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Reaserch Article

An Empirical Investigation on Hydro-Morphological Process of Surma River: Substantiation from North-East Zone of BANGLADESH

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Abstract

Objective of the study is to know the inherent morphological process of the river system in the Haor areas of sylhet basin. The specific objective is to "validate the existing conceptual Model of the CEGIS". This research for the validation of the CEGIS Model. Primary data was collected through routine measurements of discharge, sediment concentration, measurements of cross-sections, sediment concentration measurements. Secondary data was collected on water level, discharge, velocity and cross-section from the BWDB. Satellite images have been collected from USGS. A thorough review of the manuals of different numerical models was carried out. After evaluation of the models HEC-RAS 5.0.3 has been selected. Validation of the CEGIS conceptual Model was tried using both conventional way of data analysis as well as from model output. Both the models have been fine-tuned and simulated to predict the future scenarios with 20% increase of discharge as well as 20% decrease of discharge at the upstream. Findings of the study confirms the acceptability of Hypothesis 1, Hypothesis 2 could not be (conclusively) validated. Concluded that, the bankfull water levels at the downstream decrease, changes in channel dimension, the change of both the area and the top width shows a scattered pattern and change of average depth shows a decreasing trend towards downstream direction. (i) Conventional analysis, Hypotheses 3 may be considered validated (ii) From Model output, it may be stated that the Hypothesis 3 may be considered as not validated. Hypotheses 4 and 5 relate to the hypothetical 'Regime Condition' of the river. Its clear that the Surma River is not in 'Regime Condition'. So the hypothesis could not be validated through the model output. But '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.

Keywords: Hydro-morphological Process; Model Validation; Sylhet Haor Basin

Introduction

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 & 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. 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.

Study Area

The general study area is the Sylhet basin, located in the north-east hydrological zone of Bangladesh (Figure 1). It is a very large basin covering about 10,000 km2 area in the Sylhet, Sunamganj, Maulvibazar, Habiganj, Netrokona and Kishoreganj districts in Bangladesh. 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 (URL 1; DBHWD, 2012; Islam et al., 2016).

The Surma river has been studied for the validation of the CEGIS Model. A reach of 150 km each for both the rivers starting from Kanaighat for Surma has been considered.

Objectives

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 River 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.

Scope of Work

1. Review the literature on evolution process of rivers on especially on the north-eastern part of Bangladesh.
2. Routine measurement of discharge and sediment concentration in the 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.

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. Due to the limitation of time and financial resources, most of the study will be carried out by using data of secondary sources.

1. Primary data of stage, discharge and sediments will be collected for only one year
2. The model developed under this study will assess the validity of the conceptual model developed by the CEGIS in a qualitative way.
3. 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.

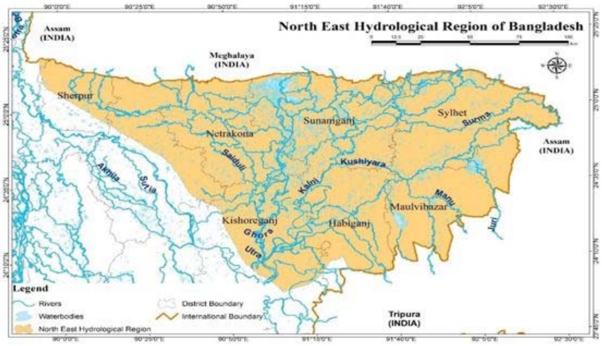

Figure 1. General Study area the North East Hydrological Region of Bangladesh

Various publications, documents and reports have been reviewed by the team in order to develop the classification system of wetlands of Bangladesh. These literatures assistance 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.

Different Numerical Models

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.

Delft3D Model

For the inspect of hydrodynamics, diluvium movement, river water pureness and quality, shoreline natural environments we will use three dimensional modeling. We called it Delft3D. Delft3D is Open Source Software. 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. To measure breezes, thickness variances, surfs, turbulence, tides and air compression and heat and mass movement solver. The D-Flow includes 3D flow and instability modeling, circular grids, domain decomposition (connect several grids; modification in both parallel and upright track acceptable), structural and parallel wide eddy imitations.

•D-Wave

The non-steady dissemination of short-crested waves over an uneven bottom, airstream stroke, force overindulgence due to bottom friction, surge contravention, refraction shoaling and indicator dispersal. SWAN model is base program of D-Wave. .

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.

•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.

•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.

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.

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.

Master Plan of Haor Area, 2012

Geological Setting:

Sylhet Basin is a sub-basin of the Bengal Basin and consists of 1320 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.

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. Even in last thirteen years the courses of Surma and Kushiyara rivers changed northward as shown in Figure 2--3. The bankline changes of Surma and Kushiyara rivers in 20 years (1990-2010) are shown in Figure 3.

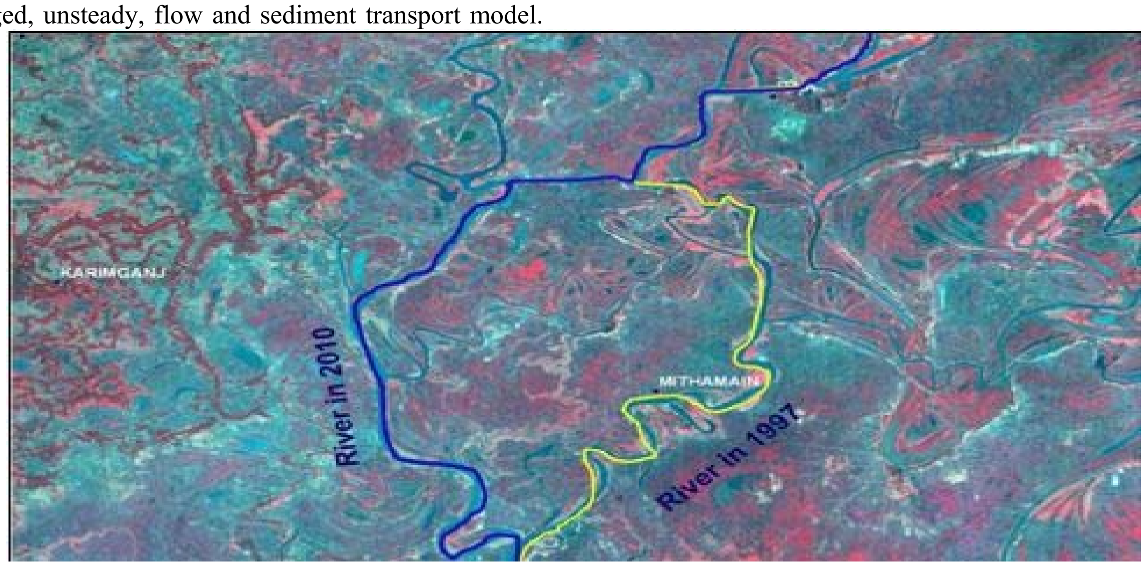

Figure 2. Changes of Surma Courses During last Decade (Source: BHWDB,2012)

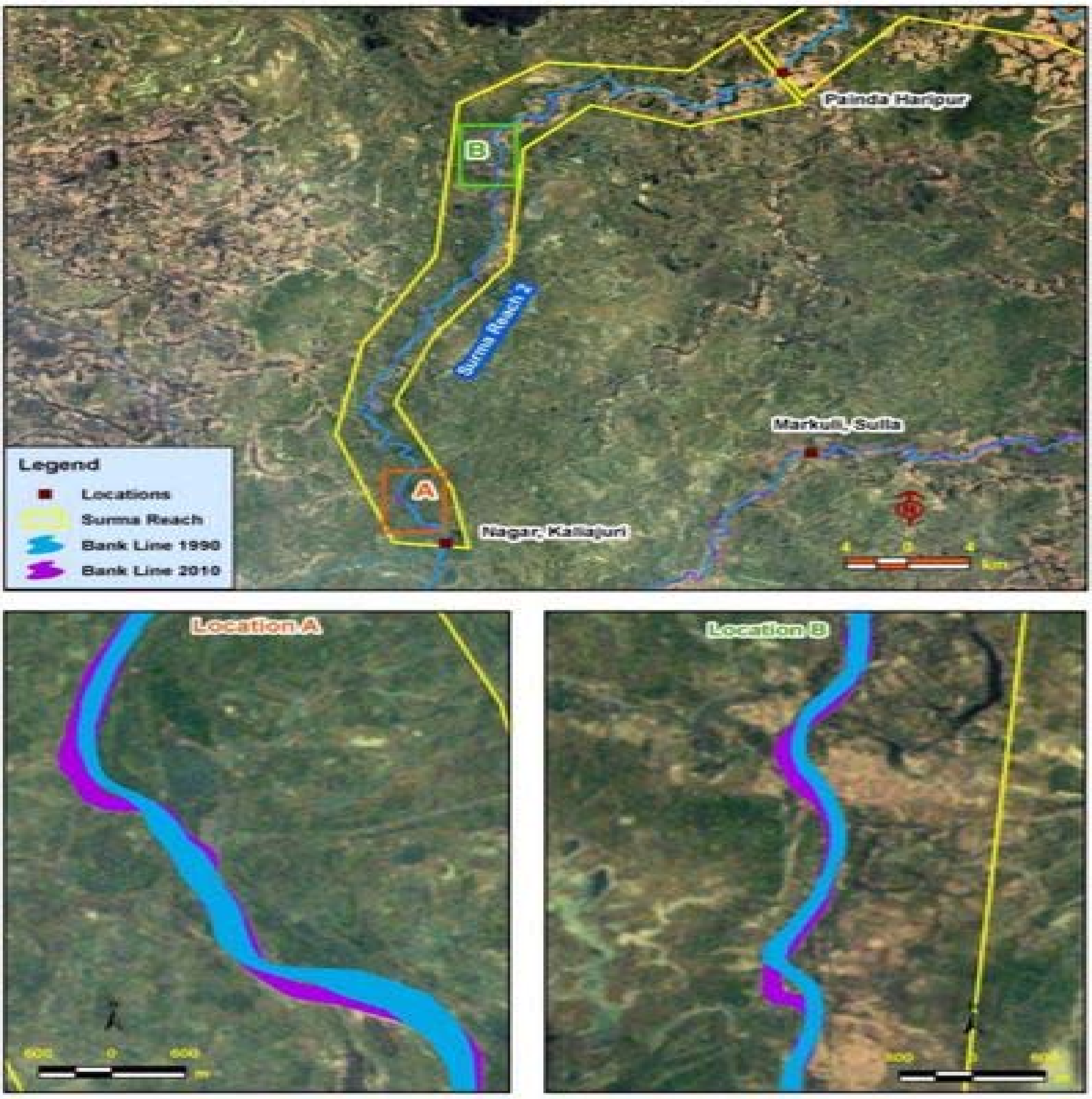

Figure 3. Bankline changes of the Surma River in 20 years (Source: BHWDB, 2012)

Morphology of the Haor Areas, 2011

The 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.

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: Haors within the Sylhet basin, Haors in the simple floodplain and trapped 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 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 CEGI.

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.

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. A Bangladesh-India Initiative is a project led by the IUCN to promote insights into trans boundary 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 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.

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. 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. 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 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 Kalni-Kushiyara River Management Project (KKMRP) proposes a number of engineering interventions for integrated water management in the Sylhet Basin. 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. 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.

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.

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.

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). 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 200405 and validated for 2005-06.

River Response of Sylhet Basin
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 QS.

$W \propto Q;$ (ii)

$W \propto QS;$ (iii)

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

$W/d \propto QS;$ (iv)

d) Channel slope S is inversely proportional to water discharge Q and directly proportional to both sediment discharge QS and median grain size D50.

$S \propto 1/Q;$ (v)

$S \propto QS;$ (vi)

$S \propto D50;$ (vii)

e) Transport of bed material QS is directly related to stream power τoU (τo = Bed Shear, U = Cross-sectional Average Velocity) and concentration of fine material CF, and inversely related to the fall diameter of the bed material D50.

$QS \propto \tau oU;$ (x)

$QS \propto CF;$ (xi)

$$Q_S \sim \frac{(\tau o U) W C_F}{D_{50}}$$ (Simons et. al., 1975)

or $QS \propto 1/D50;$ (xii)

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 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.

Hypothesis

- 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.
- Decrease in the bankfull water level at the downstream, however, indicates a decrease in channel dimensions i.e. the width and depth.
- The shallow depth caused to increase the high gradient during the dry season and thus increase the dry season water level at the upstream.
- After several years/decades (at time tα) as the river will be able to raise its level and reach regime condition, the flood level will be close to the bank level, i.e. bankfull water level will be the same along the whole river stretch.
- The channel dimensions will be closed the same at the upstream and downstream and no sedimentation would be expected during monsoon.

Methodology

Collection of Primary Data

Primary data of the Surma River has been collected. Primary data includes the following:

- Routine measurement of Discharge
- Routine measurement of Sediment Concentration
- Measurement of Cross-sections
- Sediment Concentration measurement
- Bank line survey.

Collection of Secondary Data

Secondary data of the Surma River has 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)

Bank Line Survey

Bank line survey of the Surma River has been conducted. The survey work the river was done by Total Station, GPS and Automatic Level are mapped by ArcGIS. One hundred and fifty (150) km reach on the river 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 bank of the river at the specified sections.

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 River and validate (qualitatively) the CEGIS Conceptual Model.

4.5 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, 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.

Model Calibration

The numerical model has been calibrated using the cross sections of the year 2013 for the Surma 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.

Model Validation

The numerical models have been validated using the cross sections of the year 2014 for the Surma 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 River. 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.

Analysis of Primary Data for the Surma Sediment Concentration

Sediment concentration samples of the Surma 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)

Median Grain Size

Bed Material Samples of the Surma have been collected. 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 (D50) value. The value was determined by analyzing the sample with Sieve and Hydrometer.

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). Bank Line Survey was conducted during January 14, 2017 to January 24, 2017.

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.

The Surma River

Upstream

Cross Section (RMS38): The cross section is taken at the upstream boundary, RMS38 (Figure 4). 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 4), 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.

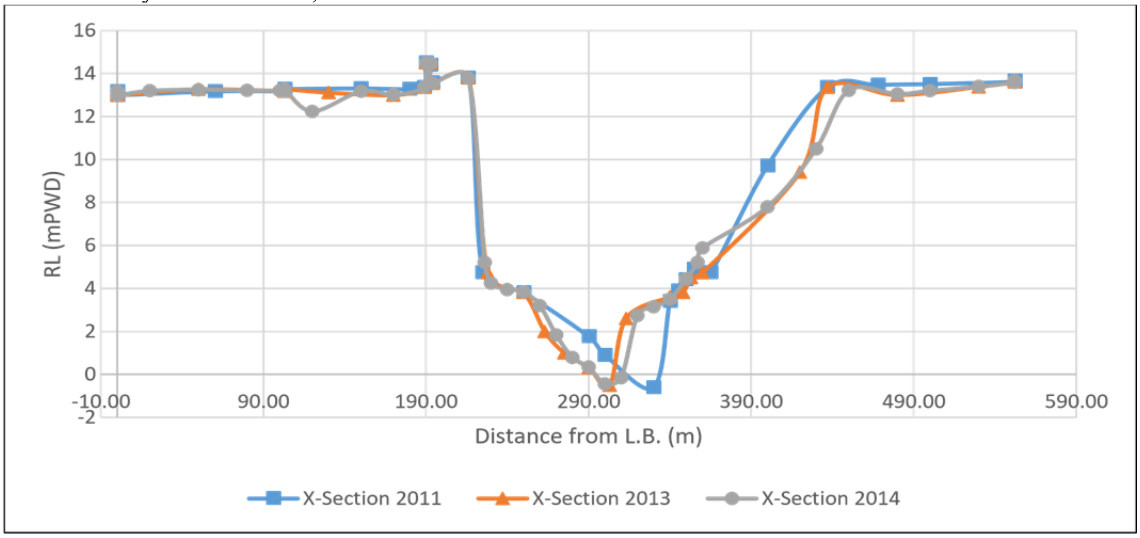

Figure 4. Comparison of Cross Sections at RMS38 on the Surma

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 5).

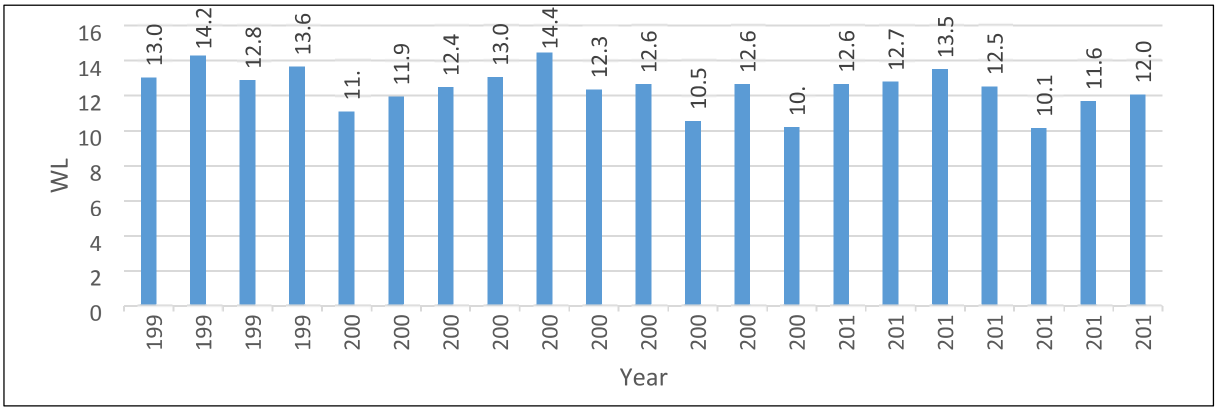

Figure 5. Comparison of Average Water Level of July at Station SW266 on the Surma

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 6.). 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.

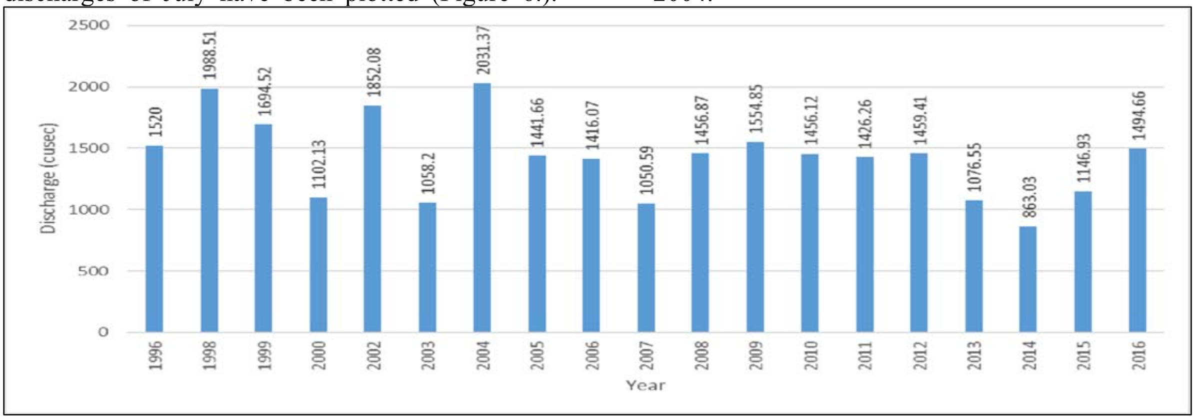

Figure 6. Comparison of Average Discharge of July at Station SW266 on the Surma

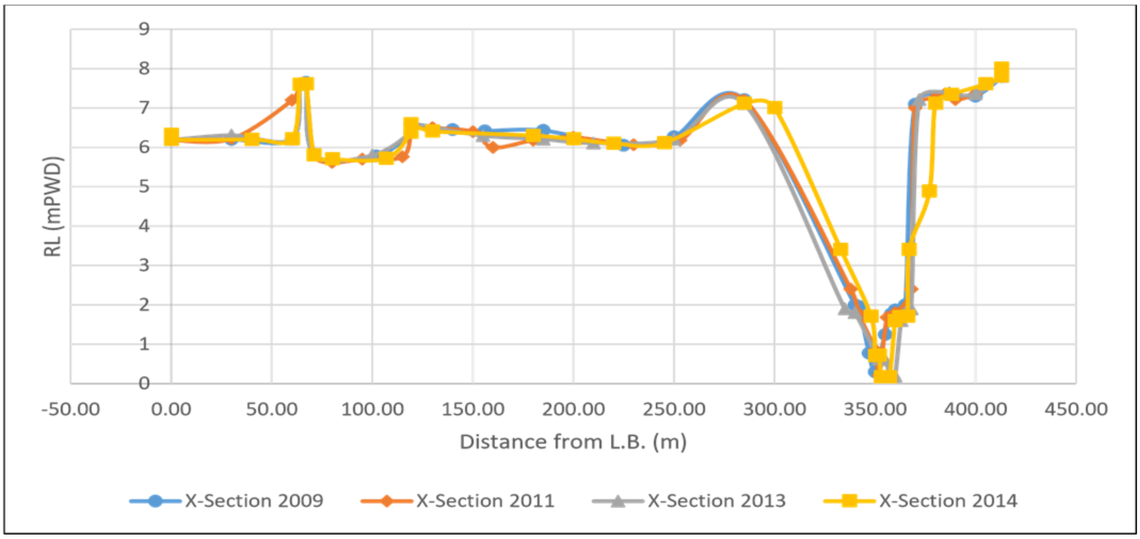

Figure 7 Comparison of Cross Sections at RMS10 on the Surma

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), 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.

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 8 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.

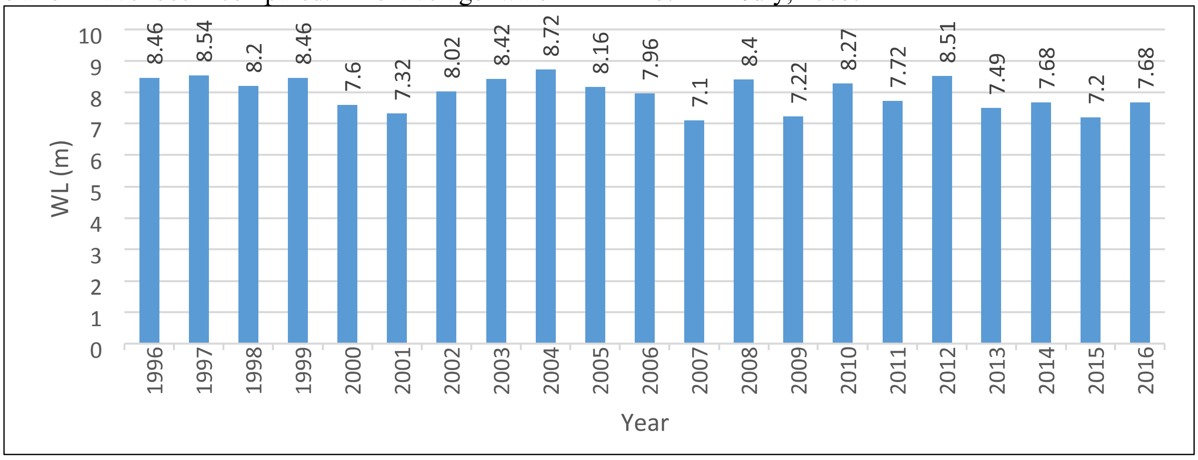

Figure 8. Comparison of Average Water Level of July at Station SW269 on the Surma

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 9 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 5.6, it can be observed that in the last 20 years, the average discharge in the monsoon season always stays above 1600 cusecs.

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 1. From the table, it can be seen that the water level slope varies between 0.015 to 0.035.

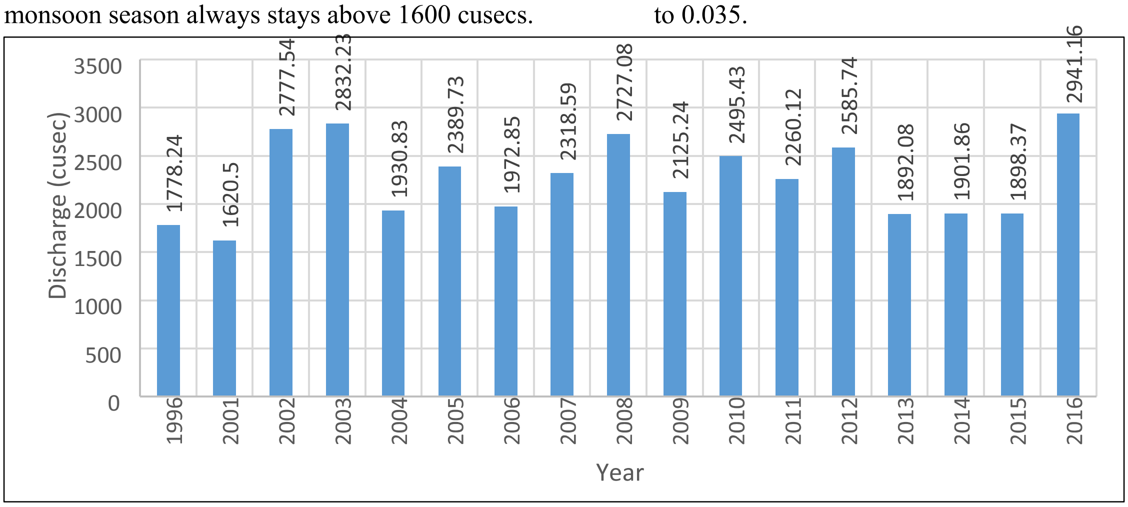

Figure 9. Comparison of Av. Disch. of July at SW269 (Surma)

Table 1 Water Level Slope Analysis for Surma River

Year	SW266 (upstream station) (mPWD)	SW269 (downstream station) (mPWD)	Water Level Slope (/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 (/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

Development of Mathematical Model

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; Gazioğlu, 2018; Büyüksalih & Gazioğlu, 2019). 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 (Gökbarlas & Gündüz, 2017).. 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.

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 HECRAS 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.

Model Setup

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, Qc = Flow in channel,
Q = Total flow, φ = KC/(KC+Kf),
KC = Conveyance in the channel, and,
Kf = Conveyance in the floodplain

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

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

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

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:

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

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

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

Where: g = Acceleration of gravity

S f = Friction slope,

Where:	*x*	=	distance along channel,
	t	=	time,
	Q	=	flow,
	A	=	cross-sectional area,
	S	=	storage from non-conveying portions of cross section
	ql	=	lateral inflow per unit distance.

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).

Satellite images

Satellite images of the Surma have been collected. Images are Landsat-6 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.

Geometry Setup

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 no 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.

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.

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.

$$Q = (h - h0) \quad (1)$$

Where:

Q_ = Discharge, m3/s
h = Stage (Water elevation), m
h0 = Gauge reading corresponding to zero discharge, m
Cr =Rating Curve constant,
B = Rating Curve constant.

The Surma River

A rating Curve has been plotted (Figure 10) for monthly average data of 20 years (19952014) for upstream section of the Surma river, Kanaighat (SW 266). For Surma river at upstream station (SW 266) the value of Cr 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.

Similarly, a rating curve at downstream station, Sunamganj (SW 269) has been plotted (Figure 11-12) and the value of Cr 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.

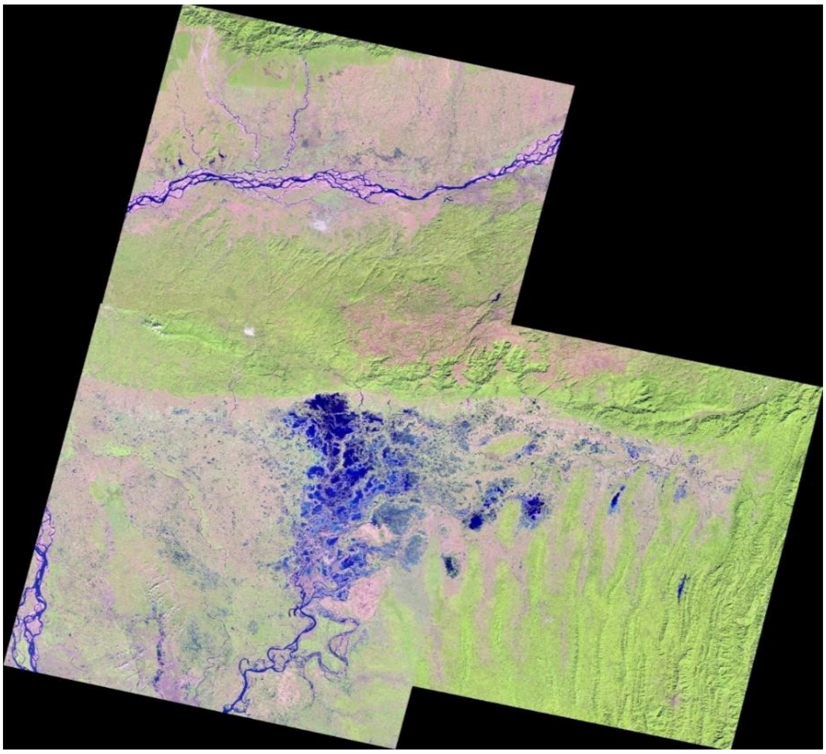

Figure 10. Satellite image of the study area

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.

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 (URL 2). 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, 1988). 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 (m3/s),*

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

R = *Hydraulic Radius (m),*

S = *Channel Slope (m/m).*

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, 1988). 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.

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

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.

Conventional Analysis

The locations of the cross sections are shown in Figure 13. The Surma: Bankfull Water level data for 2009, 2011 and 2014 have been shown in Table 2 and plotted in the graph for 2009 (Figure 14).

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 (YA>YB>YC).**

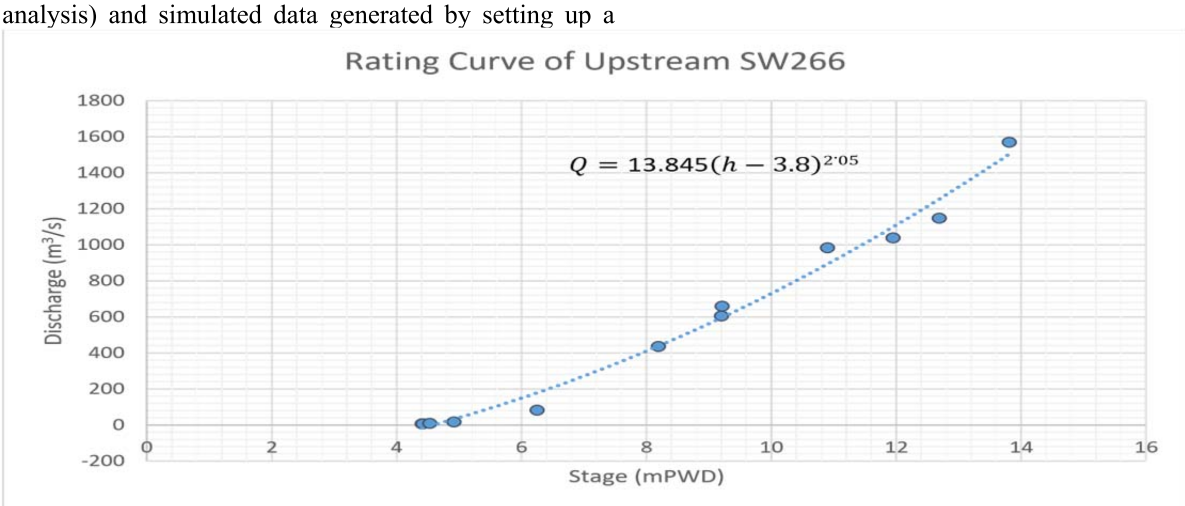

Figure 11. Rating curve at upstream Kanaighat (SW266) of the Surma River.

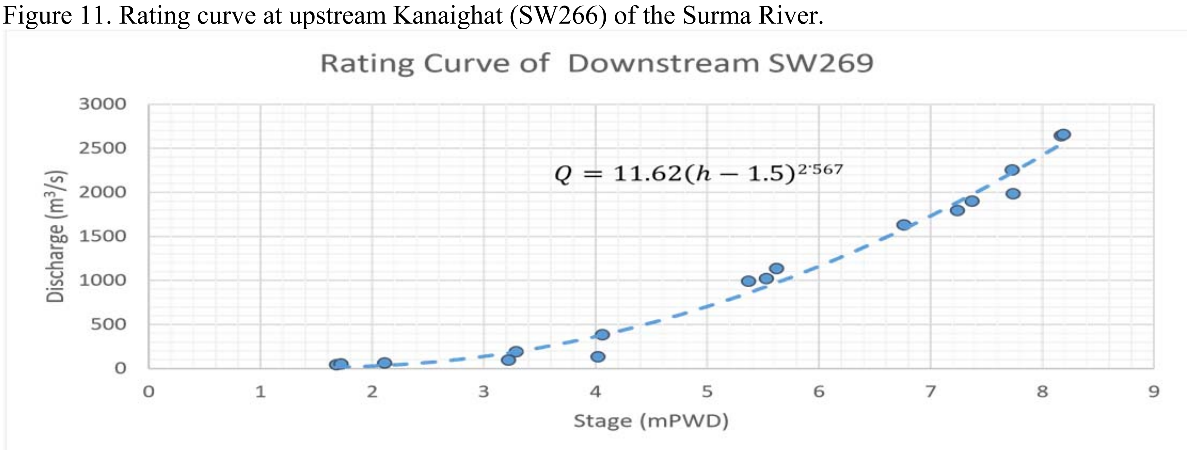

Figure 12. Rating curve at downstream Sunamganj (SW269) of the Surma River

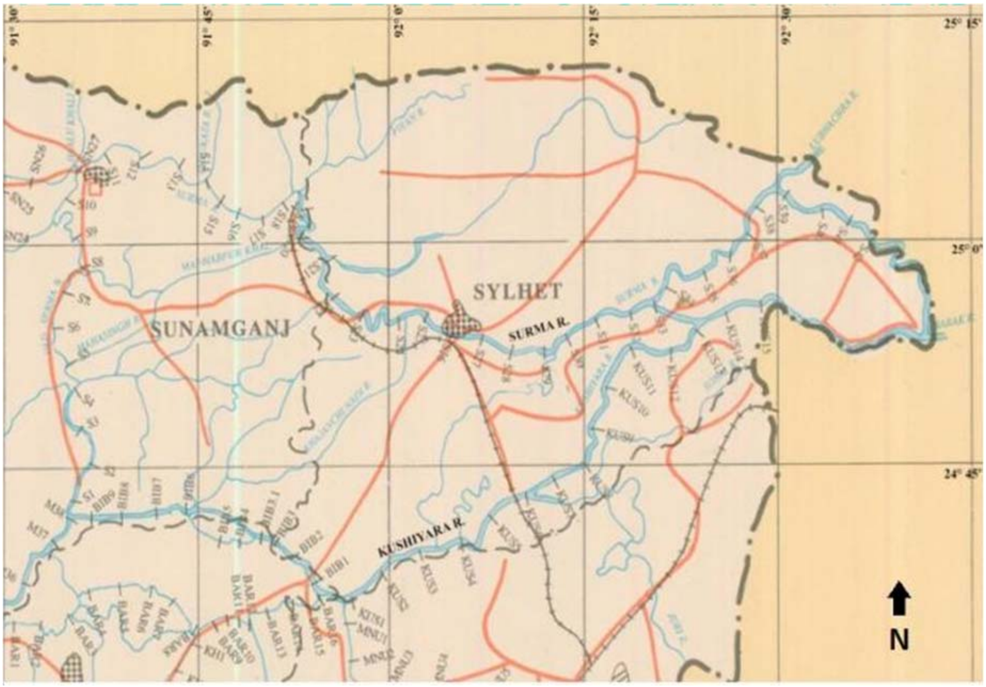

Figure 13. Locations of Cross Sections on the Surma (S1 - S42) (Source: BWDB)

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 15-18). 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 15), 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.

Table 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)**
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

Table 2. Bankfull Water Level Data Analysis between Upstream and Downstream Sections (cont.)

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

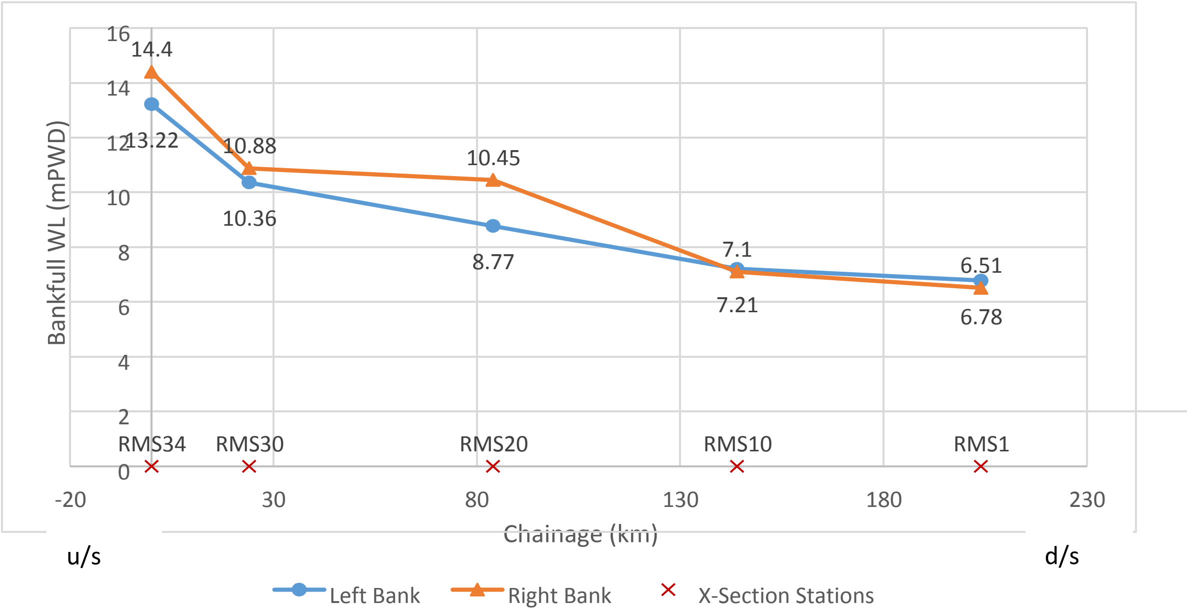

Figure 14. Bankfull Water Level of the Surma (2009)

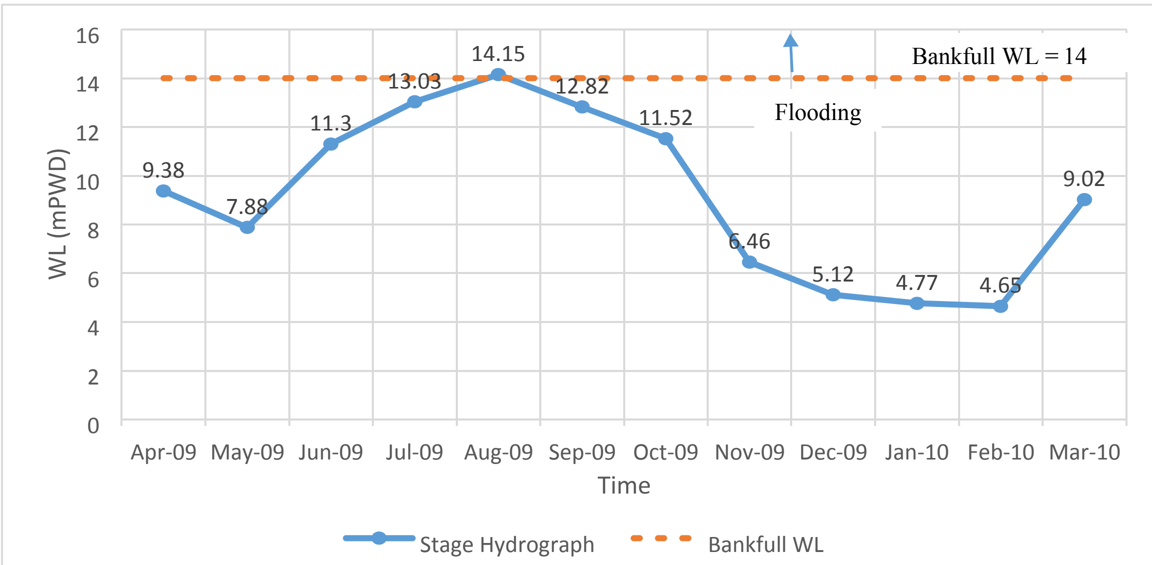

Figure 15. Stage Hydrograph of SW266 (Kanairghat; 2009-10)

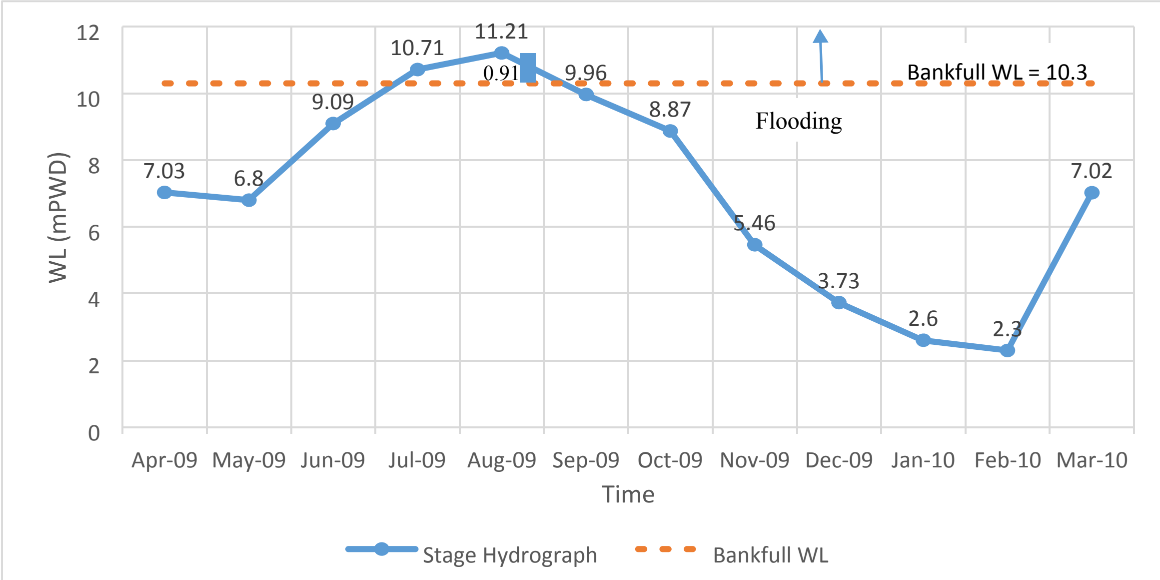

Figure 16. Stage Hydrograph of SW267 (Sylhet; 2009-10)

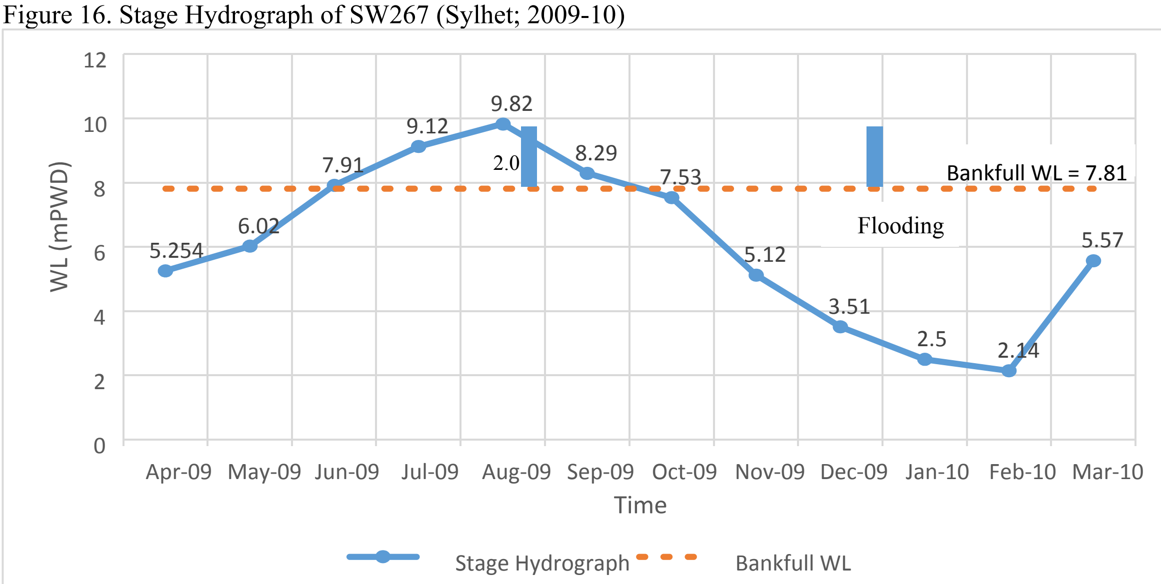

Figure 17. Stage Hydrograph of SW268 (Chhatak; 2009-10)

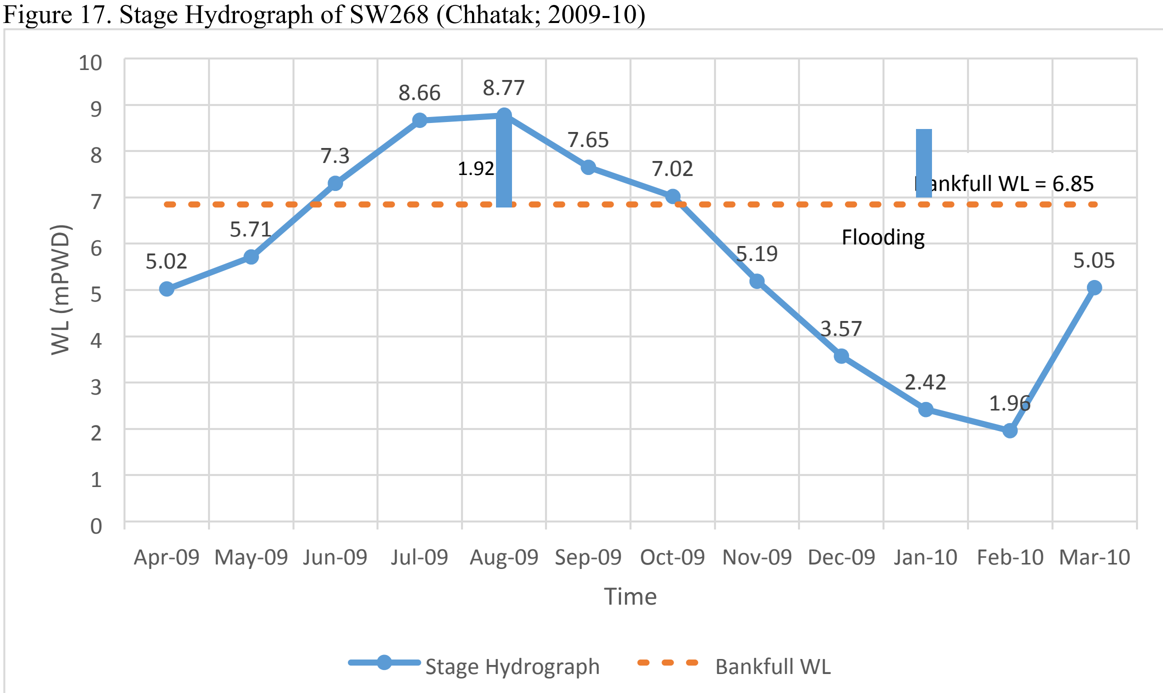

Figure 18. Stage Hydrograph of SW269 (Sunamganj; 2009-10)

From Figure 16, 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, 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), 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 18), 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.

Table 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

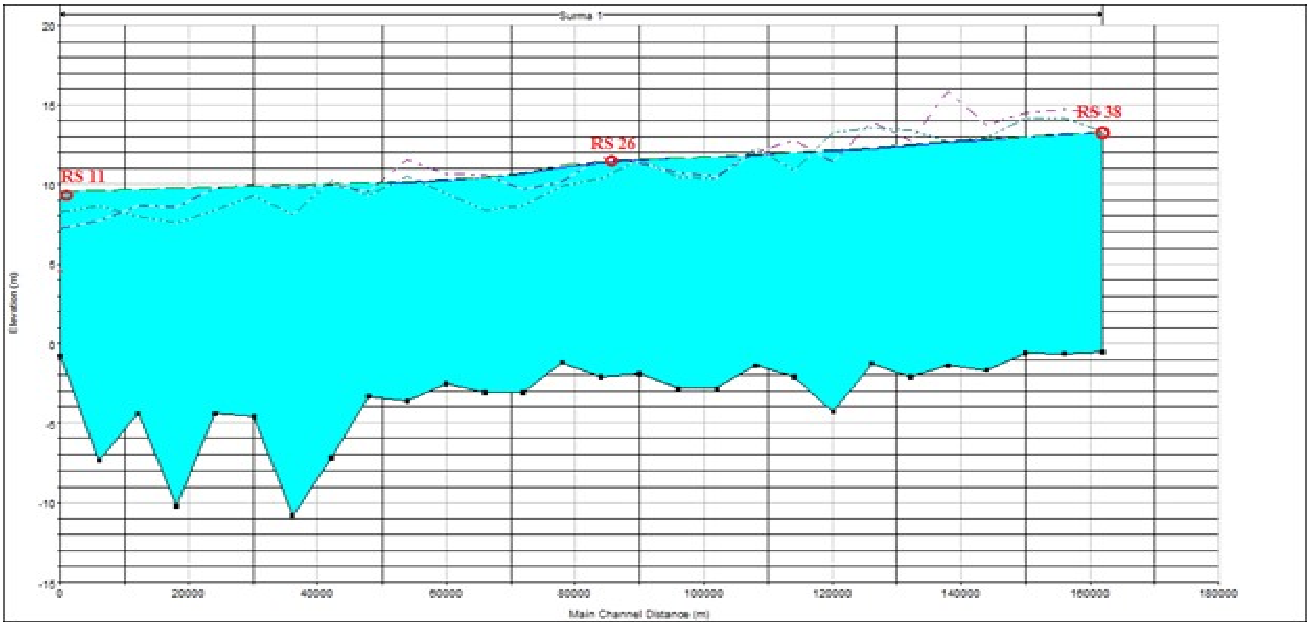

Figure 19. Simulated Longitudinal Profile of the Surma River (July 2014)

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. Let us assume that water levels at RS 38, RS 31, RS 26, RS 20 and RS 11 are Ya, Yb, Yc, Yd and Ye 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. This is summarized in the table 3 and during the simulated bankfull water level at upstream section (RS38), corresponding water levels at the intermediate and downstream sections are shown in Figures 7.8-7.12. Figures 7.4 to 7.6 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.

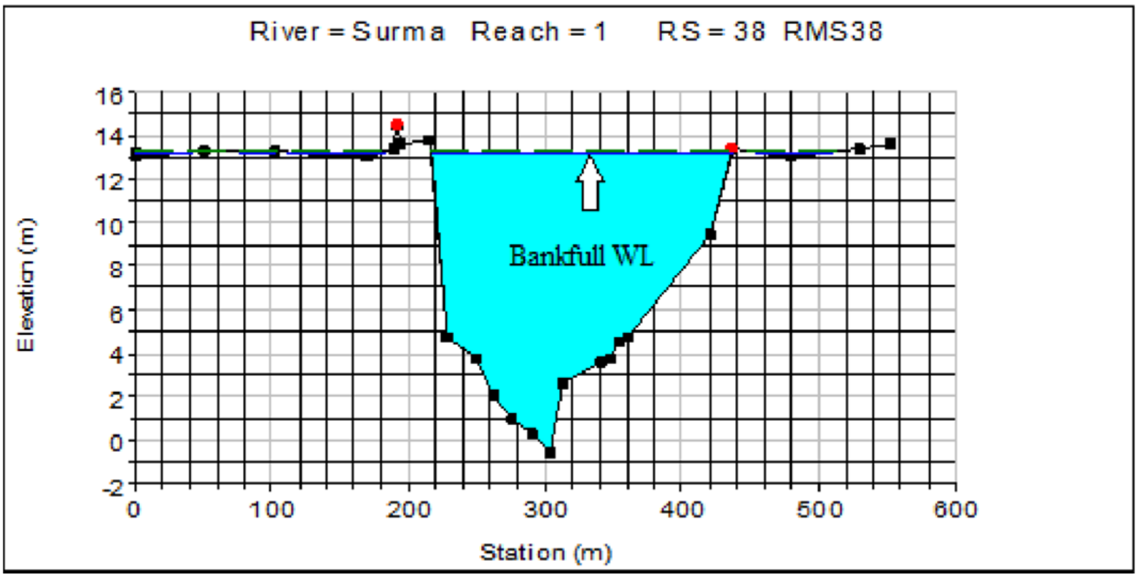

Figure 20. Simulated Water Level at Upstream (Kanaighat, RS 38, July 2014)

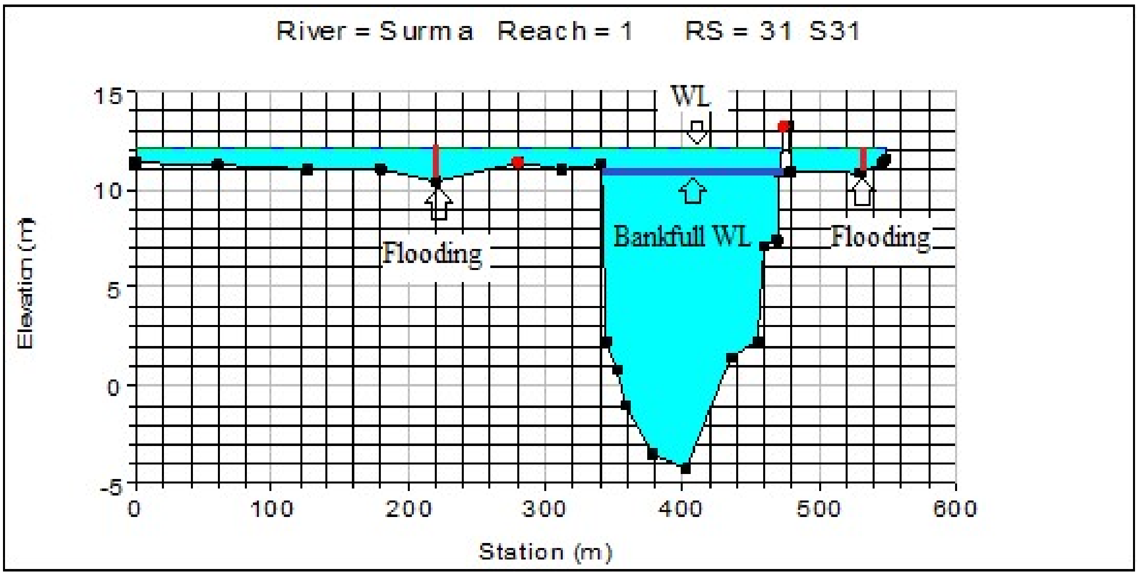

Figure 21. Simulated Water Level at RS 31 (July 2014)

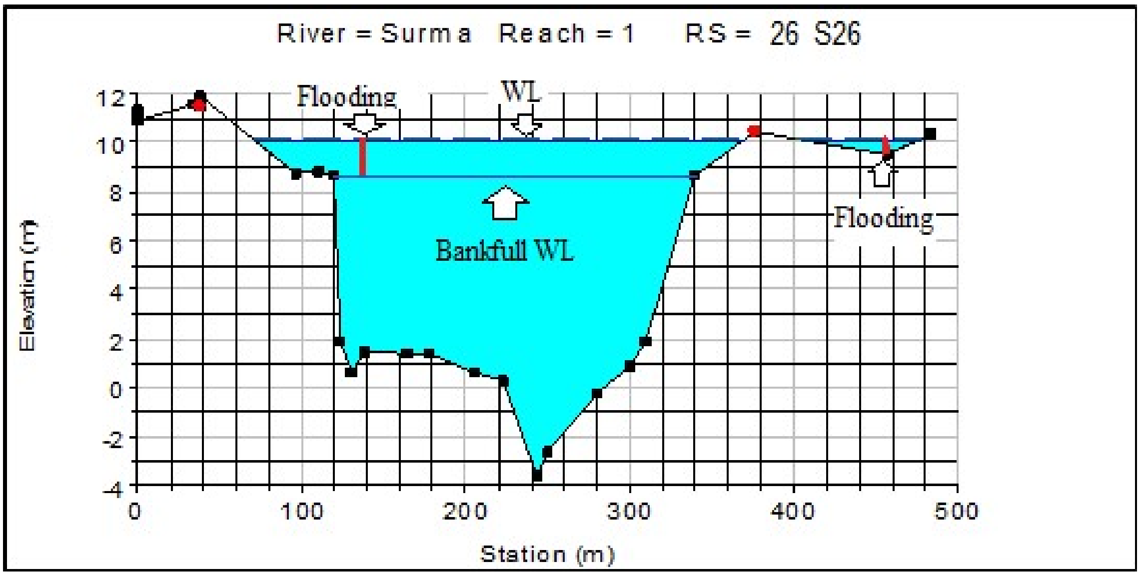

Figure 22. Simulated Water Level at RS 26 (July 2014)

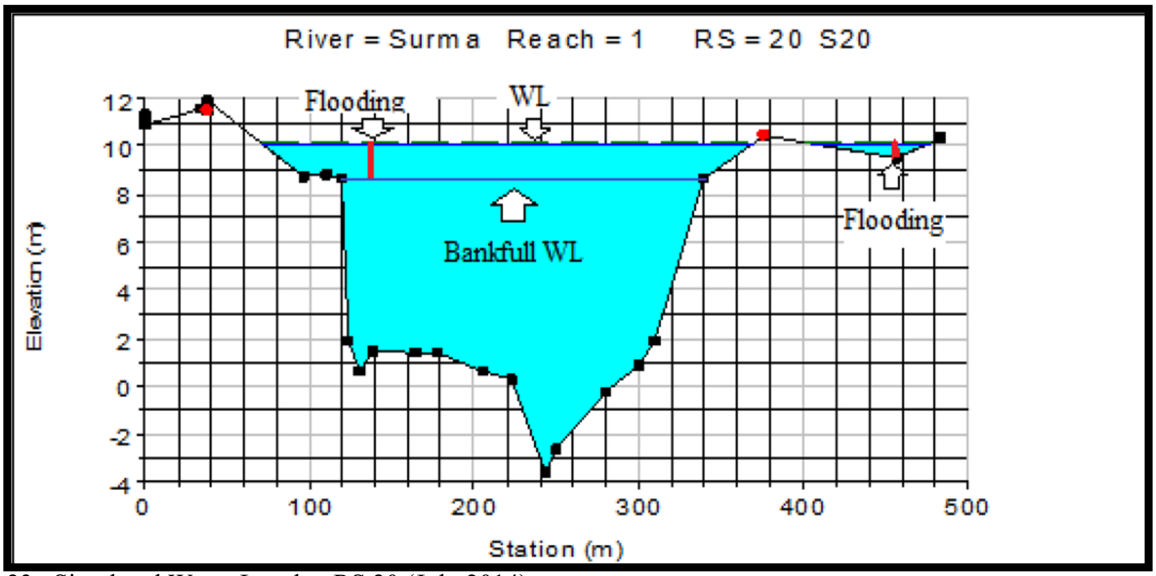

Figure 23. Simulated Water Level at RS 20 (July 2014)

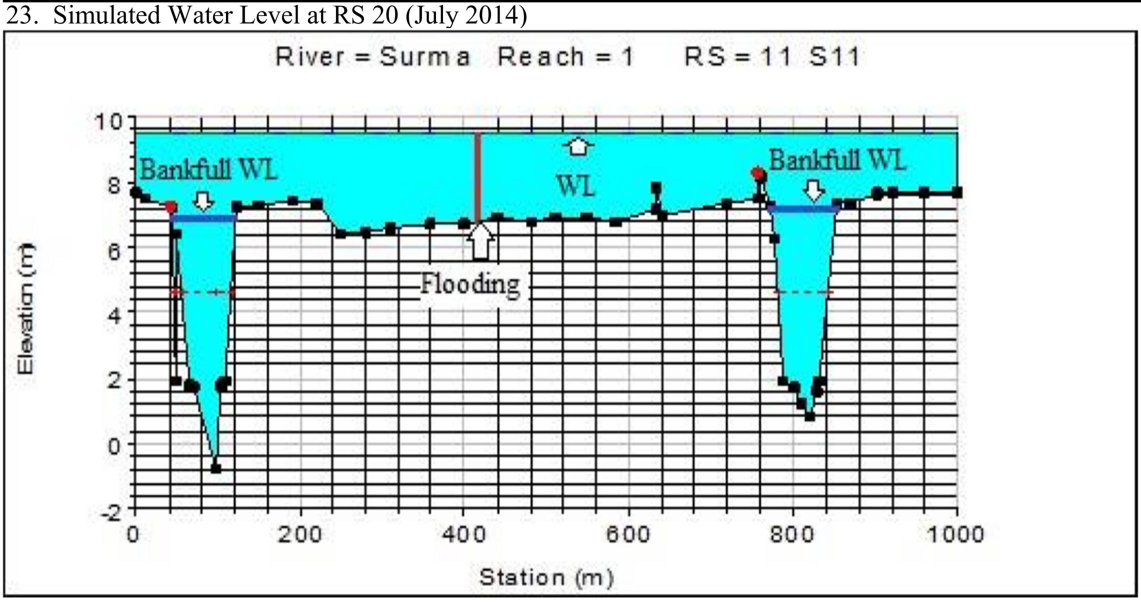

Figure 24. Simulated Water Level at Downstream (Sunamganj, RS 11, July 2014

When there is bankfull discharge at station RS 38, upstream (Fig 20), there is moderate floods at intermediate stations (Figure 19, 20 and 23) and comparatively larger floods at RS 11 (downstream, Fig 24). 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: 25) 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.**

To validate the hypothesis, stage hydrographs for the Water Level Stations on the Surma river have been plotted (Figures 26-29). Five stations have been selected, they are: RS 38 (upstream), RS 31, RS 26, RS 20 and RS 11 (downstream).

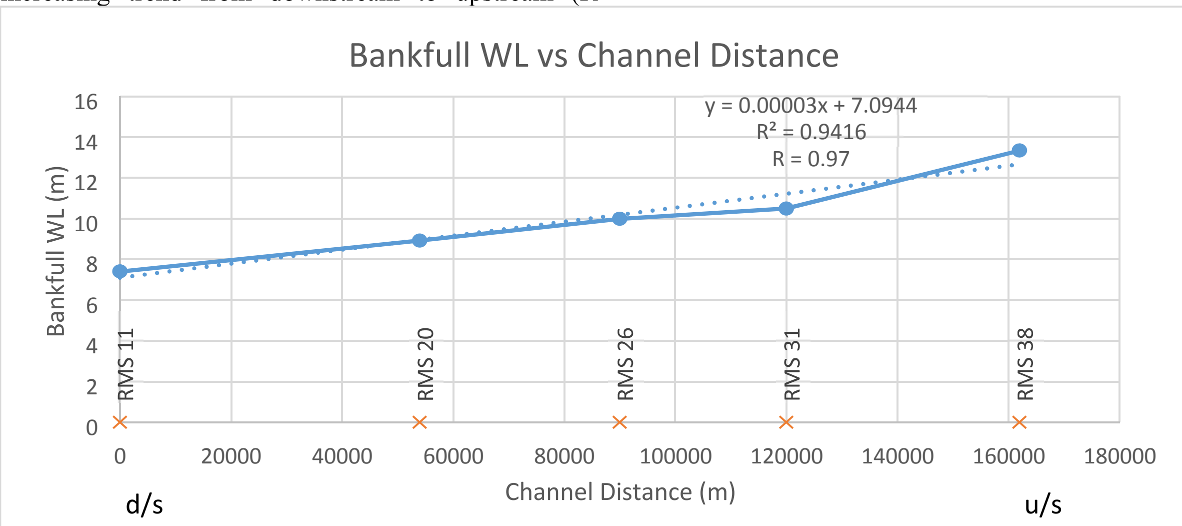

Figure 25. Bankfull Water Level vs Channel Distance of the Surma (2014)

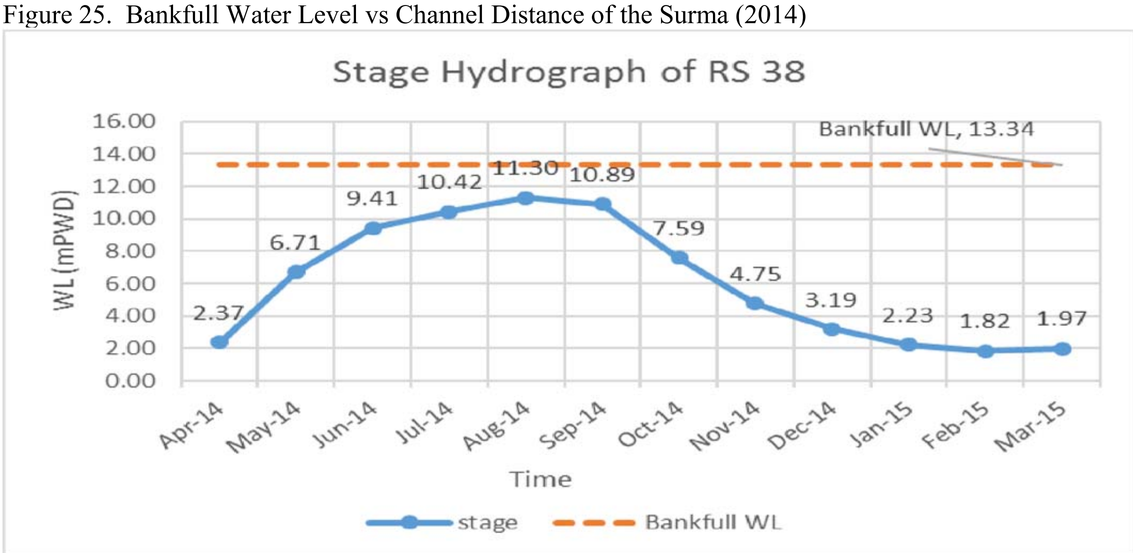

Figure 26. Simulated Stage Hydrograph for RS 38 (upstream) of the Surma, 2014-15

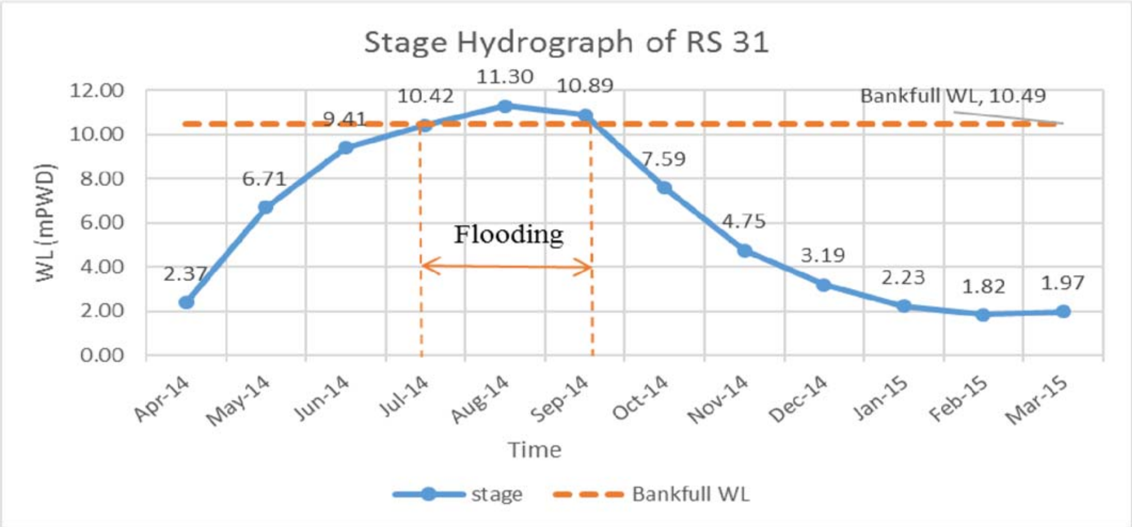

Figure 27. Simulated Stage Hydrograph for RS 31 (an intermediate section) of the Surma, 2014-15

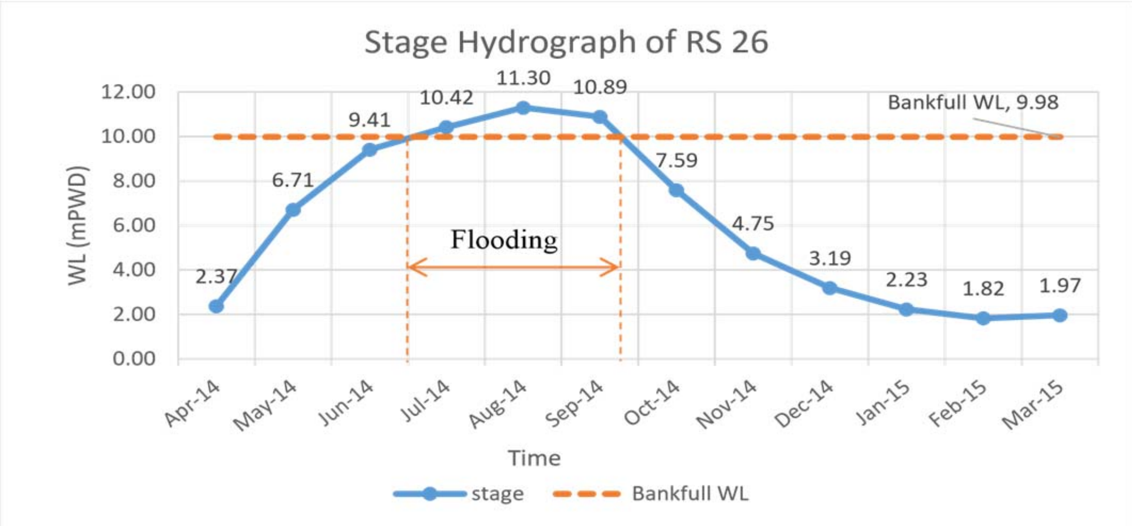

Figure 28. Simulated Stage Hydrograph for RS 26 (an intermediate section) of the Surma, 2014-15

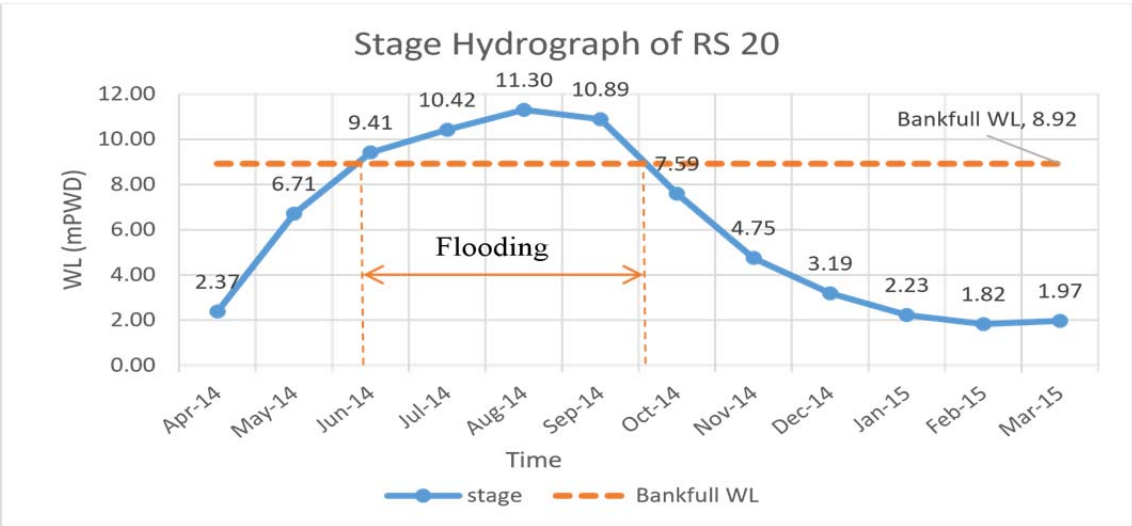

Figure 29. Simulated Stage Hydrograph for RS 20 (an intermediate section) of the Surma, 2014-15

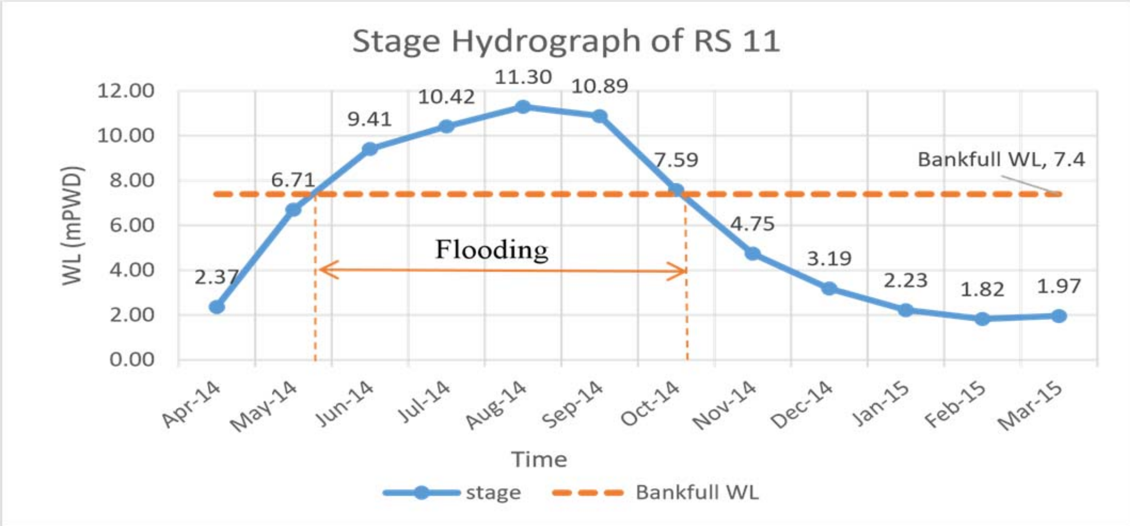

Figure 30. Simulated Stage Hydrograph for RS 11 (Downstream) of the Surma, 2014-15.

From the stage hydrograph of RS 38 (Figure 26), it is observed that no flood occurred in the section, where the bankfull water level is 13.8.

From Figure 27, 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 28), 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 29). In the most downstream section (RS 11), the extent of the flood was from mid-May to mid-October (approximately 5 months) (Figure 29).

So it can be concluded that bankfull water level Ya>Yb>Yc>Yd>Ye 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.

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.

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 4.

The channel area, average depth and channel top width of the cross sections have been plotted in Figure 31. 32 and 33 respectively. From Figure31, 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 m2 and the area at the most downstream section of the river (RMS11) is 611.78 m2. The peak channel area is at Station RMS27, which is 3385.46 m2.

It is observed from Figure 32 (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.

From Figure 33, 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 but its still not be conclusively established/validated (Check supplement 1 file where detail discussed).

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. 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 7.22 and 7.23 respectively. The monsoon season water levels and dry season water levels have also been shown in the long profiles.

In Figure 34, 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 5.

Table 4. 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 (m2)	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

Table 4. Cont.

Cross-Section Station ID, BWDB	Corresponding Water Level Station ID, BWDB	Area (m2)	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

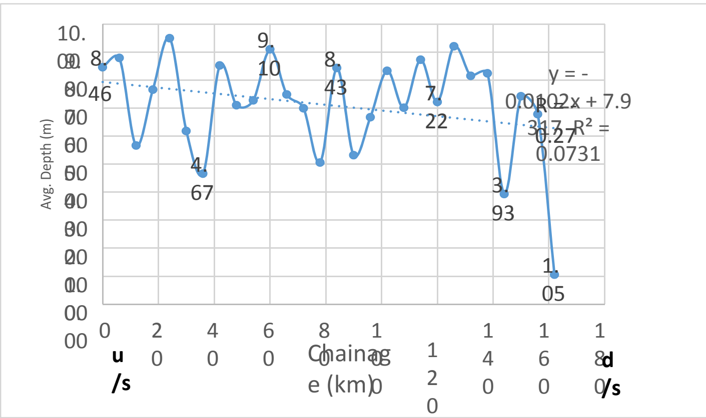

Figure 31. Channel Area vs Chainage Plot for the Surma River (2013)

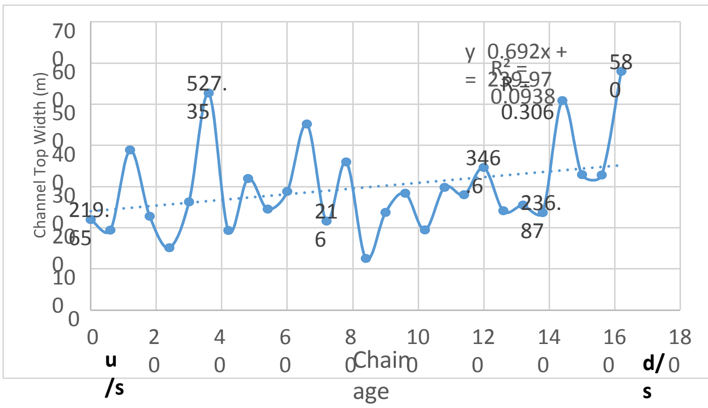

Figure 33. Channel Top Width vs Chainage Plot for the Surma River (2013)

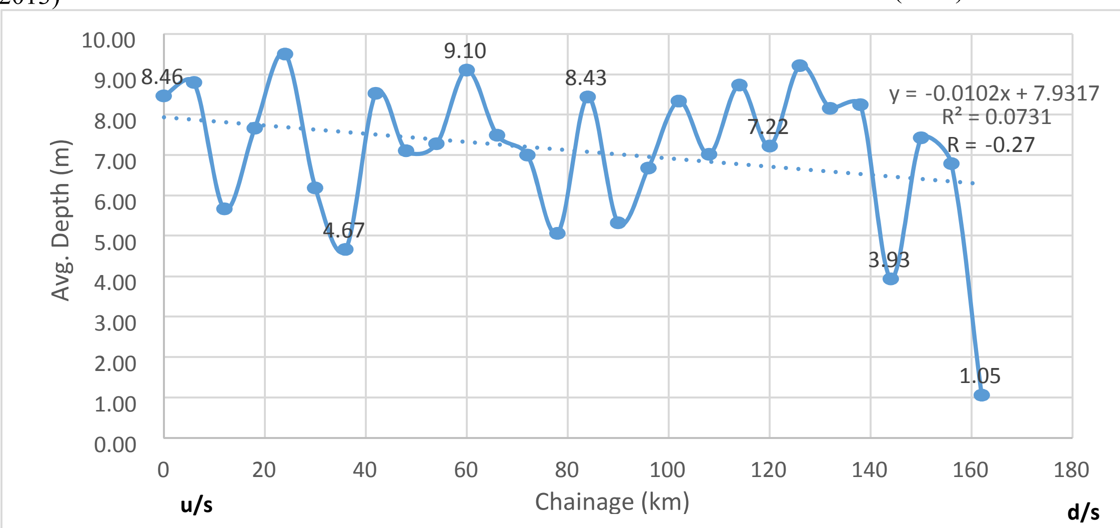

Figure32. Average Depth vs Chainage Plot for

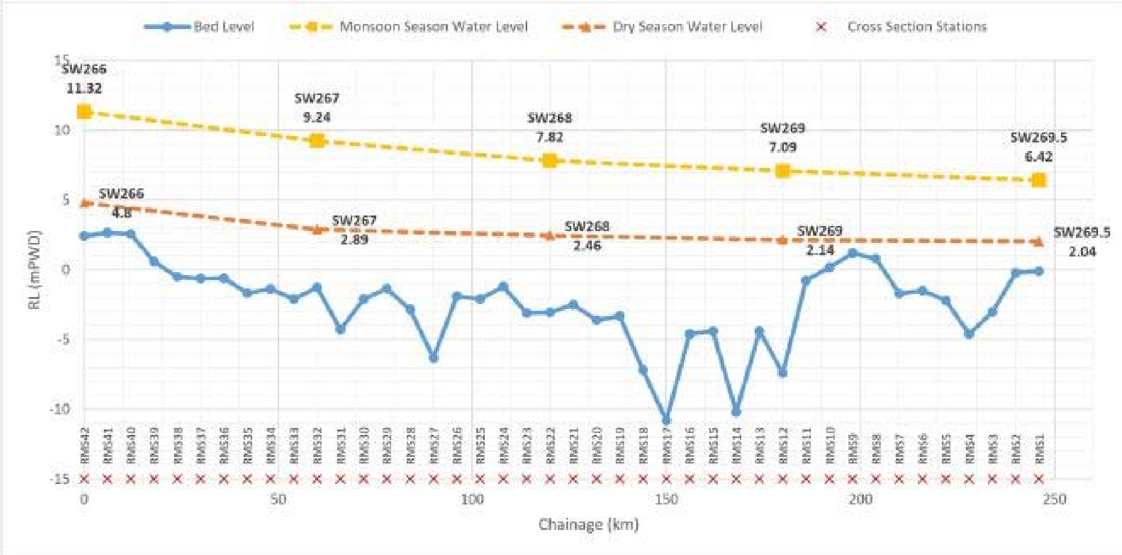

Figure 34. Long Profile of the Surma River with Water Level (2013)

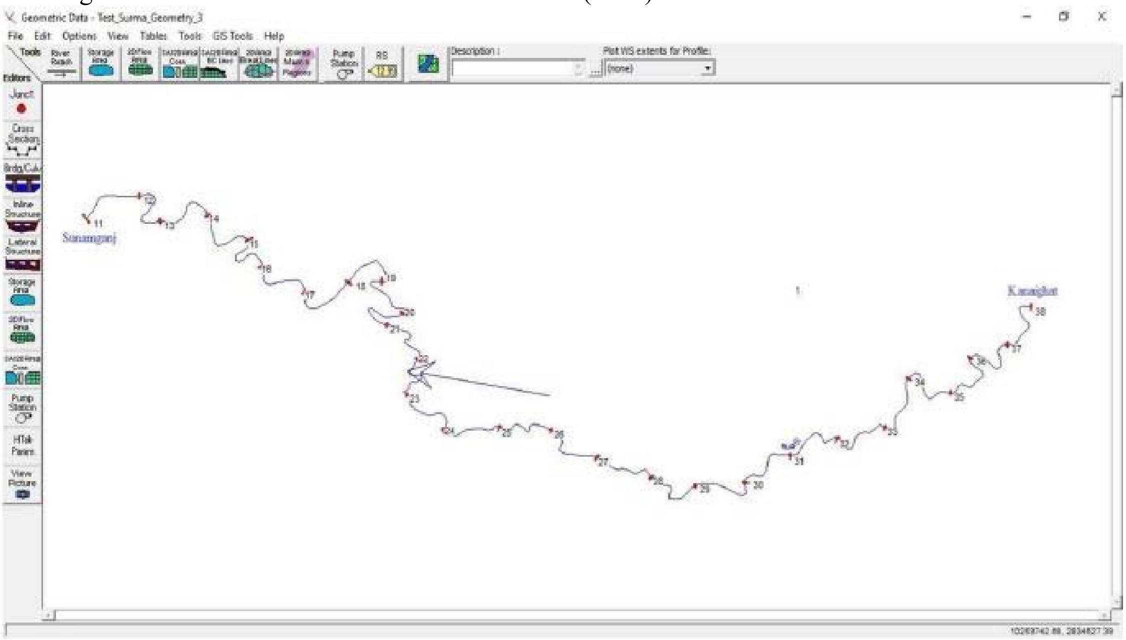

Figure 35. Cross Section of the Surma River

Table 5. 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

Table 6. 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)

Hypothesis 3

Conventional Analysis

In Figure 34, 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 5.

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 5 is rearranged to form Table 6 (for the Surma river).

From Table 6, 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.

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, 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."**

Conventional Analysis

The Hypotheses 4 and 5 are only valid for Regime condition. The characteristics of Regime condition have been explained.

Sediment Concentration

The Surma:

The first set of data was collected from August 22, 2016 to August 29, 2016 (monsoon season). The data have been plotted in Figure 36. 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 37. 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 38. 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. 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.**

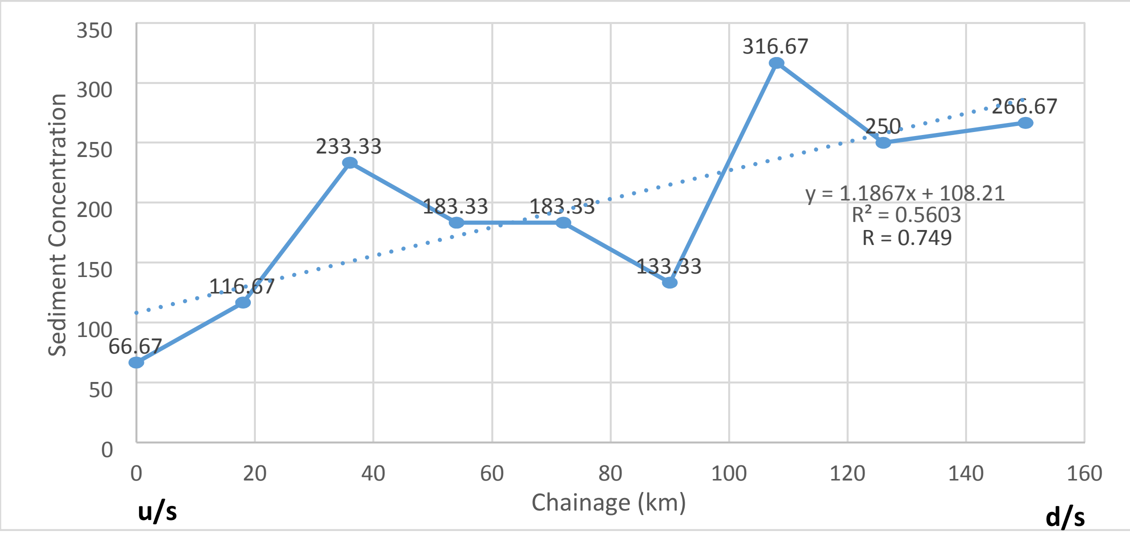

Figure 36. Analysis of Sediment Concentration of the Surma (August 2016, Monsoon Season)

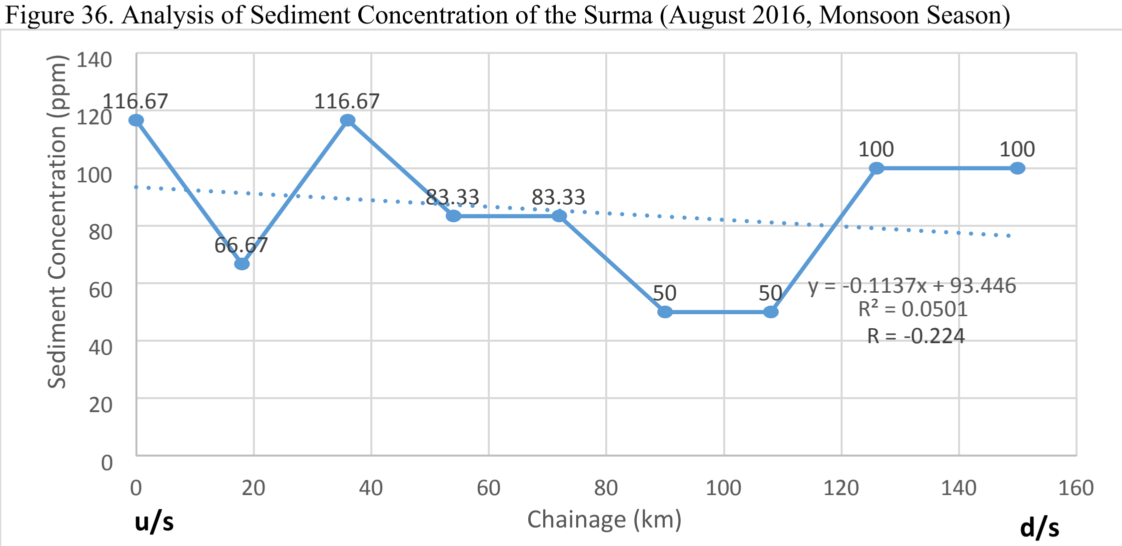

Figure 37. Analysis of Sediment Concentration of the Surma (January 2017, Dry Season)

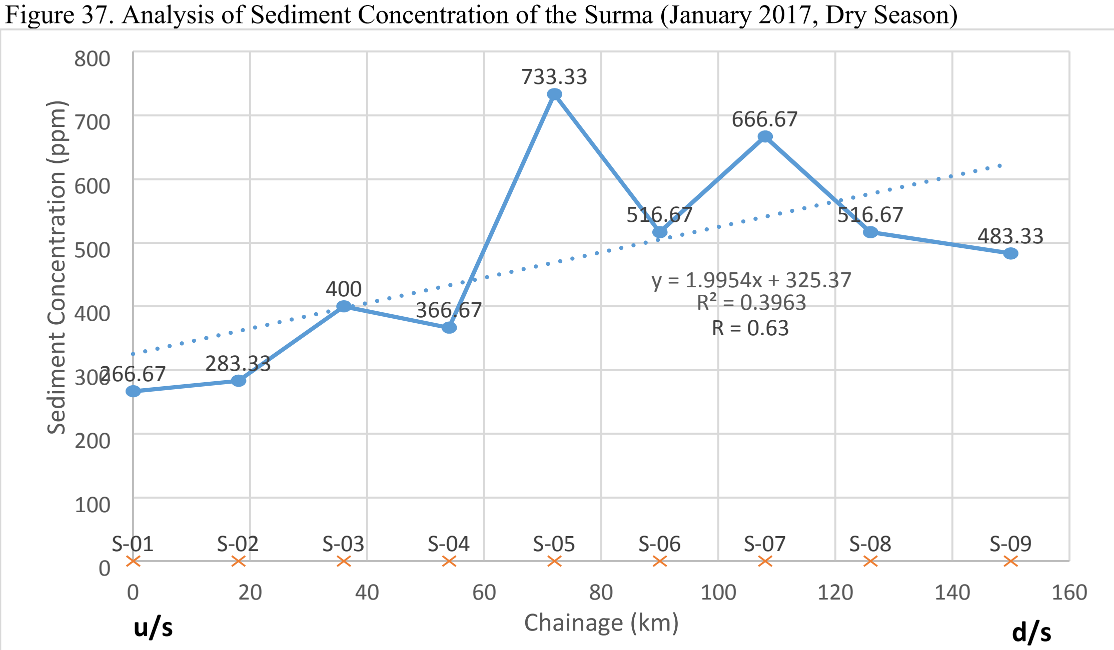

Figure 38. Analysis of Sediment Concentration of the Surma (April 2017, Pre Monsoon Season)

Median Grain Size
The Surma:
Bed Material Samples of the Surma have been collected. Median grain sizes (D50) of the bed materials of Dry Season and Pre Monsoon season along the river course are presented in Figure 7.27 and 7.28 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.

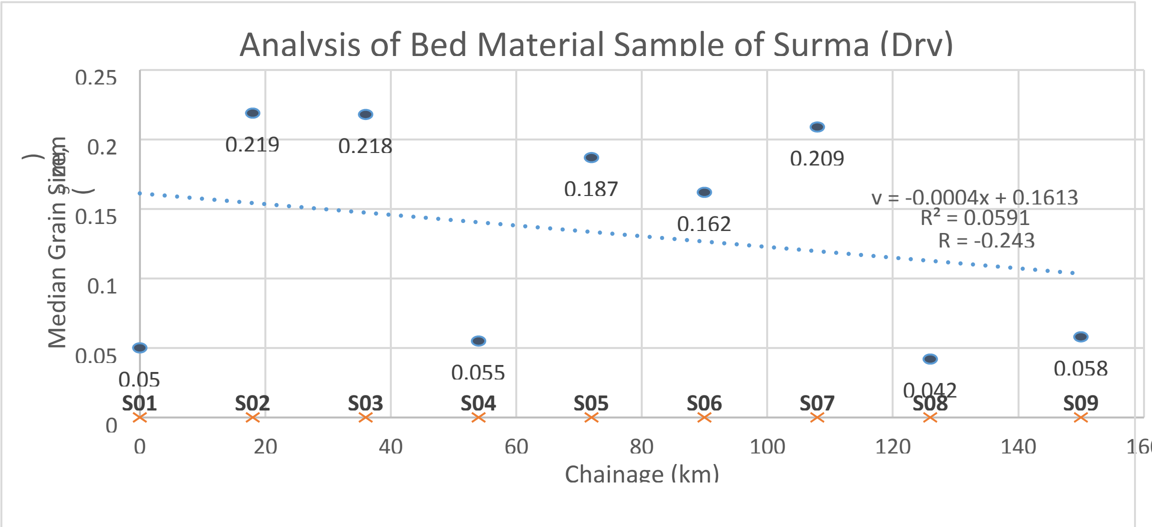

Figure 39. Analysis of Bed Material of the Surma river (January 2017, Dry season)

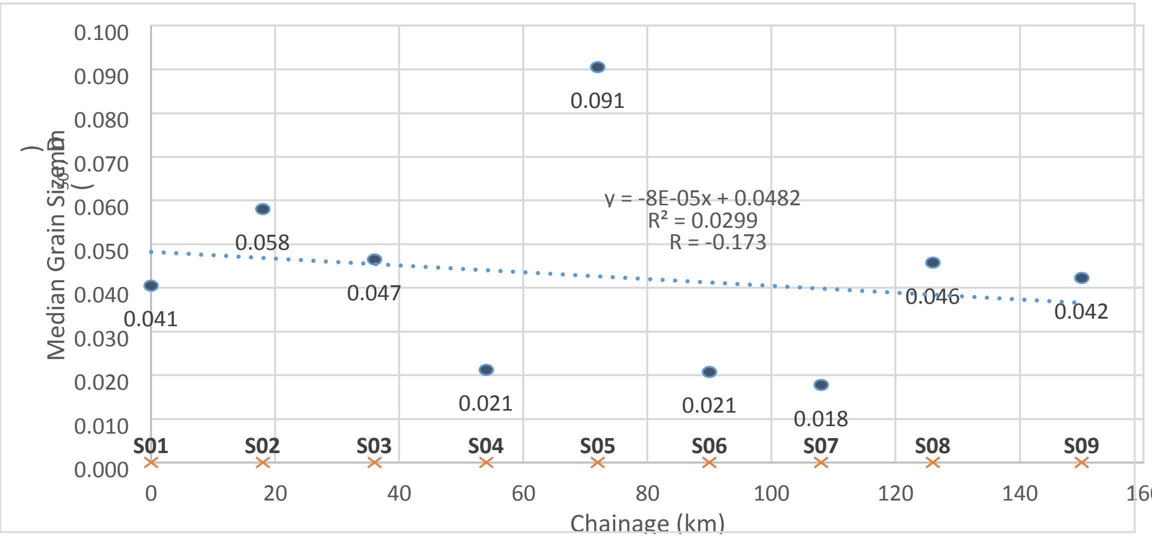

Figure 40. Analysis of Bed Material of the Surma river (April 2017, Pre Monsoon season)

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. Conventional Analysis and Model output reveal the following for both the Surma .

The bankfull water levels at different sections are different. The bank level at the d/s sections are lower than the average flood level.

I. There are variations in X-sectional Areas, width and depth.
II. There are variations in the sediment concentration.
III. There are variations in the Median Grain Size (D50).

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".

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.

The Scenario-2, considered 20% decrease of peak discharge at the u/s station RS 38 for the Surma. The likely changes for the above mentioned scenarios for both the rivers have been described briefly in the attachment 2.

Findings

The major findings of the study are as follows:

1. The analysis confirms the acceptability of Hypothesis 1 for the Surma rivers.
2. The Hypothesis 2 could not be (conclusively)established/validated.
    a. For the Surma 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.
3. The Hypothesis 3 may not be established/validated for the Surma. Detailed explanation has been given in Section 3.5.
    a. From conventional analysis: Hypotheses 3 may be considered as established/validated for the Surma river.
    b. From Model output: From the analysis of seasonal variation of the Bed level gradient, it is observed that bed level slopes are almost same at both the dry and monsoon seasons. Hence Hypothesis 3 could not be established/validated for the Surma.
4. Hypotheses 4 and 5 relate to the hypothetical 'Regime Condition' of the river. The analysis clearly demonstrates that the Surma river 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.
5. Under Scenario 1, when Peak discharge increases (20%) at upstream, there is an increase in simulated cross sections, discharges and water levels at downstream. Consequently, new areas are flooded and in other places flood depth increases.
6. Under Scenario 2, when Peak discharge decreases (20%) at upstream, there is decrease in cross sections, discharge and water levels at downstream. Consequently, flood reduction is observed.

Recommendations

1. Through the validation of the CEGIS conceptual Model the study has contributed towards enhancement of knowledge on hydro morphological process of the major river 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 river.
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 river of the Haor region.
5. Finer resolution satellite images should be collected for understanding of the shifting of the river.
6. Some permanent sediment and bed material collection stations should be established on the rivers Surma
7. A routine program of bethematric survey for one river may be taken up. The survey should be carried out in 4 seasons (namely, Pre monsoon, Monsoon, Post monsoon and Dry).

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