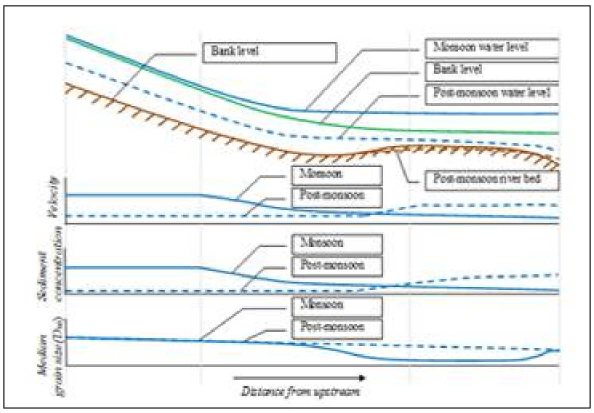
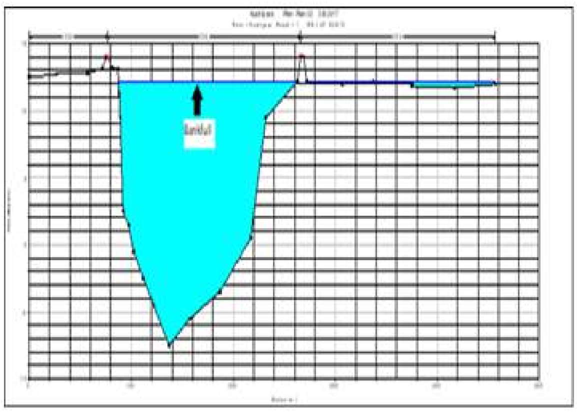
FINAL REPORT

Government of the People's Republic of Bangladesh
Ministry of Water Resources
Department of Bangladesh Haor & Wetlands Development

Model Validation on Hydro-Morphological Process of the River System in the Subsiding Sylhet Haor Basin





June, 2017

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Preface

Geomorphologically Sylhet basin is unique in nature, located in the North Eastern hydrologic zone of Bangladesh. Six out of seven Haor districts are located in this zone, they are: Sylhet, Sunamganj, Maulvibazar, Habiganj, Netrokona and Kishoreganj. Geo-morphological settings of this region attracts the rivers from the east and west side of the Sylhet basin to enter into it. The river morphology of the region is very complex.

The CEGIS has developed a conceptual model to explain the evolution of rivers in the subsiding Sylhet Basin (Haor areas) using scanty of relevant data. Validation of this model was not done earlier due to certain constraints of time and financial resources.

The primary objective of this study is the validation of the existing CEGIS Conceptual Model. Other objectives include understanding of the inherent morphological process of the river system of the Haor areas and to assess the applicability of the validated model with the enhanced knowledge on prevailing physical process of the rivers.

Under this study, the conceptual model has been examined using both conventional way as well as through model outputs. Two HECRAS 5.0.3 models were developed, one for the Surma and the other one for the Kushiyara river.

The Mid Term report on "Model Validation on Hydro-morphological process of the River System in the Subsiding Sylhet Haor Basin" was submitted to the DBHWD on 22 January 2017. The 2nd Technical Committee meeting was held on the report on 1 march 2017. The comments/suggestions received from the members of the Technical Committee (TC) and the decisions of the said TC meeting were reviewed carefully and incorporated in the (draft) Final Report. The (draft) Final Report was submitted on 1st June, 2017.
A workshop was held on 6th June, 2017 to disseminate and discuss the (draft) Final Report with stakeholders and various experts. Dr. Zafar Ahmed Khan, Senior Secretary, Ministry of Water Resources (MoWR) was the Chief Guest. Mr. Majibur Rahman, Director General, Department of Haor and Wetlands Development chaired the workshop and Md. Humayun Kabir, Additional Secretary, Ministry of Water Resources moderated the open discussion. **The (draft) Final Report was recommended for approval.**

The 1st meeting of the Steering Committee, chaired by Dr. Zafar Ahmed Khan, Senior Secretary, Ministry of Water Resources (MoWR) was held on 20th June, 2017. **The Steering Committee approved the (draft) Final Report.** The decisions and recommendations of the workshop and Steering Committee have been incorporated in the Final Report.

The Final Report has 3 volumes stitched together, namely:

Volume 1: Main Report

Appendix 1: Feedback from the Stakeholders

Volume 2: Appendix 2: Bank Line Survey Report of the Surma and Kushiyara Rivers

Volume 3: Appendix 3: Analysis of Sediment and Bed Material Samples of the Surma and Kushiyara Rivers

We acknowledge with great appreciation Ministry of Water Resources, GoB, and the DBHWD for initiating the project and giving opportunities to M/s Prosoil Foundation Consultant to carry out the research project.

The team deeply acknowledge the co-operation and guidance of the Technical Committee of the project. The team also acknowledge the ‘Department of Bangladesh Haor and Wetlands Development’ for providing logistic supports and helping the team to prepare the Report. We acknowledge the Bangladesh Water Development Board (BWDB) for providing relevant data. We acknowledge the support and co-operation received from the Center for Environmental and Geographic Information Services (CEGIS). We acknowledge the Water Resources Planning Organization (WARPO) for allowing us to use their library.

Satellite images were collected from Internet website of the United States Geological Survey (USGS). We also deeply acknowledge their support. We thank M/s Globe Survey Company who helped us in carrying out field measurements and surveys.

We are grateful to Mr. Anisul Islam Mahmud, Hon’bl Minister, Ministry of Water Resources, Mr. Muhammad Nazrul Islam, Bir Protik, Hon’bl State Minister, Ministry of Water Resources and Dr. Zafar Ahmed Khan, Senior Secretary, Ministry of Water Resources for their kind support and approval of the project. We are thankful to Mr. Majibur Rahman, Director General, Department of Bangladesh Haor and Wetlands Development and Mrs. Afroza Moazzam, former Director General, Department of Bangladesh Haor and Wetlands Development for their active support and co-operation. We appreciate the co-operation of Mr. Md. Nazmul Ahsan, Project Director and Md. Nurul Amin, Director (Admin and Finance), of the Department of Bangladesh Haor and Wetlands Development. We also thank the local people, particularly of the Northeast Region who in various ways helped the study team in conducting the field measurements and survey works.

Dhaka-29th June, 2017

H.S. Mozaddad Faruque
Senior Morphologist
And
Team Leader

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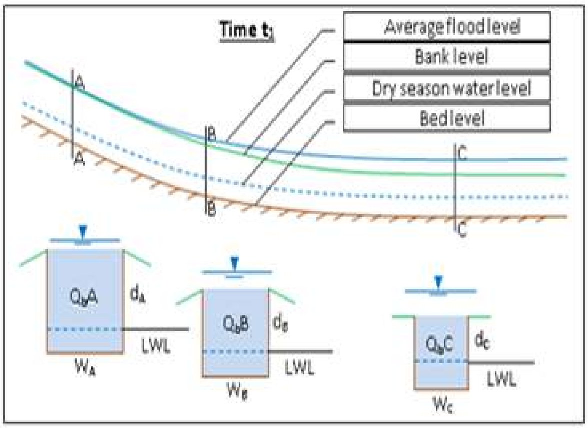
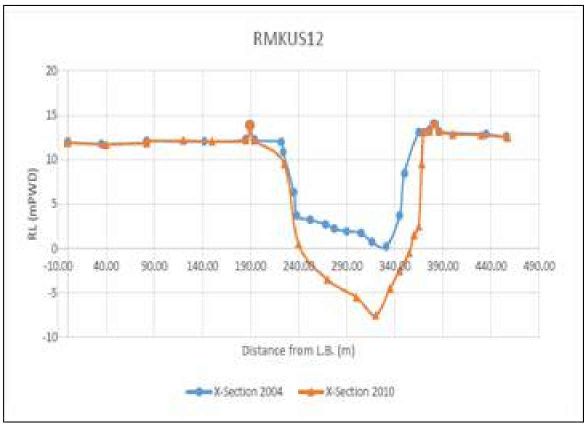
Volume 1: Main Report





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Volume 1: Main Report

June, 2017

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Bangladesh

Final Report

The Final Report on "Model Validation on Hydro-morphological Process of the River System in the Subsiding Sylhet Haor Basin", submitted in June, 2017 contains the following volumes:

Volume 1:	**Main Report** Appendix 1: Feedback from the Stakeholders
Volume 2:	Appendix 2: Bank Line Survey Report of the Surma and the Kushiyara Rivers
Volume 3:	Appendix 3: Analysis of Sediment and Bed Material Samples of the Surma and the Kushiyara Rivers

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    Surveyor
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Glossary of Terms

Avulsion	In sedimentary geology and fluvial geomorphology, avulsion is the rapid abandonment of a river channel and the formation of a new river channel.
Bankfull Level	The Bankfull level is the height of water in a natural channel at its maximum height before flooding. If the water level exceeds the bankfull limit, then a flood will occur.
Basin	A basin or catchment basin is an extent or an area of land where all surface water from rain, melting snow, or ice converges to a single point at a lower elevation, usually the exit of the basin, where the waters join another body of water, such as a river, lake, reservoir, estuary, wetland, sea, or ocean.
Calibration	Calibration is the process of finding a relationship between two quantities that are unknown. When the measurable quantities are not given a particular value for the amount considered or found a standard for the quantity.
CEGIS Conceptual Model	Model developed by the CEGIS on morphological behavior (qualitatively) of the rivers of the North Eastern zone under different scenarios.
Conceptual Model	A conceptual model is a model made of the composition of concepts, which are used to help people know, understand, or simulate a subject the model represents.
Depression	A depression is a landform sunken or depressed below the surrounding area.
Distributary	A distributary is a stream that branches off and flows away from a main stream channel
Flood	A flood is an overflow of water that submerges land which is usually dry. Flooding may occur as an overflow of water from water bodies, such as a river, lake, or ocean, in which the water overtops or breaks levees, resulting in some of that water escaping its usual boundaries, or it may occur due to an accumulation of rainwater on saturated ground in an aerial flood.

Haor	Haors are bowl-shaped depressions of considerable aerial extent lying between natural levees of the rivers or high lands of the northeast region of Bangladesh. In most cases, haors have been formed as a result of peripheral faulting leading to the depression of the haor area. In the wet seasons, the haors are full of water, but during the dry seasons, these are dried up except for the beels.
Hydro-dynamics	Hydro-dynamics a branch of physics that deals with the motion of fluids and the forces acting on solid bodies immersed in fluids and in motion relative to them—compare hydrostatics.
Hydrodynamic Model	A Hydrodynamic Model is a tool able to describe or represent in some way the motion of water.
Hydro-morphology	Hydro-morphology is the study of water forms. Water as with any fluid under the influence of forces like gravity takes on the shape of its container.
Mathematical Model	A Mathematical Model is a description of a system using mathematical concepts and language.
Morphology	The terms Morphology are used to describe the shapes of river channels and how they change in shape and direction over time.
Subsidence	Subsidence is the motion of Earth's surface as it shifts downward relative to a datum such as sea-level.
Thalweg	In hydrological and fluvial landforms, the thalweg is a line drawn to join the lowest points along the entire length of a stream bed or valley in its downward slope, defining its deepest channel.
Tributary	A tributary or affluent is a stream or river that flows into a larger stream or river main stem (or parent) river or a lake. A tributary does not flow directly into a sea or ocean.
Validation	Validation of models is conducted during the development of a simulation model with the ultimate goal of producing an accurate and credible model. Simulation models are approximate imitations of real-world systems and they never exactly imitate the real-world system. Due to that, a model is validated to the degree needed for the models intended purpose or application.

Abbreviations and Acronyms

BWDB	Bangladesh Water Development Board
CEGIS	Center for Environment and Geographic Information Services
DPP	Development Project Proforma
GIS	Geographic Information System
GoB	Government of Bangladesh
GPS	Global Positioning System
ha	hectare
HEC-RAS	Computer program that models the hydraulics of water flow through natural rivers and other channels (developed by the U.S. Army Corps of Engineers)
IWM	Institute of Water Modelling
Km	Kilometer
MIKE11	One-dimensional modelling system of DHI Water & Environment
MIKE21	Two-dimensional modelling system of DHI Water & Environment
MIKE-SHE	Modelling Software of DHI for Groundwater Flow Simulation
MoWR	Ministry of Water Resources
MPO	Master Plan Organization
NWMP	National Water Management Plan
PD	Project Director
PSC	Project Steering Committee
PSP	Proforma for Study/Survey Proposal
RFP	Request for Proposal
TOR	Terms of Reference
USGS	United States Geological Survey
WARPO	Water Resources Planning Organization

Executive Summary

The general study area is the Sylhet basin, located in the north-east hydrological zone of Bangladesh. The region is a tectonically active area and the rate of subsidence in this area is much higher than the deltaic-plains elsewhere in the country. It is reported that in the Sylhet Basin, tectonic subsidence has been active since the Miocene.

The CEGIS has developed a conceptual model to explain the evolution of rivers in the subsiding Sylhet Basin (Haor areas). Validation of this model was not done before. The concept is quoted below:

Quote

- The bankfull discharge of the channel in concern varies in the downstream direction. At the upstream, it is high and close to annual average flood discharge. This implies that in most days in a year, the river flow is confined within the bank. On the other hand, the bankfull discharge at the downstream is much less and the overbank flow occurs for several months during the monsoon.
- Decrease in the bankfull discharge at the downstream, however, indicates a decrease in channel dimensions i.e. the width and depth. This might be the reason why the width of the river decreases while it enters into the Sylhet Basin as observed from the satellite images
- After several years/decades (at time t_α) as the river will be able to raise its levee and reach regime condition, the flood level will be close to the bank level, i.e. bankfull discharge will be the same along the whole river stretch. The channel dimensions will be nearly the same at the upstream and downstream and no sedimentation would be expected during monsoon.

Unquote

The main objective of the study is to know the inherent morphological process of the river system in the Haor areas. The Specific objective of the study is to **"validate the existing**

conceptual Model of the CEGIS”. The detailed objectives and scope of studies have been given in section 1.3 and 1.4 respectively.

The methodology of the study was described both in the Inception Report and Mid Term Report and was approved by the Technical Committee and the DBHWD. The methodology includes literature review; collection of primary and secondary data; bankline survey; analysis of primary and secondary data; setting up a hydrodynamic model; calibration and validation of the model and preparation of reports. The same methodology has been followed in the preparation of the Final Report.

Different publications, reports, documents, policies, plans, acts etc. have been reviewed by the research team in order to understand the complex characteristics of the morphological process of the North Eastern Region. The details have been given in Chapter 4. Some of the notable documents are:

- Different Numerical Models
- Morphology of the Haor areas (CEGIS, 2011)
- Inland Navigation and Integrated Water Resources Management (Sarker, et al, 2014)

It was beyond the scope of the TOR to measure/determine the subsidence of the Sylhet Basin. But the literature review strongly suggests/confirms that the Sylhet Basin is subsiding at the rate of 2-4 mm/year.

The Surma and the Kushiyara rivers have been studied for the validation of the CEGIS Model. A reach of 150 km each for both the rivers starting from Kanaighat for the Surma and Sheola for the Kushiyara have been considered.

- The study has been conducted based on data from primary as well as secondary sources. Primary data of both the Surma and the Kushiyara rivers were collected.
- Routine measurements of discharge (monthly, at one fixed section for each of the Surma and the Kushiyara rivers) were made.
- Routine measurements of sediment concentration (monthly, at one fixed section for the Surma and the Kushiyara each) were made.

- Measurements of cross-sections (in 9 stations for the Surma and the Kushiyara each) were made.
- Sediment concentration measurements (3 sets of measurements, in 9 stations for the Surma and the Kushiyara each) were made.
- Bank line survey of both the Surma and the Kushiyara rivers have been conducted (for 150 km of each river).
- Secondary data on water level, discharge, velocity and cross-section of both the Surma and the Kushiyara rivers have been collected from the BWDB.
- Satellite images have been collected from the United States Geological Survey (USGS) (downloaded from internet).

A thorough review of the manuals of different numerical models were carried out. Two most commonly used one dimensional modelling software are HEC-RAS and MIKE 11. The other widely used models are Delft3D and Delft3D FM. On evaluation of the applicability of the models for this study, HEC-RAS 5.0.3 has been selected on the following major considerations, that:

- It is user friendly, requiring data on water level, discharge, and cross-section only.
- HEC-RAS is available for download for free of cost. Other models such as MIKE 11, Delft3D etc. are licensed software and quite expensive. The project study does not have any provision for purchase of such license. It may be noted that it was also mentioned in the Inception Report that HEC-RAS model would be used in the study.

Due to non-availability and discontinuity of data of the Barak river at Amalshid (bifurcation point of the Barak to form the Surma and the Kushiyara, (Fig: 6.5) two different models have been set up for two rivers, namely the Surma and the Kushiyara. The water level, velocity, discharge and cross section data have been processed and were used for calibrating and validating of the numerical model namely HEC-RAS 5.0.3.

Model for the Surma: The model has been calibrated using data of 2013 and validated with data of 2014. The river schematic setup of the Surma has been established (Fig. 8.2) starting from station Kanaighat to Sunamganj (BWDB station SW 266 to SW 269). BWDB cross-sections (of February-March 2013) for RMS 38 to RMS 10 (total 28 cross-sections) were used to setup the model geometry of the Surma river. For the Surma river model, Kanaighat (SW

266) has been taken as the upstream discharge station and the discharge hydrograph of this station (of 2013) has been considered as the Upstream Boundary Condition. Stage hydrograph (water level) of 2013 of Sunamganj (SW 269) has been used as the Downstream Boundary Condition for the Surma river.

Model for the Kushiyara: The model has been calibrated with data of 2011 and validated using data of 2012. The river schematic setup of the Kushiyara River has been done from station Sheola to Markuli (BWDB station SW 173 to SW 270) (Fig. 8.3). The cross-section geometry setup of the Kushiyara river was done for RMKUS12 to RMKUS1 and RMBIB9 to RMBIB1 (total 21 cross sections of March-April 2010). The discharge hydrograph (of 2011) of station Sheola (SW 173) has been used as Upstream Boundary Condition of the Kushiyara river. The stage hydrograph (water level) of 2011 of Markuli (SW 270) has been used as Downstream Boundary Condition for the Kushiyara river.

The theoretical explanations and analysis of the CEGIS hypotheses have been given in chapter-5. It may be mentioned that these hypotheses were also discussed in the MID Term Report.
The following hypotheses have been extracted from the above mentioned conceptual model.

(1) Hypothesis 1: The bankfull water level of the channel in concern varies in the downstream direction. At the upstream, it is high and close to annul average flood discharge.
(2) Hypothesis 2: Decrease in the bankfull water level at the downstream, however, indicates a decrease in channel dimensions i.e. the width and depth.
(3) Hypothesis 3: The shallow depth caused to increase the high gradient during the dry season and thus increase the dry season water level at the upstream.
(4) Hypothesis 4: After several years/decades (at time t_α) as the river will be able to raise its levee and reach regime condition, the flood level will be close to the bank level, i.e. bank full water level will be the same along the whole river stretch.
(5) Hypothesis 5: At regime condition the channel dimensions will rearly be the same both at the upstream and downstream and no sedimentation would be expected during monsoon.

Validation of the CEGIS conceptual Model were tried using both conventional way of data analysis as well as from model output (simulated values). Details have been presented in Chapter 9.

Both the models (Surma and Kushiyara) have been fine-tuned and simulated to predict the future scenarios with 20% increase of discharge (Scenario-1) as well as 20% decrease of discharge (Scenario-2) at the upstream. The details have been given in Chapter 10.

The bankline survey report, containing survey data and maps have been plotted and presented in Volume 2. Analysis of sediment and bed material samples have been presented in Volume 3.

The major findings of the study are as follows:

1. The analysis confirms the acceptability of Hypothesis 1 for both the Surma and the Kushiyara rivers.
2. The Hypothesis 2 could not be (conclusively)established/validated.

   For both the Surma and the Kushiyara rivers it may be concluded that, the bankfull water levels at the downstream decrease, consequently there are changes in channel dimension, the change of both the area and the top width shows a scattered pattern and the change of average depth shows a decreasing trend towards downstream direction. (see 9.2.1; 9.2.2)
3. (i) From conventional analysis, Hypotheses 3 may be considered established/validated for both the Surma and the Kushiyara rivers.

   (ii) From Model output, it may be stated that the Hypothesis 3 may be considered as established/validated for the Kushiyara but not for the Surma. (details in Sec 9.3.1 and 9.3.2)
4. Hypotheses 4 and 5 relate to the hypothetical 'Regime Condition' of the river.

   The analysis clearly demonstrates that the Surma and the Kushiyara rivers are not in 'Regime Condition'. So the hypothesis could not be confirmed/validated through the model output. But since the 'Regime Condition' is a theoretical condition of a river, the validity of these two hypotheses (4 and 5) can be accepted on Theoretical explanation basis (details given in See 5.6).

5. Under Scenario 1, when Peak discharge increases (20%) at upstream, there are increase in simulated cross sections, discharges and water levels at downstream. Consequently, new areas are flooded and in other places flood depth increase.
6. Under Scenario 2, when Peak discharge decreases (20%) at upstream, there are decrease in cross sections, discharge and water levels at downstream. Consequently, flood reduction is observed.

Concluding Remarks

1. Through the validation of the CEGIS conceptual Model the study has contributed towards enhancement of knowledge on hydro morphological process of the two major rivers of the Haor areas which will be of great benefit for the planners and the Government for implementation of the development plans in the Haor areas.
2. This HEC-RAS 5.0.3 model may be further updated to predict the changes in sediment deposition, erosion, discharge and water level in the downstream of the Surma and the Kushiyara rivers.
3. A study may be taken up to couple the two HEC-RAS Models developed under this study.
4. A study may be taken up to develop a general model to simulate and predict the morphological behavior of the rivers of the Haor region.
5. Finer resolution satellite images should be collected for understanding of the shifting of the rivers.
6. Some permanent sediment and bed material collection stations should be established both on the rivers Surma and Kushiyara.
7. A routine program of bathymetric survey for the two rivers may be taken up. The survey should be carried out in 4 seasons (namely, Pre monsoon, Monsoon, Post monsoon and Dry).

The Executive summary of the Final Report has been given in Bengali below:

Executive Summary (in Bengali)

নির্বাহী সারসংক্ষেপ

সাধারনভাবে সমীক্ষা এলাকাটি সিলেট বেসিনে (Sylhet basin) অবস্থিত, যা বাংলাদেশের উত্তর-পূর্ব হাইড্রলজিক্যাল অঞ্চলের (north-east hydrological zone) অন্তর্ভুক্ত। ভূতাত্ত্বিক গঠনের দিক থেকে এ অঞ্চলটি সক্রিয় (tectonically active)। এ অঞ্চলের ভূ-অবনমনের (subsidence) মাত্রা দেশের অন্যান্য (বদ্বীপ সমভূমি) অঞ্চলের চেয়ে অনেক বেশী। ধারণা করা হয় সিলেট বেসিনের ভূতাত্ত্বিক অবনমন মায়োসেন (Miocene) যুগ (২৩.০৩-৫.৩ মিলিয়ন বৎসর পূর্ব) থেকে সক্রিয়।

অবনমিত সিলেট বেসিনের (হাওর অঞ্চল) নদীসমূহের বিবর্তন ব্যাখ্যার লক্ষ্যে সিইজিআইএস (CEGIS) গ্রহণযোগ্যতার একটি ধারণাগত মডেল (conceptual model) প্রণয়ন করে। কিন্তু মডেলটির শুদ্ধতা/গ্রহণযোগ্যতার পরীক্ষা (Validation) ইতোপূর্বে করা হয়নি। নিম্নে ধারণাটির উদ্‌ধৃতি দেয়া হল।

- "...... নদীর পূর্ণনদী প্রবাহের মান (bank full discharge), নদীর নীচের দিকে বিভিন্ন স্থানে বিভিন্ন ধরণের হয়। নদীর উপরের অংশে (upstream) এর মান বেশী এবং এটি গড় বন্যা প্রবাহের কাছাকাছি। এ থেকে বোঝা যায় যে, (উপরের অংশে) বৎসরের প্রায় সব সময়ই নদী প্রবাহ, তার দু'কূলের মধ্যেই সীমাবদ্ধ থাকে। অপর দিকে নদীর নিম্নাঞ্চলের (downstream) পূর্ণনদী প্রবাহের মান অনেক কম থাকে এবং বর্ষা মৌসুমে এ অঞ্চলে কয়েক মাস কূল ছাপিয়ে বন্যা হয়ে থাকে।
- নদীর নিম্নাঞ্চলের (downstream) পূর্ণ নদী প্রবাহের মান কমে যাওয়া, নদীর আকৃতির কমে যাওয়াকেই নির্দেশ করে অর্থাৎ নদীর প্রস্থ ও গভীরতা কমে যায়। সিলেটে বেসিনে প্রবেশের পরে নদীর প্রস্থ কমে যাওয়ার এটি একটি কারণ হতে পারে। বিষয়টি স্যাটেলাইট ছবিতেও (satellite image) দেখা যায়।
- বহু বহু বৎসর পরে যখন নদী তার পাড়/তীর দুটিকে (levee) সু-উচ্চ করতে সক্ষম হয় এবং নদী স্থিতি অবস্থায় (regime condition) আসে তখন বন্যার পানি তল (flood level) তীরের সমতলের কাছাকাছি হয় অর্থাৎ সমস্ত নদীতেই পূর্ণনদী প্রবাহের (bank full

discharge) মান একই সমান থাকে। নদীর আকার সর্বত্রই (উপরের অংশে ও নিম্নাঞ্চল) একই থাকে এবং বর্ষা মৌসুমে (monsoon) কোন পলি জমা আশা করা যায় না।”

এ সমীক্ষার মূল উদ্দেশ্য হল, হাওর এলাকার নদীসমূহের অন্তর্নিহিত মরফোলজিক্যাল পদ্ধতি (morphological process) সম্পর্কে জ্ঞান অর্জন করা। সমীক্ষার সুনির্দিষ্ট উদ্দেশ্য হল সিইজিআইএস প্রণীত ধারণা মডেলটির শুদ্ধতা/গ্রহণযোগ্যতা যাচাই করা। সমীক্ষার বিস্তারিত উদ্দেশ্য এবং কাজের পরিধি (scope) যথাক্রমে সেকশন ১.৩ ও ১.৪ এ দেয়া হয়েছে।

সমীক্ষাটির কর্মপদ্ধতি (methodology) ইনসেপ্‌সশন রিপোর্ট ও মিড-টার্ম রিপোর্টে দেয়া হয়েছে, যা প্রকল্পের কারিগরি কমিটি (technical committee) এবং বাংলাদেশ হাওর ও জলাভূমি উন্নয়ন অধিদপ্তর কর্তৃক অনুমোদিত হয়েছে। এ কর্মপদ্ধতিতে যা অন্তর্ভুক্ত; তা হলো: প্রকাশনা পর্যালোচনা (literature review), প্রাথমিক/মৌলিক (primary) উপাত্ত সংগ্রহ, অন্যান্য সংস্থা থেকে উপাত্ত (secondary data) সংগ্রহ, নদীতীর জরীপ (bank line survey), সংগৃহীত উপাত্ত বিশ্লেষণ, হাইড্র-ডায়নামিক মডেল (hydro dynamic model) স্থাপন, মডেলের ক্যালিব্রেশন (calibration) ও শুদ্ধতা/গ্রহণযোগ্যতা যাচাই (validation) এবং রিপোর্ট প্রণয়ন।

খসড়া ও চূড়ান্ত রিপোর্ট প্রণয়নের ক্ষেত্রে উপরোল্লিখিত কর্মপদ্ধতি অনুসরণ করা হয়েছে। দেশের উত্তর-পূর্বাঞ্চলের নদীসমূহের জটিল বৈশিষ্ট্য ও নদী গঠন পদ্ধতি (morphological process) অনুধাবনের লক্ষ্যে বিভিন্ন প্রকাশনা, ডকুমেন্ট, রিপোর্ট, জাতীয় নীতি, পরিকল্পনা, আইন ইত্যাদি পর্যালোচনা করা হয়েছে যার বিশদ বিবরণ ৪র্থ অধ্যায়ে দেয়া হয়েছে। বিশেষভাবে উল্লেখযোগ্য কয়েকটি ডকুমেন্ট হলো:

- বিভিন্ন নিউমেরিক্যাল মডেল
- মরফোলজি অব দি হাওর এরিয়াস (সিইজিআইএস, ২০১১)
- ইন্‌ল্যান্ড নেভিগেশন এন্ড ইন্টিগ্রেটেড ওয়াটার রিসোর্সেস ম্যানেজমেন্ট (সরকার ও অন্যান্য, ২০১৪)

সিলেট বেসিনের অবনমনের মাত্রা নির্ণয় করা এ সমীক্ষা কাজের অন্তর্ভুক্ত ছিল না। কিন্তু প্রকাশনা পর্যালোচনায় দেখা যায় যে সিলেট বেসিন বৎসরে ২-৪ মিঃমিঃ হারে অবনমিত হচ্ছে।

মডেলের শুদ্ধতা/গ্রহণযোগ্যতা যাচাই (validation) এর লক্ষ্যে সুরমা ও কুশিয়ারা নদীতে সমীক্ষা চালানো হয়। উভয় নদীরই দুই তীরের ১৫০ কিঃমিঃ এলাকা (length) এ সমীক্ষা কার্যক্রমের অন্তর্ভুক্ত ছিল। সুরমার ক্ষেত্রে কানাই ঘাট ও কুশিয়ারা নদীর ক্ষেত্রে শেওলা থেকে এ কার্যক্রম শুরু হয়।

- সংগৃহীত মৌলিক উপাত্ত (primary data) এবং অন্যান্য সংস্থা হতে সংগৃহীত তথ্যের (secondary data) ভিত্তিতে সমীক্ষাটি পরিচালিত হয়।
- সুরমা ও কুশিয়ারা উভয় নদীর ক্ষেত্রেই রুটিন নদী প্রবাহ (discharge) পরিমাপ করা হয় (একটি স্টেশনে মাসিক ভিত্তিতে)।
- সুরমা ও কুশিয়ারা উভয় নদীর ক্ষেত্রেই রুটিন পলির ঘনত্ব (sediment concentration) পরিমাপ করা হয়।
- সুরমা ও কুশিয়ারা উভয় নদীর ক্ষেত্রেই ৯টি স্থানে ক্রস-সেকশন (cross-section) পরিমাপ করা হয়।
- উভয় নদীতেই পলির ঘনত্বের (sediment concentration) পরিমাপ করা হয় (তিনবার, ৯টি স্টেশনে)
- উভয় নদীতেই বেড মেটেরিয়াল (bed material) পরিমাপ করা হয় (২ বার, ৯টি স্টেশনে)
- উভয় নদীর জন্যই নদীতীর জরীপ (bank line survey) করা হয়। ১৫০ কিঃমিঃ দৈর্ঘ্যে নদীর উভয় তীর জরীপ করা হয়।
- বাংলাদেশ পানি উন্নয়ন বোর্ড (বাপাউ বোর্ড) হতে পানি তল (water level), প্রবাহ (discharge), বেগ (valocity) এবং ক্রস সেকশন (cross section) উপাত্তসমূহ সংগ্রহ করা হয়।
- ইন্টারনেট হতে ইউএসজিএস (USGS) এর স্যাটেলাইট ছবি ডাউনলোড করা হয়।
- বিভিন্ন নিউমেরিক্যাল মডেলের ম্যানুয়েল নিবিড়ভাবে পর্যালোচনা করা হয়। সাধারনভাবে দুটি বহুল ব্যবহৃত এক মাত্রিক (one dimensional) মডেল হচ্ছে HGC-RAS এবং MIKE 11. অন্যান্য বহুল ব্যবহৃত মডেল হচ্ছে Delft 3D এবং Delft 3D FM ব্যবহারের উপযোগিতা মূল্যায়ন শেষে HEC-RAS 5-03 মডেলটি এ সমীক্ষা কাজে ব্যবহারের জন্য নির্বাচিত করা হয়। এ নির্বাচনের ক্ষেত্রে নিম্নেবর্ণিত বিষয়াদি বিবেচনায় আনয়ন করা হয়।

- মডেলটি ব্যবহারকারী বান্ধব (user-friendly)। এ মডেলের জন্য শুধু পানির তল, প্রবাহ এবং ক্রস-সেকশনের প্রয়োজনে হয়।
- মডেলটি বিনামূল্যে ডাউনলোড করে ব্যবহার করা যায়। অপরদিকে MIKE 11 অথবা Delft 3D ইত্যাদির ক্ষেত্রে সফ্টওয়্যার লাইসেন্সের প্রয়োজন হয় এবং যা বেশ ব্যয় বহুল। এ সমীক্ষা প্রকল্পে মডেলের লাইসেন্স ক্রয়ের জন্য কোন সংস্থান নেই। লক্ষণীয় যে ইনসেপশন রিপোর্টেও উল্লেখ করা হয়েছিল যে এ সমীক্ষা কাজে HEC-RAS মডেল ব্যবহার করা হবে।
- সুরমা ও কুশিয়ারা নদী বরাক নদী হতে অমলশিদ নামক স্থানে উৎপন্ন হয়েছে। বরাক নদীর উপাত্ত স্বল্পতা ও নিরবিচ্ছিন্ন উপাত্ত না থাকার কারণে সুরমা ও কুশিয়ারা নদী দুটির জন্য দুটি আলাদা মডেল প্রণয়ন করা হয়েছে। নদীর পানি তল, বেগ, প্রবাহ এবং ক্রস সেকশন উপাত্তসমূহ বিশ্লেষণ ও প্রসেস করে তা HEC-RAS 5.03 মডেলে ক্যালিব্রেশন ও ভেলিডেশনের জন্য ব্যবহার করা হয়েছে।

সুরমা নদীর মডেল

মডেলটি ২০১৩ সালের উপাত্ত দিয়ে ক্যালিব্রেশন করা হয়েছে এবং ২০১৪ সালের উপাত্ত দিয়ে শুদ্ধতা/গ্রহণযোগ্য যাচাই করা হয়েছে। সুরমার স্কেমাটিক সেটআপ (schematic setup) কানাইঘাট হতে সুনামগঞ্জ পর্যন্ত বিস্তৃত (বাপাউ বোর্ড স্টেশন SW 266 হতে SW 269)। মডেলটির জিওমেট্রিক সেটআপ (geometric setup) নির্ধারনে বাপাউ বোর্ডের স্টেশন RMS 38 হতে RMS 10 (মোট ২৮টি) ক্রস সেকশন ব্যবহৃত হয়েছে। এ ক্রস সেকশন সমূহ বাপাউ বোর্ড ২০১৩ সালের ফেব্রুয়ারি-মার্চ মাসে পরিমাপ করে। সুরমা মডেলে কানাইঘাট (SW 266) কে উপরস্থ (upstream) প্রবাহ স্টেশন হিসাবে গণ্য করা হয়েছে এবং এ স্টেশনের ২০১৩ সালের প্রবাহ হাইড্রগ্রাফকে (discharge hydrograph) আপষ্ট্রীম বাউন্ডারী কন্ডিশন (upstream boundary condition) হিসাবে গণ্য করা হয়েছে। সুনামগঞ্জ স্টেশনের (SW 269) ২০১৩ সালের পানি তল হাইড্রগ্রাফকে (stage hydrograph) ডাউনস্ট্রীম বাউন্ডারী কন্ডিশন (down stream boundary condition) হিসাবে গণ্য করা হয়েছে।

কুশিয়ারা নদীর মডেল

মডেলটি ২০১১ সালের উপাত্ত দিয়ে ক্যালিব্রেশন করা হয়েছে এবং ২০১২ সালের উপাত্ত দিয়ে শুদ্ধতা/ গ্রহণযোগ্যতা যাচাই করা হয়েছে। কুশিয়ারার স্কেমাটিক সেটআপ (schematic setup) শেওলা হতে মারকুলি পর্যন্ত বিস্তৃত (বাপাউ বোর্ড স্টেশন ;SW 173 হতে SW 270)। মডেলটির জিওমেট্রিক সেটআপ নির্ধারনে বাংলাদেশ পানি উন্নয়ন বোর্ডের স্টেশন RMKUS 12 হতে RMKUS 1 এবং RMBIB 9 হতে RMBIB 1 (সর্বমোট ২১টি) ক্রস সেকশন ব্যবহৃত হয়েছে। এ ক্রস সেকশনসমূহ বাপাউ বোর্ড ২০১০ সালের মার্চ-এপ্রিল সময়ে পরিমাপ করে। কুশিয়ারা মডেলে শেওলা (SW 173) কে উপরস্থ প্রবাহ (upstream boundary) স্টেশন হিসাবে গণ্য করা হয়েছে এবং এই স্টেশনের ২০১১ সালের প্রবাহ হাইড্রগ্রাফকে (discharge hydrograph) আপস্ট্রীম বাউন্ডারী কন্ডিশন (upstream boundary condition) হিসাবে গণ্য করা হয়েছে। মারকুলি স্টেশনের (SW 270) ২০১১ সালের পানি তল হাইড্রগ্রাফকে (stage hydrograph) ডাউনস্ট্রীম বাউন্ডারী কন্ডিশন ((downstream boundary condition) হিসাবে গণ্য করা হয়েছে।

ধারণা মডেলটির তাত্বিক ব্যাখ্যা ও বিশ্লেষণ এবং মডেলটির হাইপোথেসিস (hypothesis) সমূহ অধ্যায় ৫ এ দেয়া হয়েছে। উল্লেখ্য এই হাইপোথেসিস সমূহ মিড-টার্ম রিপোর্টে বর্ণনা করা হয়েছে। সিইজিআইএস মডেলটি থেকে নিম্নেবর্ণিত ৫টি হাইপোথেসিস আহরণ করা হয়েছে।

(১) হাইপোথেসিস-১: পূর্ণনদী প্রবাহের মান নদীর নিচের দিকে বিভিন্নতর হয়। উপরের দিকে এর মান বেশী, যা বাৎসরিক গড় বন্যা প্রবাহের কাছাকাছি।

(২) হাইপোথেসিস-২: নদীর নীচের দিকে (downstream) পূর্ণনদী প্রবাহের মান কম হয় যা নদীর আকৃতি কমে যাওয়াকে নির্দেশ করে। অর্থাৎ নদীর প্রস্থ ও গভীরতা কমে যায়।

(৩) হাইপোথেসিস-৩: নদী স্বল্প গভীরতার কারণে শুষ্ক মৌসুমে নদী তলের ঢাল (gradient) বৃদ্ধি পায় ফলে নদীর উপরের অংশে (upstream area) পানির তলের মান বৃদ্ধি পায়।

(৪) হাইপোথেসিস-৪: বহু যুগ পর যখন নদী তার পাড়/তীর দুটিকে উচু করতে সক্ষম হয় এবং নদী স্থিতি অবস্থায় (regime condition) আসে, তখন বন্যার পানি তল (flood level) তীরের সমতলের কাছাকাছি হয় অর্থাৎ সমস্ত নদীতেই পূর্ণনদী প্রবাহ তলের মান একই থাকে।

(৫) হাইপোথেসিস-৫: নদীর স্থিতি অবস্থায় (regime condition) সমস্ত নদীতে (উপরের অংশে ও নিম্নাংশে) নদীর আকার একই প্রকার থাকে এবং বর্ষা মৌসুমে কোন পলি জমা আশা করা যায় না।

সিইজিআইএস মডেলটির শুদ্ধতা/গ্রহণযোগ্যতা যাচাই এ (validation) প্রচলিত (conventional) উপাত্ত বিশ্লেষণ ও মডেল সৃষ্ট উপাত্ত (model generated output) বিশ্লেষণ উভয় পদ্ধতিই ব্যবহার করা হয়েছে। এর বিস্তারিত বিবরণ অধ্যায় ৯ এ দেয়া হয়েছে।

উভয় মডেলই সুক্ষভাবে সমন্বিত করা হয়েছে যেন ভবিষ্যতের দৃশ্যপট (scenario) দেখানো যায়। নদীর উপরের অংশে (upstream) প্রবাহ ২০% বৃদ্ধি (দৃশ্যপট-১) এবং প্রবাহ ২০% কমে গেলে (দৃশ্যপট-২) সমগ্র নদীতে এর প্রভাব কি হবে তা এ রিপোর্টের অধ্যায় ১০ এ বর্ণনা করা হয়েছে।

নদীতীর জরীপ রিপোর্ট ভলিউম-২ এ দেয়া হয়েছে। এতে জরীপ উপাত্ত ও মানচিত্র সন্নিবেশিত করা হয়েছে।

পলি ও বেড-মেটেরিয়াল (sediment and bed material) নমুনা সমূহের বিশ্লেষণ, রিপোর্টের ভলিউম-৩ এ দেয়া হয়েছে।

এ সমীক্ষার প্রধান বিশ্লেষিত তথ্য হল:

(১) সুরমা ও কুশিয়ারা উভয় নদীর জন্যই হাইপোথেসিস ১ গ্রহণযোগ্য;

(২) হাইপোথেসিস-২ এর শুদ্ধতা/গ্রহণযোগ্যতা সুনির্দিষ্টভাবে নিশ্চিত করা যায়নি। উভয় নদীর ক্ষেত্রেই দেখা যায় যে নদীর নিম্নাঞ্চলের দিকে পূর্ণনদী প্রবাহের মান কম হয় এবং ফলশ্রুতিতে নদীর আকারের (dimension) পরিবর্তন হয়। নদীর ক্রস সেকশন ক্ষেত্রফল (area) এবং প্রস্থ বিক্ষিপ্ত প্যাটার্নের (scattered pattern) পরিলক্ষিত হয়েছে। তবে গড় গভীরতার প্রবণতা (trend) নদীর নিম্নাঞ্চলের দিকে কিছুটা কম; (সেকশন ৯.২.১, ৯.২.২)

(৩ক) প্রচলতি বিশ্লেষণ পদ্ধতি অনুযায়ী হাইপোথেসিস-৩ উভয় নদীর ক্ষেত্রেই গ্রহণ যোগ্য।

(৩খ) মডেল আউটপুট অনুযায়ী হাইপোথেসিস-৩ কুশিয়ারার জন্য গ্রহণযোগ্য; কিন্তু সুরমা নদীর জন্য নয়। (বিস্তারিত সেকশন ৯.৩.১ ও ৯.৩.২);

(৪) হাইপোথেসিস ৪ ও ৫ নদীর তাত্বিক স্থিতি অবস্থা (theoretical regime condition) সম্পর্কিত। এ সমীক্ষার বিশ্লেষণ থেকে নিশ্চিতভাবে বলা যায় যে সুরমা ও কুশিয়ারা নদী স্থিতি অবস্থায় এখনো আসেনি। এ কারণে মডেল আউটপুট দিয়ে এ দুটি হাইপোথেসিস এর শুদ্ধতা/ গ্রহণযোগ্যতা যাচাই করা সম্ভব হয়নি। কিন্তু যেহেতু স্থিতি অবস্থা নদীর একটি তাত্বিক অবস্থা, অতএব সেকশন ৫.৬ এ প্রদত্ত তাত্বিক ব্যাখ্যা অনুসরণে হাইপোথেসিস ৪ ও ৫ গ্রহণযোগ্য;

(৫) দৃশ্যপট-১: যদি নদীর উর্ধ্বাঞ্চলে (upstream) সর্বোচ্চ প্রবাহ ২০% বৃদ্ধি প্রায় তা হলে, মডেল সৃষ্ট উপাত্ত হতে দেখা যায় যে, নিম্নাঞ্চলসমূহের ক্রস সেকশন, প্রবাহ ও পানির তল বৃদ্ধি পাবে। ফলশ্রুতিতে নূতন নূতন এলাকা প্লাবিত হবে এবং অন্যান্য এলাকায় বন্যার পানির গভীরতা বৃদ্ধি পাবে;

(৬) দৃশ্যপট-২। যদি নদীর উর্ধ্বাঞ্চলে (upstream) সর্বোচ্চ প্রবাহ ২০% কমে যায়, তা হলে নিম্নাঞ্চলসমূহের ক্রস সেকশন, প্রবাহ ও পানির তল ইত্যাদি হ্রাস পাবে। ফলশ্রুতিতে বন্যার পরিমাণ কমে যাবে।

মন্তব্যঃ

১। সিইজিআইএস এর ধারণা মডেলের শুদ্ধতা/গ্রহণযোগ্যতা যাচাই এর মাধ্যমে হাওর এলাকার দুটি প্রধান নদীর হাইড্রো-মরফলজিক্যাল প্রসেস সম্পর্কিত জ্ঞান সমৃদ্ধ হয়েছে যার মাধ্যমে হাওর এলাকার উন্নয়নের লক্ষ্যে প্রকল্প প্রণয়নে পরিকল্পনাবিদগণ ও প্রকল্প বাস্তবায়নে সরকার উপকৃত হবেন।

২। বাংলাদেশ পানি উন্নয়ন বোর্ডের হাইড্রলজি ইউনিটকে শক্তিশালী করা প্রয়োজন। হাওর এলাকার নদী সমূহের ধারাবাহিক উপাত্ত সংগ্রহ (collection of continuous data) করা আবশ্যক।

৩। সুরমা ও কুশিয়ারা নদীতে কয়েকটি স্থায়ী পলি (sediment) ও বেড-মেটেরিয়াল নমুনা সংগ্রহের স্টেশন স্থাপন আবশ্যক।

৪।	এ দুটি নদীর জন্য রুটিন বেথেমেট্রিক জরীপ (bathymetric survey) কার্যক্রম গ্রহণ করা আবশ্যক। জরীপ কাজ ৪টি মৌসুমেই অর্থাৎ প্রাক-বর্ষা, বর্ষা, বর্ষা-পরবর্তি ও শুষ্ক মৌসুমে সম্পন্ন করা আবশ্যক।

৫।	নদীর গতিপথ পরিবর্তন সম্পর্কে জ্ঞান আহরণের লক্ষ্যে সুক্ষ্ম রেজুলেশন (finer resolution) স্যাটেলাইট ছবি সংগ্রহ করা আবশ্যক।

৬।	হাওর এলাকার নদীসমূহের মরফলজিক্যাল আচরণ বোঝা ও ভবিষ্যৎ বাণী (prediction) করার লক্ষ্যে একটি সাধারন মডেল প্রণয়নের জন্য একটি সমীক্ষা কার্যক্রম গ্রহণ করা যেতে পারে।

৭।	হাওর এলাকার নদীসমূহের মরফলজিক্যাল সমীক্ষা কাজের জন্য একটি প্রকল্প গ্রহণ করা যেতে পারে।

৮।	এই সমীক্ষা কাজের সময় প্রণীত দুটি মডেলকে সংযুক্ত করার লক্ষ্যে একটি সমীক্ষা কার্যক্রম গ্রহণ করা যেতে পারে।

৯।	HEC-RAS 5.03 মডেলটি আরো উন্নত ও হালনাগাদ (update) করা আবশ্যক যেন এ মডেল দ্বারা সুরমা ও কুশিয়ারা নদীর পলি জমা, নদী ভাঙ্গন, প্রবাহ ও পানি তল ইত্যাদির পরিবর্তন সম্পর্কে সহজেই আগাম ধারণা করা যায়।

1 Introduction

1.1 Background

The hydro-meteorology of Haor area is quite different from other parts of the country. The northeast region is a tectonically active area and the rate of subsidence in this area is much higher than the deltaic plains elsewhere in the country (PSP, 2015). It is reported that in the Sylhet Basin, tectonic subsidence has been active since the Miocene with a mean rate of 2-4 mm/yr (Johnson and Alam, 1991; Worm et al., 1998). The geological, hydrological and geographical settings generate a unique hydro-ecological environment in this region.

There exists a knowledge gap in scientific explanation of evolution/morphological process of the rivers of the Sylhet basin. Any intervention/investment for water resources management without sound understanding of the morphological process may become counterproductive, unsustainable and may cause adverse impacts on the environment and ecosystem. It may be noted that, considering the need for enhancement of **scientific knowledge** on river morphology, the 53-member National Council of Science and Technology (NCST), headed by the Hon'ble Prime Minister took a decision in its 7th meeting that the DBHWD will take up this project. Accordingly, the 26-member Executive Committee of the National Council of Science and Technology (ECNCST), headed by the Hon'ble Minister, Ministry of Science and Technology in its 22nd meeting (held on 29th October, 2014) took a decision for the implementation of this research project on **priority basis**.

The Center for Environmental and Geographic Information Services (CEGIS) has developed a conceptual model to explain the evolution of rivers in the subsiding Sylhet Basin (Haor areas). Validation of this model was not done. This study is intended for validation of the existing CEGIS model for understanding and explaining the morphological process of the rivers of the Sylhet basin. The validated model will be of great benefit for the planner and the Government for implementation of the development plans in the Haor areas. Moreover, the capacity and strength of the DBHWD will also be enhanced.

The developed numerical model can be used efficiently for further morphological studies of the rivers of the Haor Basin. Prediction of different scenarios considering changes of discharge due to climate change or other factors can also be made through minor modification or adjustments of the numerical model.

1.2 Study Area

The general study area is the Sylhet basin, located in the north-east hydrological zone of Bangladesh (Figure 1.1).

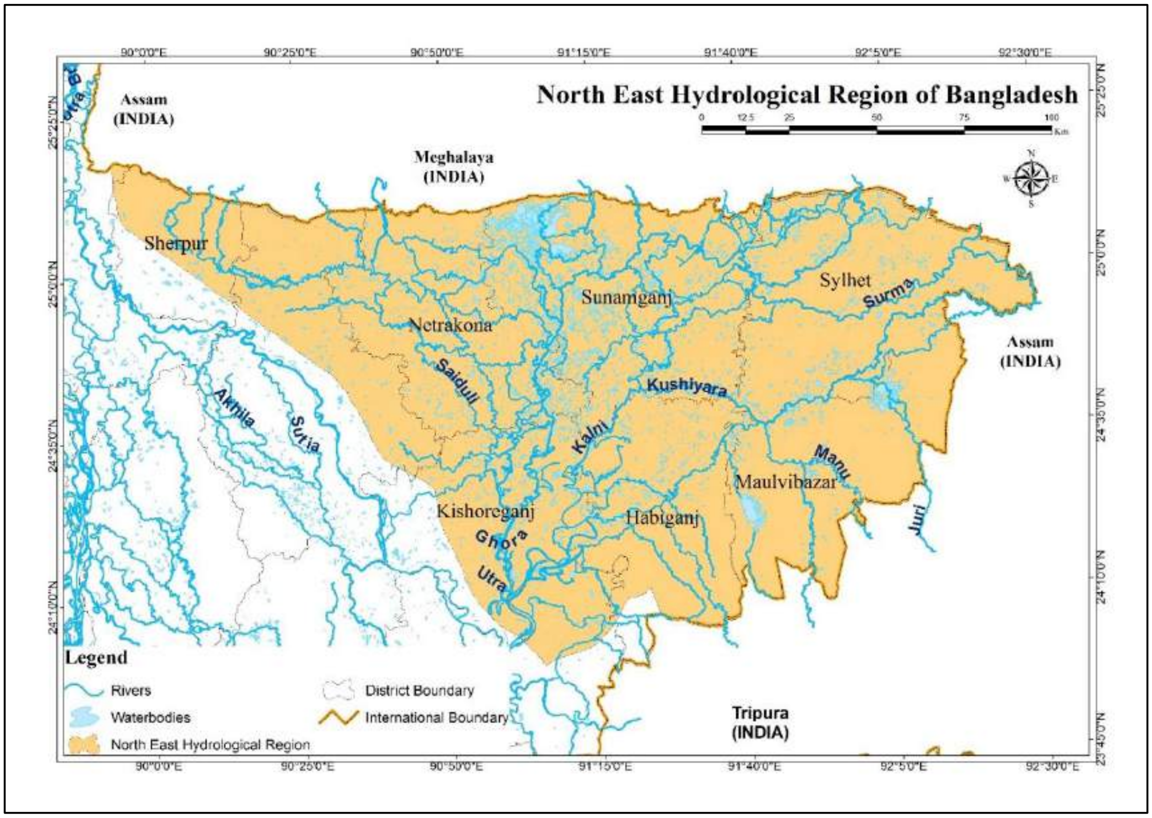

Figure 1-1 General Study area the North East Hydrological Region of Bangladesh

It is a very large basin covering about 10,000 km^2 area in the Sylhet, Sunamganj, Maulvibazar, Habiganj, Netrokona and Kishoreganj districts. Although located about 300 km away from the bay, it is reported that lowest elevation of the Sylhet basin at its northern boundary is very close to Mean Sea Level (PSP, 2015). The lowest/ depressed areas of the north-east hydrological zone of Bangladesh are known as Haors. The rivers of this zone have formed several flood basins within the large subsiding Sylhet basin, which are commonly known as

Haor and the Sylhet basin itself is known as Haor basin. There are 373 Haors in this basin (DBHWD, 2012).

The Surma and the Kushiyara rivers have been studied for the validation of the CEGIS Model. A reach of 150 km each for both the rivers starting from Kanaighat for the Surma and Shaola for the Kushiyara have been considered.

1.3 Objectives

The objectives of the study as laid down in the approved Proforma for Study Proposal (PSP), 2015 are quoted below:

Quote

Main objective is to know the inherent morphological process of the river system in the Haor areas in order to manage the river more efficiently." Specific objectives of the study are to:

1. Enhance the knowledge on hydro-morphological behavior of the Surma and Kushiyara rivers in the Sylhet basin.
2. Validate the existing conceptual model of CEGIS; and
3. Assess the applicability of the validated model with the enhanced knowledge on prevailing physical processes of the rivers.

Unquote

1.4 Scope of Works

The Scope of Works of the study as laid down in the TOR are quoted below:

Quote

1. Review the literatures on evolution process of rivers on especially on the north-eastern part of Bangladesh.
2. Routine measurement of discharge and sediment concentration in the Kushiyara and Surma River at fixed sections which will cover one hydrologic cycle.
3. Measurement of velocity, discharge, bed material and sediment concentration along the two rivers during monsoon, post-monsoon and dry period.

4. Bank line survey in both rivers which is 150 km in each river.
5. Secondary data collection, such as water level, discharge, cross sections and bathymetry data.
6. Analyze the primary and secondary data for further elaborating and validating the existing conceptual model for the evolution of the rivers in Haor areas.
7. Assess the applicability of the validated model with the enhanced knowledge on prevailing physical processes of the rivers.

Unquote

1.5 Constrains and Limitations

No attempt has been made to validate or measure the subsidence of Sylhet Basin, as it is beyond the scope of TOR. However, the available literature study confirmed the subsidence (of the order 2-4 mm/yr) of the Sylhet Basin. The major constrains and limitations as was also mentioned in the Inception Report (March, 2016) are:

Quote

1. Due to the limitation of time and financial resources, most of the study will be carried out by using data of secondary sources.
2. Primary data of stage, discharge and sediments will be collected for only one year
3. The model developed under this study will assess the validity of the conceptual model developed by the CEGIS in a qualitative way.
4. Satellite images of finer resolution are required to understand the avulsion and branching processes of the river. But budget does not include the cost of the images.
5. In the approved PSP (2015), the study period was shown as 24 months (July, 2015-June 2017). But the works of consultants started with a lag of 5 months (December, 2015). So, the Consultants had to complete the works within the specified time period.

Unquote

2 Methodology

The general approach and methodology of the study was described in the Inception Report and was approved by the technical committee and the DBHWD. The methodology discussed in the mid-term report is almost the same as that of the Inception Report, with slight modifications and adjustments.

2.1 Literature Review

As a logical approach, the team have started the work with the literature review of the morphological process of the North Eastern Region. Various publications, documents and reports have been reviewed by the team in order to understand the complex characteristics of the morphological process of the North Eastern Region. Brief description of the literatures reviewed is given in Chapter 4. Preliminarily, the following documents have been reviewed:

- Different Numerical Models
- Master Plan of Haor Area, 2012
- Morphology of the Haor Areas, 2011
- Inland Navigation and Integrated Water Resources Management, 2014
- National Water Management Plan, 2004
- Northeast Regional Water Management Project (FAP 6), 1994
- Mathematical Modelling Study to Assess Upazila Wise Surface Water and Groundwater Resources and Changes in Groundwater Level Due to Withdrawal of Groundwater at the Pilot Areas (Package-1)
- Mathematical Modelling & Topographic Survey for Integrated Water Resources Management of Chalan Beel Area Including Beel Halti Development Project

2.2 Collection of Primary Data

Primary data of both the Surma and Kushiyara rivers have been collected. Primary data include the following:

1. Routine measurement of Discharge
2. Routine measurement of Sediment Concentration
3. Measurement of Cross-sections
4. Sediment Concentration measurement
5. Bank line survey

The details of the data (collected) and collection procedure have been discussed in Chapter 5.

2.3 Collection of Secondary Data

Secondary data of both the Surma and Kushiyara rivers have been collected from the BWDB and the USGS. The data have been processed. The following data have been collected:

- Water Level
- Discharge
- Velocity
- Cross Section
- Satellite Imageries (30m x 30m resolution)

The details have been given in Chapter 5.

2.4 Bank Line Survey

Bank line survey of both the Surma and the Kushiyara rivers have been conducted. The survey works of both the rivers were done by Total Station, GPS and Automatic Level are mapped by ArcGIS. One hundred and fifty (150) km reach on each of the rivers has been surveyed. One hundred and Fifty (150) sections have been selected along the reach, with a distance of 1 km between each section. Measurements have been taken on both banks of the river at the specified sections. The details of Bank line survey have been discussed in Chapter 5.

2.5 Analysis of the Primary and Secondary Data

The water level, velocity, discharge and cross section data have been processed and these data was used for calibrating and validating of the numerical model namely HEC-RAS 2D. This model has been used to predict the change in sediment deposition, discharge and water level in the downstream of the Surma and Kushiyara rivers and validate (qualitatively) the CEGIS Conceptual Model.

2.6 Model Setup

The main objective of this study is to know the basic hydrodynamic and morphological process of the rivers of the Haor basin. In order to understand the hydrodynamic processes of the Surma and the Kushiyara, HEC-RAS Model has been used for carrying out this study. The numerical model has been setup using the secondary data collected from the BWDB.

2.7 Model Calibration

The numerical model has been calibrated using the cross sections of the year 2013 for the Surma river and 2008 for the Kushiyara river. From the data synthesis, it has been revealed that the available data of the Surma are of the year 2009, 2011, 2013 and 2014 and the available data for the Kushiyara are 2004, 2006, 2008 and 2010. There is no common year of the data availability.

2.8 Model Validation

The numerical models have been validated using the cross sections of the year 2014 for the Surma river and 2010 for the Kushiyara river.

The performance/accuracy/validity of the Conceptual Model has been evaluated by comparing the predicted numerical model results with that of the field observations of the different morphological processes in the Surma and Kushiyara Rivers.

The predicted model results have been compared with the hypothesis of the existing CEGIS Conceptual Model for assessment of the validity of the existing model.

2.9 Preparation of Reports

The reports which are being subsequently prepared and submitted to the DBHWD are:

1. Field Visit Reports
2. (draft) Inception Report
3. Inception Report
4. Status Reports
5. Mid Term Report
6. (draft) Final Report
7. Final Report

The following Table 2.1 shows the reports which have been submitted to the DBHWD so far.

Table 2.1: List of Submitted Reports

	Name of Report	Date of Submission
1.	(draft) Inception Report	15th March, 2016
2.	Inception Report	28th March, 2016
3.	Status Report - I	22nd July, 2016
4.	Mid Term Report	22nd January, 2017
5.	Status Report - I I	22nd January, 2017
6.	(draft) Final Report	1st June, 2017
7.	Final Report	29th June, 2017

The (draft) Final Report will be discussed in a workshop. Incorporating the feedback from the workshop and comments from the DBHWD, the report will be finalized and presented to the DBHWD.

The methodology which is being adopted for conducting the study is shown in the flow chart (Fig. 2.1).

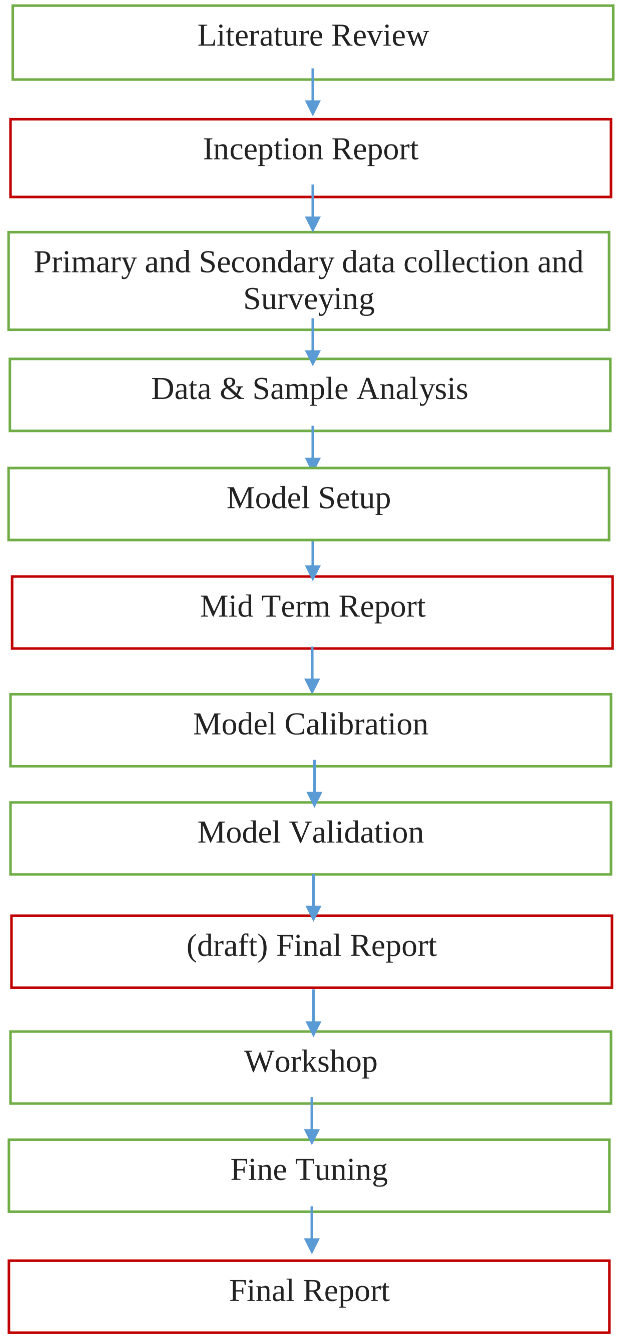

Figure 2-1: Flowchart of Methodology

3 The Sylhet Basin

The Sylhet Basin (also known as Sylhet Trough) is a sub-basin of the Bengal Basin (Figure 3.1 & 3.2) situated in the North East Hydrological Zone of Bangladesh (Figure 3.3). The basin is bounded on the north by the Shillong Massif, east and southeast by the sub-meridional trending folded belt of Assam and Tripura as the frontal deformation zone of Indo-Burman ranges and west by The Indian Platform. To the south and southwest it is open to the main part of the Bengal Basin. The great Dauki Fault separates the Basin from the Shillong Massif. It is an oval shaped trough about 130 km long and 60 km wide. The Dauki Fault with 5 km wide fault zone forms the contact between Shillong Massif and Sylhet Basin. The evolution of Sylhet Basin includes (i) a passive continental margin (Pre-Oligocene) to (ii) a foreland basin linked to the Indo-Burman Ranges (Oligocene and Miolene) to (iii) a foreland basin linked to south-directed over thrusting of Shillong Plateau (Pliocene-Holocene). The Aeromagnetic interpretation map by Hunting (1980) indicates a gradual deepening of basement towards the center of the basin and also reveals subsurface synclinal features and faults within the basin. Its topography is predominantly flat with some north-south trending ridges of twenty to several hundred meters elevation present in the north-eastern border. It is actively subsiding (Johnson & Alam, 1991). The thickness of late Mesozoic and Cenozoic strata in the Sylhet Basin ranges from about 13 to 17 km has been estimated by some authors (Evans 1964, Hiller & Elahi 1984). Much of these strata are Neogene in age (Johnson and Alam 1991). The geology and hydrocarbon potential of the Sylhet Basin have been investigated by many workers (Holtrop & Keizer 1970, Lietz & Kabir 1982, Hiller & Elahi 1984, Khan et al. 1988, Chowdhury et al. 1987) but palynological studies are lacking.

The development of Sylhet Basin began in the Early Cretaceous epoch (ca. 127 Ma) when the Indian plate rifted away from Antarctica (Johnson & Alam 1991). After a plate reorganization ca. 90 Ma, the Indian plate migrated rapidly northward and collided with Asia between ca. 55 and 40 Ma (Curray et al. 1983, Molnar 1984). The basin has been characterized by deltaic sedimentation since The Oligocene epoch.

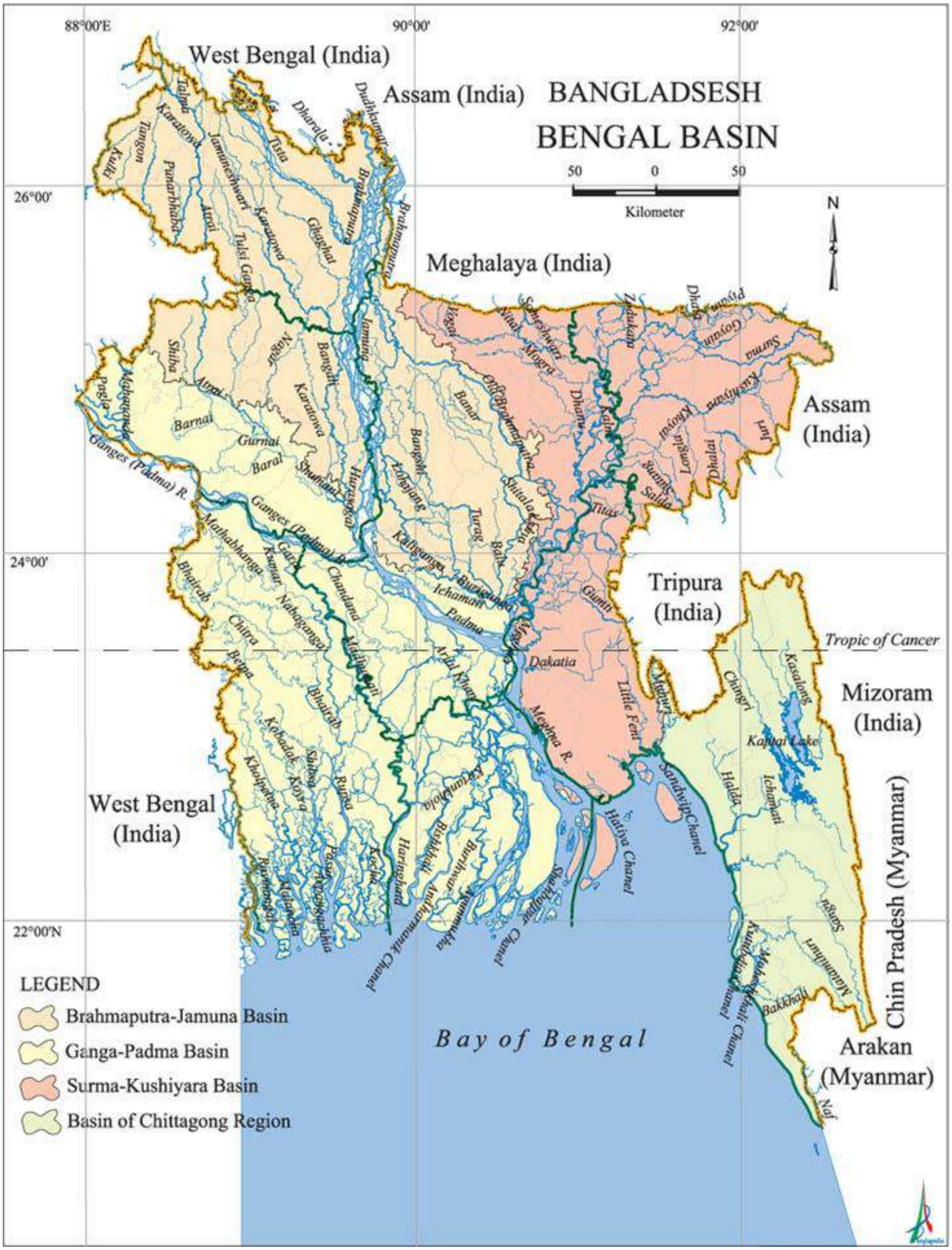

Figure 3-1 The Bengal Basin (Source: Banglapedia, 2003)

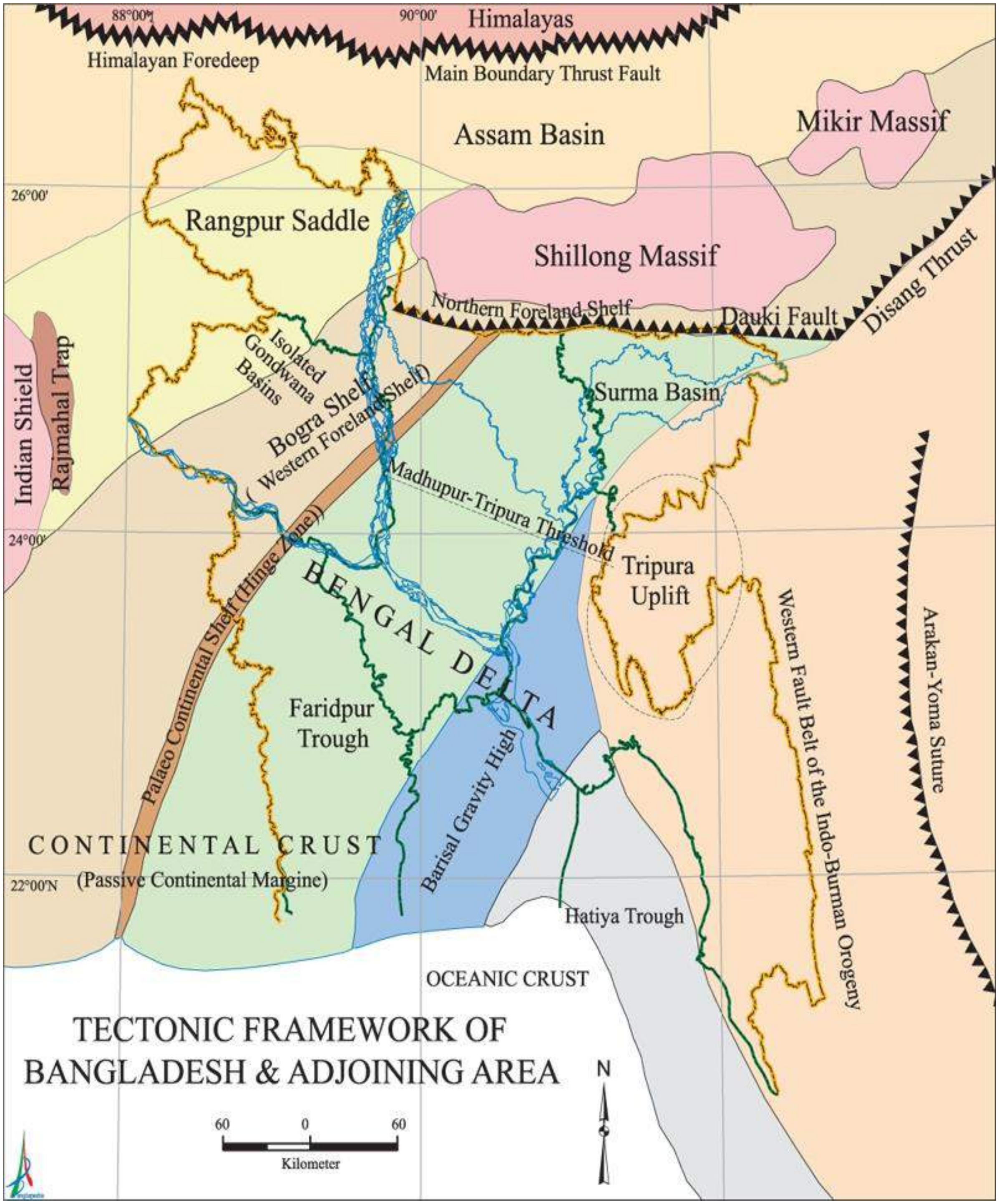

Figure 3-2 Tectonic Framework of Bangladesh (Source: Banglapedia, 2003)

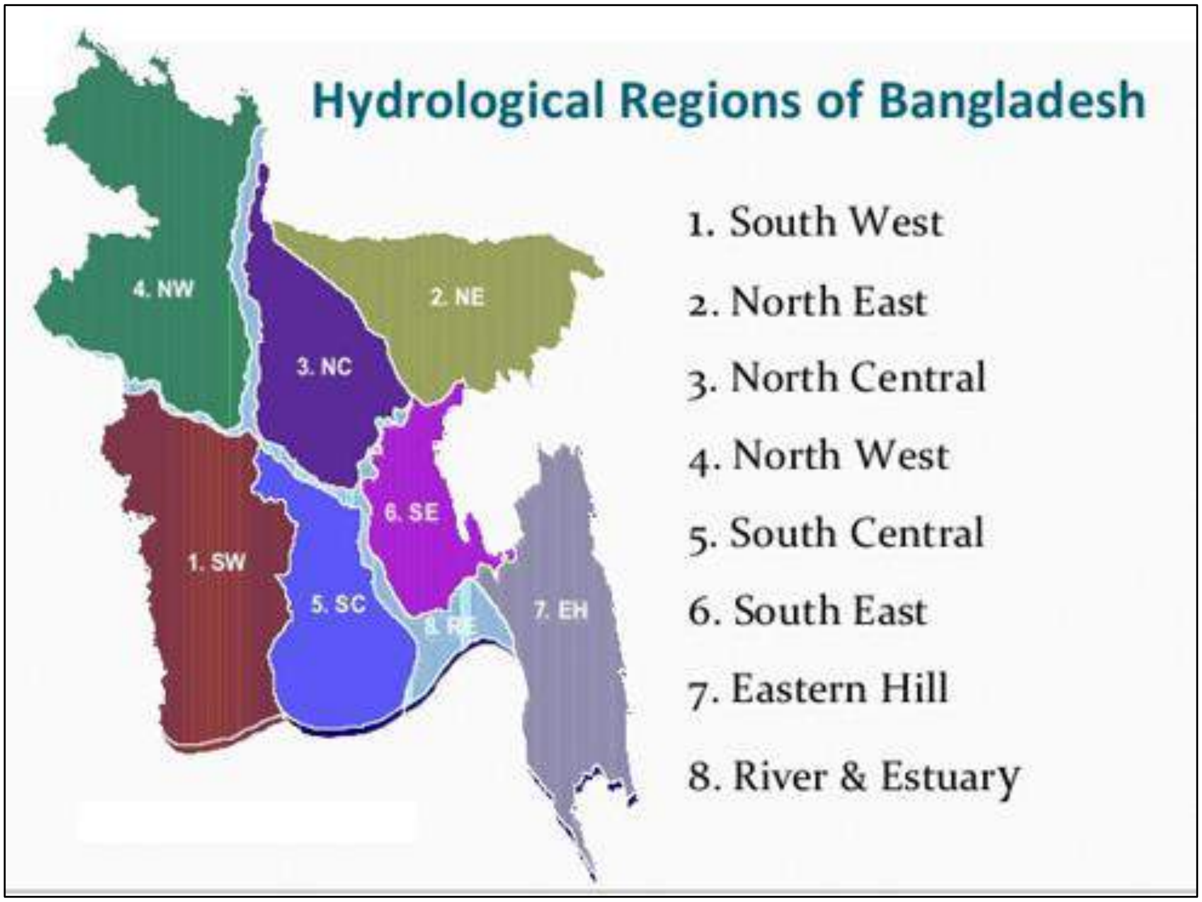

Figure 3-3: Hydrological regions of Bangladesh (Source: NWMP, 2004)

Today, the onshore part of the Bengal Basin is the site of the world's largest delta (about 60 000 km2) formed by rivers (Ganges, Brahmaputra/Jamuna, Padma, Meghna) that drain a large portion of the Himalayas (Johnson & Alam 1991). This subaerial delta feeds the world's largest submarine fan (Bengal Fan), which extends more than 3 000 km south into the Bay of Bengal (Curray & Moore 1974). The Bengal Basin gradually is being encroached on by the Indo-Burman ranges, a ~ 230-km-wide, active orogeny belt associated with eastward subduction of The Indian plate below Myanmar (Burma) (Brunnschweiler 1966, LeDain et al. 1984, Sengupta et al. 1990). In The Early Miocene, as the collision between the Indian and the Eurasian plates continued, there were further major phases of uplift in the Himalayas.

Consequently, a large volume of clastic sediments was supplied to and began progressively to fill the Basin (Imam & Shaw 1985). Sylhet Basin is characterized by a large, closed, negative gravity anomaly (as low as 84 milligals), with minimal topography (elevations of about 5 to

20 m) and numerous lakes and swamps, and is actively subsiding (Johnson & Alam 1991). On the basis of seismic data, the Sylhet Basin cumulatively comprises an approximately 17 km thick (Hiller & Elahi 1984) sedimentary column from Post - Eocene Sylhet Limestone to Recent clastics. Sylhet Basin was structurally evolved by the contemporaneous interference of two major tectonic movements, i.e. the emerging of the Shillong Massif in the north and the west prograding mobile Indo-Burman Fold Belt (Hiller & Elahi 1984). The northern and eastern parts of the basin are far more complicated than the southern and western portions. The relief and complexicity increases towards the east (Haque 1982). The anticlines are commonly faulted and many produce gas (Johnson & Alam 1991). Structural relief between paired anticlinal crests and adjacent synclinal troughs may be as much as 7 000 m (Hiller & Elahi 1984), and the synclines have acted as major late Neogene and Quaternary depocenters. The folds decrease in amplitude westward, and are not present west of about 91° (Lietz & Kabir 1982), where the Sylhet trough merges with the main part of the Bengal Basin. The SG (Early Miocene - Quaternary) is a diachronous unit consisting of a succession of alternating shales, sandstone, siltstones and sandy shales with occasional thin conglomerates, indicative of repetitive deposition from pro-delta, delta front, and paralic facies with intermittent, wholly marine facies (Holtrop & Keizer 1970). The group is divided into the Bhuban and the Bokabil Formations, based on differences in their gross lithologies (Mathur & Evans 1964).

3.1 Regional Physiographic Setting

The Sylhet basin has been characterized by deltaic sedimentation since The Oligocene epoch. Today, the onshore part of the Bengal Basin is the site of the world's largest delta (about 60000 km^2) formed by rivers (Ganges, Brahmaputra/Jamuna, Padma, Meghna) that drain a large portion of the Himalayas (Johnson & Alam 1991). This subaerial delta feeds the world's largest submarine fan (Bengal Fan), which extends more than 3 000 km south into the Bay of Bengal (Curray & Moore 1974). Physiographic Map of Bangladesh is shown in Figure 3.4. The brief physiography of the Sylhet basin is described below.

3.1.1 Old Brahmaputra Floodplain

The Old Brahmaputra floodplain stretching from the southwestern corner of the Garo Hills along the eastern rim of the Madhupur Tract down to the Meghna exhibits a gentle morphology composed of broad ridges and depressions.

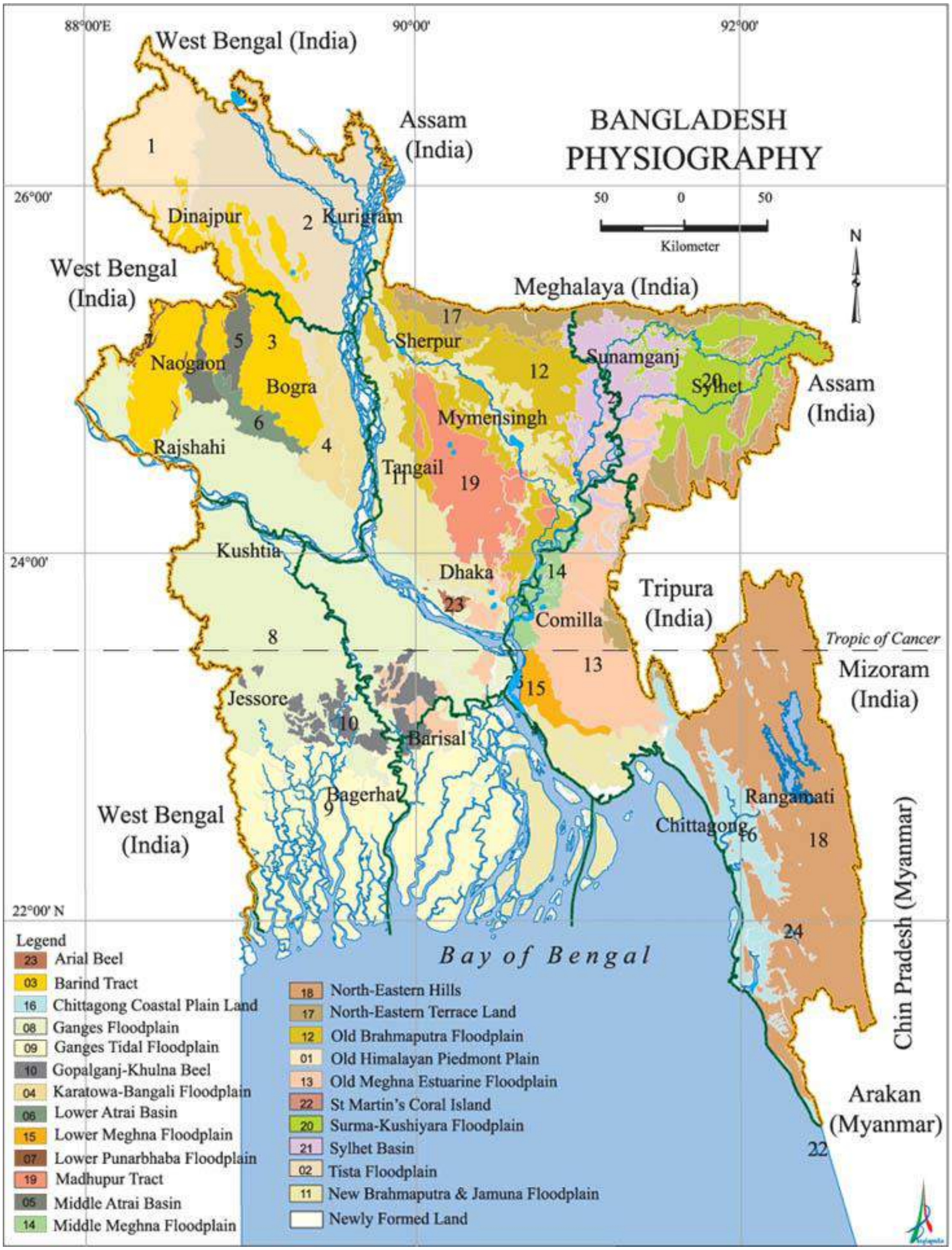

Figure 3-4 Physiography of Bangladesh (Source: Banglapedia, 2003

3.1.2 Jamuna (Young Brahmaputra) Floodplain

Due to the uplift of the two large Pleistocene blocks of Barind and Madhupur, the zone of subsidence between those turned to a rift valley and became the new course of the Brahmaputra and came to be known as the great Jamuna. Both the left and right banks of the river are included in this sub-region. The Brahmaputra-Jamuna floodplain can again be subdivided into the Bangali-Karatoya floodplain, Jamuna-Dhaleshwari floodplain.

3.1.3 Haor Basin

A large, gentle depressional feature is bounded by the Old Brahmaputra floodplain in the west, the Meghalaya Plateau's foothills in the north, Sylhet High Plain in the east and Old Meghna Estuarine floodplain on the south. Its greatest length, both East-West and North-South, is just over 113 km. Numerous lakes (Beels), large swamps and Haors cover this saucer-shaped area of about 10,000 km^2. The sinking of this large area into its present saucer-shape seems to be intimately connected with the uplift of Madhupur Tract.

3.1.4 Surma-Kushiyara Floodplain

It comprises the floodplain of rivers draining from the eastern border towards the Sylhet Basin (Haor Basin). Some small hill and piedmont areas near Sylhet are included within the boundaries. Elsewhere, the relief generally is smooth, comprising broad ridges and basins, but it is locally irregular alongside river channels. The soils are mainly heavy silts on the ridges and clays in the basins. This area is subject to flash floods in the pre-monsoon, monsoon and post-monsoon seasons, so the extent and depth of flooding can vary greatly within a few days (Banglapedia, 2003). Normal flooding is mainly shallow on the ridges and deep in the basins.

3.1.5 Meghna Floodplain

It is divided into four sub-regions:

- ***a. Middle Meghna Floodplain:*** The main channel of the Meghna upstream from its junction with the Dhaleshwari and Ganges as far as Bhairab Bazar is known as the middle Meghna.
- ***b. Lower Meghna Floodplain:*** It extends southward from the junction of the Meghna and Ganges; the sediments on the left bank of the lower Meghna comprise mixed alluvium from the Ganges, Jamuna and Meghna.

c. ***Old Meghna Estuarine Floodplain:*** The landscape in this extensive unit is quite different from that on river and tidal floodplains. The relief is almost level, with little difference in elevation between ridges and basins. Natural rivers and streams are far apart in the southern part and drainage is provided by a network of man-made canals (*khal*).

d. ***Young Meghna Estuarine Floodplain:*** This sub-unit occupies almost the level land within and adjoining the Meghna estuary. It includes both island and mainland areas. New deposition and erosion are constantly taking place on the margins, continuously altering the shape of the land areas. Seasonal flooding is mainly shallow, but fluctuates tidally, and is caused mainly by rainwater or non-saline river water.

3.1.6 Northern and Eastern Piedmont Plains

It is the generally sloping piedmont plains bordering with the northern and eastern hills. The whole area is subject to flash floods during the rainy season. On the higher parts, flooding is mainly intermittent and shallow; but it is moderately deep or deep in the basin. The sub-region covers most or parts of the upazilas of Nalitabari (Sherpur), Tahirpur, Bishwamvarpur, Dowarabazar, Companiganj (Sylhet), Gowainghat, Madhabpur, Habiganj Sadar, Chunarughat, Sreemangal, Kamalganj and Kulaura.

3.1.7 Northern and Eastern Hills

Hilly areas of Bangladesh comprise two main kinds of topography:

a. ***Low Hill Ranges:*** The comparatively low hill ranges occur between and outside the high hill ranges. They are mainly formed over unconsolidated sandstone and shale. Their summits generally are <300m above MSL. Most areas are strongly dissected, with short steep slopes, but there are some areas with rolling to early-level relief (eg in the best tea-growing areas of Sylhet region).

b. ***High Hill or Mountain Ranges:*** This sub-unit comprise an almost parallel ridge running approximately north-south and with summits reaching 300-1000 m. They have very steep slopes - generally >40%, often 100% and are subject to landslide erosion.

3.2 Hydrological Setting

3.2.1 Rivers

The North East Hydrological Region (Figure 3.3) consists of Sunamganj, Sylhet, Maulvibazar, Habiganj, Netrakona and parts of Sherpur, Mymensingh, Kishoreganj and Brahmanbaria. There are eighty-seven rivers including 20 transboundary rivers in this region. The Indian Barak River reaches the border with Bangladesh at Amalshid in Sylhet district and bifurcates to form the steep and highly flashy rivers the Surma and the Kushiyara. The Surma and Kushiyara Rivers ultimately meet and flow as the Kalni River and falls into the Meghna. There are many other rivers in the basin which also ultimately fall into the Meghna. The river system is known as Surma-Meghna River System. The principal catchments which drain from India into the regions are:

- Meghalaya Hills which from the northern boundary of Bangladesh and drain 13,466 km^2 of steep mountains along the southern face of Shillong Plateau.
- The Barak River basin which drains 25,263 km^2 in the states of Assam, Manipur and Mizoram
- Tripura Hills which drain an area of 6845 km^2 from the state of Tripura.

Total surface water supplies to the region excluding the Old Brahmaputra River are 173 km^3. Of this, 40% originates as rainfall over the region and 60% as rainfall over Indian catchments. An estimated 95% of the total surface water supply runs off during the period between May 1 and November 30. During this period tributary streams draining the Meghalaya and Tripura catchments are characterized by very flashy floods which rise to a peak in a day and recede in a day or two (FAP-6, 1994). These floods carry sediment loads are often accompanied by channel instability and erosion and can have a disastrous effect on the regions agriculture and infrastructure. However, even the main lowland rivers such as the Surma-Baulai, Kushiyara-Kalini and Meghna Rivers can display a very rapid rise and fall in water levels during flood times. The monsoon rise typically peaks between August and October. Almost 60% of the region principally, the Sylhet Depression, Sylhet Lowlands and Meghalaya Lowlands, may be inundated to a depth of 1m or more during the peak of the monsoon (FAP-6, 1994).

3.2.1.1 The Surma-Meghna River System

Surma-Meghna River System (Figure 3.5) is one of the four major river systems of Bangladesh. The other three are Ganges-Padma River System, Brahmaputra-Jamuna River System, and Chittagong Region River System. It is the longest river (669 km) system in the country. It also drains one of the world's heaviest rainfall areas (eg about 1,000 cm at Cherapunji, Meghalaya, India). East of Brahmaputra-Jamuna River System is Surma-Meghna River System. Surma originates in the hills of Shillong and Meghalaya of India.

The main source is Barak River, which has a considerable catchment in the ridge and valley terrain of Naga-Manipur hills bordering Myanmar. Barak-Meghna has a length of 950 km of which 340 km lies within Bangladesh. On reaching the border with Bangladesh at Amalshid in Sylhet district, Barak bifurcates to form flashy rivers the Surma and the Kushiyara.

3.2.1.2 The Surma

Surma flows west and then southwest to Sylhet town. From there it flows northwest and west to Sunamganj town. Then it maintains a course southwest and then south to Markuli to meet Kushiyara. The joint course flows upto Bhairab Bazar as the Kalni. Flowing north of the Sylhet basin, Surma receives tributaries from Khasi and Jaintia Hills of Shillong Plateau. East to west they are Lubha, Hari, Goyain Gang, Piyain, Bogapani, Jadukata, Shomeshwari, Kangsa and Mogra. Surma bifurcates south of Mohanganj soon after it receives Kangsa and further south the Mogra. The western channel is known as Dhanu in its upper course, Boulai in the middle and Ghorautra lower down. It joins Kalni near Bhairab Bazar of Kishoreganj district and the name Meghna is given to the course from this confluence to the Bay of Bengal. Meghna receives Old Brahmaputra on its right-bank at Bhairab Bazar and on the way to the Bay it carries the water of Padma from Chandpur.

3.2.1.3 The Kushiyara

Kushiyara receives left bank tributaries from Tripura Hills, the principal ones being Manu, north of Maulvi Bazar town and bifurcates into northern channel, the Bibiyana and a southern one, which resumes the original name, Barak. Bibiyana changes its name to Kalni lower down its course and joins Surma near Ajmiriganj. Barak receives Gopla and Khowai from Tripura Hills and falls into Surma at Madna. Unlike Surma, the tributaries of Kushiyara are less violent although prone to producing flash floods in part due to lesser elevations and rainfall of Tripura Hills.

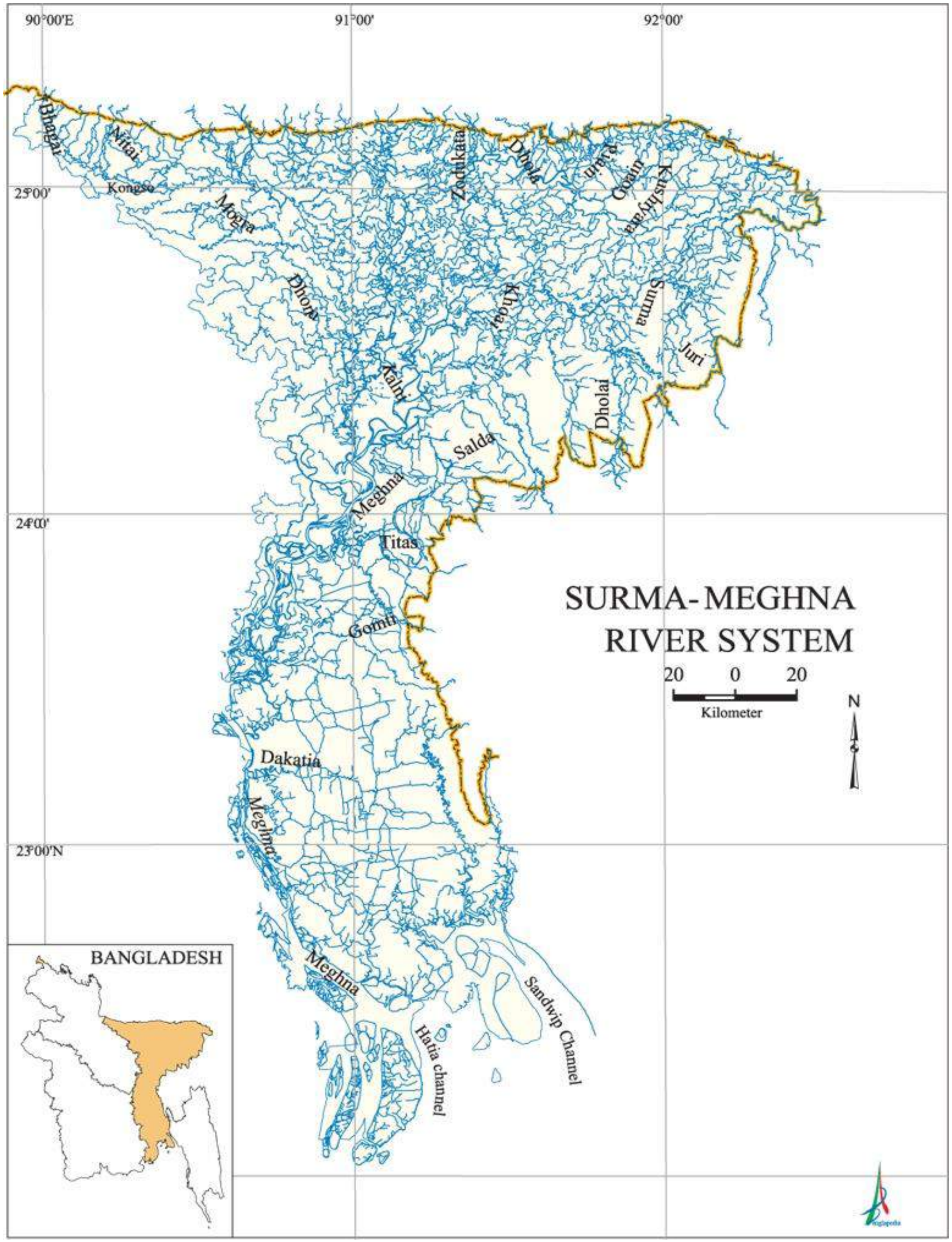

Figure 3-5 The Surma-Meghna River System (Source: Banglapedia, 2003)

Between Surma and Kushiyara, there lies a complex basin area comprised of depressions (Haors). Most of the Surma system falls in the Haor basin, where the line of drainage is not clear or well defined. In the piedmont tract from Durgapur to Jaintiapur, the network of streams and channels overflows in the rainy season and creates vast sheets of water which connect the Haors with the rivers.

3.2.1.4 The Meghna

Meghna has two distinct parts. Upper Meghna from Bhairab Bazar to Shaitnol is comparatively a small river. Lower Meghna below Shaitnot is one of the largest rivers in the world, because it is the mouth of Ganges-Padma and Brahmaputra-Jamuna rivers. It is a tidal reach carrying almost the entire fluvial discharge of Ganges, Brahmaputra and Upper Meghna river. The net discharge through this river varies from 10,000 cumec in the dry season to 160,000 cumec in the wet season. A little above the confluence, the Meghna has a railway bridge-'Bhairab Bridge'-and a road bridge-'Bangladesh-UK-Friendship Bridge' over it. The width of the river there is three quarters of a kilometre.

Several small channels branch out from Meghna, meander through the low land bordering the marginal Tippera Surface, fed by a number of hill streams and rejoin the main river downstream. The most important of these offshoots is Titas, which takes off south of Chatalpar and after meandering through two long-bends, extending over 240 km rejoins the Meghna through two channels in Nabinagar upazila. It receives the Howrah hill stream near Akhaura. Brahmanbaria and Akhaura are both on the banks of this river. Other offshoots of the Meghna are Pagli, Katalia, Dhanagoda, Matlab and Udhamdi. Meghna and these offshoots receive the waters of a number of streams from Tripura Hills including Gumti, Howrah, Kagni, Senai Buri, Hari, Mangal, Kakri, Pagli, Kurulia, Balujuri, Sonaichhari, Handachhora, Jangalia and Durduria. All of these are liable to flash floods, but Gumti, Kakri and Howrah are the major ones. They have silted their beds to the extent that they now flow above the mean level of the land when overflowing. Embankments have been built to contain them. Every other year one or the other of these streams overflow and cause considerable damage to crops, livestock and houses.

The tectonic evolution indicates that the Meghna-Old Brahmaputra drainage post-dates the Ganges drainage when the main channel of the Ganges was the sole drainage beside Calcutta. As a consequence, the delta of the old Brahmaputra-Meghna river system covers a very small area compared to the Ganges delta. Addition of the water of the Padma in recent years has not been able to make any significant contribution in enlarging the delta. The present deltaic Meghna, being the combination of Padma and Meghna, is the largest river of Bangladesh. From the beginning of the delta small islands create two main channels. The larger eastern channel and the smaller western channel measured five to eight kilometres and about two kilometres in width respectively. Near Muladi, Shafipur is an offshoot from the western bank.

Further south, Meghna divides into three channels, which are, from west to east, Ilsha, Shahbazpur and Bamni. The Ilsha channel, 5-6.5 km wide, separates Bhola from the Barisal mainland. The Shahbazpur channel, 5-8 km wide, flows between Bhola and Ramgati-Hatiya islands. The Bamni, which used to flow between the islands of Ramgati, and Char Lakkhi and Noakhali mainland forming the main outlet of the Meghna, does not seem to exist now. The estuary of Meghna may be considered to be Ilsha and Shahbazpur, which together have a width of 32 km at the sea front.

The Gumti falls into Meghna near Daudkandi. Another tributary from Tippera Surface is Dakatia. The main source of this river was Kakrai, but the Little Feni cuts back and captured this upper portion. Dakatia now has its source in Chauddagram khal (canal), which connects it with Little Feni. Dakatia sends out a channel southward, which forms the Noakhali khal. The main channel meanders westward to Shakherhat, from where the old course goes south to join Meghna at Raipur, and the new and stronger channel passes through Chandpur khal to join west of Chandpur town. For three-fourths of the year tidal currents feed the Dakatia from Meghna. Little Feni follows a very tortuous course southward, and falls into Meghna estuary, southeast of Companiganj and a few kilometres from Big Feni estuary. Little Feni is a tidal river; in the rainy season its flow is around 15,000 cusecs. (Banglapedia, 2003). Table 3.1 shows the tributaries, distributaries and branches of the Surma-Meghna River system.

Table 3.1 Tributaries, Distributaries and Branches of Surma-Meghna River System

River	Tributary	Distributary	Branch
Surma	Lubha, Pabijuri-Kusi Gang-Kusiya, Sari Gowain, Noya Gong (Khasiamara), Khasimara, Jalukhali (Chalti), Piyain (Sylhet-Sunamganj), Jadukata-Rakti	Bhabna-Bashia-Bahia Gang, Botor Khal, Piyain (Sunamganj-Netrakona), Old Surma	x
Lubha	Amri Khal	x	x
Pabijuri-Kusi Gang-Kusiya	Khepa, Nokla-Sundrakasi	Kapna, Koris	x
Sari Gowain	Lain, Naya Gang (Jaintiapur), Jaflong-Dauki, Kapna	Bar Gang, Pora Khal-Khaiya, Bekra	x
Piyain (Sylhet-Sunamganj)	Dhala, Jalia Chara (Bholaganj), Chela	x	x
Jadukata-Rakti	x	Patnai Paikartala, Baulai (Balua)	x
Botor Khal	x	Dauka	x
Piyain (Sunamganj-Netrakona)	Kaldahar-Kanyakul	x	x
Amri Khal	x	Nokla-Sundrakasi	x
Nokla-Sundrakasi	x	Lain	x
Kapna	Bekra, Pora Khal-Khaiya	x	x
Naya Gang (Jaintiapur)	Bar Gang	x	x
Pora Khal-Khaiya	Koris	Khepa	x
Jalia Chara (Bholaganj)	Umiyam	x	x
Baulai (Balua)	Patnai Paikartala, Surma, Someswari (Dharmapasha), Bhogai Kangsho	Kaldahar-Kanyakul	x
Kaldahar-Kanyakul	Dolta	x	x
Bhogai Kangsho	Malijhi, Ghagtia, Netai	x	x

River	Tributary	Distributary	Branch
Malijhi	Moharoshi	x	x
Ghagtia	Satar Khali	x	x
Netai	x	Satar Khali	Bedori Khal
Meghna (Upper)	Dasadia, Longon Bolvodra, Titas (Narsingdi Sadar-Bancharampur), Kalni	N/A	Titas, Dhanagoda
Longon Bolvodra	Kasti	x	x
Titas (Narsingdi Sadar-Bancharampur)	Arsi-Nalia	x	x
Titas	Buri, Bijni, Lahar, Sonai	Dasadia	x
Sonai	x	Kasti	x
Meghna (Lower)	Dakatia, Gumti	x	x
Kalni	Kamarkhali	x	x
Kushiyara	Juri, Naljur, Manu, Isdhar Khal-Barbhanga	Sonai-Bordal	Bijna-Guinggajuri, Bibiana
Naljur	Bhabna-Bashia-Bahia Gang, Kamarkhal	x	x
Manu	Dhalai (Maulvibazar)	x	x
Bijna-Guinggajuri	Korangi, Lungla	x	x

(Note: Underlined rivers do not have any tributary, distributary or branch.) Source: DBHWD, 2016

3.2.2 Climate

The North East Hydrological Region (Figure 3.3) has a typical tropical monsoon climate characterized by the twice-yearly reversal of air movement over the region. For about four months in winter (December through March) air flows to the region from northeast, while for about four months in summer (June through September) it flows to the region from the southwest. These airflows or winds are called monsoons; that of winter called the northeast monsoon while that of summer is called the southwest monsoon. A reversal of the monsoons takes about two months, the first occurring in spring (April-May) when the change of wind direction is from northeast to southwest via northwest, and the second occurring in autumn (October-November) when the change is from southwest to northeast via southeast. These periods of changing wind direction are called the spring and autumn reversals.

The southwest monsoon (June – September) brings moist air into the region from the Bay of Bengal. Rainfall in this season is abundant and it is often referred to as "the monsoon", meaning the rainy season. Typically, the rainfall in this season increases, northeastwards across the region and reaches a maximum on the southward-facing slopes of the Shillong Plateau in Meghalaya; Cherrapunji, on these slopes, is well known as the wettest place on Earth., its mean annual rainfall being over 12000 mm (Haor Information System, IWM).

Across the Northeast Region rainfall during the southwest monsoon (June – September) ranges from around 1500 mm in the southwest to around 4100 mm in the northeast at the border with Meghalaya. The northeast monsoon (December – March) brings dry air into the region from China and rainfall in this season ranges from around 80 mm in the southwest to around 220 mm in the northeast. The spring reversal is characterised by increasing rainfall ranging from around 490 mm in the southwest to around 1290 mm in the northeast. The autumn reversal is characterised by decreasing sporadic rainfall ranging from around 170 mm in the southwest to around 320 mm in the northeast (Haor Information System, IWM).

3.3 Subsidence of Sylhet Basin

The Bengal delta occupies most of the Bengal basin and is slowly subsiding as a result of isostatic adjustment of the crust due to rise of the Himalayas and dewatering of the Proto-Bengal Fan sediments which is now buried under thick Mio-Pliocene deltaic sediments. The rate of subsidence of the Bengal Basin and the Ganges-Brahmaputra delta varies with time and place and is influenced by the plate motion and sediment supply in the basin from the rising Himalayas (Banglapedia, 2003). Within the Bengal basin itself, elevated Pleistocene sediments, notably the Madhupur terrace and Barind tracts, serve as topographic barriers that influence river migration and sediment dispersal (Goodbred et al., 2003; Pickering et al., 2013). This partitioning of Bengal basin and its underlying tectonic controls support varying rates of subsidence across the Ganges- Brahmaputra-Meghna delta, from millennialscale rates of 1–3 mm/yr in the southern regions to 4 mm/yr or more in the northeast Sylhet basin (Goodbred and Kuehl, 2000a; Hanebuth et al., 2013). As in the southern Bengal Basin, the pattern of closely juxtaposed stable and subsiding areas is recognized in the Sylhet region as well. The northwestern and southern (Comilla Terrace) corners of the Sylhet Basin support incised stream channels that indicate relative uplift in the late Holocene (Morgan and McIntire, 1959; Coates et al., 1988; Coates, 1990) and demonstrate the complexity of tectonic motion throughout the Bengal Basin. In the Sylhet Basin, tectonic subsidence has been active since the Miocene due to overthrusting of the Shillong Massif, with a mean Plio-Pleistocene rate of 1.2 mm/yr (Johnson and Alam, 1991; Worm et al., 1998).

Analysis of different sediment rates in the Sylhet Basin suggest that the Brahmaputra periodically switched its flow between that region and the gap between the Madhupur and Barind tracts (Goodbred & Kuehl, 2000). Lack of evidence for rapid sedimentation in the Sylhet Basin between about 9,000-7,500 years BP (Before Present, datum 1st January, 1950) and between 6,000-5,000 years BP suggests that the Brahmaputra followed its western course during those periods. Continued subsidence at 2-4mm/year in the center of the Sylhet basin means that the base of the Holocene deposits in this depression could be 30-60m below its level at the time of last glacial maximum. Since the lowest parts of the Sylhet basin are <5m above present sea level, that would make Holocene sediments approximately 150-180m thick. The sediments become thinner towards the margins of the Sylhet Basin: the buried Pleistocene surface was encountered in boreholes at ca (Centiare, $1m^2$) 30m on the western margin and ca 50m on the eastern margin of the basin (Goodbred & Kuehl, 2000).

4 Literature Review

Various publications, documents and reports have been reviewed by the team in order to develop the classification system of wetlands of Bangladesh. These literatures help to better understand the diversified and complex characteristics of the wetlands of Bangladesh. Brief description of the literatures reviewed is given in the following sections. The sections may be considered as the excerpts of the respective documents.

4.1 Different Numerical Models

4.1.1 MIKE 11 Model

MIKE 11 is a river modeling package dealing with flooding, navigation, water quality, forecasting, sediment transport, a combination of these or other aspects of river engineering. It is one-dimensional river modeling software. MIKE 11 is a licensed software. MIKE 11 has a GIS interface and can handle unsteady flows. Cost of MIKE 11 is high but it comes with very good technical support. Some of its benefits are given below:

- MIKE 11 is one of the world's most well proven and widely applied 1D river modelling packages
- MIKE 11 is the preferred choice for professional river engineers when reliability, versatility, productivity and quality are keywords
- It is a powerful river modelling toolbox with more features than any other river modelling package
- MIKE 11 is the software product, which made the MIKE brand name synonymous with top quality modelling software from DHI and it remains one of the most widely used MIKE by DHI products

Typical examples of hydrodynamic river and reservoir applications are:

- Modeling of highly regulated canal systems
- Complex multiple reservoir and canal operations
- Dam break studies
- Flood assessment and mapping
- Sediment transport and long term assessment of morphology changes
- Salinity intrusion in rivers and estuaries

- Wetland restoration studies
- Ecology and water quality assessments in rivers and wetlands
- Integrated flood modelling

4.1.2 Delft3D Model

Delft3D is a three-dimensional modeling suite to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments. Delft3D is Open Source Software. The source code of Delft3D 4.01 Suite can be downloaded. But the compiled Delft3D is a Licensed Software.

The hydrodynamic modules of Delft3D are,

•D-Flow

This programme simulates non-steady flows in relatively shallow water. It incorporates the effects of tides, winds, air pressure, density differences, waves, turbulence and drying and flooding with the integrated heat and mass transport solver. The output of the programme is used in all the other programmes in Delft3D suite. D-Flow is the standard programme and covers curvilinear and rectilinear grids, full 2D hydrostatic flow, advection-diffusion module for salinity, temperature and substances, density driven flows, float tracking, meteorological influences, on-line visualization and wave-current interaction. The D-Flow includes 3D flow and turbulence modeling, spherical grids, domain decomposition (connect multiple grids; refinement in both horizontal and vertical direction allowed), structures and horizontal large eddy simulations.

•**D-Wave**

This computes the non-steady propagation of short-crested waves over an uneven bottom, considering wind action, energy dissipation due to bottom friction, wave breaking, refraction shoaling and directional spreading. The programme is based on the spectral model SWAN. This model is a development of the Delft University of Technology, which is a close partner of Deltares in a number of research fields. For many decades, both institutes have been prominent in the field of wave modeling.

4.1.3 Delft3D FM Model

The Delft3D Flexible Mesh Suite (Delft3D FM) is the successor of the structured Delft3D 4.01 Suite. The key component of Delft3D FM is the D-Flow Flexible Mesh (D-Flow FM) engine for hydrodynamic simulations on unstructured grids in 1D-2D-3D. D-Flow FM is the successor of Delft3D-FLOW and SOBEK-FLOW. Delft 3D FM is a Licensed Software.

•D-Flow Flexible Mesh:

Like Delft3D-FLOW, D-Flow FM is capable of handling curvilinear grids that provide very good performance in terms of computational speed and accuracy. In addition to this, the grid may also consist of triangles, quads, pentagons and hexagons. This provides optimal modelling flexibility and ease in setting up new model grids or modifying existing ones, or locally increasing resolution. 1D- and 2D grids can be combined, either connecting adjacent grids or a 1D grid overlying a 2D grid. Both Cartesian and spherical coordinate systems are supported. This facilitates tidal computations on the globe with tide generating forces, thus without imposing open boundary conditions. The grid generation tool RGFGRID includes new grid generation algorithms for the construction of orthogonal unstructured grids.

Flow Solver D-Flow FM implements a finite volume solver on a staggered unstructured grid. The higher-order advection treatment and near-momentum conservation make the solver very suitable for supercritical flows, bores and dam breaks. The handling of wetting-and-drying makes it suitable for flooding computations. The continuity equation is solved implicitly for all points in a single combined system. Optionally, non-linear iteration can be applied for very accurate flooding results. Furthermore, Coriolis Delft3D Flexible Mesh -Eastern Scheldt (Scaloost), Delft3D Flexible Mesh - 3D interactive modelling - Western Scheldt forcing, horizontal eddy viscosity, tide generating forces and meteorological forcings were added, making the system suitable for tidal, estuarine or river computations. For three-dimensional modelling, three turbulence models are available: algebraic, k-epsilon and k-tau. Vertical transport can be solved both explicitly and implicitly. First sigma layers were implemented, with the anti-creep option based upon the Delft3DFLOW algorithm. Fixed z-layers are also available, and z- and sigma-layers can be combined in one single model domain, but this is still ongoing research. Temperature modelling is supported either using the composite heat flux model or the excess heat flux model, which can both be driven by space-and-time varying meteorological datasets. Time integration is done explicitly for part of the advection term, and the resulting dynamic time-step limitation is automatically set based on the Courant criterium. The possible performance penalty can often be remedied by refining and coarsening the computational grid at the right locations.

Parallelization D-Flow FM models can be run as parallel computations on distributed-memory high-performance computing clusters. The parallel version is based on the familiar MPI standard, and partitioning of the model domain can be done automatically by the (included) METIS-partitioner, and/or defined by the user. Parallel computing is functional both on Windows and Linux. On Linux the PETSc matrix solver library can be coupled, and this is the preferred way for good performance. On single machines with multi-core processors speedup can also be achieved by D-Flow FM's built-in Open MP-multithreading option, which is the default setting.

•D-Wave:

D-Waves computes the non-steady propagation of short-crested waves over an uneven bottom, considering wind action, energy dissipation due to bottom friction, wave breaking, refraction (due to bottom topography, water levels and flow fields), shoaling and directional spreading. The module is based on the spectral model SWAN. This model is a development of the Delft University of Technology.

•D-Real Time Control:

Real time control often saves money in the construction, alteration and management of the water system infrastructure. The D-Real Time Control module shows to what extent the Delft3D Flexible Mesh - Makassar - Indonesia existing infrastructure can be used in a better way. It allows to simulate complex real-time control of all hydraulic structures in reservoirs and estuaries, river and canal systems. This module allows the system to react optimally to actual water levels, discharges and (forecasted) rainfall, by controlling gates, weirs, sluices and pumps. The D-Real Time Control module, using the open source RTC-Tools engine, can be coupled for controlling of hydraulic structures with various triggering mechanisms, also for parallel models if needed.

4.1.4 CCHE 2D Model

The CCHE2D model is a two-dimensional depth-averaged, unsteady, flow and sediment transport model. The CCHE2D model is available as a Free Software to the researchers and engineers that sign Beta-Testing Agreement with the NCCHE.

Flow Model

- The model strictly enforces the mass conservation within the computational domain through the user of control volume approach. This property is of fundamental importance in achieving reliable and accurate results.
- Wetting and drying of the domain as the nodes are submerged under high flows and exposed during low flows. This feature is particularly important during unsteady flows. The wet and dry nodes are distinguished based on the critical depth specified by the user. During the simulation process any node having flow depth less than the critical depth is considered dry.
- The turbulent eddy viscosity is approximated using three different approaches. The first one is based on the depth average parabolic eddy viscosity model; the second approach employs depth-averaged mixing length model; and the last approach is based on depth-averaged scheme. The last two approaches are particularly suitable for re-circulation flows and flow around hydraulic structures. The user has the option to simulate a given case with any of the above turbulent closure scheme.
- The user can provide no-slip, total-slip, partial-slip, or log-law boundary condition at the no-flow boundaries. The log-law approach results in an accurate prediction of shear stresses near the hydraulic structures that are important for computing flow and sediment transport in the vicinity of hydraulic structure.
- The model supports both steady and unsteady boundary conditions for flow with multiple inlets and outlets. At any inlet the user can specify specific discharge, total discharge, or discharge hydrograph boundary condition. At an outlet the model accepts open boundary, water surface level, stage-discharge relationship, or stage hydrograph as a boundary condition. In case of open boundary, the model uses kinematic wave approximation to assess the water surface level at the outlet. This condition should be applied judiciously and is useful in cases when water surface level at the outlet is not available.

- The model is capable of handling supercritical flow. In addition, mixed flow regime (combination of subcritical and supercritical flow) in a channel reach can be simulated using the CCHE2D model.

4.1.5 HEC-RAS Model

The Hydrologic Engineering Center's (CEIWR-HEC) River Analysis System (HEC-RAS) software allows the user to perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modeling.

Some key aspects of HEC-RAS hydrodynamic model are given below:

- Steady Flow Water Surface Profiles: This component of the modeling system is intended for calculating water surface profiles for steady gradually varied flow. The system can handle a full network of channels, a dendritic system, or a single river reach. The steady flow component is capable of modeling subcritical, supercritical, and mixed flow regimes water surface profiles.
- One- and Two-Dimensional Unsteady Flow Simulation: This component of the HEC-RAS modeling system is capable of simulating one-dimensional; two-dimensional; and combined one/two-dimensional unsteady flow through a full network of open channels, floodplains, and alluvial fans. The unsteady flow component can be used to perform subcritical, supercritical, and mixed flow regime (subcritical, supercritical, hydraulic jumps, and drawdowns) calculations in the unsteady flow computations module. The hydraulic calculations for cross-sections, bridges, culverts, and other hydraulic structures that are developed for the steady flow component can be incorporated into the unsteady flow module. Special features of the unsteady flow component include: extensive hydraulic structure capabilities, dam break analysis; levee breaching and overtopping; pumping stations; navigation dam operations; pressurized pipe systems; automated calibration features; user defined rules; and combined one and two-dimensional unsteady flow modeling.

HEC-RAS finds particular commercial application in floodplain management and flood insurance studies to evaluate floodway encroachments. Some of the additional uses are: bridge and culvert design and analysis, levee studies, and channel modification studies. It can be used for dam breach analysis; though other modeling methods are presently more widely accepted for this purpose. Users may find numerical instability problems during unsteady analyses, especially in steep and/or highly dynamic rivers and streams. It is often possible to use HEC-RAS to overcome instability issues on river problems.

In developing a steady/unsteady flow model with HEC-RAS the required data are:

- Geometric Data
- Steady Flow Data
- Unsteady Flow Data
- Quasi-Unsteady Flow Data
- Sediment Data
- Water Quality Data

Advantages: HEC-RAS is supported by the US Army Corps of Engineers and is accepted by many government agencies and private firms. It is in the public domain and peer-reviewed, and available to download free of charge from HEC's web site. Various private companies are registered as official "vendors" and offer consulting services and add on software. Some also distribute the software in countries that are not permitted to access US Army web sites. However, the direct download from HEC includes extensive documentation, and scientists and engineers versed in hydraulic analysis should have little difficulty utilizing the software.

Disadvantages: Users may find numerical instability problems during unsteady analyses, especially in steep and/or highly dynamic rivers and streams. It is often possible to use HEC-RAS to overcome instability issues on river problems.

4.2 Master Plan of Haor Area, 2012

“Master Plan of Haor Area” has been prepared by the Bangladesh Haor and Wetland Development Board (BHWDB) during April 2012. The BHWDB engaged the Center for Environmental and Geographic Information Services (CEGIS), a Public Trust under the Ministry of Water Resources (MoWR) for preparing the Plan. It consists of total 3 volumes-Summary Report, Main Report and Project Portfolio and 21 annexes. Seventeen sub-sectors having potentiality for development have been considered as Development Areas (DAs) under this Haor Master Plan. It is to be reviewed and updated every five years.

Geological Setting:

The Sylhet Trough or Sylhet Basin is a sub-basin of the Bengal Basin and consists of 13-20 km thick alluvial and deltaic sediments underlain by much older gneiss and grantic rocks. The basin is bounded by the Shillong Plateau in the north, by the Indian Burmese ranges in the east and by the Indian Shield in the west. The southern and eastern parts of the Sylhet Trough are characterized by a series of north trending folds which have formed as a result of deformation from the Indo-Burman ranges. The anticlines constitute the Tripura Hills along the southern border of the region.

Hydrology of Haor:

The Haor area encompasses 373 Haors, covering an area of about 8,400 km^2 distributed in the districts of Sylhet, Sunamganj, Moulvibazar, Habiganj, Netrakona, Kishoreganj and Brahmanbaria. The region, situated just below the hilly regions of the States of Assam, Meghalaya and Tripura of India, experiences some of the most severe hydrological events. The annual rainfall ranges from 2,200 mm along the western boundary to 5,800 mm in its northeast corner. The major rivers of the region are Surma, Kushiyara, Manu, Khowai, Someswari, etc. — having catchments in the hills of India. The annual rainfall ranges from 2,200 mm along the western boundary to 5,800 mm in its northeast corner.

The avulsion of the Brahmaputra River from the east of the Madhupur Tract to the west has a pronounced effect on the shifting characteristics of rivers like the Surma and the Kushiyara. The depressed Sylhet Basin attracts the rivers from both east and west sides. Presently all the rivers, the Surma, the Kushiyara, the Kangsho and the Someswari fall into the depressed basin before they flow south to meet with the Meghna. The Surma and the Kushiyara, the main distributaries of the Barak River, are common/border rivers between Bangladesh and India. The Barak River divides into the Surma (northern branch) and the Kushiyara (southern branch) at the Indo-Bangladesh border in Amalshid of Sylhet district. In Kishoreganj district, upstream of Bhairab Bazaar, these two rivers meet to form the Kalni River which falls into the Meghna River and ultimately flow into the Bay of Bengal. The Sari-Gowain, the Piyain, the Jadhukata, the Jalukhali, the Baulai and the Kangsho are the tributaries of the Surma River. The Sonai-Bordal, the Juri, the Dhalai, the Khowai, the Sutang and the Sonai are the left bank tributaries of the Kushiyara River.

River System:

Situated just below the hilly regions of the states of Assam, Meghalaya and Tripura of India, the Haor area has some of the most severe hydrological conditions like extreme rainfall and subsequent flooding. The area receives water from the catchment slopes of the Shillong Plateau across the borders in India to the north and the Tripura Hills in India to the southeast. The principal rivers of the area include the Surma, the Kushiyara, the Manu, the Kalni, the Baulai, the Kangsho, the Someswari, the Jadhukata and the Khowai. Haors are connected with the main rivers by numerous small rivers and khals. A large number of Transboundary Rivers enter into Bangladesh in the North East region. The major parts of the catchments of these rivers are outside the country.

Three major river systems govern in the Haor area inside Bangladesh: the Surma-Baulai, the Kalni-Kushiyara and the Kangsa-Dhanu. The Barak River (Indian River) feeds the Surma and the Kushiyara. Consequently, it plays an important role in the two major systems, the Surma-Baulai and the Kalni-Kushiyara. The rivers contributing in these systems are described below:

- **Surma-Baulai System:** This system carries the flow of the Surma and a large number of transboundary rivers flowing from the north to south. The Surma, the Baulai, the Old Surma, the Sari-Gowain, the Piyain, the Dhala, the Nawagaong, the Jalokhali/Dhomali, the Chalti, the Jadukata, the Rakti etc. are the major rivers in this system among which the Sari-Gowain, the Piyan, the Dhala, the Nawagaong, the Jalokhali/Dhomali, the Chalti, the Jadukata, and the Rakti are transboundary. This river system meets the Kalni-Kushiyara system at Bajitpur Upazila of Kishoreganj district.
- **Kalni-Kushiyara System:** The Kushiyara, the Kamarkhali, the Kalni, the Sonai-Bordal, the Juri, the Manu, the Dhalai, the Lungla, the Sutang, the Khowai, the Sonai and the Haora are the major rivers of this system. Among these rivers the Sonai-Bordal, the Juri, the Manu, the Dhalai, the Lungla, the Sutang, the Khowai, the Sonai, and the Haora are transboundary. The Gungaijuri, the Titas, the Ratna etc. are rivers which are part of this system. The Kalni-Kushiyara system meets the Surma-Baulai system at Bajitpur Upazila of Kishoreganj district.
- **Kangsa-Dhanu System:** The Someswari, the Malijhi, the Chillakhali, the Bhogai and the Nitai enter the Bangladesh border along the periphery of the Haor region.

The Kangsa and the Dhanu are the major rivers of this system. The Saiduni-Baruni and the Gorautra are other contributing rivers of this system. This system ultimately drains at the Meghna River at the borders of Bajitpur and Bhairab upazilas. The combined flow of these three systems ultimately drains through Bhairab Bazaar at the Meghna River.

Subsidence:

The North East Region of Bangladesh has experienced some of the greatest subsidence. Morgan and McIntire (1959) compared elevation from ancient channel levees found in the NE Region (near Shanir Haor) with elevations of modern levees on the Brahmaputra River and concluded that "the Sylhet Basin had subsided 30-40 feet (10-12 m) within the last several hundred years". The rate of subsidence was not defined by them. A subsidence rate of 21 mm/yr in the Surma Basin was reported in MPO (1985) and FEC (1989). This value appears to have been arrived at by using Morgan and McIntire's estimate of 10 m subsidence in 500 years, equivalent to 2 cm/yr.

FAP 6 study also collected few peat samples from the Sylhet basin estimated the age of deposition through carbon dating. They have found that the subsidence is about 1 mm/yr, which is much smaller than Morgan and McIntire's estimate.

Goodbred and Kuehl (2000) carried out a research for finding out the significance of large sediment supply, active tectonic, and estuary on margin sequence development of late quaternary stratigraphy and evolution of the Ganges-Brahmaputra delta. The result indicates that the subsidence rate is about 2.5 mm per year in this basin. Goodbred and Kuehl (2000) also found notable tectonic subsidence. They found that subsidence increases toward the Dauki fault; which implied greater subsidence in the northern region. Maximum subsidence rate of the Sylhet Basin including the soil compaction would be 3-5 mm/yr.

It has been found that subsidence is the dominating process in the Sylhet basin, especially at the northern part of the basin which controls the shifting of river courses. Thus the net subsidence during the last 200 years might be reflected on the shifting of the river courses. A comparison between the present river courses and that of the end of the eighteenth century shows that the rivers from both the west and the east shifted towards the north before turning towards the south, which is possibly an indicator of net subsidence in the north.

River shifting:

Sediment concentration and its distribution are changing the morphology of the area. An estimation of sediment yields and budget for the NE Region was carried out by FAP-6 study. The sediment budget shows an estimated amount of net accumulation of 8 million ton/year. Though the rivers are very dynamic in the context of erosion-accretion process, shifting of river course is of main concern in this area. Over the last centuries the rivers have shifted their courses several times. The historical developments of the Surma and Kushiyara rivers have been studied by analyzing old maps available in the archives of CEGIS, such as Renell's map (1776), Tassin's map (1840), the Cadastral Survey map compiled during (1910-1930), as well as the river network extracted from the 2010 satellite image.

Sediment input in this basin was reduced after the avulsion of the mighty river Brahmaputra to the Jamuna. Subsiding process has become the prevailing factor in this area. Sunamganj Sadar is found to be the most subsiding area and all rivers developed a tendency to move towards Sunamganj Sadar. The understanding of the processes of the channel avulsion and subsequent prediction are useful for any intervention in the Sylhet basin for the development of the lives and livelihoods in the area. The changes are taking place in long time scale as well as short time scale. Even in last thirteen years the courses of Surma and Kushiyara rivers changed northward as shown in Figure 4.1 and Figure 4.2. The bankline changes of Surma and Kushiyara rivers in 20 years (1990-2010) are shown in Figure 4.3 and Figure 4.4 respectively.

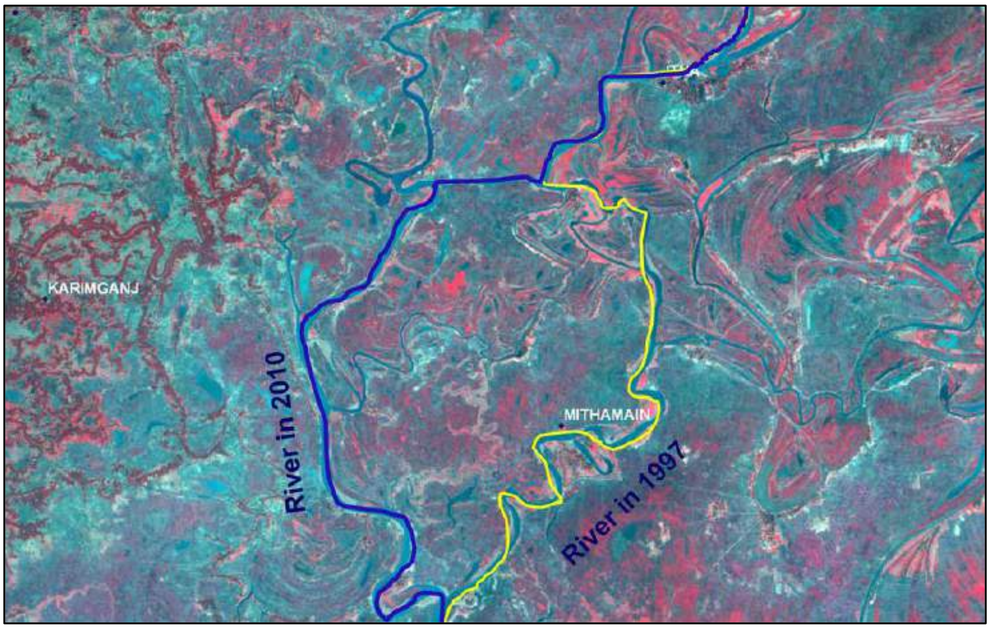

Figure 4-1 Changes of Surma courses during last decade (Source: BHWDB, 2012)

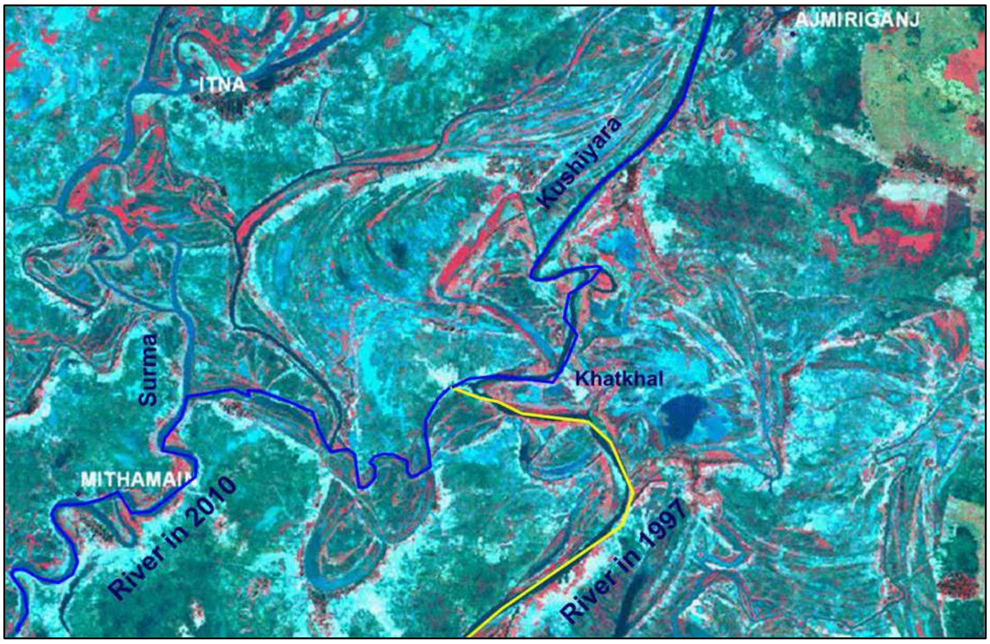

Figure 4-2 Changes of Kushiyara courses during last decade (Source: BHWDB, 2012)

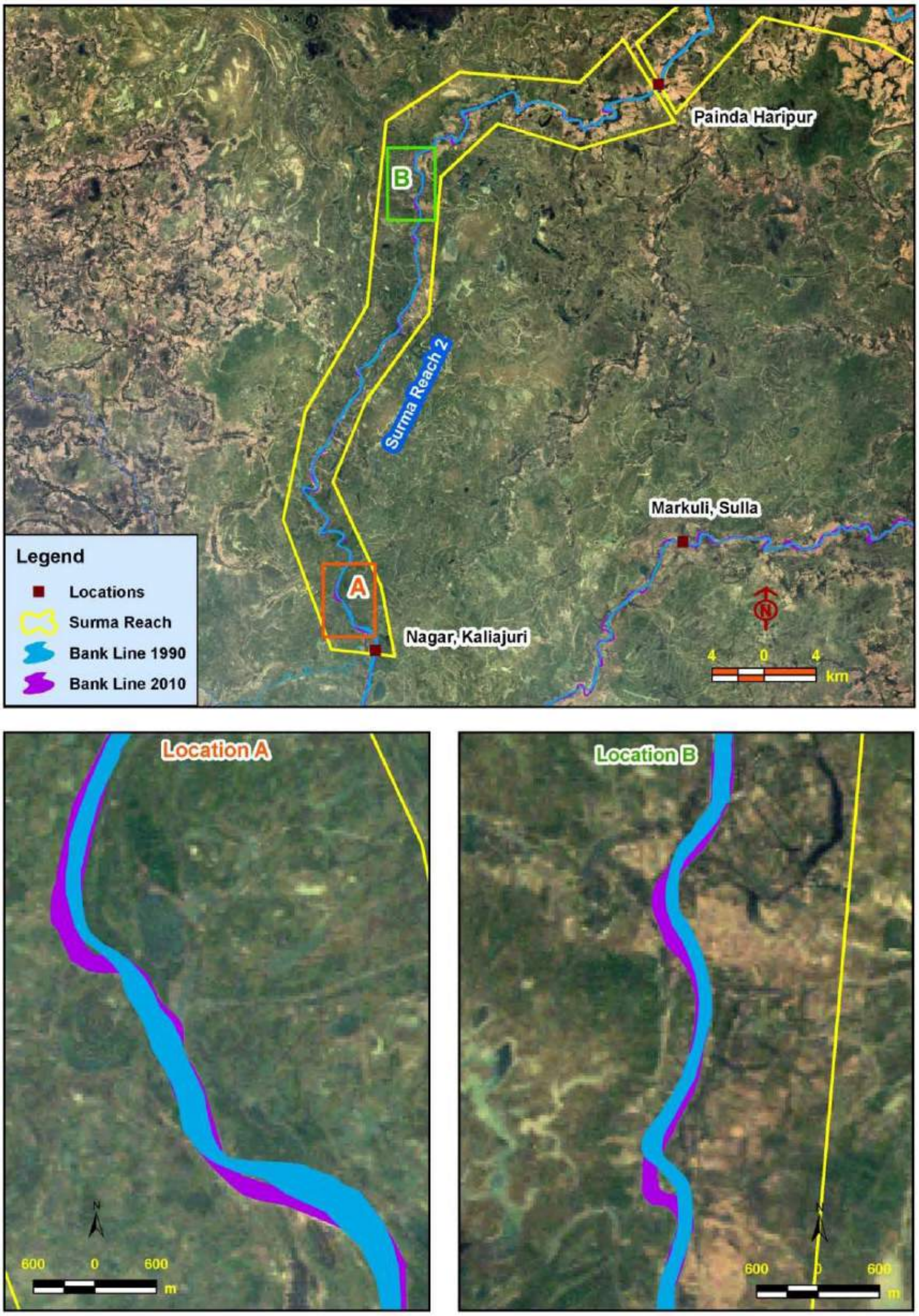

Figure 4-3 Bankline changes of the Surma River in 20 years (Source: BHWDB, 2012)

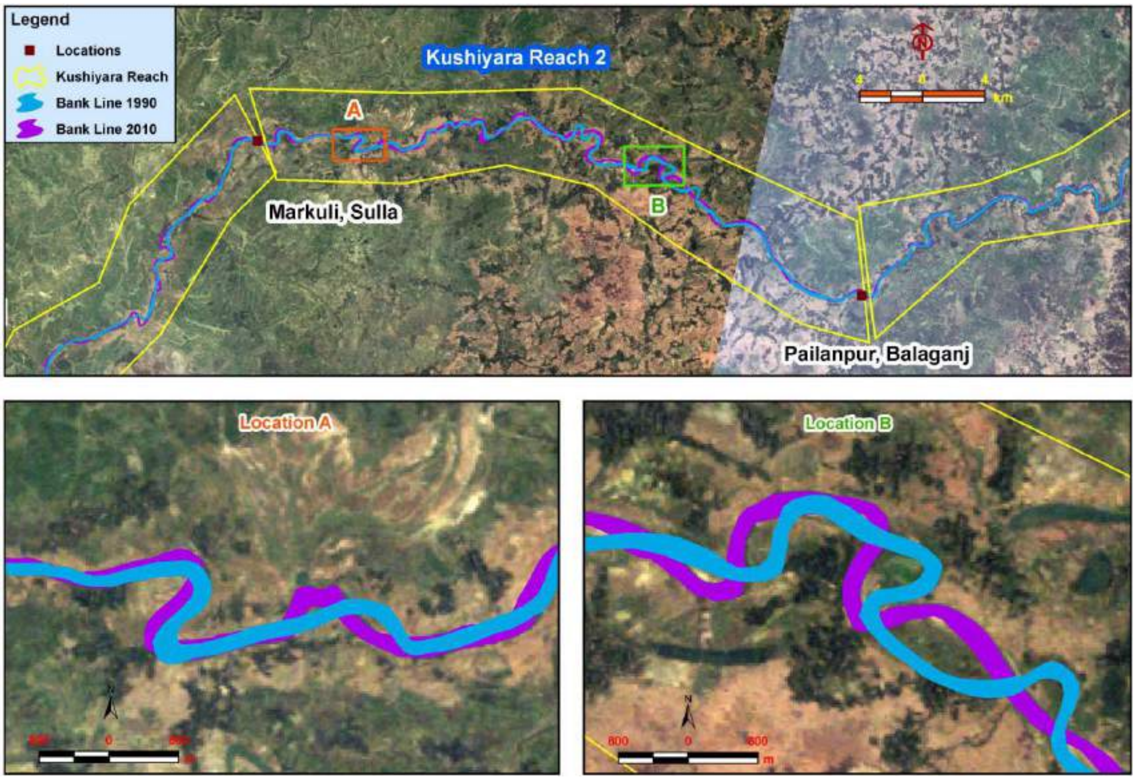

Figure 4-4 Bankline changes of the Kushiyara River in 20 years (Source: BHWDB, 2012)

4.3 Morphology of the Haor Areas, 2011

The report titled "Morphology of the Haor areas" has been prepared by the Bangladesh Haor and Wetland Development Board (BHWDB) during 2011. The BHWDB engaged the Center for Environmental and Geographic Information Services (CEGIS) for preparation of the report.

This morphological study, carried out in connection with the preparation of the "Master Plan of Haor Area", has addressed the geo-morphological development of the northeast region of Bangladesh, the physical environment of which is significantly different from other regions of the country. A first and comprehensive study on the hydro-morphological processes of this region was carried out by FAP 6 in the 1990s. They used long historical data on the hydro-morphology of this region from home and abroad and also conducted an extensive data collection campaign in the 1990s. Their knowledge was the basis for the present study. While carrying out this study, CEGIS has used historical maps, time series satellite images, and a digital elevation model based on the topographic survey conducted in the 1950s. The CEGIS has also analyzed the BWDB's time-series water level and discharge data and the hydrographic survey charts prepared by the BIWTA. Key findings of the study are given below:

Subsidence

Subsidence Review of the literatures suggests that the Sylhet basin is subsiding, but there are differences in opinions on the rate of subsidence. According to different researchers the rate of subsidence of the Sylhet basin varies from a few centimeters to one millimeter per year. The rate of subsidence is assessed to be about 3 to 5 mm/y including the subsidence for compaction. The rate of subsidence is high at the northern edge of the basin but it reduces towards the south. The avulsion of the Brahmaputra River, however, had cut the sediment supply to this subsiding basin and caused net subsidence of about one meter at the northern edge during the last two hundred years.

Classification of Haors

There are different types of Haors in the study area. Based on the geographic location and the depth of inundation, this study has primarily classified the Haors into three categories: 1) Haors within the Sylhet basin, 2) Haors in the simple floodplain and 3) trapped Haors. A tentative boundary of these types of Haors is shown in Figure 4.5. The Haors in the Sylhet basin can also be defined as flood basins within a very large subsiding basin. These Haors can be further sub-divided into two categories: Haors at the bottom of the Sylhet basin and Haors at the side slopes of the basin.

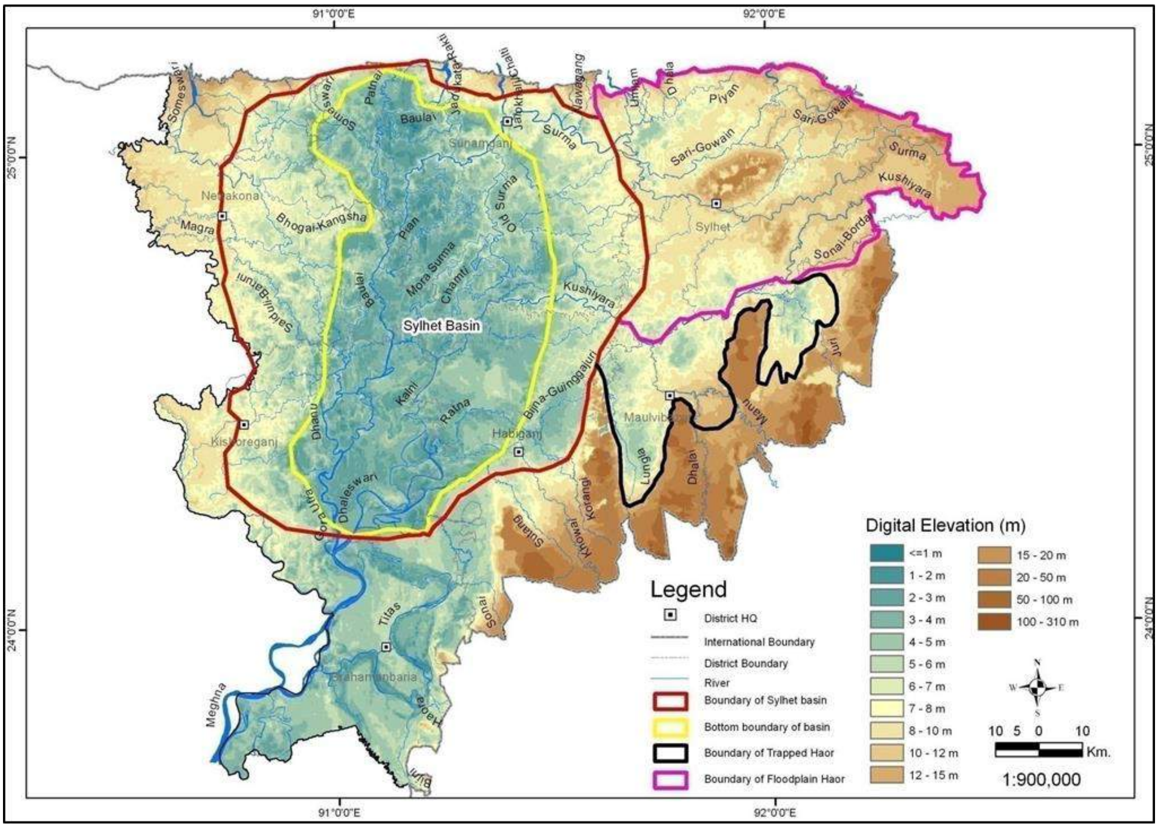

Figure 4-5 Boundaries of different types of Haors

Historical Changes of the Rivers

Analysis of historical maps shows the occurrence of several avulsions of the major rivers of the northeast region during the last 240 years. The dominant direction of these avulsions is the north, suggesting that high subsidence rate has a pronounced impact on the avulsion processes of the river.

CEGIS has a good collection of historical maps. The historical maps of Rennel (1776), Tassin (1840) and other maps based on the surveys of 1909-1930 have been used in this study. Attempt has been made to geo-reference these maps in a common projection system. There are errors in geo-referencing Rennel's and Tassin's maps, which could be several hundred meters. Errors are less while geo-referencing the maps of the last century. Over the last centuries the rivers have shifted their courses several times. Historical changes of the Surma and Kushiyara rivers have been shown in Figures 4.6, 4.7, 4.8 and 4.9 based on the old maps available in the CEGIS archives such as Renell's map (1776), Tassin's map (1840), the cartographic surveys conducted from 1910 to 1930, and river network extracted from the 2010 satellite image by CEGIS.

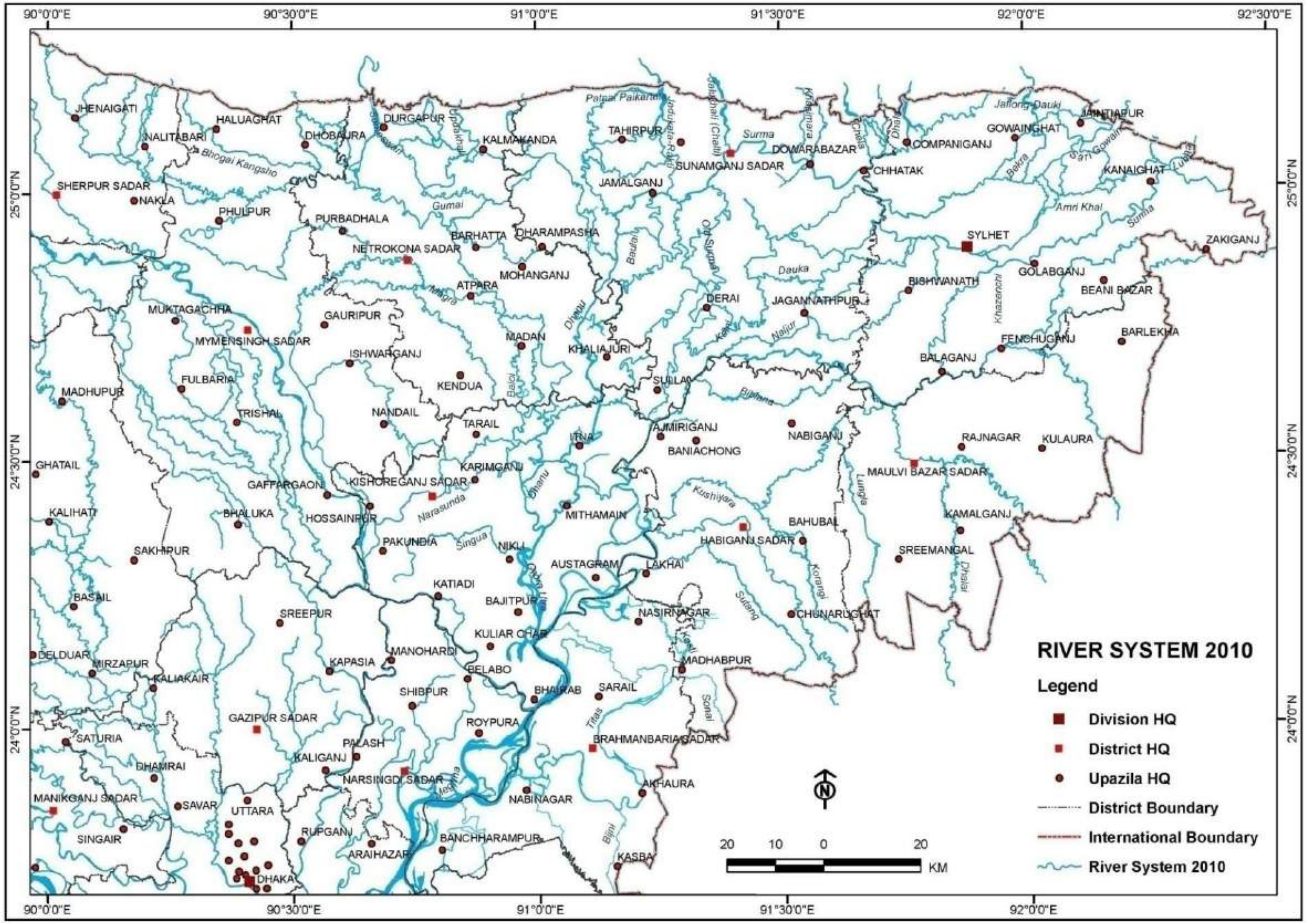

Figure 4-6 Present (2010) river system of the northeast region of Bangladesh; Source: BHWDB, 2011

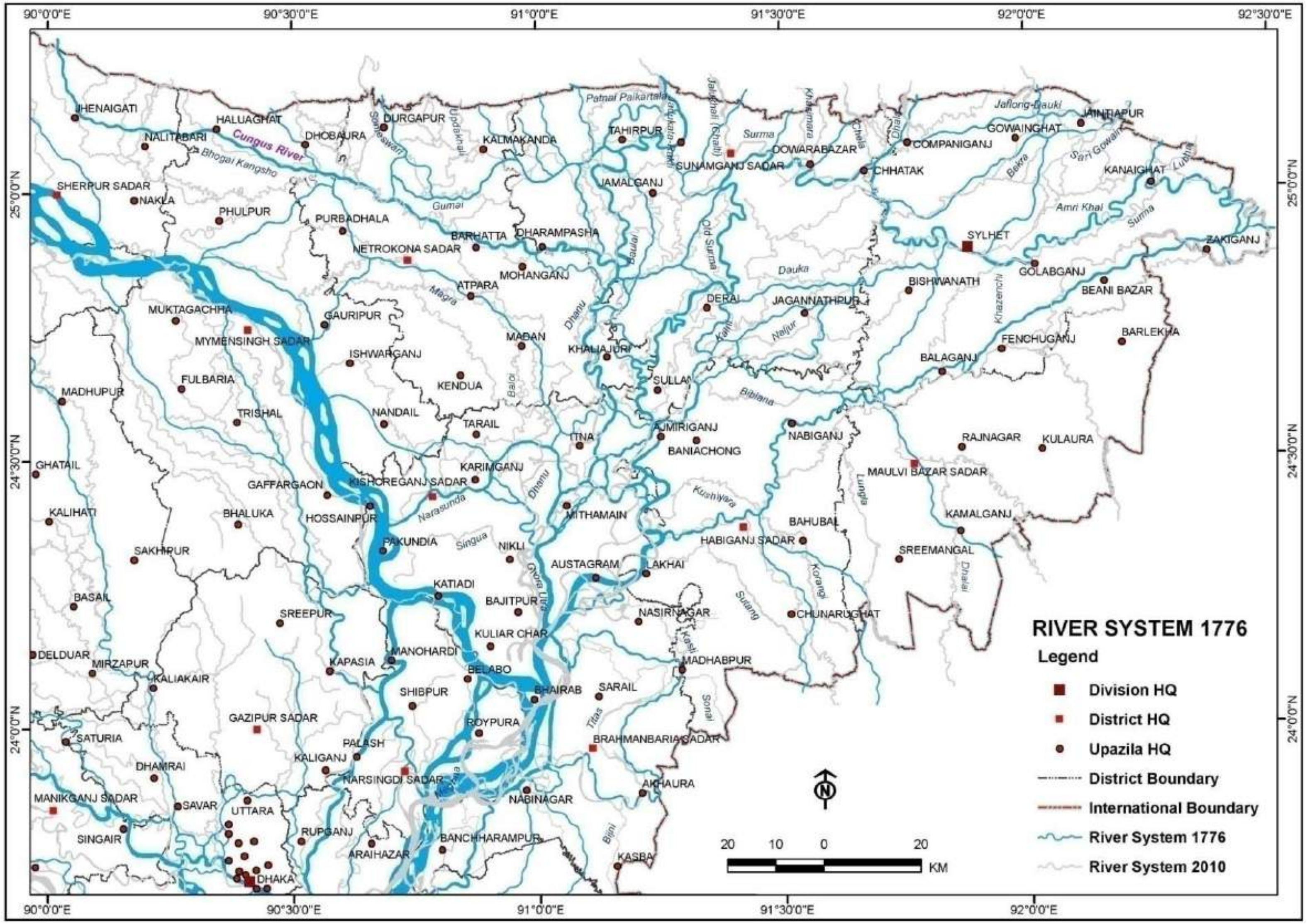

Figure 4-7 Comparison of present river courses (2010) with that shown in Rennel's map (1776); Source: BHWDB, 2011

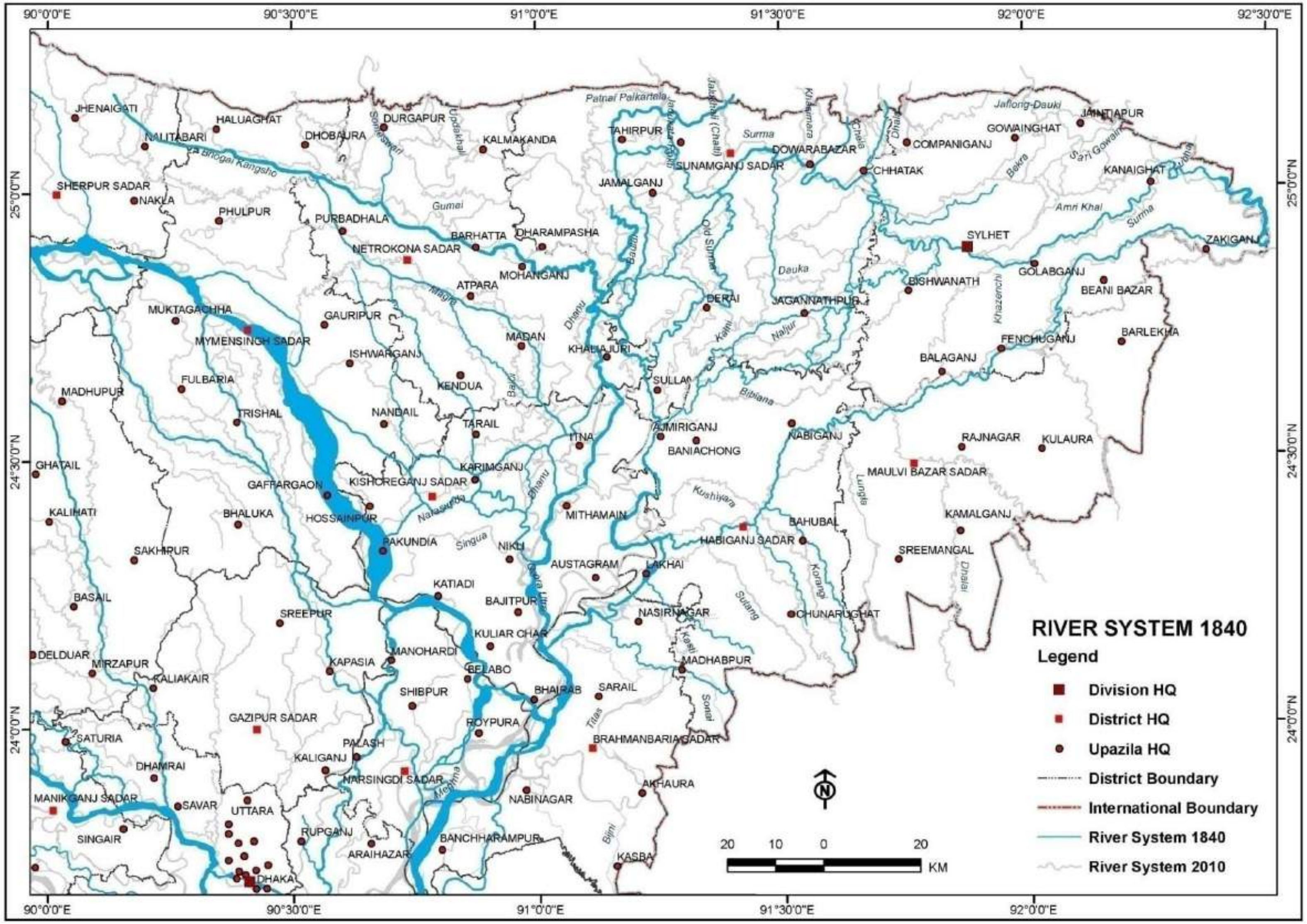

Figure 4-8 Comparison of present river courses (2010) with that shown in Tassin's map (1840); Source: BHWDB, 2011

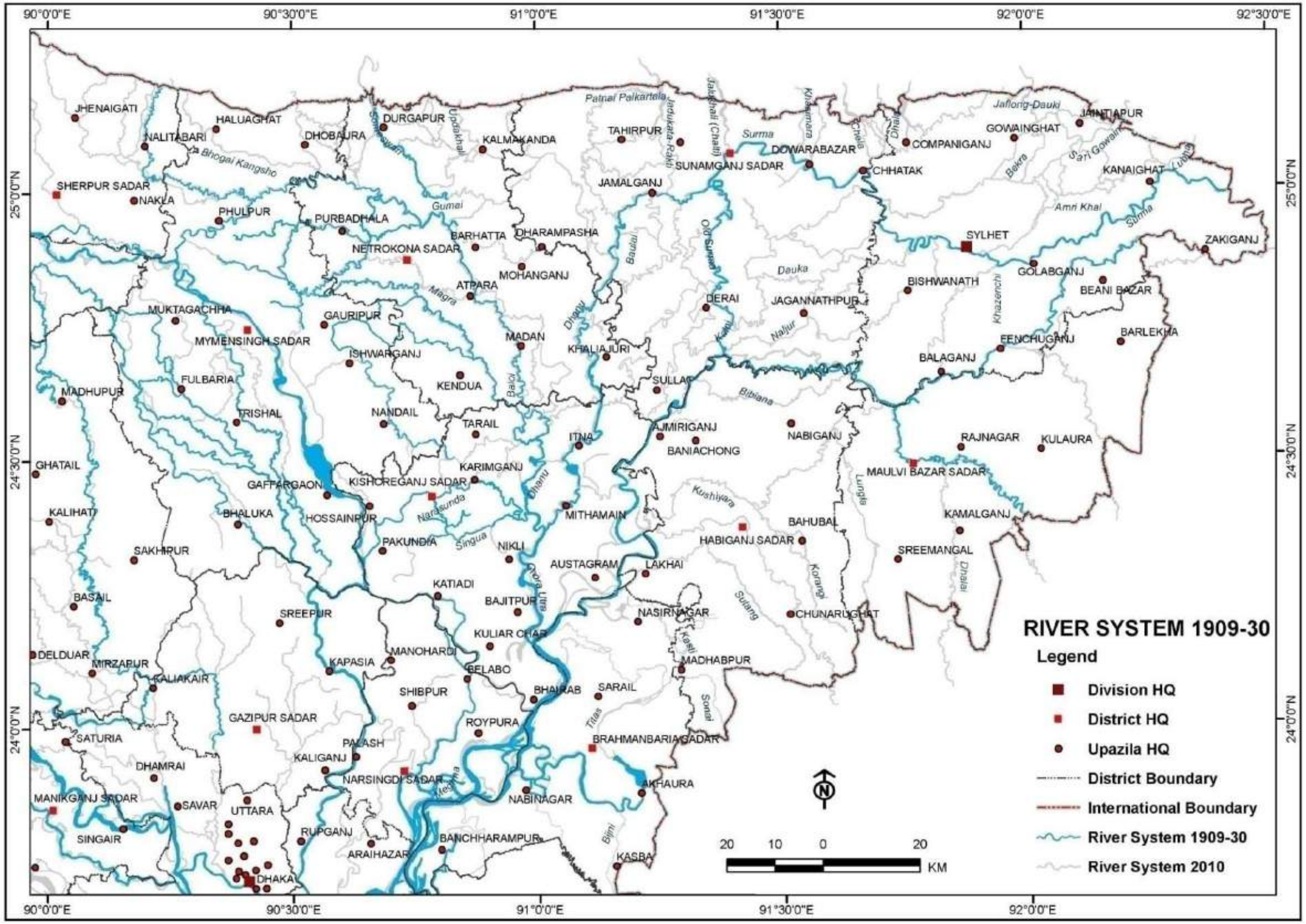

Figure 4-9 Comparison of present river courses (2010) with that surveyed in 1909-1930; Source: BHWDB, 2011

Morphological processes of the rivers

The Surma and the Kushiyara are dynamic rivers. Course shifting and avulsion are common phenomena at most of the reaches of these two rivers, especially when the rivers enter into the Sylhet basin. The morphological processes of the rivers in the Sylhet basin generally differ from that in its upstream. The rivers are morphologically more active in the Sylhet basin, river bank erosion is higher, and cut-offs of bends and avulsion of the river courses are more frequent than those outside the basin. Thus, most of the rivers in the Sylhet basin are found to be in the process of adjustment. Immediately after avulsion, the river enters into the Sylhet basin flowing over its side slopes which have much steeper gradient than the upstream floodplain. Initially, the width and depth of the rivers are small and overbank flow during the monsoon increases downstream. Furthermore, the river channel at the downstream contributes little in transporting the monsoon flow. The river evolution process starts with the formation of levees at the upstream. Initially, levee formation is associated with the sediment spreading over the banks by flood spill through sheet flow. As the formation of levees continues the difference in elevation between riverbank and flood basin becomes very significant, which often causes the breaching of the levees (locally known as dhalas). This breaching spreads the sediment, a major part of which is sand, on the adjacent Haors and contributes in widening and raising the levees. After exceeding a certain threshold limit between the elevations of the levees and basin, the river avulses to a new course and a new process of river evolution thus starts again. The process of river evolution takes several decades depending on several parameters, among which the contribution of the sediment imposed on the river from upstream is significant.

The width of the Surma and Kushiyara increases as they flow downstream meeting with the tributaries. The width reduces when it enters into the Sylhet basin, mainly due to the large contribution of the floodplain in carrying monsoon flow. River bank erosion is common along both the Surma and Kushiyara rivers. However, the rate of erosion is high in the Sylhet basin. The available depth for navigation is also less in the Sylhet basin, especially in a certain reach from where the difference in elevation between the monsoon flood and riverbank level starts to increase.

Cut-offs and avulsions are frequent within the Sylhet basin and the frequency of the occurrences mainly depends on the sediment input into the rivers. As the Kushiyara River carries more sediment than the Surma River, these are more common in the Kushiyara.

During the development of the cut-offs or avulsion, the local slopes in the reach concerned increase significantly during dry season or pre- monsoon period and thus increase the water level upstream. This is probably the main reason why the dry season and pre-monsoon water levels in the Kushiyara River have been increasing since the early 1980s.

The rivers coming from the Meghalaya and Garo Hills have formed the alluvial fans while entering the plain lands of the region. The courses of these fan-forming rivers change frequently and the extent of the fans are increasing. Among these, the fans of the Jalukhali and Jadukatha rivers are increasing rapidly and engulfing the wetlands drastically.

Model Development for Evolution of Rivers in the Sylhet Basin

The CEGIS has developed a Conceptual Model to describe/explain the evolution process of the rivers of the Sylhet Basin. The bases of development of the Conceptual Model for describing channel evolution process are historical maps, time series satellite images, DEM, long profile of river beds, monsoon and dry season surface profile and bank line profiles of the Surma and Kushiyara. For validating this conceptual model, CEGIS has used a part of a previous study related to the improvement of navigation in the Kushiyara River that was awarded by the International Union of Conservation of Nature (IUCN) to CEGIS. [The Conceptual Model has been analyzed/described in details in Chapter 5 of this report.]

Recommendations

Any physical interventions for the development of the northeast region should be based on sound knowledge on the Sylhet basin and the long-term responses of the system to the intervention concerned.

The major recommendation of this report was a detailed study to improve and validate the conceptual model for sustainable development of the Sylhet basin as the model has not been validated due to constraints of time and resources.

4.4 Inland Navigation and Integrated Water Resources Management, 2014

The book titled "Inland Navigation and Integrated Water Resources Management" by Sarker, et al (2014) was First published by Academic Foundation (New Delhi, India) in association with IUCN.

The Ecosystems for Life: A Bangladesh-India Initiative is a project led by the IUCN to promote insights into transboundary issues across the three major river systems: The Ganges, the Brahmaputra and the Meghna. The Convergence of inland navigation and integrated water resources management goals is one of the five themes of the project.

The waterways between Bangladesh and north-eastern India provide an important means of cheap transport for bulk agricultural and other goods, but they have been affected by hydro-morphological processes and withdrawal of water which has reduced their navigability in many regions, especially during the dry season. Ensuring sustainable navigability through river improvement and conservation efforts is important in securing not just environmental outcomes but also social and economic benefits.

The study was carried out with a team including morphologists, water resource engineers, navigation specialists and sociologists from Bangladesh and India. The research focused on the sustainability of the international navigation route between Ashuganj and Karimganj in the north-eastern part of Bangladesh and India to determine what physical and policy impediments exist, and to make recommendations on how to overcome those. Based on the analysis of various data sets collected through field survey and other means, the study makes a number of important recommendations for improving navigability, including:

- The importance of regular maintenance and dredging of some parts of the route within an IWRM framework.
- Improvements to navigation aids and safety.
- Amendments to the current protocol on inland water transit (IWT) and trade.
- Ways to enhance the role of the private sector.

The main objectives of this research were identifying the causes of deterioration of rivers and water traffic as well as identifying approaches for improving and maintaining navigability in line with the principles of IWRM and sustainable navigation.

Most part of the study route falls in the Kushiyara and Upper Meghna rivers. A number of literatures were reviewed and historical maps, satellite images were analyzed to understand the history of navigation and morphology of the study route. Discharge, water level, hydrographic survey charts, social survey data and traffic data were analyzed to understand the prevailing morphological processes and water traffic of the river.

Different studies reveal that there is a net subsidence in the Sylhet Basin, which is at a higher rate at the northern part of the Basin. The estimated rate of maximum subsidence was about a meter during the last 200 years after avulsion of the Brahmaputra River (CEGIS, 2011). The shifting of the courses of the Kushiyara, Surma, and Someswari and Kangsha rivers in the last 240 years followed a particular direction, towards the north, where the rate of subsidence was maximum (Figure 4.10).

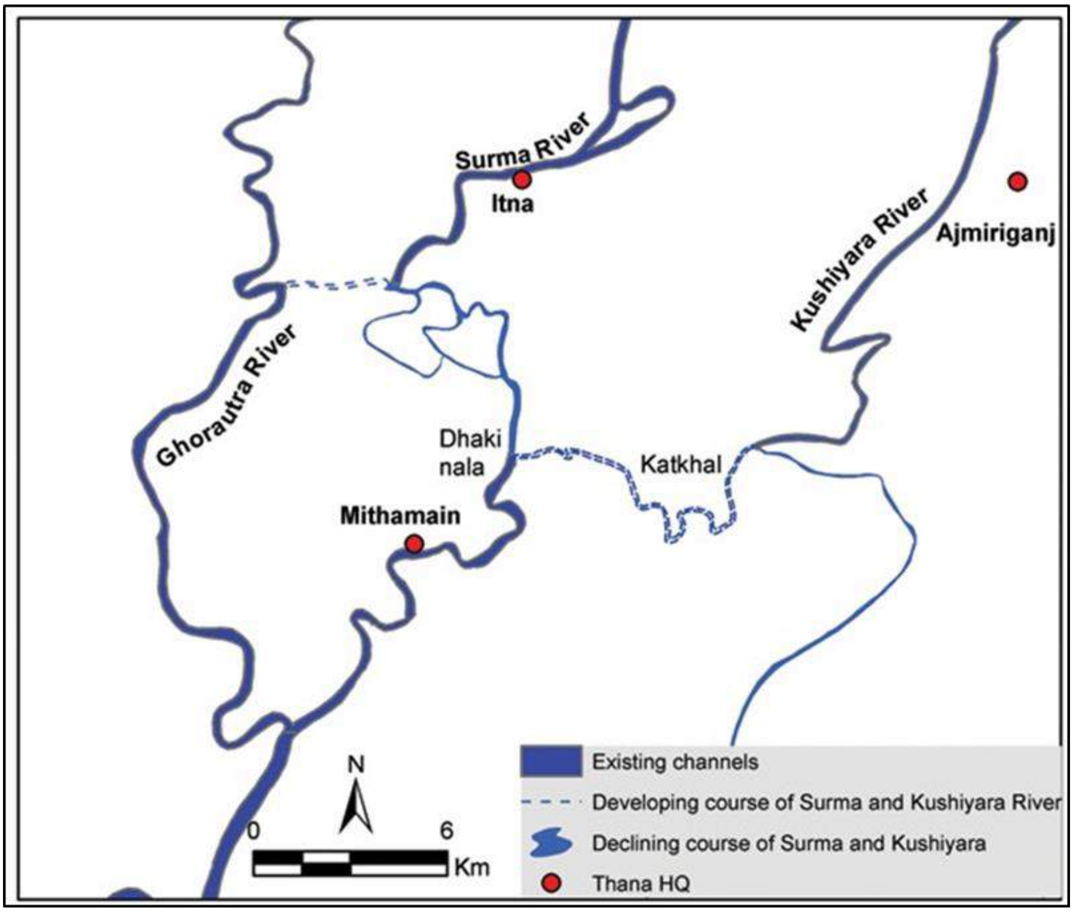

Figure 4-10 Recent Changes in the Surma-Kushiyara River Courses

These rivers shifted their courses from an upper to a lower level-from south to the north, while the ultimate flow direction of these rivers were north to south at the bottom of the Sylhet Basin. The process of the development of the rivers after their courses shifted where the topography is reverse to the direction of the flow can be described with the help of a Conceptual Model developed by the CEGIS. This model has also been used here for better understanding of the river's behavior and to identify the cause of deterioration of river navigability.

The CEGIS Conceptual model has been discussed and analyzed in details in Chapter 5 of the project Study "Model Validation on Hydro-morphological Process of the River System in the Subsiding Sylhet Haor Basin".

The navigability in the Kushiyara River has reduced for large vessels of more than two-meter drought, the duration of navigability however, has changed over time. Analysis of water level and satellite images suggested that channel changes at the downstream reaches of Ajmiriganj mainly caused the deterioration of navigability. Several changes occurred in the Kushiyara course during the last three decades, such as development of cut-offs at the downstream of Ajmiriganj and upstream of Katkhal, and avulsion of the Kushiyara to link with the Surma from Katkhal to the Dhaki. These processes have had a huge impact on deterioration of navigability of the river. The Kushiyara River is heavily loaded with sediment. It is likely that the sediment laden flow may cause frequent cut-offs or avulsion of the river courses.

It is assumed that sea level rise would be 100 cm (IPCC, 2007 and Mote et al., 2008) and rainfall will be increased by 20 per cent and cause 20 per cent increase of flood flow. It is likely that the sediment will be increased due to increased precipitations (Walling and Webb, 1996; Hovius, 1998; Zhu et al., 2008). The water levels of the Kushiyara River both dry and monsoon season are mainly influenced by water levels at Bhairab Bazaar, which are also heavily controlled by the water levels in the confluence of the Padma and Meghna River at Chandpur. CEGIS (2010) shows that increase in water level at Chandpur or upstream due to sea level rise will not be limited through back water effects; morphological adjustment processes will also contribute to the increases in water level. The increase in sediment and flood discharge as well as base discharge would contribute to increasing the dynamics of the river and thus frequently cause problems in navigation through shifting or avulsion of the river courses.

The proposed multi-purpose water resources project is at Tipaimukh on the Barak River 200 km upstream from the border between Bangladesh and India. If the dam becomes operational only for power generation without diverting the water for irrigation, dry season flow in the Kushsiyara River will be increased, which will help to improve the navigability of the river.

The Kalni-Kushiyara River Management Project (KKMRP) proposes a number of engineering interventions for integrated water management in the Sylhet Basin. Dredging and other interventions may bring a benefit for the navigation depending on methodology followed during the implementation.

The Kalni-Kushiyara is an important habitat for a large variety of animals and plants. Natural water flows without any constraint also promote biological purification processes that contribute to cleaner water in support of life. The means of communication of a large number of people living in the Sylhet Basin are fully dependent on navigation during the monsoon. Ensuring navigation in the Kalni Kushiyara all-round the year will improve access to more remote areas during post- monsoon and will inevitably generate additional commercial activity. Production of Boro, the main crop of the area, will increase as navigation reduces the risks of pre-monsoon flood damage. Drainage improvements in post-monsoon period will also increase land availability for timely plantation of Boro crops. Fish production within the channel will increase, especially during the dry season.

Inland water transport (IWT) is a competitive alternative to road and rail transport. In particular, it offers an environment friendly alternative in terms of both energy consumption, and noise and gas emissions. An efficiently run IWT system has environmental and social benefits over other modes of freight transport.

An overview of the “Protocol of Inland Water Transit and Trade” between Bangladesh and India has been discussed in the book as well as measures to improve the study route as a sustainable one.

4.5 National Water Management Plan, 2004

The National Water Management Plan was prepared by Water Resources Planning Organization (WARPO) and was approved by the Government in 2004. The Government commenced preparation of the National Water Management Plan, with the intention of operationalizing the directives given by the National Water Policy. The National Water Management Plan has been prepared to respond to the challenges and paradigms, with three central objectives consistent with Policy aims and national goals. These objectives are:

- Rational management and wise-use of the water resources of Bangladesh
- People’s quality of life improved by the equitable, safe and reliable access to water for production, health and hygiene
- Clean water in sufficient and timely quantities for multi-purpose use and preservation of the aquatic and water dependent eco-systems

The Development Strategy, agreed in the course of Plan preparation, requires that equal importance be given to each of the 6 national goals. The Plan is structured in a manner that the objectives of 84 different programmes shown in 8 clusters as well as region-wise planned for implementation in 25 years contribute individually and collectively to achieve both the overall objectives as well as to intermediate sub-sectoral goals; The short-term (2000-05) is considered a firm plan, the medium-term (2006-10) an indicative plan, and the long-term (2011-25) a perspective plan. The implementation of the plan is scheduled to be updated every five years.

The NWMP has divided Bangladesh into 8 hydrological regions namely; North West, North Central, North East, Eastern Hills, South West, South Central, South East and Rivers & Estuary (Figure 3.4). The Report discussed issues of all the hydrological regions. However, since the present study area is located in the NE region, issues of this region are discussed below.

Most of Bangladesh is located within the floodplains of the three great rivers, the Brahmaputra, the Ganges and the Meghna, but only about 8% of the total catchment area lies within Bangladesh. Flash floods resulting from transboundary rivers, local intense rainfall, impeded drainage and drainage congestion on the Meghna are the major sources of flooding in the Northeast Region.

Principal water-related issues of North East Region are:

- Environmental management of Haor Basin
- Flooding and remedial action for existing Flood Control and Drainage (FCD) schemes
- Flood proofing of villages in the Haor Basin
- Erosion of Old Brahmaputra left bank
- Drainage congestion in the Kalni-Kushiyara and other rivers
- Local development of hill irrigation

An (the then) ongoing study of the Options for the Ganges Dependent Area is expected to establish the most appropriate method of utilizing the Ganges waters secured under the Ganges Treaty which the Government intends to implement on an urgent basis. An inter-regional study of the potential of the Meghna river to serve the needs of the Northeast and Southeast regions by means of a barrage and/or by river pumping is required to establish the best choices for these regions. Most of the Northeast, Southeast and Southwest regions are dependent upon surface water. Priority can therefore be assigned to development of surface water resources in the Northeast and Southeast regions by utilization of Meghna waters. Options to cope with the identified risks in the long run exist through the development of barrages on the Brahmaputra, Ganges and Meghna rivers.

Three of the world's largest rivers: the Ganges, the Brahmaputra and the Meghna flow through the country on the final stages of their journey to the sea. Their common delta comprises much of the country as a whole, and is accordingly prone to the usual deltaic problems of geomorphologic change, seasonal erosion and accretion. Lateral flow from these, and other rivers, is the primary cause of Bangladesh's widespread floods; even so, flash flooding also occurs as a result of intense rainfall driven by Nor 'westers which usually strike in the North East during the weeks prior to the monsoon. Although often the cause of damage to life, livelihood and infrastructure, such floods also ensure hydraulic connectivity between standing water bodies and as such are essential for the sustainability of the capture fisheries which represent the principle protein source for most of the country's poor. The same floods also deposit fertile sediments, which contribute to Bangladesh's impressive food security achievements. Another notable feature of the national hydrology is its substantial rainfall, 70% to 85% of which falls between June and September inclusive. It is distributed unevenly however, with some 1200 mm typically falling in the West, increasing to almost 6000 mm in the East. Potential annual evapotranspiration of around 1300 mm is fairly uniform across the country.

The benefits of the National Water Management Plan are to fulfill the objectives previously stated. Special attention will be given to improving the water management of the Sundarbans and the Haor Basins of the Northeast.

Among the twelve suggested Programmes for the Main Rivers, the “Meghna Barrage and Ancillary Works” and “North East and South East Regional Surface Water Distribution Networks” programmes are suggested with an objective to increase dry season water availability in the NE and SE regions.

The Investment Portfolio mentioned the primary as well as the secondary or supportive agencies assigned for each programme. The responsibility of overall coordination of implementation of the NWMP lies with the National Water Resources Council. The WARPO is responsible for the overview of implementation of the plan.

4.6 Northeast Regional Water Management Project (FAP 6), 1994

The Northeast Regional Management Project (NERP) is Component 6 of the 26 studies of the World Bank-coordinated Flood Action Plan (FAP) and one of five regional water management studies within the FAP prepared by Flood Action Plan Co-ordination Organization (FPCO). It is a water resources planning exercise covering the Northeastern region of Bangladesh and is funded by the Canadian International Development Agency.

NERP consists of two phases. Under Phase I, a Regional Water Resources Development Plan was prepared, using a strategic planning process based on specialist studies of key areas including existing water resources development, hydrology, ground water, river sedimentation and morphology, agriculture, fisheries, water transport, biodiversity (wetland and upland), human resources development, and institutions. Brief description of the physical setting and hydrology of the region as mentioned in the report is given below:

The Northeast region has area of about 24,200 km^2 which is about 17.5% of the total area of Bangladesh. The region experiences some of the most severe hydrological conditions in the country. The region receives very large amount of water from the catchments on the slope of the Shillong Plateau across the border in India to the north and the Tripura Hills in India to the southeast. Run-off from these catchments discharge into a large central depression in the region, the Haor area or Central basin which remain flooded for more than six months each year.

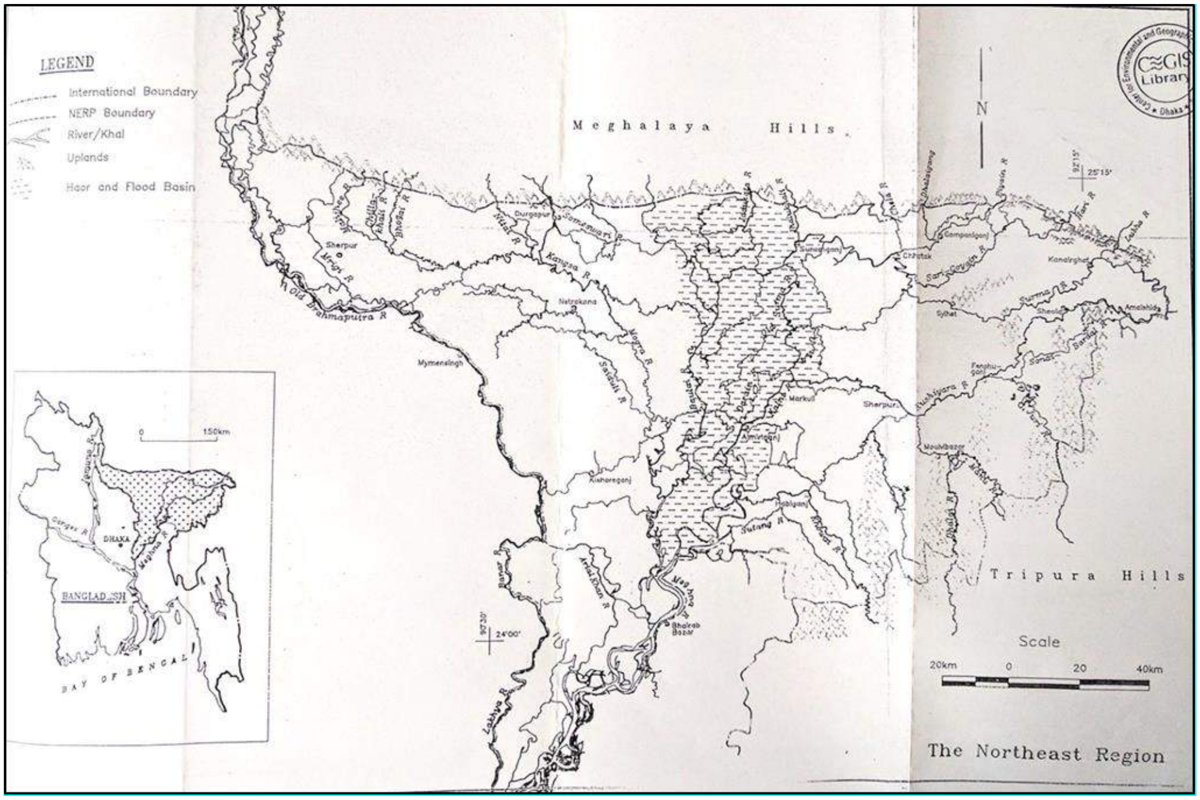

Figure 4-11 The Northeast Region (Source: FAP 6)

Principal rivers of the region include the Surma and the Kushiyara which drain the eastern side of the region, the Kangsha which drains the western side, and the Kalni and Baulai which drain the Central Basin. These rivers all discharge into the Meghna a short distance upstream of Bhairab Bazar. The Old Brahmaputra River and its distributary channel, the Lakhya form the western boundary of the region and discharge into the Meghna, downstream of Bhairab Bazar. The downstream reach of the Old Brahmaputra below the Lakhya offtake is virtually abandoned and only carries flow during the flood season. The main source of flow into the Old Brahmaputra-Lakhya is spill from Jamuna-Brahmaputra just upstream of Bahadurabad.

The physical setting and hydrology have produced a unique hydraulic regime, which creates a variety of difficulties for inhabitants. Flash floods are generated in the steep, upland catchments adjacent to the region in India. These flash floods spill onto low-lying floodplain lands in the region, inundating crops, damaging infrastructure by erosion and channel shifting, and often result in substantial quantities of coarse sand being deposited on agricultural land or in drainage channels. The main lowland rivers such as the Surma-Baulai, Kalni-Kushiyara, and Kangsha are currently adjusting their channel morphology in response to natural large-scale channel changes and the effects of past engineering works; embankment construction, distributary channel closures, and loop cutting. Many reaches on these rivers exhibit non-stationary trends in discharge and water levels. Past morphologic developments have often caused low-lying distributary channels in the deeply flooded Central Basin to be abandoned or obstructed, accompanied by gradual sediment infilling and obstruction of drainage.

NERP described the future likely characteristics of the region, focusing on important trends over the period of 1991-2015. Biophysical changes of the region would result from changes in rainfall patterns, morphological changes in the major rivers and developments in upstream catchments. Rainfall and flooding influences the regional morphology through their influence on the sediment supply. The most sensitive sub regions are the Meghalaya fans in the north and the Tripura piedmont areas in the south. The main lowland rivers such as Upper Kushiyara (upstream of the Manu), the Upper Surma (upstream of Sylhet) and the Meghna are less sensitive. The projection was the lower Kalni River would continue to aggrade. This would increase the sills into Baulai River and eventually lead to a partial avulsion from the Kalni River near Ajmiriganj towards the Baulai River. Pre-monsoon flood levels between Madna and Sherur would increase affecting the 5000 km^2 of the Central Basin.

India proposed to construct a dam at Tipaimukh and a barrage as Fulerhat on the Barak River. During operations, the project would moderate flows along the Kushiyara River and Upper Surma River. This would decrease the monsoon flood levels and substantially increase dry season flows. However, the system moderation would be outside the control of Bangladesh.

The cumulative effects of the foregoing (Tipaimukh Dam plus aggradation on the Kushiyara-Kalni and Surma-Baulai) would be increased winter discharges and siltation along the Kalni River, with pre-monsoon and post-monsoon water levels higher by as much as 1.5 m at Markuli, but peak monsoon water levels higher by only 0.3 m. Ramifications include greater depth and extent of monsoon flooding, retarded post-monsoon drainage, and earlier and more severe pre-monsoon flooding of unprotected areas adjacent to the river. Major avulsions appear to be either in progress or imminent on the Dauki-Piyain, Dhalai Gang, Jadukata and Someswari Rivers. However, channel avulsions are inherently unpredictable and could occur on any of the fans in the region over the Plan period. Avulsion from the Someswari down the

Atrakhali would impact over much of the Kangsha River basin all the way down into the Central Basin, with flood conditions reduced in one area but intensified in other areas. The impact of the other ongoing and potential avulsions mentioned would be largely restricted to the fan areas.

The Regional Plan proposes a water management strategy for the development of regional water management systems through 2015. The strategy is based on three key principles: a mix of structural and non-structural measures is required as there is a limit to what extent nature can be controlled; development oriented stance is sought since it offers higher benefits than defense oriented stance; the strategy should impact a large number of people as most of the people in the region are poor. The strategy includes a portfolio of 44 specific projects for implementation over the proposed 20 years by a variety of government, non-governmental, and private agencies. NERP Phase II will consist of feasibility study and implementation of one or more of these projects.

4.7 Mathematical Modelling Study to Assess Upazila Wise Surface Water and Groundwater Resources and Changes in Groundwater Level Due to Withdrawal of Groundwater at the Pilot Areas (Package-1)

"Mathematical Modelling Study to Assess Upazila Wise Surface Water and Groundwater Resources and Changes in Groundwater Level Due to Withdrawal of Groundwater at the Pilot Areas (Package-1)" has been prepared by the Bangladesh Water Development Board (BWDB) during November 2013. The BWDB appointed Institute of Water Modelling (IWM) for conducting the study.

The main purpose of the study was to assess the impact of climate change on the availability of water resources in the two Pilot Areas (PA-1 and PA-2). The PA-1 includes 15 Upazilas of the districts of Barisal, Patuakhali, Barguna, Pirojpur and Jhalokathi. The PA-2 spreads over 10 Upazilas of Chittagong district. An integrated hydrological model describing the condition in the unsaturated and saturated zone of the subsurface together with rainfall, overland flow, evapotranspiration and the condition of flow in the river has been used for the study. In addition, issues of climate change have been duly considered in the study.

Major activities of the study include cross-section survey, hydrometric data collection, computation of water demand, model calibration and validation. Models developed under this study are based on MIKE 11 for surface water model and MIKE-SHE for groundwater model. Two main components of MIKE 11, such as Rainfall-Runoff and hydrodynamic module, have been used to simulate the river flow. The hydrodynamic model takes into account schematized rivers/channels of an area. The connectivity of the river/channel systems and influence of other rivers/channels outside the model area were identified from the river network maps. The external boundary conditions (inflow-discharge and outflow-water levels) are applied to the model from observed or synthetic data. The model can be used for simulation the changes in discharge and water level in the channel system in and around the catchment under consideration.

Both the models have been integrated and simulated dynamically. The coupled model was calibrated using the data for the period 2000-2005 and validated for the period 2006-2009. The validated model was simulated for base conditions and climate change conditions. The models have been used to simulate water resources under present and future hydrological conditions of 2030 and 2050 due to climate change. Surface water resources at upstream and downstream locations of the rivers Baleswer, Bishakhali, buriswar and Tetulia have been assessed for both present and future under climate change conditions. Available surface water salinity data for the year 2012 has also been reviewed to assess the suitability of surface water for different uses particularly for agricultural use.

The consultant recommended localized climate change models for properly and effectively monitoring and evaluation of the effects of climate change on the water resources of coastal region. Comprehensive data collection is essential to address and monitor future climate change aspects.

4.8 Mathematical Modelling & Topographic Survey for Integrated Water Resources Management of Chalan Beel Area Including Beel Halti Development Project

"Mathematical Modelling & Topographic Survey for Integrated Water Resources Management of Chalan Beel Area Including Beel Halti Development Project" has been prepared by the Bangladesh Water Development Board (BWDB) during June 2007. The BWDB engaged Institute of Water Modelling (IWM) for conducting the study.

The study area of the project spreads in six districts (Rajshahi, Natore, Naogaon, Bogra, Pabna and Sirajganj). It consists of the Chalan Beel project area (Polders A, B, C and D), Barnai Project, Baral Project, Naogaon Polder Area, Bogra Polders II & III, and Sirajganj Integrated Rural Development Project (SIRDP). All the FCD schemes in the Lower Atrai Basin were designed to provide full flood protection from outer floodwaters and minimize the internal flooding/drainage congestion. However, lack of adequate study during planning and implementation of these schemes resulted in poor and unsatisfactory outcome. The problems associated with the study area are interlinked with various hydrological, hydraulic, environmental, social and economic aspects-both of inside and outside the study area. Instead of using conventional approaches, the use of mathematical modelling was done to analyze as well as provide solutions to such a complex physical system.

The overall objective of the project was to provide support for Feasibility Study (FS) Consultant (Main consultant), in formulating an integrated water resources management (IWRM) plan of the areas concerned, with the results of surface and groundwater models.

After reviewing the available data at IWM and BWDB, the survey and primary data collection plan was finalized. Latest hydrological and meteorological data as well as hydro-geological and groundwater related data and information were collected from different organizations.

Flood Control and Drainage Modelling:

For flood control and drainage modelling, the one-dimensional hydrodynamic model MIKE11 was used. The study area was extracted from the existing North West Region Model (NWRM) and detailed by including khals and floodplains and redefining connections based on the information and data obtained from survey works. The project model was updated incorporating the recent (the then) hydrologic data. The project model was calibrated for 2004-05 and validated for 2005-06. After validation, the model was used to simulate the design hydrological events and options as suggested by the Main Consultant. The following options were identified for the model assessment to support the Feasibility Study:

- Base condition;
- Full FCD condition;
- Flood improvement by excavating selected peripheral rivers;
- Flood diversion through the polders/projects;
- Combination of flood diversion and river dredging.

For investigating the flow pattern/propagation in the Beel Halti area, a detailed floodplain modelling was carried out using MIKE FLOOD. MIKE FLOOD is a tool that integrates the one-dimensional model MIKE11 and two-dimensional MIKE21 into a single, dynamically coupled modelling system.

Groundwater model study and irrigation expansion:

The main purpose of the groundwater model study was to assess and evaluate the overall water resources of the study area with the view to bring potential areas under irrigation coverage for increasing agricultural production through optimum utilization of available water resources. To assess the water resources availability in the study area, integrated MIKE11-MIKE SHE modelling system was adopted.

Modelling Study:

The models developed under the study include surface water model and groundwater model. Both the models have been coupled and run dynamically. The present study does not focus on groundwater hence, only the surface water model has been discussed here.

The surface water model was developed mainly to assess the dry period availability of surface water resources at key locations. The hydrodynamic model, developed under FCD study was tailored for dry season requirements. The model consisted of 25 rivers and polders. The model had 16 upstream and 2 downstream boundaries. Upstream boundaries were provided with discharge generated from water level using rating curve and measured water levels, downstream boundaries were provided with measured time series water levels only. The calibrated and validated model was applied for assessment of the surface water resources.

Management information system (MIS):

Besides the survey, data acquisition and modelling activities, an MIS was developed for the project area. The MIS contains large volume of relevant data of the project area along with user-friendly graphical user interface (GUI) based on GIS applications.

5 River Response of Sylhet Basin

5.1 Theory of River Response

The response of channel pattern and longitudinal gradient to variation in selected parameters has been discussed by Simons and Senturk (1977). In more general terms, Lane (1955) studied the changes in river morphology in response to varying water and sediment discharge. Similarly, Leopold and Maddock (1953), Schumm (1971) and Santos and Simons (1972) have investigated channel response to natural and imposed changes. These studies support the following general relationships for alluvial rivers:

a) Depth of flow d is directly proportional to water discharge Q.

$d \propto Q;$ *(i)*

b) Channel width W is directly proportional to both water discharge Q and sediment discharge Q_S.

$W \propto Q;$ *(ii)*
$W \propto Q_S;$ *(iii)*

c) Channel shape, expressed as width to depth W/d ratio is directly related to sediment discharge Q_S.

$W/d \propto Q_S;$ *(iv)*

d) Channel slope S is inversely proportional to water discharge Q and directly proportional to both sediment discharge Q_S and median grain size D_{50}.

$S \propto 1/Q;$ *(v)*
$S \propto Q_S;$ *(vi)*
$S \propto D_{50};$ *(vii)*

e) Transport of bed material Q_S is directly related to stream power $\tau_o U$ (τ_o = Bed Shear, U = Cross-sectional Average Velocity) and concentration of fine material C_F, and inversely related to the fall diameter of the bed material D_{50}.

$Q_S \propto \tau_o U;$ *(x)*
$Q_S \propto C_F;$ *(xi)* or, $Q_S \sim \frac{(\tau o U) W C_F}{D_{50}}$ (Simons et. al., 1975)
$QS \propto 1/D_{50};$ *(xii)*

5.2 The CEGIS Conceptual Model

CEGIS (2011) has developed a conceptual model to explain the river evolution processes in the depressed Sylhet Basin, after their avulsion (shifting to new courses).

Data availability for the development of models to describe and explain the channel evolution process is limited. Therefore, a number of assumptions were needed to be made during the development of the model. It is assumed that (1) the river reaches at the upstream of the Sylhet Basin are in regime condition and (2) flood profile of the river is assumed to be parallel to the bank line.

In most cases with natural rivers, the annual average flood is close but higher to the bankfull level *(Chang, 1979)*. The gradient of the topography is flatter than that of the side slope of the Sylhet Basin, which varies 15 to 25 cm/km. However, the gradient of the bottom of the Sylhet Basin is very flat.

Following hypotheses and its explanations have been extracted from the CEGIS Conceptual Model.

5.3 Hypothesis 1*

"The bankfull water level of the channel in concern varies in the downstream direction. At the upstream, it is high and close to annual average flood discharge." **(Figure 5.1 & 5.2)**

5.3.1 Explanation

The hypothesis is explained in the following sections:

(*: Excerpt from the CEGIS Conceptual Model)

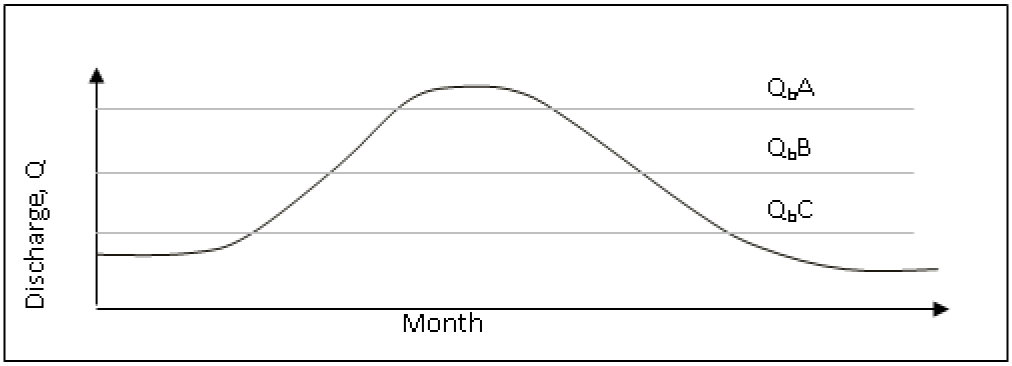

Figure 5-1 Conceptual model for describing the channel evolution processes in a subsiding Basin, showing a simplified discharge hydrograph showing bankfull water levels of different reaches of the river at time t1 (Source: CEGIS 2011)

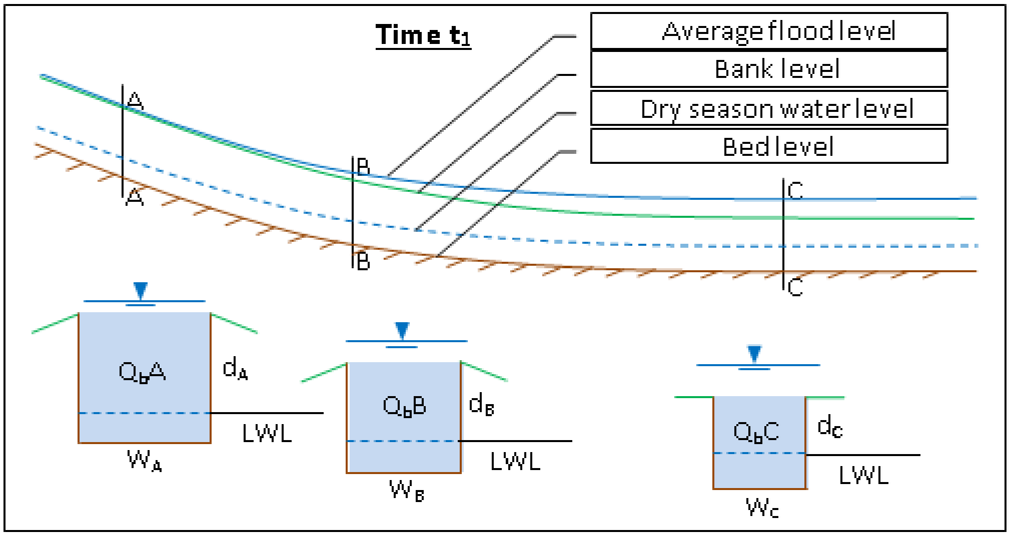

Figure 5-2 Conceptual model for describing the channel evolution processes in a subsiding Basin, showing the long profiles of river bank, riverbed, flood level and dry season water level at time t_1 without having any influence of sediment (Source: CEGIS 2011)

Assumption: River sedimentation has not been considered.

The model in Figure 5.2 shows the channel evolution after time t_1 from its avulsion. Channel dimensions are considered as the function of the dominant discharge and often bankfull discharge is considered as the dominant discharge (*Chang, 1979; Bridge, 2003*). The hypothesis implies that in most days in a year, the river flow is confined within the bank. On the other hand, the bankfull water level at the downstream is much less and the overbank flow occurs for several months during the monsoon.

In the figures, Q_b = bankfull discharge,
d = depth,
W = width,
A, B and C denote sections A-A, B-B and C-C respectively.

5.3.2 Theoretical Analysis

The Conceptual Model of the CEGIS has been analyzed in the light of above mentioned established equations of Channel Response to various parameters (section 5.1). From the collected data as well as data generated from the model of the Surma and Kushiyara rivers the CEGIS conceptual model will be validated.

i. In a catchment of steep slope, the height (RL) of the bank of upstream section is at much higher level than height of the bank of downstream section. The river bed slope is also likely to have similar sloping pattern.
   Hence, bankfull water level at upstream will be greater than that of downstream.
ii. Moreover, downstream area will remain flooded for a longer period than that of the upstream areas.
iii. In general, it appears that the Hypothesis 1 is in agreement for the rivers having catchment of steep slope.

5.3.3 Validation Criteria

- If it is found that at bankfull water level $Y_A > Y_B > Y_C$, then the hypothesis is accepted, where Y_A, Y_B and Y_C are the bankfull water levels at sections A-A, B-B and C-C respectively (upstream to downstream sections).
- If it is found that months of overflow at downstream is greater than that of the upstream, then the Hypothesis 1 can be accepted.

5.4 Hypothesis 2*

"**Decrease in the bankfull water level at the downstream, however, indicates a decrease in channel dimensions i.e. the width and depth.**"

(*: Excerpt from the CEGIS Conceptual Model)

5.4.1 Explanation

Assumption: River sedimentation has not been considered.

This might be the reason why the width of the river decreases while it enters into the Sylhet Basin as observed from the satellite images.

From Figure 5.2, it can be observed that the width and depth in the upstream section A-A is significantly larger than the width and depth in the downstream sections; B-B and C-C, i.e. $W_A > W_B > W_C$ and $d_A > d_B > d_C$.

5.4.2 Theoretical Analysis

i. Theoretically it has been established that for alluvial rivers (from equation i and ii),

$$d \propto Q \qquad (i)$$
$$W \propto Q \qquad (ii)$$

where, *d* is depth of flow, *Q* is discharge and *W* is the width of channel.

From eqn. (i) and (ii) we may conclude that with decrease of *Q*, both *d* and *W* will decrease.

ii. If it is found that bankfull discharge at downstream is smaller than the bankfull discharge at upstream ($Q_{bC} < Q_{bA}$), then it can be assumed that (at bankfull discharge) at downstream, both *d* and *W* will decrease, i.e. channel dimension will decrease. This phenomenon can be expressed as,

$$Q^{-} \sim d^{-} \qquad (xiii)$$
$$Q^{-} \propto W^{-} \qquad (xiv)$$

i.e, $d_{bC} < d_{bB} < d_{bA}$ and $W_{bC} < W_{bB} < W_{bA}$

or in other words, $d_{bA} > d_{bB} > d_{bC}$ and $W_{bA} > W_{bB} > W_{bC}$

iii. Hypothesis 2 is agreeable if condition mentioned above is fulfilled that is

a. $Q_{bA} > Q_{bB} > Q_{bC}$, where Q_{bA}, Q_{bB} and Q_{bC} are bankful discharges,

b. $d_{bA} > d_{bB} > d_{bC}$, where d_{bA}, d_{bB}, d_{bC} are bankfull depths,

c. $W_{bA>}$ $W_{bB>}$ W_{bC}, where W_{bA}, d_{bB}, d_{bC},are bankfull widths at sections A-A, B-B and C-C respectively (upstream to downstream).

5.4.3 Validation Criteria

- Let us consider sections A, b and C located from upstream to downstream direction. If it is found that,
  a. $A_{bA}>A_{bB}>A_{bC}$
  b. $d_{bA}>d_{bB}>d_{bC}$
  c. $W_{bA}>W_{bB}>W_{bC}$

Where, A_{bA}, A_{bB} and A_{bC} are the bankfull cross sectional area at section A, B and C respectively.

d_{bA}, d_{bB} and d_{bC} are the bankfull water depths at section A, B and C respectively.

W_{bA}, W_{bB} and W_{bC} are the bankfull width of the section A, B and C respectively.

5.5 Hypothesis 3*

"**The shallow depth caused to increase the high gradient during the dry season and thus increase the dry season water level at the upstream.**"

5.5.1 Explanation

Assumption: Sedimentation occurs in the channel bed.

It was mentioned in the FAP 6 that only 25 per cent of monsoon flow is carried by the channel within the Basin. This process facilitates the sedimentation within the riverbed. Thus a considerable amount of sedimentation occurs within the riverbed, a part of which is expected to be washed away during flood recession when the flow is confined within the riverbank and have attained considerable flow velocity to erode a part of the sediment deposits during monsoon. Shallow depth and high velocity generally exert high shear stress also on the riverbank and result in a wider section than expected from bankfull discharge of the reach concerned. The processes of sedimentation on the long profile and channel dimensions at different reaches are shown in Figure 5.3. In the figure, Q_bA, Q_bB and Q_bC are the bankfull discharges, d_A, d_B and d_C are the water depths and WA, W_B and W_C are the channel widths at the sections A-A, B-B and C-C respectively. Moreover, d_B' and d_C' are the water depths at

(*: Excerpt from the CEGIS Conceptual)

sections B-B and C-C after sedimentation.

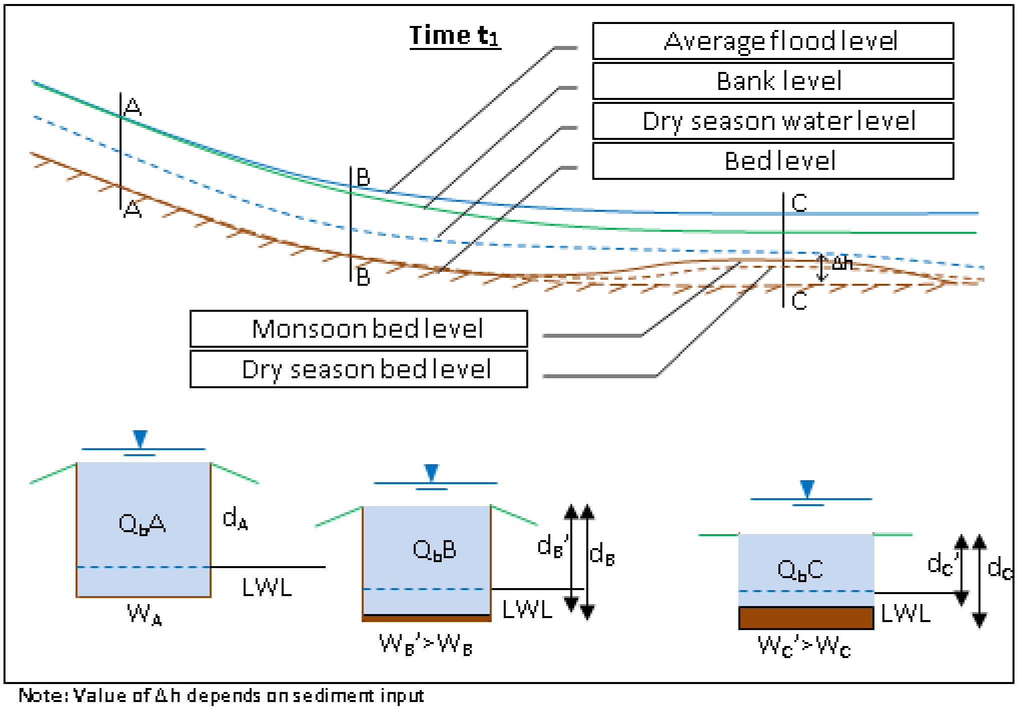

Figure 5-3: Conceptual model for describing the channel evolution processes in a subsiding Basin, showing long profiles with the influence of sediment (Source: CEGIS 2011)

5.5.2 Theoretical Analysis

The Hypothesis 3 is not clear enough. If the hypothesis can be re-written in the following way, theoretical explanation can be given:

The shallow depth causes to increase the high gradient during the dry season (from the point of deposited reaches/submersed bars/dune, to downstream). This may cause increase of dry season water depth at the section of deposited reach (from the point of submersed bars/dune, to some distance to downstream). Moreover, deposited reach will cause to produce backwater effect at the upstream.

Hypothesis can be explained considering 3 scenarios, namely:

1. During dry season, the shallow depth causes increase of the gradient (bed slope) from section of deposited reach (submersed bars/dune), to the downstream.

2. Increase of the dry season water depth at the section of deposited reach (dunes), if erosion occurs.
3. Backwater impact caused by the deposited reach.

The analysis on the Hypothesis 3 is described below:

i. During monsoon and recession of monsoon, more sedimentation at the bed will occur in a particular section. Consequently, Q_s, sediment discharge will be higher in the monsoon/immediate post monsoon season then the dry season.

As we know from equation (iii),

$$W \propto Q_s \qquad (iii)$$

where W is the width and Q_s is sediment discharge. Hence, with increase in Q_s, W is likely to increase, which may be expressed as

$$Q_s^+ \sim W^+ \qquad (xv)$$

And due to sedimentation, d will decrease during post monsoon period from that of monsoon periods, which may be expressed as

$$d_m > d_{pm} \qquad (xvi)$$

where, d_m is the water depth at monsoon season and d_{pm} is the water depth at post monsoon season.

But if there occurs erosion in the post monsoon season, then dry depth will be greater than the post monsoon depth, i.e $d_{dr} > d_{pm}$.

When sedimentation occurs at a section, the bed level is raised, thus the slope of bed level from that section (below the channel) becomes steeper than but of the original one. It is known from the equations v, vi, vii that,

$$S \propto 1/Q \quad \text{or} \quad S^+ \sim Q^- \qquad (xvii)$$
$$S \propto Q_S \quad \text{or} \quad S^+ \sim Q_s^+ \qquad (xviii)$$
$$S \propto D_{50} \quad \text{or} \quad S^+ \sim D_{50}^+ \qquad (xix)$$

That is in a section with increase of slope *(S)*, discharge *(Q)* will decrease and sediment discharge (Q_s) will increase and median grain size (D_{50}) will increase.

From Manning's Equation,

$$V = \frac{1}{n} R^{2/3} S^{1/2} \qquad (xx)$$

Where *V*= velocity, *R*= hydraulic radius, *S*= slope of the channel, *n*= Manning's Coefficient. Thus in a section with increase at *S*, *V* will increase or

$$S^{+} \sim V^{+} \qquad (xxi)$$

Now if this velocity exceeds the self-cleansing velocity, then the sediment that has been deposited in monsoon will again be cut off (cleared), may be partially. Shallow depth and high velocity generally exert high shear stress (τ_o) both on the bed and river bank which may result in wider and deeper channel. Thus the depth of water d_{dry}, will start to increase at the section of high deposition (dune). And there will be degradation downstream. Ultimately the dunes will move downstream. The dunes can often form as a series of dunes in a river stretch.

Backwater impact caused at immediate upstream of the deposited reach may induce increased water level and continuation of sediment deposition at upstream. **This hypothesis appears to be in agreement, considering the sedimentation of rivers, section of deposited reach (dunes) and if the velocity reaches self-cleansing velocity (Figure 5.4).**

5.5.3 Validation Criteria

- If it is found that
  a. The channel slope from upstream to downstream is greater in dry season than that of the monsoon season
  b. There is backwater effect towards upstream

  Then the Hypothesis 3 can be accepted.

5.6 Hypothesis 4 and 5*

The Hypothesis 4: "**After several years/decades (at time tα) as the river will be able to raise its levee and reach regime condition, the flood level will be close to the bank level (Figure 5.4), i.e. bankfull water level will be the same along the whole river stretch.**"

The Hypothesis 5: **"The channel dimensions will be closed the same at the upstream and downstream and no sedimentation would be expected during monsoon."**

5.6.1 Explanation

A simplified diagram is presented in Figure 5.5 for showing the spatial variation of river gradient, flood profile, bank profile, riverbed profile, flow velocity, sediment concentration, bed material sizes both in monsoon and dry season of a river, which is approaching towards regime conditions after its avulsion into the Sylhet Basin. The long profile of the river shows the flood, bank and bed profiles during monsoon. During monsoon, average flow velocity in the channel will remain the same within the upstream river reaches, which is in regime condition (as previously assumed). As the overbank flow increases at the downstream, the flow velocity in the river reduces. The reduction of the flow velocity facilitates sedimentation within the river and thus reduces the sediment concentration substantially at the downstream. This explains the presence of the lower riverbed level at the downstream of depositing reaches, although the flow velocity remains very low at that reach also. Sediment concentration during monsoon at that location is too low to raise the riverbed through deposition. At the end of monsoon, discharge reduces and water level remains at a stage lower than the bank level. The depositing reach will cause to produce back water effect at the upstream. The river is shallow at this reach and thus the gradient is much higher than at the upstream. Flow velocity at the upstream is much less than in monsoon, but it starts to increase at the depositing reach. This high velocity helps to erode a part of the depositing sediment during the preceding monsoon and thus increase the sediment concentration in the downstream direction.

The proposed conceptual model shows relations between the different parameters such gradient, bank level, flood level and flow velocity, sedimentation process in the riverbed and floodplain and their spatial variation along the river which is in the way to reaching regime condition. During the evolution phase of the rivers in the Sylhet basin, the rivers adjust their

(*: Excerpt from the CEGIS Conceptual Model)

morphology continuously. The process that triggers the progression of the whole process towards the downstream is the adjustment of the bank level. This process will cause to push the sediment deposited reaches to the downstream. The rivers will reach regime condition after time t_α, after which bank level will be parallel to the annual average flood level (Figure 5.4) and no bed aggradation/ degradation will occur during monsoon or dry season.

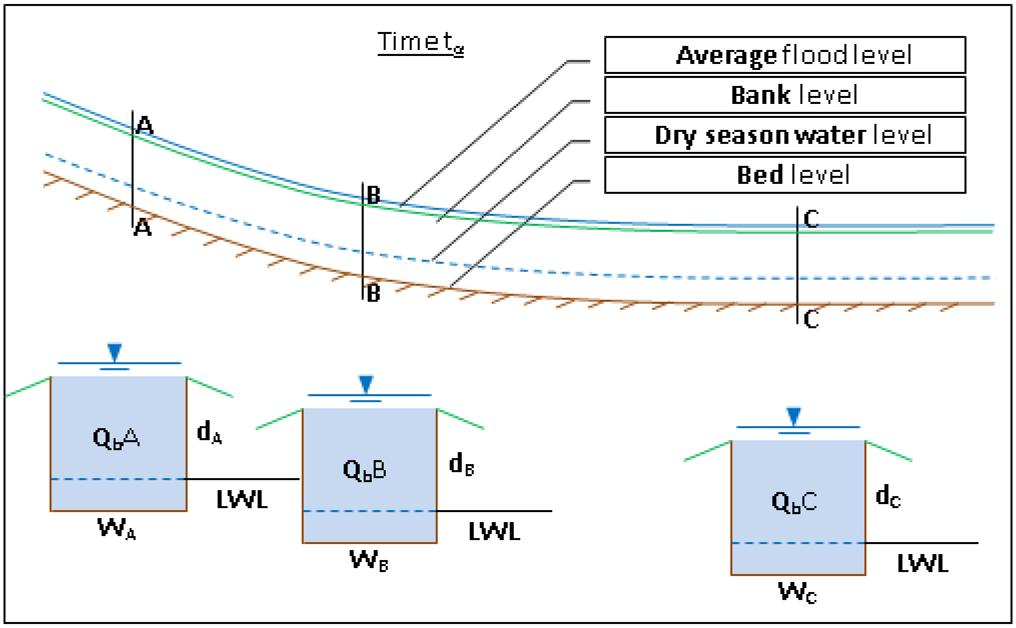

Figure 5-4: Conceptual model for describe the channel evolution processes in a subsiding Basin, showing the long-profiles at time t_α, when the river would be in regime condition (Source: CEGIS 2011)

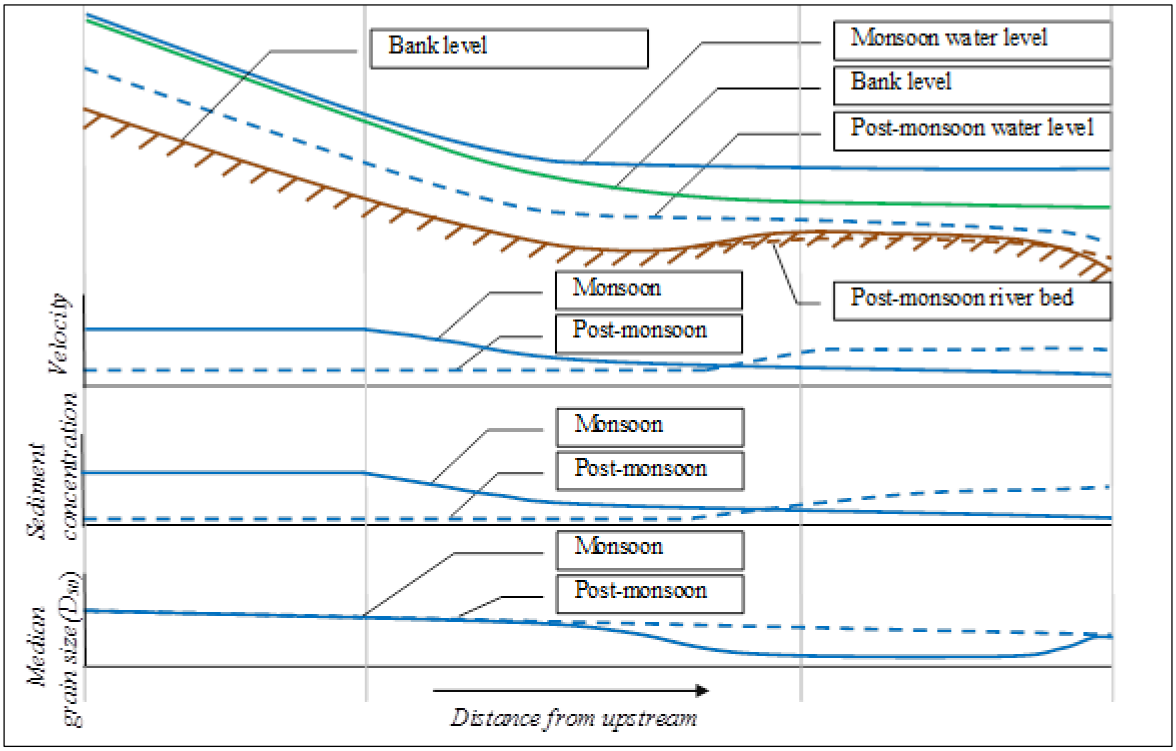

Figure 5-5: Simplified diagram showing the relations between the different parameters such gradient, bank level, flood level, flow velocity, sediment concentration and bed material size during monsoon and dry season at time t_1 (Source: CEGIS 2011)

However, it is also mentioned in the Conceptual Model is that it is unlikely that the rivers in the Sylhet Basin may reach regime conditions, as the subsiding Basin needs to have a high difference in elevation between the levee and flood Basin, which may cause avulsion of the rivers. Moreover, a major part of the river sediment deposits on the floodplain along rivers where the bank level starts to become lower than the annual average flood level. This may also trigger avulsion of the rivers towards the plain which is not getting sediment for a long time. The adjustment process of the rivers is not followed at the downstream only. The downstream adjustment also triggers flood and bank level adjustment at the upstream as well. As the adjustment of river channels to any disturbance takes several years/decades, the rivers have to act with several disturbances simultaneously. The Kushiyara River has been adjusting to its avulsion to the present course for the last several decades, at the same time cut-offs in the 1980s and 1990s put the river into a simultaneous process of major adjustments. In the 1990s, a process of avulsion had already been started and the river also acted to adjust with the changes. Thus under natural conditions, the process would not be as straightforward as shown in the model (Figure 5.1, 5.2, 5.3 and 5.4) or in the simplified diagram (Figure 5.5). If the different disturbances in the river system are recognized properly the model would be helpful in explaining the different observed changes in rivers.

5.6.2 Theoretical Analysis

Hypothesis 4 and 5 are for regime or equilibrium condition of the river. By definition,

"A channel is said to be in regime, if there is neither silting nor scouring in the channel."

Moreover, in regime or equilibrium condition, in a section, the bank level and the average flood level are the same.

A channel shall be in "true regime" if the following conditions are satisfied:

1. Discharge is uniform;
2. Flow is uniform;
3. Silt charge is constant; i.e. the amount of silt is constant;
4. Silt grade is constant; i.e. the type and size of silt is always the same;
5. Channel is flowing through a material which can be scoured easily as it can be deposited (such soil is known as incoherent alluvium), and is of the same grade as it is transported.

In a natural process, it may take hundreds of years to attain such conditions. But truly speaking, all these conditions can never be satisfied.

However, in general, theoretically the hypotheses of regime condition are accepted.

5.6.3 Validation Criteria

- If there is no variation in bankfull water level at different sections of the river reach, the river is in regime (equilibrium) condition.
- If it is found that X-section areas at different sections do not change/vary then the river is in regime condition.
- If there is no variation in sediment concentration, then the river reach is in regime condition.
- If there is no variation in Median grain size (D_{50}), then the river reach is in regime condition.

6 Data Collection

Data of the Surma and the Kushiyara Rivers have been collected from both the primary and secondary data sources. River wise data collection plan and analysis are presented in the following sections.

6.1 The Surma River

6.1.1 Primary Data

Primary data includes the following:

6. Routine measurement of Discharge (monthly, in a fixed section)
7. Routine measurement of Sediment Concentration (monthly, in a fixed section)
8. Bed Material Sampling (2 measurements, in 9 stations)
9. Measurement of Sediment Concentration (3 measurements, in 9 stations)
10. Measurement of Cross Sections (in 9 stations)
11. Bankline Survey

6.1.1.1 Routine Measurement of Discharge and Sediment Concentration

Consultants have measured discharge and sediment load in the Surma River in one fixed station. The station is located between two existing BWDB discharge stations which are SW267(Sylhet Sadar) & SW268 (Chhatak). The location of the station is 24° 55' 51"N and 91° 42' 8"E. The measurements were taken during from January, 2017 to June 2017. The details of the plan are presented in Table 6.1. The sediment samples will be analyzed in the Prosoil Laboratory to determine the sediment concentration. The results of the analysis are presented in Appendix 3.

Table 6.1 Plan for Routine Measurement on the Surma River

Type of Data Collection	**No. of measurements**	**Location of Station with ID**	**No. of Samples**	**No. of Samples specified in the TOR**	**Timeline**
Discharge	1(one) measurement per month Total measurements = 6	S-06 (Sylhet Sadar) 24° 55' 51''N 91° 42' 8''E	6	Not specified	Jan 2017 - Jun 2017
Sediment Measurement	1(one) measurement per month Total measurements = 6		6	Not specified	Jan 2017 - Jun 2017

The discharge and sediment measurement station has been established on the Surma river by the survey team. Monthly data have been collected from this station. Water level have also been collected from this station on a daily basis.

Figure 6-1 Installed Water Level Gauge on the Surma near Sylhet Bypass Bridge (Station ID: S-06)

6.1.1.2 Sediment Concentration

Sediment concentration of the Surma have been collected. Measurements have been taken from 9 stations as shown in Table 6.2. A number of 3 sets of measurements have been collected. The first set of data was collected from August 22, 2016 to August 29, 2016 (monsoon season). The 2nd set of data have been collected from January 14, 2017 to January 24, 2017 (post monsoon season). The 3rd set of data have been collected from April 10, 2017 to April 18, 2017 (dry season). The location of the sediment collection stations and details of sediment collection plan of the Surma River are presented below (Table 6.2 and 6.3). The locations of the stations are shown in Figure 6.3 and Table 6.5. The sediment concentration has been determined in the Prosoil Laboratory by using the ASTM Standard Test Method D 3977-97 (Test Method B: Filtration).

Figure 6-2 Collection of Sediment Concentration Samples

Table 6.2 List of Sediment Collection Stations on the Surma River

Station ID	**Corresponding BWDB Station ID**	**Location**	**Upazilla**	
		Lat.	**Long.**	
S-01	SW266	25° 0' 16"N	92° 16' 11"E	Kanairghat
S-02		24° 56' 11"N	92° 11' 52"E	Kanairghat
S-03		24° 53' 58"N	92° 5' 40"E	Kanairghat
S-04		24° 51' 53"N	91° 57' 56"E	Golabganj
S-05	SW267	24° 54' 18"N	91° 50' 3"E	Sylhet Sadar
S-06		24° 55' 51"N	91° 42' 8"E	Sylhet Sadar
S-07	SW268	24° 59' 47"N	91° 41' 8"E	Companiganj
S-08		25° 0' 15"N	91° 36' 27"E	Chhatak
S-09		25° 3' 57"N	91° 31' 16"E	Dowarabazaar

Table 6.3 Sediment Collection Plan on the Surma River

No. of measurements	**No. of Stations**	**Station ID**	**No. of Samples**	**Timeline**
3	9 sections (15 km apart)	S01, S02, S03, S04, S05, S06, S07, S08, S09	8 samples per section Total measurements = 216	**1st set:** Aug 22, 2016 - Aug 29, 2016 (monsoon) **2nd set:** Jan 14, 2017 – Jan 24, 2017 (dry) **3rd set:** Mar 31, 2017 - April 15, 2017 (pre monsoon)

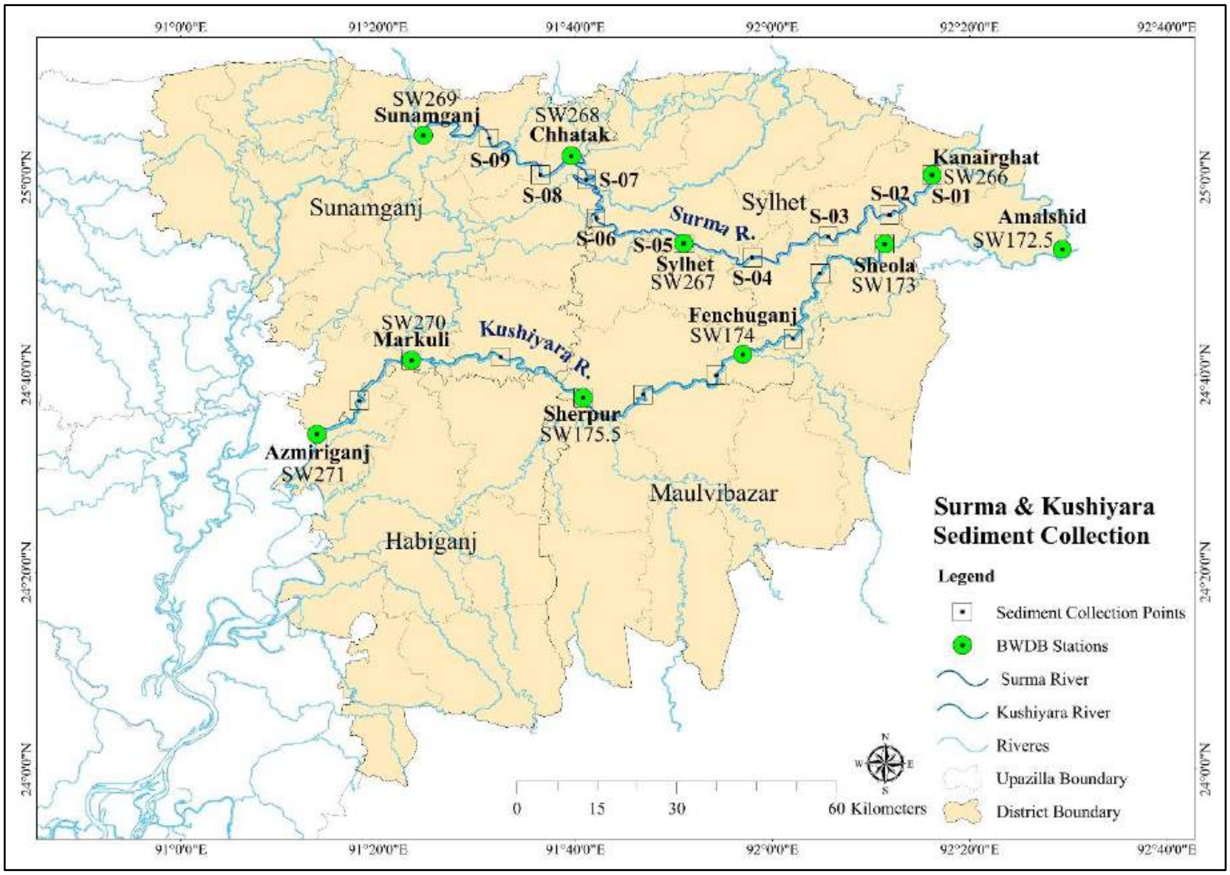

Figure 6-3 Locations of Sediment Collection Stations on the Surma

6.1.1.3 Bed Material Sampling

Bed Material Samples of the Surma have been collected. Measurements have been taken from 9 stations as shown in Table 6.2. A number of 2 sets of measurements have been collected. The 1st set of data have been collected from January 14, 2017 to January 24, 2017 (post monsoon season). The 2nd set of data have been collected from April 10, 2017 to April 18, 2017 (dry season). The locations of the stations are shown in Figure 6.3 and Table 6.5. The details of Bed material collection are shown in Table 6.4. The bed material samples have been analyzed in the Prosoil Laboratory to determine the Median Grain Size (D_{50}) value. The value was determined by analyzing the sample with Sieve and Hydrometer.

[a]

[b]

[c]

Figure 6-4 (a) The Bed Material Sampler; (b) Surveyors Carrying the Sampler to Site; (c) Collection of Bed Material Sample on Surma River

Table 6.4 Bed material Sample Collection Plan on the Surma

Type of Data Collection	No. of measurements	No. of Stations	Station ID	No. of Samples	Timeline
Bed material Sample Collection	2	9 sections (15 km apart)	S01, S02, S03, S04, S05, S06, S07, S08, S09	8 samples per section Total measurements = 144	**1st set:** Jan 14, 2017 – Jan 24, 2017 (dry) **2nd set:** Mar 31, 2017 - April 15, 2017 (pre monsoon)

6.1.1.4 Bank Line Survey

Bank line survey of both the sides of the river has been done by Total Station, GPS and Automatic Level and has been mapped by ArcGIS. One hundred and fifty km reach of the river has been surveyed; 150 sections have been selected along the reach, with a distance of 1 km between each section. The total length of the Surma river is 249 km (BWDB, 2011). The 150 km river reach is shown in Figure 6.5 (bold blue lines indicate the surveyed river reach). Measurements were taken on both the banks of the river at the specified sections. Bank Line Survey was conducted during January 14, 2017 to January 24, 2017. The result and detailed procedure of the bank line survey has been given in Annexure 3. The summary of bank line survey plan on the Surma river is given below:

- Data to be collected are: RL, GPS location and limited topographic survey
- 1 measurement during the project period
- 150 km reach on the Surma river
- 150 sections on the river (every section 1 km apart)
- 2 measurements on each section (one on each bank)
- Total no. of points: 150*2=300 points
- Timeline: Jan 14, 2017 to Jan 24, 2017

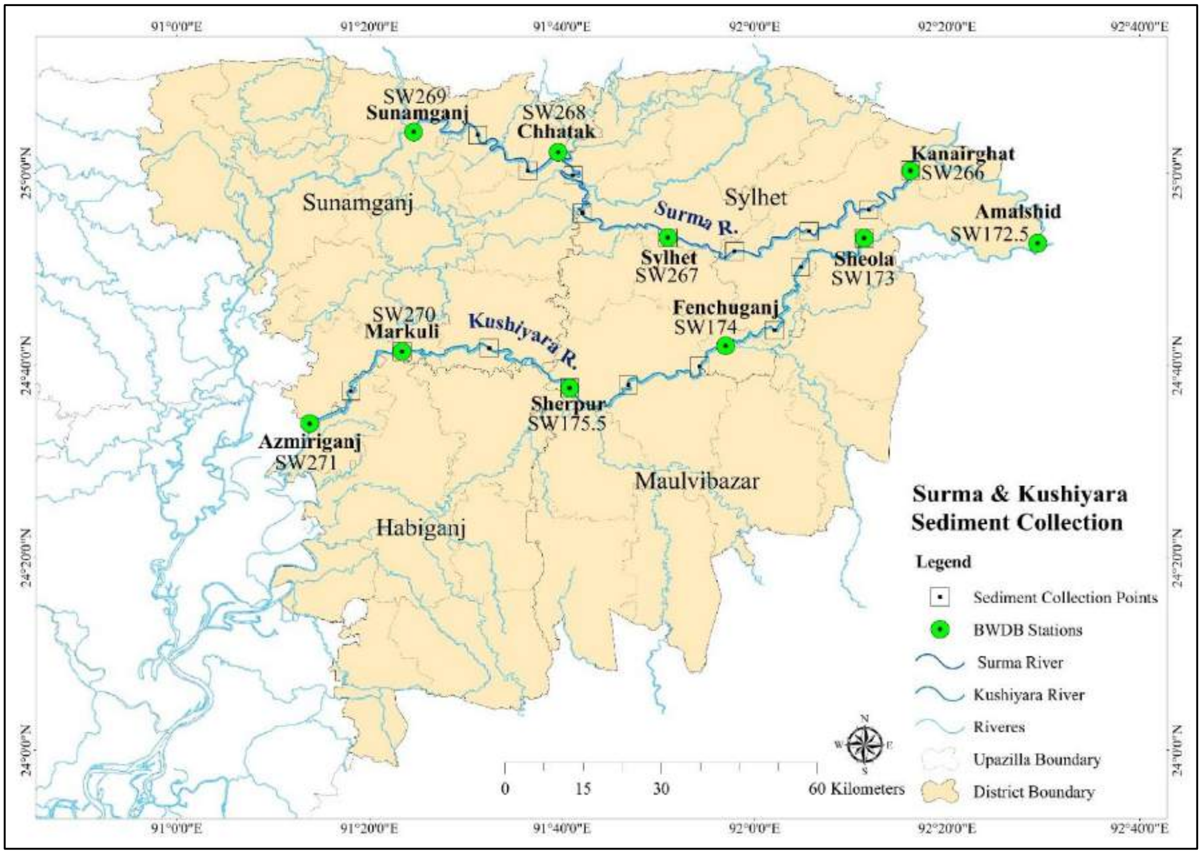

Figure 6-5 River Reaches for Bank Line Survey on the Surma and the Kushiyara

Figure 6-6 Bank Line Survey on the Surma

6.1.2 Secondary Data Collection

The following data have been collected from the BWDB and the United States Geological Survey (USGS):

From the BWDB:

- Water Level (1985-2016)
- Discharge (1986-2016)
- Velocity (1986-2016)
- Cross Section (2009, 2011, 2013 and 2014)

The data were collected depending on the availability of the source in the BWDB archive.

6.1.2.1 Water Level

There are 7 BWDB stations on the Surma River which are presented below in Table 6.5. Water level data of all the 7 stations have been collected from the BWDB. The data collected ranges from 1985 to 2016.

Table 6.5 List of BWDB Water Level Stations on Surma

Station ID	Station Name	Location		Upazilla	District
		Lat.	Long.		
SW266	Kanairghat	25° 0' 14''	92° 16' 12''	Kanairghat	Sylhet
SW267	Sylhet	24° 53' 18''	91° 50' 60''	Sylhet Sadar	Sylhet
SW268	Chhatak	25° 2' 10''	91° 39' 36''	Chhatak	Sunamganj
SW269	Sunamganj	25° 4' 16''	91° 24' 36''	Sunamganj Sadar	Sunamganj
SW269.5	Dirai_on Kalni	25° 4' 2''	91° 22' 48''	Derai	Sunamganj
SW270	Markuli	24° 41' 28''	91° 23' 24''	Nabiganj	Habiganj
SW271	Azmiriganj	24° 33' 58''	91° 13' 48''	Ajmiriganj	Habiganj

6.1.2.2 Discharge and Velocity

There are 3 discharge stations on Surma River. These stations are shown below in Table 6.6. Discharge and Velocity data of all the 3 stations have been collected from the BWDB. The data collected ranges from 1986 to 2016.

Table 6.6 List of BWDB Discharge Stations on the Surma

Station ID	Station Name	Location		Upazilla	District
		Lat.	Long.		
SW266	Kanairghat	25° 0' 14"	92° 16' 12"	Kanairghat	Sylhet
SW267	Sylhet	24° 53' 18"	91° 50' 60"	Sylhet Sadar	Sylhet
SW269	Sunamganj	25° 4' 16"	91° 24' 36"	Sunamganj Sadar	Sunamganj

6.1.2.3 Cross Section

Cross-section data of the Surma have been collected from the BWDB. The data were available for the years 2009, 2011, 2013 and 2014. The cross section measurements are taken 6 km apart from each other. There are 42 sections (S1 to S42) where the BWDB takes cross-section measurements (Figure 6.7) on the Surma river.

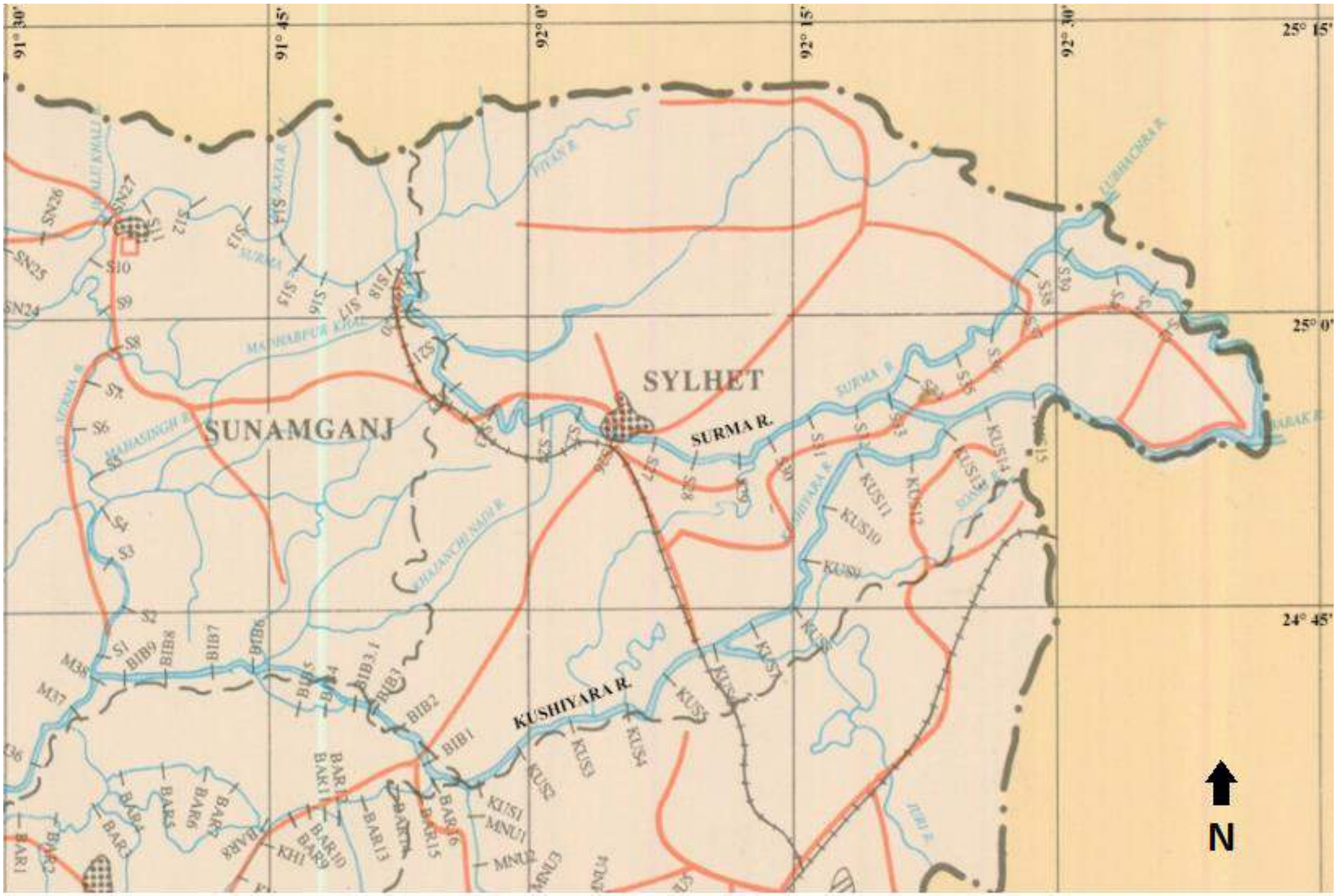

Figure 6-7 Locations of Cross Sections on the Surma (S1 - S42) (Source: BWDB)

6.2 The Kushiyara River

6.2.1 Primary Data

Primary data includes the following:

1. Routine measurement of Discharge (monthly, in a fixed section)
2. Routine measurement of Sediment Concentration (monthly, in a fixed section)
3. Bed Material Sampling (2 measurements, in 9 stations)
4. Measurement of Sediment Concentration (3 measurements, in 9 stations)
5. Measurement of Cross Sections (in 9 stations)
6. Bankline Survey

6.2.1.1 Routine Measurement of Discharge and Sediment Concentration

Consultants have measured discharge and sediment load in Kushiyara River in 1 fixed station. The station is located between 2 existing BWDB discharge stations which are SW173 (Sheola) & SW268 (Fenchuganj). The location of the station is 24° 43' 39"N and 92° 2' 6"E. The measurements were taken during January, 2017 to June 2017. The details are presented in the table (Table 6.7) below. The sediment samples will be analyzed in the Prosoil Laboratory to determine the sediment concentration. The results of the analysis are presented in Appendix 3.

Table 6.7 Plan for Routine Measurements on the Kushiyara River

Type of Data Collected	No. of measurements	Location of Station with ID	No. of Samples	No of Samples specified in the TOR	Timeline
Discharge	1 (one) measurement per month, Total measurements = 6	K-03 (Golabganj) 24° 43' 39"N 92° 2' 6"E	6	Not specified	Jan 2017 - Jun 2017
Sediment Measurement	1 (one) measurement per month, Total measurements = 6		6	Not specified	Jan 2017 - Jun 2017

The discharge and sediment measurement station has been established on the Kushiyara river by the survey team. Monthly data have been collected from this station. Water level have also been collected from this station on a daily basis.

Figure 6-8 Installed Water Level Gauge on the Kushiyara near Sherpur Bridge (Station ID: K-03)

6.2.1.2 Sediment Concentration

Sediment concentration data on Kushiaya River have been collected. Measurements were taken from 9 stations as shown in Table 6.8. A number of 3 sets of measurements have been collected. The first set of data was collected from August 22, 2016 to August 29, 2016 (monsoon season). The 2nd set of data have been collected from January 14, 2017 to January 24, 2016 (post monsoon season). The 3rd set of data was collected from April 10, 2017 to April 18, 2017 (dry season). The location of the sediment collection stations and details of sediment collection plan of Kushiyara River are presented below in Table 6.8 and Table 6.9. The locations of the stations are shown in Figure 6.9. The sediment concentration is being determined in the Prosoil Laboratory by using the ASTM Standard Test Method D 3977-97 (Test Method B: Filtration).

Table 6.8 List of Sediment Collection Stations on the Kushiyara River

Station ID	Corresponding BWDB Station ID	Location		Upazilla
		Lat.	Long.	
K-01	SW173	24° 53' 14"N	92° 11' 22"E	Beani Bazar
K-02		24° 50' 15"N	92° 4' 49"E	Golab Ganj
K-03		24° 43' 39"N	92° 2' 6"E	Golab Ganj
K-04	SW174	24° 39' 55"N	91° 54' 16"E	Fenchuganj
K-05		24° 37' 60"N	91° 46' 53"E	Balaganj
K-06	SW175.5	24° 38' 25"N	91° 39' 18"E	Balaganj
K-07		24° 41' 48"N	91° 32' 27"E	Jagannathpur
K-08	SW270	24° 41' 37"N	91° 24' 30"E	Markuli
K-09		24° 37' 21"N	91° 18' 5"E	Sulla

Table 6.9 Sediment Collection Plan on Kushiyara River

No. of measurements	No. of Sections	Station ID	No. of Samples	Timeline
3	9 sections (15 km apart)	K01, K02, K03, K04, K05, K06, K07, K08, K09	8 samples per sec, Total measurements = 216	**1st set:** Aug 22, 2016 - Aug 29, 2016 (monsoon) **2nd set:** Jan 14, 2017 – Jan 24, 2017 (dry) **3rd set:** March 31, 2017 - April 15, 2017 (post monsoon)

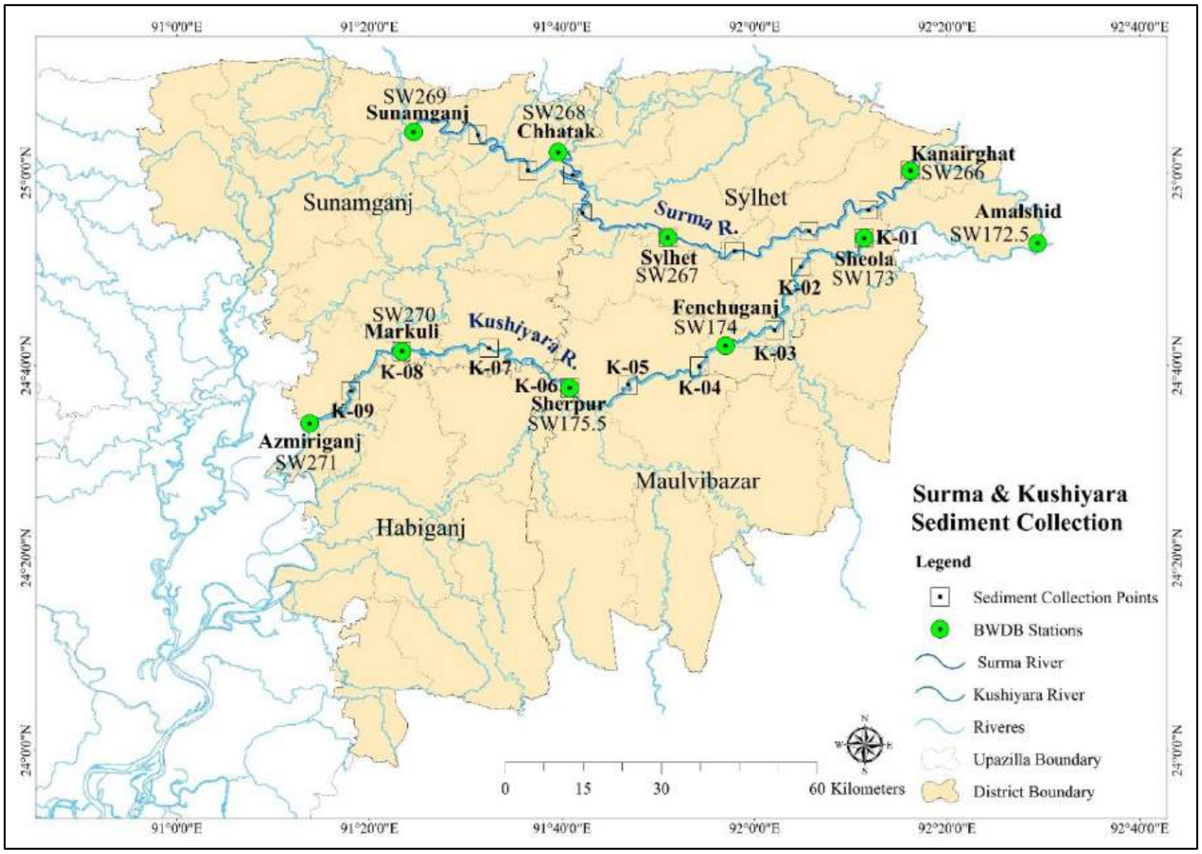

Figure 6-9 Location of Sediment Collection Station on the Kushiyara

6.2.1.3 Bed Material Sampling

Bed Material Samples of the Kushiyara have been collected. Measurements have been taken from 9 stations as shown in Table 6.8. A number of 2 sets of measurements have been collected. The 1st set of data have been collected from January 14, 2017 to January 24, 2017 (post monsoon season). The 2nd set of data have been collected from April 10, 2017 to April 18, 2017 (dry season). The locations of the stations are shown in Figure 6.9 and Table 6.11. The details of Bed material collection plan are given in Table 6.10. The bed material samples have been analyzed in the Prosoil Laboratory to determine the Median Grain Size (D_{50}) value. The value was determined by analyzing the sample with Sieve and Hydrometer.

Table 6.10 Bed material Sample Collection Plan on the Kushiyara

No. of measurements	No. of Sections	Station ID	No. of Samples	Timeline
2	9 sections (15 km apart)	K01, K02, K03, K04, K05, K06, K07, K08, K09	8 samples per sec, Total measurements = 144	**1st set:** Jan 14, 2017 – Jan 24, 2017 (dry) **2nd set:** March 31, 2017 - April 15, 2017 (post monsoon)

6.2.1.4 Bank Line Survey

Bank line survey of both the sides of the river have been done by Total Station, GPS and Automatic Level and have been mapped by ArcGIS. One hundred and fifty km reach of the river have been surveyed; 150 sections will be selected along the reach, with a distance of 1 km between each section. The total length of the Kushiyara River is 288 km (BWDB, 2011). The 150 km river reach is shown in Figure 6.5 (bold blue lines indicate the surveyed river reach). Measurements were taken on both banks of the river at the specified sections. Bank Line Survey have been conducted during January 14, 2017 to January 24, 2017. The summary of bank line survey on Kushiyara River is given below:

- Data to be collected are: RL, GPS location and limited topographic survey
- 1 measurement during the project period
- 150 km reach on the river Kushiyara
- 150 sections on the river, every section 1 km apart
- 2 measurements to be collected on each section (1 on each bank)
- Total no. of points: 150*2=300 points
- Timeline: Jan 14, 2017 to Jan 24, 2017

Figure 6-10 Bank Line Survey on the Kushiyara River

6.2.2 Secondary Data Collection

The following data have been collected from the BWDB and the United States Geological Survey (USGS):

From the BWDB:

- Water Level (1985-2016)
- Discharge (1986-2016)
- Velocity (1986-2016)
- Cross Section (2004, 2006, 2008 and 2010)

The data were collected depending on the availability of the source in the BWDB archive.

6.2.2.1 Water Level

There are 4 BWDB stations in the Kushiyara River which are shown below in Table 6.11. Water level data of all the 4 stations have been collected from the BWDB. The data collected ranges from 1985 to 2016.

Table 6.11 List of BWDB Water Level Stations on Kushiyara

	Station ID	Station Name	Location		Upazilla	District
			Lat.	Long.		
1.	SW172.5	Amalshid	24° 52' 42"	92° 29' 24"	Zakiganj	Sylhet
2.	SW173	Sheola	24° 53' 14"	92° 11' 24"	Beanibazar	Sylhet
3.	SW174	Fenchuganj	24° 42' 3"	91° 57' 0"	Fenchuganj	Sylhet
4.	SW175.5	Sherpur	24° 37' 40"	91° 40' 48"	Balaganj	Sylhet

6.2.2.2 Discharge and Velocity

There are 3 discharge stations on Kushiyara River. These stations are shown in Table 6.12. Discharge and Velocity data of all the 3 stations have been collected from the BWDB stations. The data collected ranges from 1986 to 2016.

Table 6.12 List of BWDB Discharge Stations on Kushiyara

Station ID	Station Name	Location		Upazilla	District
		Lat.	Long.		
SW172.5	Amalshid	24° 52' 42"	92° 29' 24"	Zakiganj	Sylhet
SW173	Sheola	24° 53' 14"	92° 11' 24"	Beanibazar	Sylhet
SW175.5	Sherpur	24° 37' 40"	91° 40' 48"	Balaganj	Sylhet

6.2.2.3 Cross Section

Cross-section data have been collected from the BWDB on Kushiyara River. The data have been collected for the years 2004, 2006, 2008 and 2010. The cross section measurements are taken 6 km apart from each other. There are 15 sections (KUS1 to KUS15), where the BWDB takes cross section measurements in the Kushiyara (Figure 6.11).

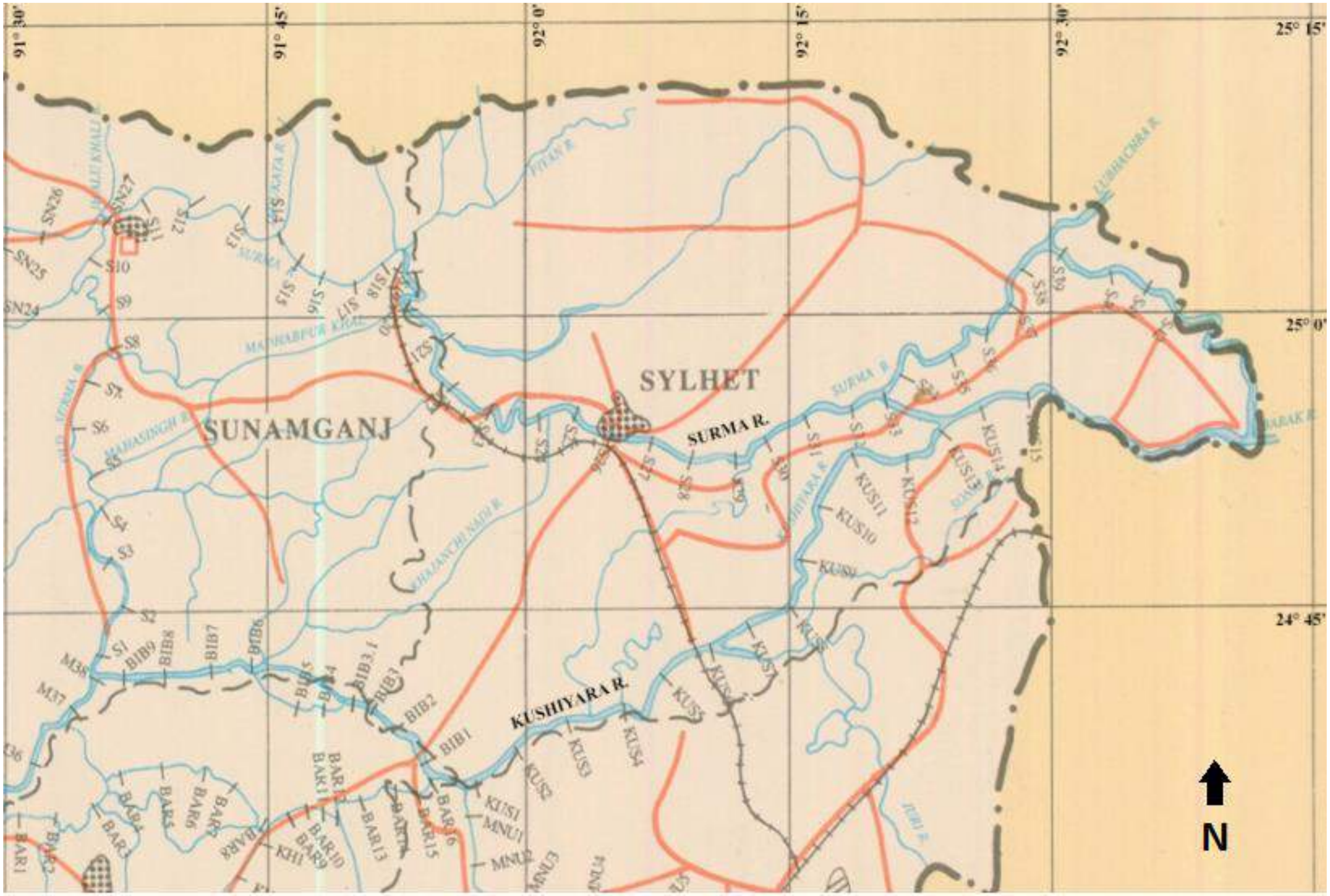

Figure 6-11 Location of Cross Sections of Kushiyara River (KUS1 - KUS15) (Source: BWDB)

7 Data Analysis

Data of the Surma and the Kushiyara Rivers have been collected from both the primary and secondary data sources.

The water level, velocity, discharge data and cross section data have been processed and used for calibrating and validating of the numerical model namely HEC-RAS 2D. This model has been used to predict the change in sediment deposition, discharge and water level in the downstream of the Surma and the Kushiyara as well as to validate the existing conceptual model.

- **Sediment concentration and Bed Material Size**
  Sediment concentration and Bed Material data have been analyzed to calculate the D_{50} (Median Grain Size) value of the bed material of the river. This value has been used in setting up the morphological part of the numerical model.
- **Discharge and Velocity**
  Discharge and velocity data have been used in setting up the upstream boundary of the numerical model.
- **Water Level**
  Water level data have been used in setting up the downstream boundary of the numerical model.
- **Cross Section**
  Cross Sections of the rivers have been used in setting up the numerical model. The model has been calibrated using cross sections of 2013 and validated using cross sections of 2014. Cross sections of other years (for Surma 2009, 2011, 2013, 2014 and for Kushiyara 2006, 2008, 2010) have also been plotted.
- **Bank Line Survey**
  The bank lines of both rivers have been plotted on ArcGIS. The surveyed data have been compared with satellite images to identify the shift in bank lines of both the Surma and the Kushiyara rivers. The comparison has also helped to understand the general trend in the shift of bank lines.

7.1 Analysis of Primary Data for the Surma

7.1.1 Sediment Concentration

Sediment concentration samples of the Surma have been collected from 9 stations as shown in Table 6.2. A number of 3 sets of measurements have been collected. The sediment concentration has been determined in the Prosoil Laboratory by using the ASTM Standard Test Method D 3977-97 (Test Method B: Filtration). The detailed sediment concentrations data sheet and analysis are given in Appendix 3.

The first set of data was collected from August 22, 2016 to August 29, 2016 (monsoon season). The 2nd set of data have been collected from January 14, 2017 to January 24, 2017 (Dry season). The 3rd set of data have been collected from April 10, 2017 to April 18, 2017 (Pre monsoon season).

7.1.2 Median Grain Size

Bed Material Samples of the Surma have been collected. Measurements have been taken from 9 stations as shown in Table 6.2. A number of 2 sets of measurements have been collected. The 1st set of data have been collected from January 14, 2017 to January 24, 2017 (Dry season). The 2nd set of data have been collected from April 10, 2017 to April 18, 2017 (Pre monsoon season). The bed material samples have been analyzed in the Prosoil Laboratory to determine the Median Grain Size (D_{50}) value. The value was determined by analyzing the sample with Sieve and Hydrometer. The detailed analysis of the median grain size is given in Appendix 3.

7.1.3 Bank Line Survey

Bank line survey of both the sides of the river has been done by Total Station, GPS and Automatic Level and has been mapped by ArcGIS. One hundred and fifty km reach of the river has been surveyed; 150 sections have been selected along the reach, with a distance of 1 km between each section. The total length of the Surma river is 249 km (BWDB, 2011). The 150 km river reach is shown in Figure 6.5 (bold blue lines indicate the surveyed river reach). Measurements were taken on both the banks of the river at the specified sections. Bank Line Survey was conducted during January 14, 2017 to January 24, 2017. The result and detailed procedure of the bank line survey has been given in Appendix 2.

7.2 Analysis of Primary Data for the Kushiyara

7.2.1 Sediment Concentration

Sediment concentration samples of the Kushiyara have been collected from 9 stations as shown in Table 6.5. A number of 3 sets of measurements have been collected. The sediment concentration has been determined in the Prosoil Laboratory by using the ASTM Standard Test Method D 3977-97 (Test Method B: Filtration).

The first set of data was collected from August 22, 2016 to August 29, 2016 (monsoon season). The 2nd set of data have been collected from January 14, 2017 to January 24, 2017 (Dry season). The 3rd set of data have been collected from April 10, 2017 to April 18, 2017 (Pre monsoon season). The detailed sediment concentrations data sheet and analysis are given in Appendix 3.

7.2.2 Median Grain Size

Bed Material Samples of the Kushiyara have been collected. Measurements have been taken from 9 stations as shown in Table 6.2. A number of 2 sets of measurements have been collected. The 1st set of data have been collected from January 14, 2017 to January 24, 2017 (Dry season). The 2nd set of data have been collected from April 10, 2017 to April 18, 2017 (Pre monsoon season). The bed material samples have been analyzed in the Prosoil Laboratory to determine the Median Grain Size (D_{50}) value. The value was determined by analyzing the sample with Sieve and Hydrometer. The detailed analysis of the median grain size is given in Appendix 3.

7.2.3 Bank Line Survey

Bank line survey of both the sides of the river has been done by Total Station, GPS and Automatic Level and has been mapped by ArcGIS. One hundred and fifty km reach of the river has been surveyed; 150 sections have been selected along the reach, with a distance of 1 km between each section. The total length of the Surma river is 288 km (BWDB, 2011). The 150 km river reach is shown in Figure 6.5 (bold blue lines indicate the surveyed river reach). Measurements were taken on both the banks of the river at the specified sections. Bank Line Survey was conducted during January 14, 2017 to January 24, 2017. The result and detailed procedure of the bank line survey has been given in Annexure 2.

7.3 Analysis of Secondary Data

7.3.1 River Data Analysis

Secondary data of the Surma and the Kushiyara rivers have been collected from the BWDB. The data have been used for setting up the numerical model. In addition, the data at upstream and downstream stations of previous years (2009, 2011, 2013 and 2014) have been analyzed and compared to understand the general trend of change in river bedform.

7.3.1.1 The Surma River

Upstream

Cross Section (RMS38): The cross section is taken at the upstream boundary, RMS38 (Figure 7.1). The location of this station is 25° 0' 14"N and 92° 16' 12"E. The data at this station are available for the years 2011, 2013 and 2014. After plotting the cross sections (Figure 7.1), it is observed that the shape of the left bank of the river remains almost same throughout the period. The main channel is getting narrower. At the right bank, the channel gets wider throughout the years. This implies that the river bank is shifting towards north.

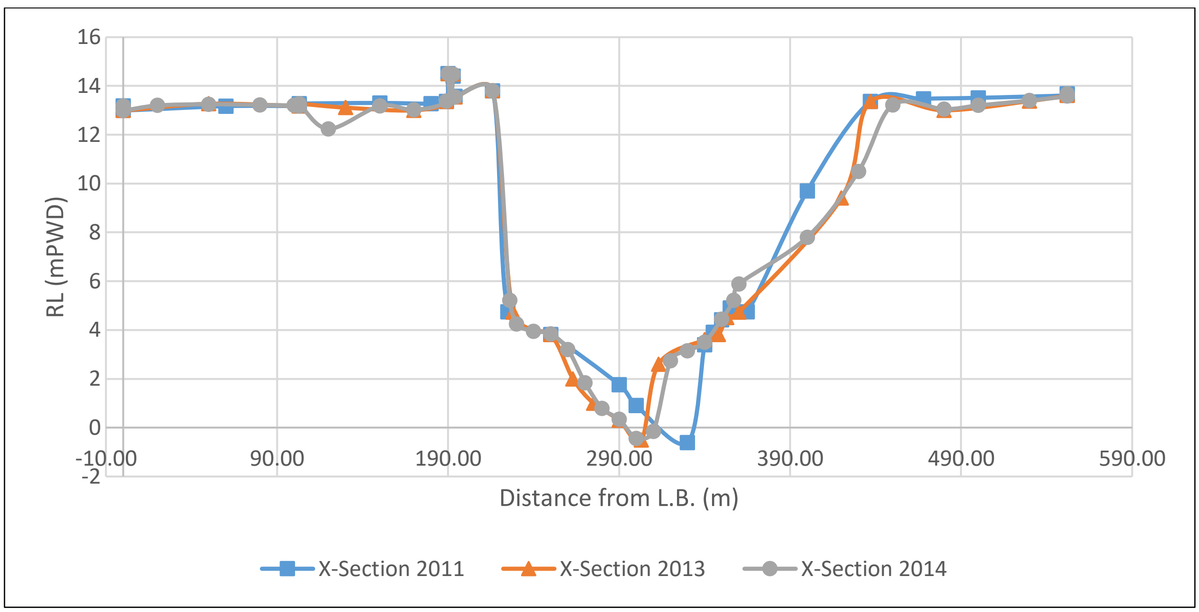

Figure 7-1 Comparison of Cross Sections at RMS38 on the Surma

Water Level (SW266): The data of Water Level Station at the upstream section of the Surma river, (SW266, Kanairghat) have been analyzed. The location of this station is 25° 0' 14"N and 92° 16' 12"E. Water level data from 1996 to 2016 at this station have been compared. The average water level of July is plotted in the following graph to observe the water level in the monsoon season. From the graph, it can be observed that in the last 20 years, the average water level at the monsoon season always stays above 10m, highest being 14.46 m in July, 2004 and lowest being 10.15m in July, 2014 (Figure 7.2).

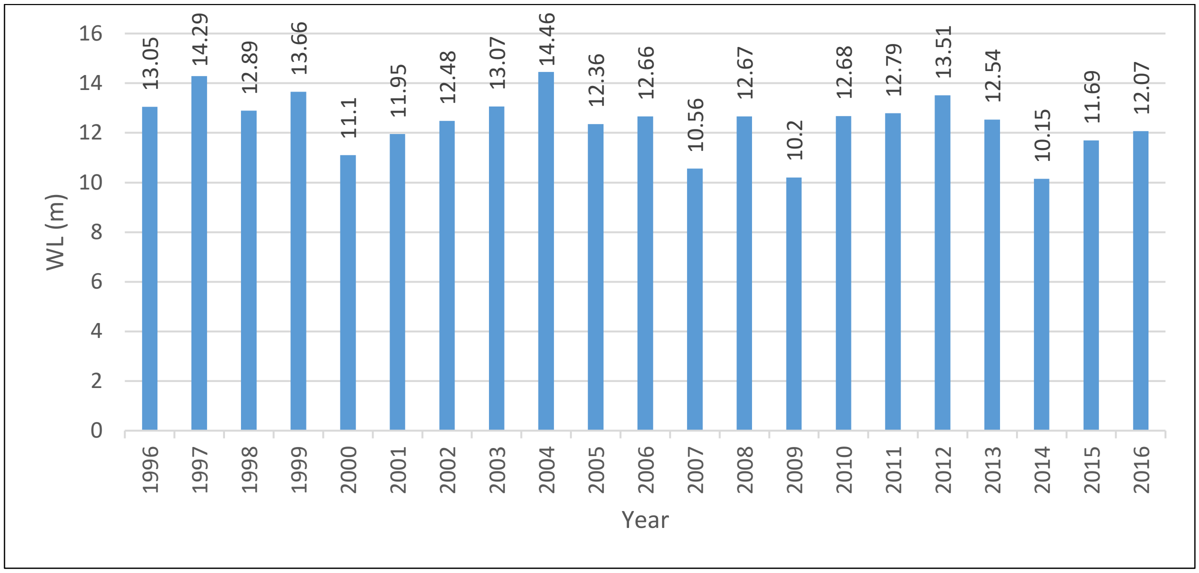

Figure 7-2 Comparison of Average Water Level of July at Station SW266 on the Surma

Discharge (SW266): The data of Discharge Station at the upstream section of the Surma river (SW266, Kanairghat) have been analyzed. The location of this station is 25° 0' 14"N and 92° 16' 12"E. Discharge data from 1996 to 2016 at this station have been compared. The average discharges of July have been plotted (Figure 7.3). The plot shows the discharge of the Surma at SW266 in the monsoon season. From the graph, it can be observed that in the last 30 years, the lowest discharge was 863.03 cusecs in July, 2014. Apart from 2014, the discharge was always above 1000 cusecs, the highest being 2031.37 cusecs in July, 2004.

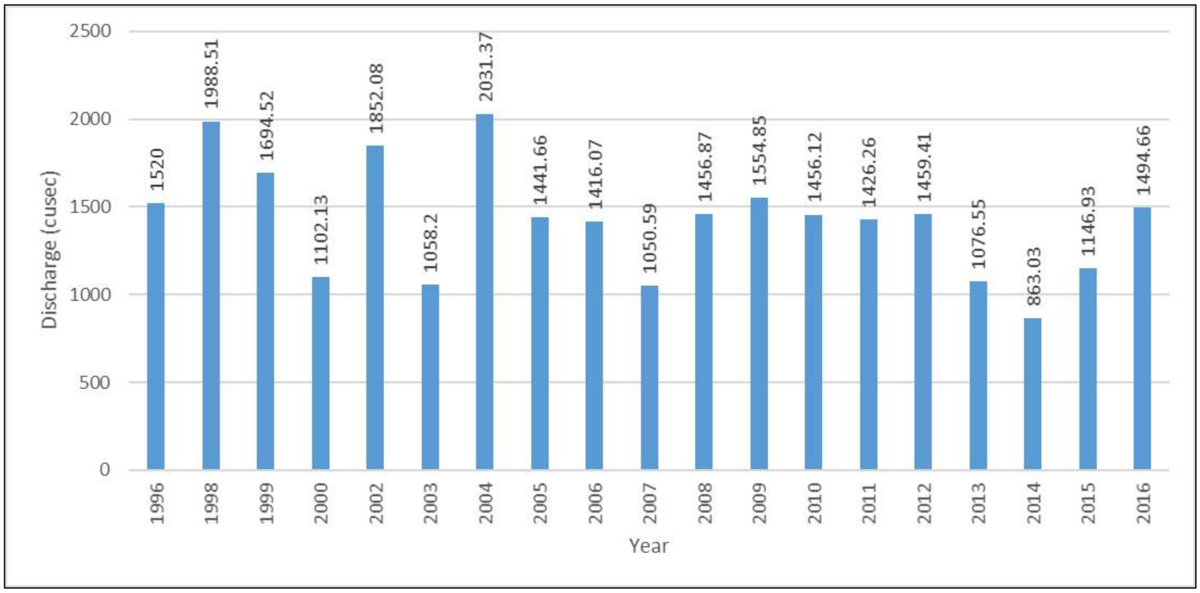

Figure 7-3 Comparison of Average Discharge of July at Station SW266 on the Surma

Downstream

Cross Section (RMS10): The cross section taken at the downstream boundary is RMS10 (Figure 5.5). The data at this station are available for the years 2009, 2011, 2013 and 2014. The location of the section is 25° 4' 16''N and 91° 24' 36''E. After plotting the cross sections (Figure 7.4), it is observed that the shape of the left bank of the river remains almost same throughout the period, except in 2011 where there is a sharp slope in left of the road. The shape of the main channel remains almost the same. At the right bank, the channel gets wider in 2014 which implies that the right bank is moving towards the north-east.

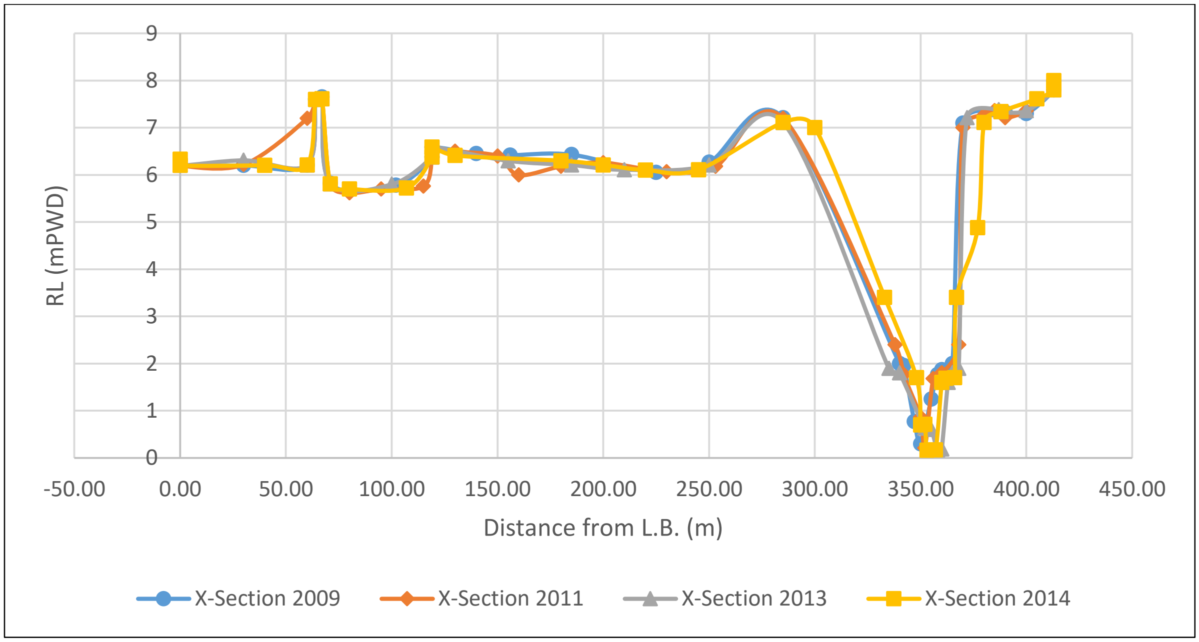

Figure 7-4 Comparison of Cross Sections at RMS10 on the Surma

Water Level (SW269): The data of Water Level Station at downstream section of the Surma river (SW269, Sunamganj) have been analyzed. The location of the station is 25° 4' 16''N and 91° 24' 36''E. Water level data from 1996 to 2016 at this station have been compared. The average water level of July is plotted, as shown in Figure 7.5 to observe the water level in the monsoon season. From the graph, it can be observed that in the last 20 years, the average water level at the monsoon season always stays above 7m in this section, highest being 8.72m in July, 2004 and lowest being 7.1m in July, 2007.

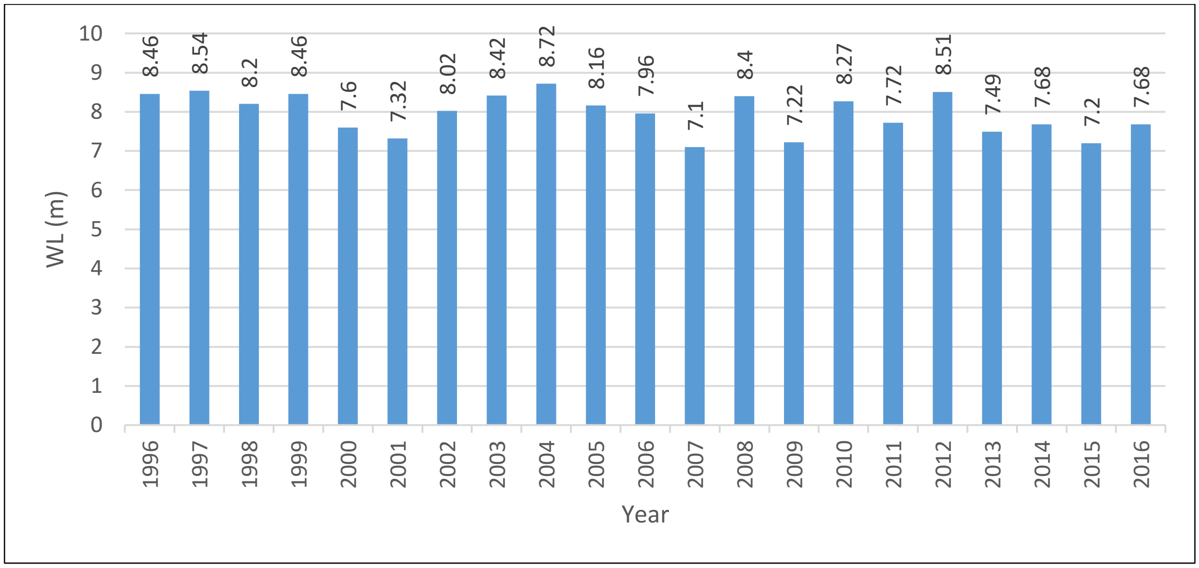

Figure 7-5 Comparison of Average Water Level of July at Station SW269 on the Surma

Discharge (SW269): The data of Discharge Station at the downstream section of the Surma river (SW269, Sunamganj) have been analyzed. The location of the station is 25° 4' 16''N and 91° 24' 36''E. Discharge data from 1996 to 2016 at this station have been compared. The average discharge of July is plotted in Figure 7.6 to observe the discharge in the monsoon season. From the graph, it can be observed that in the last 20 years, the lowest discharge was 1620.5 cusecs in July, 2001 and the highest discharge was 2941.16 cusecs in July, 2016. From Figure 7.6, it can be observed that in the last 20 years, the average discharge in the monsoon season always stays above 1600 cusecs.

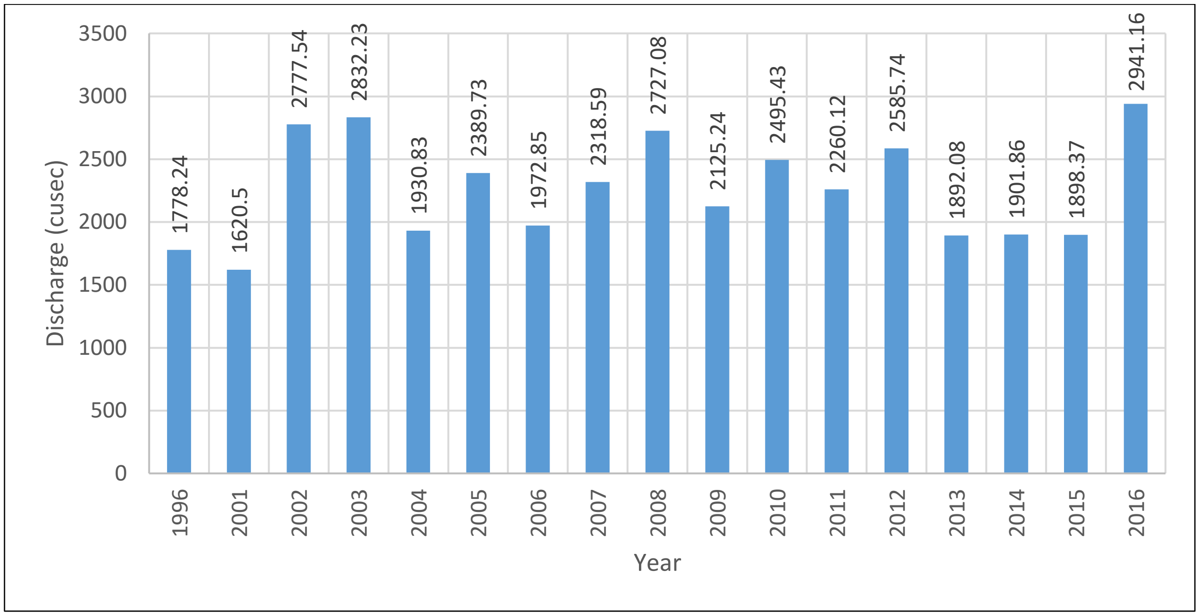

Figure 7-6 Comparison of Average Discharge of July at Station SW269 on the Surma

From the above analysis, it can be observed that the average discharge on SW269 (downstream) is higher than the average discharge on SW266 (upstream). The discharge is higher in the downstream section because of a number tributaries flowing in the main river.

Water Level Slope: The water level slopes for 20 years between the upstream station (SW266) and downstream station (SW269) have been calculated and shown in Table 7.1. From the table, it can be seen that the water level slope varies between 0.015 to 0.035.

Table 7.1 Water Level Slope Analysis for Surma River

Year	**SW266 (upstream station) (mPWD)**	**SW269 (downstream station) (mPWD)**	**Water Level Slope (per km)**
1996	13.05	8.46	0.028
1997	14.29	8.54	0.035
1998	12.89	8.2	0.029
1999	13.66	8.46	0.032
2000	11.1	7.6	0.022
2001	11.95	7.32	0.029

Year	SW266 (upstream station) (mPWD)	SW269 (downstream station) (mPWD)	Water Level Slope (per km)
2002	12.48	8.02	0.028
2003	13.07	8.42	0.029
2004	14.46	8.72	0.035
2005	12.36	8.16	0.026
2006	12.66	7.96	0.029
2007	10.56	7.1	0.021
2008	12.67	8.4	0.026
2009	10.2	7.22	0.018
2010	12.68	8.27	0.027
2011	12.79	7.72	0.031
2012	13.51	8.51	0.031
2013	12.54	7.49	0.031
2014	10.15	7.68	0.015
2015	11.69	7.2	0.028
2016	12.07	7.68	0.027

7.3.1.2 The Kushiyara River

Upstream

Cross Section (RMKUS12): The cross sections are taken at the upstream boundary, RMKUS12 (Figure 7.7). The data at this station are available for the years 2004 and 2010. The location of this section is 24° 53' 14''N and 92° 11' 24''E. After plotting the cross sections, it is observed from Figure 5.16 that the shape of the left bank and right bank of the river remains almost same. Erosion rate in the main channel is quite high. The RL of the deepest point in the cross section in 2004 was .22 mPWD. Whether the deepest point in the cross section in 2010 is -7.5 mPWD.

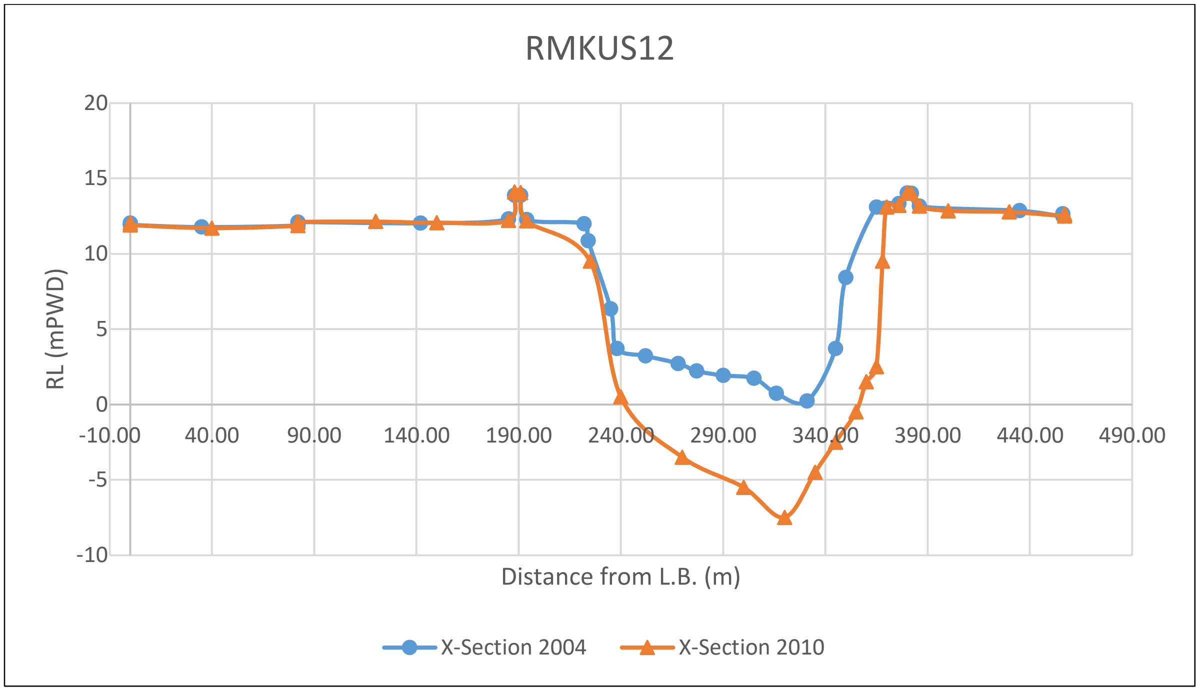

Figure 7-7 Comparison of Cross Sections at RMKUS12 on the Kushiyara

Water Level (SW173): The data of Water Level Station at the upstream section of the Kushiyara river (SW173, Sheola) have been analyzed. The location of this station is 24° 53' 14"N and 92° 11' 24"E. Water level data from 1993 to 2013 at this station have been compared. The average water level of July is plotted in the following graph to observe the water level in the monsoon season. From the graph, it can be observed that in the last 20 years, the average water level at the monsoon season always stays above 10m, highest being 14.27m in July, 2004 and lowest being 10.45m in July, 2010 (Figure 7.8).

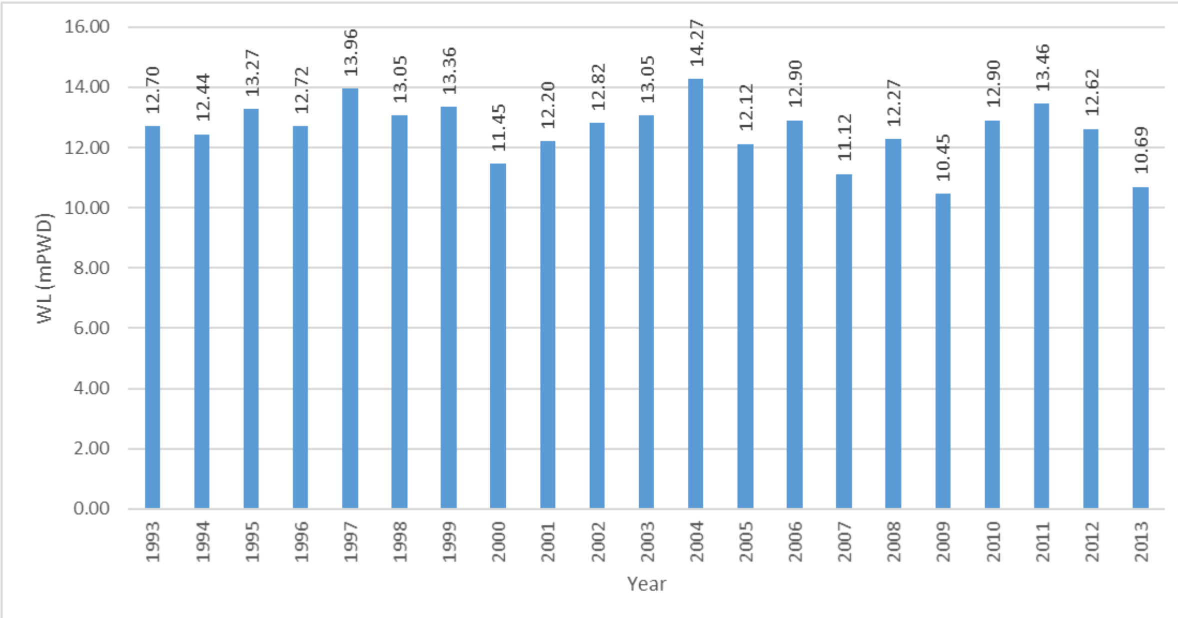

Figure 7-8 Comparison of Average Water Level of July at Station SW173 on the Kushiyara

Discharge (SW173): The Discharge Station at the upstream section of the Kushiyara river is SW173 (Sheola). The location of this station is 24° 53' 14"N and 92° 11' 24"E. Discharge data from 1993 to 2013 at this station have been compared (Figure 7.9). The average discharge of July is plotted in the following graph to observe the discharge in the monsoon season. From the graph, it can be observed that in the last 20 years, the lowest discharge was 1073.48 cusecs in July, 2014 and the highest discharge was 2321.42 cusecs in July, 1999. In this period, the discharge was always above 1000 cusecs.

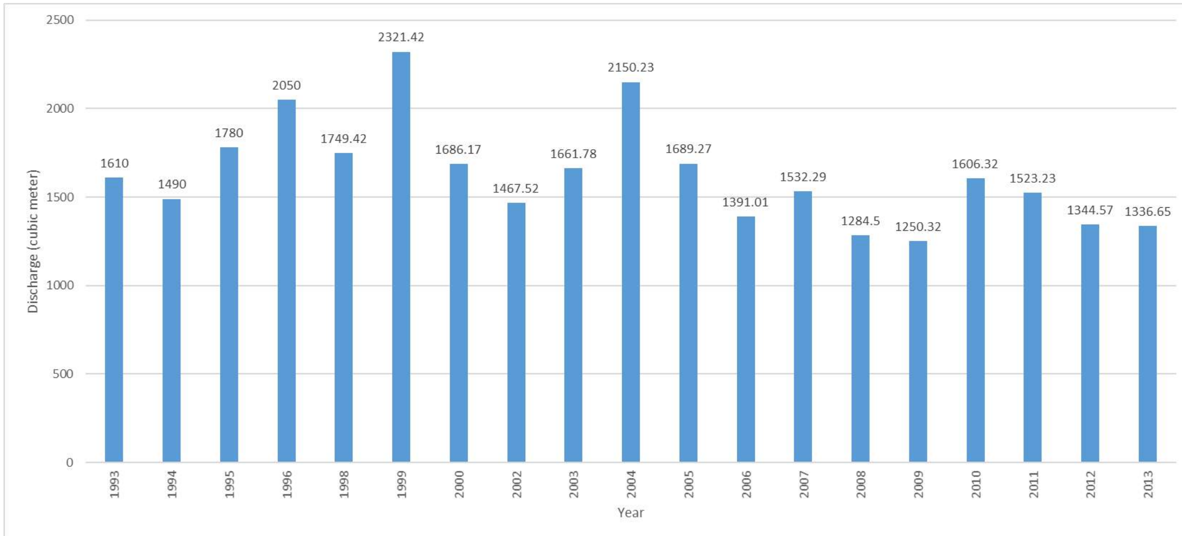

Figure 7-9 Comparison of Average Discharge of July at Station SW173 on the Kushiyara

Downstream

Cross Section (RMKUS1): The cross sections are taken at the upstream boundary, RMKUS1 (Figure 7.16). The data at this station are available for the years 2004, 2006, 2008 and 2010. The location of this section is 24° 37' 40''N and 91° 40' 48''E. After plotting the cross sections (Figure 7.10), it is observed that two channels have developed in this cross section. The shape of the left channel remained almost same, only getting slightly wider at the top in 2010. The depth of the right channel remained almost same throughout the period. In the recent years (2008 and 2014), the channel has shifted slightly to the right bank with sediment deposition on the left side of the channel.

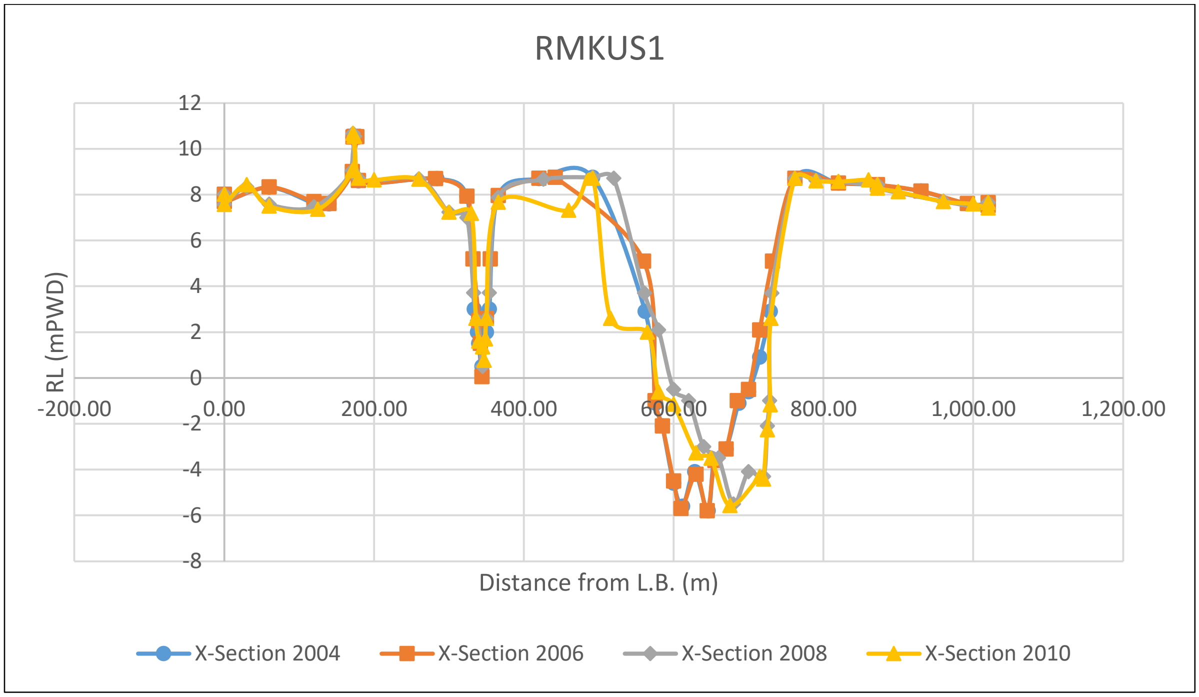

Figure 7-10 Comparison of Cross Sections at RMKUS1 on Kushiyara

Water Level (SW175.5): The Water Level Station at the upstream section of the Kushiyara river is SW175.5 (Sherpur). The location of this station is 24° 37' 40"N and 91° 40' 48"E. Water level data from 1992 to 2012 at this station have been compared. The average water level of July is plotted in the following graph to observe the water level in the monsoon season. From Figure 7.11, it can be observed that in the last 20 years, the average water level at the monsoon season always stays above 7m, highest being 9.22m in July, 2004 and lowest being 7.93m in July, 2007.

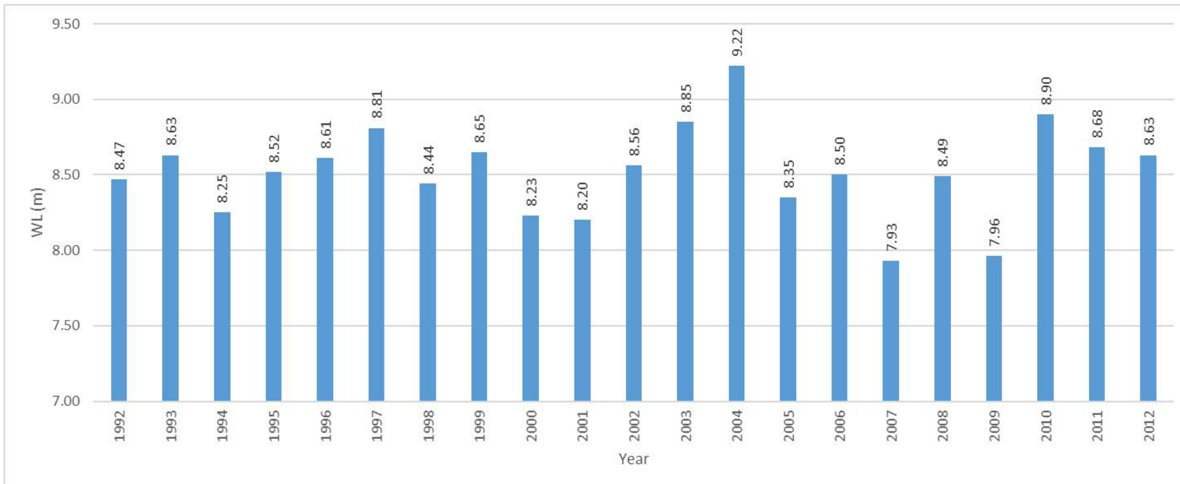

Figure 7-11 Comparison of Average Water Level of July at Station SW175.5 on Kushiyara

Discharge (SW175.5): The Discharge Station at the upstream section of the Kushiyara river is SW175.5 (Sherpur). The location of this station is 24° 37' 40''N and 91° 40' 48''E. Discharge data from 1992 to 2012 at this station have been compared. The average discharge of July is plotted in Figure 7.12 to observe the discharge in the monsoon season. From the graph, it can be observed that in the last 30 years, the lowest discharge was 1207.96 cusecs in July, 2009 and the highest discharge was 2290.98 cusecs in July, 1998. In this period, the discharge was always above 1200 cusecs.

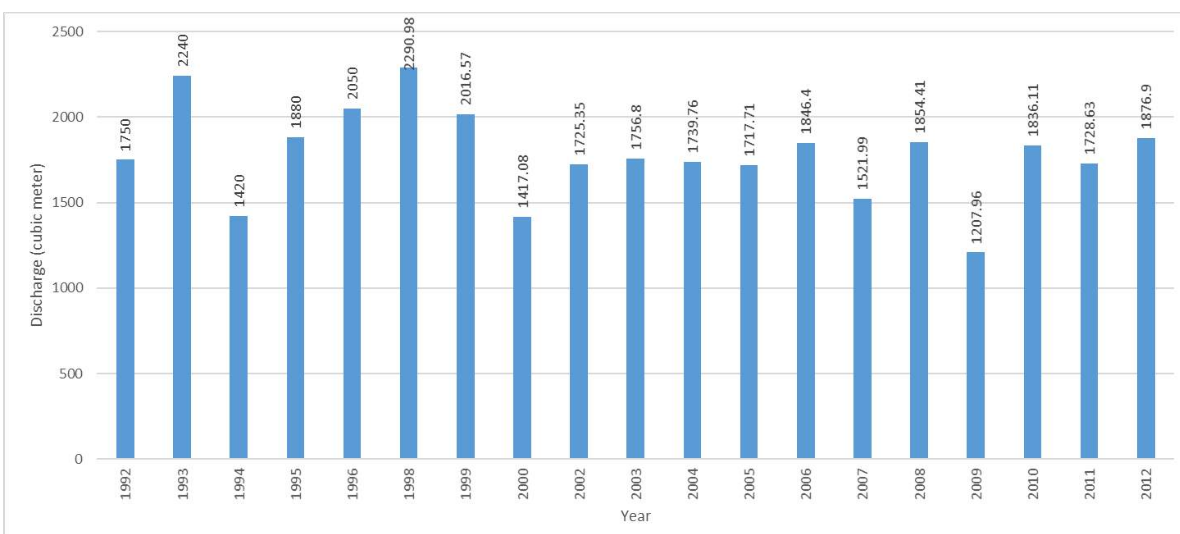

Figure 7-12 Comparison of Average Discharge of July at Station SW175.5 on Kushiyara

Water Level Slope: The water level slopes for 19 years between the upstream station (SW175) and downstream station (SW175.5) have been calculated and shown in Table 7.2. From the table, it can be seen that the water level slope varies between 0.027 to 0.057.

Table 7.2 Water Level Slope Analysis for the Kushiyara

Year	SW175 (upstream station) (mPWD)	SW175.5 (downstream station) (mPWD)	Water Level Slope (per km)
1993	12.7	8.63	0.045
1994	12.44	8.25	0.046
1995	13.27	8.52	0.052
1996	12.72	8.61	0.045
1997	13.96	8.81	0.057
1998	13.05	8.44	0.051
1999	13.36	8.65	0.052
2000	11.45	8.23	0.035
2001	12.2	8.2	0.044
2002	12.82	8.56	0.047
2003	13.05	8.85	0.046
2004	14.27	9.22	0.055
2005	12.12	8.35	0.041
2006	12.9	8.5	0.048
2007	11.12	7.93	0.035
2008	12.27	8.49	0.042
2009	10.45	7.96	0.027
2010	12.9	8.9	0.044
2011	13.46	8.68	0.053
2012	12.62	8.63	0.044

7.3.2 Historical Data Analysis

7.3.2.1 The Surma River

7.3.2.1.1 Velocity Analysis

There are 3 discharge stations on Surma River (SW266, Kanairghat, SW267, Sylhet and SW269, Sunamganj). Discharge and Velocity data of all the 3 stations have been collected from the BWDB.

Velocity data of Monsoon (June-September) season and Dry (January-March) season of 2010-2016 have been plotted. The data are shown in Table 7.3. The average velocity of Monsoon season and average velocity of dry season for the last 20 years (1996-2016) have also been plotted in Figure 7.16. Velocity analysis of 2010, 2012 and 2016 are given in Figure 7.13, 7.14 and 7.15. From the Table and Figures, it can be observed that the change in velocity in monsoon and dry seasons over the years do not show any specific trend of change. The trend of change in velocity does not follow the regime condition velocity as shown in Figure 5.5.

Table 7.3 Velocity Analysis for Surma River

Year	Season	SW266 (m/s)	SW267 (m/s)	SW269 (m/s)
2010	Monsoon	1.38	1.195	1.116
	Dry	0.43	0.132	0.145
2011	Monsoon	1.195	0.939	0.904
	Dry	0.457	0.145	0.235
2012	Monsoon	1.07	1.098	1.103
	Dry	0.385	0.095	0.085
2013	Monsoon	0.845	1.075	0.944
	Dry	0.56	Not available	0.07
2014	Monsoon	0.835	0.91	0.9113
	Dry	0.353	0.0833	0.07
2015	Monsoon	0.825	1.022	0.916
	Dry	0.417	0.337	0.273

Year	Season	SW266 (m/s)	SW267 (m/s)	SW269 (m/s)
2016	Monsoon	1.1	1.047	1.108
	Dry	0.31	0.08	0.057
Average (1996-2016)	Monsoon	1.164	1.194	1.07
	Dry	0.424	0.298	0.099

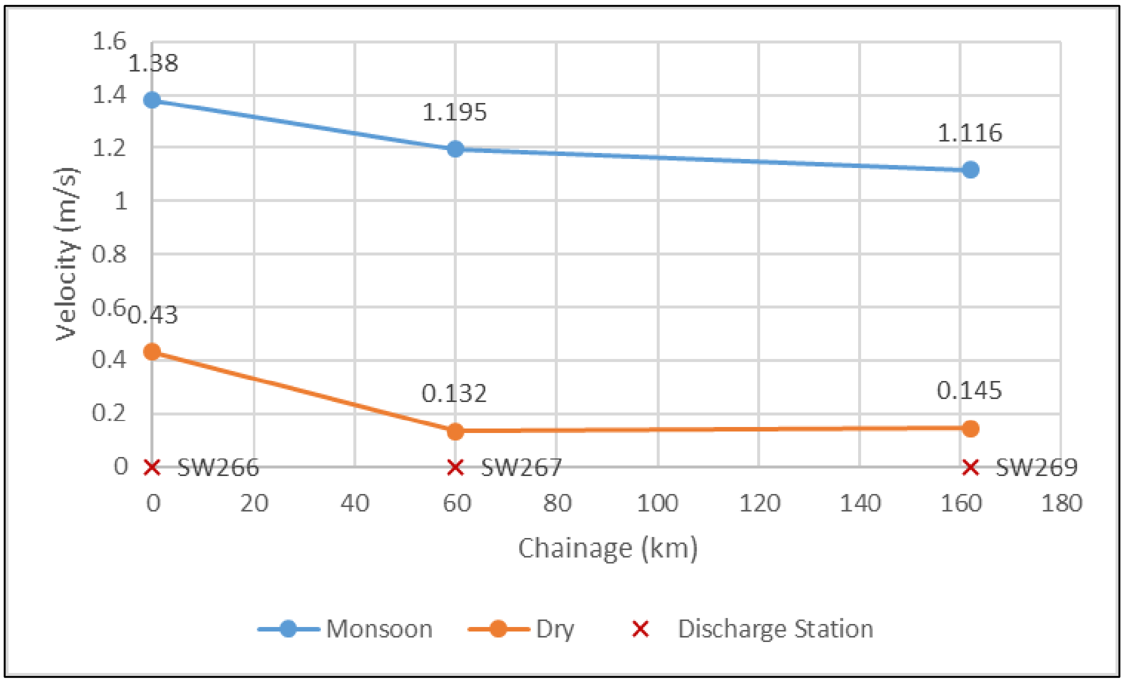

Figure 7-13 Velocity Analysis for the Surma River (2010)

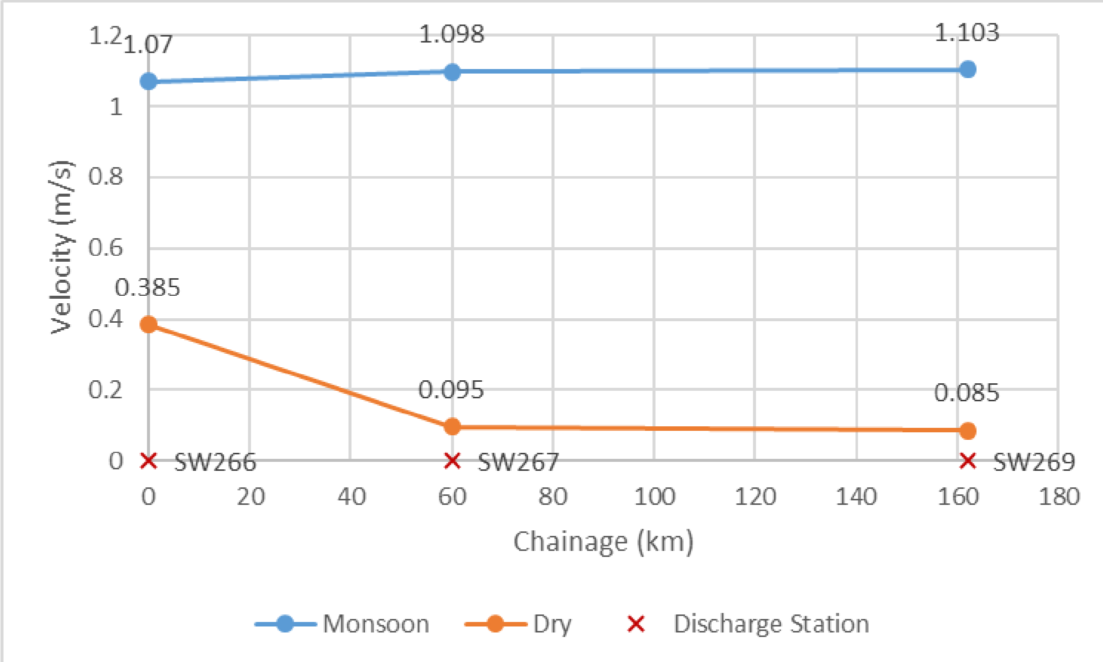

Figure 7-14 Velocity Analysis for the Surma River (2012)

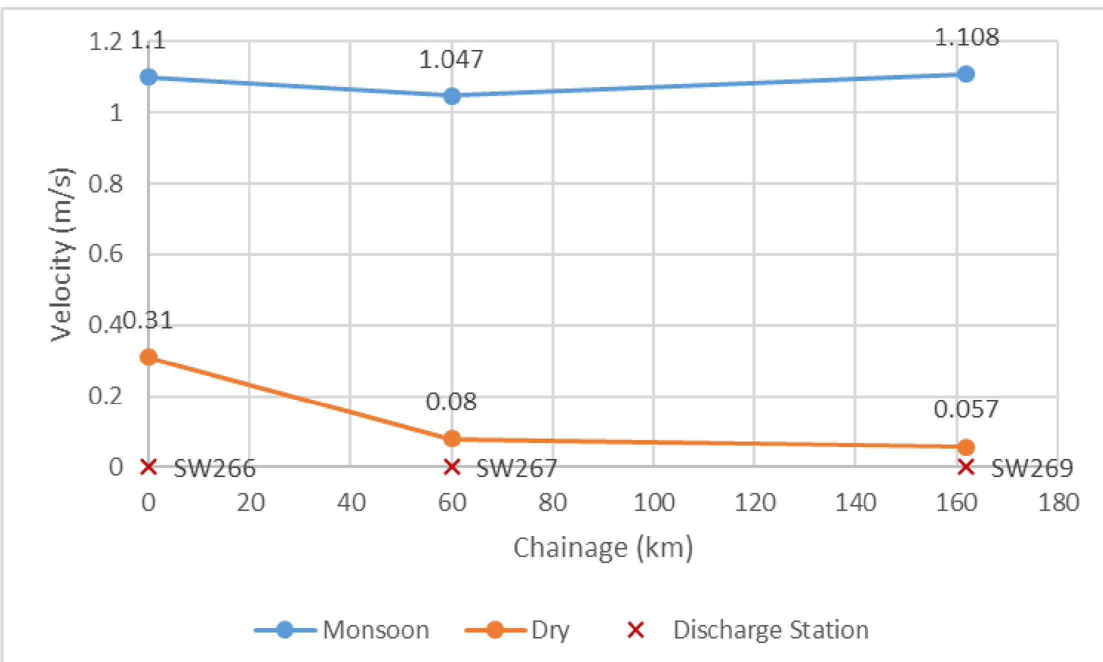

Figure 7-15 Velocity Analysis for the Surma River (2016)

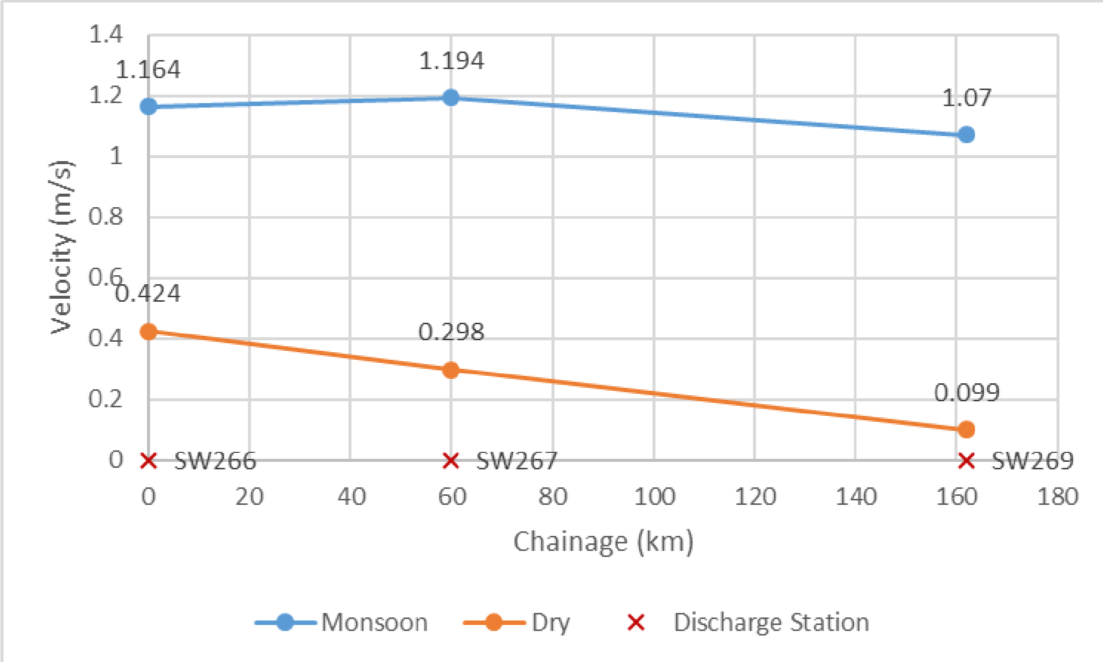

Figure 7-16 Velocity Analysis for the Surma River (Average of 1996-2016)

7.3.2.1.2 Cross Section

The cross section data have been analyzed for the years 2009, 2011, 2013 and 2014. The cross section measurements are taken 6 km apart from each other.

Cross sections at upstream (RMS34) and downstream (RMS1) sections have been plotted in Figure 7.17, 7.18 and 7.19 (for 2009, 2011 and 2014 respectively). From these figures, the difference in RL between the upstream and downstream sections can be shown.

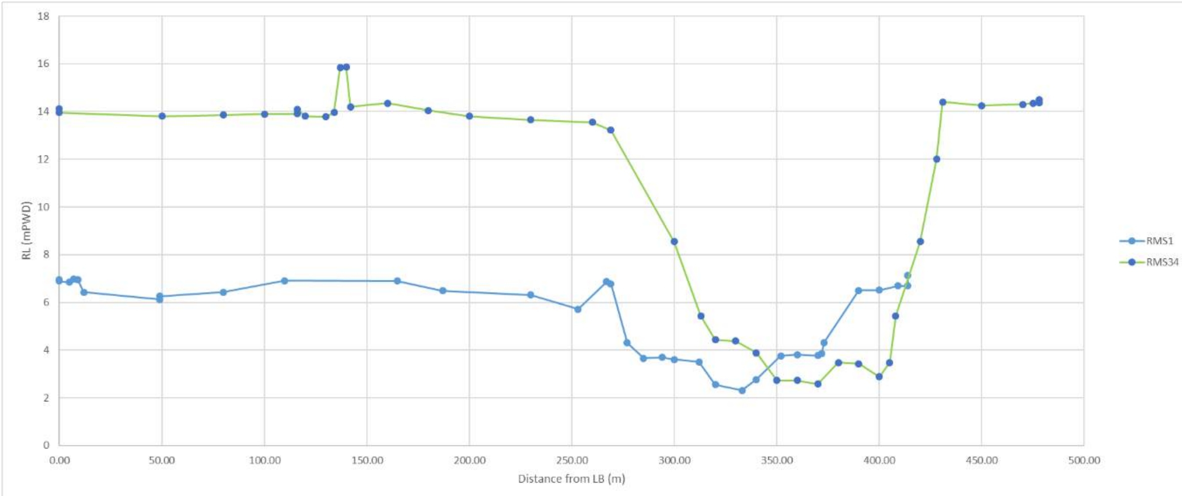

Figure 7-17 Cross Section Analysis of 2009 (Jan-Apr)

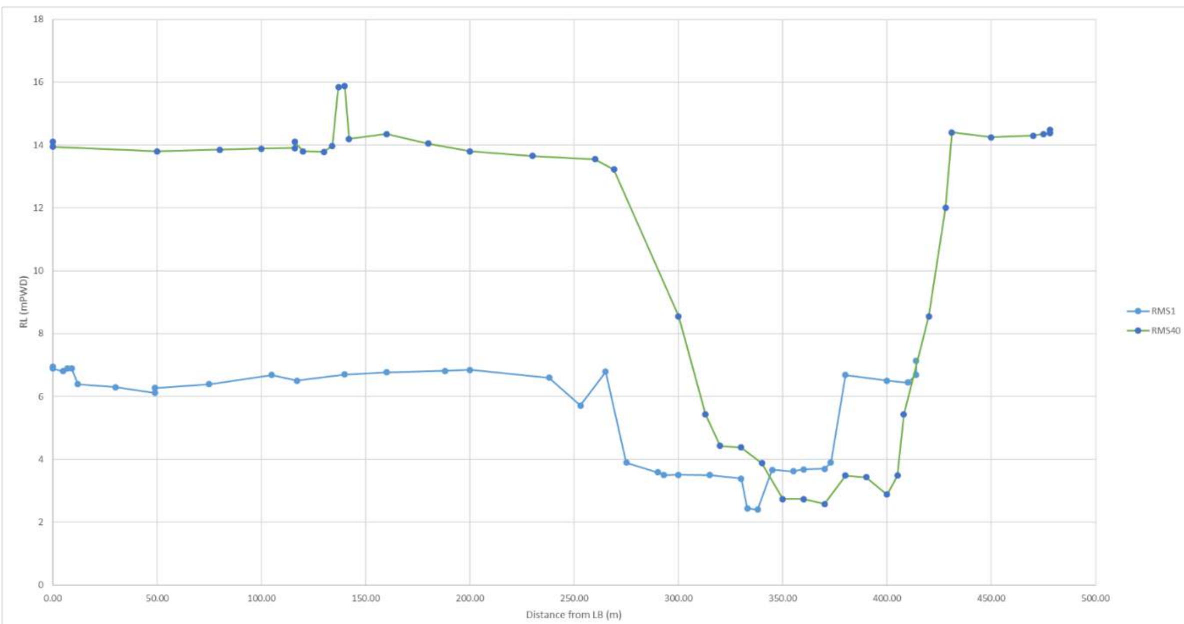

Figure 7-18 Cross Section Analysis of 2011 (Jan-Feb)

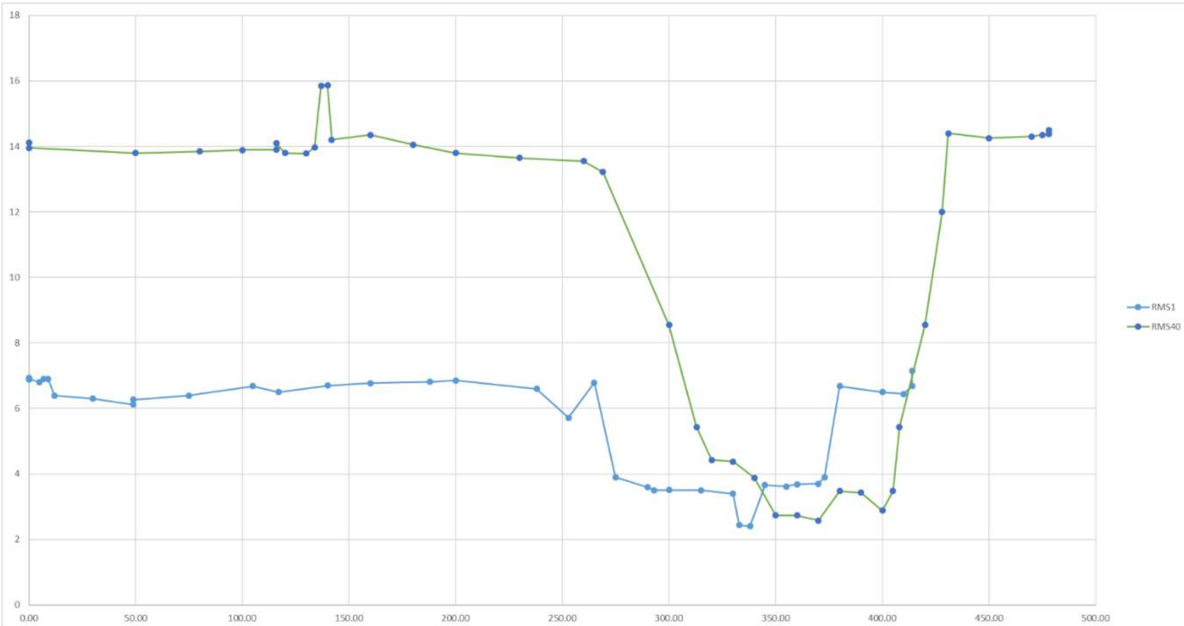

Figure 7-19 Cross Section Analysis of 2014 (Nov-Dec)

7.3.2.1.3 Rating Curve

Stage (Y) vs Discharge (Q) relationships (i.e. Rating Curve) for each of the three sections on Surma have been developed for 2010-2015. A best fit curve is drawn after plotting the Stage and Discharge data. For this case, the relationship between the stage and the discharge is a single-valued relation which is expressed as $Q=C_r(Y\text{-}a)^{\beta}$; where, Q is the stream discharge, a is a constant which represents the gauge reading corresponding to zero discharge, Y is the stage, C_r and β are rating curve constants.

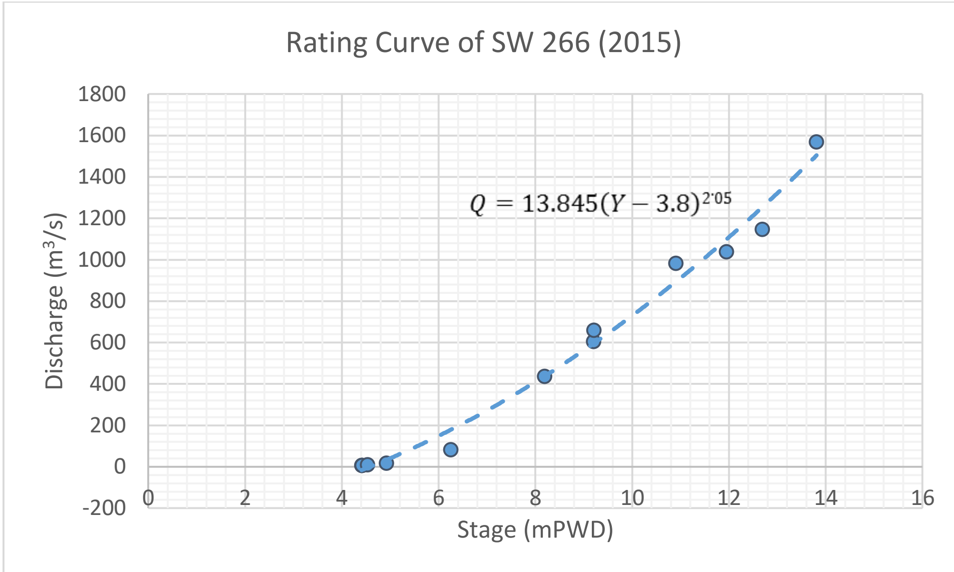

Figure 7-20 Rating Curve of Kanaighat, SW266 (2015)

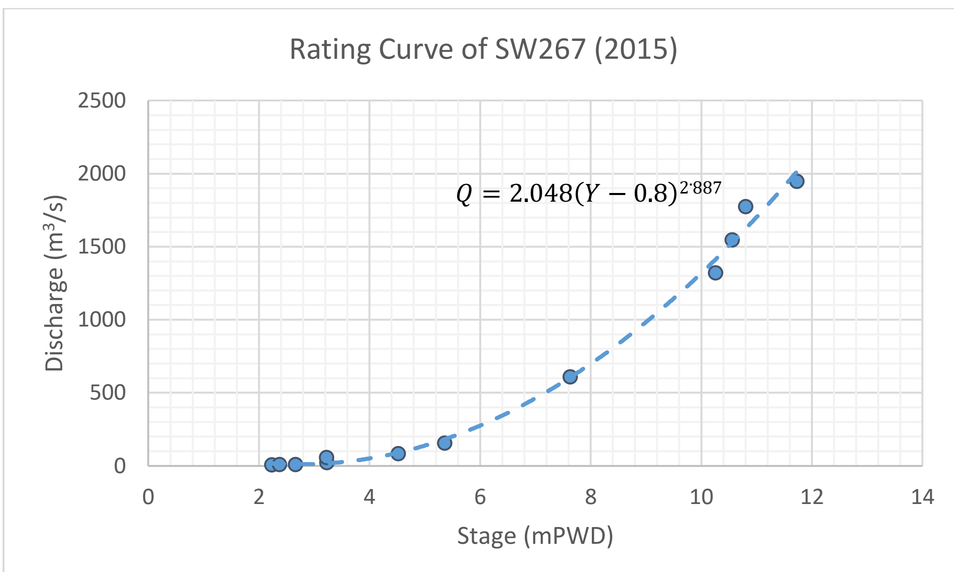

Figure 7-21: Rating Curve of Sylhet, SW267 (2015)

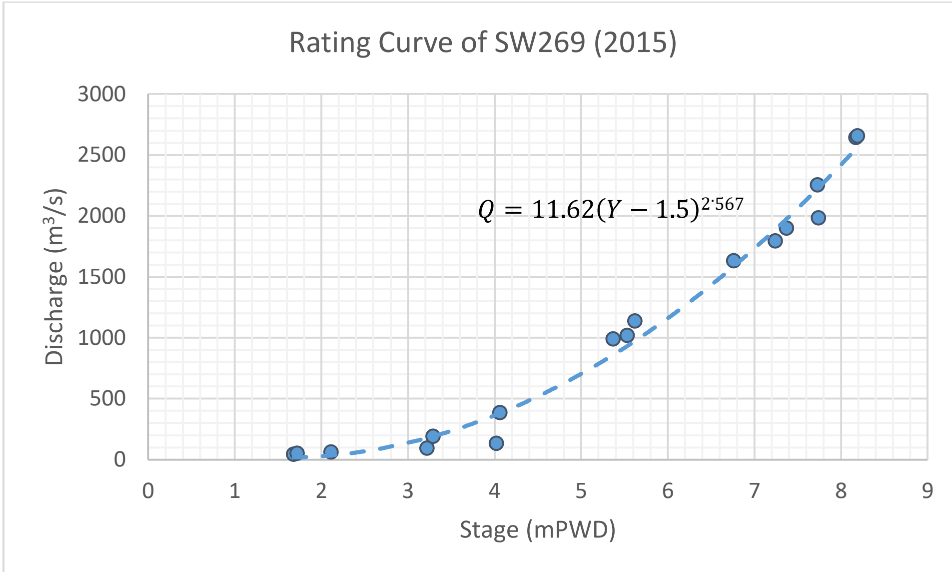

Figure 7-22 Rating Curve of Sunamganj, SW269 (2015)

From the rating curves developed for stations SW266, SW267 and SW269, the bankfull discharge can be calculated. The calculations for the year 2015 is shown below in Table 7.4.

Table 7.4 Bankfull Discharge Calculation

Station ID	**Rating Curve Equation**	**Bankfull Water Level**	**Bankfull Discharge**
SW266	$Q = 13.845(Y-3.8)^{2.05}$	13.8	1553.43
SW267	$Q = 2.048(Y-.8)^{2.887}$	9.5	1056.14
SW269	$Q = 11.62(Y-1.5)^{2.567}$	7.11	972.29

7.3.2.1.4 Discharge Hydrographs

Discharge hydrographs for each of the three sections on Surma have been plotted for 2010-2015. The hydrographs of station SW266, SW267 and SW269 for the year of 2015 are given below.

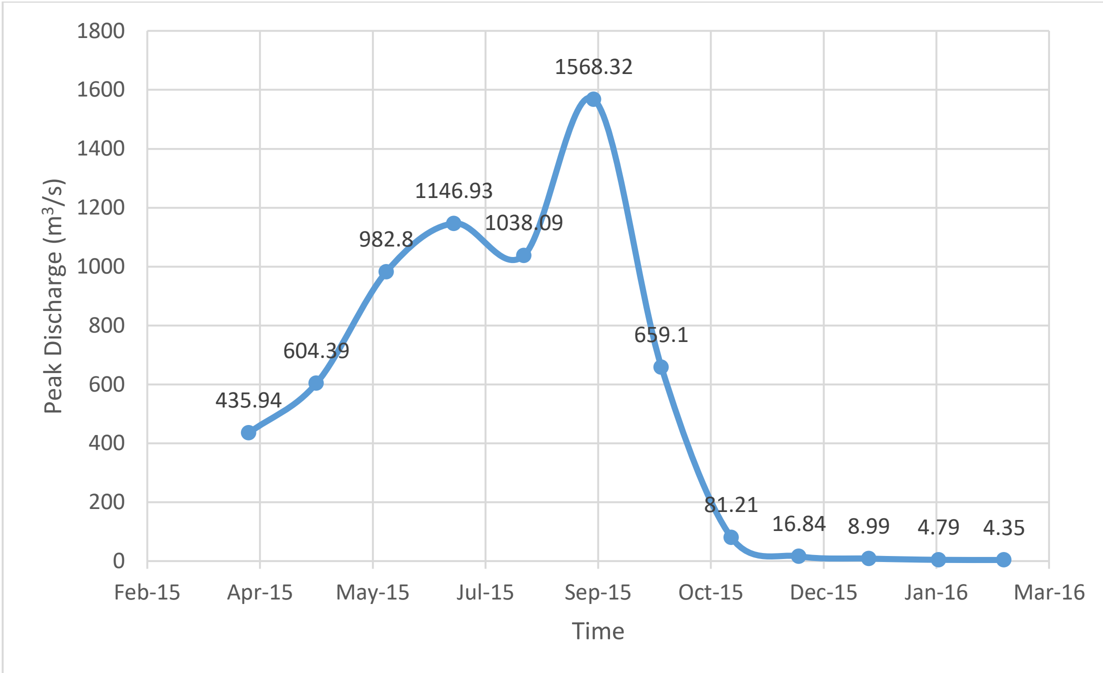

Figure 7-23 Discharge Hydrograph of SW266 for 2015

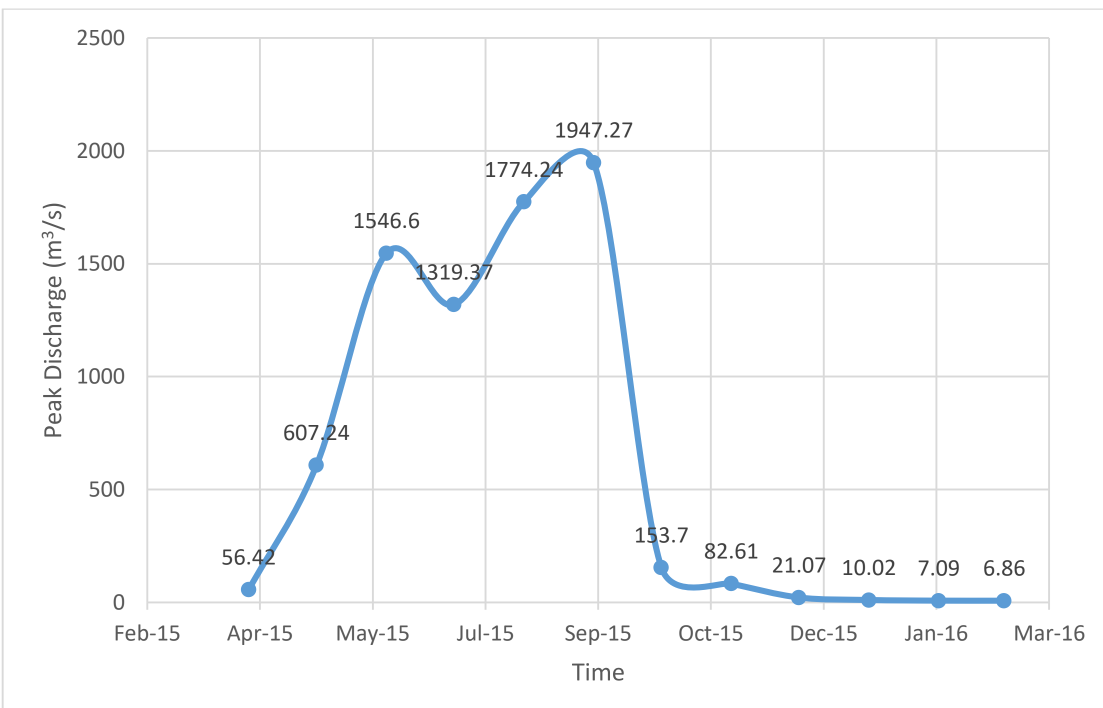

Figure 7-24 Discharge Hydrograph of SW267 for 2015

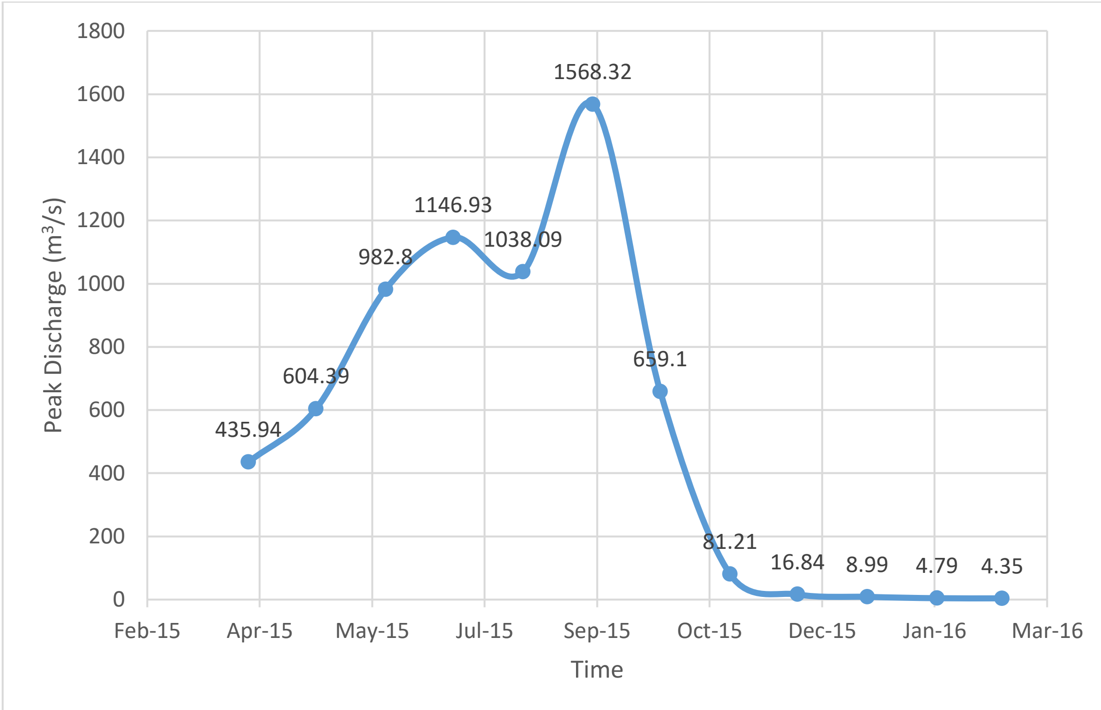

Figure 7-25 Discharge Hydrograph of SW269 for 2015

7.3.2.2 The Kushiyara River

7.3.2.2.1 Velocity Analysis

There are 2 discharge stations on the Kushiyara River (SW173, Sheola and SW175.5, Sherpur). Discharge and Velocity data of the 2 stations have been collected from the BWDB.

Velocity data of Monsoon (June-September) season and Dry (January-March) season of 2010-2016 have been plotted. The data are shown in Table 7.5. The average velocity of Monsoon season and average velocity of dry season for the last 20 years (1996-2016) have also been plotted in Figure 7.29. Velocity analysis of 2010, 2012 and 2016 are given in Figure 7.26, 7.27 and 7.28. From the Table and Figures, it can be observed that the change in velocity in monsoon and dry seasons over the years do not show any specific trend of change. The trend of change in velocity does not follow the regime condition velocity as shown in Figure 5.5, which clearly demonstrates that the Kushiyara river is not in the regime condition.

Table 7.5 Velocity Analysis for Kushiyara River

Year	Season	SW173 (m/s)	SW175.5 (m/s)
2010	Monsoon	1.441	0.93
	Dry	0.578	0.349
2011	Monsoon	1.736	1.2
	Dry	0.89	0.33
2012	Monsoon	1.149	0.89
	Dry	0.77	0.28
2013	Monsoon	1.698	1.17
	Dry	0.396	0.131
2014	Monsoon	0.978	0.35
	Dry	0.35	0.119
2015	Monsoon	1.365	1.19
	Dry	0.413	0.334
2016	Monsoon	1.229	0.86
	Dry	0.329	0.14
Average (1996-2016)	Monsoon	1.32	0.96
	Dry	0.507	0.229

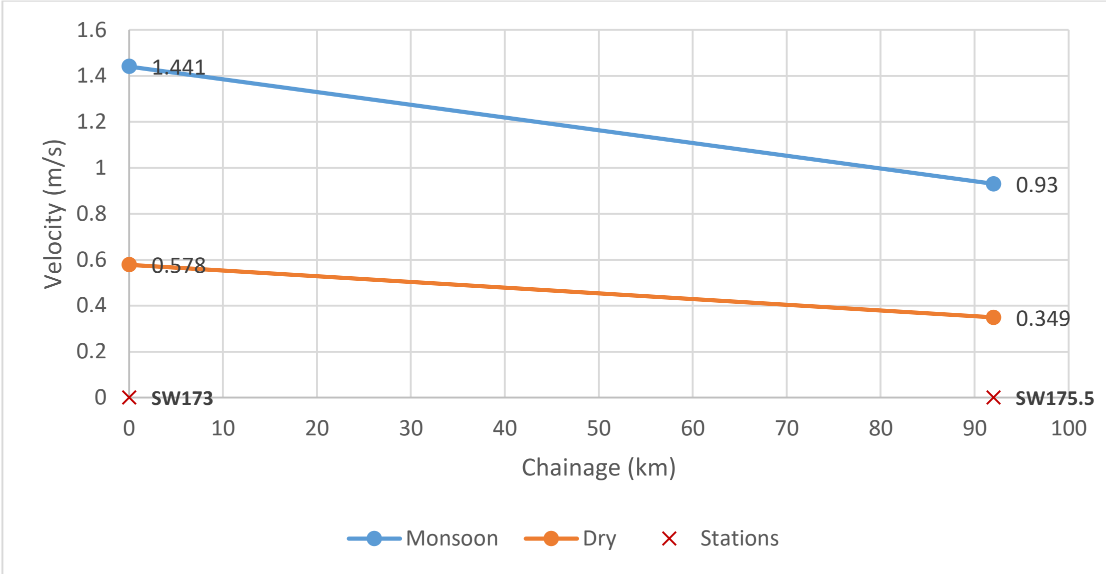

Figure 7-26 Velocity Analysis for the the Kushiyara River (2010)

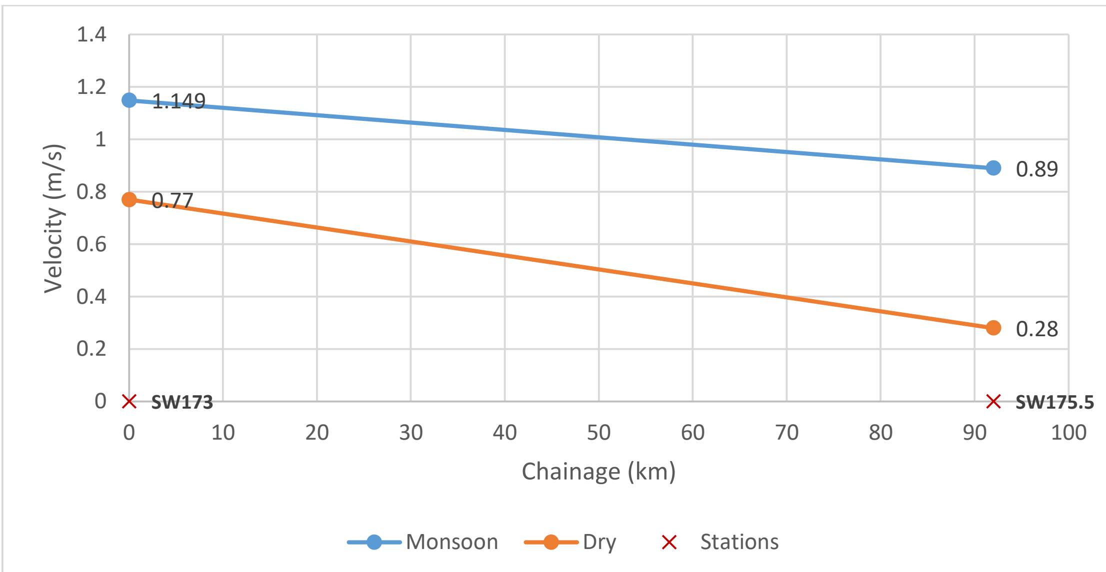

Figure 7-27 Velocity Analysis for the Kushiyara River (2012)

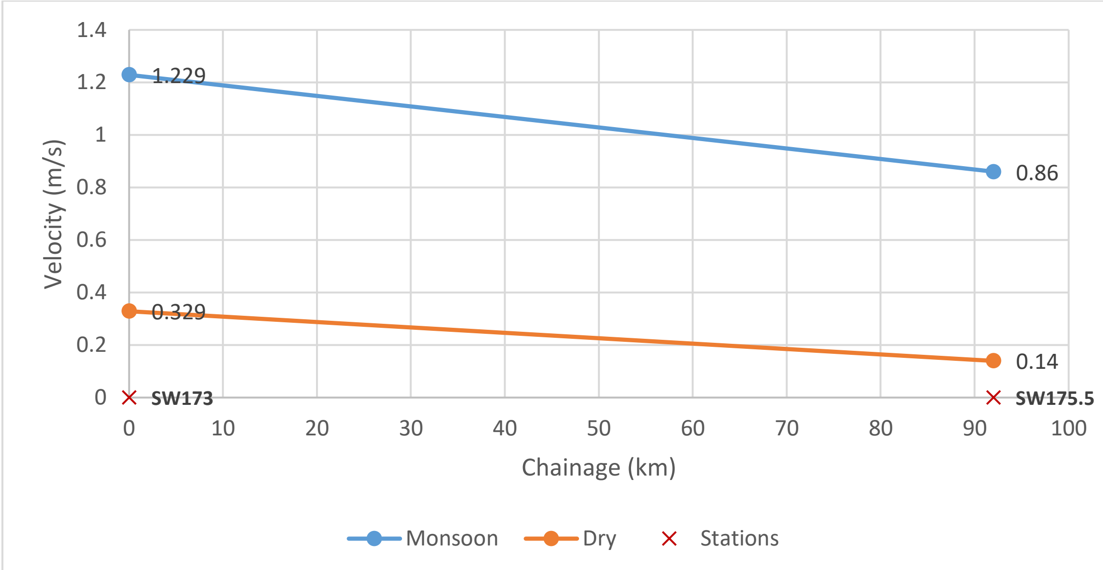

Figure 7-28 Velocity Analysis for the Kushiyara River (2016)

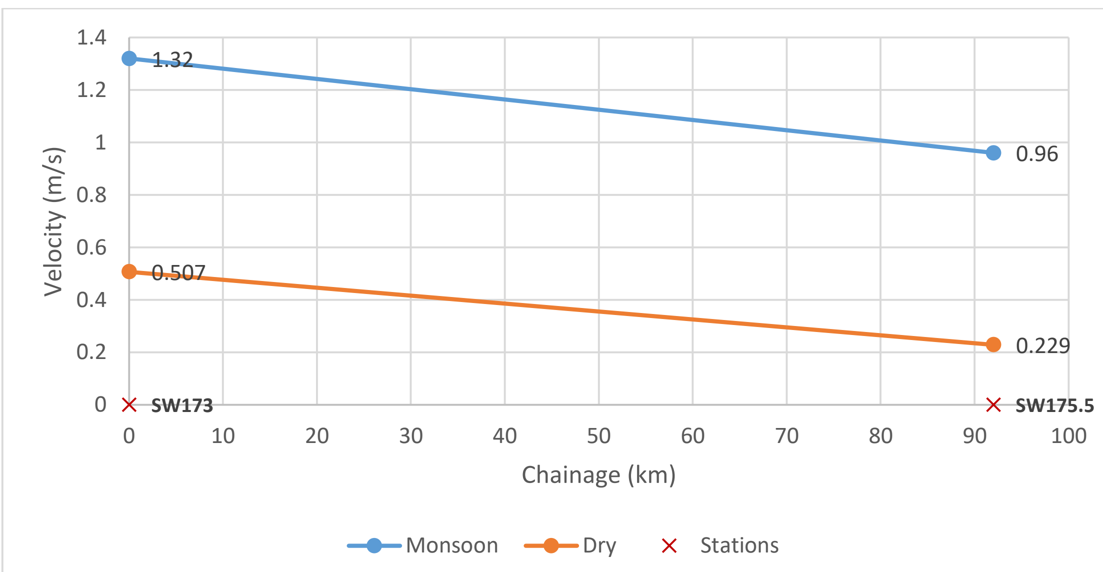

Figure 7-29 Velocity Analysis for the Kushiyara River (Average of 1996-2016)

7.3.2.2.2 Cross Section

The cross section data have been analyzed for the years 2006, 2008 and 2010. The cross section measurements are taken 6 km apart from each other.

Cross sections at upstream (RMKUS12) and downstream (RMKUS1) sections have been plotted in Figure 7.30, 7.31 and 7.32 (for 2006, 2008 and 2010 respectively). From these figures, the difference in RL between the upstream and downstream sections can be shown.

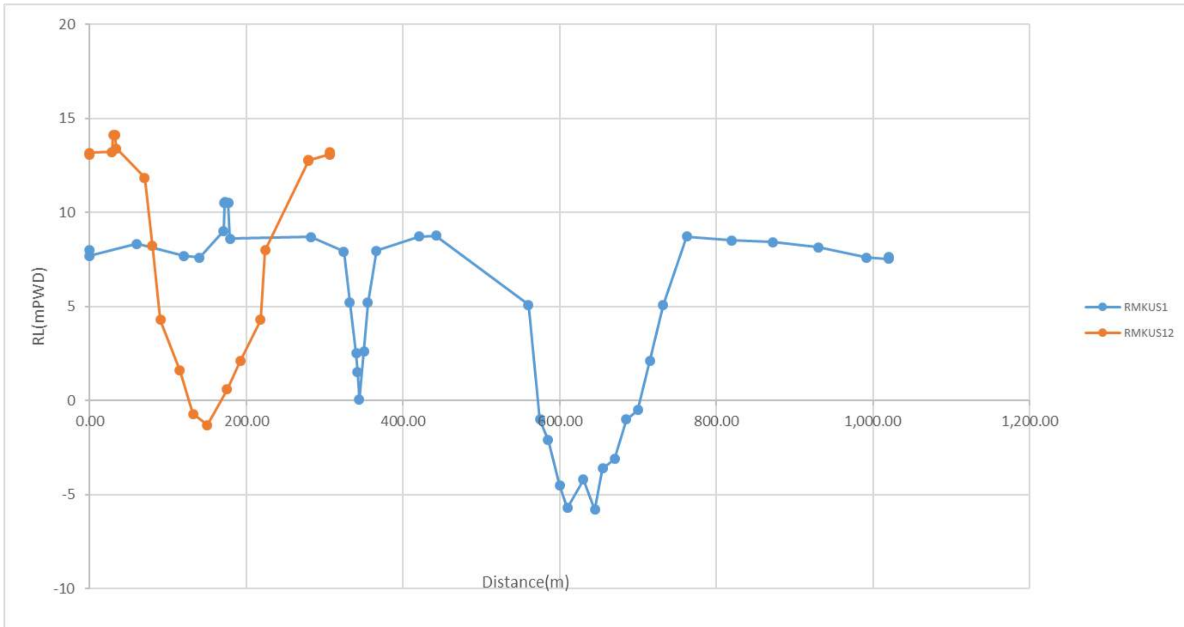

Figure 7-30 Cross Section Analysis of 2006 (Jan-Apr)

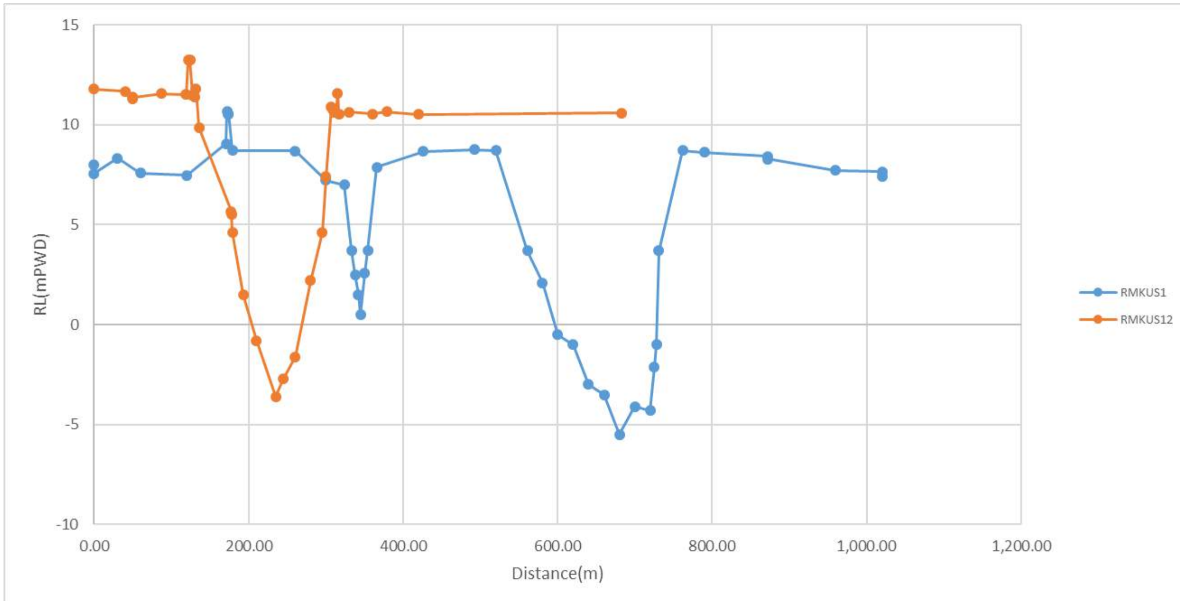

Figure 7-31 Cross Section Analysis of 2008 (Jan-Feb)

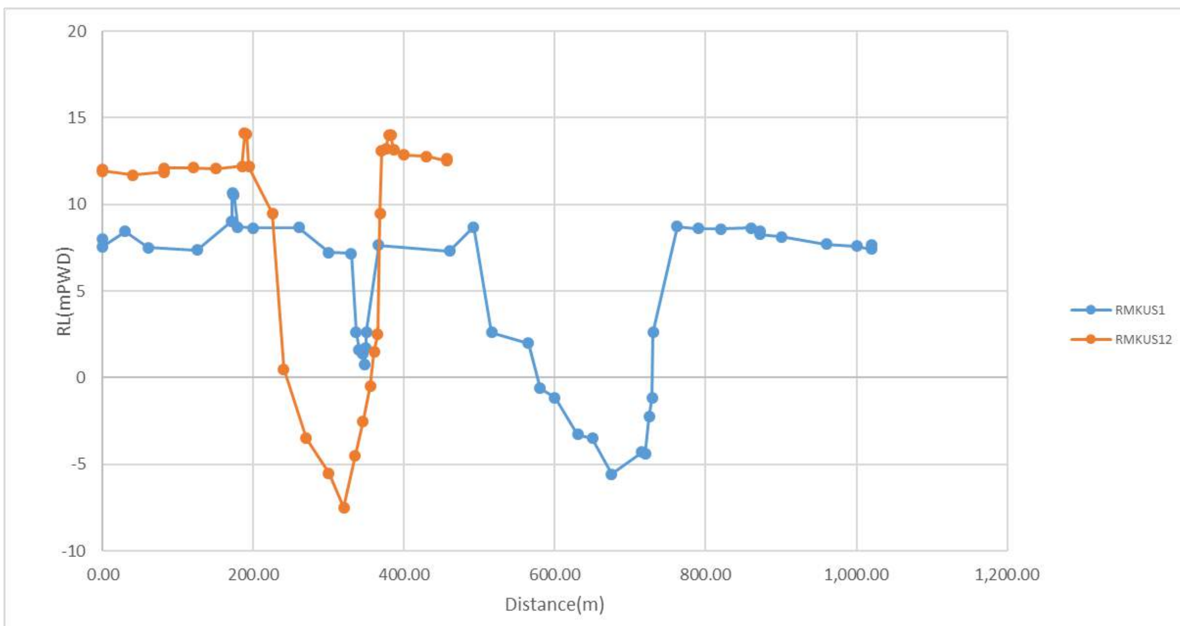

Figure 7-32 Cross Section Analysis of 2010 (Nov-Dec)

7.3.2.2.3 Rating Curve

Stage (Y) vs Discharge (Q) relationships (i.e. Rating Curve) for each of the two sections on the Kushiyara have been developed for 2010-2015. A best fit curve is drawn after plotting the Stage and Discharge data. For this case, the relationship between the stage and the discharge is a single-valued relation which is expressed as $Q=C_r(Y-a)^{\beta}$; where, Q is the stream discharge, a is a constant which represents the gauge reading corresponding to zero discharge, Y is the stage, C_r and β are rating curve constants.

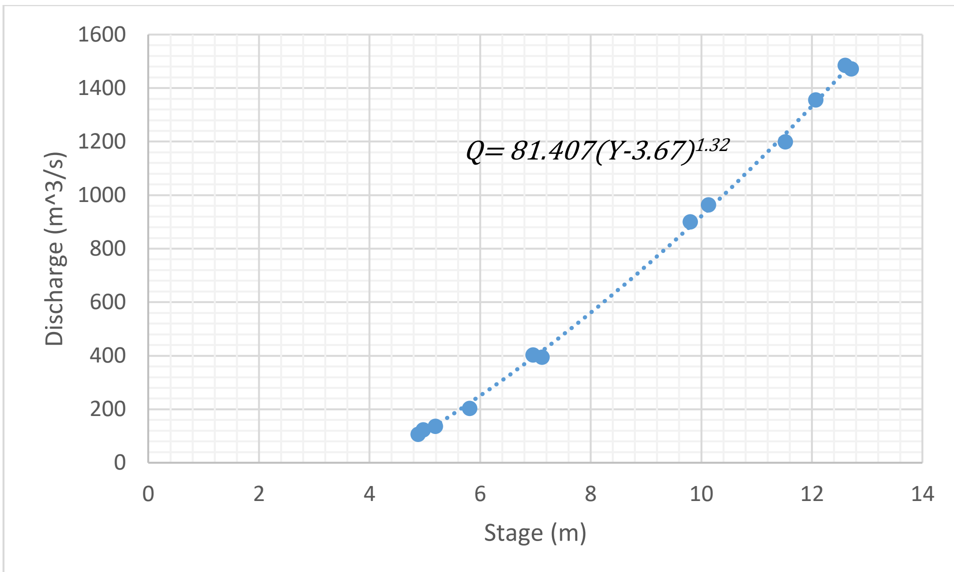

Figure 7-33 Rating Curve of Sheola, SW173 (2015)

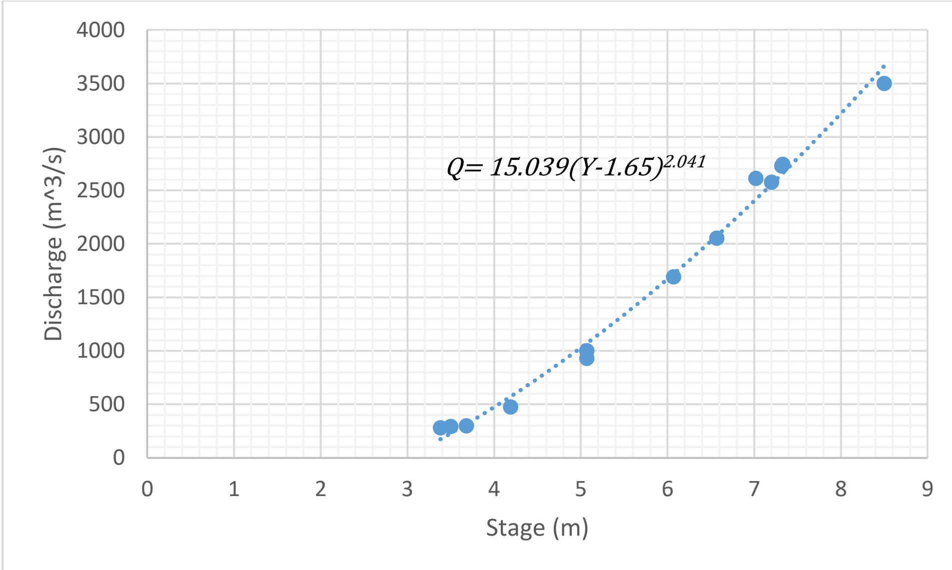

Figure 7-34 Rating Curve of Sherpur, SW175.5 (2015)

From the rating curves developed for stations SW173 and SW175.5, the bankfull discharge can be calculated. The calculations for the year 2015 is shown below in Table 7.6.

Table 7.6 Bankfull Discharge Calculation

Station ID	Rating Curve Equation	Bankfull Water Level	Bankfull Discharge
SW173	$Q = 81.407(Y-3.67)^{1.32}$	13.14	1582.86
SW175.5	$Q = 15.039(Y-1.65)^{2.041}$	10.9	1409.66

7.3.2.2.4 Discharge Hydrographs

Discharge hydrographs for each of the two sections on Kushiyara have been plotted for 2010-2015. The hydrographs of station SW173 and SW175.5 for the year of 2015 are given below in Figure 7.36 and Figure 7.37.

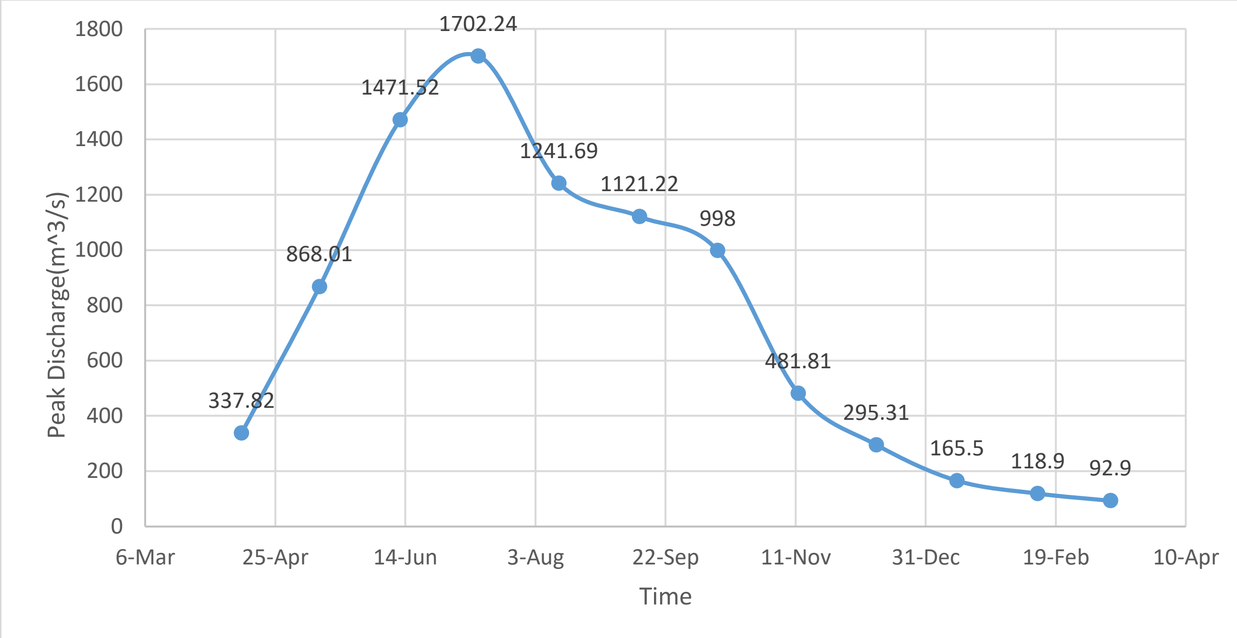

Figure 7-35 Discharge Hydrograph of SW173 for 2015

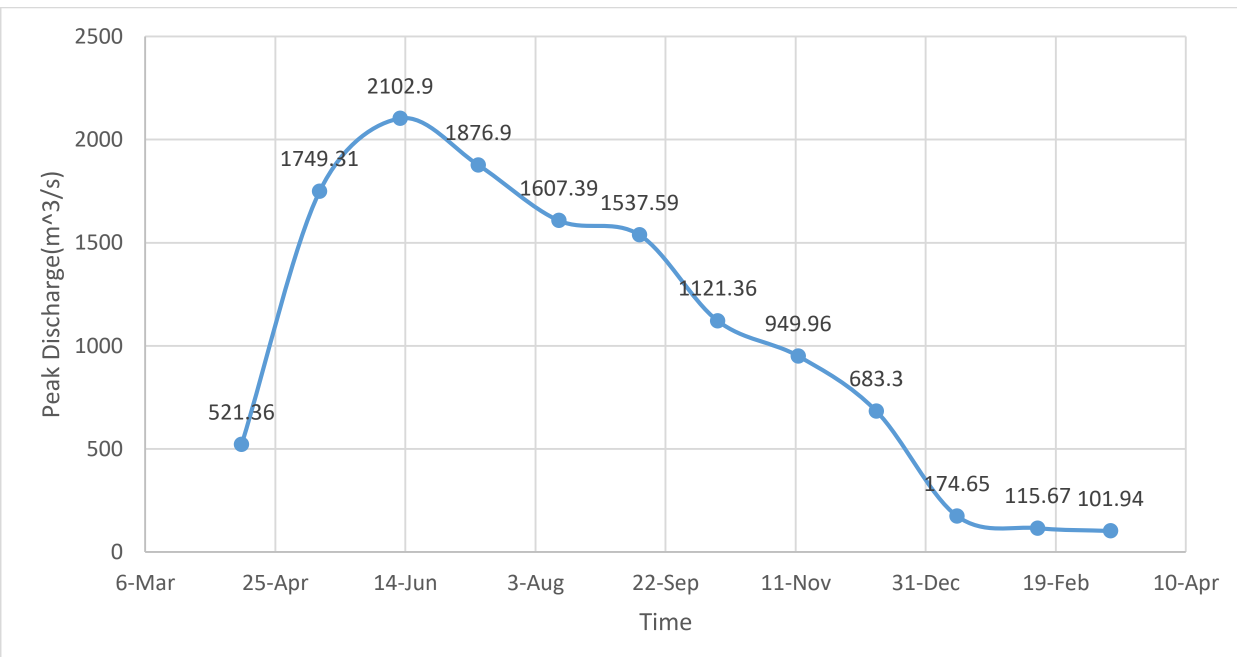

Figure 7-36 Discharge Hydrograph of SW175.5 for 2015

8 Development of Mathematical Model

8.1 Selection of Model

The main objectives of this study are to know the basic hydrodynamic and morphological process of the rivers of the Haor basin and also to validate the CEGIS conceptual model. The Surma and Kushiyara rivers are mainly flowing over the Sylhet basin. The Sylhet basin, which is a low-lying subsiding area attracts the rivers from both east and west sides. Even the Surma and Kushiyara rivers are found to be shifted westward to feed the deepest basin area (BHWDB, 2012). Sediment concentration and its distribution are also responsible for shaping the morphology of the area. The CEGIS has developed a conceptual model for rivers of the North Eastern Zone, which describes the morphological changes associated with river flows. So, it is essential to choose a well-calibrated hydrodynamic model which can depict the hydro-morphological processes of the Haor Basin and able to validate the said conceptual model.

Two most commonly used one-dimensional modeling tools are HEC-RAS and MIKE11. The other models which are also widely used are Delft3D and Delft3D FM. For selection of model, a thorough review of the manuals of different models were carried out (pl. see section 4.2 for details)

The following key points were revealed for the selection of appropriate model:

- HEC-RAS is available for download for free of charge. MIKE 11 on the other hand, is high in cost. The Budget of the project does not include any separate cost for purchase of a modelling software.
- Delft3D and Delft3D FM are both 3 dimensional modelling software and the availability of the required mesh bathymetric data is time consuming and expensive.
- MIKE11 requires hydrologic data and topographic data which includes high quality and fine resolution LIDAR (Light Detection and Ranging) data. The results are very much influenced by the resolution of the topographic data. However, such high quality LIDAR data is very expensive and the budget does not have any provision for collection of such data.

- HEC-RAS only requires cross-section data, discharge data at upstream of the reach and water level data at the downstream. For this particular study, the necessary data were readily available and collected from the BWDB.
- For a longer reach such as the Surma River and the Kushiyara River, the cross-section, discharge and water level data sets are enormous. HEC-RAS is capable of handling such enormous data sets with efficiency.
- The simulation run time for longer reaches is also less for HEC-RAS comparative to other models.
- HEC-RAS Model has been used in several research programs (including Masters and Bachelor's Degree Thesis) of the BUET.
- In this study, the model will be used only for validation of the CEGIS Conceptual Model in a qualitative way. Hence, a user friendly model, requiring data on water level, discharge and sediment concentration has been chosen.
- HEC-RAS is user friendly and the HEC-RAS website provides a number of resources, which include helping the user download software, learn how to use HEC-RAS, resolve problems and service.
- MIKE11 has a GIS interface and can handle unsteady flows. Cost of MIKE11 is high as it is a licensed software but it comes with very good technical support.

After thorough evaluation, HEC-RAS 5.0.3 Model has been considered for carrying out the study. The main objective of HEC-RAS program is to compute water surface elevation at locations of interest for a given flow value (Hydrologic Engineering Center, 1991). The HEC-RAS system contains four one-dimensional river analysis components for: (1) steady flow water surface profile computations; (2) unsteady flow simulation (3) movable boundary sediment transport computations; and (4) water quality analysis. A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the four river analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed. The computational procedure is based on solution of the one-dimensional energy equation using the standard step method. This is a shareware program available without any technical support. It was also mentioned in the Inception Report that HEC-RAS Model will be used to carry out the study.

8.2 Model Setup

8.2.1 HEC-RAS Modeling Theory

When the river is rising, water moves laterally away from the channel, inundating the floodplain and filling available storage areas. As the depth increases, the floodplain begins to convey water downstream generally along a shorter path than that of the main channel. When the river stage is falling, water moves toward the channel from the overbank supplementing the flow in the main channel.

This channel/floodplain problem has been addressed in many different ways. A common approach is to ignore overbank conveyance entirely, assuming that the overbank is used only for storage. This assumption may be suitable for large streams such as the Mississippi River where the channel is confined by levees and the remaining floodplain is either heavily vegetated or an off-channel storage area. Fread (1976) and Smith (1978) approached this problem by dividing the system into two separate channels and writing continuity and momentum equations for each channel. To simplify the problem, they assumed a horizontal water surface at each cross section normal to the direction of flow; such that the exchange of momentum between the channel and the floodplain was negligible and that the discharge was distributed according to conveyance, i.e.:

$$Q_c = \phi Q$$

Where, Q_c = Flow in channel,

Q = Total flow,

$\varphi = K_C / (K_C + K_f)$,

K_C = Conveyance in the channel, and,

K_f = Conveyance in the floodplain

With these assumptions, the one-dimensional equations of motion can be combined into a single set:

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

$$\frac{\partial Q}{\partial t}+\frac{\partial(\Phi^2 Q^2/A_c)}{\partial x_c}+\frac{\partial((1-\Phi)^2 Q^2/A_f\ )}{\partial x_f}+gA_c\left[\frac{\partial Z}{\partial x_c}+S_{fc}\right]+gA_f\left[\frac{\partial z}{\partial x_f}+S_{ff}\right]=0$$

in which the subscripts c and f refer to the channel and floodplain, respectively. These equations were approximated using implicit finite differences, and solved numerically using the Newton-Raphson iteration technique. The model was successful and produced the desired effects in test problems. The continuity equation describes conservation of mass for the one-dimensional system. From previous text, with the addition of a storage term, S, the continuity equation can be written as:

$$\frac{\partial A}{\partial t}+\frac{\partial S}{\partial t}+\frac{\partial Q}{\partial x}-q_1=0$$

Where: x = distance along channel,

t = time,

Q = flow,

A = cross-sectional area,

S = storage from non-conveying portions of cross section,

q_l = lateral inflow per unit distance.

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

$$\frac{\partial Q}{\partial t}+\frac{\partial (VQ)}{\partial x}+gA(\frac{\partial z}{\partial x}+S_f)=0$$

Where: g = Acceleration of gravity

S_f = Friction slope,

The HEC-RAS Unsteady flow engine combines the properties of the left and right overbank into a single flow compartment called the floodplain. Hydraulic properties for the floodplain are computed by combining the left and right overbank elevation, Area, conveyance, and storage into a single set of relationships for the floodplain portion of the cross section. The reach length used for the floodplain area is computed by taking the arithmetic average of the left and right overbank reach lengths (LL + LR)/2 = LF. The average floodplain reach length is used in both the continuity and momentum equations to compute their respective terms for a combined floodplain compartment (Left and right overbank combined together).

8.2.2 Collection of Satellite Images

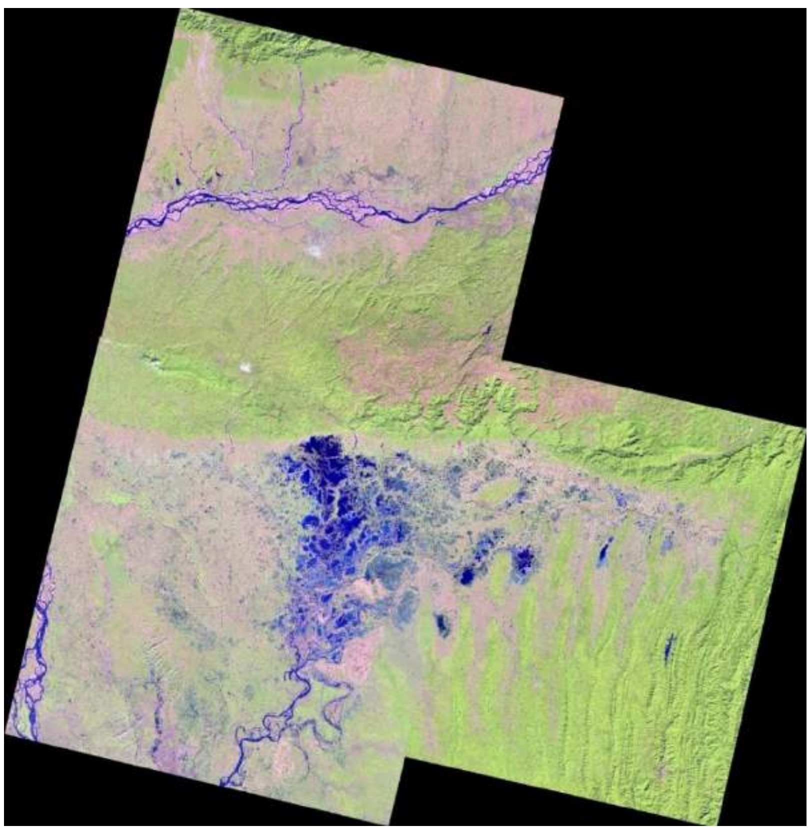

Figure 8-1 Satellite image of the study area

Satellite images of the Surma and the Kushiyara have been collected. Images are Landsat-8 Satellite images of WRS Path-Row 136-43, 135-43, 135-42. The Images have been collected from United States Geological Survey (USGS) for thalweg delineation of the Surma and Kushiyara Rivers. These images are of 30mX30m resolution and dated from 30th November, 2015 to 16th December, 2015. Then these images were mosaicked in and the thalwegs of the Surma and Kushiyara Rivers were delineated in ArcGIS.

8.2.3 Geometry Setup

8.2.3.1 River Schematics

The river system schematic is required for any geometric data set within the HEC-RAS system. The schematic defines how the various river reaches and flow areas are connected, as well as establishing a naming convention for referencing all other data. The delineated thalweg was imported in HEC-RAS geometry editor to establish the river schematics. Due to the non-availability and discontinuity of data at Amalsidh (Bifurcation point of the Surma and Kushiyara), two different models have been set up for two different rivers.

The Surma River

For the Surma river, a total reach length of 179.36 km (out of total length of 249 km) has been considered starting from Kanaighat (BWDB station: SW266) to Sunamganj (BWDB station: SW269). The river schematic setup of the Surma River has been Shown in Figure 8.2.

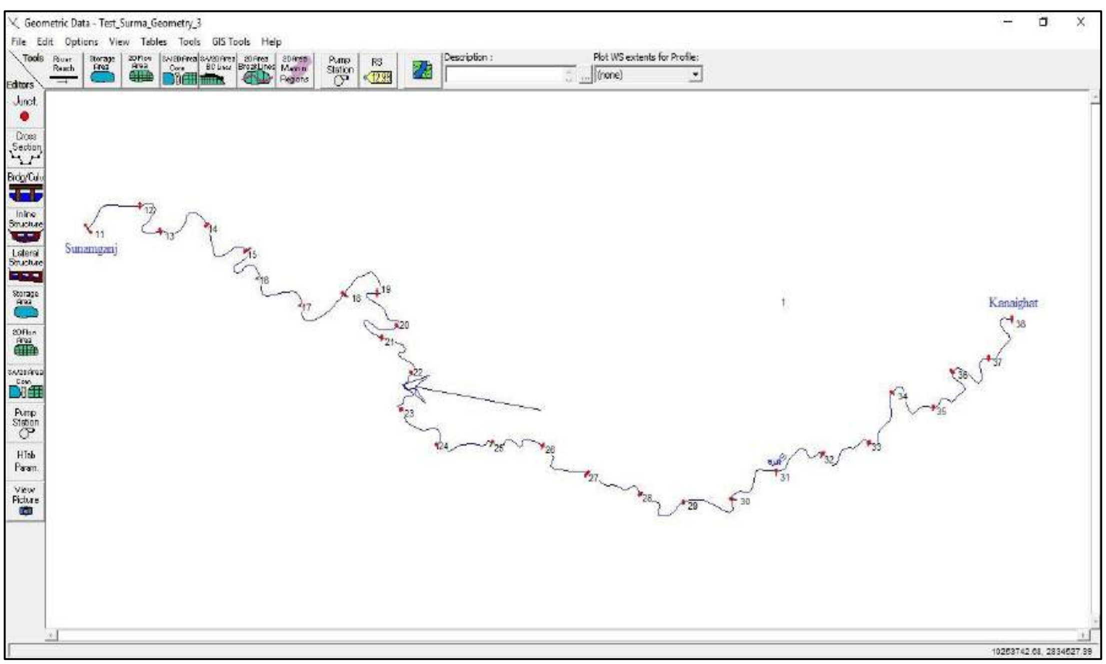

Figure 8-2: The Surma River Schematic in HECRAS Geometry Editor

The Kushiyara River

For the Kushiyara river, 180.62 km (out of total length of 288 km) has been considered starting from Sheola (BWDB station: SW173) to Markuli (BWDB station: SW270). The river schematic setup of the Kushiyara River has been shown in Figure 8.3.

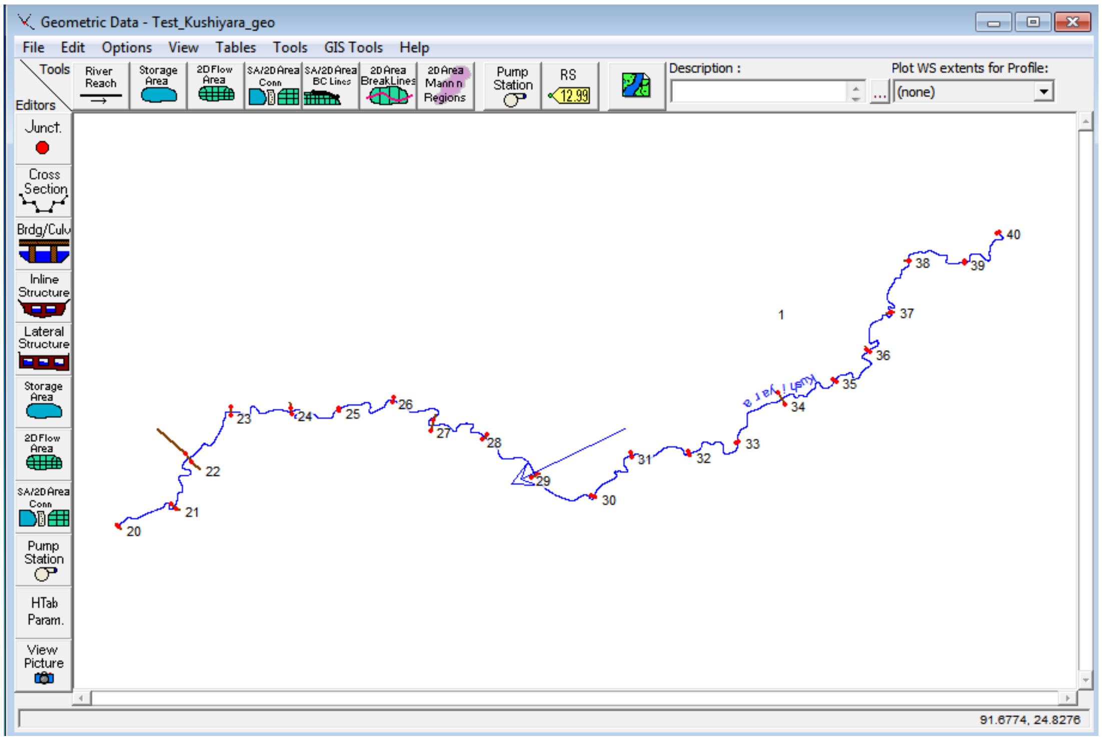

Figure 8-3 The Kushiyara River Schematic in HECRAS Geometry Editor

8.2.3.2 Cross Section Geometry

Boundary geometry for the analysis of flow in natural streams is specified in terms of ground surface profiles (cross sections) and the measured distances between them (reach lengths). Cross sections are located at intervals along a stream to characterize the flow carrying capability of the stream.

The Surma River:

Cross Sections collected from the BWDB have been used to setup the geometry of model. BWDB cross sections from RMS38 to RMS10 (total 29 cross sections) were used to set up the model geometry of the Surma River. These cross sections are of year 2013 (Feb-March).

BWDB collects cross sections at an interval of approximately 6km. So reach lengths of 6km have been used in this model. The cross section of 2 stations, one at the upstream (SW 266) and one at the downstream (SW269) are shown in Figure 8.4 and 8.5 respectively. The locations of above mentioned stations are Shown in Figure 8.6 (with Red marks).

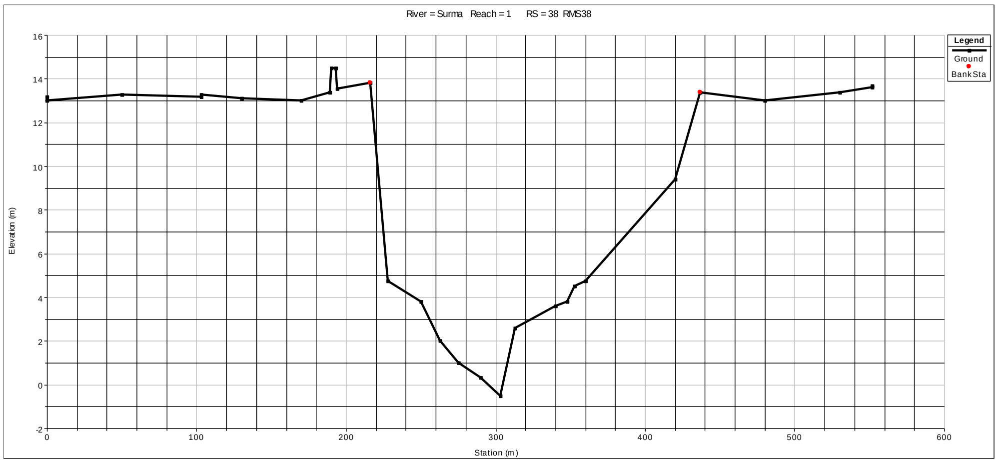

Figure 8-4 The Surma Cross Section, RMS38 corresponding to SW 266, Kanaighat, 2013

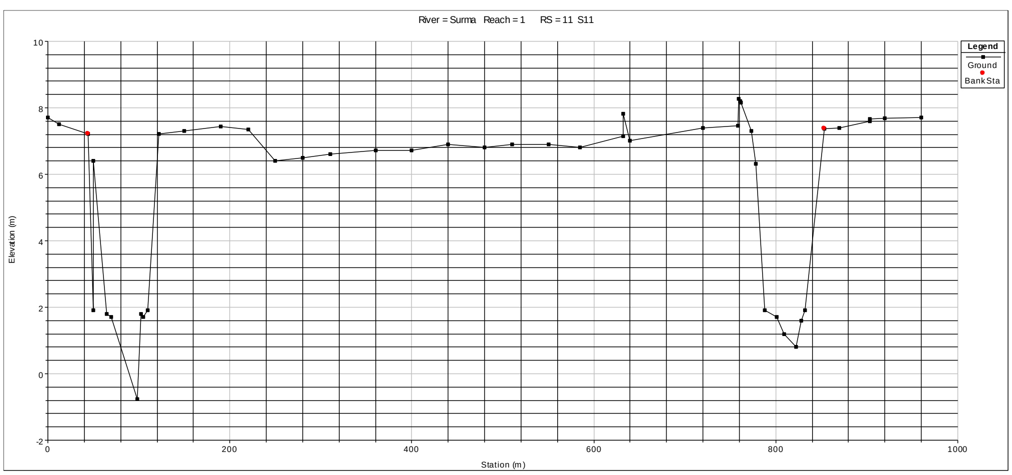

Figure 8-5 The Surma Cross Section, RMS11 corresponding to SW 269, Sunamganj, 2013

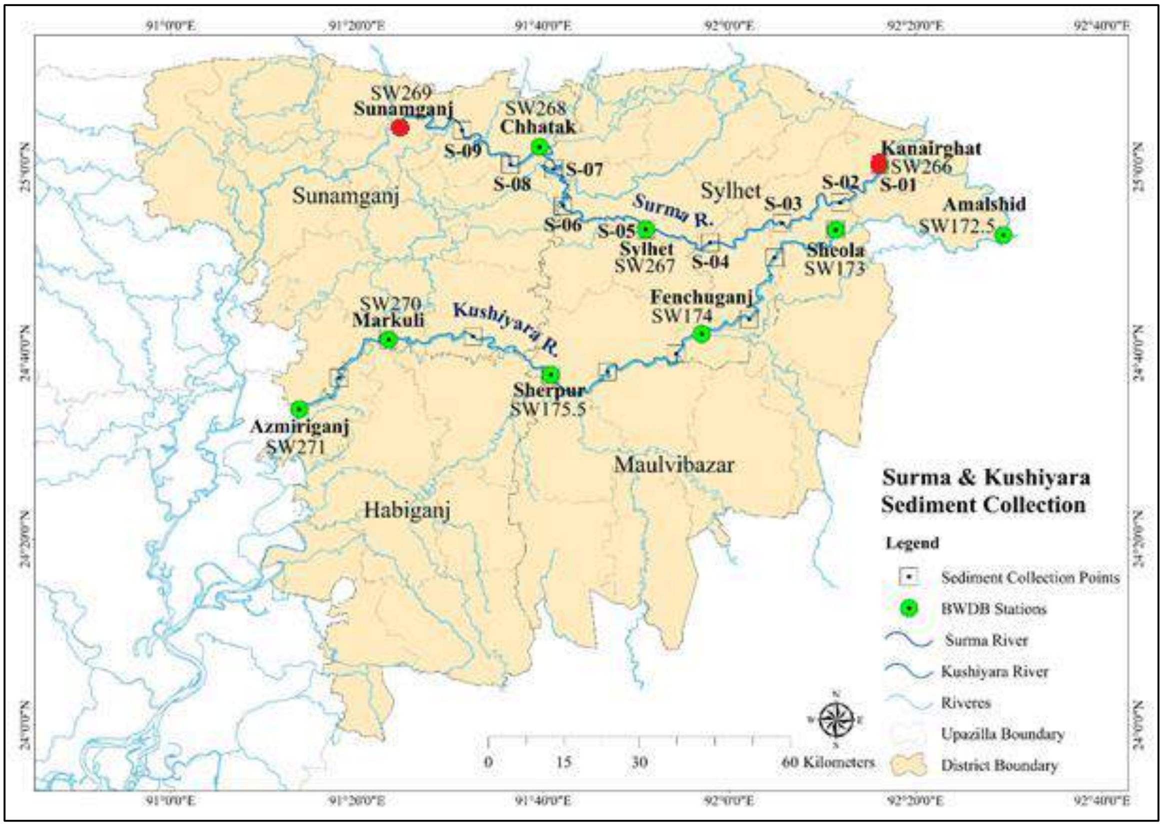

Figure 8-6 Location of Upstream and Downstream crosssection in the Surma

In the upstream cross section Kanaighat **(**SW 266) there is only one major flow channel, but in the downstream cross section Sunamganj (SW 269) there are two major flow channel.

The Kushiyara River:

Cross Sections collected from the BWDB have been used to setup the geometry of model. BWDB cross sections from RMKUS12 to RMKUS1 and RMBIB9 to RMBIB1 (total 21 cross sections) were used to set up the model geometry of the Kushiyara River. These cross sections are of year 2010 (March-April). BWDB collects cross sections at an interval of approximately 6km. So reach lengths of 6km have been used in this model. The cross sections of 2 stations, one at the upstream (SW 173) and one at the downstream (SW270) are shown in Figure 8.7 and 8.8 respectively. The location of the above mentioned stations are shown in Figure 8.9 (with red marks).

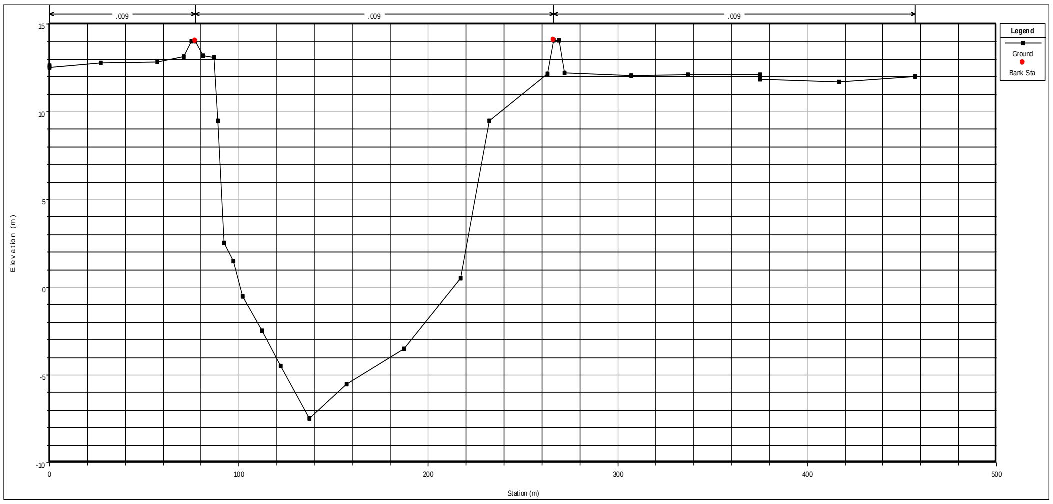

Figure 8-7 The Kushiyara Cross Section, RMKUS12

corresponding to SW 173, Sheola, 2010

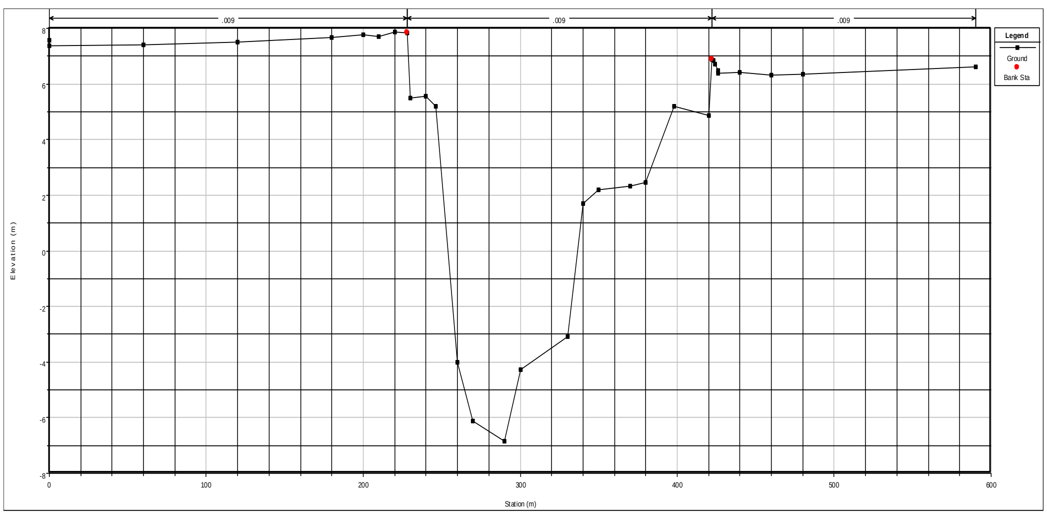

Figure 8-8 The Kushiyara Cross Section, RMBIB12

corresponding to SW 270, Marculi, 2010

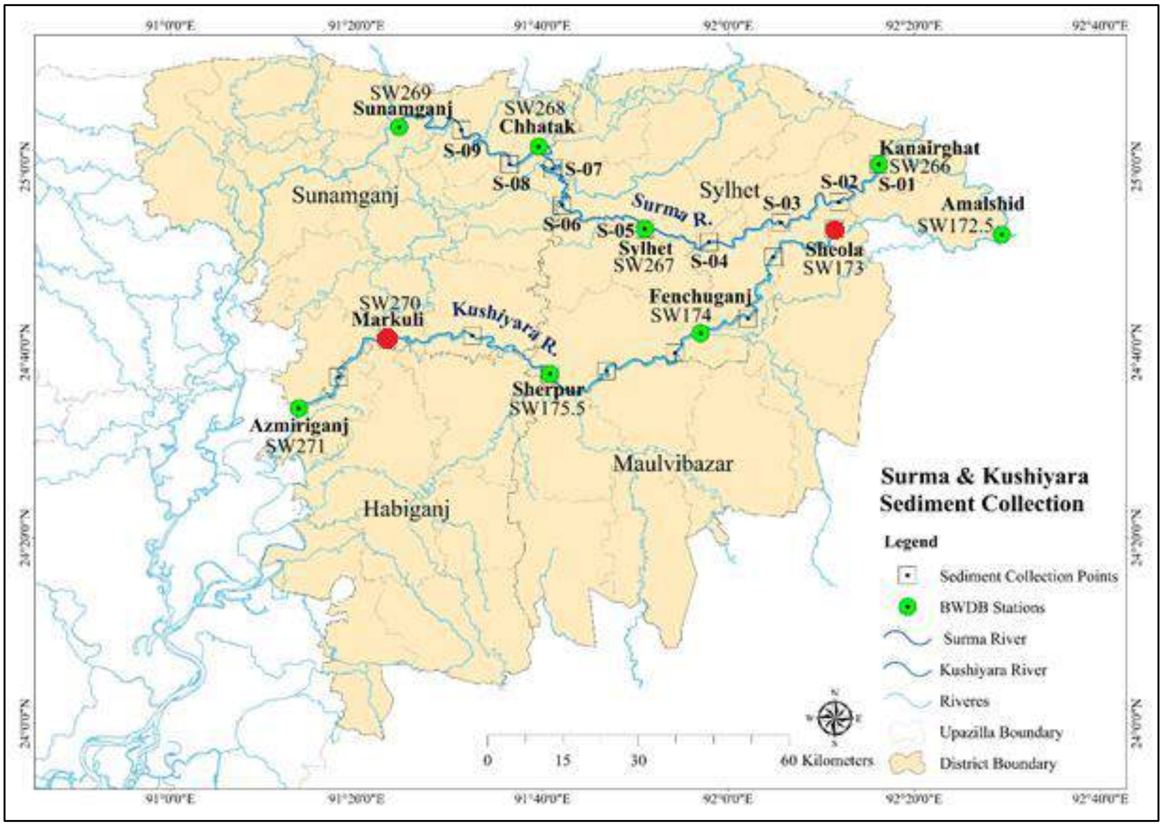

Figure 8-9 Location of Upstream and Downstream crosssection in the Kushiyara

In the Kushiyara river both in the upstream cross section at Sheola (SW 173) and in the downstream cross section at Markuli (SW270) there is only one major flow channel.

8.2.4 Rating Curve

In hydrology, a rating curve is a graph of discharge versus stage for a given point on a stream, usually at gauging stations, where the stream discharge is measured across the stream channel with a flow meter. Numerous measurements of stream discharge are made over a range of stream stages. The rating curve is usually plotted as discharge on X-axis versus stage (surface elevation) on Y-axis.

Daily water level data of all the stations on the Surma and the Kushiyara are available but for the discharge data only the monthly data are available. Stage discharge relationship can be expressed by the following equation.

$$Q = C_r(h - h_0)^{\beta} \quad (1)$$

Where: Q = Discharge, m^3/s

h = Stage (Water elevation), m

h_0 = Gauge reading corresponding to zero discharge, m

C_r = Rating Curve constant,

β = Rating Curve constant.

The Surma River

A rating Curve has been plotted (Figure 8.10) for monthly average data of 20 years (1995-2014) for upstream section of the Surma river, Kanaighat (SW 266).

For Surma river at upstream station **(**SW 266) the value of C_r and β are obtained as 13.845 and 2.05 and water level corresponding to zero discharge is 3.8 m. so the equation becomes

$$Q = 13.845(h - 3.8)^{2.05}$$

Now using this equation, the daily discharge data with respect to daily stage data were calculated and used in the model.

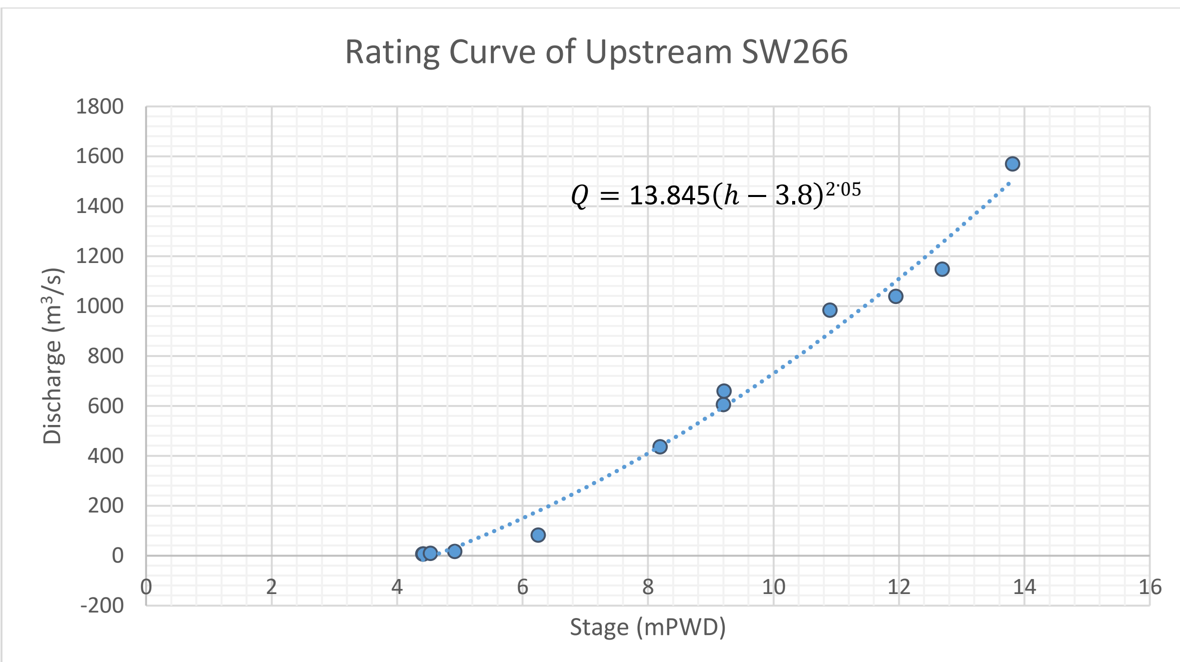

Figure 8-10 Rating curve at upstream Kanaighat (SW266) of the Surma River

Similarly, a rating curve at downstream station, Sunamganj (SW 269) has been plotted (Figure 8.11) and the value of C_r and β are obtained as 11.62 and 2.567 and water level corresponding to zero discharge is 1.5 m. so the equation becomes.

$$Q = 11.62(h - 1.5)^{2.567}$$

Now using this equation, daily stage data with respect to the daily discharge data were calculated and used in the model.

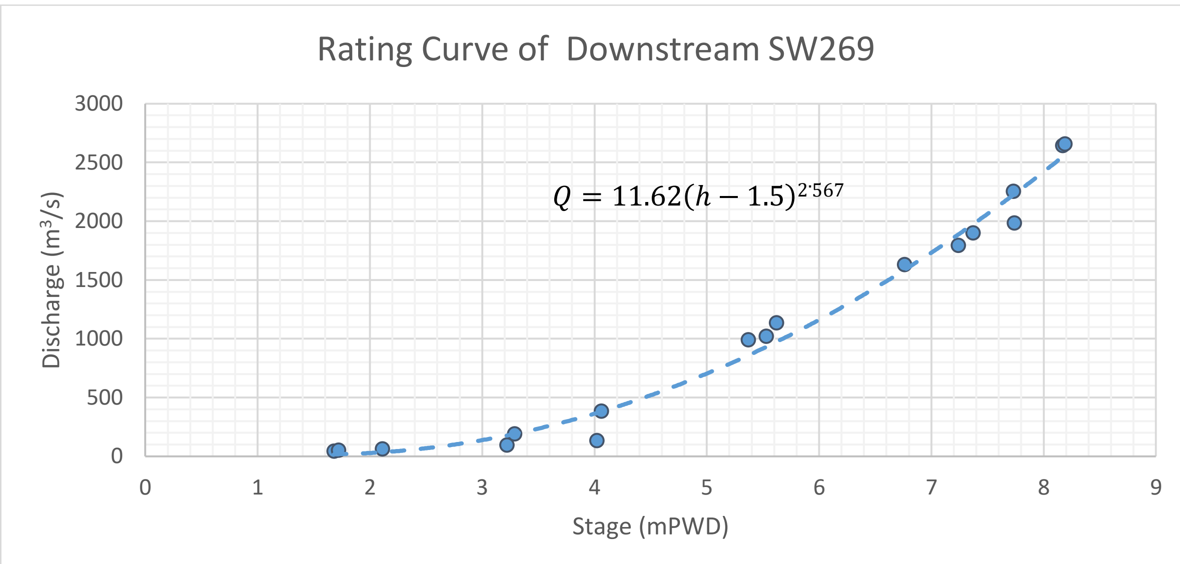

Figure 8-11 Rating curve at downstream Sunamganj (SW269) of the Surma River

The Kushiyara River

A rating Curve has been plotted (Figure 8.12) for monthly average data of 20 years (1995-2014) for upstream section of the Kushiyara river, Sheola (SW 173).

For Kushiyara river at upstream station (SW 173) the value of C_r and β are obtained as 81.4 and 1.3 and water level corresponding to zero discharge is 3.67 m. so the equation becomes

$$Q = 81.4(h - 3.67)^{1.3}$$

Now using this equation, the daily discharge data with respect to daily stage data were calculated and used in the model.

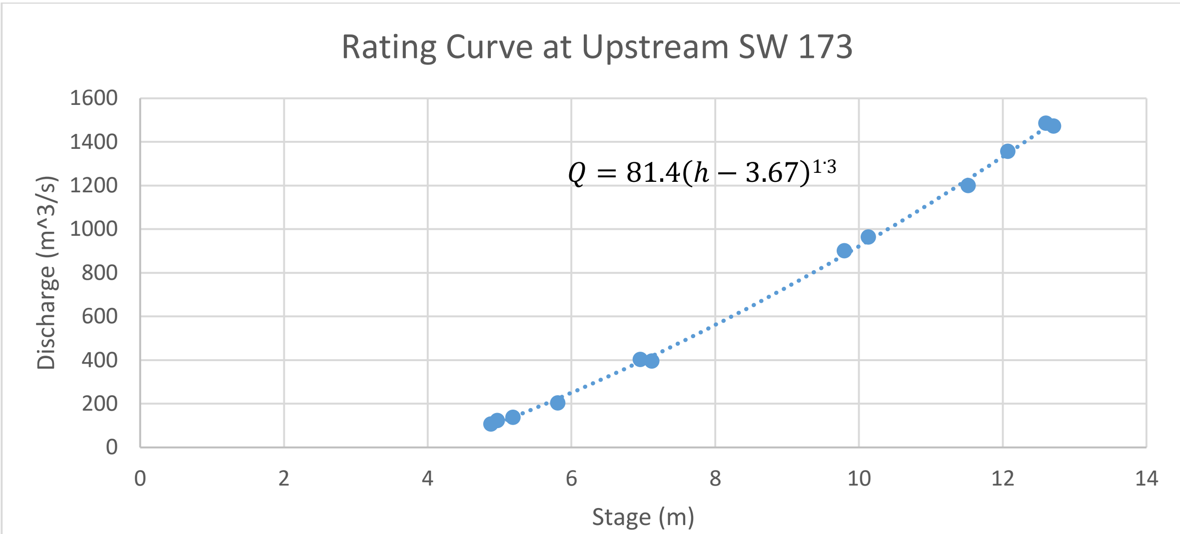

Figure 8-12 Rating curve at upstream Sheola (SW173) of the Kushiyara River

Similarly, a rating curve at downstream station, Markuli **(**SW 270) has been plotted (Figure 8.13) and the value of C_r and β are obtained as 79.3 and 2.03 and water level corresponding to zero discharge is 1.65 m. so the equation becomes.

$$Q = 79.3(h - 1.65)^{2.03}$$

Now using this equation, daily stage data with respect to the daily discharge data were calculated and used in the model.

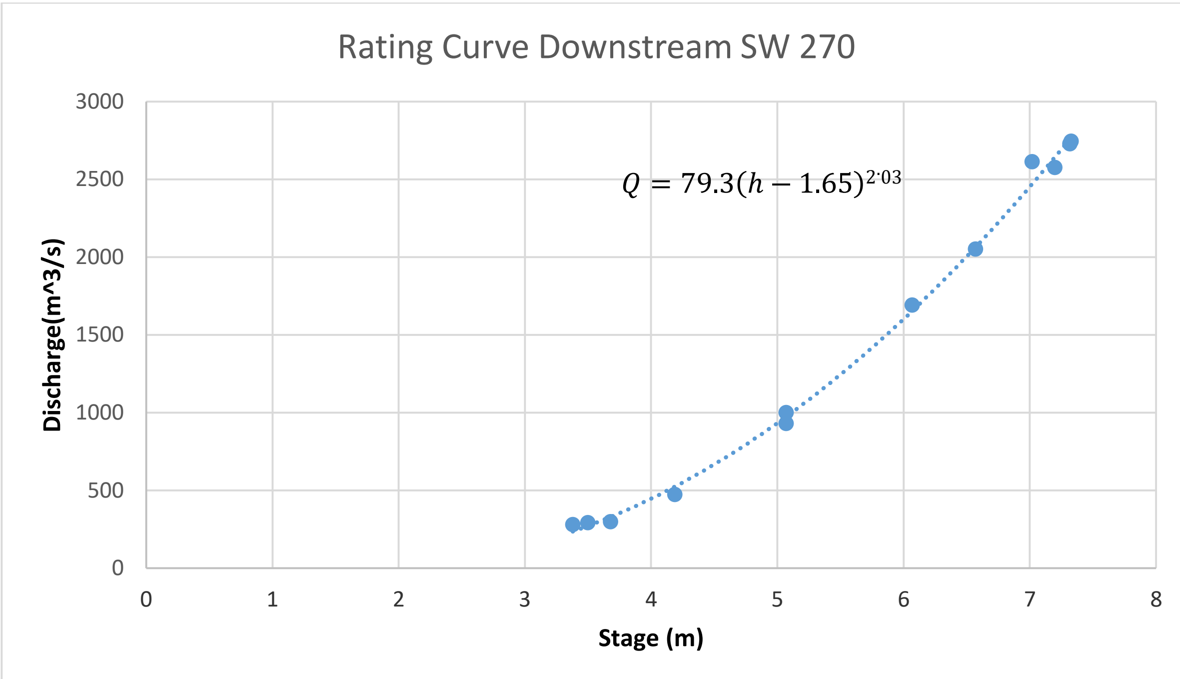

Figure 8-13 Rating curve at downstream Markuli (SW270) of the Kushiyara River

8.2.5 Boundary Conditions

Boundary conditions must be established at all of the open ends of the river system being modeled. Upstream boundary conditions are required at the upstream end of all reaches that are not connected to other reaches or storage areas. Upstream ends of a river system can be modeled with the following types of boundary conditions: flow hydrograph (most common upstream boundary condition); stage hydrograph; flow and stage hydrograph. Downstream ends of the river system can be modeled with the following types of boundary conditions: rating curve, normal depth (Manning’s equation); stage hydrograph; flow hydrograph; stage and flow hydrograph

8.2.5.1 The Surma River

8.2.5.1.1 Upstream Boundary Condition

For setting up an unsteady hydrodynamic model, a flow hydrograph of discharge versus time has been considered as Upstream Boundary Condition. In case of the Surma River, Kanaighat

(SW266; Lat. 25.004°, Long. 92.270°) is the upstream discharge station. Flow hydrograph of the year 2013 of this station has been used as Upstream Boundary Condition (Figure 8.14).

8.2.5.1.2 Downstream Boundary Condition

A stage hydrograph of water surface elevation versus time was used as the downstream boundary condition. For the Surma river, Sunamganj Station (SW269; Lat. 25.071°, Long. 91.410°) is at the downstream end of the Model. Stage hydrograph of the year 2013 of Sunamganj station was used as a Downstream Boundary Condition (Figure 8.15).

8.2.5.2 The Kushiyara River

8.2.5.2.1 Upstream Boundary Condition

For setting up an unsteady hydrodynamic model, a flow hydrograph of discharge versus time has been considered as Upstream Boundary Condition The flow hydrograph of station Sheola (SW173; Lat. 24.887°, Long. 92.190°) has been used as Upstream Boundary Condition of the Kushiyara River. Flow hydrograph of the year 2011 of this station has been used as Upstream Boundary Condition (Figure 8.16).

8.2.5.2.2 Downstream Boundary Condition

A stage hydrograph of water surface elevation versus time was used as the downstream boundary condition. The stage hydrograph of Markuli Station (SW270; Lat. 24.691°, Long. 91.390°) has been used as Downstream Boundary Condition of the Kushiyara River. Stage hydrograph of the year 2011 of this station was used as a Downstream Boundary Condition (Figure 8.17)

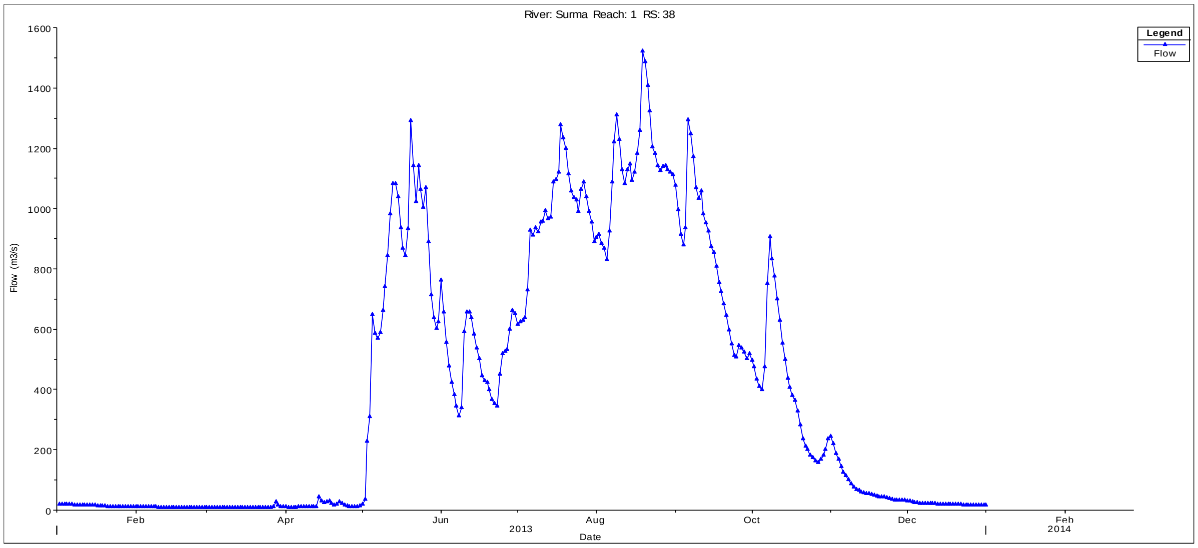

Figure 8-14 Upstream Boundary Condition of the Surma River at Kanaighat (SW 266), Year 2013, (Q vs Time)

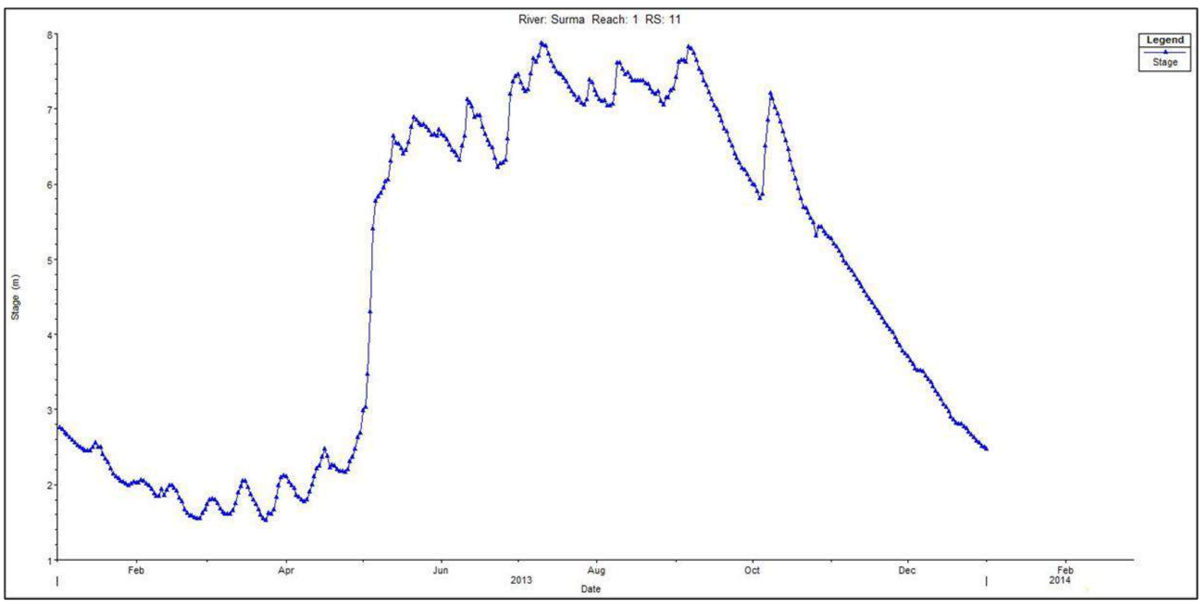

Figure 8-15 Downstream Boundary Condition of the Surma River at Sunamganj (SW 266), Year 2013, (Stage vs Time)

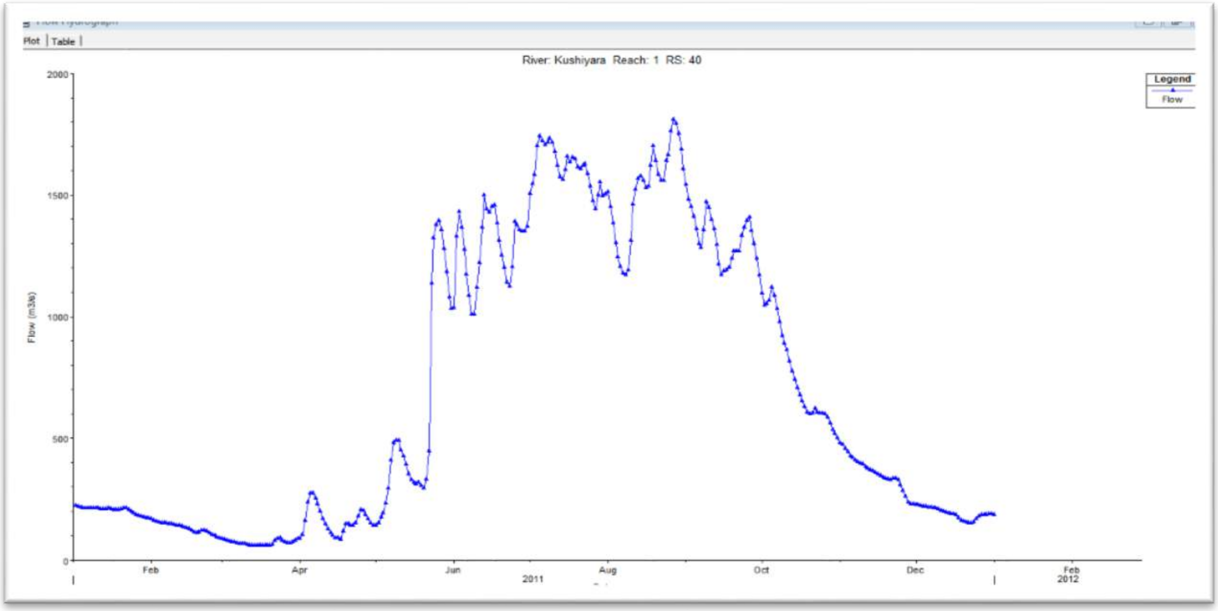

Figure 8-17 Upstream Boundary Condition of the Kushiyara River at Sheola (SW 173), Year 2011, (Q vs Time)

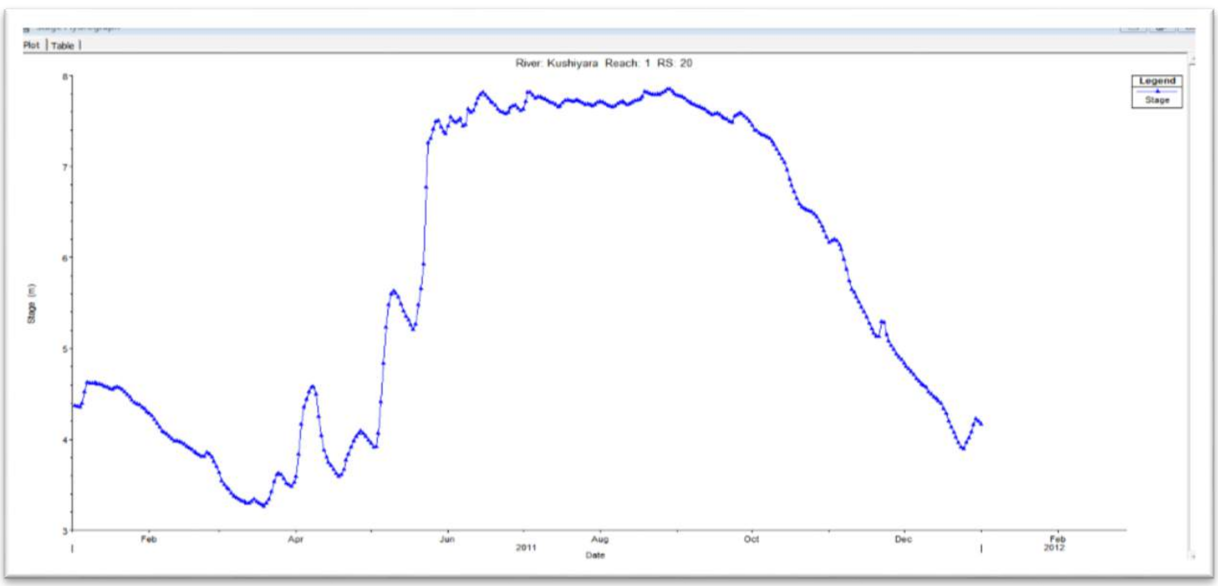

Figure 8-16 Downstream Boundary Condition for the Kushiyara River, at Markuli(SW 270), Year 2011, (Stage vs Time)

8.2.6 Calibration of Model

In general calibration is the setting or correcting of a measuring device or base level, usually by adjusting it to match or conform to a dependably known and unvarying measure (http://whatis.techtarget.com/). To simulate the model with base and different flow conditions, it is necessary to test the model's performance. A set of field data are prerequisite for the testing. This testing provides an impression about the degree of the accuracy of the model in reproducing river processes. This process is known as calibration. Consistent and rational set of theoretically defensible parameters and inputs of the model provide the basis for finalizing these inputs and parameter with good comparison of the model generated outputs with the observed data (Khan et al, 2017). For this study one dimensional HEC-RAS 5.0.3 model has been calibrated hydro-dynamically.

Unsteady flow calibration: Two separate models were developed for the two rivers i.e. The Surma and the Kushiyara. The data regarding to the flood year 2013 and 2011 has been used for calibration of Manning's roughness co-efficient `n' for the Surma River and Kushiyara River respectively. The model has been simulated using the daily hydrograph for the whole year. For this study, effort has been made to calibrate Manning's roughness coefficient for single value using aforesaid data and subsequently, different values have been used to justify their adequacy for simulation of flow in the Surma and the Kushiyara Rivers.

Manning’s ‘n’ value has been calculated as it is the most important parameter for calibration. Because the discharge in a channel is highly depend on it. From the Manning’s equation we know

$$Q = \frac{1}{n} A R^{2/3} S^{1/2}$$

Where: Q = Discharge (m^3/s),

n = Manning's roughness co-efficient `n',

R = Hydraulic Radius (m),

S = Channel Slope (m/m).

8.2.6.1 The Surma River

The calibration graph of the Surma is shown in Figure 8.18. In case of the Surma river for n value of 0.019, the maximum deviation between the observed water level and the Simulated water level in wet season (May to October) was ±4.5% (±50 cm) and in dry season (November to April) (-)18% (-56 cm), which can claim that the model is well calibrated for the Surma river.

When the 'n' value was changed from 0.019 to 0.020, a very well calibrated graph for dry season was observed. But in case of wet season large variation (+)10% (+ 120 cm) between the Simulated and Observed water level is obtained. This is graph shown in Figure 8.19.

From the above discussion it appears that, for the Surma if the point of interest is the wet season flow (May-Oct), 'n' value of 0.019 may be used, on the other hand if the point of interest is the dry season flow (Nov-April), n value of 0.020 may be used.

In this study for model simulation 'n' value of 0.019 has been selected as it is the best fit through all the seasons, and the interest was the bankfull discharge.

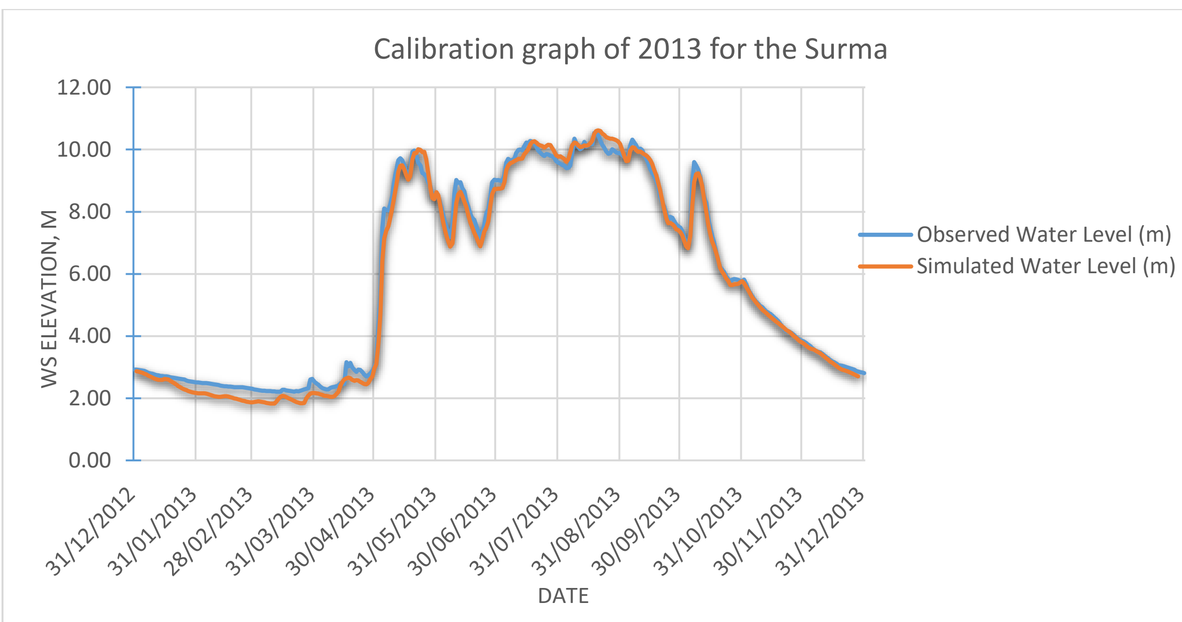

Figure 8-18 Calibration of the Surma River for 'n' value 0.019

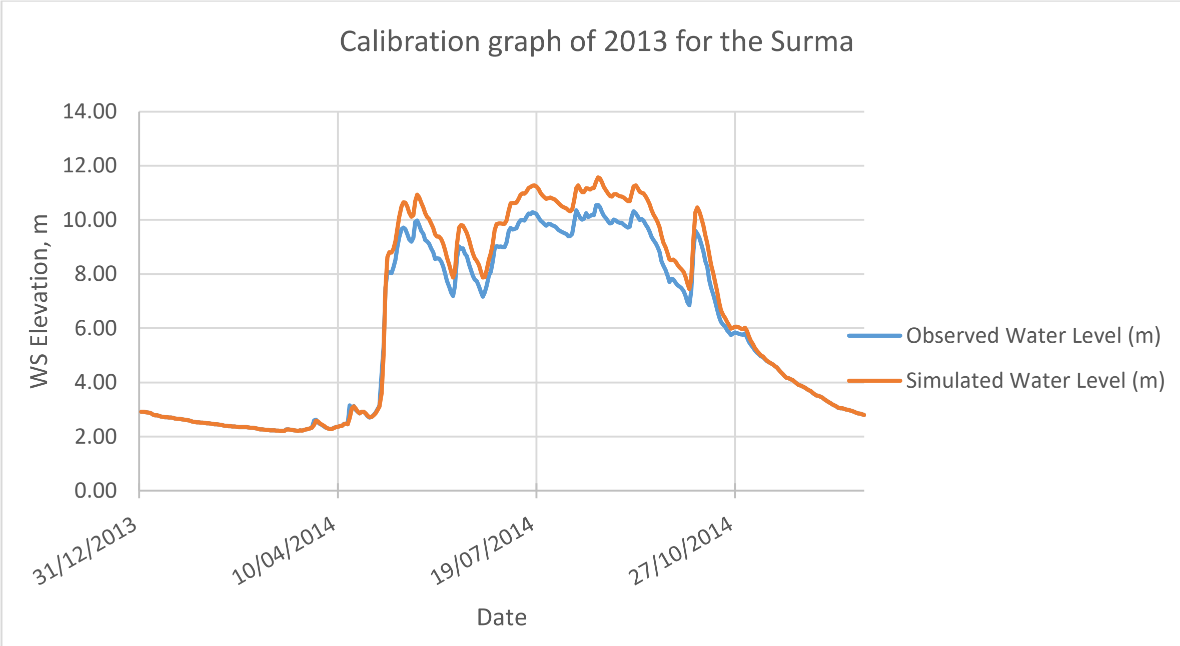

Figure 8-19 Calibration of the Surma River for ‘n’ value 0.020

8.2.6.2 The Kushiyara river

The calibration graph of Kushiyara river is shown in Figure 8.20. For the Kushiyara river for n value of 0.009, the maximum deviation between the observed water level and the Simulated water level in wet season (May to October) was ±1.5% (±13 cm) and in dry season (November to April) was ±1.5% (± 6cm). which can claim that the model is well calibrated for the Kushiyara river. For the Kushiyara ‘n’ Value of 0.009 has been used in the model.

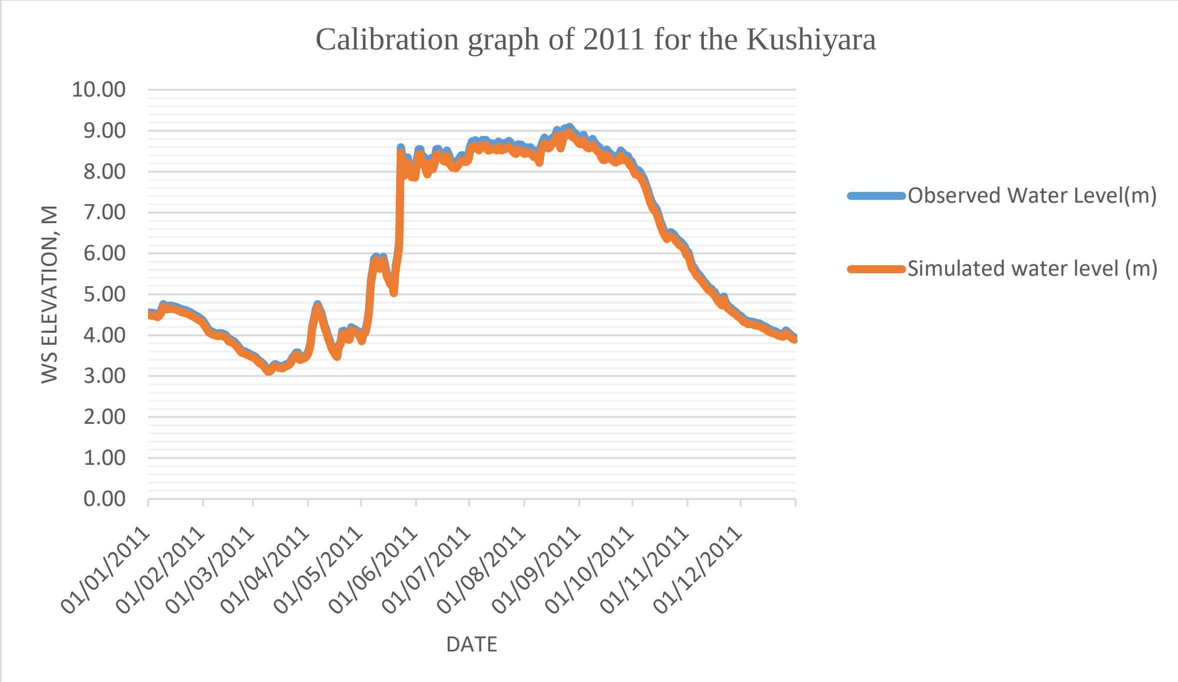

Figure 8-20 Calibration of the Kushiyara River ('n' value 0.009)

8.2.7 Validation of model

A model may be considered to be validated if the model simulated data reasonably match with the observed field data. Model validation involves testing of a model with a data set representing `observed' field data (Khan et al, 2017). It is accomplished by comparing the measured with the simulated data. This data set represents an independent source different from the data used to calibrate the model. Previously calibrated n values of the respective reach of the rivers are used for model validation. Due to the uncertainty of prediction, this step is very important prior to widespread application of model output. The calibrated HEC-RAS 5.0.3 based model has been used to validate the flow for the year 2014 for the Surma river and the year 2012 for the Kushiyara river.

8.2.7.1 The Surma River

The validation graph of the Surma is shown in Figure 8.21. For the Surma river the maximum deviation between the observed water level and the Simulated water level in wet season (May to October) is ±6% (±60 cm) and in dry season (November to April) is ±20% (±55 cm). Which shows that the model is well validated for simulation of the water level of the Surma river.

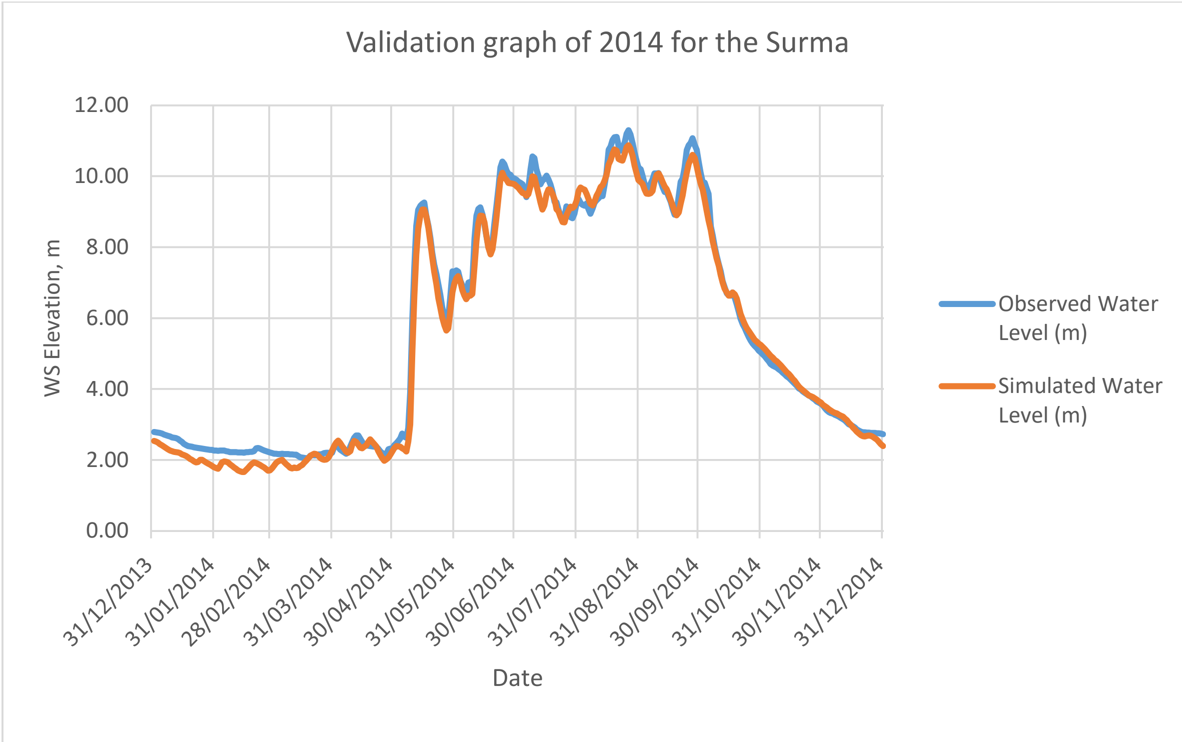

Figure 8-21 Validation of the Surma River

8.2.7.2 The Kushiyara River

The validation graph of the Kushiyara River is shown in Figure 8.22. For the Kushiyara river the maximum deviation between the observed water level and the Simulated water level in the wet season (May to October) is ±4.9% (±14 cm) and in dry season (November to April) is 10% (±8 cm). Which shows that the model is well validated for simulation of the water level of the Kushiyara river.

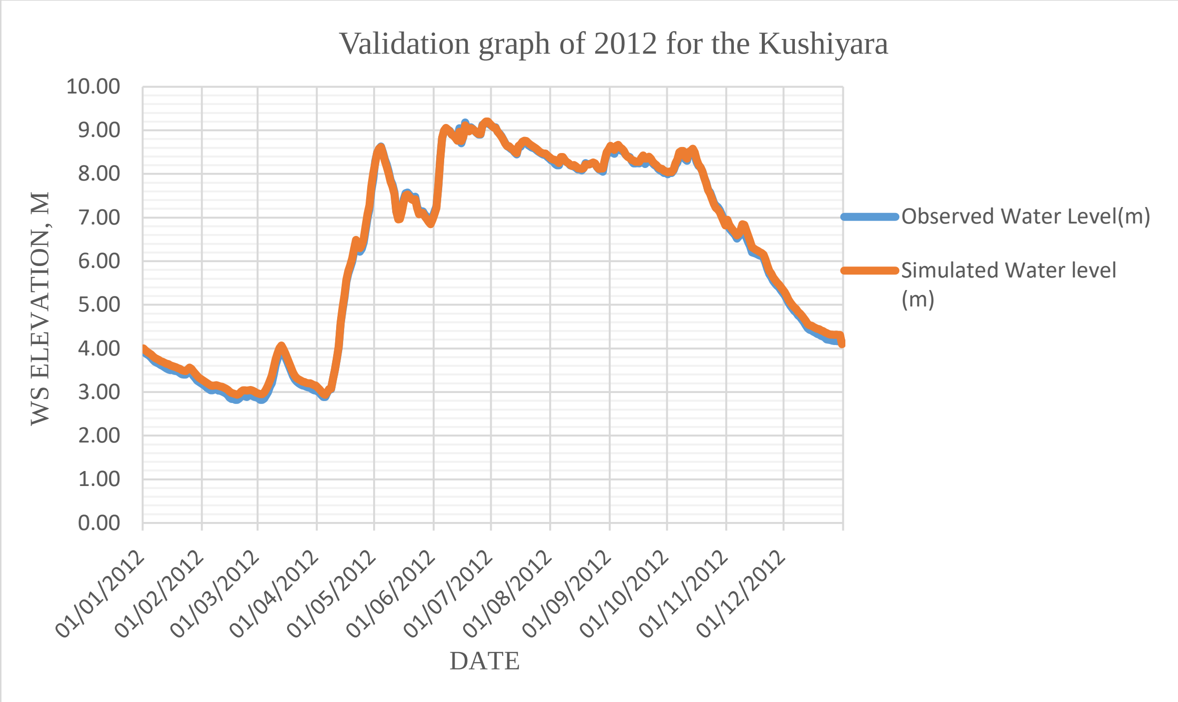

Figure 8-22 Validation of the Kushiyara River

8.3 Applicability of Model

The PSP, 2015 of the project briefly discussed the need and justification of the study as well as its applicability. The main issues in river management in the Sylhet basins are: sedimentation in the river bed, frequent breaching of levee and shifting of the river courses causing pre-monsoon flooding, sand spreading in the haor and on agricultural lands. It has been observed by different researchers that the evolution processes of the rivers in the Sylhet basin are quite different from other parts of the country. Previous studies could not explain (conclusively) the evolution process of the river system in the subsiding basin in a deterministic way. The recent study of the CEGIS (2011) has developed a conceptual model to explain the evolution of the rivers in the subsiding Sylhet basin (haor areas). The model has been used in the morphological study for the Haor Master Plan, 2012. The model was useful in identifying the causes of deterioration of navigability in the Kushiyara River. It also helped in assessment and identification of future development opportunities and in planning of interventions to improve navigability. But this model was developed using scanty of relevant data. Validation of this model could not be done due to constraints of resources.

The model addresses the basic science of the morphological process of the Sylhet basin. The validated model clarifies the evolution process of the river system in the Sylhet Basin. Using this model, the morphological processes observed in the Surma, the Kushiyara and other rivers in this basin could be explained in a realistic way and future scenarios of these rivers could be predicted. This model can also be used for better understanding of the river's behavior and to identify the cause of deterioration of river navigability. Validation of the model will be useful in the planning process of proper and effective management of rivers of the Sylhet basin.

Moreover, the study is very much relevant for detailed design of projects outlined in the Master Plan of Haor Areas, 2012, specially for flood management, drainage improvement and navigation improvement projects.

The Conceptual Model has been validated from the points of (i)theoretical aspect and (ii)through development of a numerical model (HEC-RAS 3.5 model, details are given in Chapter 7).

The developed numerical model can be used as a tool for further morphological studies leading to enhancement of knowledge as well as project planning. The developed model can be used for generation of scenarios and consequent changes, which is of great importance for the planners and designers. Two scenarios were generated using this model (one with 20% increase at upstream and another with 20% decrease of discharge at upstream), details of which have been presented in Chapter 10. The model needs to be updated, if there occur any substantial changes in the catchments of the Surma and Kushiyara rivers. Similar models can be developed for other rivers of the region and may finally be coupled (together) to form a General Model for the region.

9 Validation of the CEGIS Conceptual Model Hypotheses

The conceptual model on the Hydro-morphological process of the river systems in the subsiding Sylhet basin developed by CEGIS has been validated by both the means of analyzing historical data (conventional analysis) and simulated data generated by setting up a numerical model namely HECRAS-2D. Both primary and secondary data have been collected and used in the analysis process. Five hypotheses have been extracted from the CEGIS conceptual model (details in Chapter 5).

9.1 Hypothesis 1

The Hypothesis 1 states that **the bankfull water level of the channel in concern varies in the downstream direction**. **At the upstream, it is high and close to annual average flood discharge.** To validate this Hypothesis, bankfull water levels of the Surma and the Kushiyara from both historical and simulated data have been analyzed.

9.1.1 Conventional Analysis

The Surma:

Bankfull Water level data for 2009, 2011 and 2014 have been shown in Table 9.1 and plotted in the graph for 2009 (Figure 9.1). The locations of the cross sections are shown in Figure 6.7. Here, RMS34 is the most upstream section and RMS1 is the most downstream section in the Surma river reach. From the data, it can be seen that the bankfull water levels at the downstream sections of the river reach are always lower than the bankfull water levels at the upsteam sections of the river reach. **This analysis validates the Hypothesis 1 which describes that the bankfull water level of the channel varies in the downstream direction ($Y_A > Y_B > Y_C$).**

Table 9.1 Bankfull Water Level Data Analysis between Upstream and Downstream Sections

Cross Section Station ID, BWDB	Corresponding Water Level Station ID, BWDB	RL of Left Bank (mPWD)	RL of Right Bank (mPWD)
2009			
RMS34	-	13.22	14.4
RMS30	SW267	10.36	10.88
RMS20	SW268	8.77	10.45
RMS10	SW269	7.21	7.1
RMS1	SW269.5	6.78	6.51
2011			
RMS34	-	13.16	14.1
RMS30	SW267	11.5	10.85
RMS20	SW268	8.6	10.36
RMS10	SW269	7	7.11
RMS1	SW269.5	6.79	6.68
2014			
RMS34	-	12.96	13.8
RMS30	SW267	11.5	10.85
RMS20	SW268	8.6	10.21
RMS10	SW269	7.11	8
RMS1	SW269.5	6.79	6.68

[Source: BWDB]

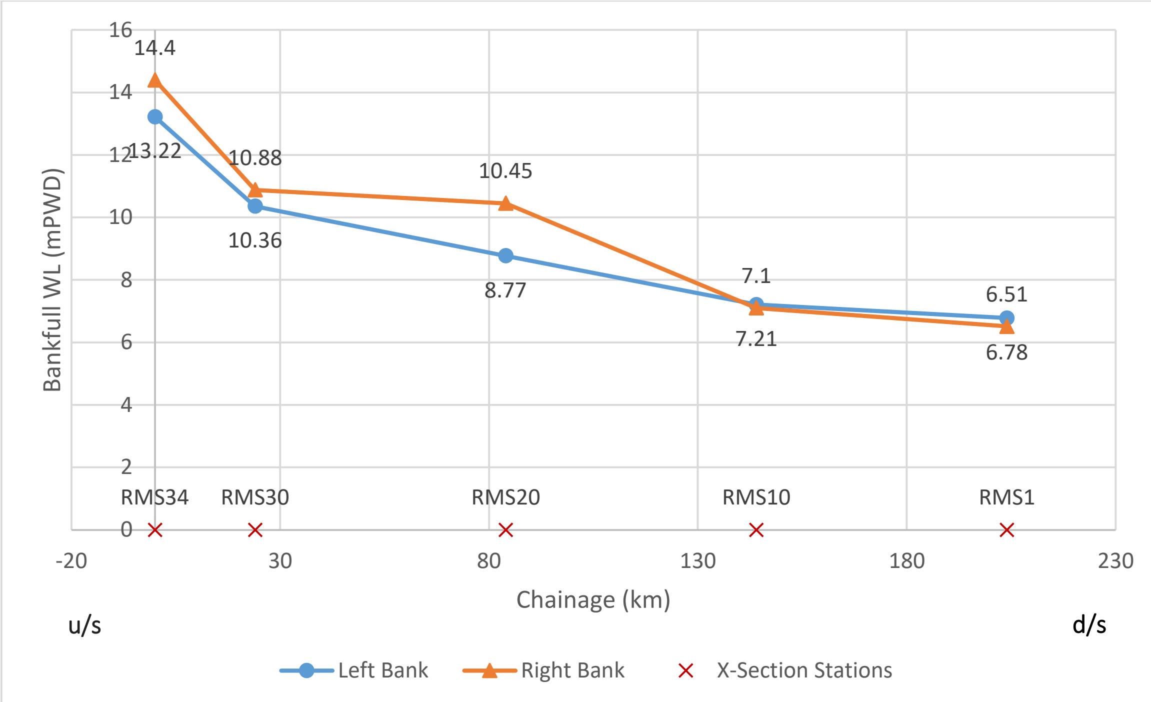

Figure 9-1 Bankfull Water Level of the Surma (2009)

The **Hypothesis 1** also implies that in most days in a year, the river flow is confined within the bank. On the other hand, the bankfull water level at the downstream is much lower and the overbank flow occurs for several months during the monsoon. To validate this assumption, stage hydrographs for the Water Level Stations on the Surma rivers have been plotted (Figure 9.2 to Figure 9.6). The Water Level data have been selected for 2009, 2011 and 2014, as the latest corresponding cross section data on the Surma River is available for those years only. Here, the most upstream section on the reach is SW266 (Kanairghat), while the most downstream section is SW269 (Sunamganj). The corresponding bankfull water level of the Water Level Stations are shown in the stage hydrographs in dashed line. The bankfull water level gives the indication of the extent of flood in the adjacent areas of the water level stations.

From the stage hydrograph of SW266 (Figure 9.2), it can be said that almost no flood occurred in the section. The water level peaked at 14.15 mPWD in August, where the bankfull water level is 14.

From Figure 9.3, it is seen that at station SW267, the flood period was from early July to early September (about 2 months, peak in August; 11.21 mPWD). Further downstream at Station 268 (Figure 9.4), the flooded period was from mid-June to mid-October (about 4 months, peak in August; 9.82 mPWD). In the most downstream section (SW269) in Figure 9.5, the extent of the flooding was from early June to mid-October (approximately 3.5 months). The bankfull water level was 6.85 mPWD, while the peak water level was at 8.77 in August. This shows that in August, the flooding water level over the bankfull water level at SW269 was 1.92 m (Figure 9.5), which is very high in comparison with the upstream sections.

This phenomenon validates the Hypothesis 1 of the conceptual model of the CEGIS for the Surma which states that flooding occurs in the downstream direction of a river reach.

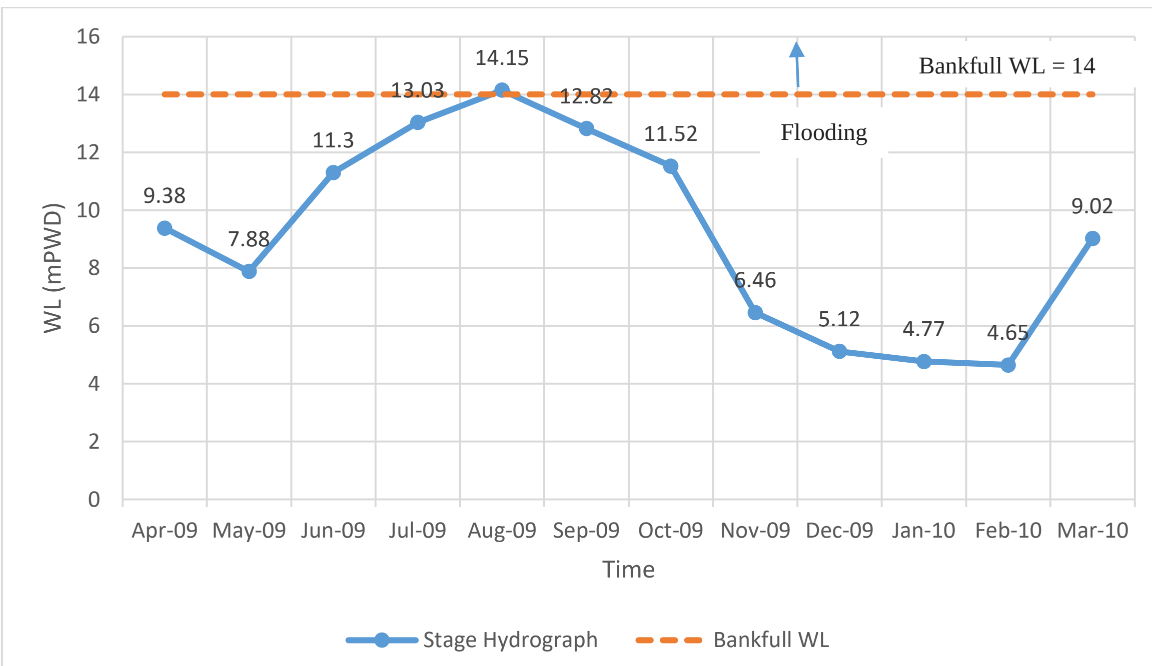

Figure 9-2 Stage Hydrograph of SW266 (Kanairghat; 2009-10)

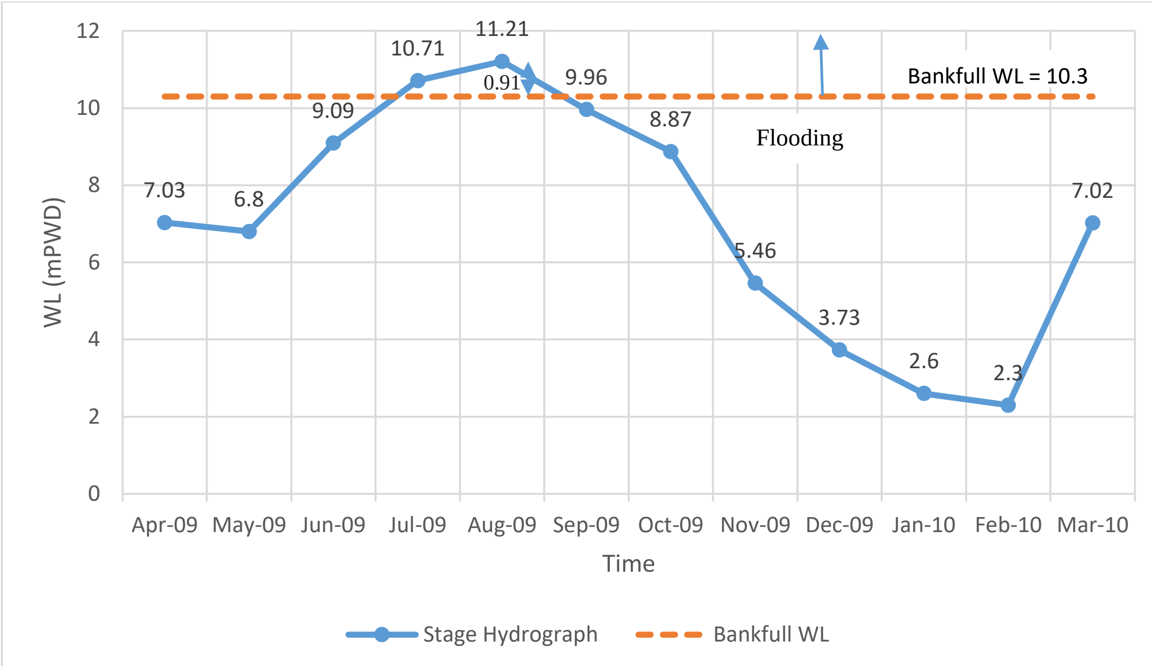

Figure 9-3 Stage Hydrograph of SW267 (Sylhet; 2009-10)

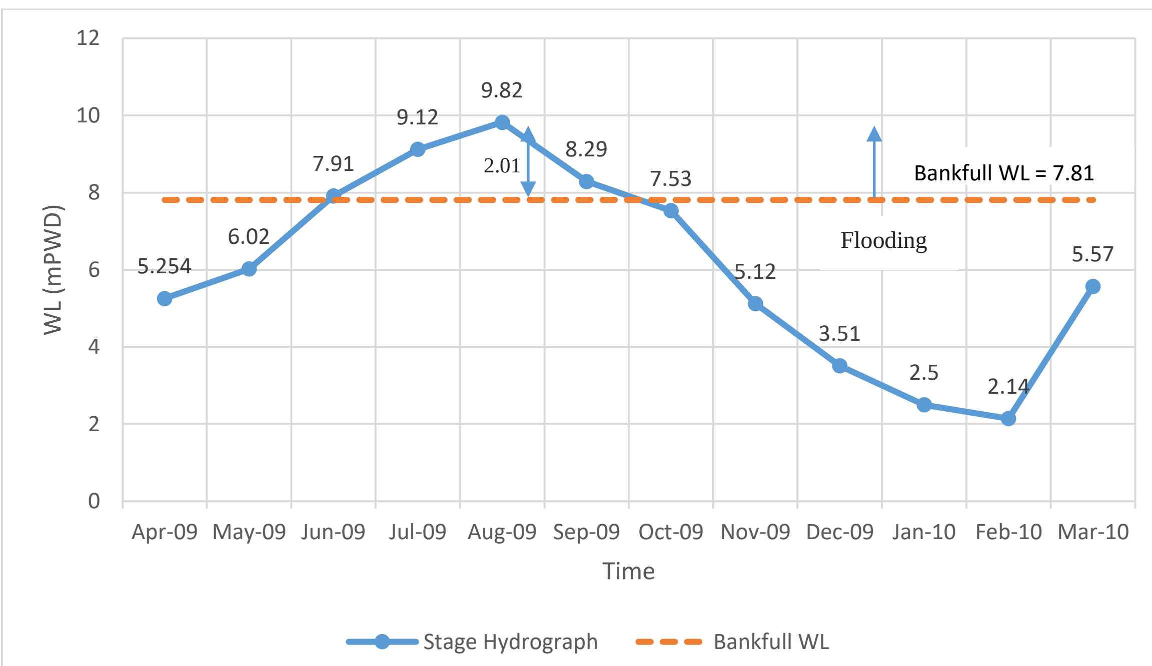

Figure 9-4 Stage Hydrograph of SW268 (Chhatak; 2009-10)

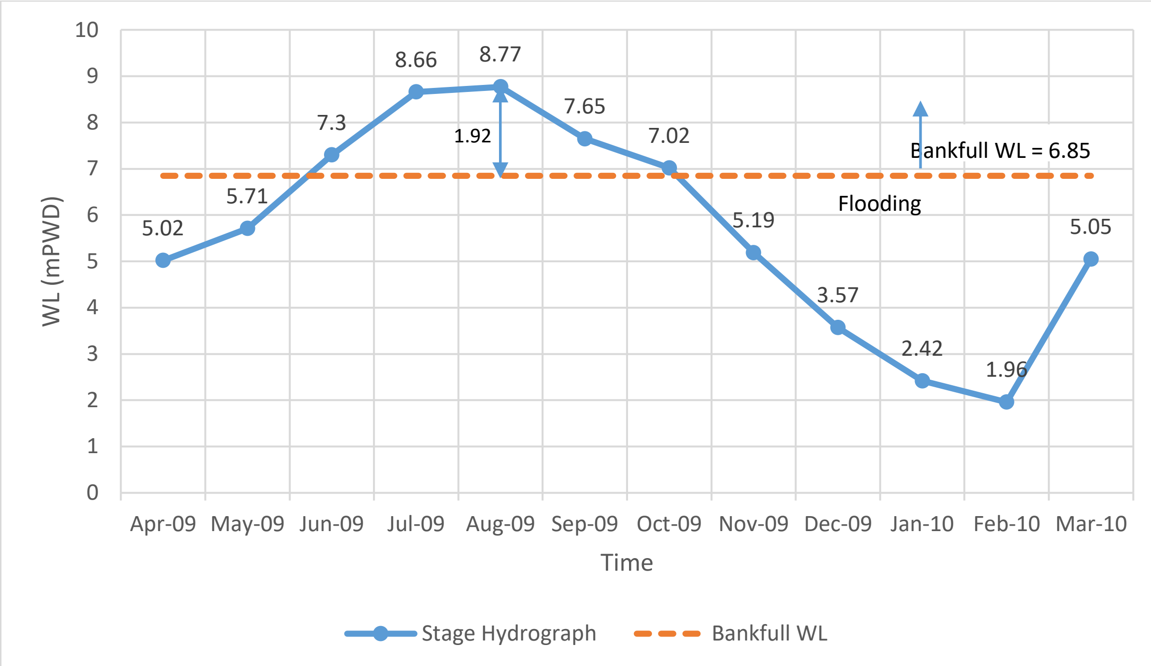

Figure 9-5 Stage Hydrograph of SW269 (Sunamganj; 2009-10)

The Kushiyara:

Bankfull Water level data for 2006, 2008 and 2010 have been shown in Table 9.2 and plotted in the graph for 2006 (Figure 9.6). The locations of the cross sections are shown in Figure 6.11. Here, RMKUS12 is the most upstream section and RMKUS1 is the most downstream section in the Kushiyara river reach. From the data, it can be seen that the bankfull water levels at the downstream sections of the Kushiyara river reach are lower than the bankfull water levels at the upsteam sections of the river reach for most of the sections. **This analysis validates the Hypothesis 1 which describes that the bankfull water level of the channel varies in the downstream direction (Y_A>Y_B>Y_C).**

Table 9.2 Bankfull Water Level Data Analysis between Upstream and Downstream Sections

Cross Section Station ID, BWDB	Corresponding Water Level Station ID, BWDB	RL of Left Bank (mPWD)	RL of Right Bank (mPWD)
2006			
RMKUS12	SW172	13.14	14.09
RMKUS7	-	11.72	11.66
RMKU5	SW174	14.09	11.32
RMKU1	SW175.5	10.9	10.8
2008			
RMKUS12	SW172	13.46	14.21
RMKUS7	-	11.3	11.78
RMKU5	SW174	13.9	11.32
RMKU1	SW175.5	10.7	11.2
2010			
RMKUS12	SW172	17	20.6
RMKUS7	-	11.41	11.89
RMKU5	SW174	12.6	11.65
RMKU1	SW175.5	11.1	11

[Source: BWDB]

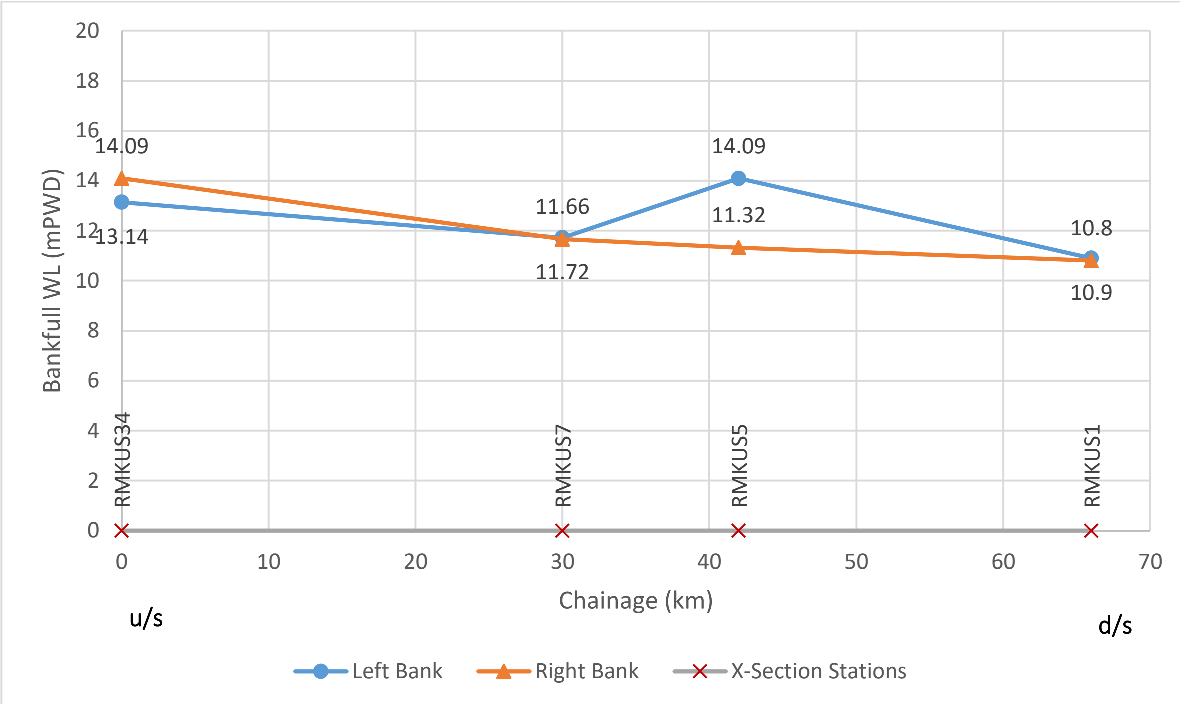

Figure 9-6 Bankfull Water Level of the Kushiyara (2006)

The Hypothesis 1 also implies that in most days in a year, the river flow is confined within the bank. On the other hand, the bankfull water level at the downstream is much lower and the overbank flow occurs for several months during the monsoon. To validate this assumption, stage hydrographs for the Water Level Stations on the Kushiyara rivers have been plotted (Figure 9.7 to Figure 9.10). The Water Level data have been selected for 2008, 2010 and 2013, as the latest corresponding cross section data on the Kushiyara River is available for those years only. Here, the most upstream section on the reach is SW173 (Sheola), while the most downstream section is SW270 (Markuli). The corresponding bankfull water level of the Water Level Stations are shown in the stage hydrographs in dashed line. The bankfull water level gives the indication of the extent of flood in the adjacent areas of the water level stations.

From the stage hydrograph of SW173 (Figure 9.7), it can be said that no flood occurred in the section. The water level peaked at 9.47 mPWD in July 2012, where the bankfull water level was 12 mPWD.

From Figure 9.8, it is seen that at station SW174, the flood period was from late May to early October (about 4.5 months, peak in July; 8.95 mPWD). Further downstream at Station SW175.5 (Figure 9.9), the flooded period was from mid-May to late October (about 5.5 months, peak in October; 9.5 mPWD). In the most downstream section (SW270) in Figure 9.10, the extent of the flood was from mid-May to late October (approximately 5.5 months). The bankfull water level was 7.2 mPWD, while the peak water level was at 8.73 in mid-June. This shows that the flooding water level over the bankfull water level at station SW 175.5 was 1.75 m in October (Figure 9.9), which is high in comparison with the upstream sections.

This phenomenon validates the Hypothesis 1 of the conceptual model of the CEGIS for the Kushiyara which states that flooding occurs in the downstream direction of a river reach is greater than that of the upstream area.

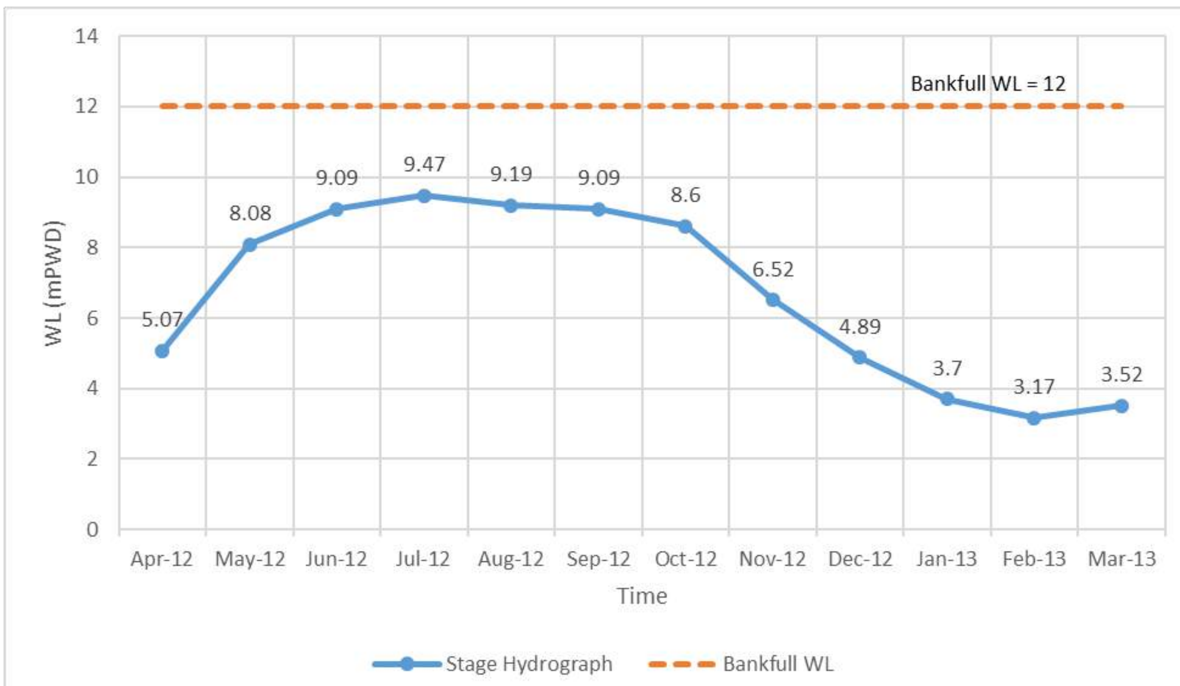

Figure 9-7 Stage Hydrograph of SW173 (Sheola; 2012-13)

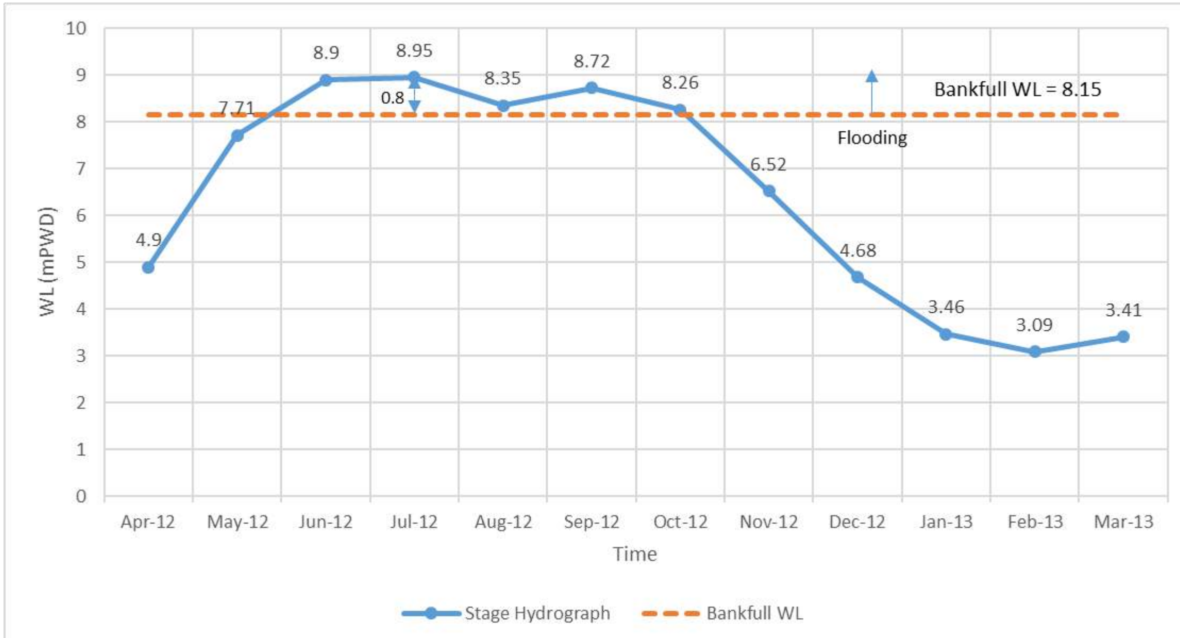

Figure 9-8 Stage Hydrograph of SW174 (Fenchuganj; 2012-13)

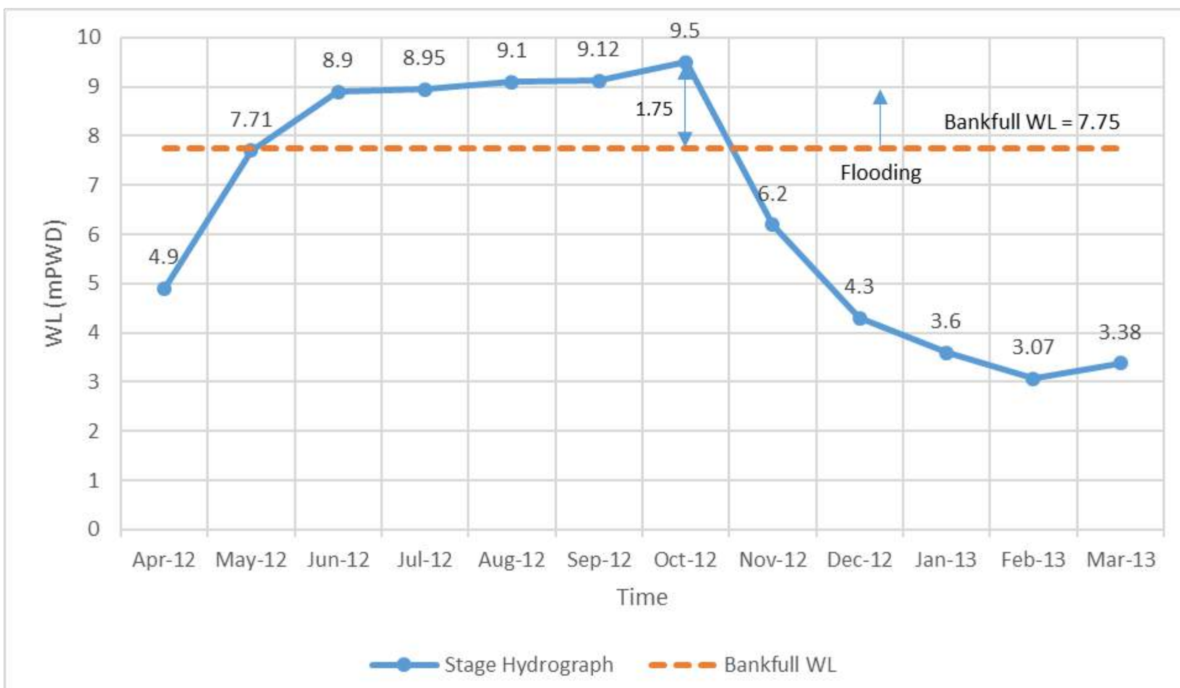

Figure 9-9 Stage Hydrograph of SW175.5 (Sherpur; 2012-13)

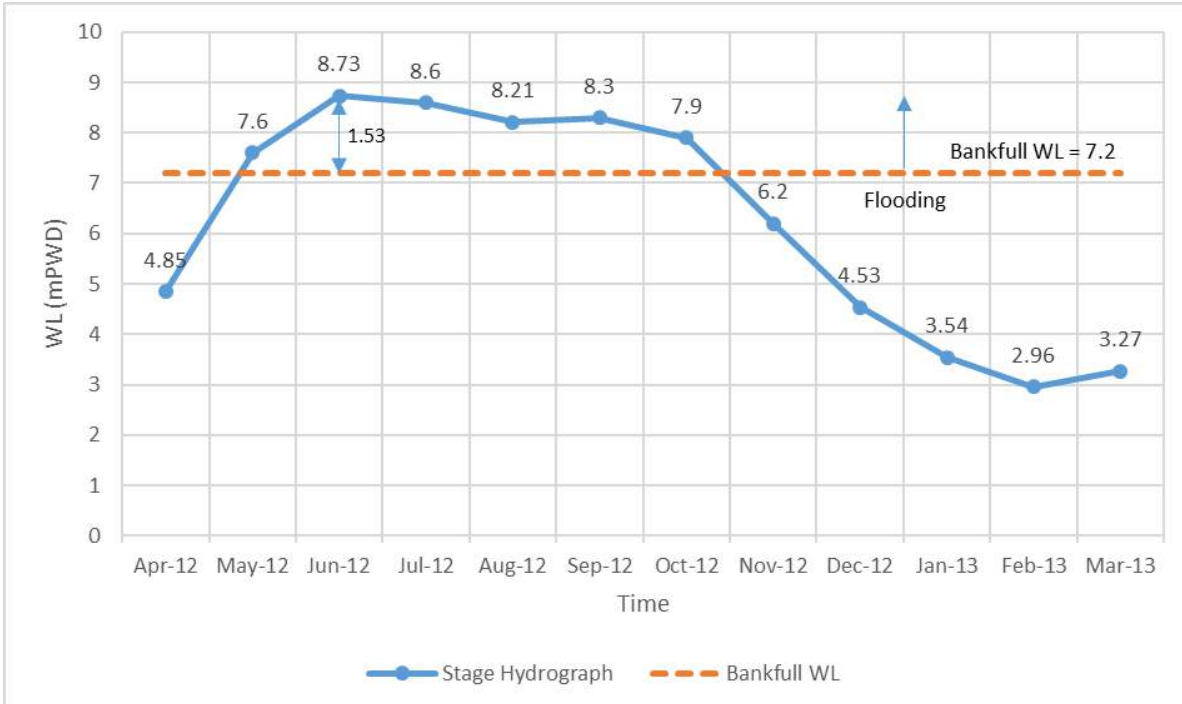

Figure 9-10 Stage Hydrograph of SW270 (Markuli; 2012-13)

9.1.2 Model Output Analysis

The Surma:

To validate Hypothesis 1, simulation was done for July 2014 and resulting bankfull water levels at upstream (section RS 38), at downstream (RS 11) and three intermediate stations at RS 31, 26 and 20 have been observed. Location of the station have been shown in Figure 6.3.

Let us assume that water levels at RS 38, RS 31, RS 26, RS 20 and RS 11 are Y_a, Y_b, Y_c, Y_d and Y_e respectively. The simulated result in the long profile of the river shows that when there is bankfull water level at upstream, there is a little overflow in the intermediate sections and noticeable overflow in the downstream section (Table 9.3). This is summarized in the following table.

Table 9.3 Simulated Bankfull Water Levels in the Surma River, July 2014

Location	Station Name, ID, Location	Corresponding WL Station ID	Bankfull Water Level (m)	Water Level (m)	Overflow Depth (m)
Upstream	RS 38 (RMS38) Kanaighat	SW 266	13.34 (Y_a)	13.34	0
Intermediate section	RS 31 (RMS31)		10.49(Y_b)	12.09	1.60
Intermediate section	RS 26 (RMS26) Sylhet Sadar	SW 267	9.98 (Y_c)	11.54	1.56
Intermediate section	RS 20 (RMS20)		8.92 (Y_d)	10.13	1.21
Downstream	RS11 (RMS11) Sunamganj	SW 269	7.4 (Y_e)	9.5	2.1

It is observed from the table that bankfull water level decreases towards downstream.

$Y_a > Y_b > Y_c > Y_d > Y_e$

Simulated longitudinal profile of the Surma is given in Figure 9.11.

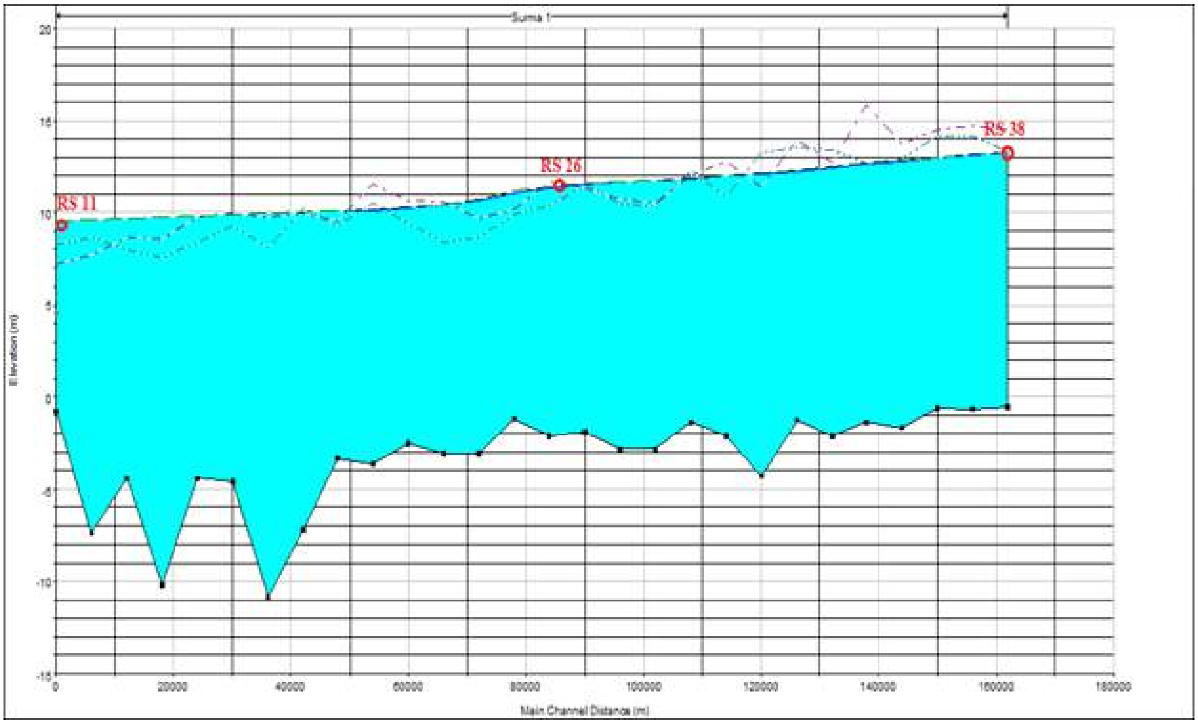

Figure 9-11 Simulated Longitudinal Profile of the Surma River (July 2014)

During the simulated bankfull water level at upstream section (RS38), corresponding water levels at the intermediate and downstream sections are shown in Figures 9.12-9.16.

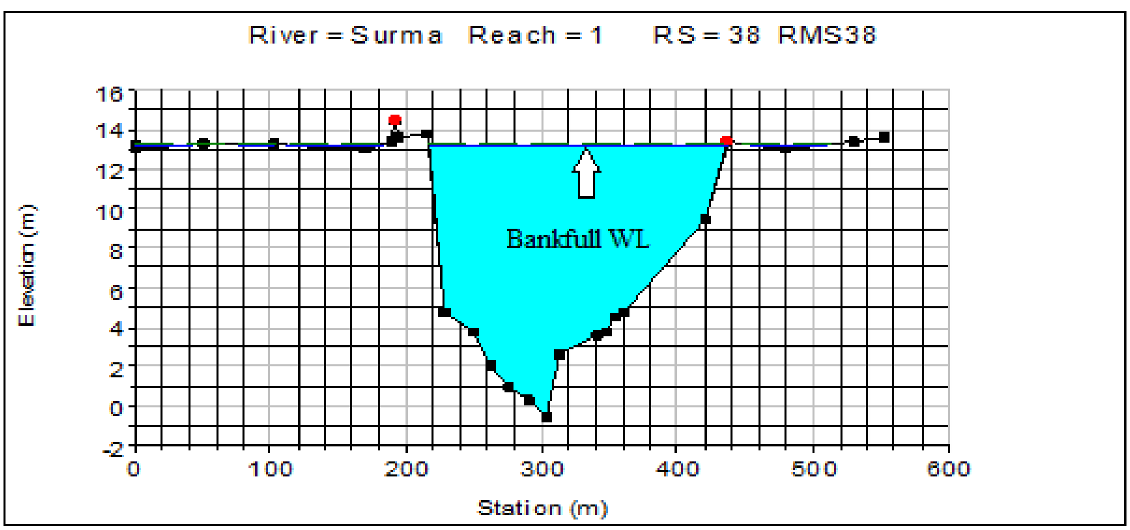

Figure 9-12 Simulated Water Level at Upstream (Kanaighat, RS 38, July 2014)

Figures 9.3 to 9.6 show the simulated water levels (July 2014) at sections RS31, RS26, RS20 and RS11 respectively, when water level at the upstream (RS38) is at bankfull level.

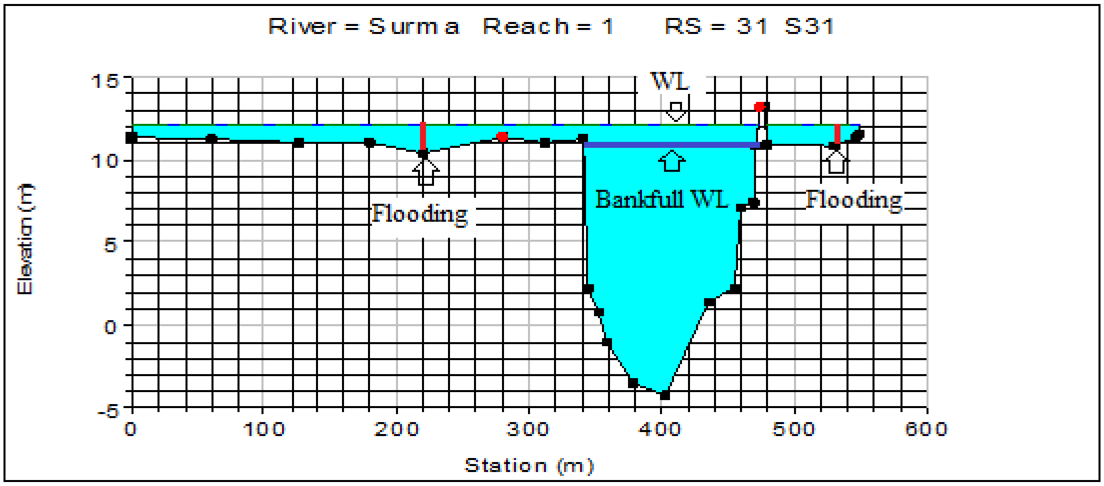

Figure 9-13 Simulated Water Level at RS 31 (July 2014)

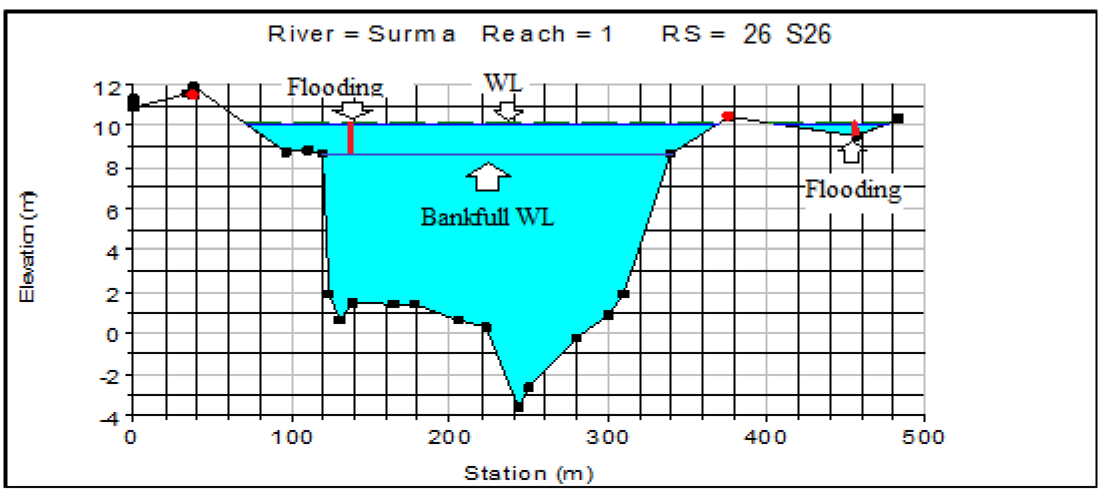

Figure 9-14 Simulated Water Level at RS 26 (July 2014)

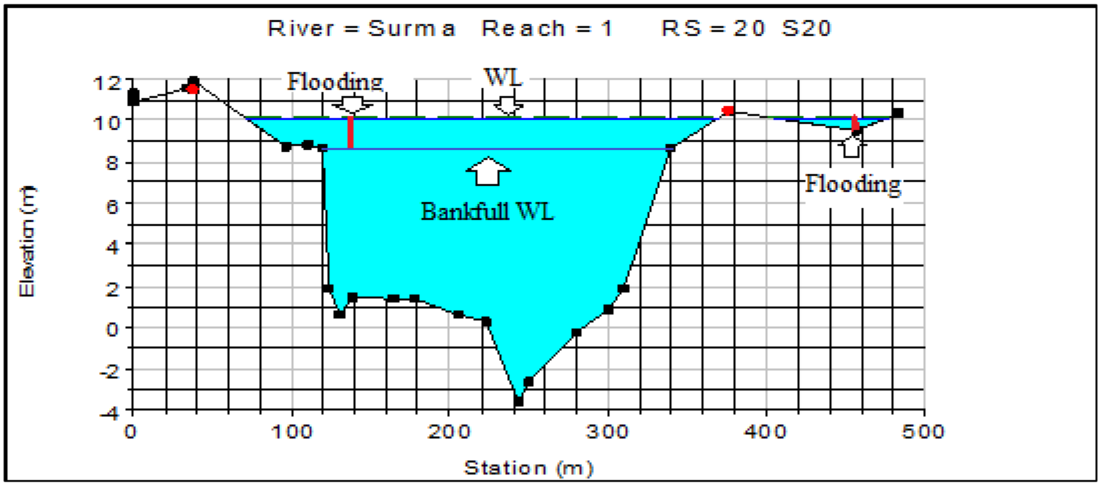

Figure 9-15 Simulated Water Level at RS 20 (July 2014)

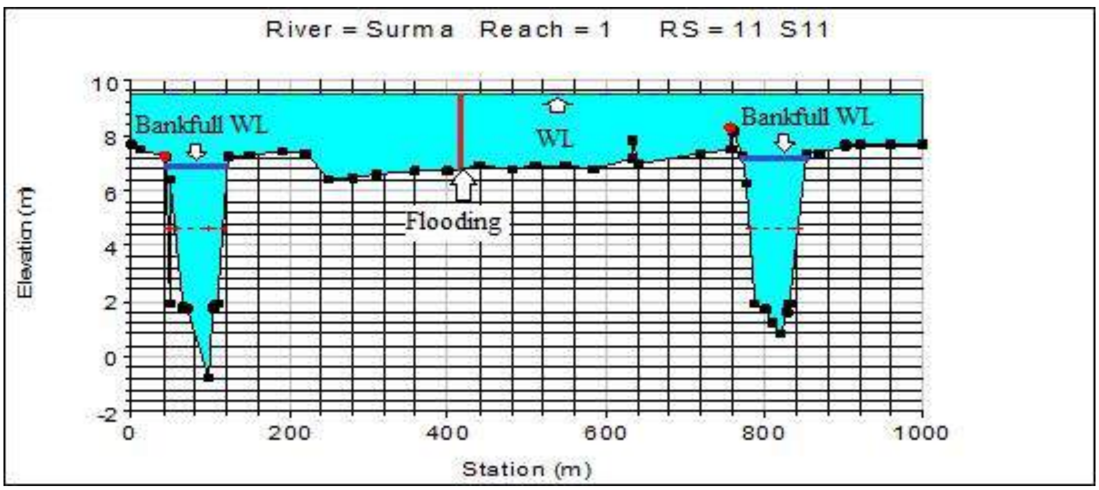

Figure 9-16 Simulated Water Level at Downstream (Sunamganj, RS 11, July 2014)

When there is bankfull discharge at station RS 38, upstream (Fig 9.12), there is moderate floods at intermediate stations (Figure 9.13, 9.14 and 9.15) and comparatively larger floods at RS 11 (downstream, Fig 9.16). It is further observed that at RS 11, the river developed two channels.

Bankfull water level vs channel distance for the selected 5 stations (RS 38, RS 31, RS 26,RS 20 and RS 11)has been plotted (Fig: 9.17) The Trend line shows a increasing trend from downstream to upstream (R= +0.97). **Conversely, it may be stated that the trend line of bankfull water level shows a decreasing trend from upstream to downstream.**

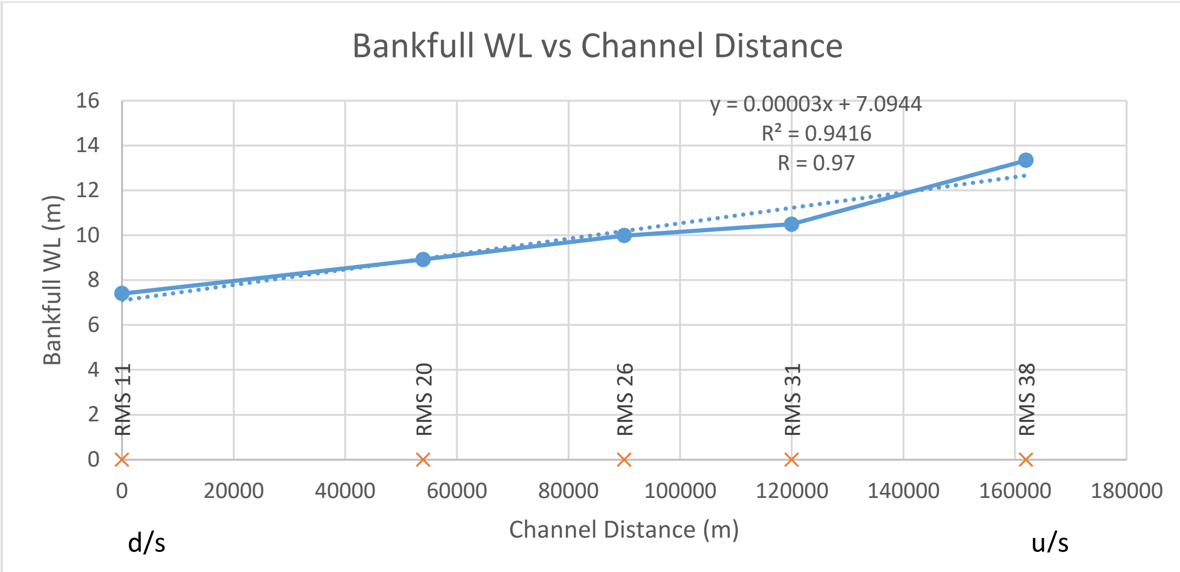

Figure 9-17 Bankfull Water Level vs Channel Distance of the Surma (2014)

To validate the hypothesis, stage hydrographs for the Water Level Stations on the Surma river have been plotted (Figures 9.18-9.22). Five stations have been selected, they are: RS 38 (upstream), RS 31, RS 26, RS 20 and RS 11 (downstream).

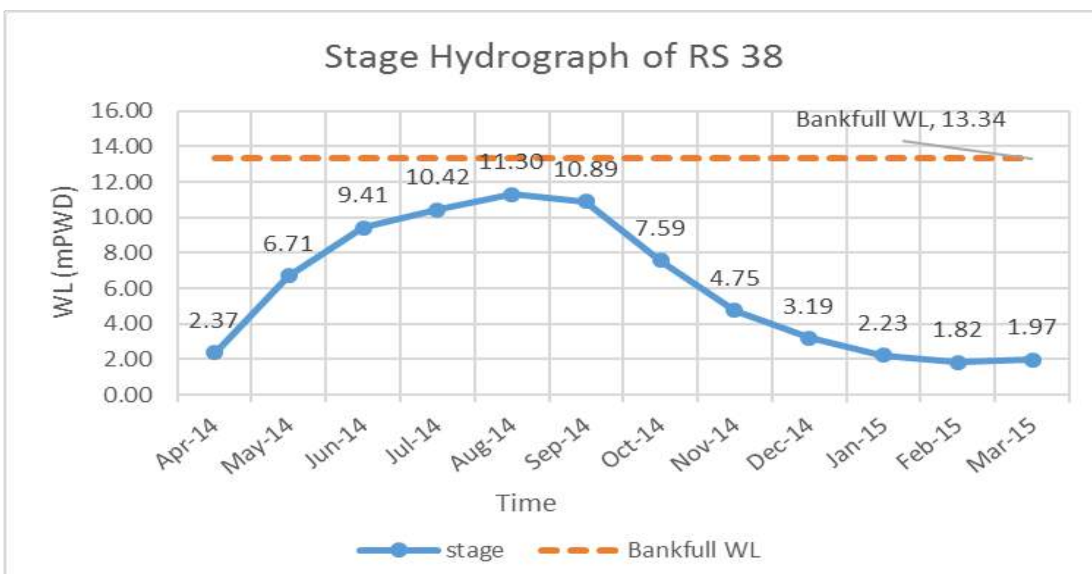

Figure 9-18 Simulated Stage Hydrograph for RS 38 (upstream) of the Surma, 2014-15

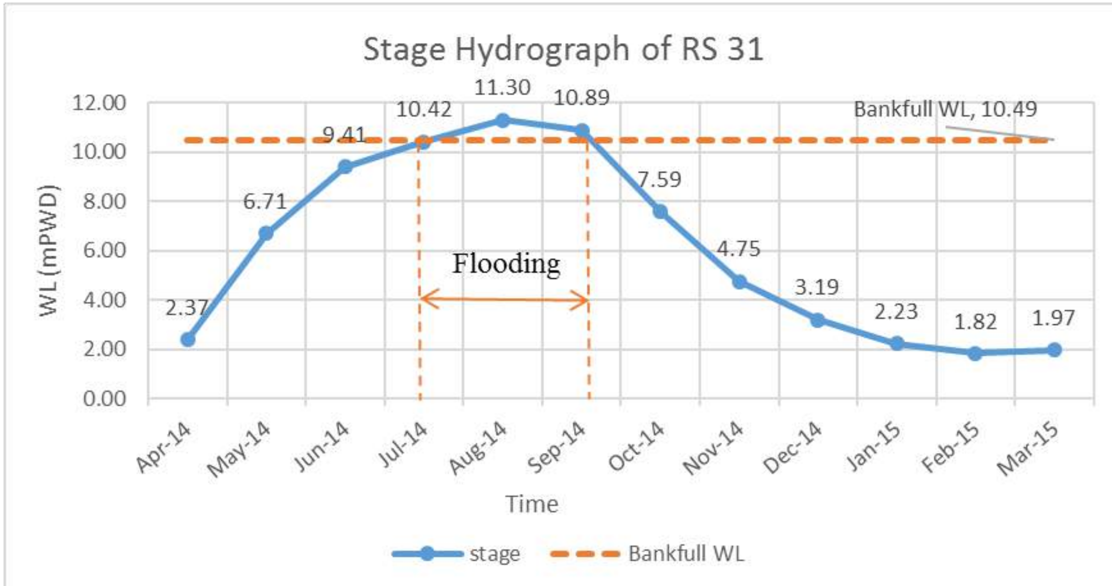

Figure 9-19 Simulated Stage Hydrograph for RS 31 (an intermediate section) of the Surma, 2014-15

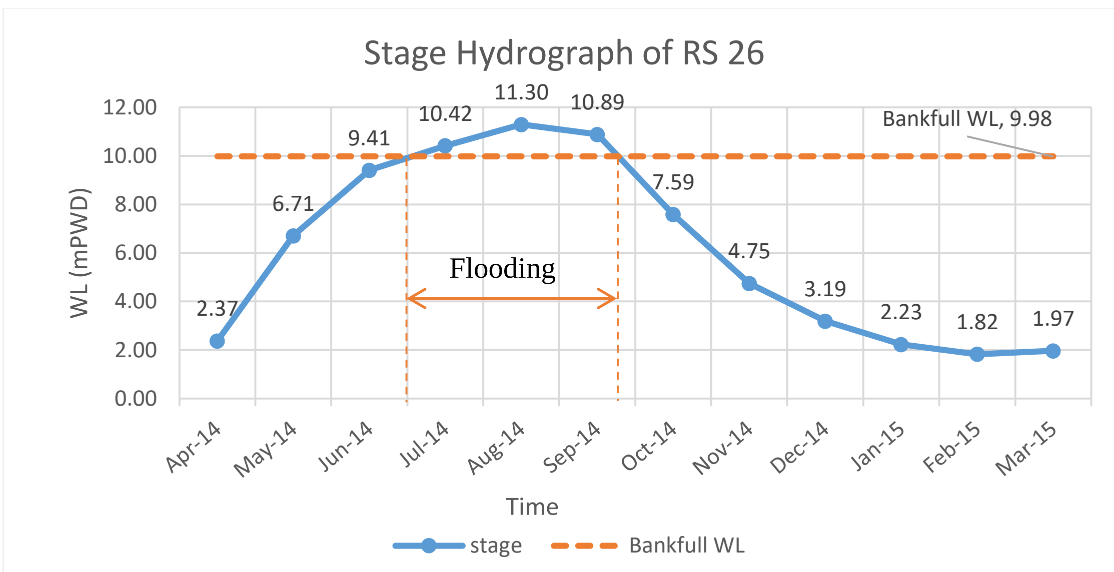

Figure 9-20 Simulated Stage Hydrograph for RS 26 (an intermediate section) of the Surma, 2014-15

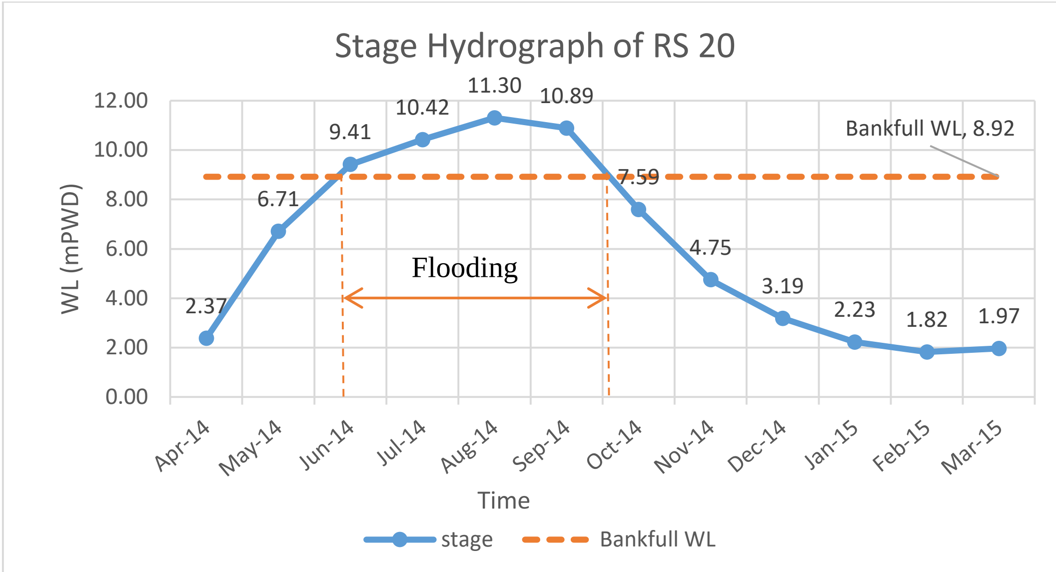

Figure 9-21 Simulated Stage Hydrograph for RS 20 (an intermediate section) of the Surma, 2014-15

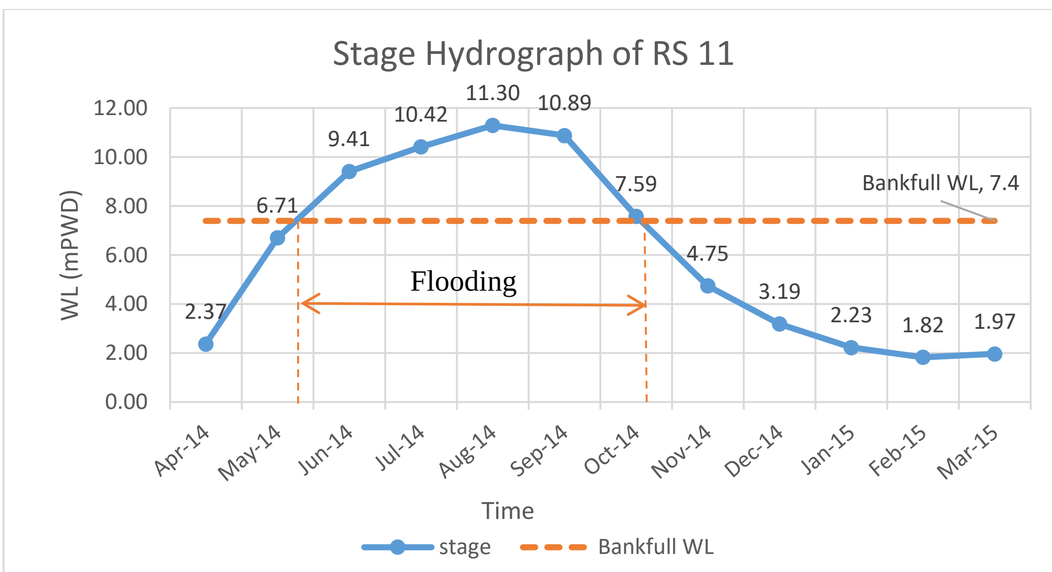

Figure 9-22 Simulated Stage Hydrograph for RS 11 (Downstream) of the Surma, 2014-15

From the stage hydrograph of RS 38 (Figure 9.18), it is observed that no flood occurred in the section, where the bankfull water level is 13.8.

From Figure 9.19, it is observed that at station RS 31, the flood period was from mid-July to mid-September (2 months). Further downstream at Station RS 26 (Figure 9.20), the flood period was from mid-June to early October (3.5 months). At RS 20, it is from mid-June to early October (3.5 months) (Figure 9.21). In the most downstream section (RS 11), the extent of the flood was from mid-May to mid-October (approximately 5 months) (Figure 9.22).

So it can be concluded that bankfull water level $Y_a>Y_b>Y_c>Y_d>Y_e$ and the downstream area remain flooded for a longer period than that of the upstream areas hence **the hypothesis 1 can be accepted for the Surma.**

The Kushiyara:

Similar analysis was done for the river Kushyara and the simulated water level July 2012 are shown in the following table:

Table 9.4 Simulated Bankfull Water Levels of the Kushiyara River, July 2012

Location	Station name, ID, Location	Corresponding WL Station	Bankfull Water Level (m)	Water Level (m)	Overflow Depth (m)
Upstream	RS 40 (KUS12) (Sheola)	SW173	12.5(Y_a)	12.5	0
Intermediate section	RS 34 (KUS6) (Fenchugonj)	SW174	10(Y_b)	11.5	1.5
Intermediate section	RS 28 (BIB1) (Sherpur)	SW175.5	9.5 (Y_c)	10.5	1
Downstream	RS 20 (BIB9) (Markuli)	SW 270	8.1(Y_d)	9.5	1.4

Location of the station have been shown in Figure 6.9. It is observed that when there is bankfull water level at upstream (RS 40), which is 12.5 meters, there is 1.5m flood in an intermediate section (RS 34) and 1m flood in RS 28 and 1.4m flood at the downstream (RS 11). It can also be observed from the following longitudinal profile (Fig 9.23).

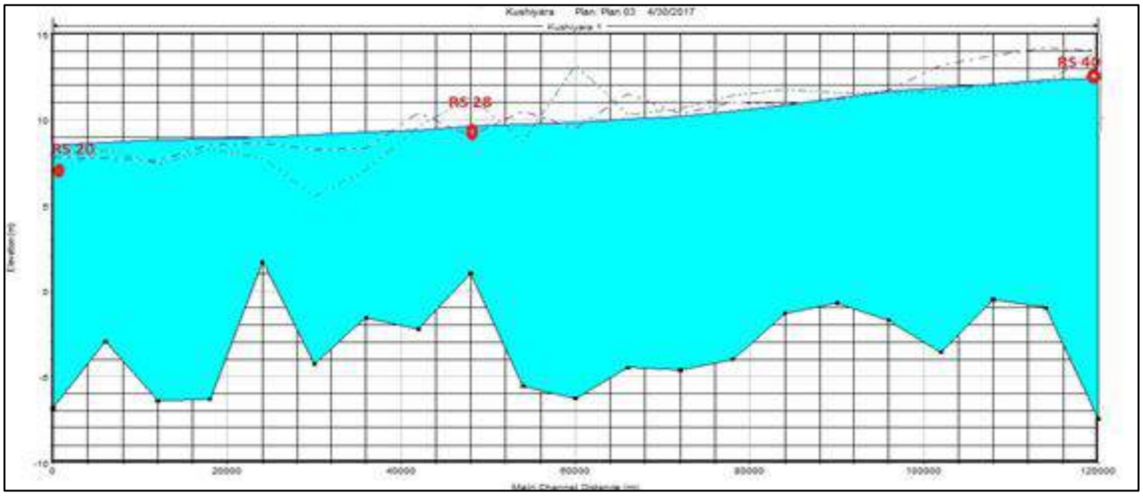

Figure 9-23 Simulated Longitudinal Profile of the Kushiyara (July 2012)

The scenario can also be observed from the cross sectional profiles (Figures 9.24-9.27).

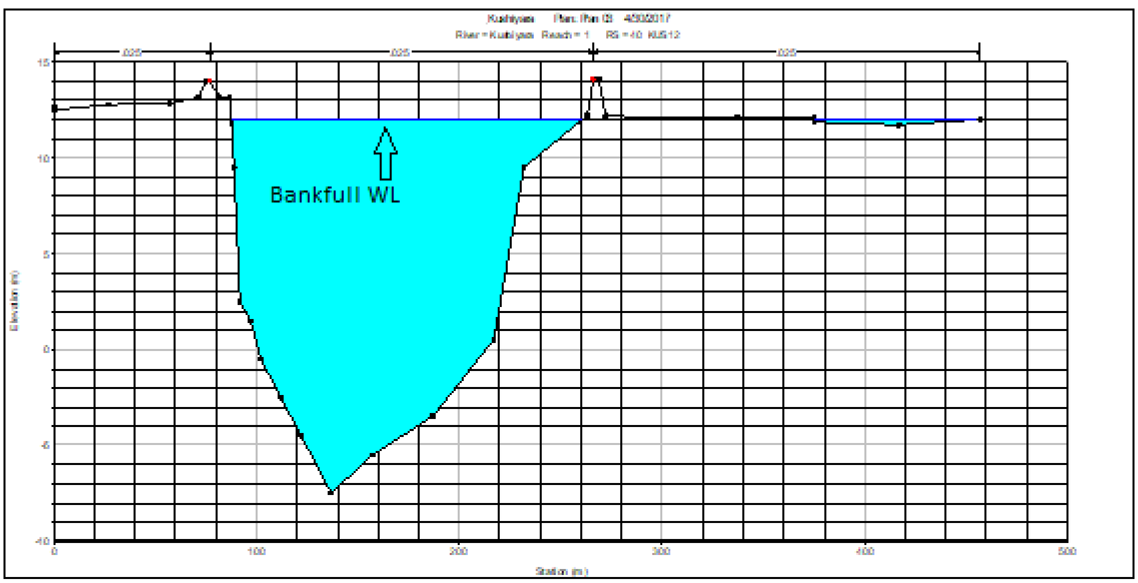

Figure 9-24 Simulated Water Level at RS 40, Sheola, July 2012 (Upstream)

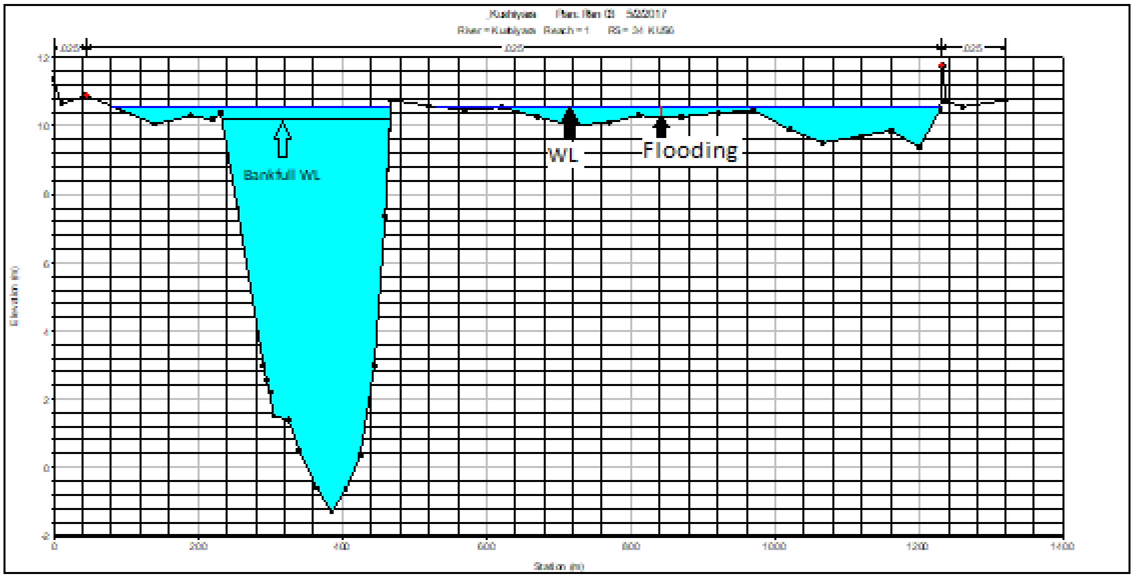

Figure 9-25 Simulated Water Level at RS 34, Fenchuganj, July 2012 (an intermediate section)

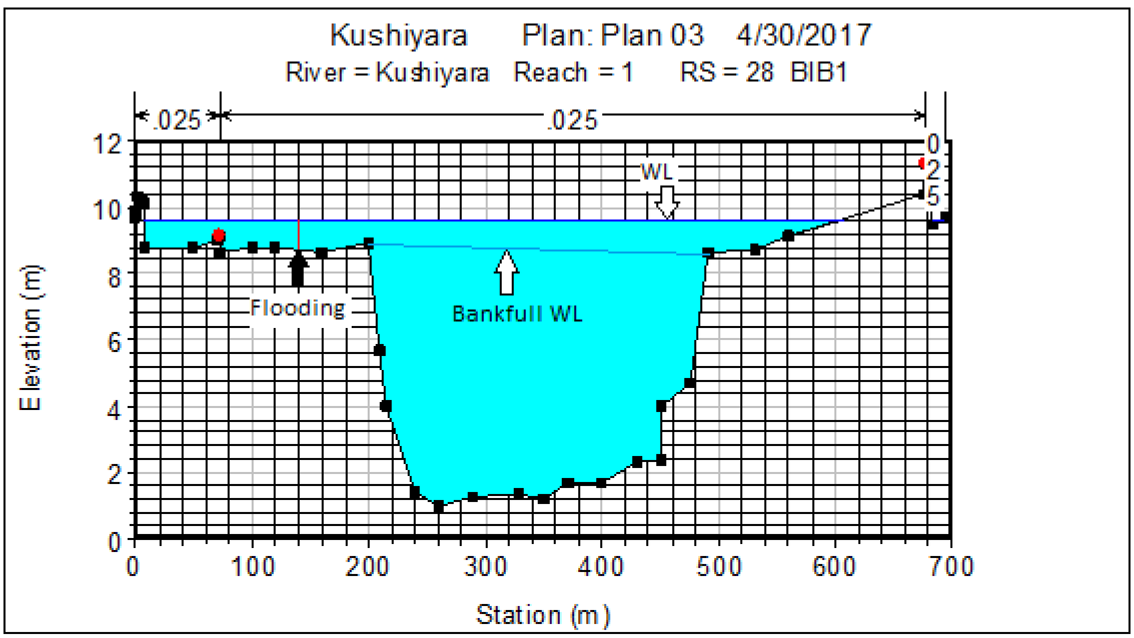

Figure 9-26 Simulated Water Level at RS 28, Sherpur, July 2012 (an intermediate section)

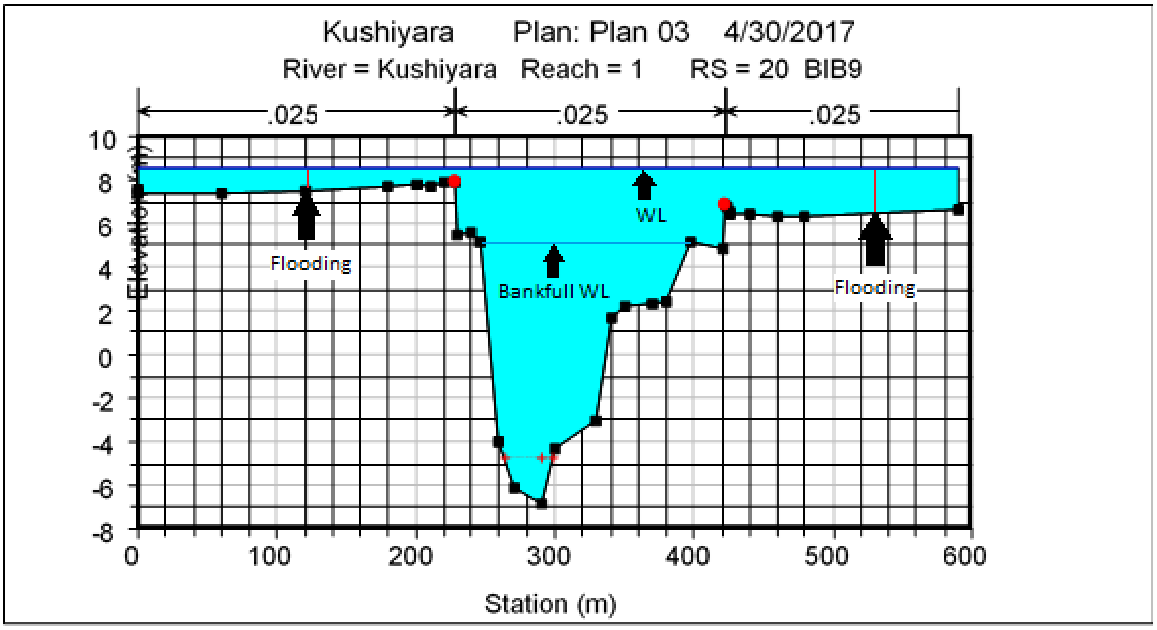

Figure 9-27 Simulated Water Level at RS 34, Markuli, July 2012 (Downstream)

Bankfull water level vs channel distance for the selected 4 stations (RS 40, RS 34, RS 28 and RS 20) have been plotted (Figure 9.28). The Trend line shows a decreasing trend from upstream to downstream.

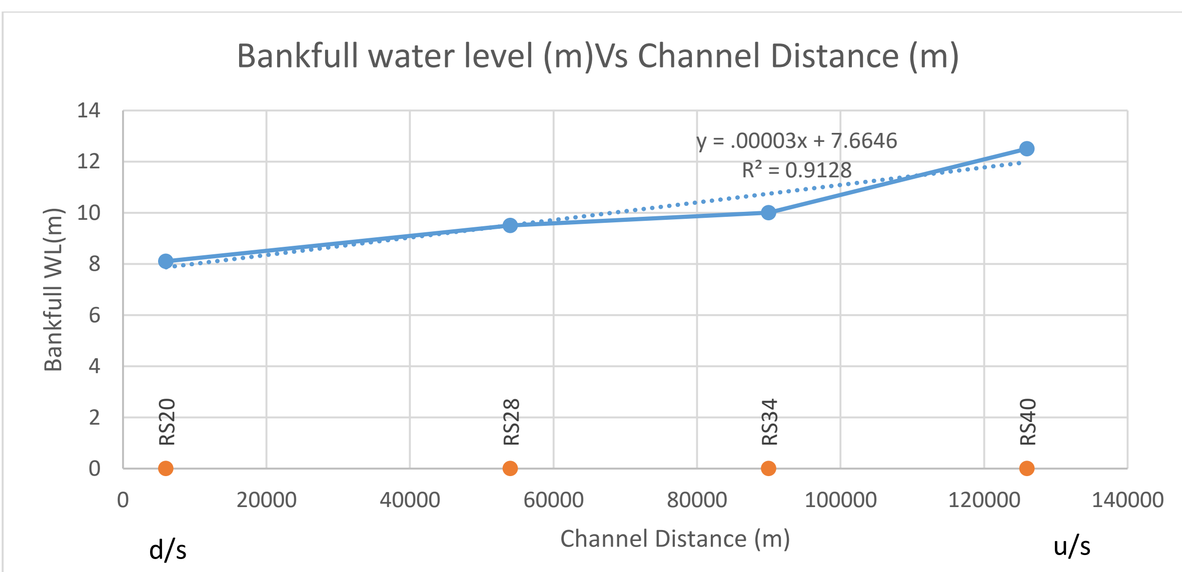

Figure 9-28 Bankfull Water Level vs Channel Distance (2012)

To validate this hypothesis, stage hydrographs for the water level stations of four locations of the Kushiyara have been plotted (Figure 9.29 -9.32).

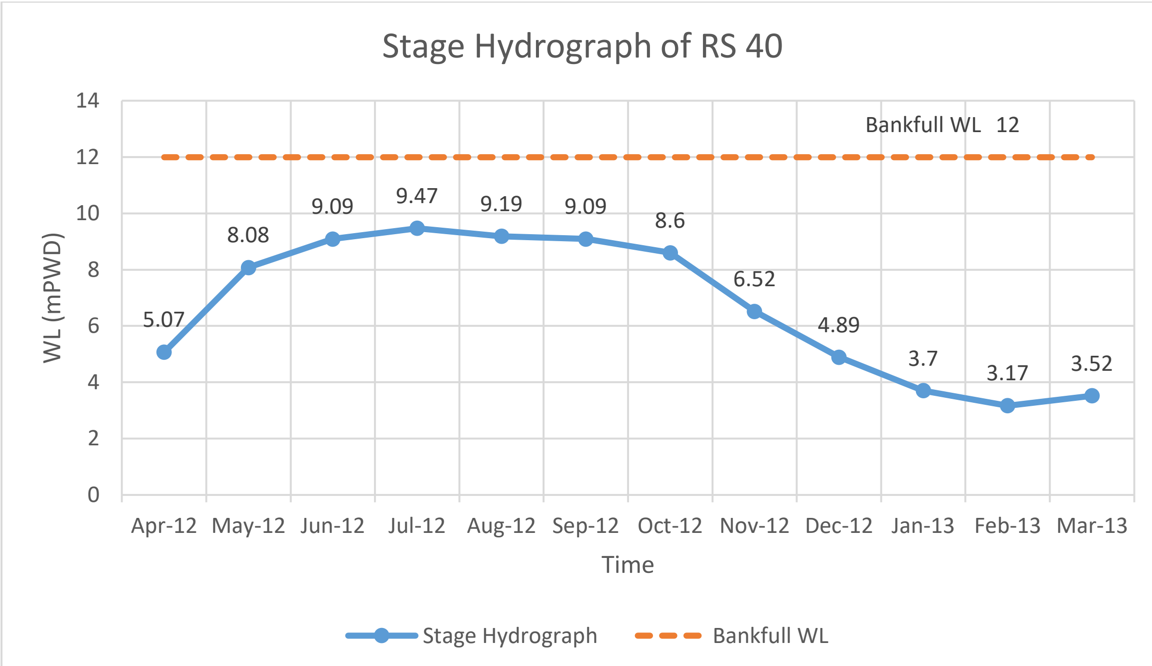

Figure 9-29 Simulated Stage Hydrograph for RS 40 (upstream, 2012-13)

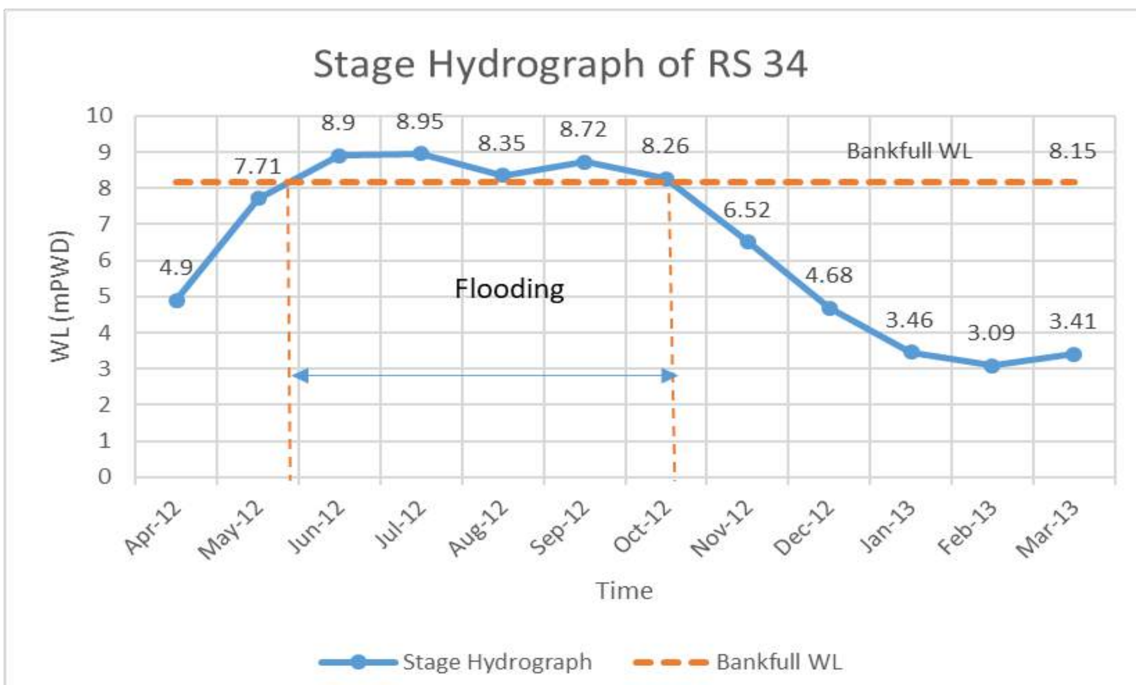

Figure 9-30 Simulated Stage Hydrograph for RS 34 (an intermediate section, 2012-13)

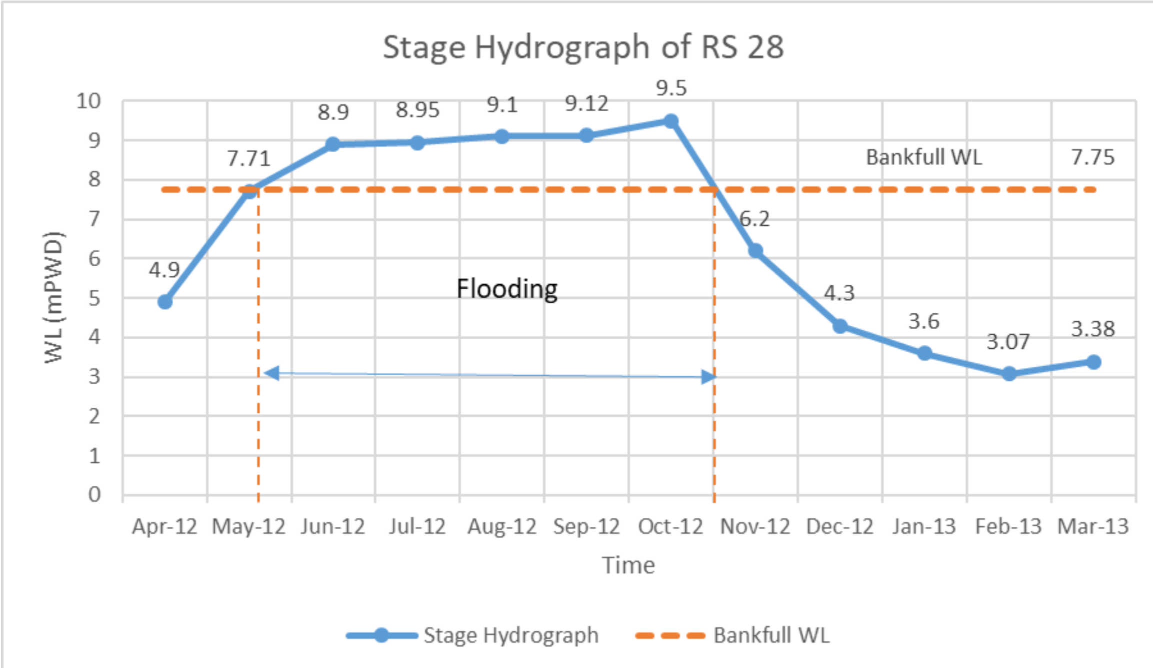

Figure 9-31 Simulated Stage Hydrograph for RS 28 (an intermediate section, 2012-13)

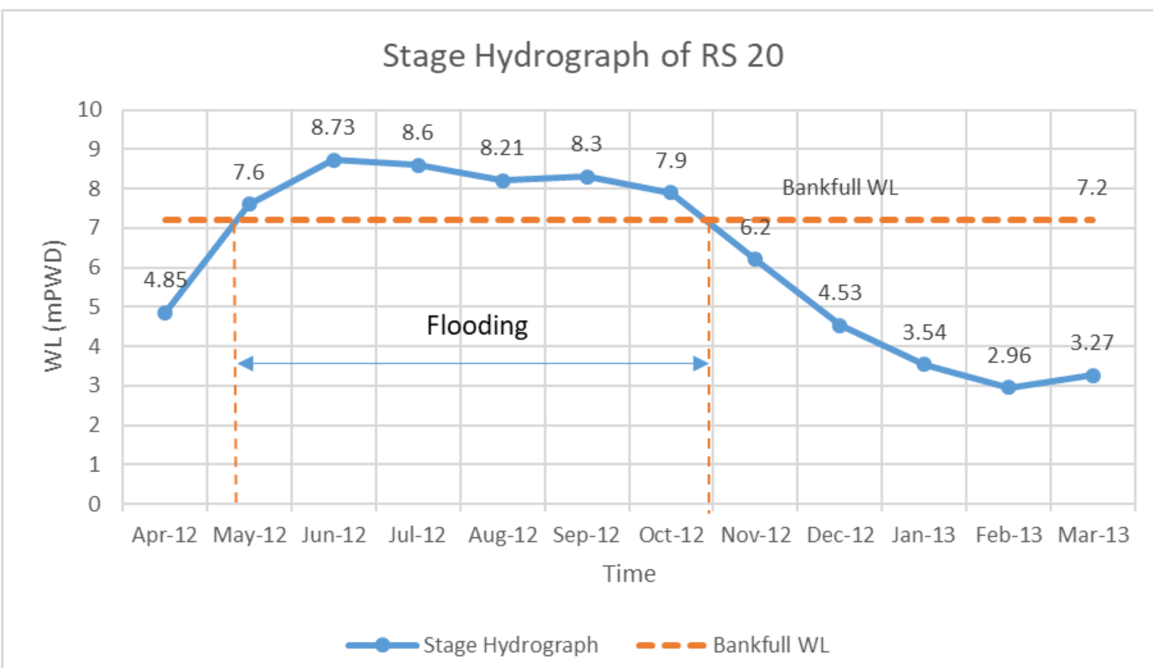

Figure 9-32 Simulated Stage Hydrograph for RS 20 (downstream, 2012-13)

From the stage hydrograph of RS 40 (Figure 9.29), it can be said that no flood occurred in the section and the bankfull water level is 12 mPWD.

From Figure 9.30, it is observed that at an intermediate station RS 34, the flood period was from early June to mid October (4.5 months). Further at the intermediate Station RS 28 (Figure 9.31), the flooding period was from early June to End-September (4 months). In the most downstream section (RS 20) in (Figure 9.32), the extent of the flood was from mid-May to end October (approximately 5.5 months).

Like river Surma, it has also been observed for the Kushiyara that, bankfull water level $Y_a>Y_b>Y_c>Y_d>Y_e$ and mostly downstream areas remain flooded for a longer period than that of the upstream areas. Hence **hypothesis 1 can be accepted for the Kushiyara river.**

9.2 Hypothesis 2

The Hypothesis 2 states that the **Decrease in the bankfull water level at the downstream indicates a decrease in channel dimensions i.e. the width and depth.**

9.2.1 Conventional Analysis

The Surma:

For the Surma River, 28 cross section stations have been selected. These stations cover the 150 km river reach which has been selected previously as the study area. The cross sections have been taken from February 2013 to March 2013 by the BWDB. The main channel area, top width and average depth of the 28 cross sections have been calculated and presented in the Table 9.5.

Table 9.5 Channel Area, Channel Top Width and Average Depth of the Selected Cross Sections on the Surma (2013)

Cross-Section Station ID, BWDB	Corresponding Water Level Station ID, BWDB	Area (m^2)	Channel Top width (m)	Avg. Depth (m)
38		1858.91	219.65	8.46
37		1707.67	194.23	8.79
36		2202.34	388.86	5.66
35		1746.94	227.94	7.66
34		1434.45	150.98	9.50
33		1625.7	262.75	6.19
32		2460.18	527.35	4.67
31		1646.43	193.04	8.53
30	SW267	2268.99	319.33	7.11
29		1784.15	245.2	7.28
28		2620.52	288	9.10
27		3385.46	452	7.49
26		1511.6	216	7.00
25		1820.02	359.89	5.06
24		1054.33	125	8.43
23		1260.85	237	5.32
22		1893.91	283.55	6.68
21		1620.79	194.46	8.33
20	SW268	2091.25	298.18	7.01

Cross-Section Station ID, BWDB	Corresponding Water Level Station ID, BWDB	Area (m^2)	Channel Top width (m)	Avg. Depth (m)
19		2444.23	280	8.73
18		2503.61	346.6	7.22
17		2221.03	241.19	9.21
16		2080.04	255	8.16
15		1952.45	236.87	8.24
14		2001.44	508.9	3.93
13		2440.99	328.81	7.42
12		2225.03	328	6.78
11	SW269	611.78	580	1.05

[Source: BWDB]

The channel area, average depth and channel top width of the cross sections have been plotted in Figure 9.33, 9.34 and 9.35 respectively. From Figure 9.33, it can be seen that **the trend of change in the channel area from upstream to the downstream section on the Surma has a scattered pattern** (R= 0.017), showing slightly increase towards downstream. The area at the most upstream section of the river (RMS38) is 1858.91 m^2 and the area at the most downstream section of the river (RMS11) is 611.78 m^2. The peak channel area is at Station RMS27, which is 3385.46 m^2.

It is observed from Figure 9.34 (trend line) that **the average depth of the cross sections is decreasing in the downstream sections, which appears in line with the conceptual model hypothesis which describes that there is a decrease in the channel dimension in the downstream direction.** But the R value (R=-0.27) is not statistically significant.

In the most upstream section, the average depth of the cross section (RMS38) is 8.46m and in the most downstream section, the average depth of the cross section (RMS11) is 1.05m.

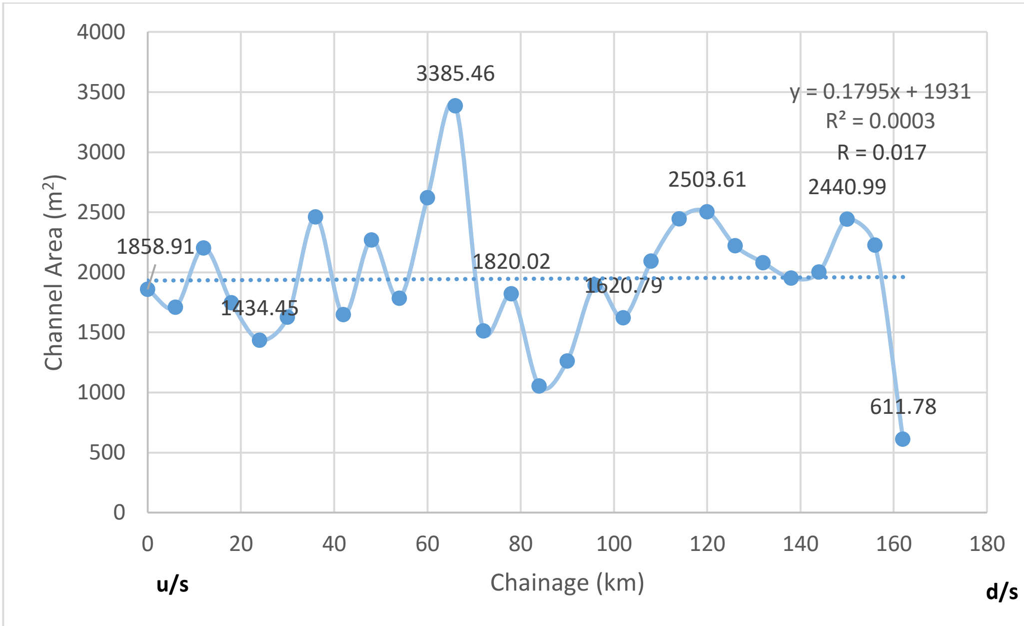

Figure 9-33 Channel Area vs Chainage Plot for the Surma River (2013)

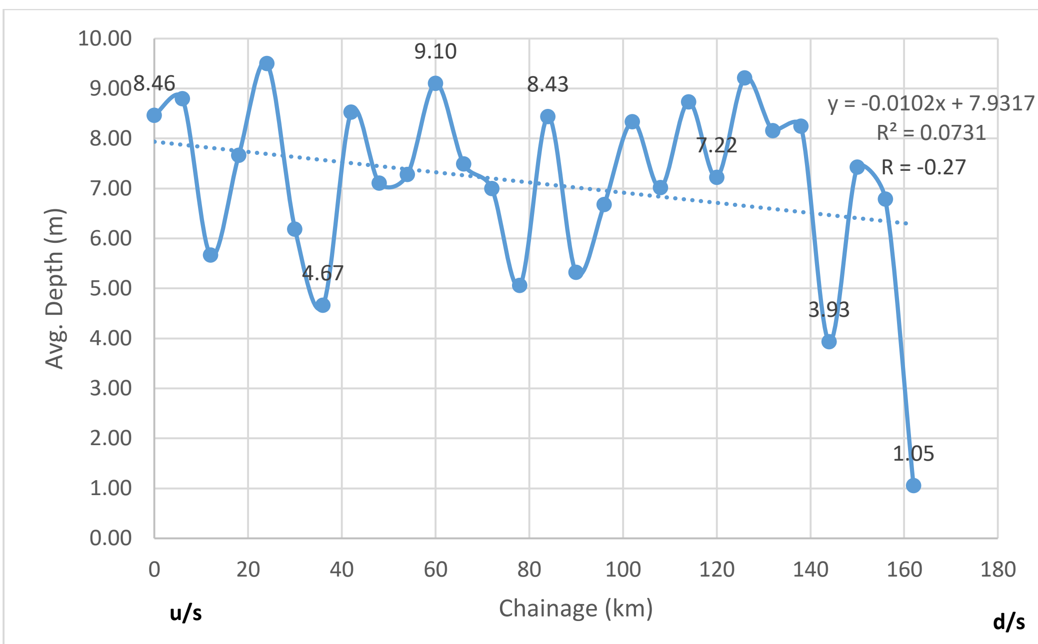

Figure 9-34 Average Depth vs Chainage Plot for the Surma River (2013)

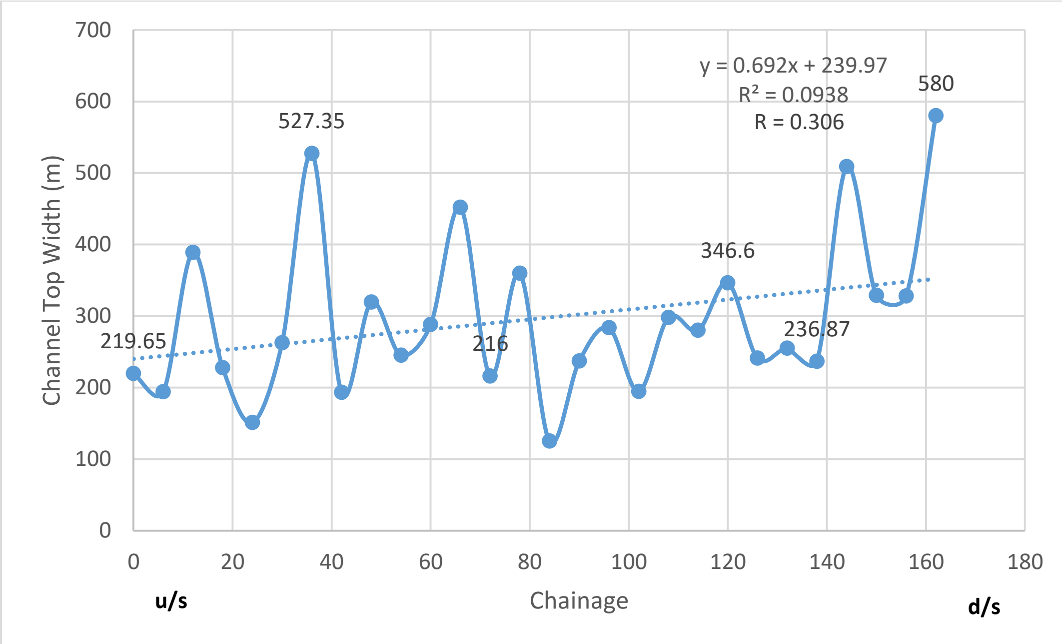

Figure 9-35 Channel Top Width vs Chainage Plot for the Surma River (2013)

From Figure 9.35, it can be observed that the top width plot shows a scattered pattern. **The trend line shows a slight increase in the downstream direction (R=0.306), which does not follow the conceptual model hypothesis.** In the most upstream section, the channel top width of the cross section (RMS38) is 219.65m and in the most downstream section, the channel top width of the cross section (RMS11) is 580m.

From the above analysis it may be concluded for the Surma river that:

I. The bankfull water level decreases in the downstream direction.

II. There are changes of channel area but the change shows scattered pattern. The trend line shows slight increase in area (R=0.017), which is not statistically significant.

III. There are changes of average depth. But the changes show a scattered pattern. The trend line shows a decrease in depth towards downstream. The R value (R=-0.27) of the trend line is not statistically significant.

IV. There is change of top width, but the changes show a scattered pattern. The trend line shows an increase of width towards downstream. But the R value (R=0.306) is not statistically significant.

So Hypothesis 2 could not be established/validated for the Surma.

However, Hypothesis 2 may be modified as mentioned below:

Decrease in the bankfull water level at the downstream, however indicates change in channel dimensions.

The Kushiyara:

For the Kushiyara River, 21 cross section stations have been selected. These stations cover the 150 km river reach which has been selected previously as the study area. The cross sections have been taken from February 2012 to March 2012. The main channel area, top width and average depth of the 21 cross sections have been calculated and presented in the Table 9.6.

Table 9.6 Channel Area, Channel Top Width and Average Depth of the Selected Cross Sections on the Kushiyara (2012)

Cross-Section Station ID	Area (m^2)	Channel Top width (m)	Avg. Depth (m)
40	1806	151.48	11.92
39	1598.36	178.42	8.96
38	939	130	7.22
37	1170.98	165.81	7.06
36	1449.14	257.25	5.63
35	959.46	132.77	7.23
34	1674.67	310.99	5.38
33	1407.57	175.75	8.01
32	1410.34	243.29	5.80
31	2090.16	352.7	5.93
30	1844.29	527.75	3.49
29	3244	894.25	3.63
28	2162.07	578.4	3.74
27	2744.65	1419.25	1.93
26	2869.53	416	6.90
25	1688	457	3.69

Cross-Section Station ID	Area (m^2)	Channel Top width (m)	Avg. Depth (m)
24	2344.46	1104	2.12
23	3006.27	742	4.05
22	6682	4976	1.34
21	2256.17	980	2.30
20	1745.01	590	2.96

[Source: BWDB]

The channel area, average depth and channel top width of the cross sections have been plotted in Figure 9.36, 9.37 and 9.38 respectively. From Figure 9.36, it can be observed that **the trend of change in the channel area from upstream to the downstream section on the Kushiyara has a scattered pattern** (R= 0.557), showing slight increase towards downstream. The area at the most upstream section of the river (station 40) is 1806 m^2 and the area at the most downstream section of the river (station 20) is 1745.01 m^2. The peak channel area is at Station 22, which is 6682 m^2.

It is seen from Figure 9.37 (trend line) that **the average depth of the cross sections is decreasing in the downstream sections, which appears in line with the conceptual model hypothesis which describes that there is a decrease in the channel dimension in the downstream direction.** But the R value (R=-0.83) is not statistically significant.

In the most upstream section, the average depth of the cross section (Station 40) is 11.92m and in the most downstream section, the average depth of the cross section (Station 20) is 2.96m.

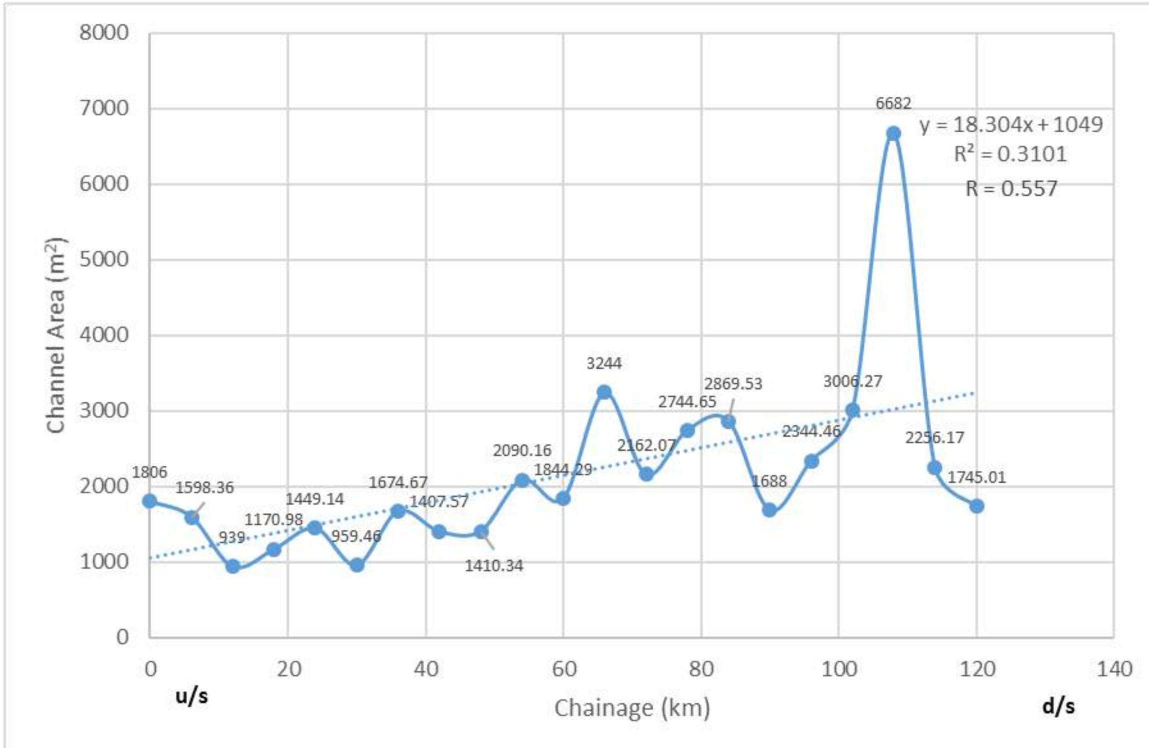

Figure 9-36 Channel Area vs Chainage Plot for the Kushiyara River (2012)

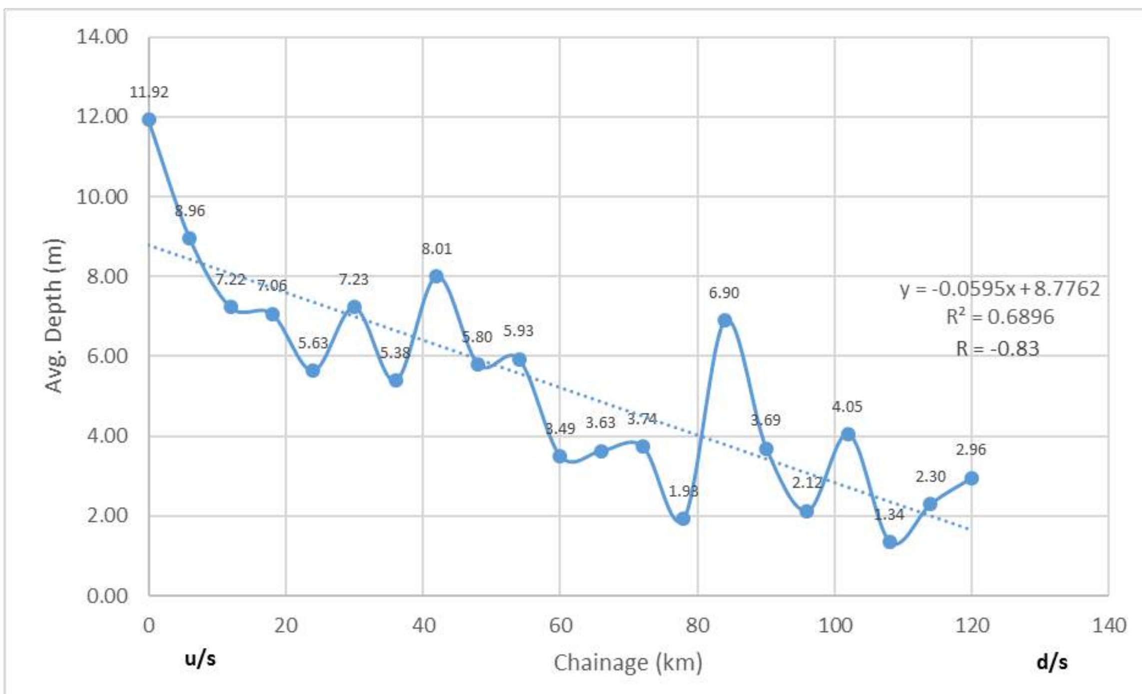

Figure 9-37 Average Depth vs Chainage Plot for the Kushiyara River (2012)

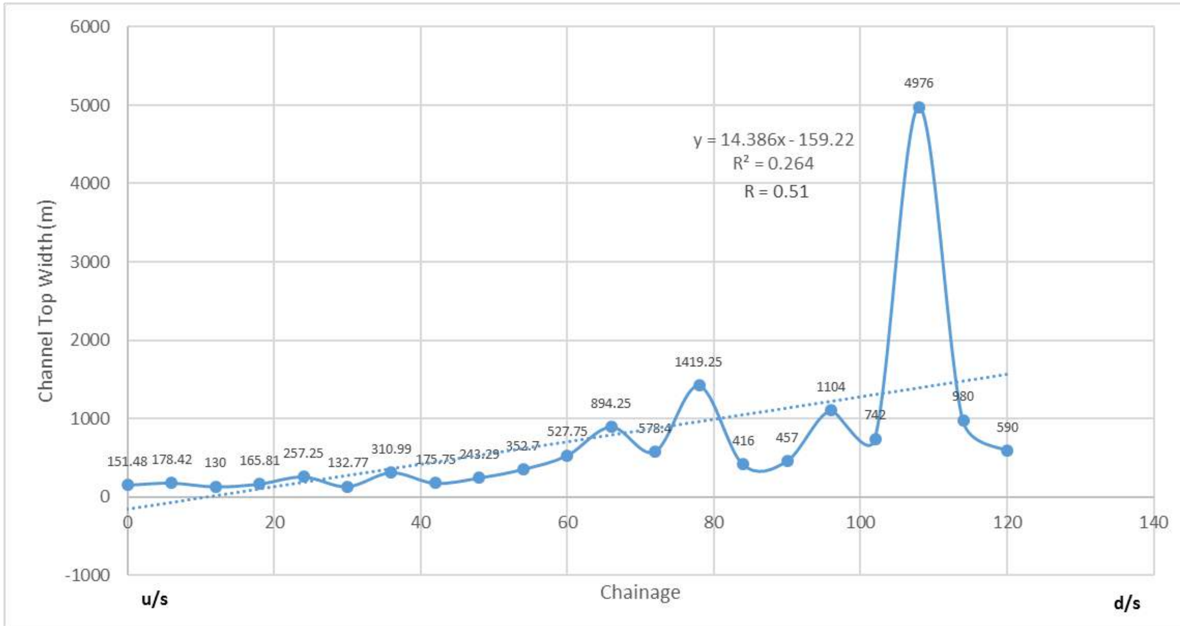

Figure 9-38 Channel Top Width vs Chainage Plot for the Kushiyara River (2012)

From Figure 9.38, it can be observed that the top width shows a scattered pattern. **The trend line shows a slight increase in the downstream direction (R=0.51), which does not follow the conceptual model hypothesis.** In the most upstream section, the channel top width of the cross section (station 40) is 151.48m and in the most downstream section, the channel top width of the cross section (station 20) is 590m.

From the above analysis it may be concluded for the Kushiyara River that:

I. The bankfull water level decreases in the downstream direction.

II. There are changes of channel area but the change shows scattered pattern. The trend line shows slight increase of channel area (R=0.557), which is statistically not significant.

III. There are changes of average depth. But the changes show a scattered pattern. The trend line shows a decrease in average depth towards downstream. The R value (R=-0.83) of the trend line is not statistically significant.

IV. There is change of top width, but the changes show a scattered pattern. The trend line shows an increase of width towards downstream. But the R value (R=0.51) is not statistically significant.

So Hypothesis 2 could not be established/validated for the Kushiyara.

The analysis suggests that the Hypothesis 2 may be slightly modified in the following way:

"Decrease in the bankfull water level at the downstream, however indicates a change in channel dimensions."

9.1.1 Model Output Analysis

It has been mentioned in chapter 5 that, if the upstream, intermediate and downstream sections are A-A, B-B and C-C and corresponding bankfull water levels, areas and top widths are Y_a, Y_b, Y_c; A_a, A_b, A_c and W_a, W_b, W_c respectively. Hypothesis 2 will be validated if,

$$Y_a > Y_b > Y_c,$$

$$A_a > A_b > A_c;$$

$$W_a > W_b > W_c$$

The Surma:

Among the 28 cross sections of the river Surma calibrations were done for 4 stations namely, RS 31, RS 26 and RS 20. The upstream section is RS 38 downstream section is RS. Let us assume, the bankfull water levels and bankfull areas of RS 38, RS 31, RS 26, RS 20 and RS 11 are Y_a, Y_b, Y_c, Y_d, Y_e and Aa, Ab, Ac, Ad, Ae respectively. The HECRAS model generated bankfull water levels and cross sectional area of these Stations which are shown below in Table 9.7.

Table 9.7 Simulated Bankfull Water Elevation, Maximum depth and Cross Sectional Area of Five Selected Stations in the Surma

Location and Station ID	Bankfull Water Elevation(m) *	Maximum Depth at Bankfull Condition	Bankfull Area (m^2)**
Upstream, RS 38(SW266), Kanaighat	13.34 (Y_a)	14.34	1858.91 (A_a)
Intermediate section, RS 31	10.49 (Y_b)	14.49	1646.43 (A_b)
Intermediate section, RS 26(SW267), Sylhet Sadar	9.98 (Y_c)	11.98	1511.6 (A_c)
Intermediate section, RS 20	8.92 (Y_d)	12.92	2091.25 (A_d)
Downstream, RS 11(SW269), Sunamganj	7.4 (Y_e)	8.4	611.78 (A_e)

Note: *From Table 9.3
**From Table 9.5

It was shown in Section 9.1.2 that the bankfull water level decreases towards the downstream direction

or

$Y_a > Y_b > Y_c > Y_d > Y_e$

Cross Sectional Area: The data of simulated bankfull cross sections for all the 28 stations of the Surma are shown in Table 9.8.

Table 9.8 Simulated Cross Sectional Area, Top Widths and Average Depths (at bankfull condition)

Cross-Section Station ID	Area (m^2)	Channel Top width (m)	Avg. Depth (m)
38	1858.91	219.65	8.46
37	1707.67	194.23	8.79
36	2202.34	388.86	5.66
35	1746.94	227.94	7.66
34	1434.45	150.98	9.50

Cross-Section Station ID	Area (m^2)	Channel Top width (m)	Avg. Depth (m)
33	1625.7	262.75	6.19
32	2460.18	527.35	4.67
31	1646.43	193.04	8.53
30	2268.99	319.33	7.11
29	1784.15	245.2	7.28
28	2620.52	288	9.10
27	3385.46	452	7.49
26	1511.6	216	7.00
25	1820.02	359.89	5.06
24	1054.33	125	8.43
23	1260.85	237	5.32
22	1893.91	283.55	6.68
21	1620.79	194.46	8.33
20	2091.25	298.18	7.01
19	2444.23	280	8.73
18	2503.61	346.6	7.22
17	2221.03	241.19	9.21
16	2080.04	255	8.16
15	1952.45	236.87	8.24
14	2001.44	508.9	3.93
13	2440.99	328.81	7.42
12	2225.03	328	6.78
11	611.78	580	1.05

When all the 28 cross sections are plotted (Figure 9.39), the bankfull areas show a scattered pattern, the trend line shows slight increase from d/s to u/s (R=0.27). The R value is statistically not significant. **Conversely it may be stated that areas slightly decrease towards downstream, which is in line with the Hypothesis 2.**

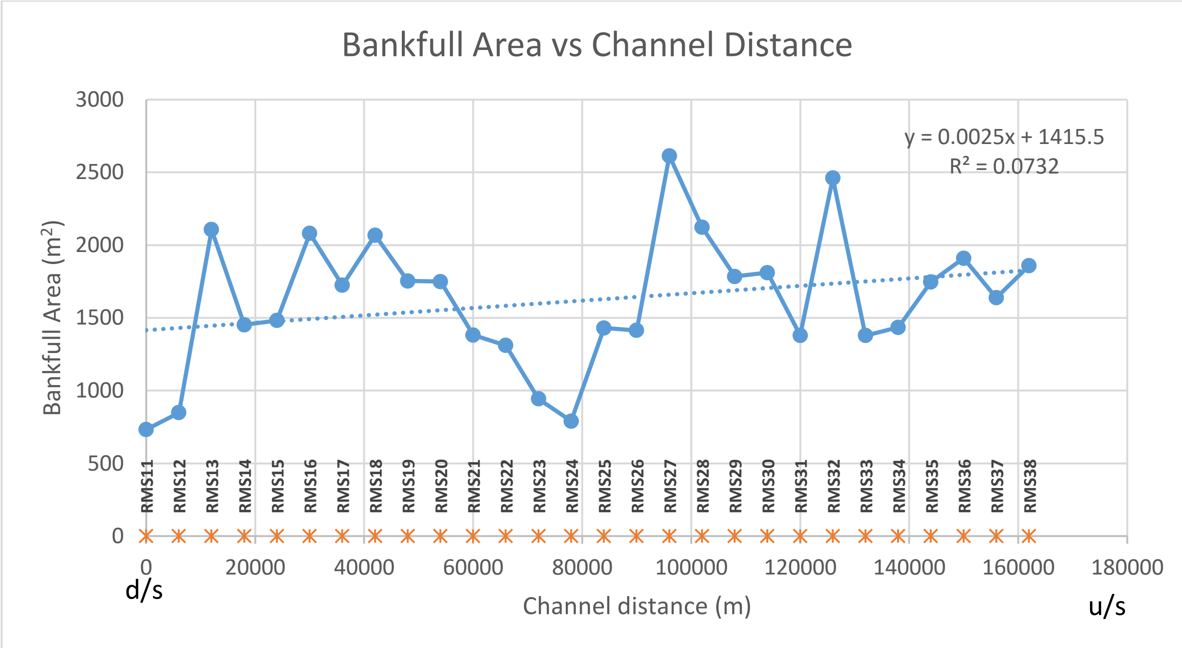

Figure 9-39 Bankfull Area vs Channel Distance for 28 Stations of the Surma (2014)

However, when bankfull area vs channel distance for the selected 5 stations (RS 38, RS 31, RS 26, RS 20 and RS 11) is plotted (Fig: 9.40), the Trend line shows an increasing trend (R= +0.73) from d/s to u/s, or **conversely the areas show slightly decrease from u/s to d/s**. Although apparently there is slightly decrease in X-sectional area in trend lines, which is in line with the Hypothesis 2, but actually the changes are of scattered pattern. **Thus the proposition of "decrease in cross sectional area towards d/s" could not be established/validated for the river Surma.**

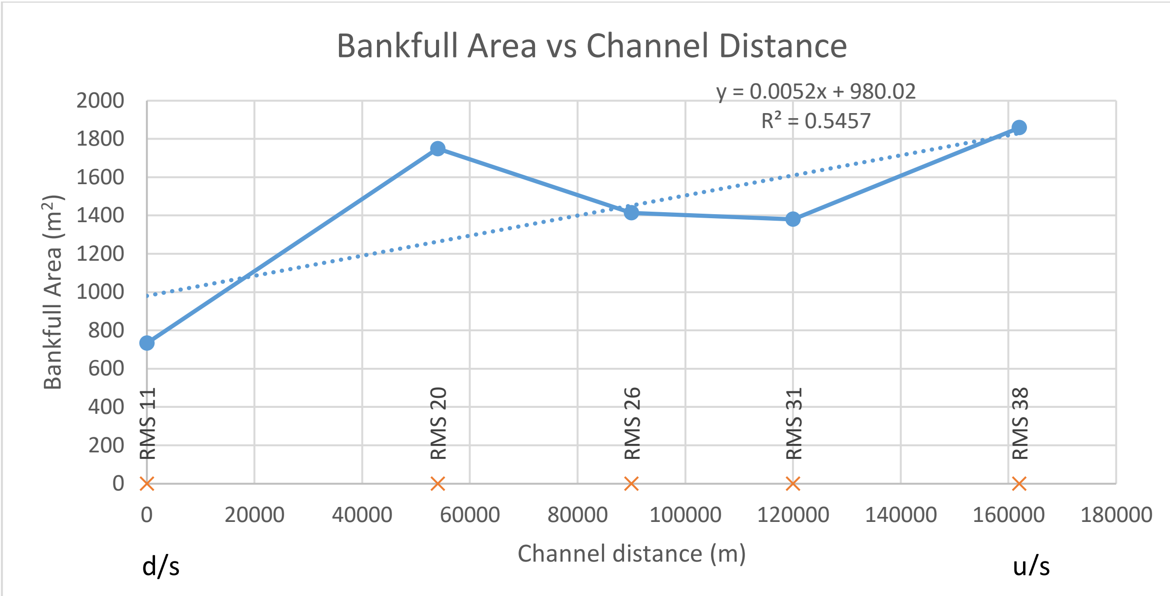

Figure 9-40 Bankfull Area vs. Channel Distance for Selected 5 Stations of the Surma (2014)

Top Width: Top width vs channel distance has been plotted (Figure 9.41). the variation from upstream to downstream shows a scattered pattern. Observing the widths of all the 28 cross sections also proves the variation in widths are actually anomalous.

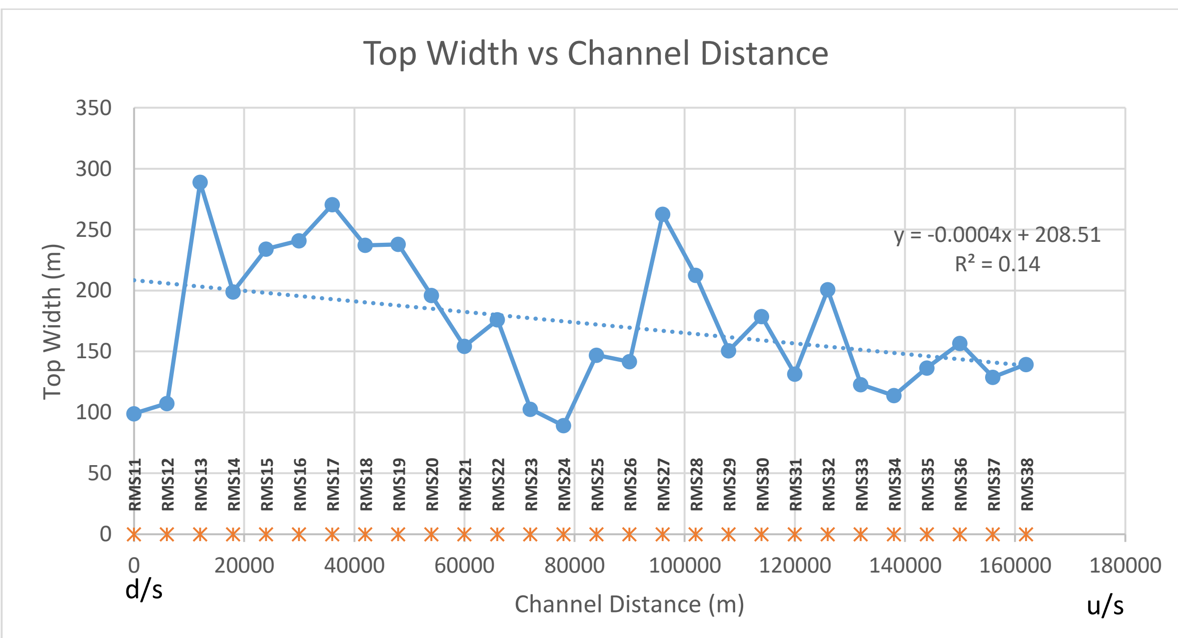

Figure 9-41 Top Width vs Channel Distance for 28 Stations of the Surma (2014)

The trend of change of the top width along the channel length indicates a decreasing trend towards Upstream (R=- 0.37). But this trend is not statistically significant. **Conversely, it may be stated that the trend line shows slightly increase in top width towards downstream direction, which contradicts Hypothesis 2.**

For above mentioned 5 stations (RS 38, RS 31, RS 26, RS 20 and RS 11) the top width vs channel distance was plotted (Figure 9.42).

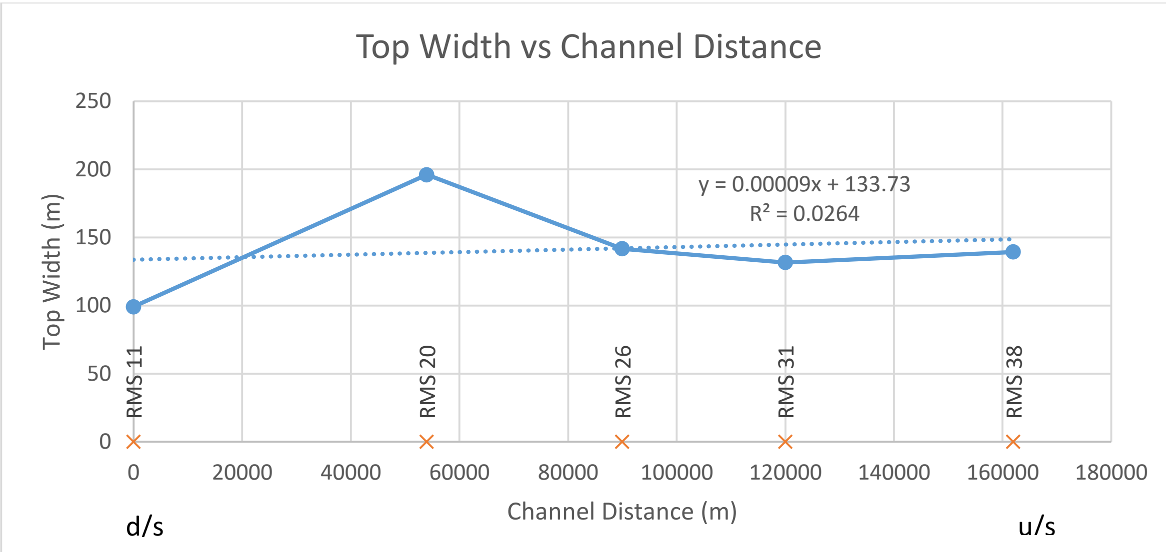

Figure 9-42 Top Width vs Channel Distance for Selected 5 Station of the Surma (2014)

The trend line of top width shows a slight increase towards upstream (R=+0.164). This trend is not statistically significant. It is noted that RS 20 shows a wide variation. **Conversely the trend line shows slight decrease towards downstream**, which is in line with the hypothesis.

So it is seen that when only 5 stations were considered. There is a decreasing trend towards downstream but in case of plot for all the 28 stations, the trend is increasing. **Hence it may be concluded that the changes of top widths are of scattered pattern.**

Average Depth: By dividing the each cross sectional area with their corresponding top widths, average depths were calculated (Table 9.8). Average depth vs channel distance has been plotted (Figure 9.43). the variation from downstream to upstream shows a scattered pattern.

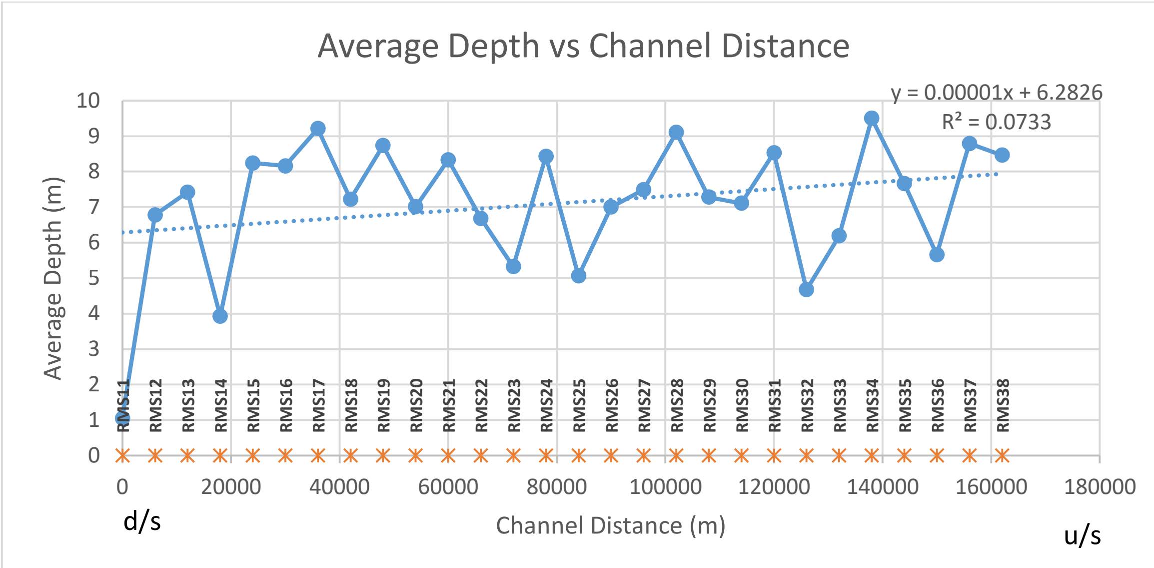

Figure 9-43 Average Depth vs Channel Distance for 28 Station of the Surma (2014)

The trend line shows a change of the average depth along the channel length an increasing trend towards upstream (R= +0.27). But this trend is not statistically significant. **Conversely it may be stated that the trend line shows slight decreasing trend from u/s to d/s direction, which is in line with the hypothesis.**

For above mentioned 5 stations (RS 38, RS 31, RS 26, RS 20 and RS 11) the average depth vs channel distance was plotted (Figure 9.44).

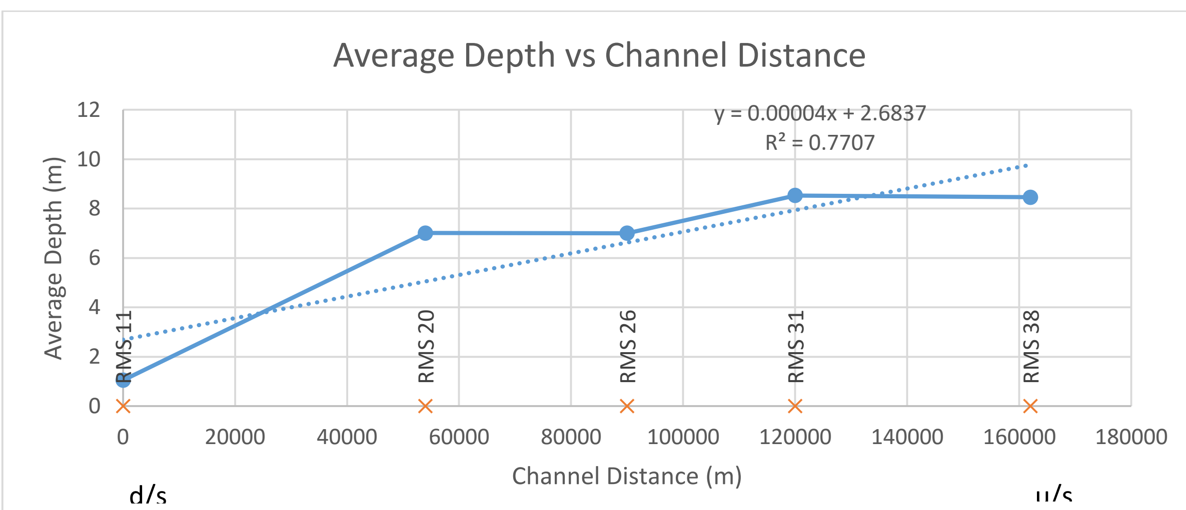

Figure 9-44 Average Depth vs Channel Distance for Selected 5 Station of the Surma (2014)

The change of the average depth for selected five stations along the channel length indicates an increasing trend towards upstream (R=+ 0.87). **Conversely it may be stated that the trend line shows slightly decreasing trend from u/s to d/s direction, which is in line with the hypothesis.**

Hence for the Surma, we can conclude that, “The bankfull water levels at the downstream decreases, consequently there are changes in channel dimension, the change of top width shows a scattered pattern and the change of average depth shows a decreasing trend towards downstream direction.”

Hence Hypothesis 2 could not be conclusively established/validated for the Surma.

The Kushiyara:

Similar exercises were carried out for the river Kushiyara. The values of discharge, water level and area of upstream, intermediate and downstream sections are given below.

Table 9.9 Simulated Bankfull Water Elevation, Maximum depth and Cross Sectional Area of four Selected Station of the Kushiyara

Location and Station ID	**Bankfull WL (m)***	**Max. depth at Bankfull Condition (m)**	**Area (m2)****
Upstream, RS 40 (SW 173), Sheola	12.5 (Ya)	12.5	1806 (Aa)
Midsection, RS34 (SW 174), Fenchugong)	10(Yb)	11.5	1674.67 (Ab)
Midsection, RS 28 (SW 175.5), Sherpur)	9.5 (Yc)	10.5	2162.07 (Ac)
Downstream, RS 20 (SW 270), Markuli)	8.1 (Yd)	9.5	1745.01 (Ad)

Note: *From Table 9.4
**From Table 9.5

It is observed from Table 9.9 that the bankfull water levels decrease towards the downstream

or

$Y_a > Y_b > Y_c > Y_d$

Cross Sectional Area: The simulated bankfull cross sections for the 21 stations of the Kushiyara are shown in Table 9.10.

Table 9.10 Simulated the Cross Sectional Area, Top Widths and Average Depths (at bankfull condition)

Cross-Section Station ID	Area(m^2)	Channel Top width(m)	Avg-Depth (m)
40	1806	151.48	11.92
39	1598.36	178.42	8.95
38	939	130	7.22
37	1170.98	165.81	7.06
36	1449.14	257.25	5.63
35	959.46	132.77	7.22
34	1674.67	310.99	5.38
33	1407.57	175.75	8.00
32	1410.34	243.29	5.79
31	2090.16	352.7	5.92
30	1844.29	527.75	3.49
29	3244	894.25	3.62
28	2162.07	578.4	3.73
27	2744.65	1419.25	1.93
26	2869.53	416	6.89
25	1688	457	3.69
24	2344.46	1104	2.12
23	3006.27	742	4.05

Cross-Section Station ID	Area(m^2)	Channel Top width(m)	Avg-Depth (m)
22	6682	4976	1.34
21	2256.17	980	2.30
20	1745.01	590	2.95

When all the 21 cross sections are plotted (Figure 9.45), the bankfull areas show a scattered pattern (R= -0.55). The R value is statistically not significant. The trend line shows a decreasing trend from d/s to u/s direction. **Conversely it may be stated that the trend line shows slightly increasing trend from u/s to d/s direction, which contradicts the Hypothesis 2.**

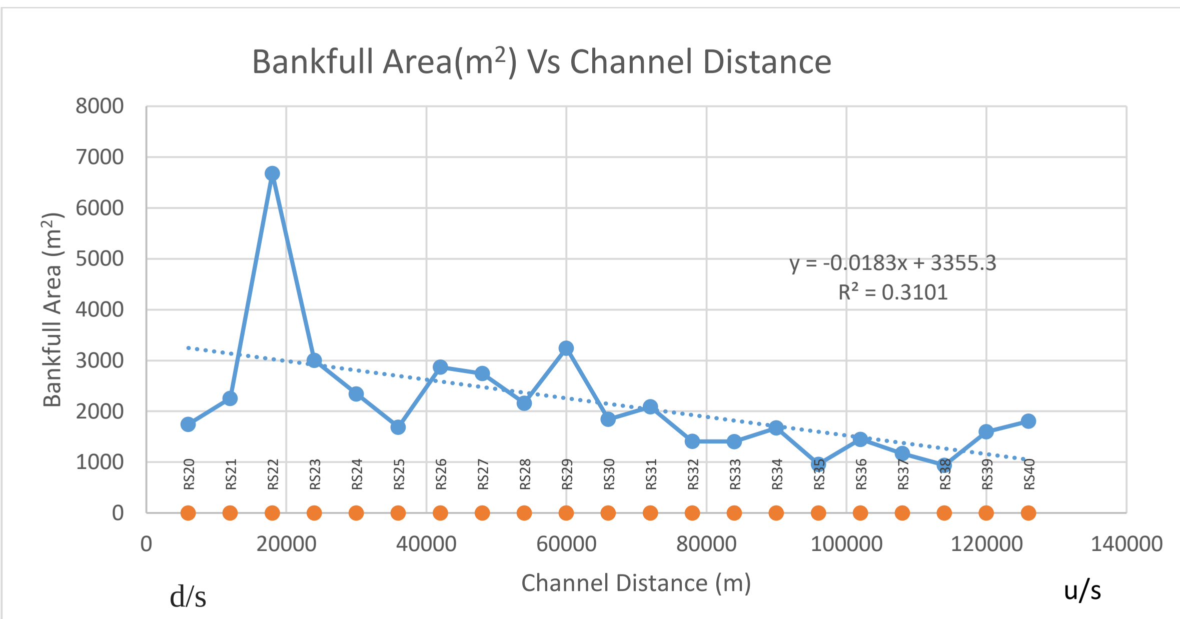

Figure 9-45 Bankfull Area vs Channel Distance for 21 Stations of the Kushiyara (2012)

However, when bankfull area vs channel distance for the selected 4 stations (RS 40, RS 34,RS 26,RS 20)is plotted (Figure 9.46), the Trend line shows a decreasing trend (R= -0.4) from d/s towards u/s. **Conversely it may be stated that the trend line shows slightly increasing trend from u/s to d/s direction, which contradicts the Hypothesis 2.**

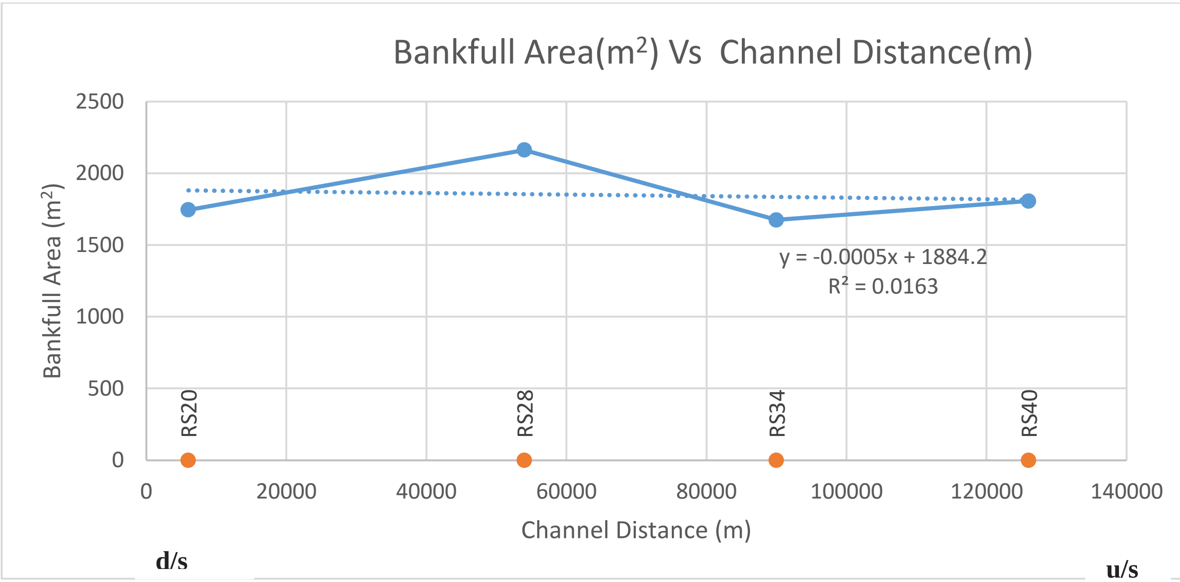

Figure 9-46 Bankfull Area vs Channel Distance for 4 Stations of the Kushiyara (2012)

Thus the proposition of "decrease in cross sectional area towards d/s" could not be established/validated for the river Kushiyara.

Top Width: Top width vs channel distance has been plotted (Figure 9.47). the variation from downstream to upstream shows a scattered pattern. Observing the areas of all the 21 cross sections, it may be concluded that the variation in widths are actually anomalous.

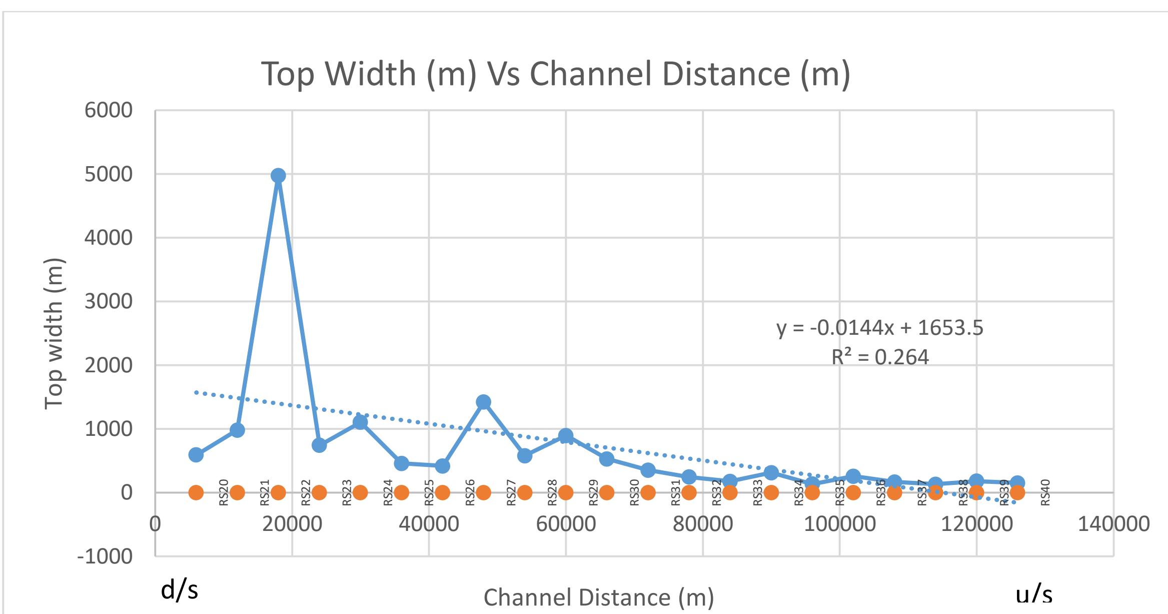

Figure 9-47 Top Width vs Channel Distance for 21 Stations of the Kushiyara (2012)

The change of the top width along the channel length indicates a decreasing trend towards upstream (R= -0.51). But this trend is not statistically significant. **Conversely it may be stated that the trend line shows slight increasing trend from u/s to d/s direction, which contradicts the Hypothesis 2**.

For above mentioned 4 stations (RS 40, RS 34, RS 28, RS 20) the top width vs channel distance was plotted (Figure 9.48).

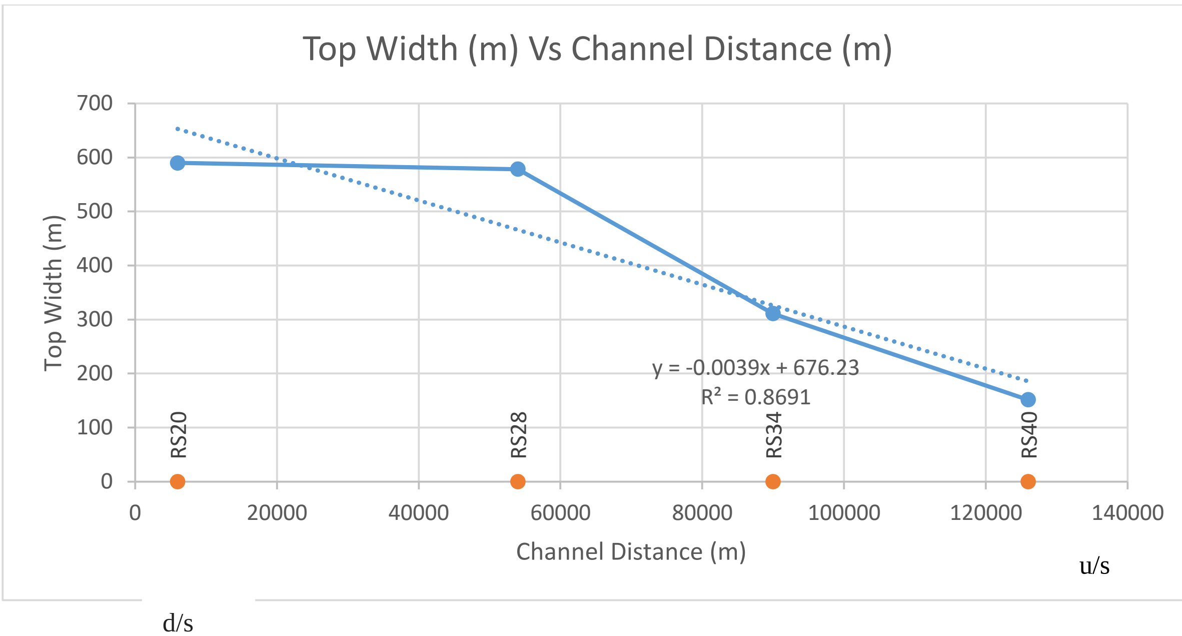

Figure 9-48 Top Width vs Channel Distance for Selected 4 Stations of the Kushiyara (2012)

The trend line of top width also shows a decrease towards upstream (R=-0.92). This trend is however statistically significant. **Conversely for selected four stations, the trend of the top width shows an increasing trend towards d/s direction, which contradicts the Hypothesis 2.**

So it may be concluded that there is an increasing trend of change of Top Width towards downstream direction (although R value is not statistically significant). This contradicts Hypothesis 2.

Average Depth: By dividing the each cross sectional area with their corresponding top widths, average depths were calculated (Table 9.10). Average depth vs channel distance has been plotted (Figure 9.49).

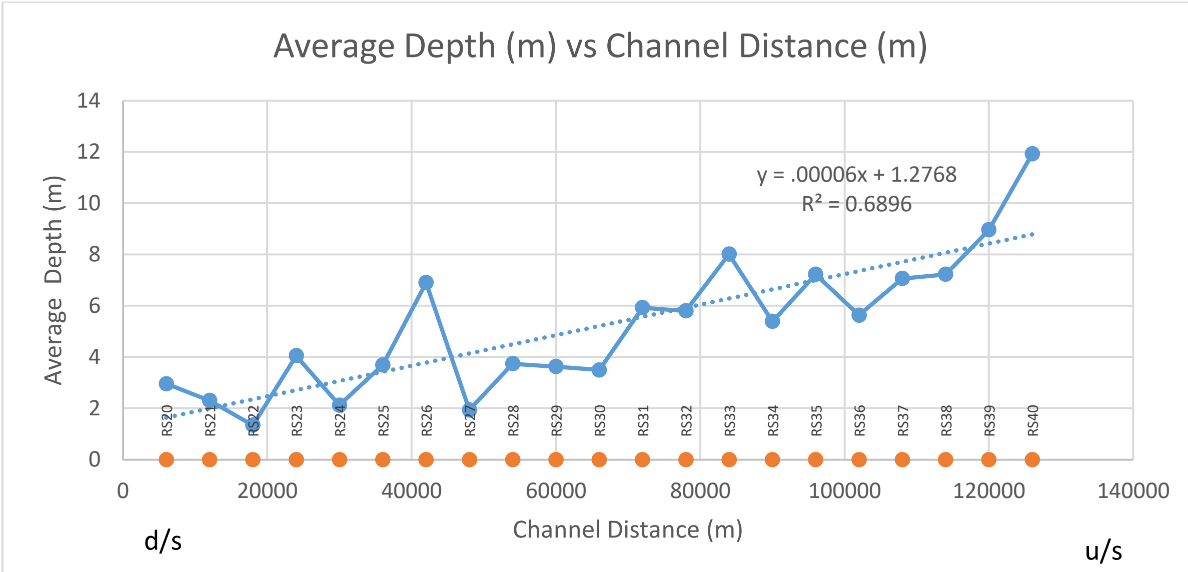

Figure 9-49 Average Depth vs Channel Distance for 21 Stations of the Kushiyara (2012)

The change of the average depth along the channel length indicates an increasing trend towards upstream (R= +0.83). This trend is statistically significant. **Conversely it may be stated that the trend line shows slight decreasing trend from u/s to d/s direction which is in line with the Hypothesis 2.**

For above mentioned 4 stations (RS 40, RS 34, RS 28, RS 20) the average depth vs channel distance was plotted (Figure 9.50).

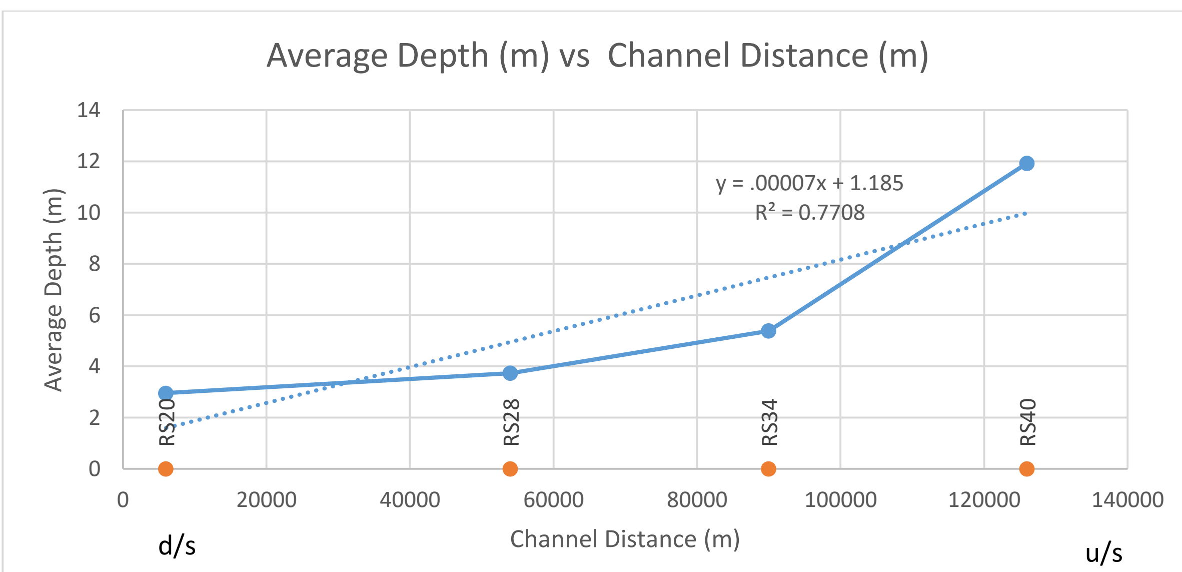

Figure 9-50 Average Depth vs Channel Distance for 4 Stations of the Kushiyara (2012)

The change of the average depth for selected four stations of the Kushiyara indicates an increasing trend towards upstream (R= +0.87). The R value is Statistically significant. **Conversely it may be stated that the trend line shows slight decreasing trend from u/s to d/s direction which is in line with the Hypothesis 2.**

Observations:

- The change of cross-sectional area shows a slightly increasing trend towards d/s direction (although the R values are not statistically significant), which does not match with the CEGIS proposition.

- The change of Top width also shows a scattered pattern. This also contradicts CEGIS Hypothesis 2
- The changes of Average depth show a decreasing trend towards d/s direction which is in line with the CEGIS Hypothesis 2

Examining the results with a holistic approach it may be concluded that Hypothesis 2 cannot be conclusively established/validated for the Kushiyara.

Hence for the Kushiyara, we can conclude that, “The bankfull water levels at the downstream decreases and consequently there is changes in channel dimension, the changes in top width shows scattered pattern but the average depth shows a slightly deceasing trend towards downstream direction.

9.3 Hypothesis 3

9.3.1 Conventional Analysis

The Hypothesis 3 states that **"the shallow depth caused to increase the high gradient during the dry season and thus increase the dry season water level at the upstream."** As mentioned in Section 5.5, the hypothesis may be rewritten with slight adjustments as **"The shallow depth causes to increase the high gradient during the dry season (from the point of deposited reaches/submersed bars/dune, to downstream). This may cause increase of dry season water depth at the section of deposited reach (from the point of submersed bars/dune, to some distance to downstream). Moreover, deposited reach will cause to produce backwater effect at the upstream"**.

The long profile of both the Surma and Kushiyara rivers have been plotted and presented in Figure 9.51 and 9.52 respectively. The monsoon season water levels and dry season water levels have also been shown in the long profiles.

In Figure 9.51, the long profile and water levels for different seasons in the Surma river are shown. The data used to plot the long profile are of the year 2013. From the figure, it can be seen that in the Surma river, the water depth in the most downstream section is lower than that of the upstream sections. Also, the water level gradient is higher in the upstream water level stations for both monsoon and dry seasons. The summary of the findings is given in Table 9.11.

Table 9.11 Water Depth and Water Level Gradient for the Surma, 2013

Stations	Water Level (mPWD)		Bed Level (mPWD)	Water Depth (m)		WL Gradient between 2 Successive Stations (m/km)	
	Monsoon	Dry		Monsoon	Dry	Monsoon	Dry
SW266	11.32	4.8	2.41	8.91	2.39	-	-
SW267	9.24	2.89	-1.27	10.51	4.16	-0.0267	-0.0295
SW268	7.82	2.46	-3.05	10.87	5.51	-0.0060	-0.0225
SW269	7.03	2.14	-7.4	14.43	9.54	-0.0593	-0.0672
SW269.5	6.42	2.04	-0.1	6.52	2.14	0.1198	0.1121

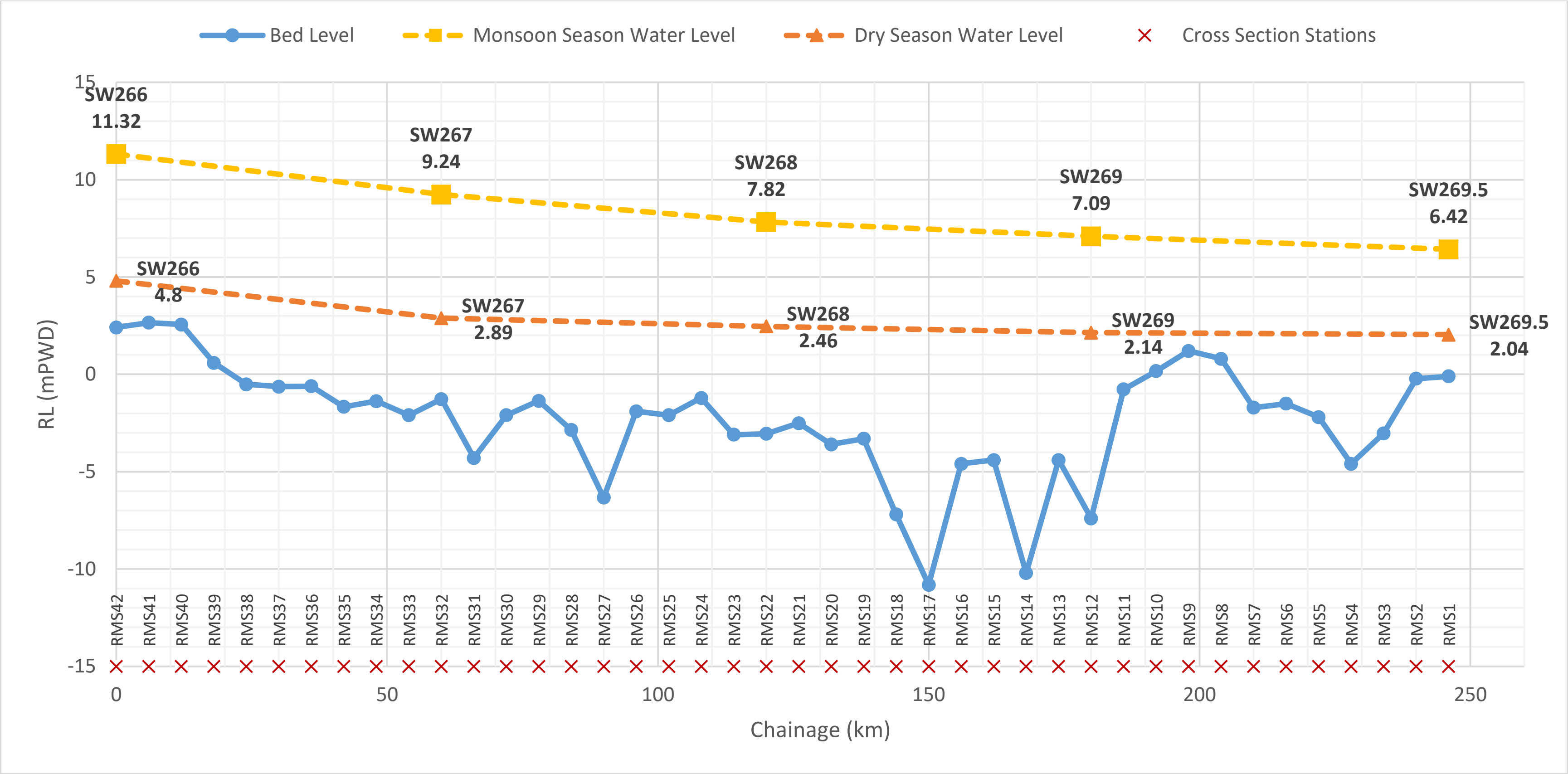

Figure 9-51 Long Profile of the Surma River with Water Level (2013)

Since the cross sectional profiles of the bed for monsoon seasons are not available, for simplicity we may assume the gradient of water level and the gradient of the bed level for 2 successive stations are the same. So the Table 9.11 is rearranged to form Table 9.12 (for the Surma river).

Table 9.12 Comparison of Water Leverl Gradient (Monsoon) and Bed Level Gradient (Dry) for the Surma River

Stations	**Water Level Gradient between 2 Successive Stations (m/km)**	**Bed Level between 2 Successive Stations (m/km)**
	Monsoon	**Dry**
SW266 - SW267	0.0267 (decreasing)	0.0295 (decreasing)
SW267 - SW268	0.0060 (decreasing)	0.0225 (decreasing)
SW268 - SW269	0.0593 (decreasing)	0.0672 (decreasing)
SW269 - SW269.5	0.1198 (increasing)	0.1121 (increasing)

From Table 9.12, it is observed that the dry season gradient is greater than the monsoon season gradients in 3 reaches (SW266 – SW267, SW267 – SW268 and SW268 – SW269). However, in one reach (SW269 – SW269.5) dry season gradient is slightly lower than that of the monsoon season gradient.

The analysis suggests that the Hypothesis 3 can be validated/established for the Surma River.

In Figure 9.52, the long profile and water levels for different seasons in the Kushiyara river are shown. The data used to plot the long profile are of the year 2010. From the figure, it can be seen that in the Kushiyara river, the water depth in the most downstream section is higher than that of the upstream sections. Also, the water level gradient is higher in the upstream water level stations for both monsoon and dry seasons. The summary of the findings is given in Table 9.13.

Table 9.13 Water Depth and Water Level Gradient for the Kushiyara, 2010

Stations	Water Level (mPWD)		Bed Level (mPWD)	Water Depth (m)		WL Gradient between 2 Successive Stations (m/km)	
	Monsoon	Dry		Monsoon	Dry	Monsoon	Dry
SW172	15.98	6.4	0.5	15.48	5.9	-	-
SW73	13.79	4.41	-3.61	17.4	8.02	-0.1067	-0.1178
SW174	10.93	3.4	-1.3	12.23	4.7	0.2872	0.1844
SW175.5	9.08	3	-5.57	14.65	8.57	-0.0807	-0.1290

Since the cross sectional profiles of the bed for monsoon seasons are not available, for simplicity we may assume the gradient of water level and the gradient of the bed level for 2 successive stations are the same. So the Table 9.13 is rearranged to form Table 9.14 (for the Kushiyara river).

Table 9.14 Comparison of Water Leverl Gradient (Monsoon) and Bed Level Gradient (Dry) for the Kushiyara River

Stations	Water Level Gradient between 2 Successive Stations (m/km)	Bed Level between 2 Successive Stations (m/km)
	Monsoon	Dry
SW172 – SW173	0.1067 (decreasing)	0.1178 (decreasing)
SW173 – SW174	0.2872 (increasing)	0.1844 (increasing)
SW174 – SW175.5	0.0807 (decreasing)	0.1290 (decreasing)

From Table 9.14, it is observed that the dry season gradient is greater than the monsoon season gradients in 2 reaches (SW172 – SW173 and SW174 – SW175.5). However, in one reach (SW173 – SW174) dry season gradient is lower than that of the monsoon season gradient.

The analysis suggests that the Hypothesis 3 can be validated/established for the Kushiyara River.

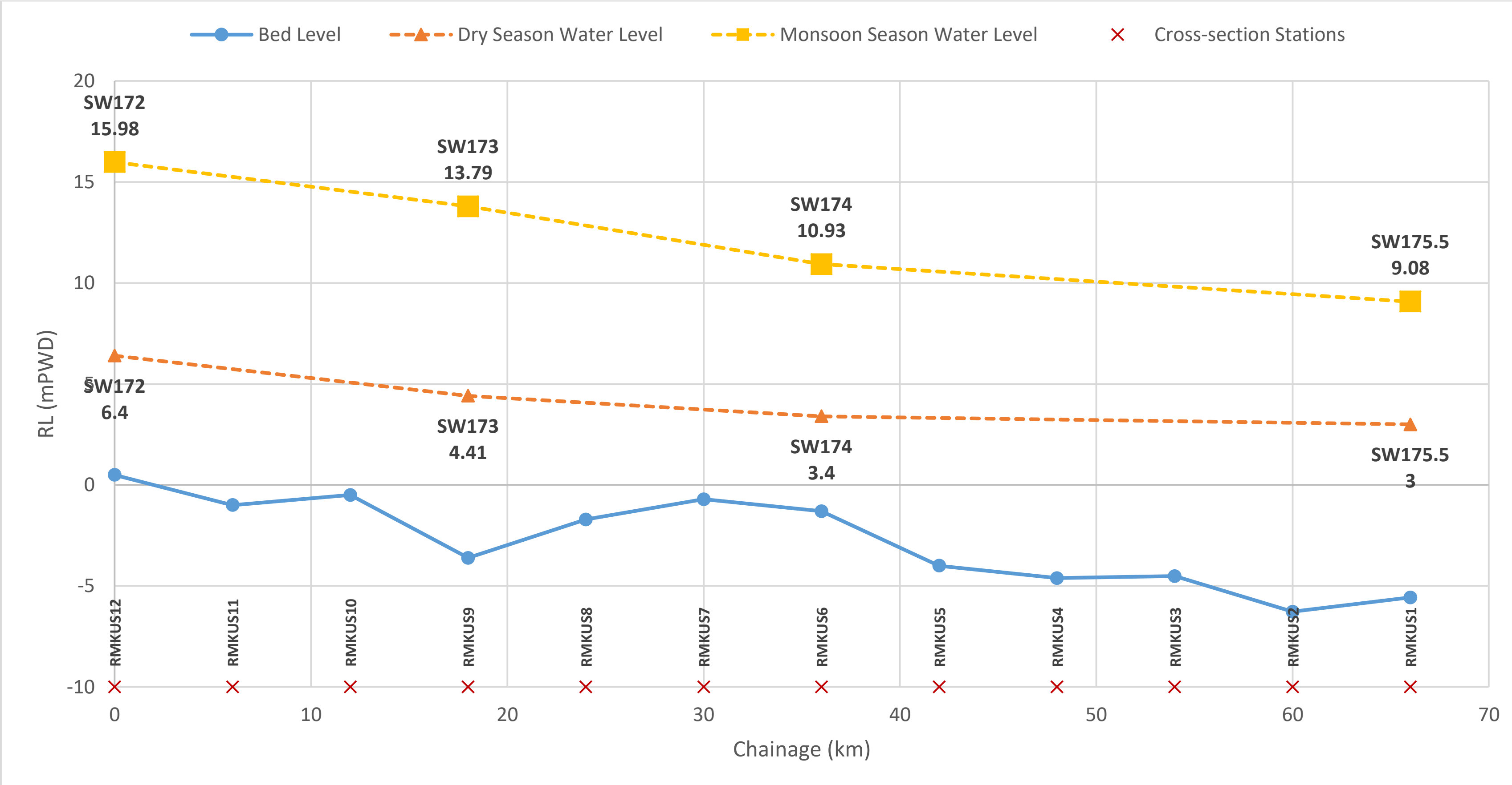

Figure 9-52 Long Profile of the Kushiyara with Water Level (2010)

9.3.2 Model Output Analysis

The Surma:

For the Surma river, data of twenty-eight cross sections are available. Five cross sections have been considered to validate the hypothesis. The model was run for year 2014 and two period were considered one is Monsoon season (June-September) and other is Dry Season (January – March). Average sedimentation of each period have been considered to observe the seasonal changes of the cross section, whether there is any erosion, deposition or no changes over the season. Water level gradient and bed level gradient of the Surma and change of wetted width in the river reach have also been calculated to validate the hypothesis. The Schematic Diagram (Figure 9.53) of the Surma river 162 km reach is given below:

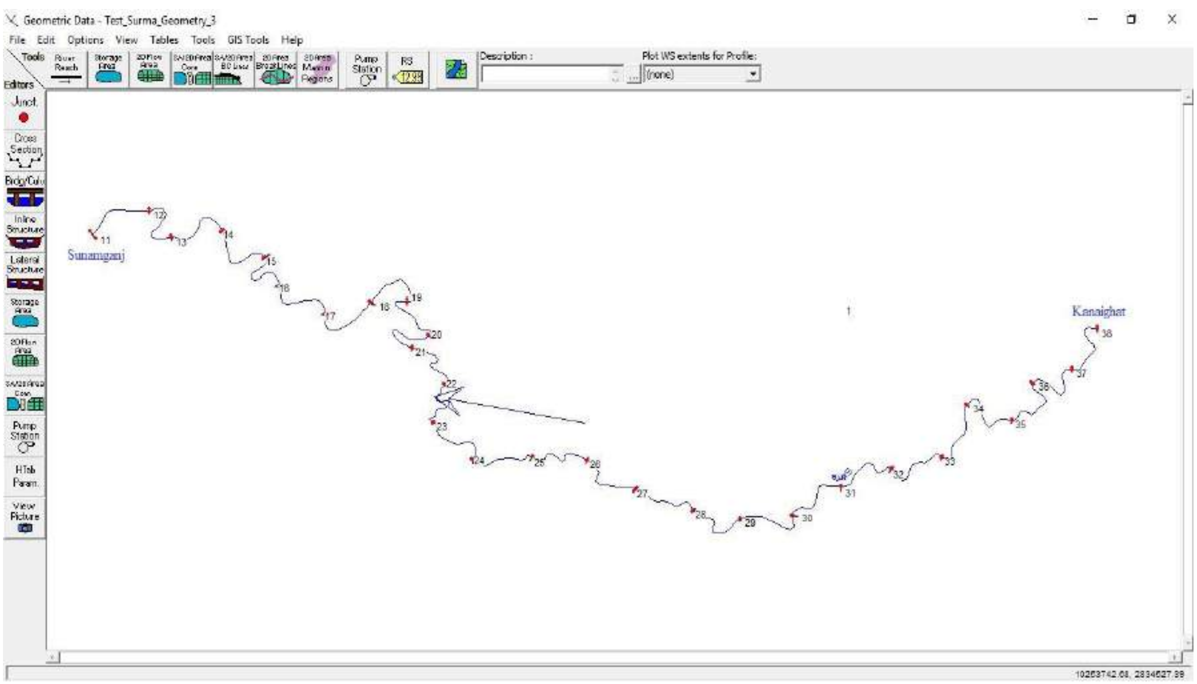

Figure 9-53 Cross Section of the Surma River

Analysis of the previously mentioned five Cross sections (RS 38,RS 31,RS26, RS20 and RS 11) are given below. Figure 9.54 shows the change of cross section between February 2014 and August 2014 of Station 38. Neither erossion or deposition is observed in this section.

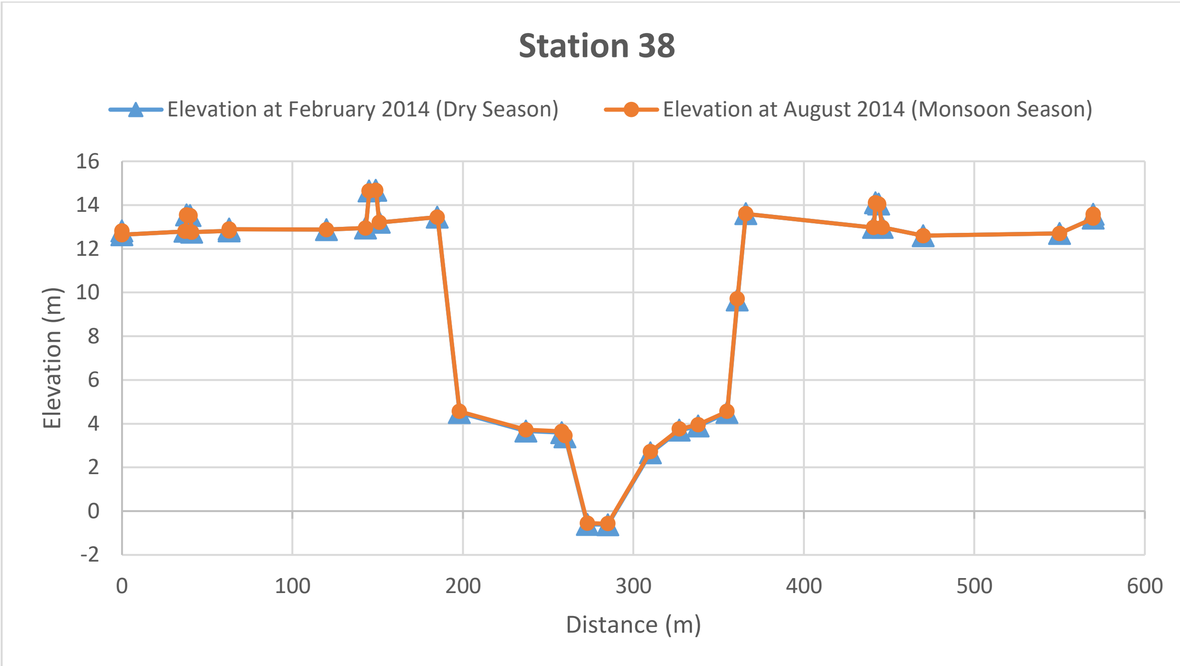

Figure 9-54 Non-Silting and Non-Eroding Cross Section 38 of the Surma

Figure 9.55 shows the cross section 31 remains same over the 2 seasons. So in this cross section neither erosion nor deposition have been observed.

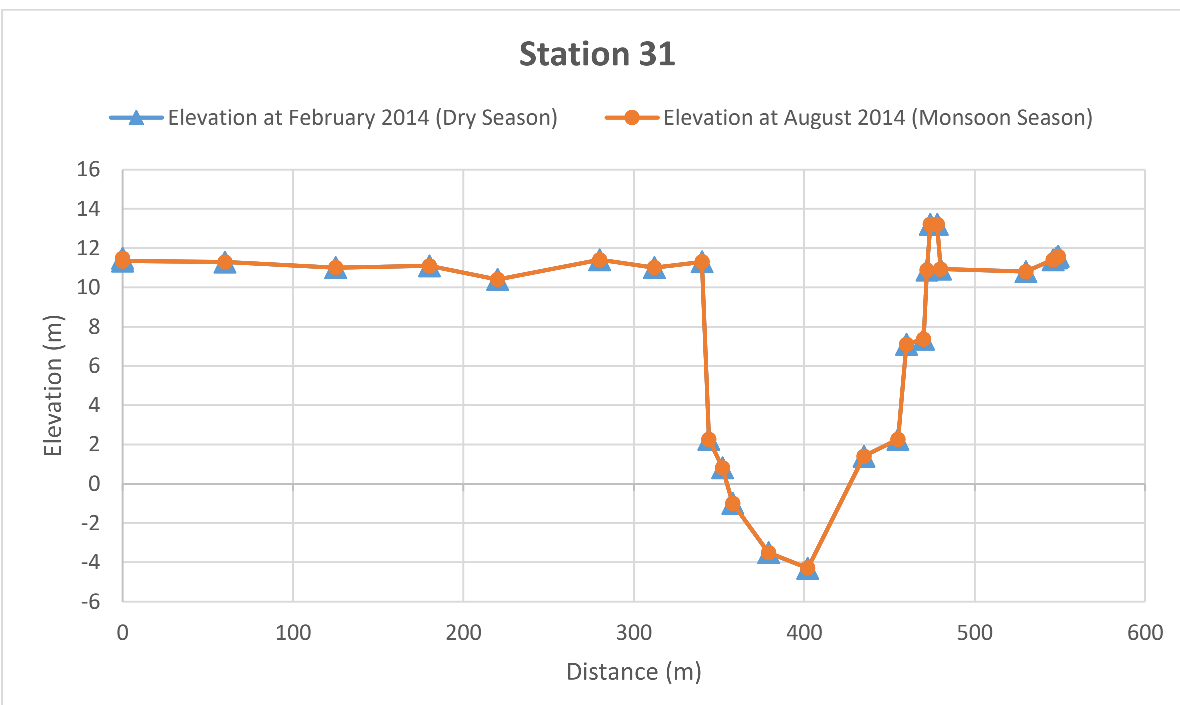

Figure 9-55 Non-Silting and Non-Eroding Cross Section 31 of the Surma

At cross section 26 neither erosion or deposition was observed (Figure 9.56).

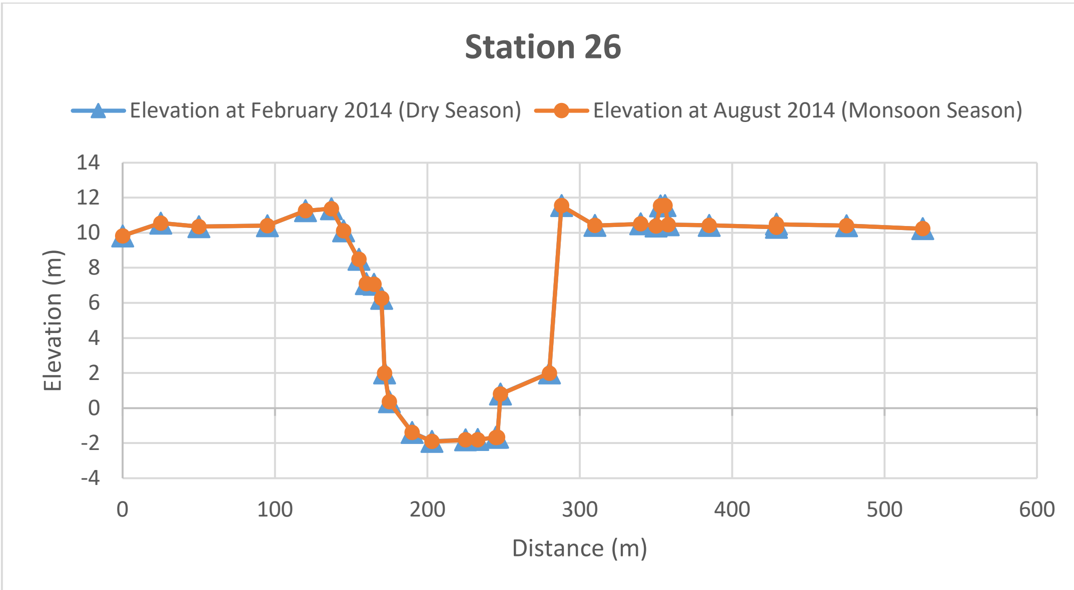

Figure 9-56 Non-Silting and Non-Eroding Cross Section 26 of the Surma

At downstream cross section 20 deposition has occurred (Figure 9.57).

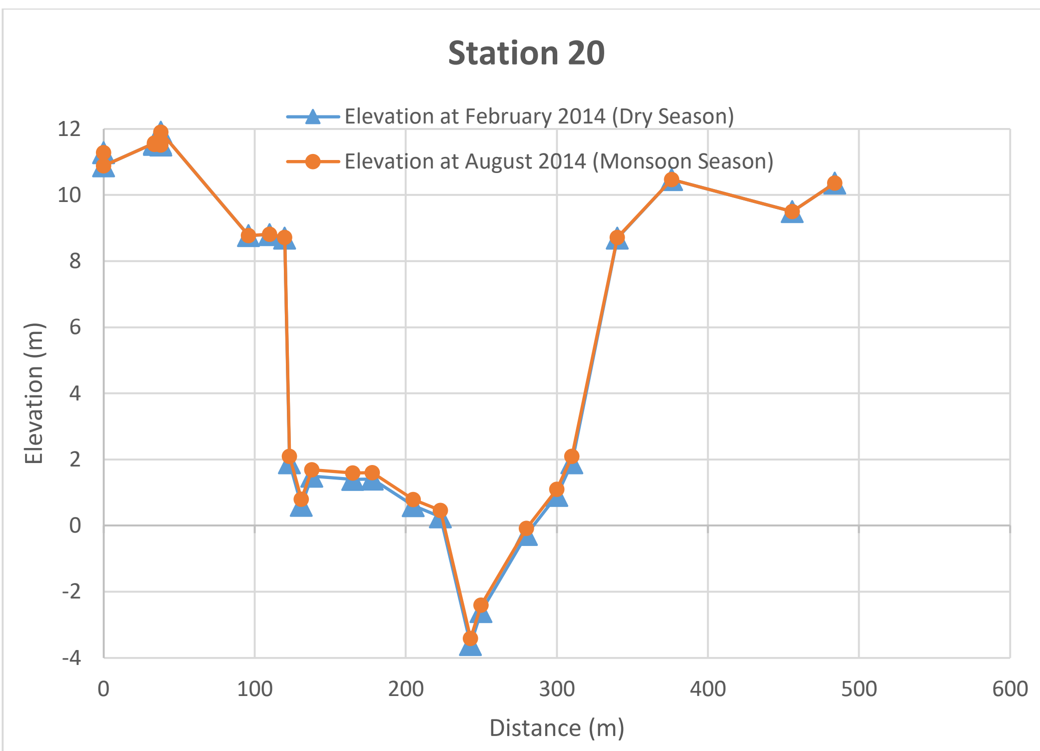

Figure 9-57 Siltation at the Cross Section 20 of the Surma during Monsoon

At downstream cross section 11 neither erosion or deposition has occurred (Figure 9.58)

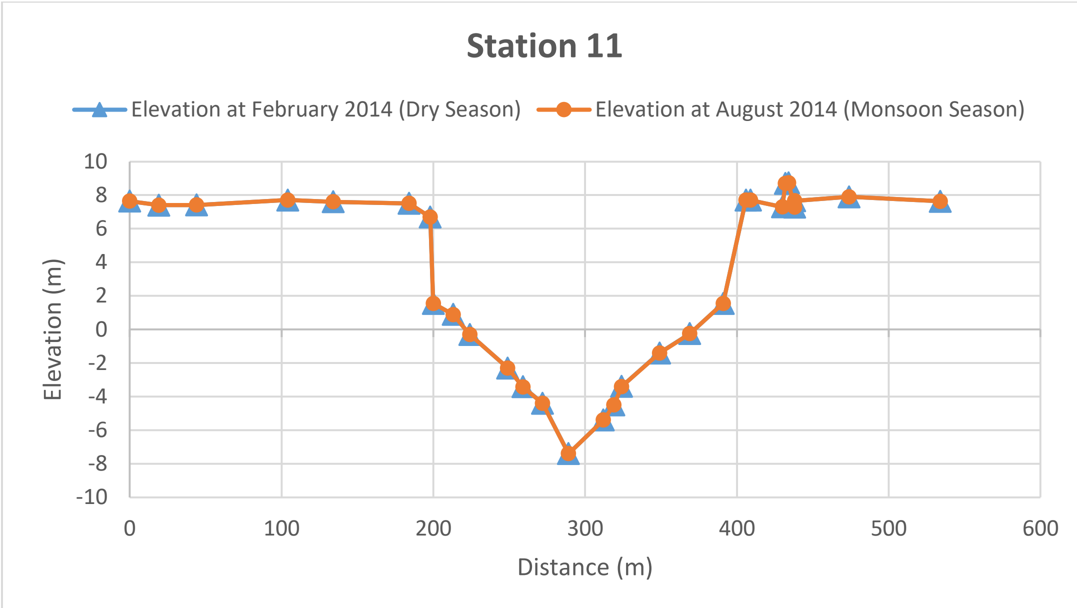

Figure 9-58 Non-Silting and Non-Eroding Cross Section 11 of the Surma

The river shows neither erosion nor deposition at the 4 stations (RS 34, RS 31, RS 26 and RS 11) but siltation at station 20 during monsoon. **So from the above analysis it was observed that there are virtually no changes in bed level gradient.**

Water Level and Channel Slope:

Water level Slopes have been calculated from upstream to downstream. As before five selected stations and 2 seasons have been considered for this purpose. Water level Gradient for Dry seasons and Monsson seasons are shown in Table 9.15. Bed level gradations for the two seasons were also calculated and presented in Table 9.15.

Table 9.15 Water Level and Bed Level Gradients for Dry and Monsson Seasons

Station name, ID, Location	Chainage (m)	Avg. WL Dry season (February 2014) (m)	Avg. WL Monsoon season (August 2014) (m)	WL Gradient for Dry season *	WL Gradient for Monsoon season *	Bed Level Gradient for Dry season *	Bed Level Gradient for Monsoon season *
RS 38, (SW 266) (Kanaighat)	0	1.90	10.38	-	-	-	-
RS 31	42000	1.87	9.385	0.00000087	0.000024	0.000088	0.000088
RS 26, (SW 267) (Sylhet Sadar)	72000	1.86	8.975	0.00000011	0.000014	-0.000080	-0.000080
RS 20	108000	1.86	7.86	0.000000093	0.000031	0.000047	0.000042
RS 11, (SW 269) (Sunamganj)	162000	1.86	7.29	0.00000000019	0.000011	0.000070	0.000074

Note*: Gradient between two successive stations

Water level gradient of the Surma for Dry season and Monsoon season are shown in Figure 9.59 and 9.60 and Bed level gradient of the Surma are shown in Figure 9.61 and 9.62.

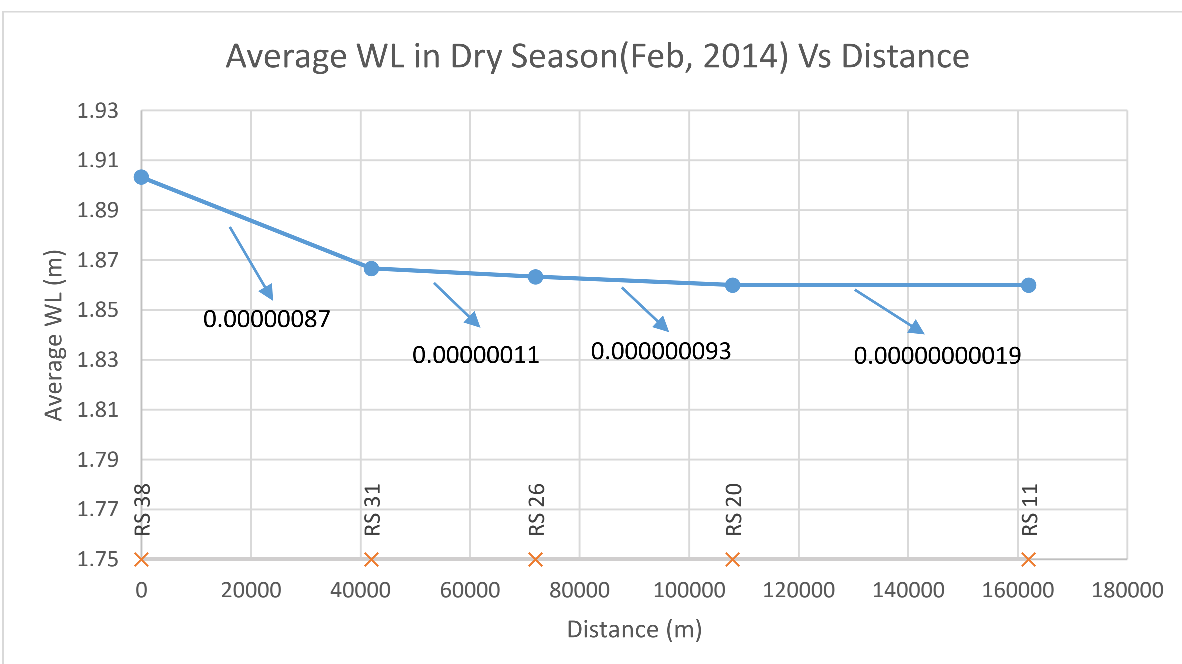

Figure 9-59 Average Water Level Gradient Graph for Dry Season of the Surma (Feb, 2014)

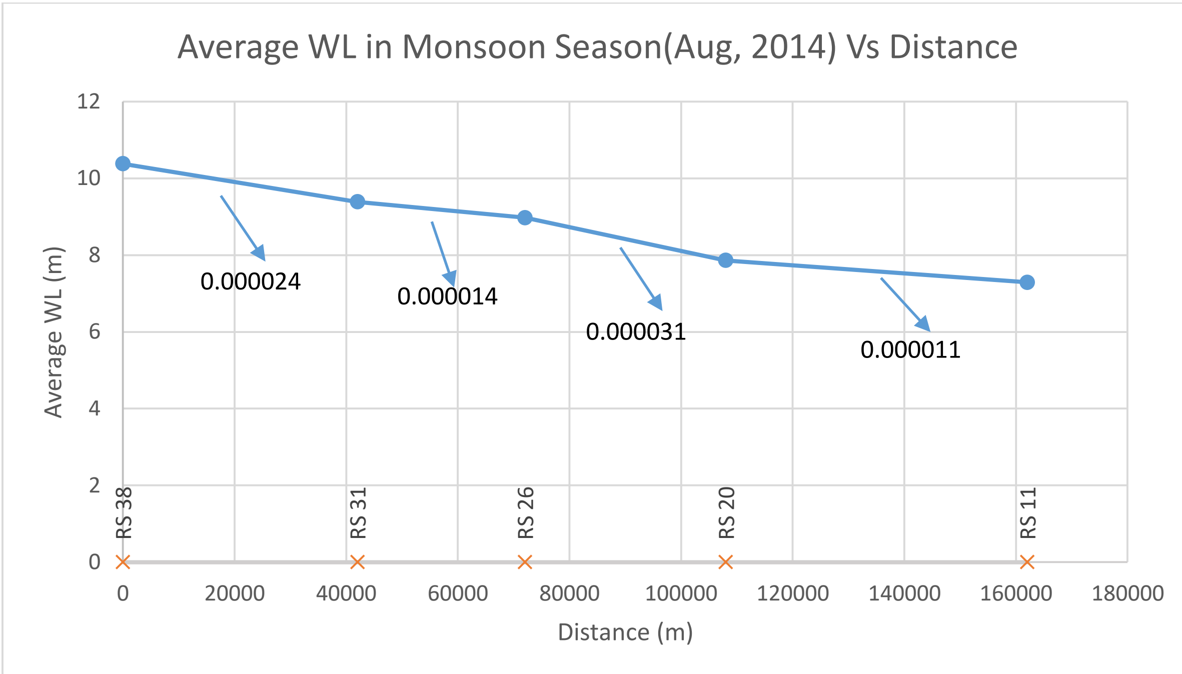

Figure 9-60 Average Water Level Gradient Graph for Monsson Season of the Surma (Aug, 2014)

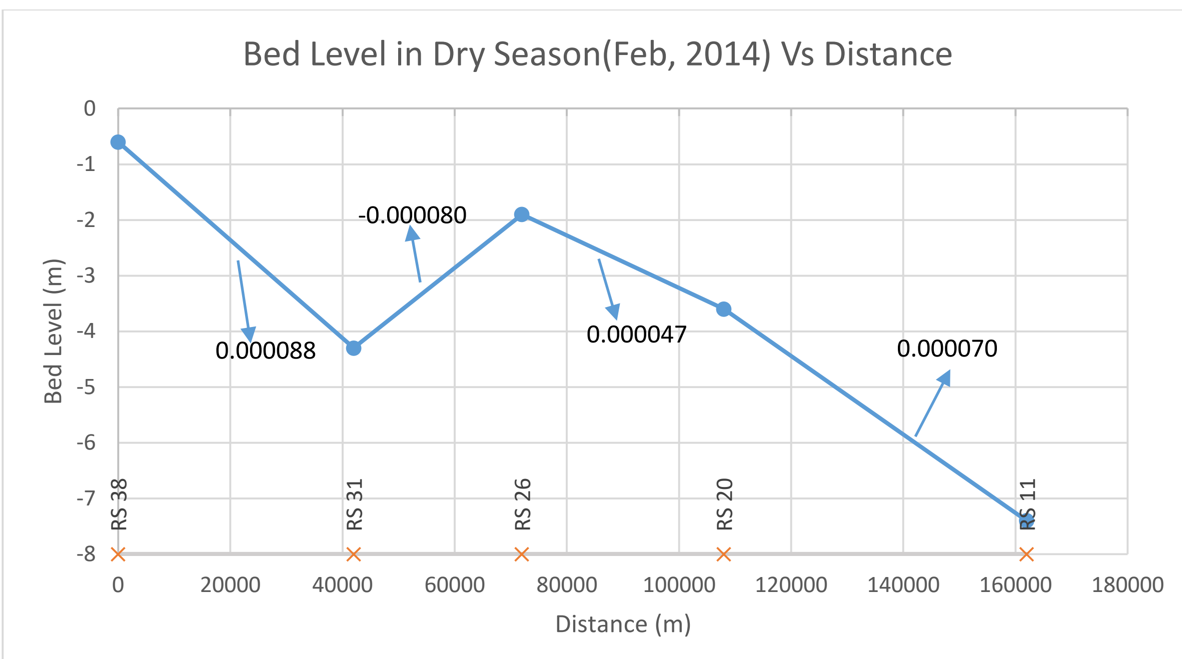

Figure 9-61 Bed Level Gradient Graph for Dry Season of the Surma (Feb, 2014)

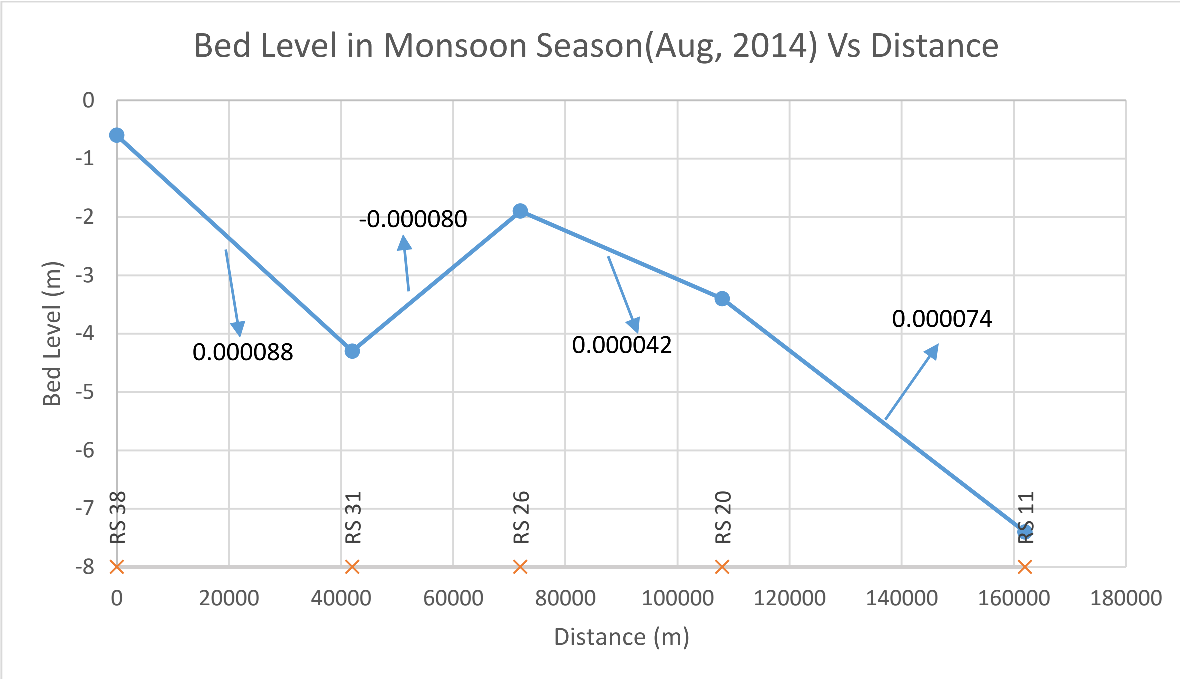

Figure 9-62 Bed Level Gradient Graph for Monsson Season of the Surma (Aug, 2014)

It is observed that monsoon season water level gradient is higher than the dry season water level gradient. Bed slope at both the seasons are almost same. Sedimentation of about 20 cm was observed during monsoon at RS 20 of the Surma and in other sections there were no sedimentation or erosion.

So the Hypothesis 3 could not be established/validated for the Surma from bed level slope consideration.

The Kushiyara:

For the Kushiyara river, data of twenty-one cross sections are available. Eleven cross sections have been considered to validate the hypothesis. The model was run for year 2012 and two period were considered one is Monsoon season (June-September) and other is Dry Season (January –March). Average sedimentation of each period have been considered to observe the seasons changes of the cross section; whether there is any erosion, deposition or no changes over the year. Water Level Gradient and the bed level gradient of the Kushiyara and change of wetted width in the river reach have also been calculated to validate the hypothesis. The Schematic Diagram (Figure 9.63) of the Kushiyara river 150 km reach is shown below:

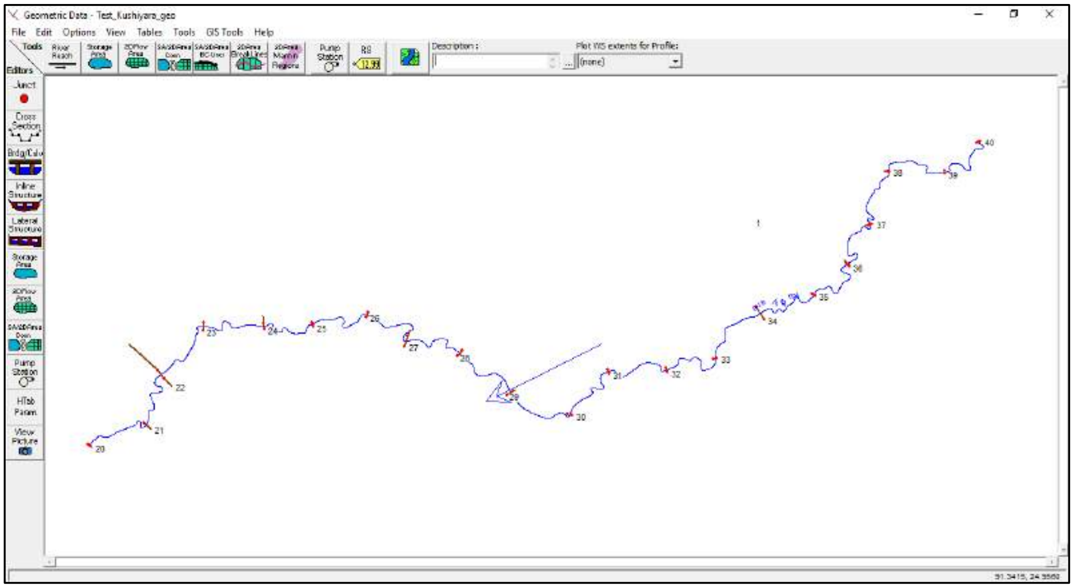

Figure 9-63 Cross Section of Kushiyara River

As mentioned earlier four Cross section have been considered (RS 40,RS 34,RS28 and RS20) to validate the hypothesis. Figure 9.64 shows the change of cross section of station 40 between February 2012 and August 2012. Erossion is observed in the monsson season.

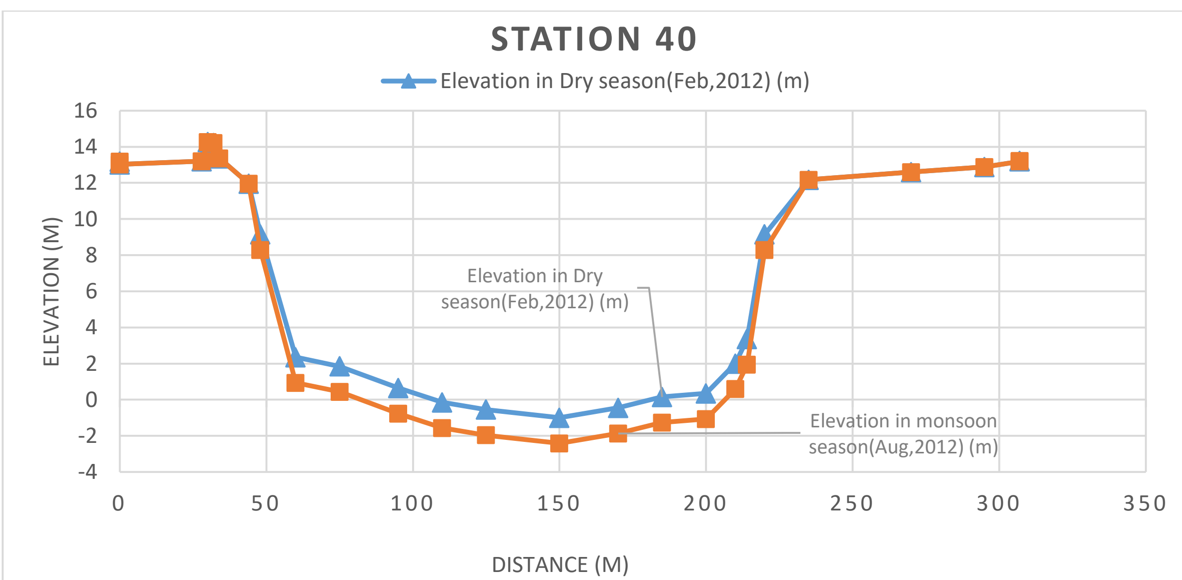

Figure 9-64 Eroding Cross Section 40 in Monsoon (2012)

At cross section 34, the cross section remains the same over the seasons. So in this cross section neither erosion nor deposition have been observed (Figure 9.65).

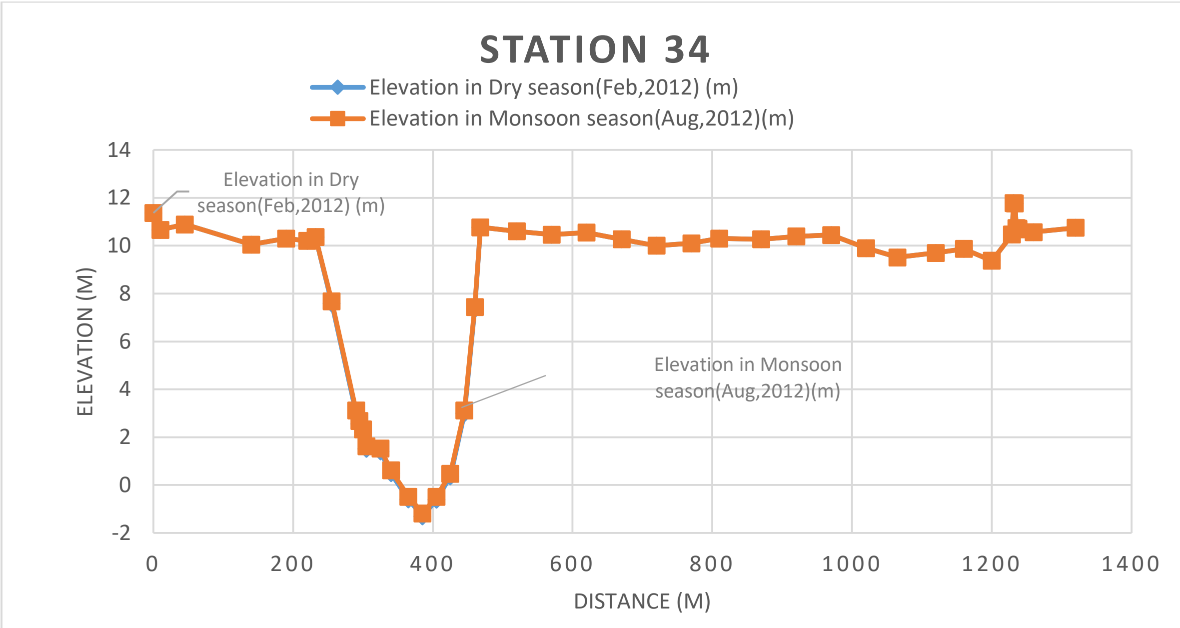

Figure 9-65 Stable (Non Silting and Non Eroding) Cross Section 34 in Monsoon (2012)

At cross section 28 erosion was observed and net erosion was about 1.0 m (Figure 9.66) in the monsson season.

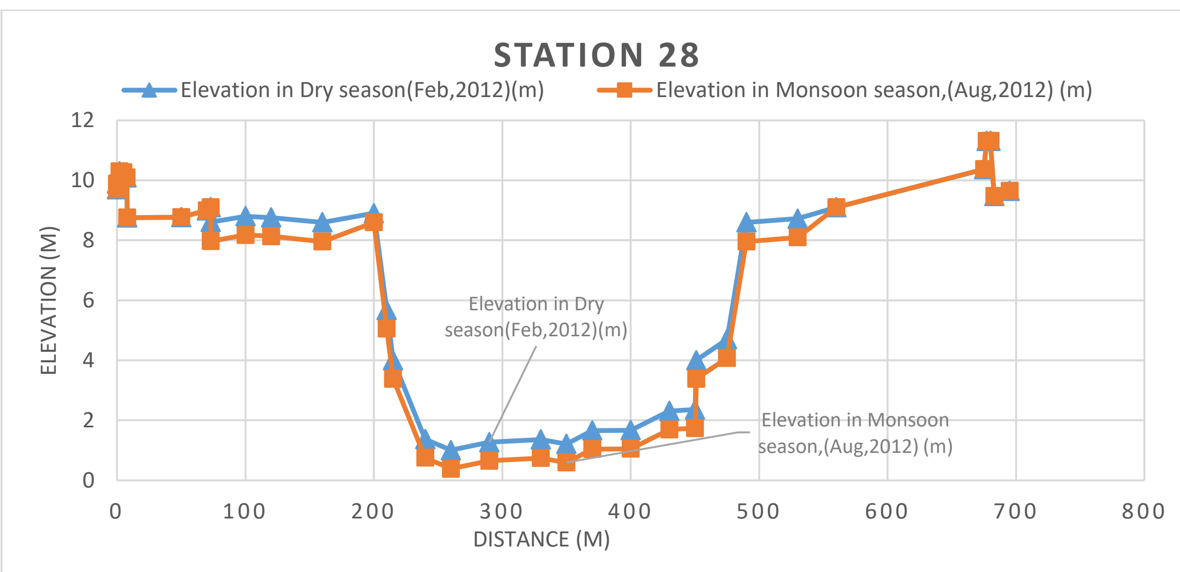

Figure 9-66 Eroding Cross Section 28 in Monsoon (2012)

At downstream cross section 20 erosion has occurred and net erosion was about 2.0 m (Figure 9.67) in the monsson season.

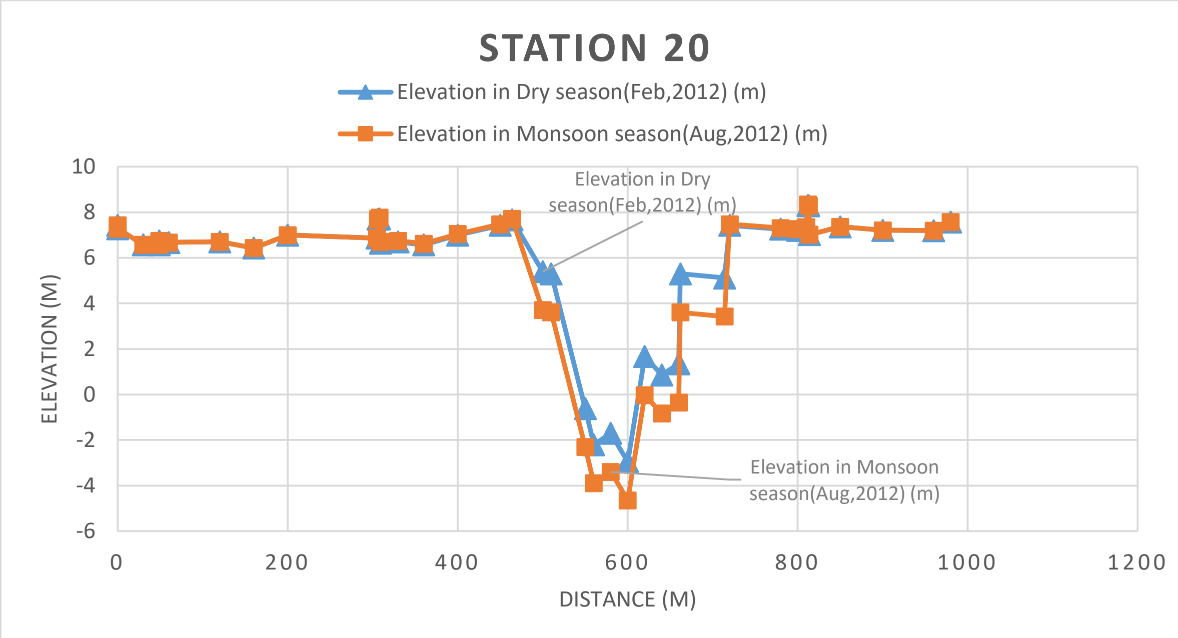

Figure 9-67 Eroding Cross Section 20 in Monsoon (2012)

The Kushiyara river shows erosion pattern in the upstream station (RS 40), neither erosion nor deposition at the intermediate stations (RS 34) again erosion at the d/s stations (RS 28 to RS 20). **So from the above analysis it is observed that there is change of bed level gradations.**

Water Level and Channel Slope:

Water Level and Channel Slope have been calculated from upstream to downstream. As before four selected stations and two seasons have been considered for this purpose. Water and Bed Level Gradients for Dry season and Monsson seasons are shown in Table 9.16.

Table 9.16: Water Level and Bed Level Gradient for Dry, Monsson Seasons of the Kushiyara

Station name, ID, Location	**Chain-age (m)**	**Average WL Dry season (February, 2012) (m)**	**Average WL Monsoon season (August, 2012) (m)**	**WL Gradient for Dry season ***	**WL Gradient for Monsoon season ***	**Bed Gradient for Dry season ***	**Bed Gradient for Monsson season ***
RS 40,(KUS12) (Sheola)	0	4.89	9.09	_	_	_	_
RS 34, (KUS6) (Fenchugong)	36000	4.23	8.70	0.0000016	0.0000065	0.000005	-0.000003
RS 28, (BIB1) (Sherpur)	72000	4.12	8.62	0.0000004	0.0000045	-0.000007	-0.000001
RS 20, (BIB9) (Markuli)	114000	4.00	8.46	0.0000007	0.0000032	0.000006	0.000001

Note*: Gradient between two successive stations

Average Water Level vs. Distance showing the Water Level gradients for dry and monsoon seasons are shown in Figure 9.68 and Figure 9.69 respectively. Bed level gradient vs Distance showing the bed level gradients for dry and monsoon seasons are shown in Figure 9.70 and Figure 9.71 respectively.

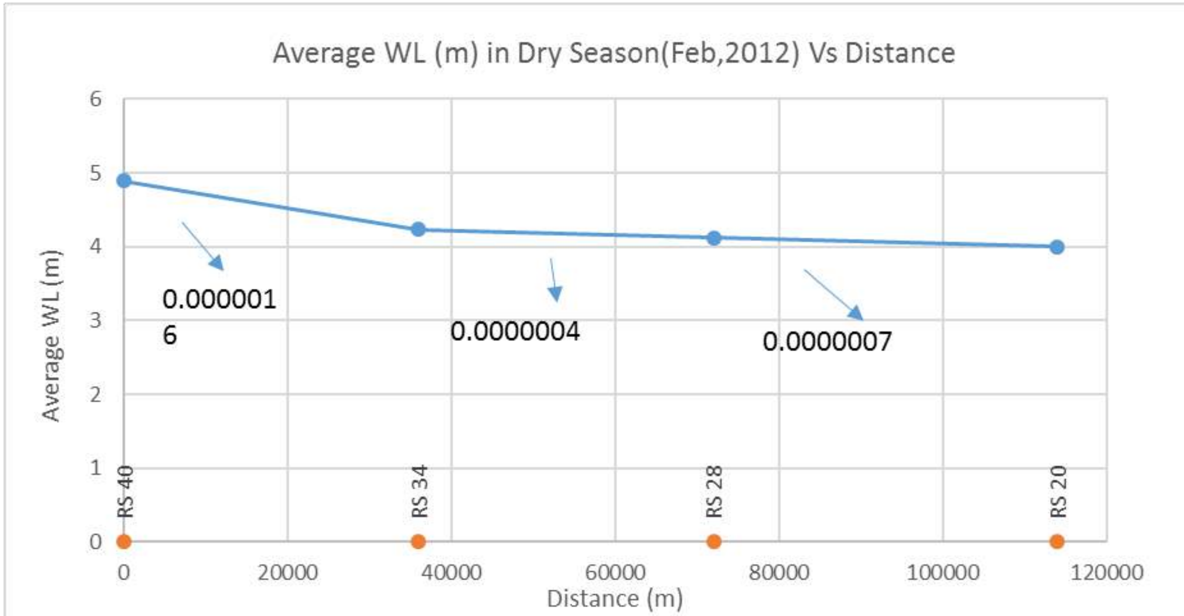

Figure 9-68 Average Water Level Gradient Graph for Dry Season of the Kushiyara (2012)

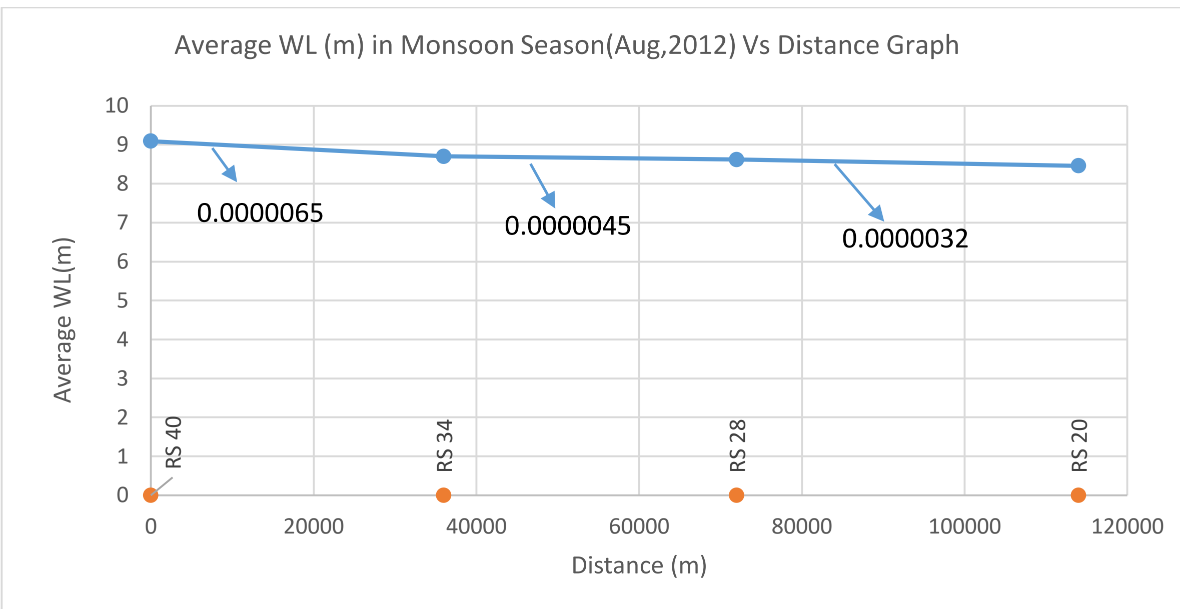

Figure 9-69 Average Water Level Gradient Graph for Monsson Season of the Kushiyara (2012)

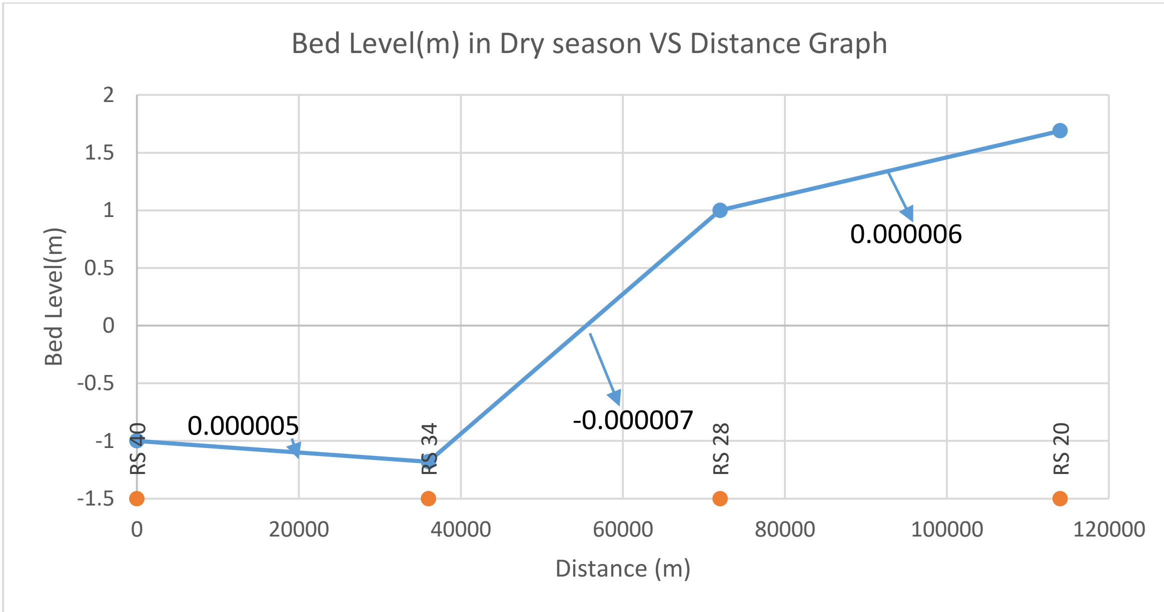

Figure 9-70 Average Bed Level Gradient Graph for Dry Season of the Kushiyara (2012)

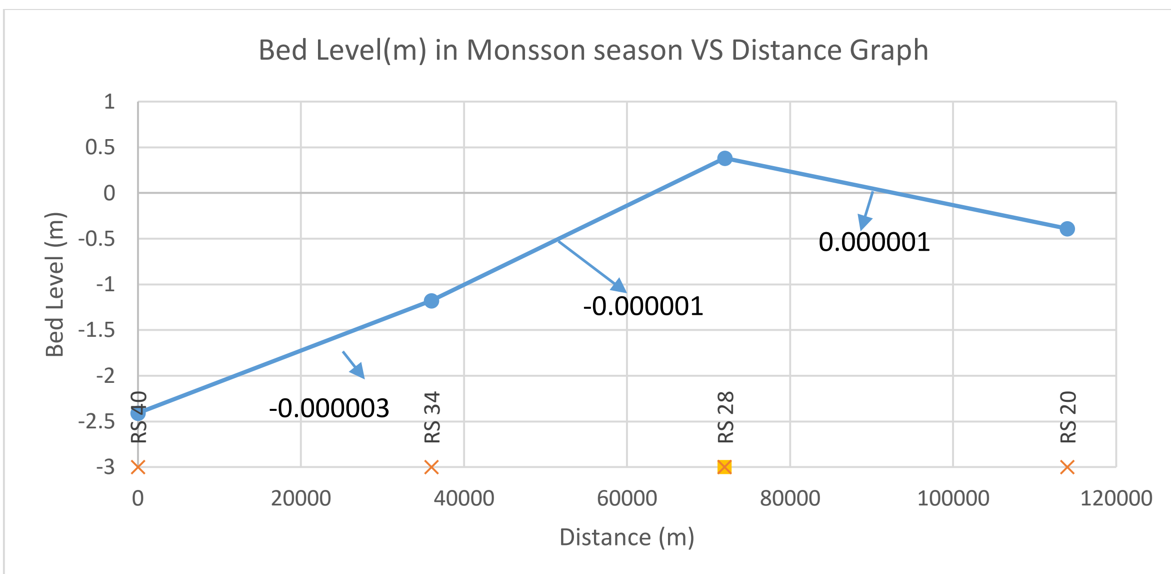

Figure 9-71 Average Bed Level Gradient Graph for Monsoon Season of the Kushiyara (2012)

It is observed that monsoon season water level gradient is higher than that of the dry season water level gradient. In most cases the dry season bed level gradient is greater than that of the monsoon season.

So Hypothesis 3 can be considered as established/validated from the consideration of bed level gradient for the Kushiyara.

9.4 Hypotheses 4 & 5

The Hypothesis 4 states that "**After several years/decades (at time tα) as the river will be able to raise its levee and reach regime condition, the flood level will be close to the bank level (Figure 5.4), i.e. bankfull water level will be the same along the whole river stretch.**"

The Hypothesis 5 states that **"The channel dimensions will be closed the same at the upstream and downstream and no sedimentation would be expected during monsoon."**

9.4.1 Conventional Analysis

The Hypotheses 4 and 5 are only valid for Regime condition. The characteristics of Regime condition have been explained in section 5.6.2.

9.4.1.1 Sediment Concentration

The Surma:

Sediment concentration samples of the Surma have been collected from 9 stations as shown in Table 6.2. A number of 3 sets of measurements have been made to validate the conceptual model.

The first set of data was collected from August 22, 2016 to August 29, 2016 (monsoon season). The data have been plotted in Figure 9.72. From the figure, it is apparent from the trend line that the sediment concentration along the river course is increasing towards downstream (R= 0.749), which is statistically significant.

The 2nd set of data have been collected from January 14, 2017 to January 24, 2017 (Dry season). The data have been plotted in Figure 9.73. From the figure, it is apparent from the trend line that the sediment concentration along the river course is decreasing towards downstream (R= -0.224), which is not statistically significant.

The 3rd set of data have been collected from April 18, 2017 to April 25, 2017 (Pre Monsoon season). The data have been plotted in Figure 9.74. From the figure, it is apparent from the trend line that the sediment concentration along the river course is increasing towards downstream (R= 0.63), which may however be considered as statistically significant.

The trend of change in sediment concentration from upstream to downstream in the Surma river does not follow the hypothetical trend of regime condition as described in the Conceptual model (Figure 5.5). The trend line of change in sediment concentration is rather opposite to which is described in the conceptual model **which clearly shows that the Surma river is not in regime condition.**

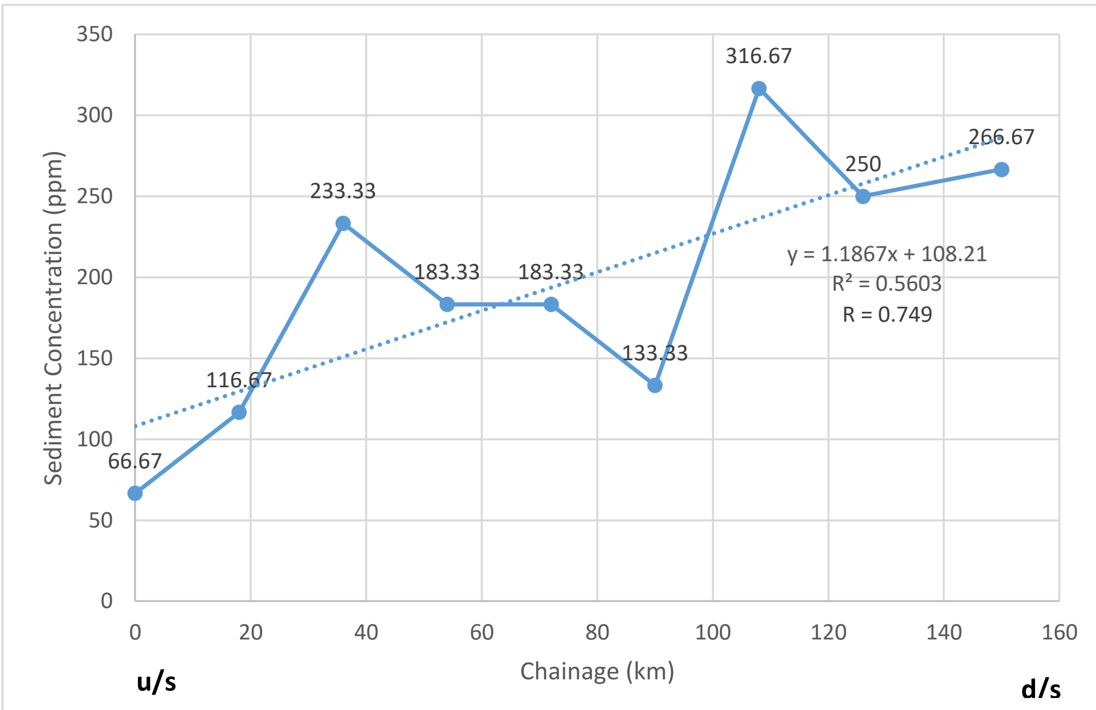

Figure 9-72 Analysis of Sediment Concentration of the Surma (August 2016, Monsoon Season)

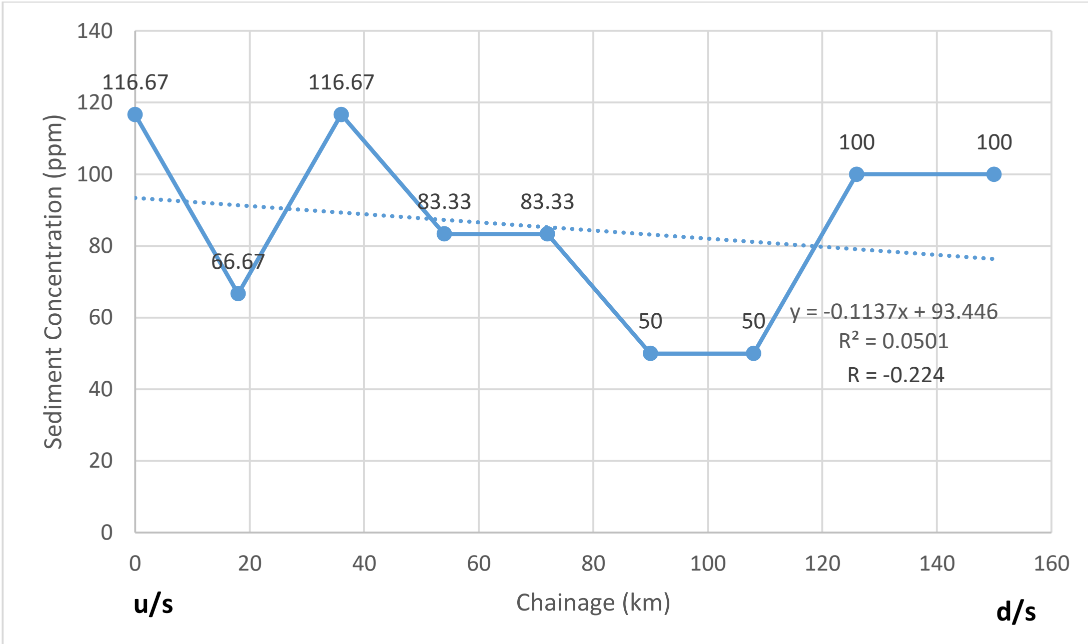

Figure 9-73 Analysis of Sediment Concentration of the Surma (January 2017, Dry Season)

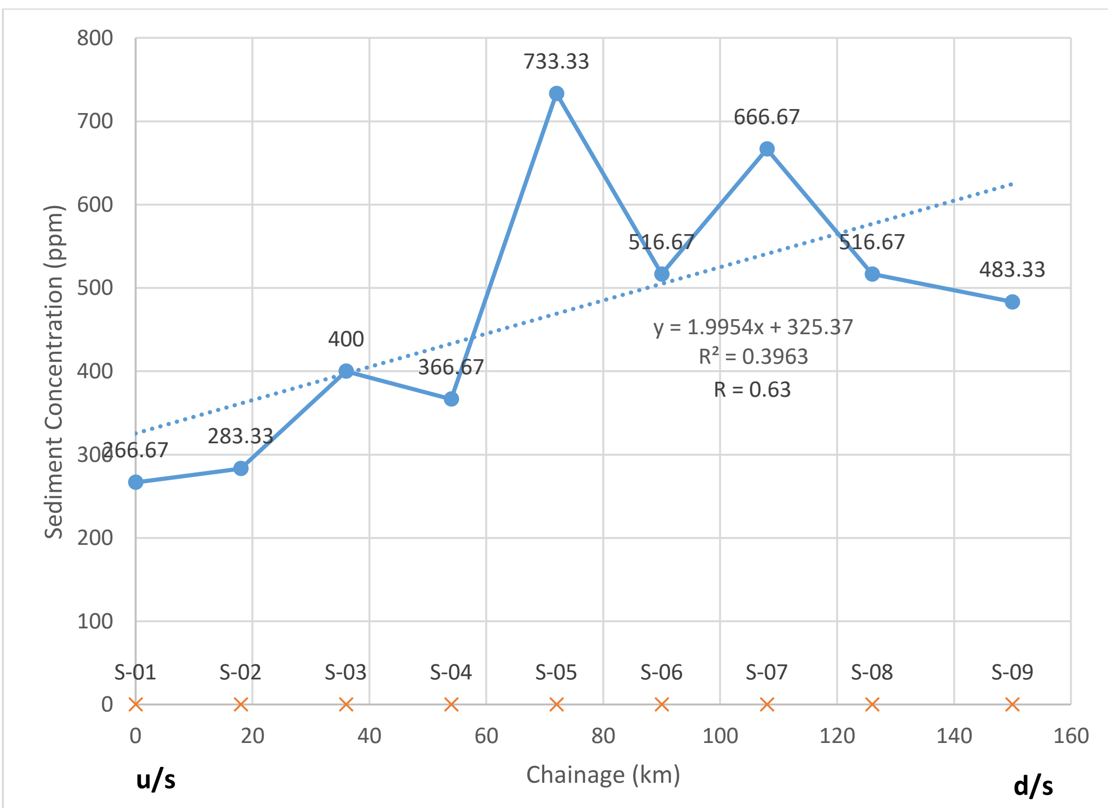

Figure 9-74 Analysis of Sediment Concentration of the Surma (April 2017, Pre Monsoon Season)

The Kushiyara:

Sediment concentration samples of the Kushiyara have been collected from 9 stations as shown in Table 6.8. A number of 3 sets of measurements have been made to validate the conceptual model.

The first set of data was collected from August 22, 2016 to August 29, 2016 (monsoon season). The data have been plotted in Figure 9.75. From the figure, it is apparent from the trend line that the sediment concentration along the river course is increasing towards downstream (R= 0.705), which is statistically significant.

The 2^{nd} set of data have been collected from January 14, 2017 to January 24, 2017 (Dry season). The data have been plotted in Figure 9.76. From the figure, it is apparent from the trend line that the sediment concentration along the river course is decreasing towards downstream (R= -0.265), which is not statistically significant.

The 3^{rd} set of data have been collected from April 18, 2017 to April 25, 2017 (Pre Monsoon season). The data have been plotted in Figure 9.77. From the figure, it is apparent from the trend line that the sediment concentration along the river course is also increasing towards downstream (R= -0.386), which is not statistically significant.

The trend of change in sediment concentration from upstream to downstream in the Kushiyara river does not follow the hypothetical trend of regime condition as described in the Conceptual model (Figure 5.5) which **clearly shows that the Kushiyara river is not in regime condition.**

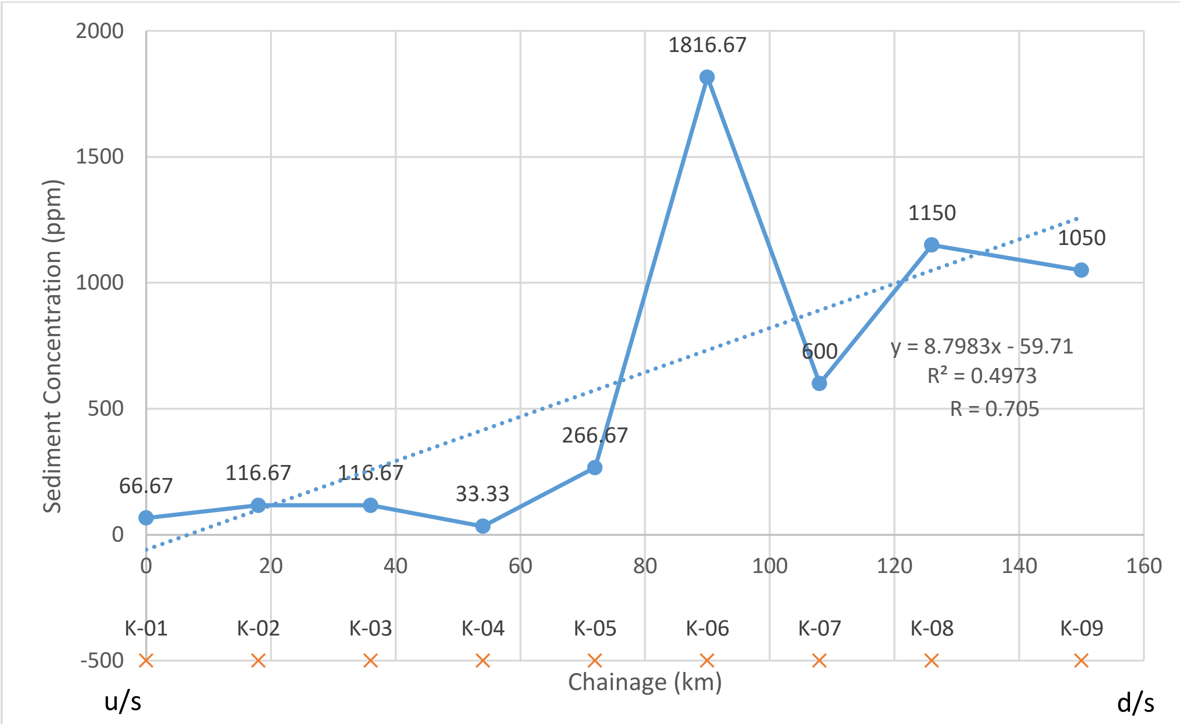

Figure 9-75 Analysis of Sediment Concentration of the Kushiyara (August 2016, Monsoon Season)

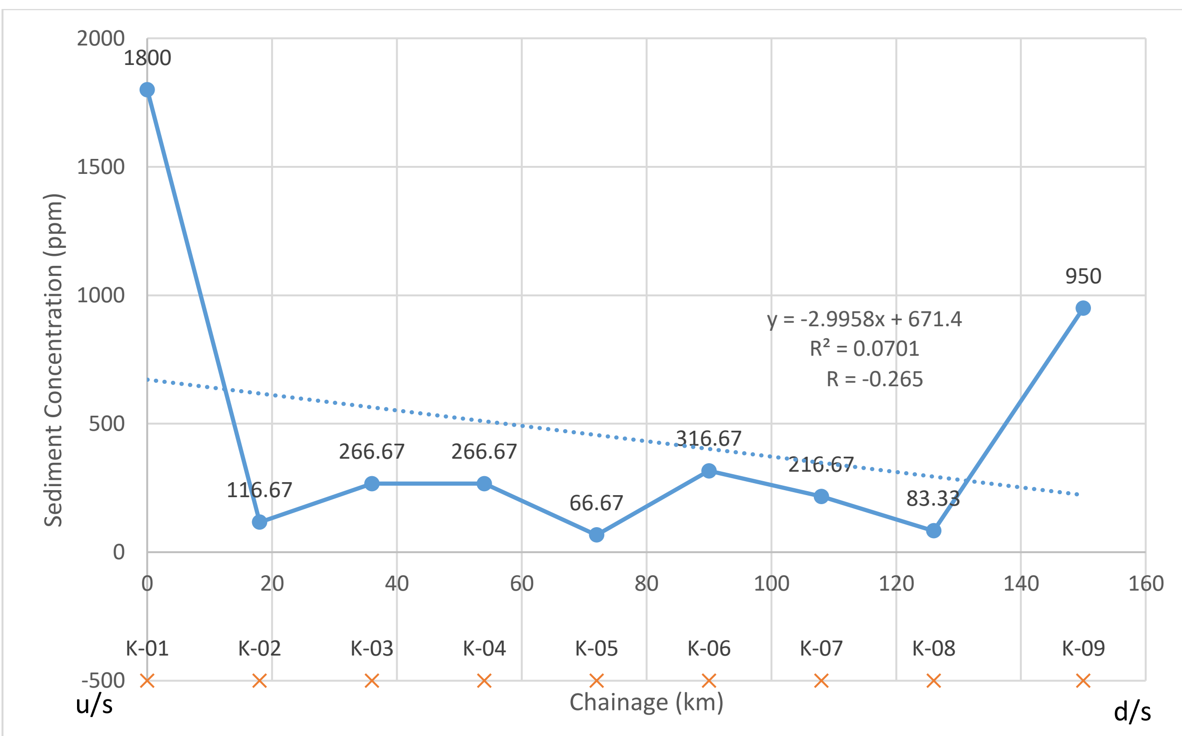

Figure 9-76 Analysis of Sediment Concentration of the Kushiyara (January 2017, Dry Season)

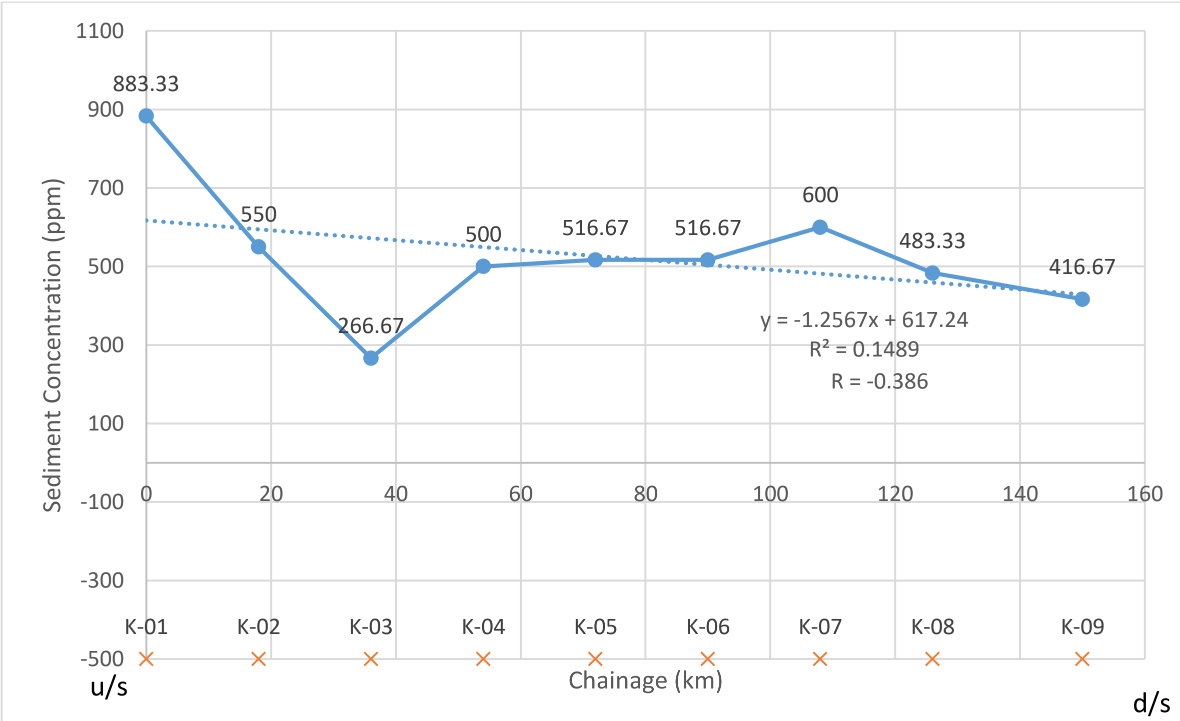

Figure 9-77 Analysis of Sediment Concentration of the Kushiyara (April 2017, Pre Monsoon Season)

9.4.1.2 Median Grain Size

The Surma:

Bed Material Samples of the Surma have been collected. Two measurements have been taken from 9 stations as shown in Table 6.2. Median grain sizes (D_{50}) of the bed materials of Dry Season and Pre Monsoon season along the river course are presented in Figure 9.78 and 9.79 respectively. Overall, the Median Grain Size along the river course shows a scattered pattern. It can be observed from the trend line in both the seasons that the median grain size value is decreasing in the downstream sections, although R values are not statistically significant, yet **it confirms that the river is not in regime condition** as was also conceived in the conceptual model.

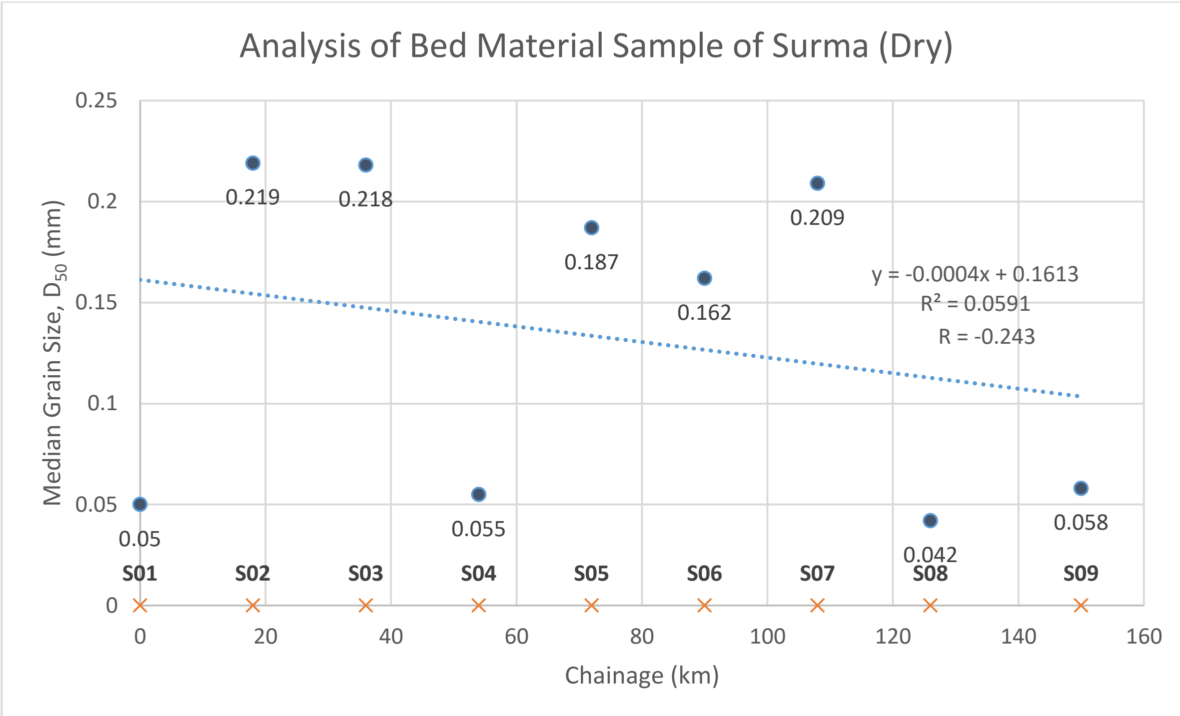

Figure 9-78 Analysis of Bed Material of the Surma river (January 2017, Dry season)

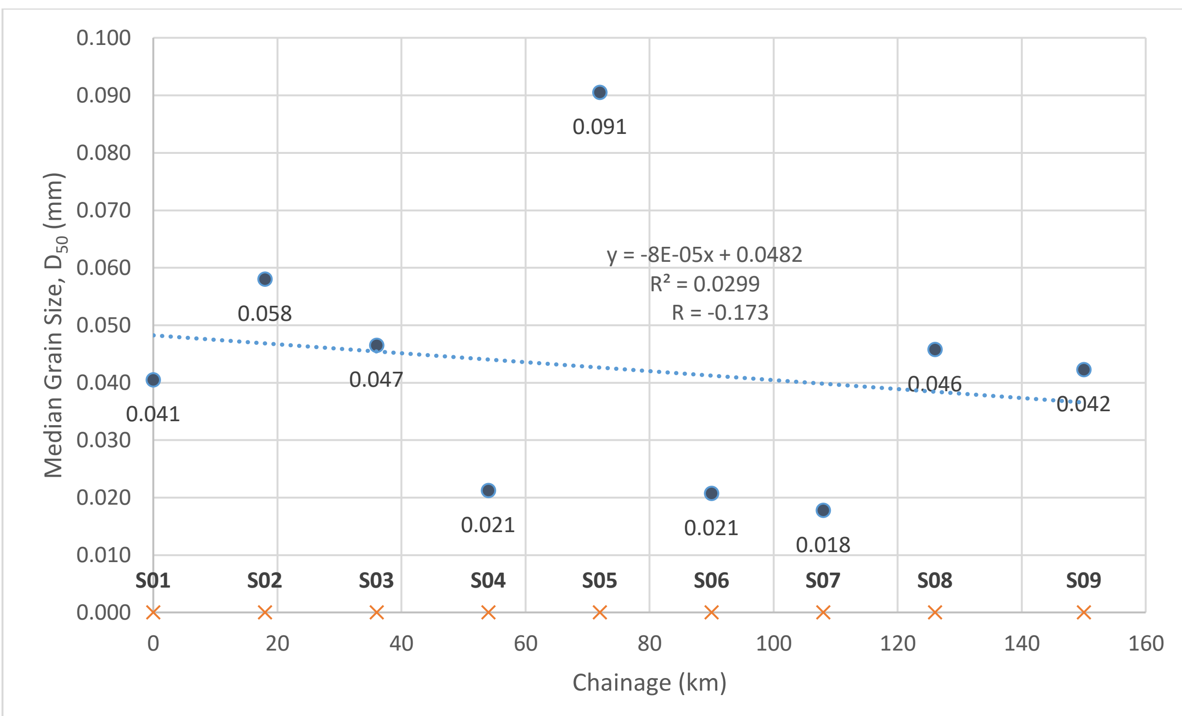

Figure 9-79 Analysis of Bed Material of the Surma river (April 2017, Pre Monsoon season)

The Kushiyara:

Bed Material Samples of the Kushiyara have been collected from 9 stations as shown in Table 6.8. A number of 2 sets of measurements have been done. Median grain sizes (D_{50}) of the bed materials of Dry Season and Pre Monsoon season along the river course are presented in Figure 9.80 and 9.81 respectively. Overall, the Median Grain Size along the river course shows a scattered pattern. It can be observed from the trend line in both the seasons that the median grain size value is decreasing in the downstream sections (R values are not statistically significant) which **confirms that the river is not in regime condition**.

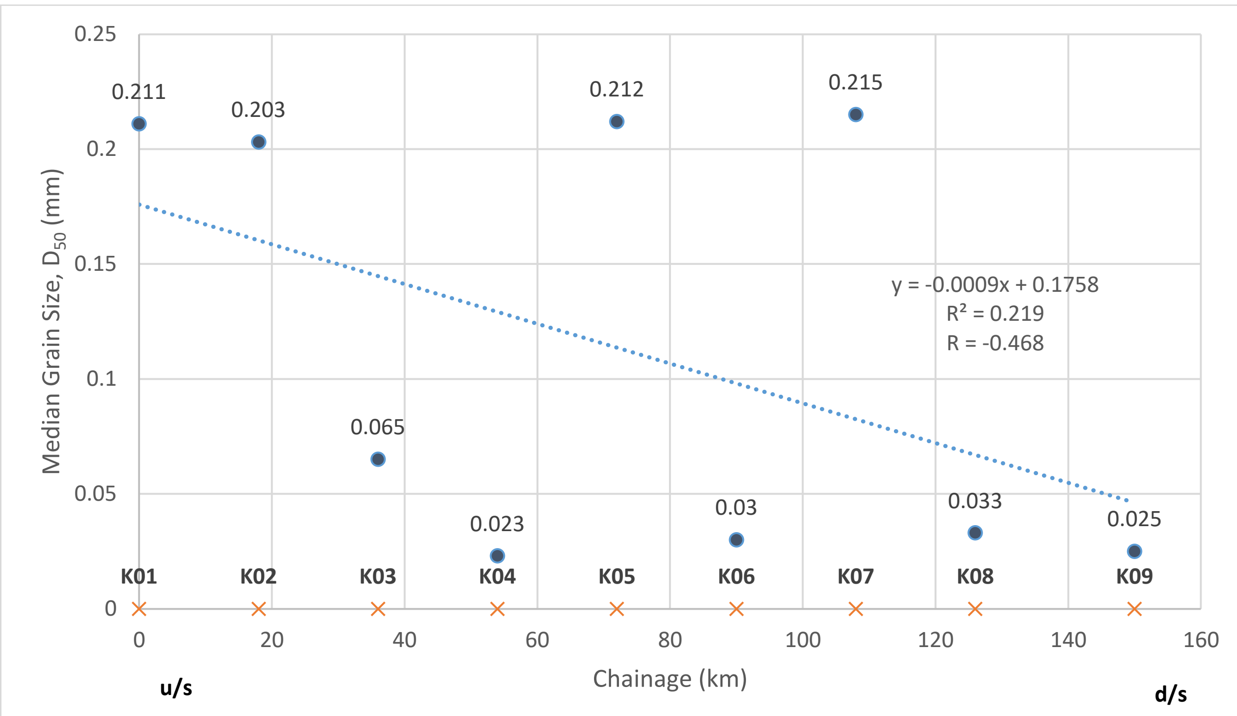

Figure 9-80 Analysis of Bed Material of the Kushiyara river (January 2017, Dry season)

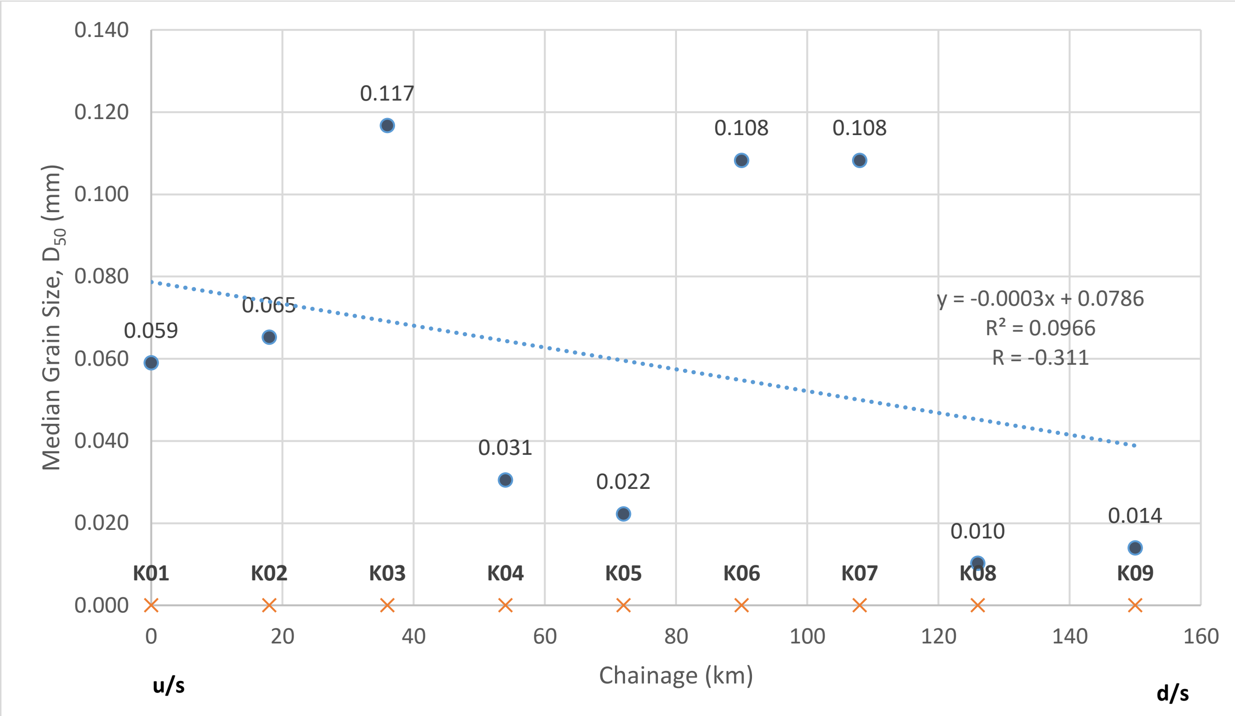

Figure 9-81 Analysis of Bed Material of the Kushiyara river (April 2017, Pre Monsoon season)

From the above analysis, it can be said the Hypotheses 4 and 5 for the Surma and Kushiyara rivers cannot be established/validated.

9.4.2 Model Output Analysis

Hypothesis 4 and 5 are valid only for regime or equilibrium condition of a river. The necessary conditions for considering a river reach to be in a "Regime" condition have been discussed elaborately in See 5.6.2.

Conventional Analysis and Model output reveal the following for both the Surma and the Kushiyara rivers:

1. The bankfull water levels at different sections are different. The bank level at the d/s sections are lower than the average flood level. (see section 9.1.1 and 9.2.1).

2. There are variations in X-sectional Areas, width and depth. (see section 9.2.1 and 9.2.2).

3. There are variations in the sediment concentration. (see section 9.4.1.1).

4. There are variations in the Median Grain Size (D_{50}). (see section 9.4.1.2).

From the above observation it may be concluded that none of the Surma and Kushiyara river are in “Regime” condition.

Hence Hypotheses 4 and 5 cannot be validated for the Surma and Kushiyara. But from Theoretical consideration both the hypotheses can be accepted for regime condition of a river. It was also mentioned earlier that it may take thousands of years for a river to reach to the “Regime Condition”.

10 Scenario Generation

Due to impact of Global climate change or in a very wet year the discharge at the u/s may increase. Similarly, for a very dry year or withdrawal of upstream water the discharge at the u/s may decrease. Two scenarios were generated using the HEC-RAS Model to observe likely changes of cross-sectional area, discharge and water levels at different stations due to 2 hypothetical conditions.

The Scenario-1, considered 20% increase of peak discharge at the u/s station RS 38 for the Surma and RS 40 for the Kushiyara.

The Scenario-2, considered 20% decrease of peak discharge at the u/s station RS 38 for the Surma and RS 40 for the Kushiyara.

The likely changes for the above mentioned scenarios for both the rivers have been described briefly in the following sub-sections.

10.1 The Surma

HECRAS 5.0.3 model has been validated with the data of 2014. At first peak discharges for each month of the year 2014 were identified and plotted as a discharge hydrograph (Figure 10.1).

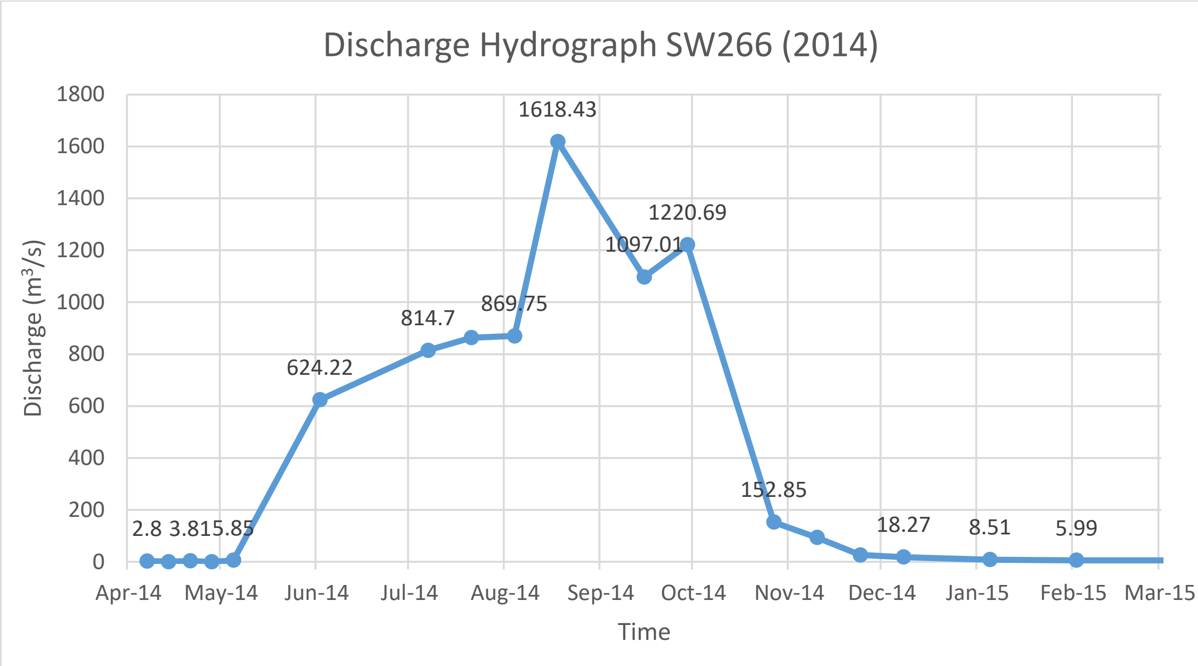

Figure 10-1 Monthly peak Discharges of the Surma for 2014

From the hydrograph, the highest value of discharge has been identified as 1618.43 m^3/s in August 2014. Then a discharge value 20% more than the highest value, that is 1942.12 m^3/s was put as upstream boundary condition at station RS 38. Similar discharge (1940 m^3/s) was found on 13 August 2010. The model was given a run for 2010 and corresponding water levels were taken from the model output. The simulated water level value of 2010 was put as downstream boundary condition at RS 11 and finally the model was run and after simulation, bankfull areas were found.

Similarly, simulation was done for 20% decrease from the peak discharge of 1618.43 m^3/s, that is 1294.74 m^3/s. Similar discharge (1300.26 m^3/s) was found on 18 October 2012. This value of discharge has been considered as the upstream boundary condition at RS 38. The simulated WL of 2012 at station RS 11 was taken as the downstream boundary condition. As mentioned earlier, changes of 20% increase in discharge is denoted as Scenario 1 and 20% decrease is denoted as Scenario 2.

10.1.1 Changes in Area

Changes of cross sectional area for Scenario 1 and 2 are shown in Table 10.1:

Table 10.1 Simulated Area for Scenario 1 and Scenario 2 in 28 Stations of the Surma River

SL	Station(u/s to d/s)	Distance From downstream	Bankfull Area(m^2)	Reference year 2014 Area (m^2)	Scenario 1: Area (m^2)	Scenario 2: Area (m^2)
1	RS38	162000	1858.91	1658.84	1955.3	1480.29
2	RS37	156000	1638.27	1543.24	1799.37	1395.02
3	RS36	150000	1909.11	1885.77	2343.4	1708.16
4	RS35	144000	1746.94	1549.41	1827.29	1408.09
5	RS34	138000	1434.45	1306.69	1485.11	1200.09
6	RS33	132000	1378.24	1437.31	1708.88	1323.21
7	RS32	126000	2460.18	2083.07	2625.09	1886.62
8	RS31	120000	1380.01	1502.89	1706.02	1404.66
9	RS30	114000	1810.31	2059.63	2367.02	1910.83
10	RS29	108000	1784.15	1622.49	1855	1501.79
11	RS28	102000	2122.33	2423.28	2701.28	2247.01
12	RS27	96000	2612.76	3077	3511.66	2807.34
13	RS26	90000	1413.71	1372.8	1569.93	1269.12
14	RS25	84000	1430.71	1597.25	1915.47	1490.61
15	RS24	78000	790.5	977.45	1085.46	917.94
16	RS23	72000	943.82	1108	1314.82	1000.84
17	RS22	66000	1310	1721.85	1955.47	1638.47
18	RS21	60000	1381.77	1501.59	1658.87	1427.48
19	RS20	54000	1748.81	1919.88	2145.41	1814.15
20	RS19	48000	1753.91	2280.83	2491.68	2177.53
21	RS18	42000	2067.91	2304.72	2559.41	2169.33
22	RS17	36000	1723.43	2388.38	2564.59	2291.97
23	RS16	30000	2080.04	2259.76	2447.35	2154.88
24	RS15	24000	1482.36	2127.72	2306.02	2024.76
25	RS14	18000	1452.23	2361.83	2705.48	2148.98
26	RS13	12000	2105.93	2686.89	2912	2538.73
27	RS12	6000	848.51	2462.19	2670.04	2319.03
28	RS11	0	732.78	1792.28	2242.75	1384.75

Note: Scenario 1: 20% increase in Peak discharge at UpStream (RS 38)

Scenario 2: 20% decrease in Peak discharge at Upstream (RS 38)

The 5 reference stations were selected as RS 38 (Upstream boundary), RS 11 (Downstream boundary) and RS 31, RS 26, RS 20 are intermediate calibrated Stations.

Analyzing Table 10.1 for selected stations RS 38, RS 31, RS 26, RS 20 and RS 11, Table 10.2 has been developed; which shows the changes of area both in numerical value as well as percentage for both the Scenarios.

Table 10.2 Changes in Area for Scenario 1 and 2 for five selected Stations with respect to Reference Year (2014) of the Surma River[3]

SL	Station from u/s to d/s	Distance from d/s (m)	Reference year 2014 Area (m^2)	Scenario 1: Increase (+) Decrease (-) Area (m^2)	Scenario 2: Increase (+) Decrease (-) Area (m^2)
1	RS38	162000	1658.84	1955.3,(+17.87%)	1480.29,(-10.76%)
2	RS31	120000	1502.89	1706.02,(+13.52%)	1404.66,(-6.54%)
3	RS26	90000	1372.80	1569.93,(+14.36%)	1269.12,(-7.55%)
4	RS20	54000	1919.88	2145.41,(+11.75%)	1814.15,(-5.51%)
5	RS11	0	1792.28	2242.75,(+25.13%)	1384.75,(-22.74%)

Note: Scenario 1: 20% increase in Peak discharge at UpStream (RS 38)
Scenario 2: 20% decrease in Peak discharge at Upstream (RS 38)
3: Developed from Table 10.1

It is seen that for Scenario 1, areas of RS 38, RS 31, RS 26, RS 20 and RS 11 increase about 17.87%, 13.52%, 14.36%, 11.75% and 25.13% respectively with respect to the reference year 2014.

For Scenario 2, areas decrease about 10.76%, 6.54%, 7.55%, 5.51% and 22.74% for the stations RS 38, RS 31, RS 26, RS20 and RS 11 respectively.

The changes in area of 28 cross sections along the channel for Scenario 1 can be observed from the following graph (Figure 10.2).

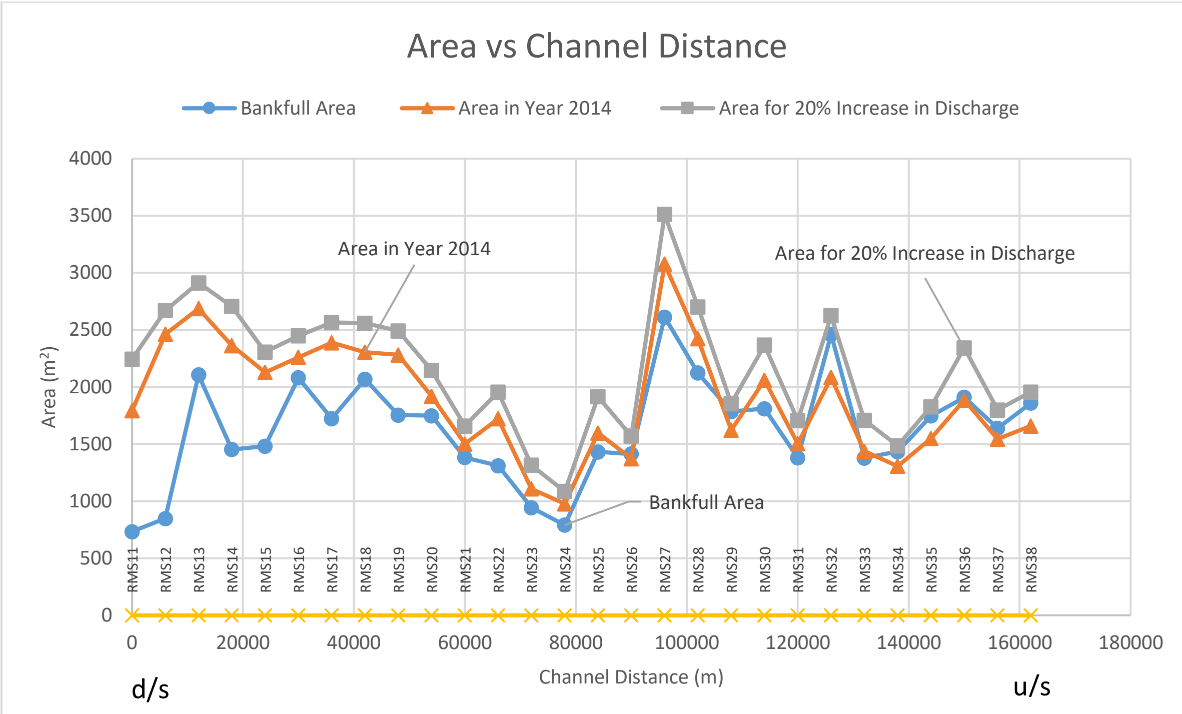

Figure 10-2 Area vs Distance for the Surma (2014); Scenario 1

Similarly, for 20% decrease in discharge, that is Scenario 2, changes in area along the channel are shown in the following graph (Figure 10.3).

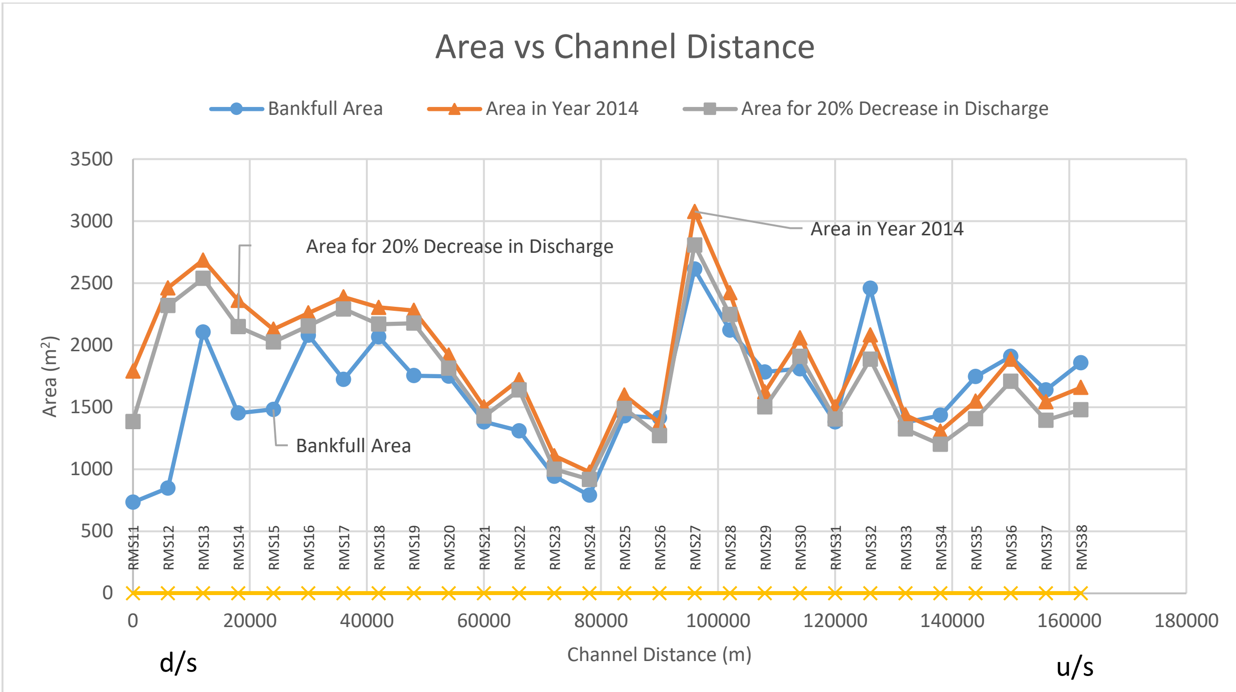

Figure 10-3 Area vs Distance for the Surma (2014); Scenario 2

10.1.2 Changes in Discharge

Similar analysis was done to see the change in discharge. Changes in discharge are shown in the following Table (Table 10.3):

Table 10.3 Simulated Discharge for Scenario 1 and 2 in 28 Stations of the Surma River

SL	Station(u/s to d/s)	Distance From downstream	Bankfull Discharge (m^3/s)	Reference year 2014 Discharge (m^3/s)	Scenario 1: Discharge (m^3/s)	Scenario 2: Discharge (m^3/s)
1	RS38	162000	1759	1618.43	1942.12	1294.74
2	RS37	156000	1599.87	1614.41	1942.12	1294.74
3	RS36	150000	1499.02	1610.42	1961.81	1297.73
4	RS35	144000	1763.97	1602.31	1961.23	1297.09
5	RS34	138000	1759.53	1594.47	1942.12	1294.74
6	RS33	132000	1370	1570.64	1942.12	1294.74
7	RS32	126000	1773.05	1560.42	1955.2	1302.94
8	RS31	120000	1280	1546.68	1965.32	1302.53

SL	Station(u/s to d/s)	Distance From downstream	Bankfull Discharge (m^3/s)	Reference year 2014 Discharge (m^3/s)	Scenario 1: Discharge (m^3/s)	Scenario 2: Discharge (m^3/s)
9	RS30	114000	1206.5	1536.89	1965.16	1298.03
10	RS29	108000	1765.3	1527.74	1942.12	1294.74
11	RS28	102000	1184.62	1519.35	1952.82	1308.43
12	RS27	96000	1190.03	1512.28	1942.12	1304.65
13	RS26	90000	1209.23	1510.42	1981.12	1298.75
14	RS25	84000	1205.2	1508.98	1980.11	1294.74
15	RS24	78000	967.69	1508.01	1979.45	1294.74
16	RS23	72000	1197.81	1507.59	1977.84	1294.74
17	RS22	66000	506.09	1461.37	1975.66	1362.49
18	RS21	60000	1199.39	1456.97	1974.39	1341.39
19	RS20	54000	1200	1453.27	1973.56	1338.76
20	RS19	48000	503.22	1448.07	1973.02	1337.6
21	RS18	42000	1196.78	1440.96	1972.61	1336.24
22	RS17	36000	500.65	1432.68	1972.44	1335.83
23	RS16	30000	1213.54	1423.57	1972.34	1335.3
24	RS15	24000	499.98	1415.21	1972.32	1335.15
25	RS14	18000	499.61	1407.86	1972.32	1335.07
26	RS13	12000	500	1402.11	1972.31	1335.02
27	RS12	6000	500	1396.94	1972.35	1335
28	RS11	0	590	1389.1	1942.12	1294.74

Note: Scenario 1: 20% increase in Peak discharge at UpStream (RS 38)
Scenario 2: 20% decrease in Peak discharge at Upstream (RS 38)

Changes in discharge in five selected cross sections are shown below (Table 10. 4):

Table 10.4 Changes in Discharge for Scenario 1 and 2 for five selected Stations with respect to Reference year (2014) of the Surma River[3]

SL	Station from u/s to d/s	Distance from d/s (m)	Reference year 2014 Discharge (m^3/s)	Scenario 1: Increase (+) Decrease (-) Discharge (m^3/s)	Scenario 2: Increase (+) Decrease (-) Discharge (m^3/s)
1	RS38	162000	1618.43	1942.12,(+20.25%)	1294.74,(-15.17%)
2	RS31	120000	1546.68	1965.32,(+27.41%)	1302.53,(-14.23%)
3	RS26	90000	1510.42	1981.12,(+31.16%)	1298.75,(-14.01%)
4	RS20	54000	1453.27	1973.56,(+35.80%)	1338.76,(-7.88%)
5	RS11	0	1389.10	1942.12,(+39.81%)	1294.74,(-6.79%)

Note: Scenario 1: 20% increase in Peak discharge at UpStream (RS 38)
Scenario 2: 20% decrease in Peak discharge at Upstream (RS 38)
3: Developed form Table 10.3

The changes in discharge for **Scenario 1** along the cross section can be visible from the following graph (Figure 10.4).

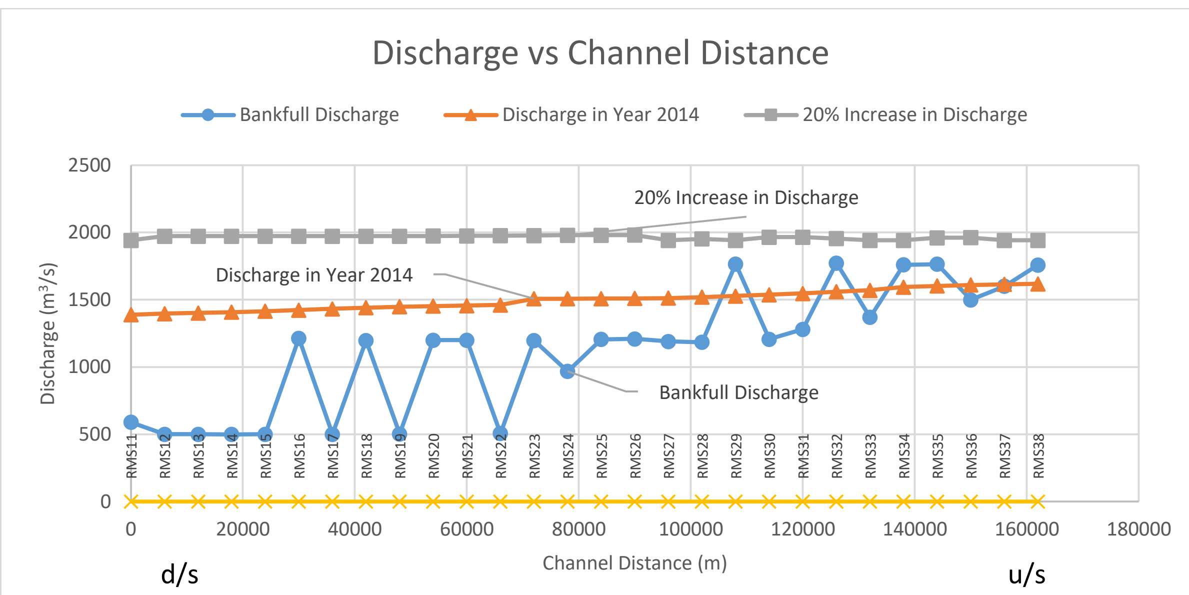

Figure 10-4 Discharge vs Distance for the Surma (2014); Scenario 1

For **Scenario 2**, the graph is shown in Figure 10.5:

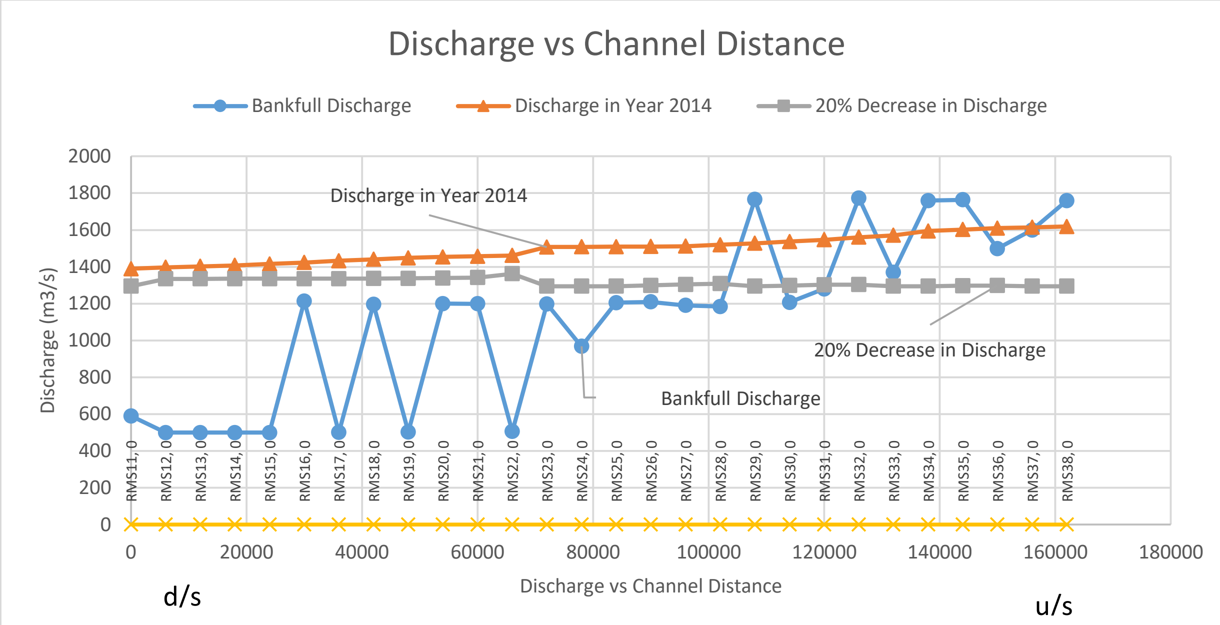

Figure 10-5 Discharge vs Distance for the Surma (2014); Scenario 2

10.1.3 Changes in Water Level

Changes in water levels for Scenario 1 and Scenario 2 have been shown in Table 10.5.

Table 10.5 Simulated Water Level for Scenario 1 and 2 in 28 Stations of the Surma River

SL	Station (from u/s to d/s)	Distance from d/s	Bankfull Water Level (m)	Reference year 2014 Water Level (m)	Scenario 1: Water Level (m)	Scenario 2: Water Level (m)
1	RS38	162000	13.34	12.3	13.66	11.46
2	RS37	156000	12.71	12.17	13.49	11.33
3	RS36	150000	12.18	12.08	13.33	11.24
4	RS35	144000	12.8	11.93	13.15	11.13
5	RS34	138000	12.61	11.74	12.94	10.99
6	RS33	132000	11.22	11.6	12.74	10.86
7	RS32	126000	12.26	11.49	12.57	10.78
8	RS31	120000	10.49	11.34	12.4	10.67

SL	Station (from u/s to d/s)	Distance from d/s	Bankfull Water Level (m)	Reference year 2014 Water Level (m)	Scenario 1: Water Level (m)	Scenario 2: Water Level (m)
9	RS30	114000	10.13	11.26	12.29	10.62
10	RS29	108000	11.84	11.14	12.12	10.52
11	RS28	102000	9.98	11.07	12.04	10.46
12	RS27	96000	9.95	11.03	12	10.42
13	RS26	90000	9.98	10.87	11.81	10.29
14	RS25	84000	9.73	10.7	11.61	10.18
15	RS24	78000	8.87	10.4	11.27	9.93
16	RS23	72000	9.19	10.01	10.88	9.55
17	RS22	66000	7.44	9.75	10.62	9.34
18	RS21	60000	8.96	9.63	10.44	9.22
19	RS20	54000	8.92	9.53	10.31	9.13
20	RS19	48000	7.37	9.47	10.22	9.08
21	RS18	42000	8.72	9.41	10.15	9.02
22	RS17	36000	6.37	9.37	10.1	8.97
23	RS16	30000	8.63	9.33	10.04	8.93
24	RS15	24000	6.33	9.28	9.98	8.88
25	RS14	18000	7.3	9.21	9.89	8.79
26	RS13	12000	7.29	9.15	9.8	8.72
27	RS12	6000	7.9	9.1	9.74	8.67
28	RS11	0	7.4	8.97	9.6	8.4

Note: Scenario 1: 20% increase in Peak discharge at UpStream (RS 38)
Scenario 2: 20% decrease in Peak discharge at Upstream (RS 38)

Changes in water level in selected 5 stations are shown in Table 10.6.

Table 10.6 Changes in Water Level for Scenario 1 and 2 for Five Selected Stations With Respect to Reference Year (2014) of the Surma River[3]

SL	Station from u/s to d/s	Distance from d/s (m)	Reference year 2014 Water level (m)	Scenario 1: Increase (+) Decrease (-) Water level (m)	Scenario 2: Increase (+) Decrease (-) Water level (m)
1	RS38	162000	12.3	13.66,(+11.06%)	11.46,(-6.83%)
2	RS31	120000	11.34	12.40,(+9.35%)	10.67,(-5.91%)
3	RS26	90000	10.87	11.81,(+8.65%)	10.29,(-5.34%)
4	RS20	54000	9.53	10.31,(+8.18%)	9.13,(-4.20%)
5	RS11	0	8.97	9.60,(+7.02%)	8.40,(-6.35%)

Note: Scenario 1: 20% increase in Peak discharge at UpStream (RS 38)
Scenario 2: 20% decrease in Peak discharge at Upstream (RS 38)
3: Development Form Table 10.5

For scenario 1, it is seen that flood is occurring in each station (RS 38, RS 31, RS 26, RS 20 and RS 11). At station 38, In the reference year 2014 there was no flood but under Scenario-1 there is flood of 32 cm. In the other stations flood depth increased by 106 cm, 94 cm, 78 cm and 63 cm at stations 31, 26, 20 and 11 with respect to the reference year respectively. The plots of the simulated discharge results of the cross sections are given below (Figure 10.6, 10.7, 10.8, 10.9 and 10.10).

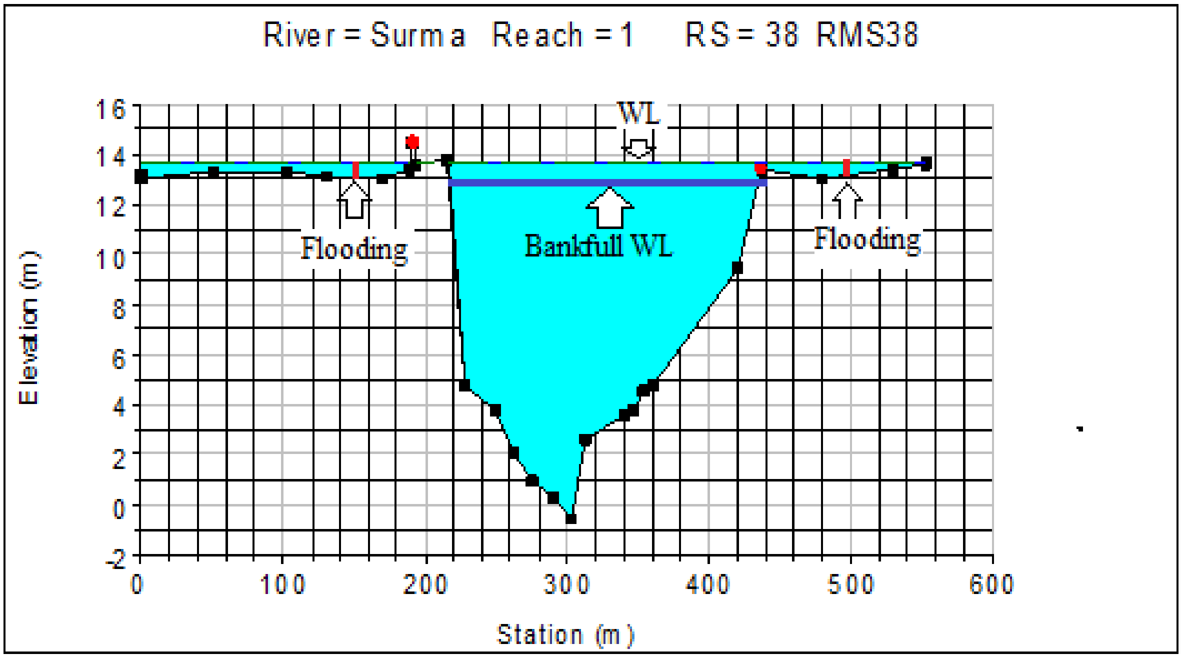

Figure 10-6 Changes in Water Level at RS 38 for Scenario 1,(The Surma)

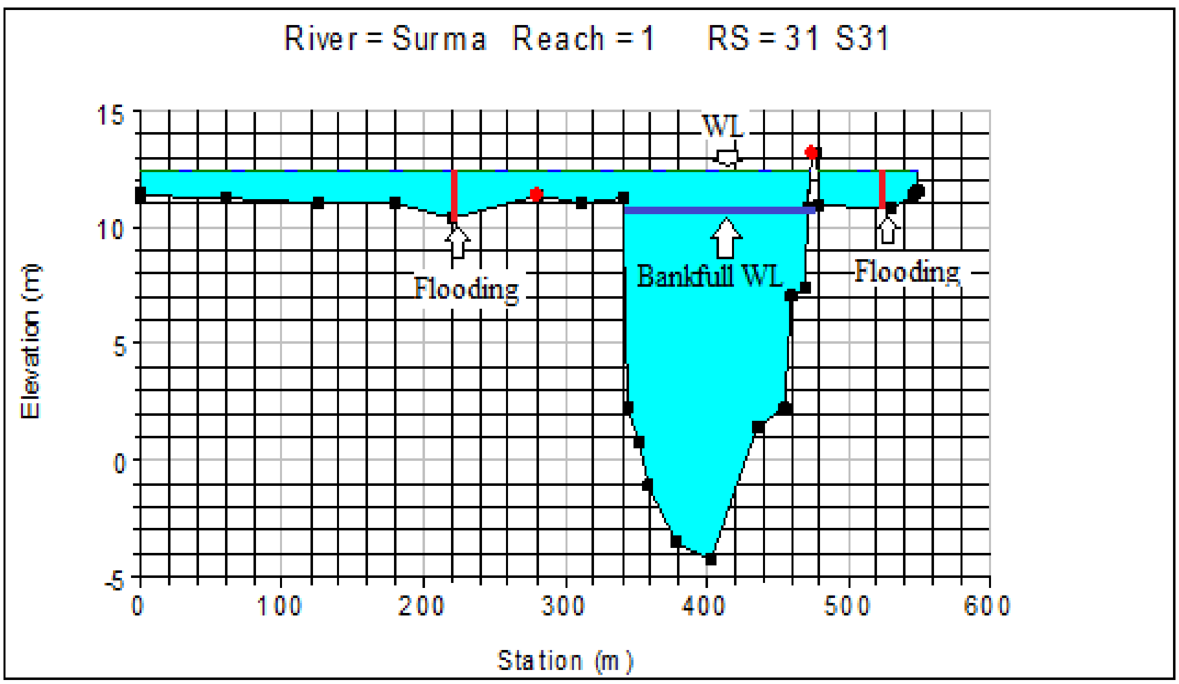

Figure 10-7 Changes in Water Level at RS 31 for Scenario 1,(The Surma)

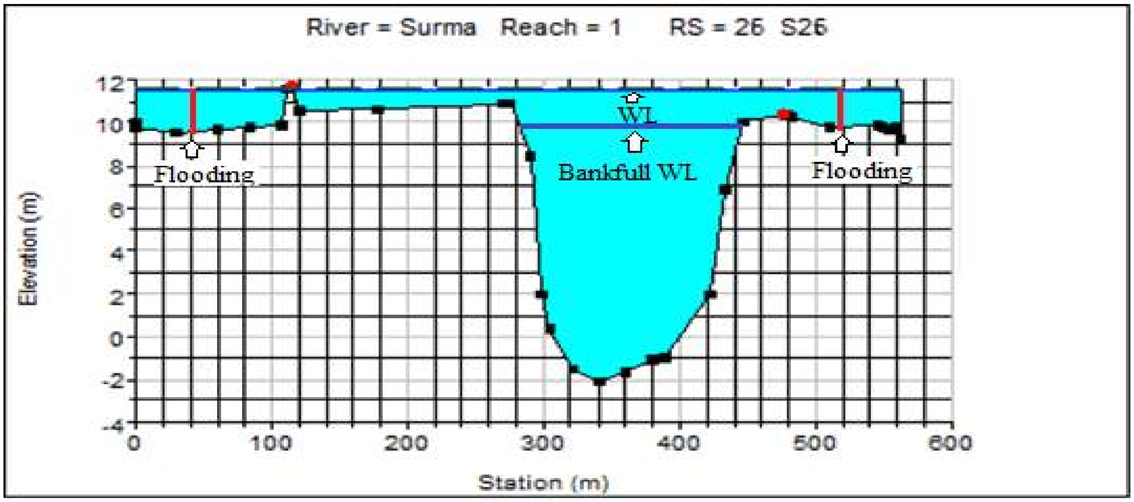

Figure 10-8 Changes in Water Level at RS 26 for Scenario 1,(The Surma)

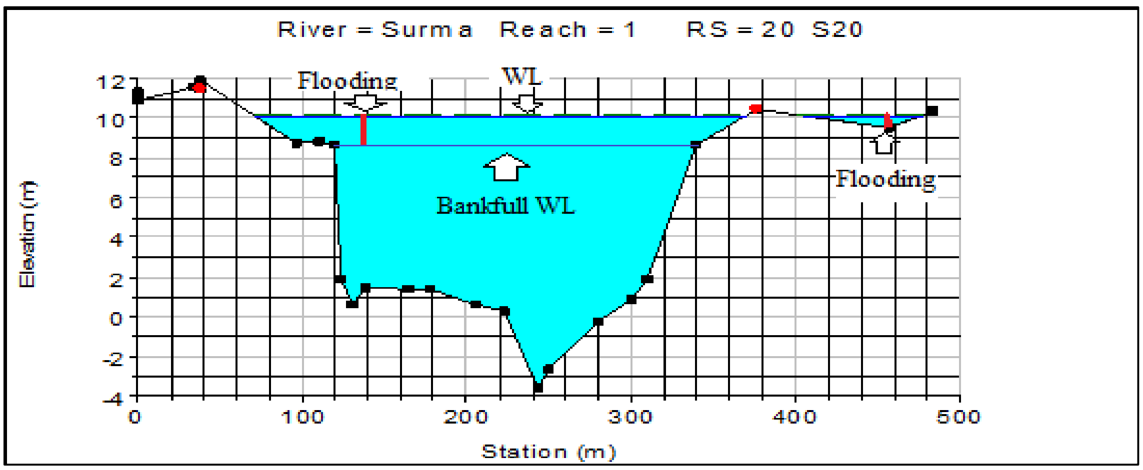

Figure 10-9 Changes in Water Level at RS 20 for Scenario 1,(The Surma)

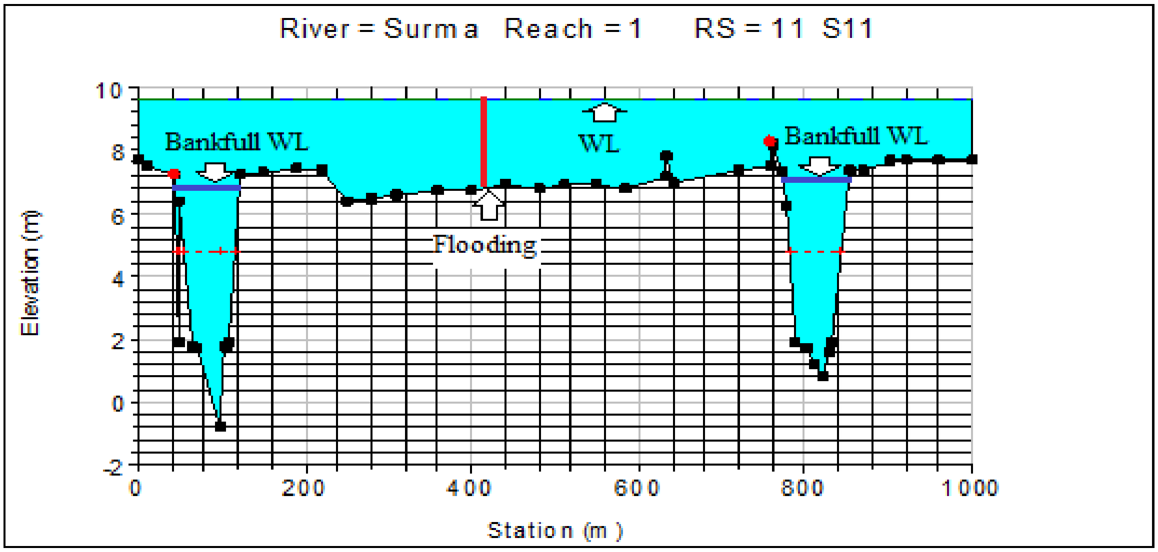

Figure 10-10 Changes in Water Level at RS 11 for Scenario 1,(The Surma)

Similarly, for scenario 2, the simulated results are shown. All the station shows a decrease in water Level. There is no flood in station RS 38 and flood depth reduced by 67 cm, 58 cm, 40 cm, and 57 cm in station RS 31, RS 26, RS 20 and RS 11 respectively with respect to the reference year (are shown in Figure 10.11,10.12,10.13,10.14 and 10.15).

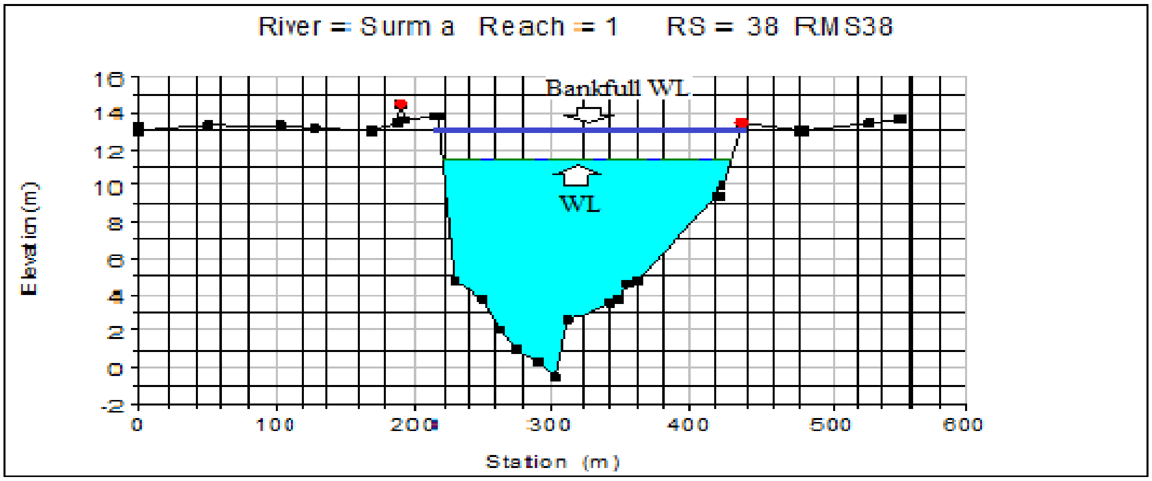

Figure 10-11 Changes in Water Level at RS 38 for Scenario 2,(The Surma)

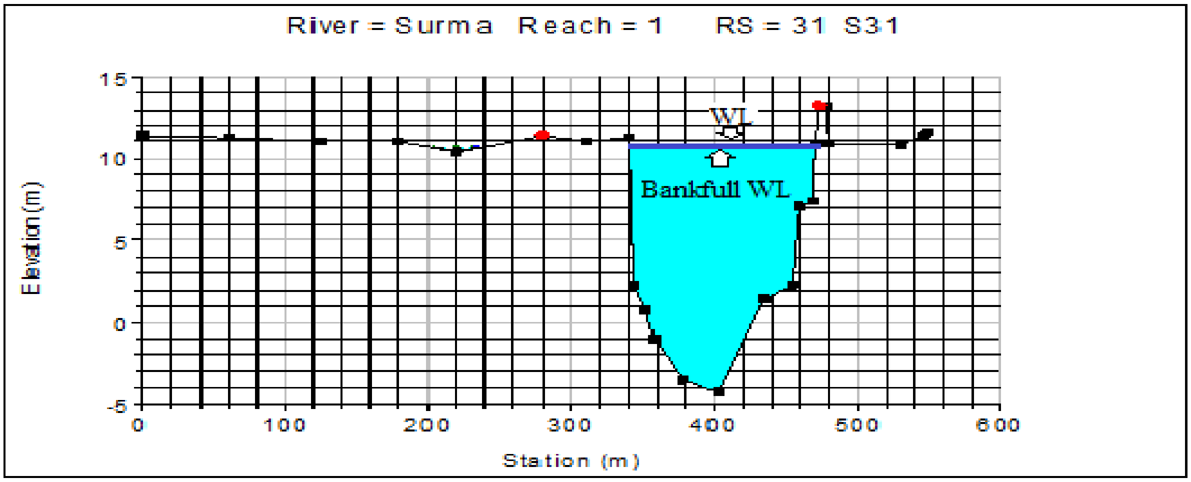

Figure 10-12 Changes in Water Level at RS 31for Scenario 2,(The Surma)

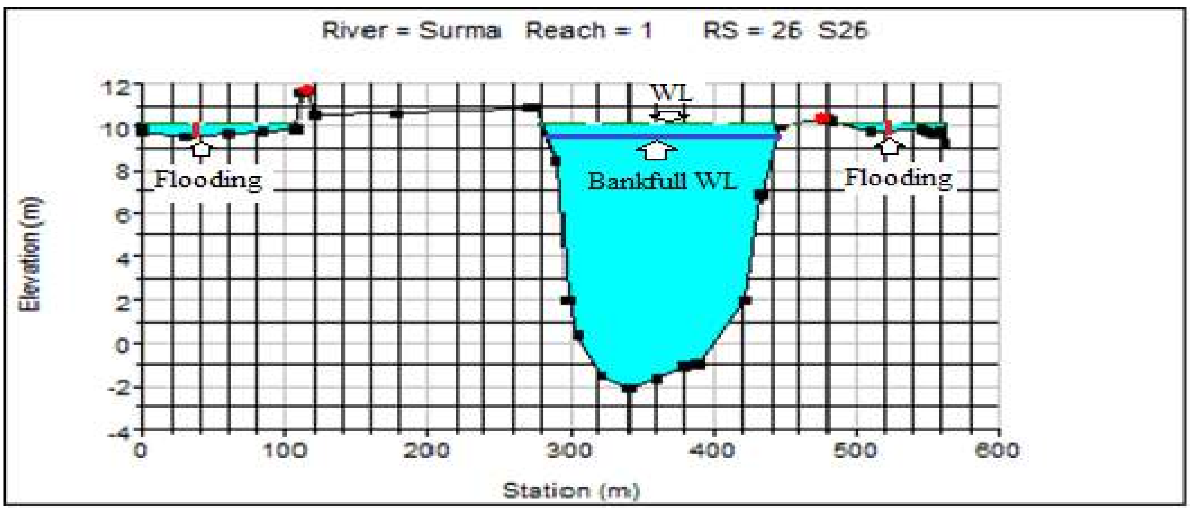

Figure 10-13 Changes in Water Level at RS 26 for Scenario 2,(The Surma)

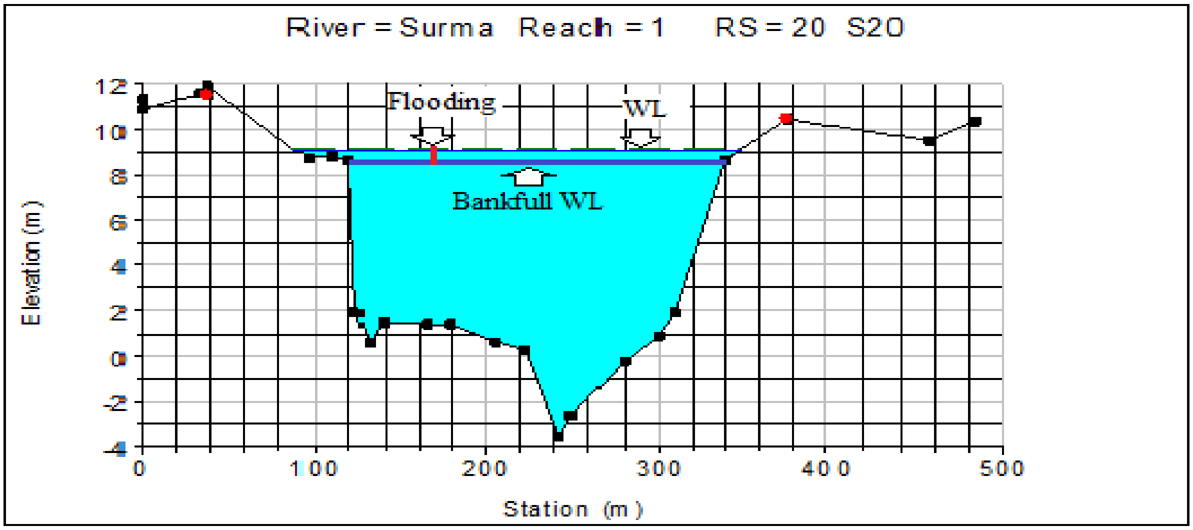

Figure 10-14 Changes in Water Level at RS 20 for Scenario 2,(The Surma)

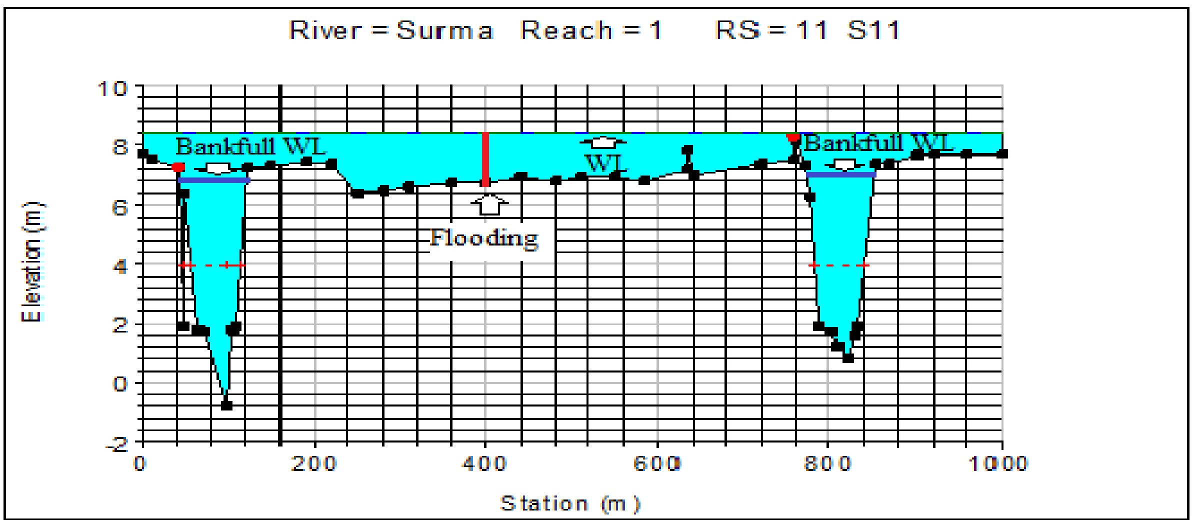

Figure 10-15 Changes in Water Level at RS 11 for Scenario,(The Surma)

The changes in water level for Scenario 1 and 2 along the channel length can be seen from the plots (Figure 10.16 and 10.17).

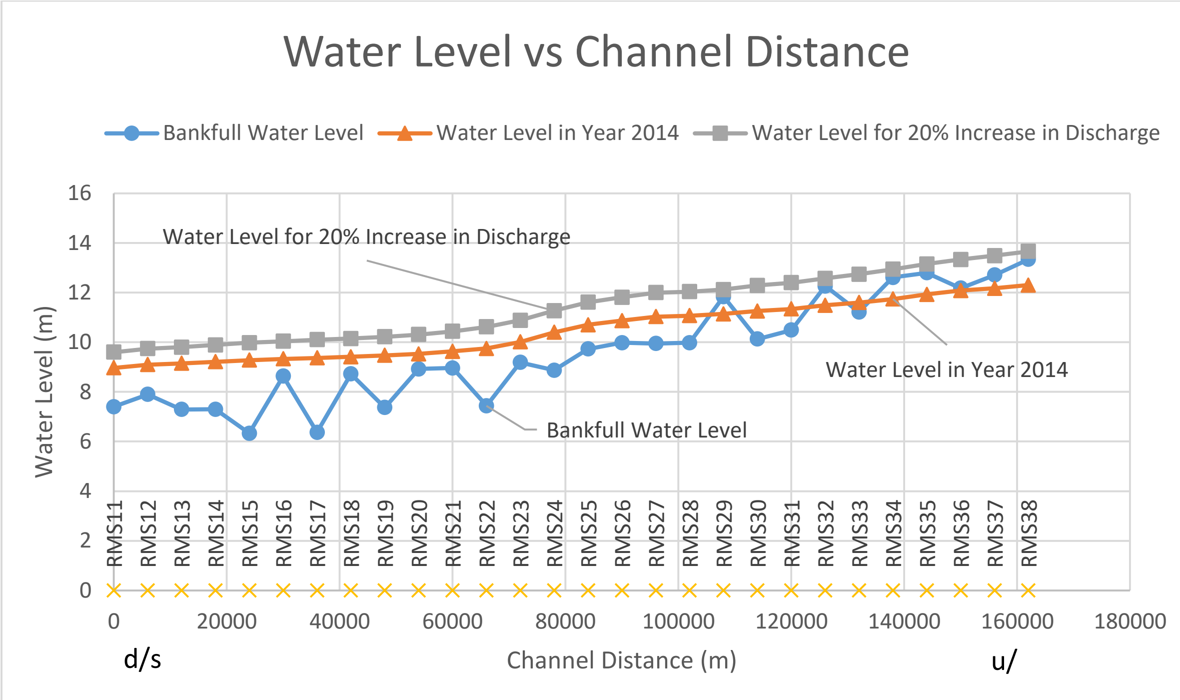

Figure 10-16 Water Level vs Distance for the Surma (2014); Scenario 1

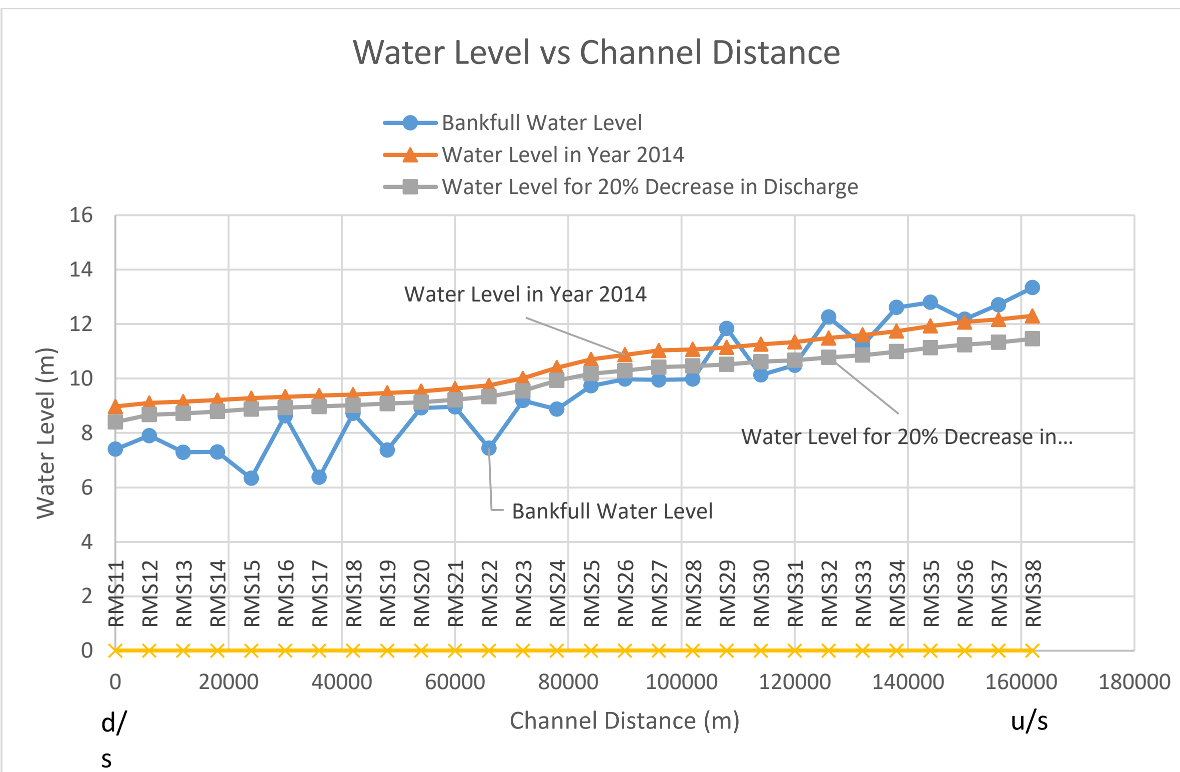

Figure 10-17 Water Level vs Distance for the Surma (2014); Scenario 2

10.2 The Kushiyara

HECRAS 5.0.3 model has been validated with the data of 2012. At first peak discharges for each month of the year 2012 were identified and plotted as a discharge hydrograph (Figure 10.18).

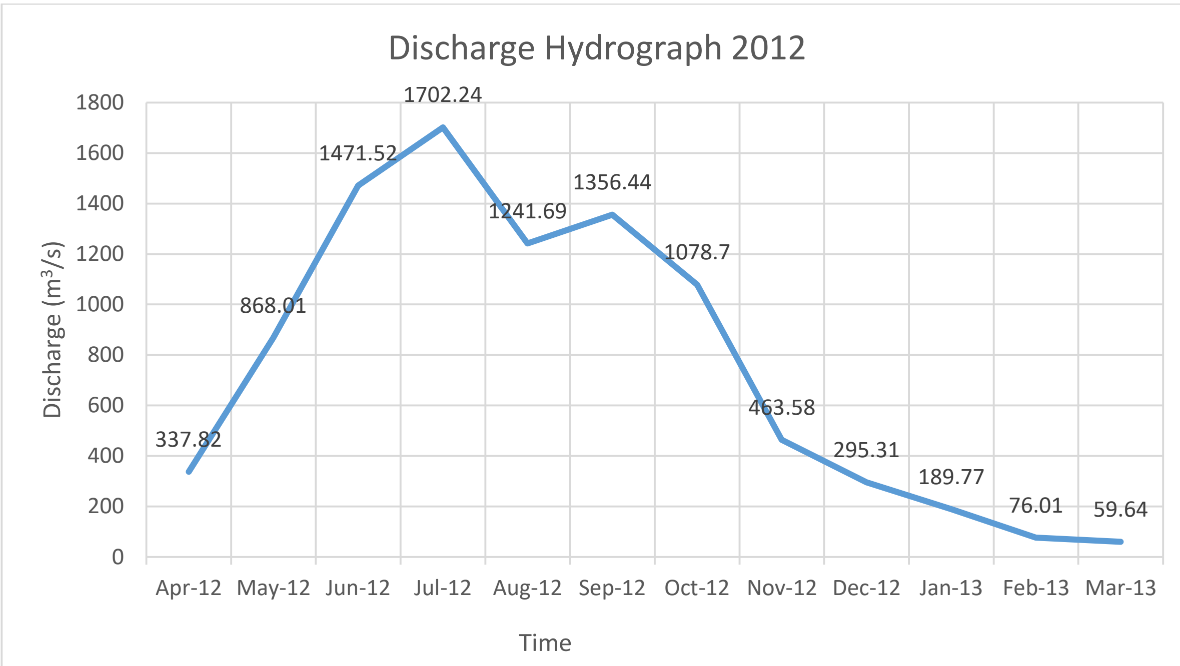

Figure 10-18 Monthly Peak Discharges of the Kushiyara for 2012

From the hydrograph, the highest value of discharge has been identified as 1702.24 m^3/s in July 2012. Then a discharge value 20% more than the highest value, that is 2042.7 m3/s was put as upstream boundary condition at station RS 40. Similar discharge (2040 m^3/s) was found on 11 July 1996. The model was given a run for 1996 and corresponding water levels were taken from the model output. The simulated water level value of 1996 was put as downstream boundary condition at RS 20 and finally the model was run and after simulation, bankfull areas were found.

Similarly, simulation was done for 20% decrease from the peak discharge of 1702.24 m^3/s, that is 1361.7 m^3/s. Similar discharge (1365.29 m^3/s) was found on 11 September 2011. This value of discharge has been considered as the upstream boundary condition at RS 40. The simulated WL of 2011 at station RS 20 was taken as the downstream condition. As mentioned