow Profile = 100 (100 year frequency flow)

Table F- 1: Map Type Identifiers

Map Type Identifier	Map Type
d	Depth Grid
v	Velocity Grid
a	Vulnerability Map
r	Risk Map
x	Flood extent
u	Duration of flooding