Space Borne Hydrodynamic Model Development: The Case of Ganges and Brahmaputra River Basin

Mehedi Maswood

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Committee:

Faisal Hossain

Rebecca B. Neumann

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Department of Civil and Environmental Engineering

University of Washington

Abstract

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River Basin

Mehedi Maswood

Chair of the Supervisory Committee:

Associate Professor Faisal Hossain

Department of Civil and Environmental Engineering

River modeling is an important component of flood forecasting system that can simulate the water flow dynamics of a stream network and forecast river levels in flood prone regions. Around the world, especially in the developing regions, many large river basins are mostly ungauged. For these basins river model setup is very challenging due to lack of necessary in-situ and routine measurement of river bathymetry, flood plain and river boundary data. Moreover, lack of data sharing among the countries occupying the trans-boundary rivers, also a hurdle to river model development. For such basins, proxy approaches depending on the satellite based remotely sensed data could be an alternative solution. In this study, one dimensional hydrodynamic model has been developed for the Ganges, Brahmaputra and Meghna basin region using the Hydrologic Engineering Center River Analysis System (HEC-RAS). Only 7% of the total basin area has good quality in-situ measurement of river hydraulics. For the remaining part,

remotely sensed data have been utilized for river model development. This study utilized: a) LANDSAT/MODIS for identifying flow path of river network, b) Shuttle Radar Topographic Mission (SRTM) for extracting river profile c) Radar altimeter for establishing depth-width relationship and d) Precipitation data to generate sub basin wise flow data. Simulated model results have been tested at two downstream low lying locations. The outcome of the study showed significant improvement of root mean square error (RMSE) for river level simulation from 3.0m to 1.0m. A step by step 'rule book' has been documented to facilitate the setting up river models for similar type basins around the world for operational water agencies.

Dedication

This thesis dedicated to my wife and my children

ACKNOWLEDGEMENTS

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PEER REVIEWED PUBLICATION

Maswood, M. and F. Hossain (2015). Advancing River Modeling in Ungauged River Basins using Remote Sensing: The Case of Ganges-Brahmaputra-Meghna Basins. *Journal of River Basin Management* (accepted).

1. CHAPTER 1 – INTRODUCTION

1.1 Background

Water is not confined to political borders. Rivers and lakes that cross international boundaries have great importance with respect to economic and political aspects. Transboundary basins connect population of different countries and help to generate earnings and livelihoods of millions of people worldwide. Around the world, more than 260 rivers and lakes shared by countries which account 40% of the Earth's land surface and 60 percent of the global fresh water (Hossain et al., 2013; Wolf et al., 1999). Transboundary rivers play a vital role for economic development and poverty alleviation by supporting income and livelihood of hundreds of millions of people. For example, Nile, Niger, GBM (Ganges, Brahmaputra and Meghna Basin), Indus, Salween, Zambezi, Mekong, Irrawaddy are some very prominent trans-boundary rivers that host some of the world's largest population centers (Figure 1). According to United Nations (UN) estimation, approximately forty percent of the world population lives in rivers and lakes basins that encompass two or more countries are very dependent on the available fresh water (UN Water, Thematic Paper 2008). Increase in population, urbanization and economic development put more stresses on water to fulfill the requirement for agricultural, municipal and industrial uses. Moreover, change in climate pattern has added more pressures on many transboundary water resources with variations in water availability.

According to the global report published by UNDP (2004), each year nearly 196 million people around the world are vulnerable to catastrophic flooding. The statistics have shown that within twenty years nearly 175 of total 1760 riverine floods were transboundary and caused nearly thirty two percent of the total causalities, fourteen percent of financial damage and about

sixty percent of affected individuals (Bakker, 2006). Transboundary floods are more devastating in terms of financial and human life due to lack of knowledge about upstream river condition. Another notable issue is less developed countries face more causalities than the developed countries (Bakker, 2006).

Nations sharing transboundary rivers have differences in terms of social and economic aspects and their ability to manage water resources infrastructure both in political and legal context. These differences create challenges for operative and coordinated development as well as joint supervision of transboundary water resources. The different ground network coverage, monitoring procedures to data recording and sharing and insufficient resources are the key challenges for coordinated surface water modeling in rivers in these basins (Akanda, 2012). Lack of basin-wide coordination among the sharing countries brings severe consequence to downstream flood prone regions. Downstream countries continuously face difficulties in forecasting transboundary flooding by extensively relying on real time in situ data (Hossain et al., 2013).

1.2 Motivation

Bangladesh, a low lying riverine country located in the confluence zone of the Ganges, the Brahmaputra and the Meghna rivers is very vulnerable to flooding and has a serious requirement to improve its flood forecasting. Located at the lowest reach of the fluvial system, the country's water induced disasters is a regular phenomenon and the tasks of prediction the propagation of floods and planning and designing mitigation measures are quite difficult (Paudyal et al., 2002). The county is crisscrossed by more than three hundreds rivers and among them fifty seven rivers are transboundary. The geographical setting of Bangladesh is such that

ninety three percent of the catchment area lies outside the country and responsible for transboundary flooding inside Bangladesh. During the Monsoon season (June to September) heavy rainfall occurs over the vast Ganges, Brahmaputra and Meghna basin area. It causes devastating floods each year due to swelling of the rivers from increased runoff from the upstream.
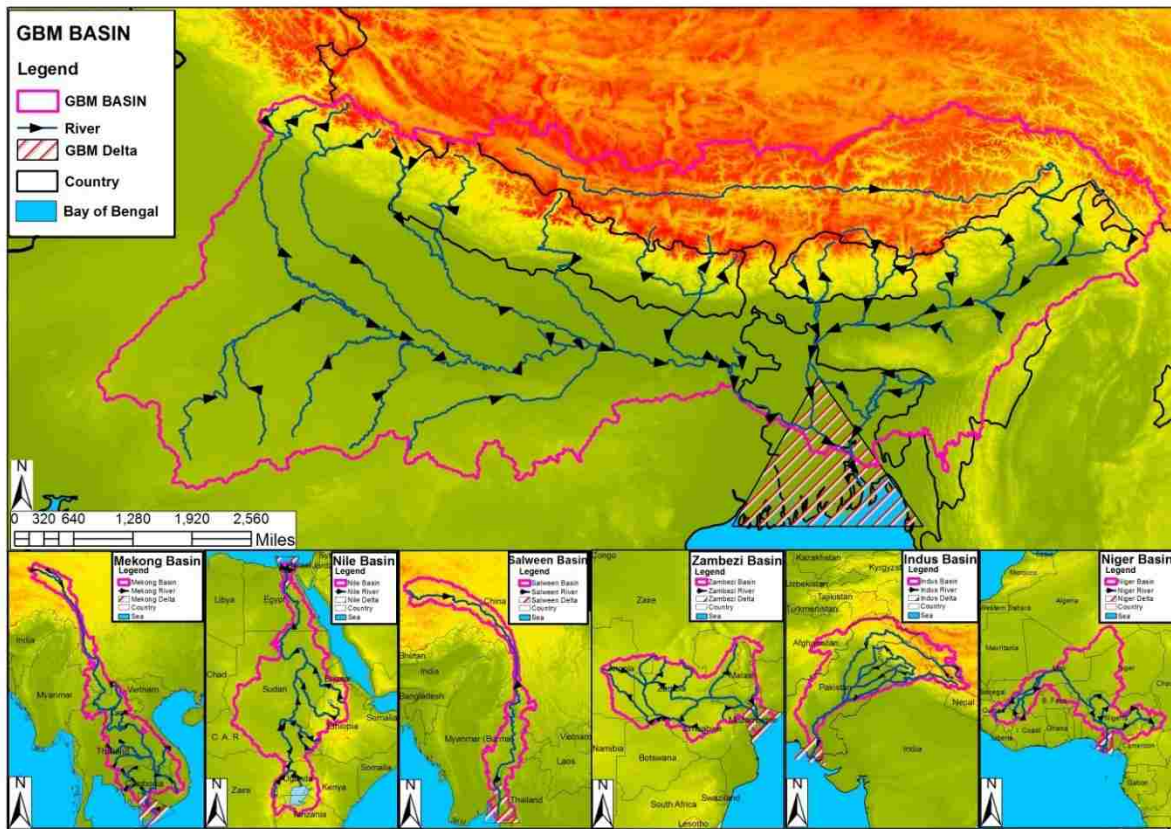
Figure 1.1: GBM basins and similarly ungauged river basin around the world showing the major river network, delta (flood prone region) and flow direction
Upper panel shows the GBM basin delta (triangle) whereas lower panel shows the similar type river delta around the world.

The flooding condition in Bangladesh is extremely dependent on the situation at the confluence zone of the Ganges and the Brahmaputra river that forms one of the world most densely populated river delta (Figure 1.1). Over long periods, deposition of sediments formed

this river delta at the Ganges and Brahmaputra rivers mouth which has rich agricultural land and provides easy access to water and water based transport. As a low-lying and river dominated delta, inhabitants of this land face rain induced extreme floods, tropical cyclones and associated storm surges. The geographical setting of delta acts as a frontline region against the sea level rise. Around the world, most of the river deltas like Mekong, Salween, Zambezi, Nile, Niger, Irrawaddy, Indus etc. are densely populated and work like economic power house for their nations. As the world's increasing population becomes progressively urban, big cities in these deltas are becoming more reliant on key resources such as water, food and energy, many of which are sustained by the freshwater resources of river deltas.
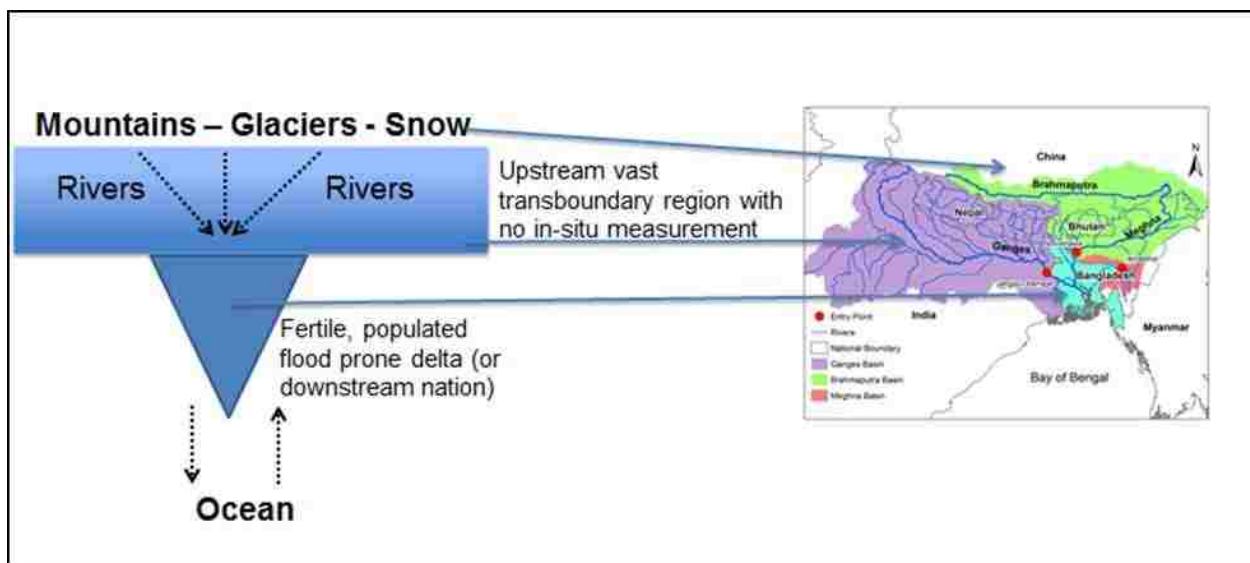
Figure 1.2: Schematic representation of flood forecasting problem in flood prone downstream nations in large and ungauged transboundary basins

The left panel shows the conceptual schematic where the rectangular region represents the vast ungauged region. The interface between the delta and the upstream region is where flow conditions are required from a river model to initialize a flood forecasting system (shown as red circles). The real world example for GBM basins and Bangladesh is shown on the right panel and can be conceptualized for Mekong, Nile, Niger, Salween, Indus (See Figure 1.1 lower panels).

But these river deltas are most vulnerable due to lack of upstream in-situ measurement. The schematic shown in the Figure 1.2 demonstrate the conceptual river modeling problem for the downstream flood prone nations. Most of the cases, rivers originated from the mountains, lake, glaciers and snowpack can be represented by river model scheme without any difficulties. But for the downstream flood prone nations (i.e. typically a delta shown as triangle in Figure 1.1) vast areas starting from the foot of the mountains all the way upstream edge of the downstream flood prone region, remain unknown. Although the downstream nations are facing the severe consequences of flood but due to lack of information they cannot develop a real time flood forecasting system utilizing sophisticated rive modeling technique. Accurate hydrodynamic modeling of the rivers in the vast upstream region can facilitate to understand the river flow dynamics and flood forecasting for the flood prone region.

The primary motivation of this study is to facilitate the flood forecasting system for the downstream nations of transboundary basins by setting up a river (hydrodynamic) model to improve the upstream boundary conditions of the forecasting domain. Instead of conventional data sources (from in-situ networks), this study has investigated suitability of alternate data source with a rational mindset. The question we ask in this study is, *To what level of accuracy can we achieve in river modeling by applying alternate data sources, such as from satellite platforms over the ungauged regions?* The next section provides a review of literature on the aspects relevant to the study.

1.3 Literature Review

In situ gauge measurement techniques have been considered as the most widely recognized procedure to estimate and understand the global distribution of surface water. This

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technique provides a point-based observation of water surface to understand the movement of water. Over half a century, developed nations have been collecting river stage (height) data for their river basins. On the other hand, due to financial constraint developing countries stream gauge sites are much sparser and less frequently measured (Alsdorf et al. 2007). Scientists and researchers in the field of water resources management have pointed out important issues that might influence the dense network of gauges for stream flow measurement for flood prone deltas. One major issue is real time data availability of the in-situ records. And the second one is specific to measurement technique. Basically in-situ gauge measurement technique does not give proper indication of flow over floodplains, wetlands. Moreover, it has considerable amount of installation and maintenance cost (Lettenmaier and Alsdorf, 2003; Prigent et al.,2001; Matthews and Fung, 1987).

Over the years, researchers have been trying to find alternate solutions to the deficiency of in-situ measurements for ungauged basins. Two such methods that have become popular: a) satellite based surface water estimation; and b) hydrodynamic and hydrologic modeling frame work (Siddique-E-Akbor et al., 2011). Satellite based surface water estimation has the advantage over the other techniques as it not only overcomes the political boundary limitation but also cost-effective for river flow estimation for the ungauged basin. Technological advancement has provided a new way by incorporating satellite based surface water estimation into hydrodynamic-hydrologic model to simulate river levels for various water management problems.

Satellite based remotely sensed data acquiring technique has widened its application field such as water resource management, flood forecasting and disaster preparedness. Advancement of satellite technology has facilitated to capture data varying from local scale to global scale

which are updated regularly over the internet (Nishat et al., 2010). With the advancement of satellite orbital precision and availability of multi temporal satellite data, this technique has emerged three aspects of water science: 1. Straight measurement of water surface level from radar altimeter; 2. Estimation of water level at their point of contact with the land surface using visible and near-infrared satellite images and topographic data; and 3. Correlation of satellite estimated water surface areas with ground measurements of stage or discharge (Smith et al., 1997).

Satellites can visualize the surface water utilizing both active and passive sensors. LANDSAT has passive sensors known as Thematic Mapper ™ and Enhanced Thematic Mapper Plus (ETM+) and both of them have been used for surface water analysis. The greatest problem of the visible/infrared sensors is that these sensors are incapable to penetrate the cloud while imaging the Earth's surface (Rasid and Pramanik, 1993; Melack et al., 1994; Neal et al., 2009). With the advancement of satellite technologies new method has emerged to estimate flood extent using microwave radar [Synthetic Aperture Radar (SAR)] that can penetrate cloud and vegetation to provide meaningful land water mask to validate hydraulic models (Schumann et al., 2009).

Over the last couple of years significant advancement has been made in identifying flood inundation extent using various sensors to evaluate the performance of river models in sparsely gauged or ungauged basins (Brakenridge et al., 2007). Space-borne radar altimeters have facilitated to estimate water level of rivers (Birkett, 1995, 1998; Schumann et al., 2009). Initiated and matured in oceanography this technique (e.g., ENVISAT, JASON, Topex/POSEIDON) is now capable of measuring water level of wide rivers precisely and produces the opportunity to quantify discharge from space.

The Shuttle Radar Topography Mission (SRTM) was an international research effort that has utilized a technique known as Interferometric Synthetic Aperture Radar. The mission has acquired most complete high resolution digital topographic database of the Earth surface. Earth surface elevation provided by SRTM has facilitated many studies to determine river slope and discharge (e.g., Woldemichael et al., 2010; LeFavour and Alsdorf, 2005). Recently, some new satellite missions popularly known as Surface Water Ocean Topography (SWOT), Global Precipitation Measurement (GPM), Soil Moisture Active Passive (SMAP) etc. have been designed with various perspective. Among those missions, SWOT will be launched to capture more reliable water level data that might help researcher to estimate discharge more accurately.

With the advancement of satellite based Earth observation technique new opportunities have emerged to improve the calibration and validation of hydrologic and hydrodynamic model. Researchers have investigated the potential of integrating satellite based observations of floods with hydrodynamic models for calibration purpose (Werner et al., 2005; Mason et al., 2003). Coupled hydrologic-hydrodynamic model has been simulated integrating remotely sensed information to improve the model outcomes by detecting and amending the bias (Montanari et al., 2009). Initiatives have been taken to estimate discharge in an ungauged basin by incorporating river stage data acquired from Synthetic Aperture Radar (SAR) image and digital terrain model (DTM) by simulating coupled model (Neal et al., 2009). Although this technique is susceptible to measurement bias but it has provided new ways of discharge estimation for high flows. In the near future new sophisticated satellite missions will be launched that will facilitate hydrologic and hydrodynamic model for generating better output.

Large scale water resources modeling for basins like GBM, Indus, Salween, Mekong, Irrawaddy, Niger, Nile etc. can facilitate efficient and effective water management and reduction

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in water induced disaster. To the best of our knowledge good quality modeling at a continental scale has not been reported in literature and the only GBM-wide hydrologic model currently in existence for water management are that reported by Nishat et al., 2010 and Siddique-E-Akbor et al., 2014. On the other hand, several studies have been conducted to understand the complex hydrology of the riverine delta of Bangladesh by integrating hydrodynamic model with remotely sensed data (Siddique-E-Akbor et al., 2011; Hossain et al. 2013). GRACE (Gravity Recovery and Climate Experiment) satellite data with the help of Land surface model (LSM) simulated time series data for the Bengal Basin of Bangladesh have been tested to find the seasonal variability in groundwater storage associated with severe groundwater abstraction for dry season irrigation and wet season recharge (Shamsudduha et al., 2012).

1.4 Objective of the Study

In this research work we have investigated to figure out to what extent we can advance river modeling in GBM basin using alternate data sources, such as from the satellite platforms over the ungauged regions. The objectives of the study are therefore as follows:

I.   Demonstrate how a combination of proxy approaches: satellites and hydrodynamic modeling can be synthesized to improve upstream boundary conditions of forecast modeling domain.

II. Share the experience of River Modeling of the entire GBM basin against current hurdles of lack of in-situ data upstream of a dynamic Delta.

III.   Develop a guide of basic steps for hydraulic modeling for any agency in any basin as a '*Do it Yourself*' for stakeholder agencies (e.g. Salween, Senegal, Niger, Indus, Mekong etc.).

1.5 Thesis Outline

The following chapters are organized as follows. Chapter 2 is on materials and methods where the tools, data and models are discussed. Chapter 3 is on model results and discussions where the levels of accuracy of model outcomes have been discussed. Finally Chapter 4 is the conclusion where the summary of the key findings of the study have been outlined. Appendices elaborating on specific components of the study are provided in the last section of this thesis.

2. CHAPTER 2 – MATERIALS & METHODS

2.1 Study Area

2.1.1 Overview

The study area consists of the Ganges, Brahmaputra and Meghna system that represents the one of the largest outlets of freshwater with one of the most highly inhabited floodplains (Akanda, 2012). Both the Ganges and the Brahmaputra river originate from the Himalayan region and travel through the Indo-Gangetic plain and the Tibetan Plateau respectively. The entire GBM basin located within 21^0 68' and 31^0 43' North Latitude and 73^0 43' and 97^0 68' East Longitude. The Ganges river flows southwest into India and then turns southeast, being joined by many tributaries (refer to Figure 2.1). The main stem of the Ganges has a total length of 2,525 km up to its outfall into Bay of Bengal. The Ganges river and its tributaries have formed a large flat and fertile plain on the both side of river banks. Although seasonal flood is very common in the rivers in this basin but abundant water resources, fertile soil and suitable climate have driven to develop agriculture based civilization and one of the mostly densely populated regions of the world. On the other hand, the Brahmaputra river (known as Yalung Zangbo in China) flows east through the southern area of China, then flows south into eastern India, turns southwest and then enters Bangladesh (known as Jamuna). It traverses a distance of 2,900 km before joining the Bay of Bengal. The Brahmaputra basin area is located at one of the heaviest rainfall region in the world and very active earthquake seismic zone. Every year this river causes notorious flood and river bank erosion that create mayhem and misery to the inhabitants of this region. The GBM rivers and their tributaries have contributed to form the one of the largest deltaic plains on earth comprising most of Bangladesh geographic area. Fertile floodplains and fresh water source has attracted majority of the region's population to inhabit along the river banks.

2.1.2 Climate

The monsoon climate and physical geography of the basin area highly influenced the availability of the water within this region. The presence of the Bay of Bengal on the south and the Himalayas on the north control the climatic character of the basin area. The basin area varies from sub-humid to hot and humid climate. Southwest monsoon determines the hydrologic cycle of the basin area. As a result, nearly seventy to eighty percent of the total rainfall occurs from June to September which is popularly known as monsoon season. According to the report produced by Indian Ministry of Water Resources (Ganga and Brahmaputra Basin, 2014 version 2.0), average annual rainfall for the Ganges basin and Brahmaputra basin located within the Indian region are 1059 mm and 2720 mm, respectively. For the Ganges basin temperature varies between 18^0C to 32^0C whereas for Brahmaputra basin in ranges from 16^0C to 38^0C. The influence of seasonal climate on the basin area creates a great challenge to make efficient planning and management of the available water resources.

2.1.3 Topography

The GBM basin consists of around 1.75 million squared kilometers with catchment areas lying in India, Bangladesh, China, Nepal and Bhutan (Nishat et. al, 2009). As mentioned earlier in Chapter 1, only 7% of the total catchment area located within Bangladesh. Report published by Indian Ministry of Water Resources has classified the Ganges basin into three large topographic divisions, namely the Himalayan Young Fold Mountains, the Gangetic Plain and the Central Indian highlands. According to the SRTM (90m resolution) digital elevation model (DEM), Ganges basin elevation varies between 8000 m to 0 m (near Coast). The terrain of the

basin is very rocky in the north eastern part and flat towards lower part. On the other hand, Brahmaputra basin consists of part of Tibetan plateau and mountain ranges of Himalaya, alluvial plains of Assam and the vast low lands of Bangladesh. Although maximum area of this basin falls between 10 to 100 m elevation ranges but the highest elevation of 8401 m is found in this basin.
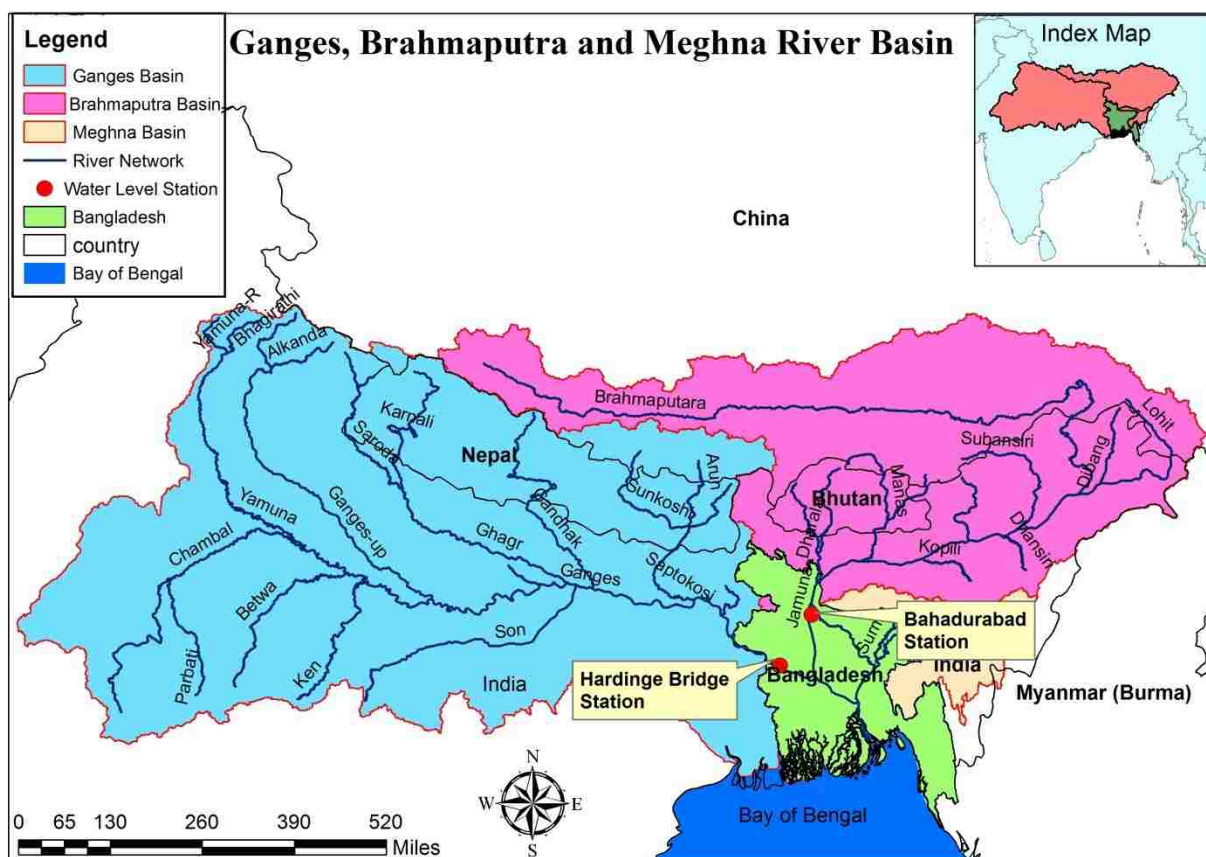
Figure 2.1: Ganges, Brahmaputra and Meghna river basin area showing the gauging station at upstream points of the flood forecasting domain (Hardinge Bridge on Ganges and Bahadurabad Station on Jamuna).

2.1.4 Major Rivers

Bangladesh situated at the bottommost part of the GBM system crisscrossed by more than three hundreds rivers and among those rivers, there are around fifty-seven rivers are transboundary. Most of these transboundary rivers (54 rivers) originated from the upper part of Ganges and Brahmaputra basin located within India. The Ganges river (also known as "Ganga" in the local vernacular) is the prime river of India and it flows east through the Gangetic plains of Northern India to enter into the country of Bangladesh. The principle tributaries joining the main river are the Yamuna, the Ramganga, the Ghagara, the Gandak, the Saptokosi, the Mahananda, the Son. Chambal and Betwa are the two important tributaries. On the other hand, Brahmaputra basin is named after its major river Brahmaputra. Upper reach of the river is fed by glacier, whereas its middle reach receives a number of tributaries like the Manas, the Subansiri, the Kameng, the Dhansiri, the Debang, the Lohit, the Kopil, the Dudhani, the Krishani etc. And its lower reach located within the Bangladesh region. During the monsoon period, excessive rainfall over the GBM basin leads to floodplain inundation. The Ganges and the Brahmaputra exceed a combined discharge of 100,000 m3/s and can inundate up to 80% area of the country (Hopson et al., 2009).

2.2 Data

Two distinct groups of data have been utilized in this study. These are: 1. Ground based (in-situ) data 2. Satellite based data. This research work has been initiated from the previously developed 'Major rivers model of Bangladesh' calibrated and validated by Siddique-E-Akbor et al. (2011). In this study, we hereafter refer to the model as 'The Base Model'. This base model incorporated surveyed cross-sections into the major rivers located within the Bangladesh region.

The rivers modeled in this HEC-RAS setup are Ganges, Jamuna, Old Brahmaputra, Surma, Padma and Meghna. A total of 226 surveyed river cross sections have been used in the base model (Figure 2.2). In situ gauged measured water levels and field measured discharge data have been used to generate rated discharge for the river boundary data. In our study, the base model has been extended for the entire GBM basin and this new model has used the ground based water level data measured at the two stations (shown in Figure 2.1) situated on the Ganges and Jamuna river (in India this river is known as Brahmaputra river) known as Hardinge Bridge and Bahadurabad station respectively. These two stations are the upstream boundary points for the Bangladesh domain which has been used to evaluate the GBM model performance.
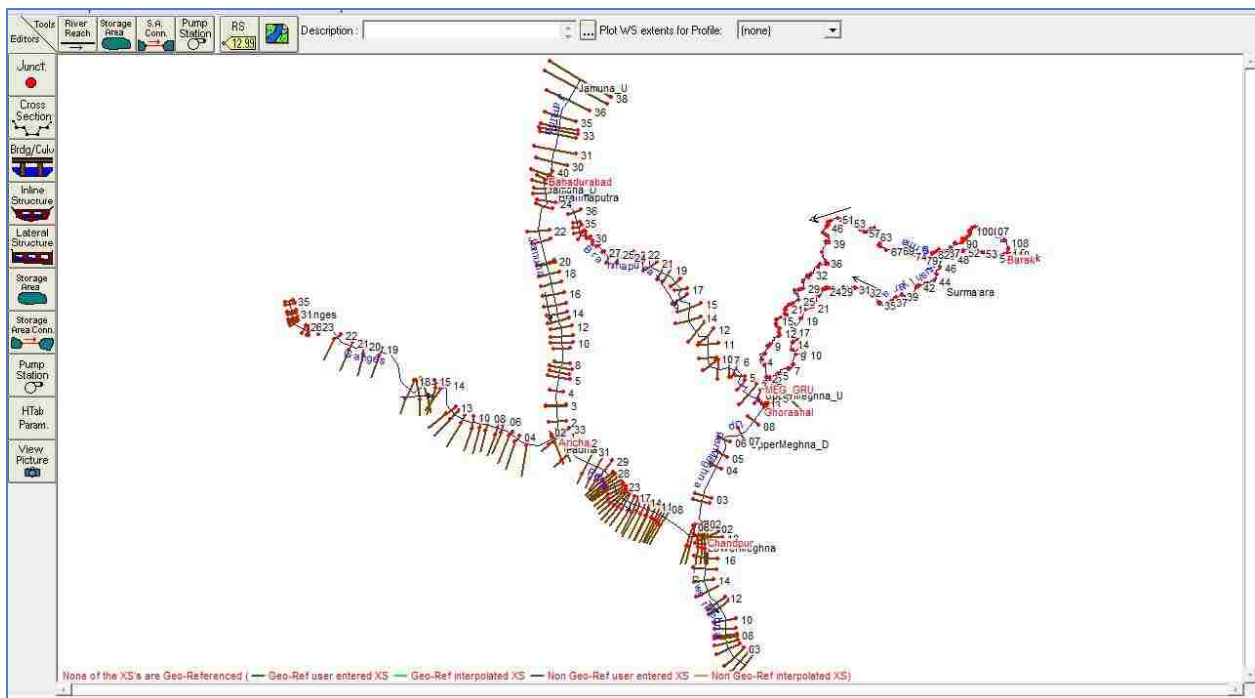
Figure 2.2: The Base model developed on the basis of ground based measurement for the flood prone Bangladesh region (after Siddique-E-Akbor et al., 2011)

The setup of hydrodynamic model consists of major four components. These are: 1) Setting up of river network 2) Incorporate river bathymetry (cross-section) data along the river

network 3) Define river floodplain and bed characteristics (Mannings n) 4) Assign river boundary and lateral flow data. By digitizing river network or exporting the ArcGIS shape file, river network can be included in the HEC-RAS model through 'Geometric Data' window. 'Geometric Data' window has GIS tools button that facilitates to add river network. 'Geometric Data' window also has 'Cross section' button on the left panel to include river bathymetry data along the river. 'Cross Section Data' window allows to define the extent of river cross-section and assign the Manning's Roughness value. HEC-RAS main window has 'Steady / Unsteady Flow Data' option to assign boundary data for the model simulation and to acquire river hydraulics.
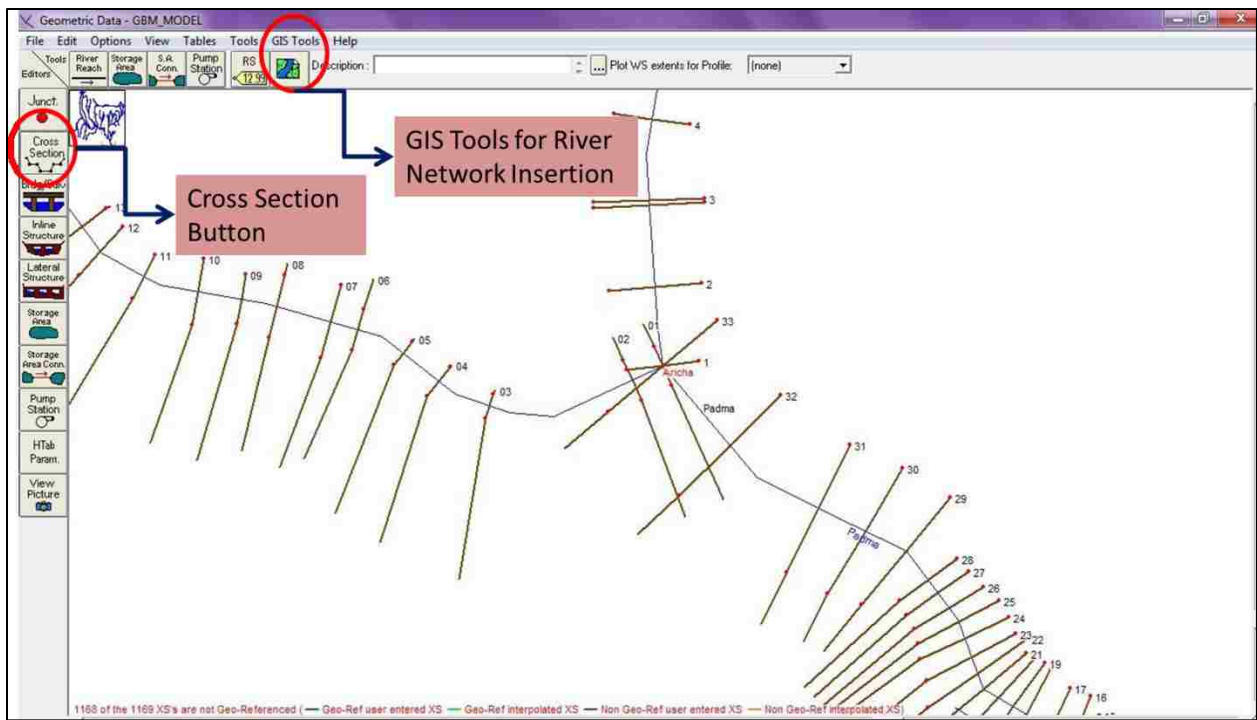
Figure 2.3: HEC-RAS Geometric Data window for setting up river network and cross section.
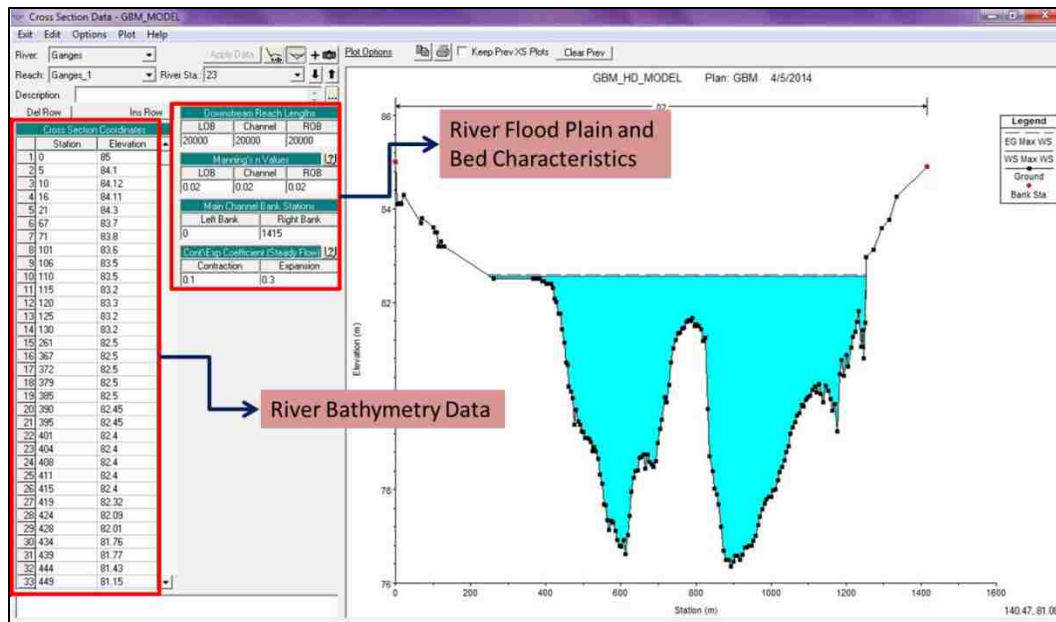
Figure 2.4: HEC-RAS cross section data setup window
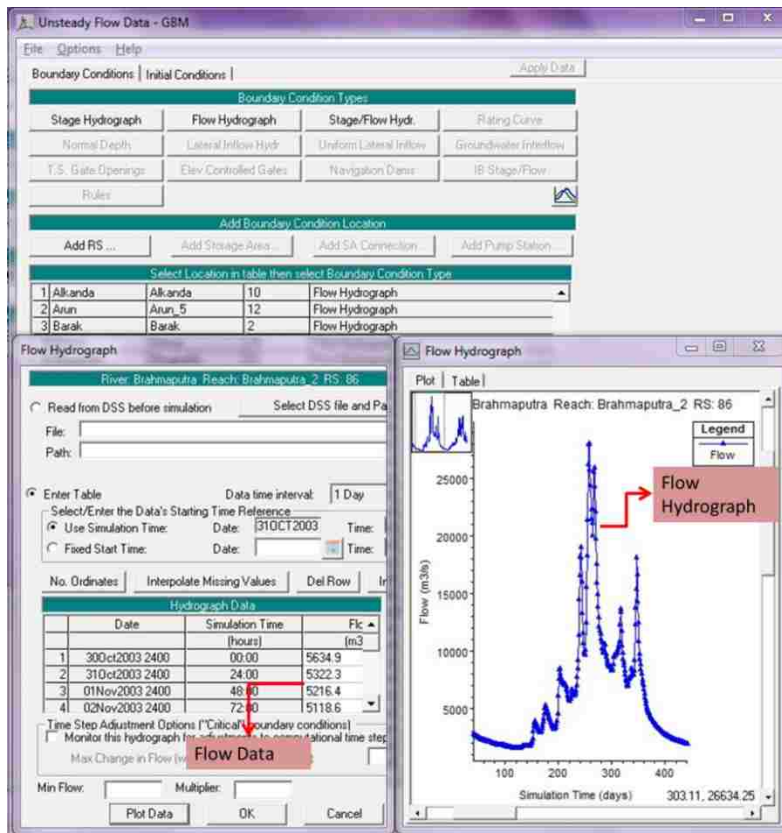
Figure 2.5: HEC-RAS unsteady flow boundary data setup window.

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The development of the entire GBM basin model has mostly relied on satellite remote sensing data. Initially, most recent river networks located within the Indian region have been digitized from the LANDSAT/MODIS based satellite data. Since 1972, LANDSAT (name indicating LAND + SATellite) satellite has been involved in capturing high resolution imagery of the Earth surface in the visible and near infrared wavelengths and at this moment LANDSAT-8 currently captures latest images of the Earth surface. This is the one of the longest running enterprises. In this study, LANDSAT-7 images have been processed to generate land/water classification. LANDSAT-7 images consist of eight bands data and these bands data have been processed to prepare land/water masks. This technique facilitates to delineate multiple streams, braided bars and floodplains.
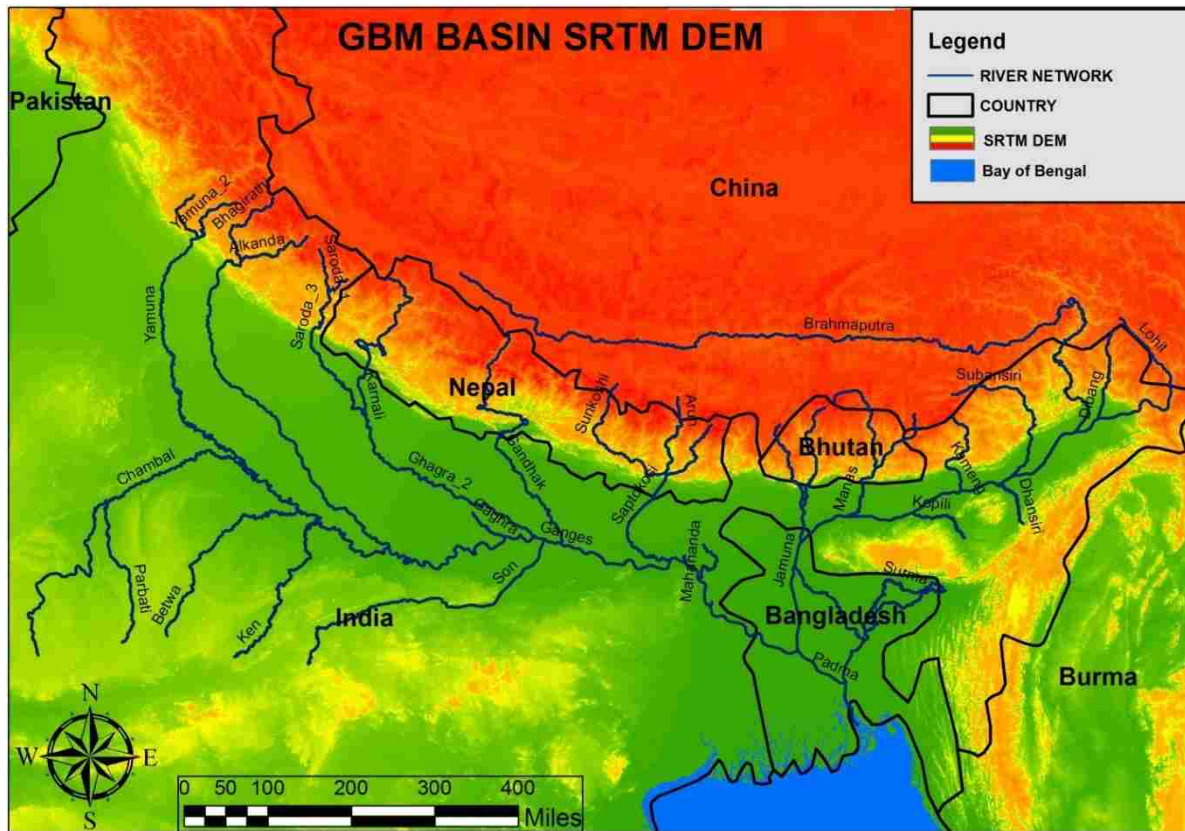
Figure 2.6: SRTM Digital Elevation Model for the entire GBM basin.

Shuttle Radar Topographic Mission (SRTM) satellite based elevation data have been utilized to capture river bathymetry (cross section) data. In the year 2000, with a view to generate most complete high resolution digital topographic database of Earth surface, SRTM satellite has been launched (http://srtm.usgs.gov/mission.php). This satellite mission during its 11-day flight captured three dimensional topographic map of the Earth surface. In our study, the 90m X 90m (3 arc seconds) resolution Digital Elevation Model (DEM) images produced by SRTM were mosaicked together for the GBM basin area (Figure 2.6). Later SRTM elevation data were incorporated in the model as river bathymetry data.

In our study, we progressively developed three different HEC-RAS hydrodynamic model setups. Initial two model setups have utilized the base model boundary data whereas the final one assimilated the hydrological model simulated basin runoff data. The final setup of our HEC-RAS model has incorporated the large scale and spatially distributed (spatial scales ranging from 12.5 to 25 km) VIC hydrological model generated sub basin runoff done by Siddique-E-Akbor et al., 2014 for the entire GBM basin. National Climatic Data Center (NCDC) of USA's Global Summary of the Day (GSOD) precipitation data have been used as an input in the VIC model. This data source was improved with data collected from International Centre for Integrated Mountain Development (ICIMOD) located in Nepal. Besides the precipitation data, snow extent data from MODIS satellite and daily temperature and wind speed data from NCDC have been used as inputs for VIC model. Later to generate the sub basin wide flow for the HEC-RAS model VIC model outputs were further processed by using VIC Route model.

The advancement of satellite radar altimetry has demonstrated the capability to estimate surface water height for the largest rivers, wetlands and lakes around the world (Birkett and Beckley, 2010). This technique allows emission and reception of a microwave pulse from a

nadir pointing antenna to estimate the time required to travel the target point distance. The information of satellite altitude along with a number of corrections (instrument-related and geo-physical) has led to derive the surface height. The system is capable of taking measurement day/night and all weather with little interruption due to canopy and vegetation cover. Some prominent radar altimeters are Envisat, JASON-1 and 2, Topex/Poseidon, IceSAT, Altika etc. In our study, we assessed the performance of our final HEC-RAS model at ungauged upstream points by utilizing Envisat satellite data. Envisat ('Environmental Satellite') was an Earth observation satellite operated to improve the environmental studies. In this study, this radar altimetry stage data have been used to build the depth versus width relationship at certain river locations in the ungauged regions located within India.

2.3 Model

The main objective of this study is to develop a one dimensional hydrodynamic model for an international river basin by incorporating satellite estimated data for the unknown upstream region and assess the model performance at the downstream field measured data. For this purpose, a calibrated and validated model developed by Siddique-E-Akbor et al., 2011 for the downstream Bangladesh region has been used. In our study, we named the model as the base model. To conduct our study, this base model has been further extended for the entire GBM basin utilizing the same HEC-RAS (version 4.1.0) platform. HEC-RAS stands for Hydrologic Engineering Centers River Analysis System developed by U.S. Army Corps of Engineers. Capable of solving one dimensional steady and unsteady flow condition, this software consists of four modules. Those modules are 1. Steady Flow Water Surface Profiles 2. Unsteady Flow Simulation 3. Sediment Transport / Movable Boundary Computations 4. Water Quality Analysis. Physical laws that govern the unsteady flow of water in a river are:1.The principle of

conservation of mass (continuity) and 2.The principle of conservation of momentum. HEC-RAS model resolves the physical laws to calculate water level and discharge along the river. In this study, three different model setups have been developed and simulated for the unsteady flow condition.

In this study, Variable Infiltration Capacity Model (VIC) setup over the GBM basin reported by Siddique-E-Akbor et al., (2014) has been utilized to get the boundary flow data for the hydrodynamic model. VIC is an open source macro scale semi-distributed hydrological model first developed by Liang et al., (1994) and used to transform rainfall to basin wise runoff at the outlet. It resolves the water and energy balance equation by taking precipitation, temperature (minimum and maximum) and wind speed as input. This is a lumped model with grid size larger than 1 km and takes inputs of time series of daily and sub-daily meteorological drivers (e.g. precipitation, air temperature, wind speed). In this study, the outputs of VIC model have been redistributed on the basis of GBM sub basins by using VIC Route Model to capture flow data at each sub basin outlet. Later, these sub basin wise flow data was applied as boundary data in the HEC-RAS model.

2.4 Methodology for Hydrodynamic Model Development

The study has been conducted with a view to construct a hydrodynamic model for the entire GBM basin by incorporating satellite based data so that it can simulate the river flow dynamics for the entire basin. If the developed model provides satisfactory results then it might be a useful technique for the downstream flood prone nations for improving their flood forecasting system. Although the research work has targeted to develop single hydrodynamic

model for the entire GBM basin but the model construction work was not completed in one instance. Instead we followed step by step procedure and the process required three iterations which showed progressive improvement. Uncertainties in the outcome of the satellite data based hydrodynamic model have insisted us to follow this procedure. Three different versions of hydrodynamic model have been developed by systematically incorporating satellite based data. During these three iteration processes each model showed some improvement than the previous one. The following flow chart (Figure 2.7) gives a graphical representation of the procedure and data that have incorporated for the models development.
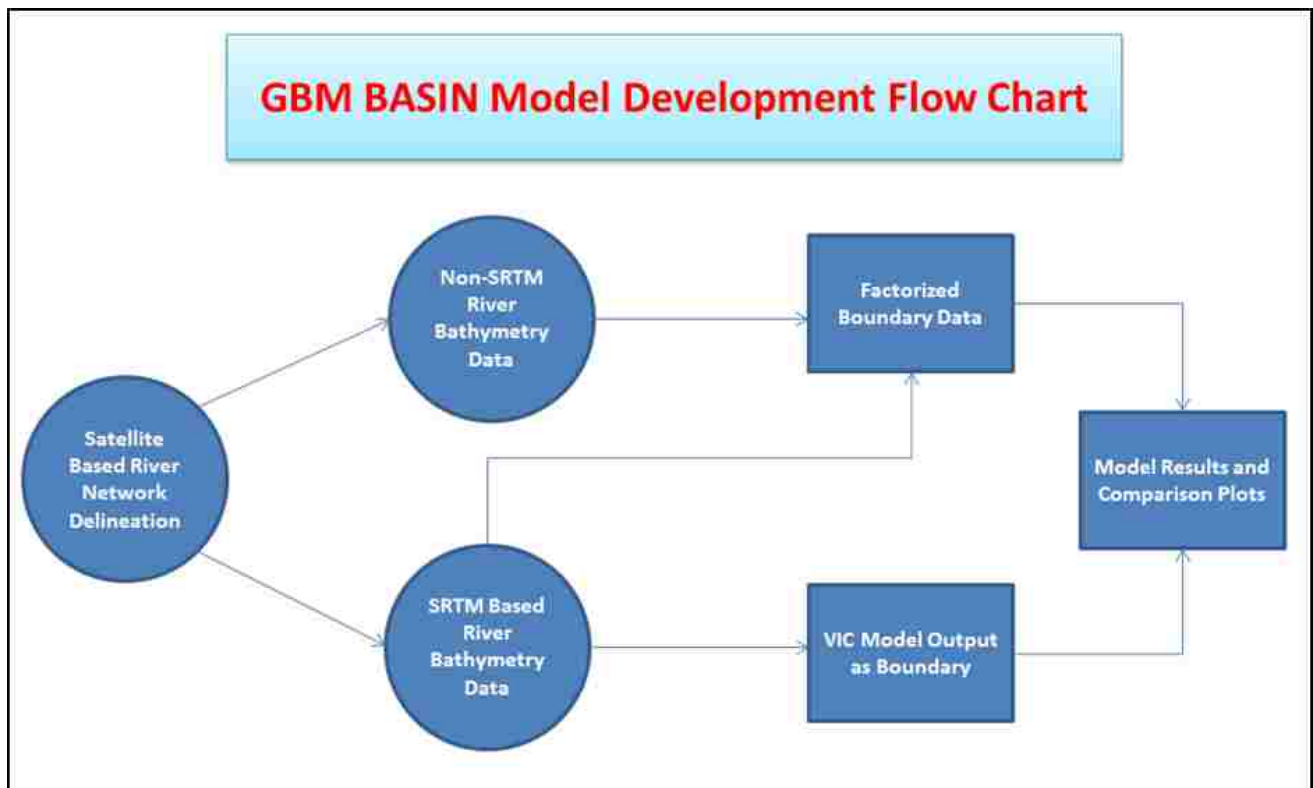
Figure 2.7 : The flow chart showing the GBM basin river model development work.

In our study, we named the three different model setups as follow:

1. Non-SRTM RAS Model with Factorized Boundary Flow Data

2. SRTM RAS Model with Factorized Boundary Flow Data

3. SRTM RAS Model with Hydrological Model Derived Boundary Flow Data

The first model was developed by utilizing the ground based model data for the Bangladesh region. For this setup, the satellite derived river network for the entire GBM basin has been incorporated. River bathymetry and boundary data have been generated from the downstream base model data. Figure 2.8 shows the setup for the Non-SRTM RAS Model with Factorized Boundary Flow data.
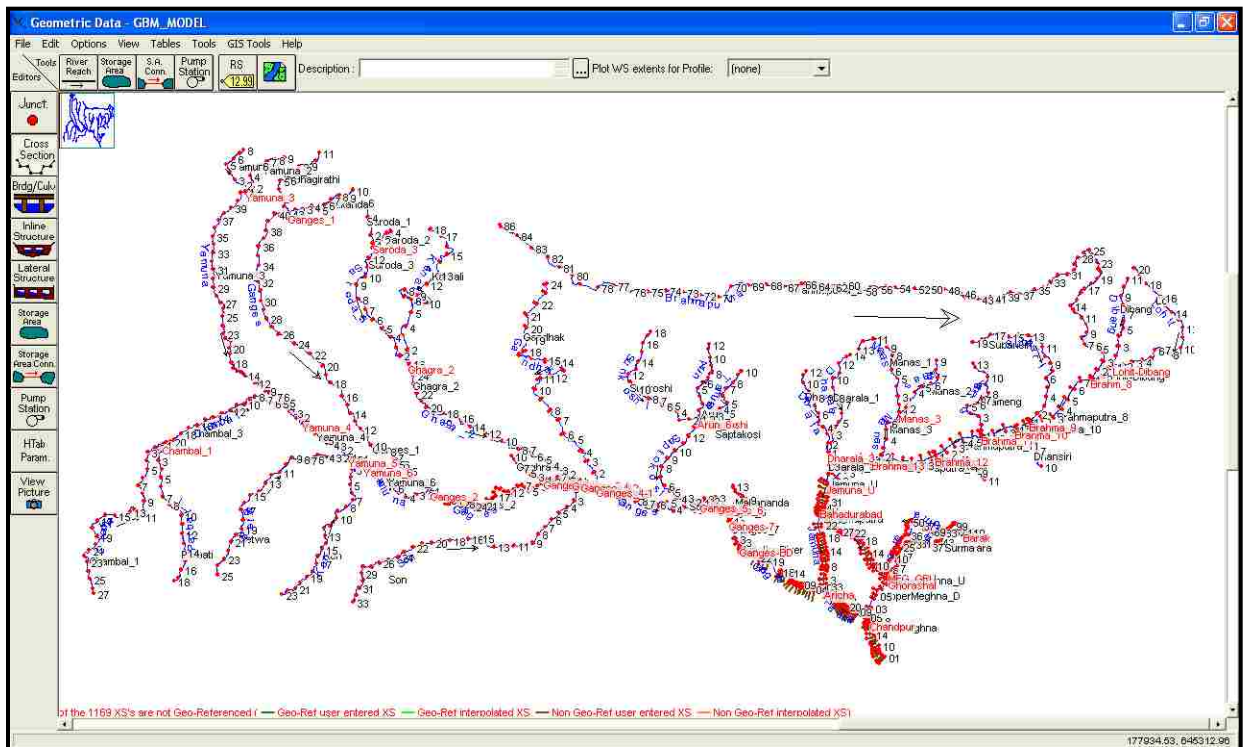
Figure 2.8 : Plan View of Non SRTM Bathymetry with Factorized Boundary Data Based HEC RAS Model

In the second model setup, river bathymetry data was derived from the SRTM DEM. But the same boundary data have been applied for the model simulation. For this setup, rivers located at the upstream steep gradient zone (mostly Himalayan region) have been excluded from the model to ensure smooth simulation. Keeping the same river network and bathymetry data the final setup was developed. In this setup, hydrological model simulated runoff data have been applied as boundary data.
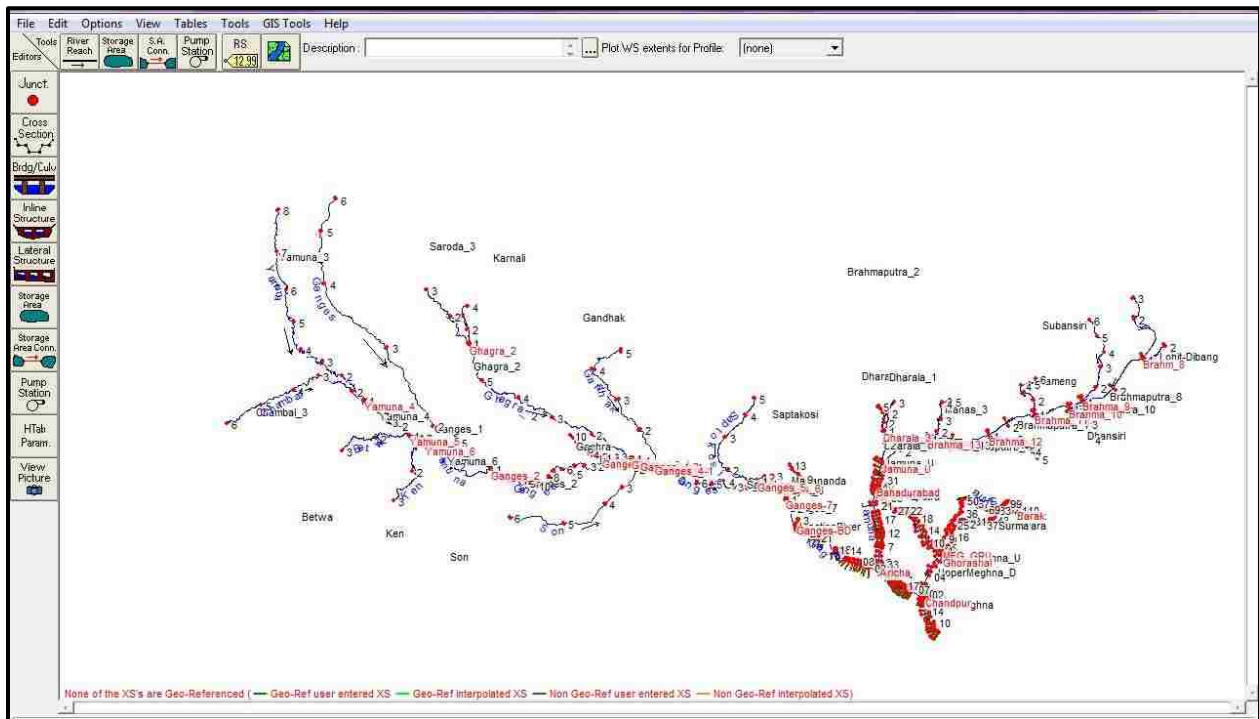
Figure 2.9 : Plan View of SRTM Bathymetry with VIC Generated Boundary Data Based HEC RAS Model

2.4.1 Satellite Based River Network Delineation

At the beginning of the study, the focus has been drawn to obtain the most recent river network for the entire GBM basin. Rivers located within the GBM basins are morphologically very active and change their river courses at decadal timescales. With the advancement of satellite technology and web based computer application has motived us to utilize the available

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applications to acquire river network. Google Earth, a geo-browser based on satellite and aerial imagery of the globe has become very popular to observe Earth surface. Taking advantage of the Google Earth software, the rivers of the GBM basin have been digitized. As a result, most up to date river network for the entire GBM basin has been acquired.
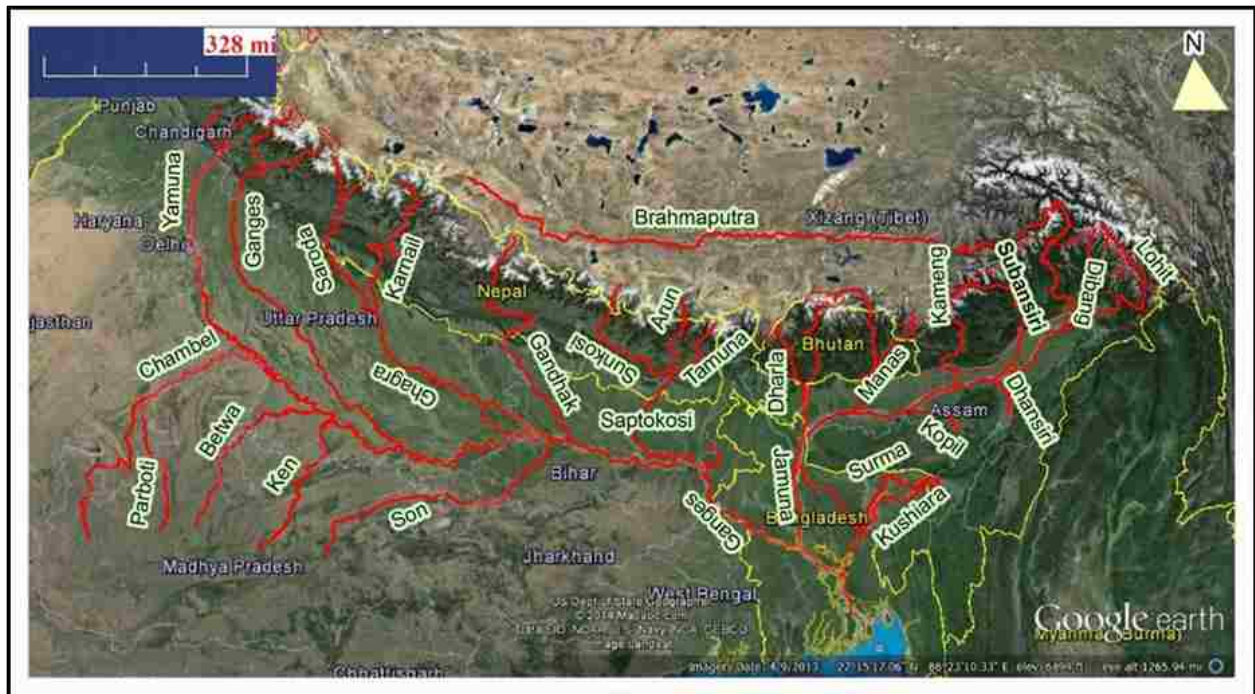
Figure 2.10 : Digitized river network for the entire GBM basin area

The digitized river network was converted to Keyhole Markup Language (KML) which is Google Earth file format. Later, the river network file was processed in ArcGIS to convert it in layer file. In Arc Toolbox under the 'Conversion Tools' menu the option 'kml to layer' has been used for this purpose. Figure 2.11 shows the process followed for this conversion:
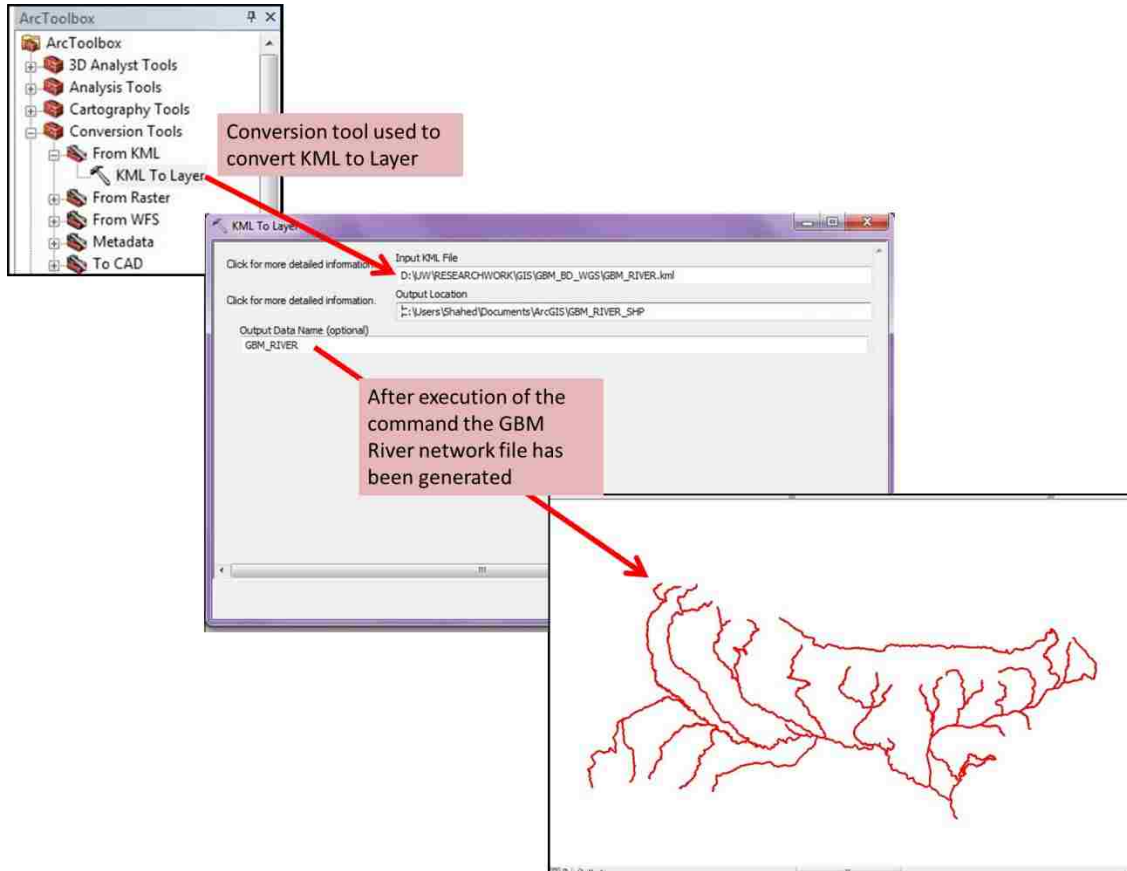
Figure 2.11 : Steps followed to convert digitized KML river network file to layer file

HEC –RAS model has limitation to directly incorporate the ArcGIS based river network file into the model. The two ways it can be brought to HEC-RAS model are as follows: One approach is to use ArcGIS shape file as background file in 'Geometric Data' of HEC-RAS model and digitize the whole network. The second approach is to convert the network file to point file and extract coordinates for each point. Finally, the coordinates of the entire river network are transported into the HEC-RAS 'Geometric Data' file. In this study, we followed the second approach that made the transfer of entire GBM network smooth and less time-consuming.

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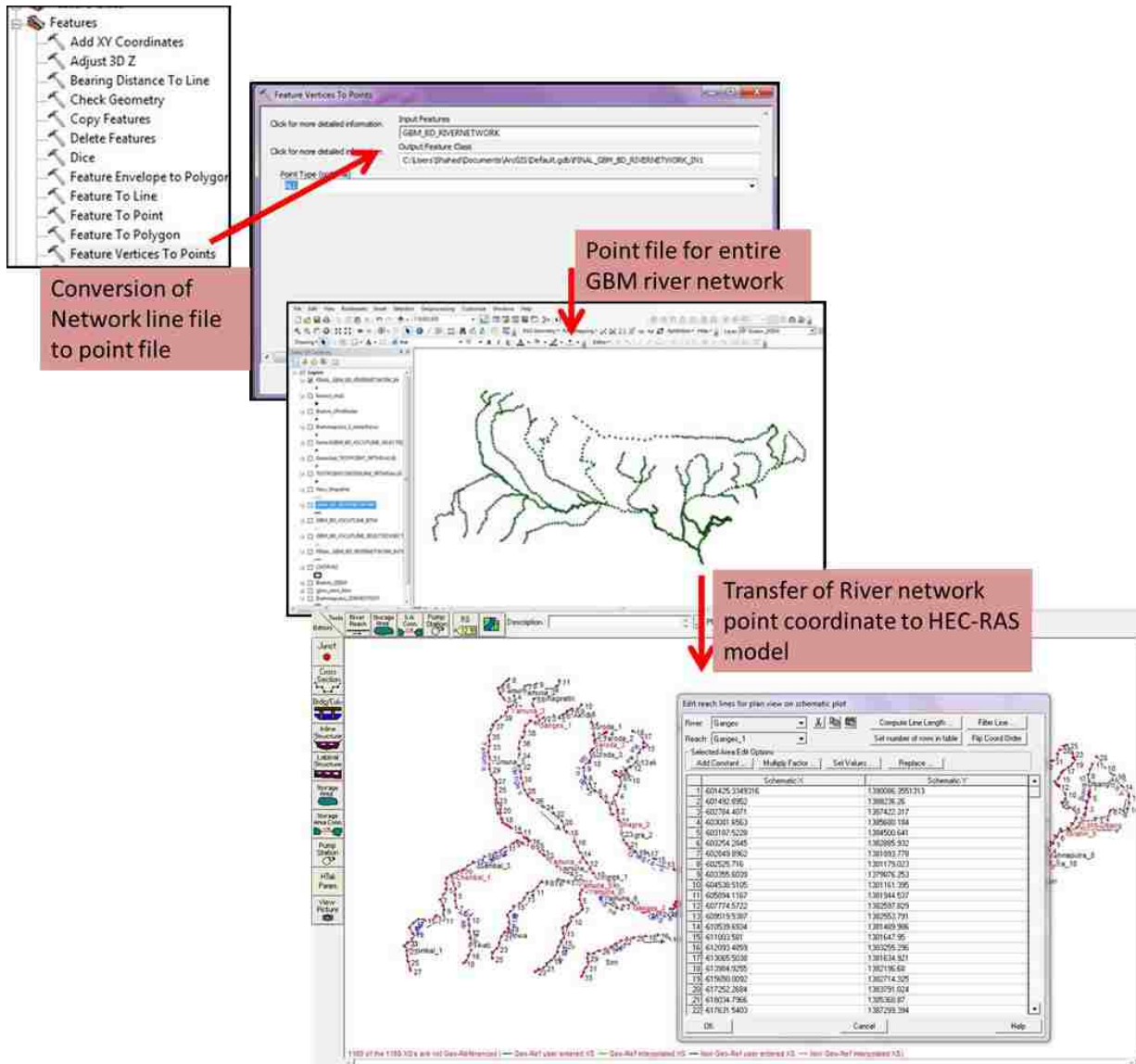
Figure 2.12: Steps followed to insert river network into HEC RAS model

Figure 2.12 shows steps followed to incorporate the entire GBM river network into HEC-RAS model. The river network point coordinates have been transferred by utilizing the option of HEC-RAS 'Reach Invert Lines Table' located under 'GIS Tools' of Geometric Data window.

Table 1: River length that included in non-SRTM RAS model

RIVER NAME	MODEL LENGTH (km)	RIVER NAME	MODEL LENGTH (km)
Ganges	1966.5	Mahananda	129.19
Brahmaputra	2592.69	Old Brahmaputra	248.62
Old Brahmaputra	248.62	Subansiri	366.35
Yamuna	1433.62	Kameng	232.65
Jamuna	216.96	Manas	396.35
Meghna	211.03	Dhansiri	332.42
Chambal	907.28	Kopili	194.03
Betwa	505.99	Padma	117.9
Ken	457.42	Surma	395.72
Son	645.64	Kushiyara	290.34
Saroda	470.33	Dharla	348.57
Karnali	519.41	Gandhak	686.31
Ghagra	492.32	Saptokosi	280.12

In this study, the base model (Bangladesh model) rivers were not digitized as this model was already developed and cross sections chainage already assigned (see Siddique-E-Akbor et al., 2011 for further details). Only the rivers located upstream of the base model domain were digitized. The newly developed river network has been compared with an alternate data source to justify the importance of digitized river network. River network developed from the SRTM DEM was compared with the newly developed network. SRTM DEM derived river network has shown significant variation with the recently digitized river network – a humbling lesson that was learned as part of this study.

Table 2: River length that included in the SRTM RAS model

RIVER NAME	MODEL LENGTH (km)	RIVER NAME	MODEL LENGTH (km)
Ganges	1909.90	Mahananda	129.19
Brahmaputra	809.89	Old Brahmaputra	248.62
Old Brahmaputra	248.62	Subansiri	216.48
Yamuna	1162.64	Kameng	121.36
Jamuna	216.96	Manas	126.90
Meghna	211.03	Dhansiri	155.60
Chambal	395.41	Kopili	194.03
Betwa	212.48	Padma	117.90
Ken	200.83	Surma	395.72
Son	343.89	Kushiyara	290.34
Saroda	185.28	Dharla	217.96
Karnali	93.78	Gandhak	360.70
Ghagra	492.32	Saptokosi	280.12

Figure 2.13 : Comparison between SRTM DEM generated river network (Blue color) and newly (corrected) digitized river network (Red color)
As shown in the figure, the red line represent the digitized river network from Google Earth whereas the blue line represent the SRTM DEM generated river course.

The Figure 2.13 shows a comparison between the digitized river network (Red line) and the SRTM (Blue line) derived river network. The left panel shows that the SRTM DEM derived

river network fails to capture the main stream location while right panel shows that the digitized river network correctly pick the main stream.

2.4.2 Non-SRTM River Bathymetry Data

Two procedures were followed to develop river bathymetry data set to incorporate in the HEC-RAS model. The first one was based on the surveyed (in-situ) river bathymetry data that has been collected for the major rivers inside Bangladesh (the forecasting domain). The bed level for river bathymetry was calculated with respect to Public Works Datum (PWD) which was established by the Department of Public Works, Bangladesh. The PWD datum is 0.46 m below the Mean Sea Level (MSL) datum. Due to lack of data sharing attitude among the transboundary nations it is impossible to get the river bathymetry data for the upstream part of the rivers located within India. To overcome the limitations, one set of bathymetry data has been created by extending the existing surveyed river bathymetry data within the Bangladesh region for the whole GBM basin. Initially, the river slope or river bed profile was calculated from the rivers located within the Bangladesh. These rivers slope were gradually extended 'backwards' (interpolated) to upstream rivers in the India and included in the RAS model.

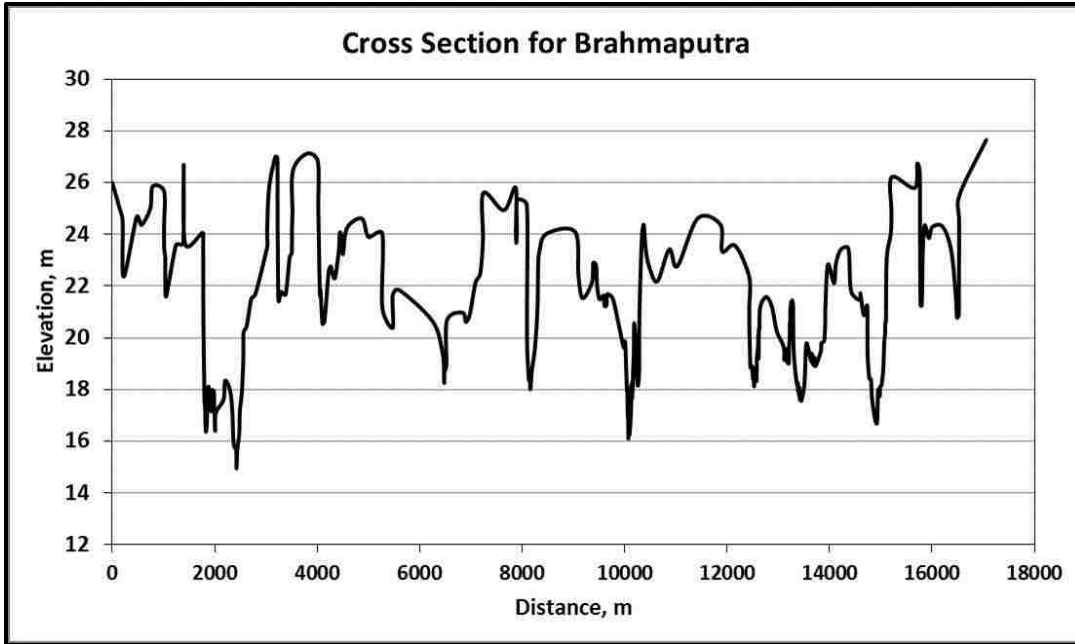**Figure 2.14 : Surveyed cross section for the Brahmaputra river (Jamuna) at the most upstream point for downstream flood prone region**
The cross-section elevation data have been calculated with respect to Public Works Datum (PWD) established by Department of Public Works, Bangladesh.
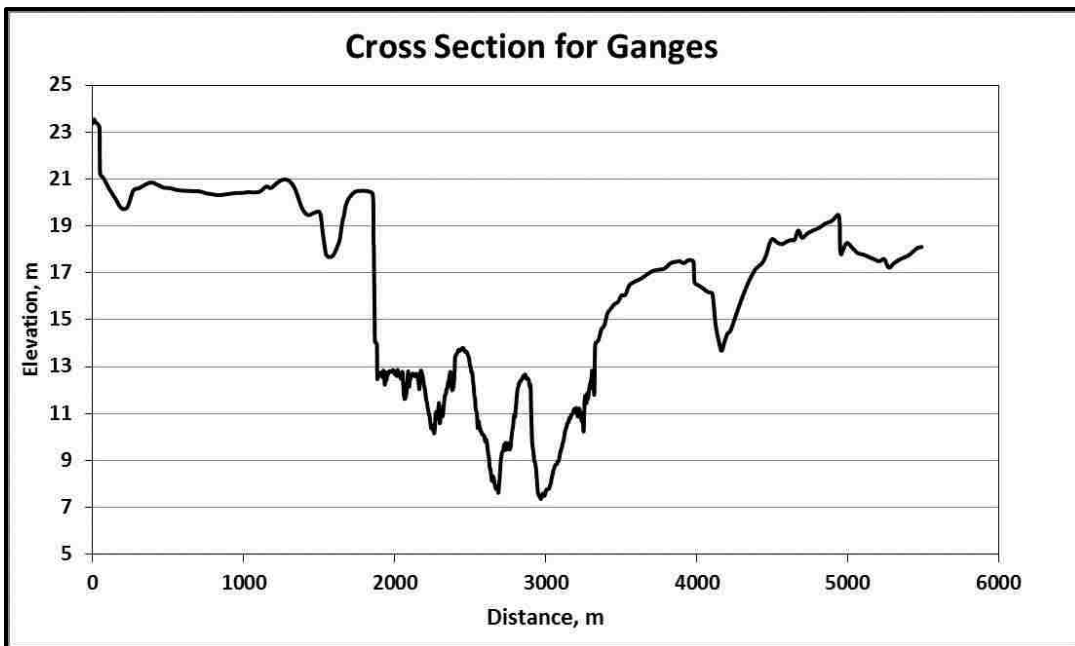
Figure 2.15 : Surveyed cross section for the Ganges river at the most upstream point for the downstream flood prone region.

Geographical setting of Ganges and Brahmaputra rivers are such that after collecting flows from its tributaries it enters Bangladesh. As a result, most upstream surveyed river cross section of Bangladesh part has been considered as the lowest river cross section for the Indian side. Figure 2.14 and Figure 2.15 shows the two prominent cross sections for Ganges and Brahmaputra river.

2.4.3   SRTM River Bathymetry Data

In order incorporate more reliable bathymetry data into the HEC-RAS model SRTM DEM has been utilized. For this purpose, river slope from SRTM DEM was extracted and incorporated to construct another setup of hydrodynamic model. SRTM is a global scale and high resolution Digital Elevation model from which land surface as well as water surface elevation can be extracted. This satellite mission used C-band and X-band radar interferometer to capture elevation from space and the data is freely available on the internet. Ninety meter (90m) resolution digital elevation model has been used in this research work. The work has been done to acquire better river bathymetry data that might be helpful to improve model results. The option 'Extraction' under the 'Spatial Analyst Tools' of ArcGIS was used for acquiring the elevation data along the river network.
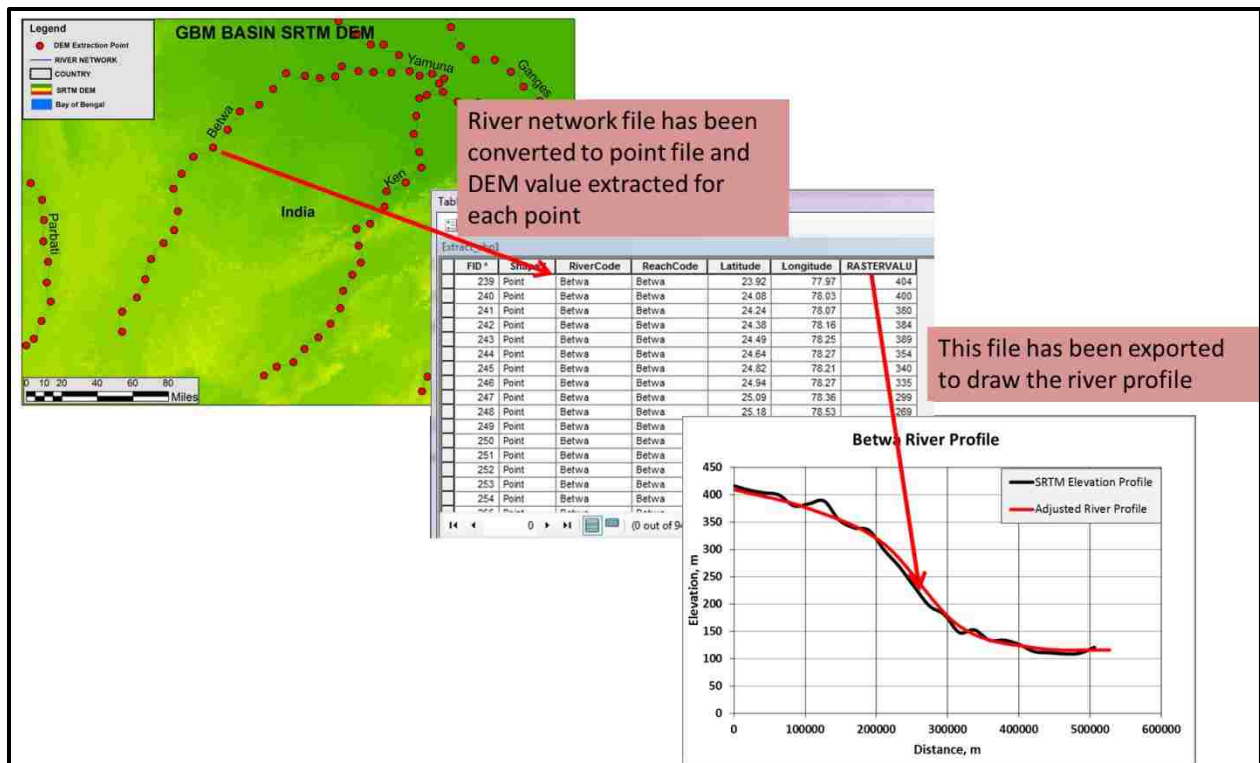
Figure 2.16 : Extraction of SRTM elevation value along the river network

Herein, the assumption made is that the ground surface slope along the river is parallel to the river bed slope and thus should be a good alternative for adjusting river cross section (river bed) profiles. The slope has been calculated along the river by estimating elevation difference between the each river reach. This slope assessed from SRTM derived profiles (example shown in Figure 2.17) was then applied to adjust the river bed profile computed by the earlier 'backward' extension of river bed slopes measured inside Bangladesh. Figure 2.16 schematically shows the procedure that has followed to extract river slope. Initially the river network shape file has been converted to point shape file in ArcGIS environment. Later, by using Spatial Analysis Tool raster data (DEM value) has been extracted from the SRTM DEM. In the next phase, raster value has been exported and profile has drawn to finalize the adjusted river profile. In this way,

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the river bed slopes for upstream (ungauged) regions were made physically more dependable to the surrounding reality.
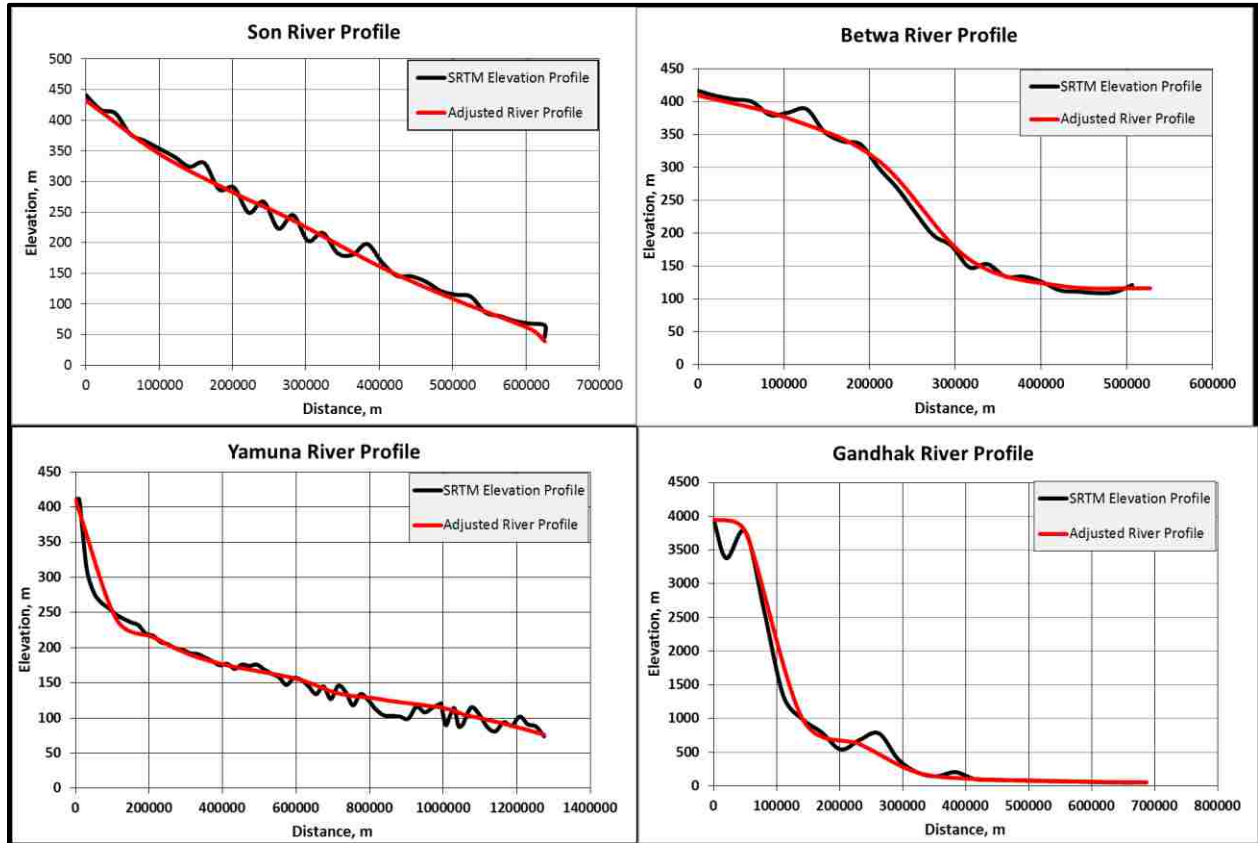
Figure 2.17 : Example of SRTM DEM extracted river bed profiles calculation and its adjustment for Son, Betwa, Yamuna and Gandhak Rivers
The black line is showing the extracted river profile from the SRTM DEM and the red line representing the profile that has been considered as the slope along the rivers. This profile has been adjusted with river bed profile computed by the 'backward' extension of river bed slopes measured inside Bangladesh. **Appendix A** contains adjusted profile for the other river.

2.4.4 Factorized Boundary Flow Data

The measured boundary flow data for the downstream region have been applied as upstream boundary data by 'factorizing'. All rivers located within Ganges and Brahmaputra basin area basically contribute their flows to Ganges and Brahmaputra river and later these two
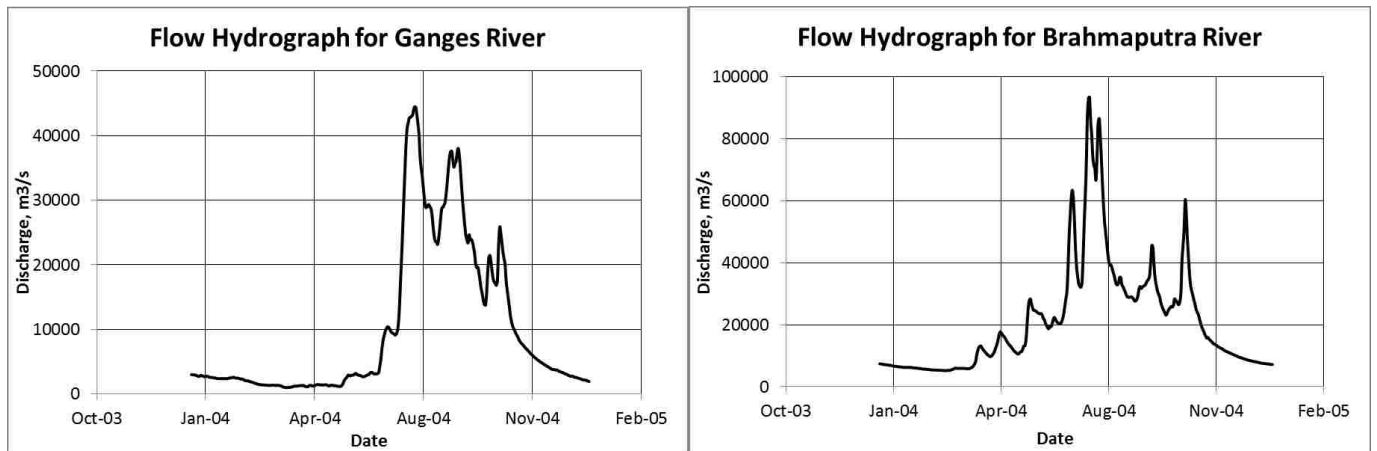
Figure 2.18: Flow hydrograph that has been used for generating Factorized Boundary Data

rivers enter Bangladesh. Hardinge Bridge and Bahadurabad Stations are the upstream points for Bangladesh to keep the record of historical flow for the Ganges and Bahadurabad rivers. In this study, the initial set of boundary data have been generated for the entire GBM basin from the RAS model for Bangladesh. These boundary (discharge) data were re-distributed 'upstream' (we call it 'factorized') in the upstream most boundary locations to all the upstream rivers according to the sub-basin area drained by each river located in the upstream ungauged region.

2.4.5 VIC Model Output as Boundary Data

Another set of boundary data were prepared from hydrological model generated flow to apply as boundary data for hydrodynamic model. The VIC hydrologic model simulated output has been organized to generate upstream boundary data for the GBM HEC-RAS model. Simulated model results were compared against the observe river level data measured at Hardinge Bridge and Bahadurabad station inside Bangladesh.
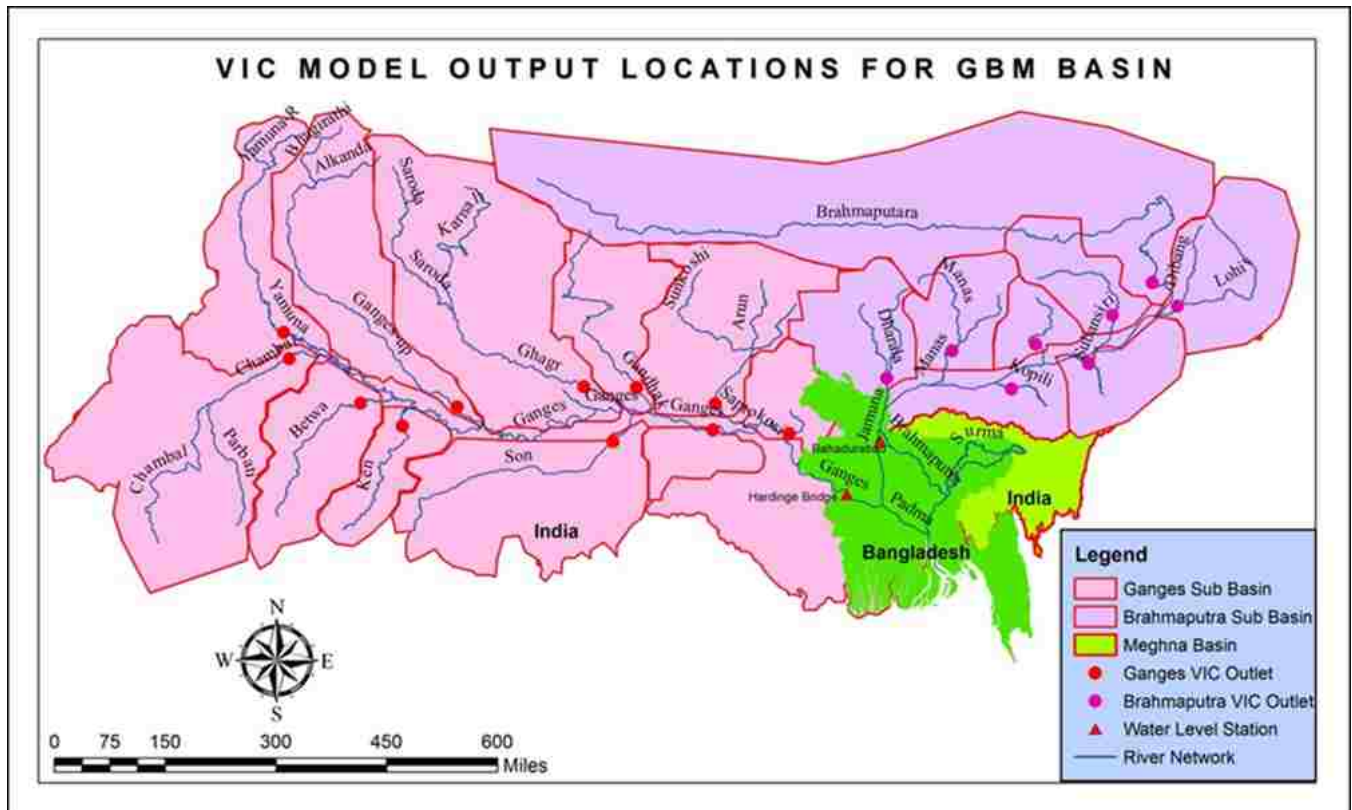
Figure 2.19 : VIC model generated stream flow for each sub basin
VIC model result for the GBM basin was subdivided into sub basins to capture lateral (tributary) flow contribution to the river system at the downstream confluence point. The areas bounded by red boundary line represent the sub basins. Red and pink circular points show the locations of each sub basin outlet points for Ganges and Brahmaputra basins, respectively. [Note: river 'Jamuna' is the local name for Brahmaputra inside Bangladesh]

VIC model transform the input rainfall into model simulated runoff over the catchment area. Due to presence of long monsoon period over the GBM basin, it is reasonable to consider transformation of rainfall to runoff and eventually stream flow over the basin area. Thus, the river model's simulation of water levels can be dynamically updated by incorporating this hydrologic contribution. The VIC hydrological model was therefore simulated for the entire GBM basin to produce daily fluxes (runoff and stream flow) at spatial scales ranging from 12.5km to 25 km (*Siddique-E-Akbor, et. al, 2014*).

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In this study, VIC model output has been redistributed sub basin wise to generate river boundary data to apply in GBM RAS model. Initially VIC model runoff flow directions have been derived from the SRTM DEM by using hydrological tool of ArcView. The flow paths were not confined to specific catchment boundary and needed to do some manual modification to
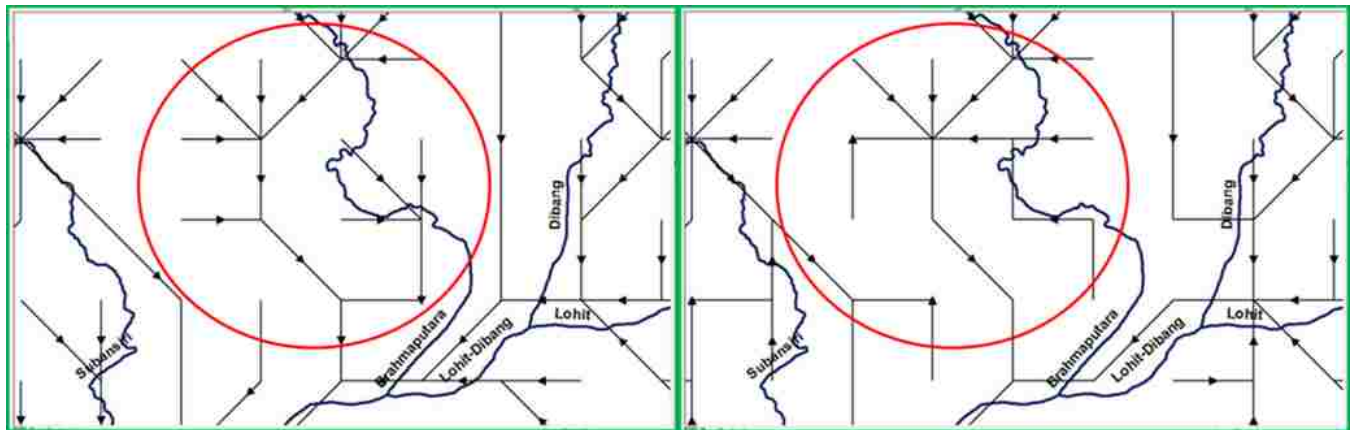
Figure 2.20 : VIC model generated flow direction readjustment

correct the flow direction. In this study, we subdivided the Ganges basin and Brahmaputra basin into some small sub basins according to the tributary rivers. The Ganges basin has been subdivided into eleven sub basin. Those are Chambel, Yamuna, Ganges, Betwa, Ken, Son, Mahananda, Saptokosi, Ganges Lateral, Ghagra, Gandhak. On the other hand Brahmaputra basin has been separated into eight sub basin. Those are Brahmaputra, Dhansiri, Dharla, Kamen, Kopili, Lohit, Manas and Subansiri. The correct route model simulated results have been applied to GBM RAS model as boundary data to capture water level and discharge at intermediate points. **Appendix B** contains the flow hydrograph for each sub basins.

2.4.6   Land Water Classification

Although the hydrodynamic model has been developed for the entire GBM basin but due to lack of surveyed data the model performance cannot be evaluated for the upstream ungauged
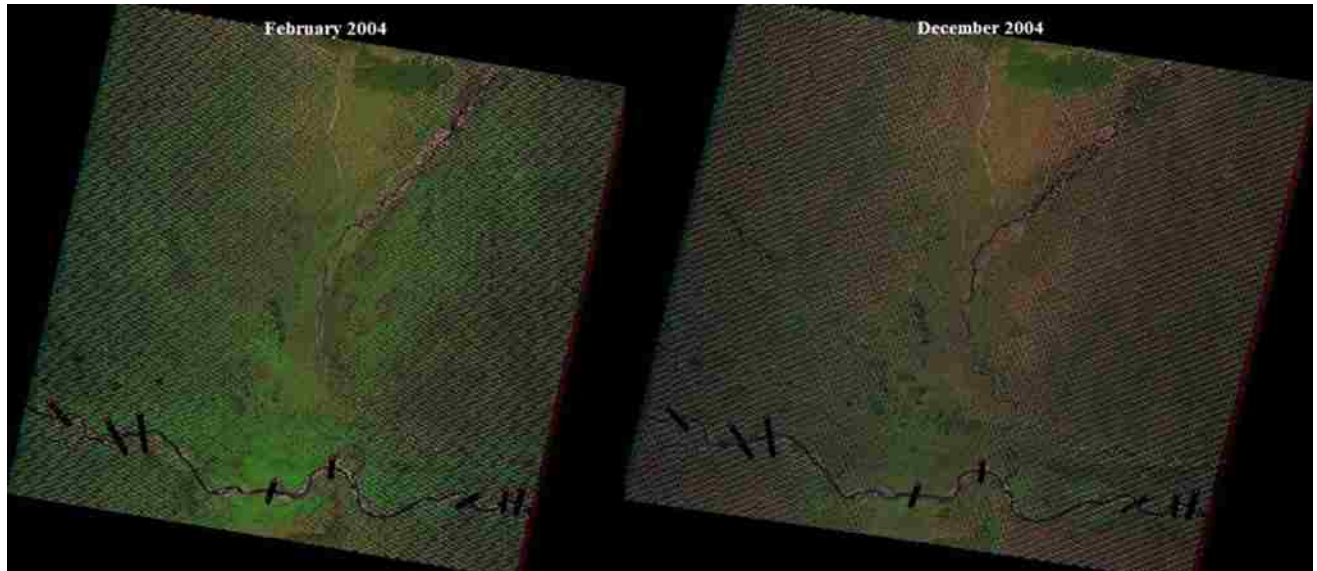
Figure 2.21 : LANDSAT Satellite image for the Ganges Basin area

locations. In this study, an alternate way was utilized to assess the model performance for the ungauged upstream river locations and also to develop a relationship between water level and river width. For this purpose, LANDSAT satellite images were downloaded (http://glovis.usgs.gov) and processed for further use. Two samples of downloaded data are shown in the Figure 2.21.

There are two techniques available to classify LANDSAT images. These are: 1. Supervised Classification and 2. Unsupervised Classification. In our study, we have applied unsupervised classification to distinguish land and water suggested by Moller Jensen (1990). The images downloaded for this study are captured by LANDSAT-7 satellite. The images consist of

several bands data that has been taken by Enhanced Thematic Mapper Plus (Shown in the Table 3).

Table 3 : Wavelength and resolution of bands for LANDSAT image

ETM+		
Landsat 7	Wavelength (micrometers)	Resolution (meters)
Band 1	0.45 – 0.52	30
Band 2	0.52 – 0.60	30
Band 3	0.63 – 0.69	30
Band 4	0.77 – 0.90	30
Band 5	1.55 -1.75	30
Band 6	10.40 – 12.50	60 * (30)
Band 7	2.09 2.35	30
Band 8	0.52 – 0.90	15

Following the Moller-Jensen (1990), guide line LANDSAT images have been processed to generate land-water classified images. LANDSAT band-4 data has been used to generate water- no water classification. For this purpose, ArcGIS Raster Calculation tool of Spatial Analyst Toolbar has been used. In the Raster Calculator window the following conditional expression has been executed:

Con (" File Name " < 45, 1, 0)

The executed command classified the land and water into 0 and 1 value respectively. Here value 1 represent water and 0 stands for land surface. The Figure 2.22 graphically represents the steps followed to classify images.
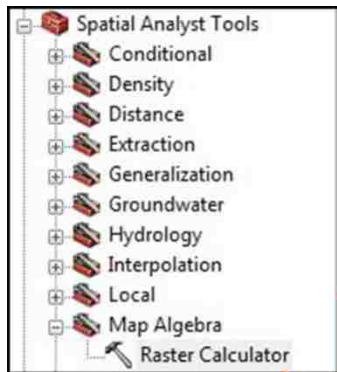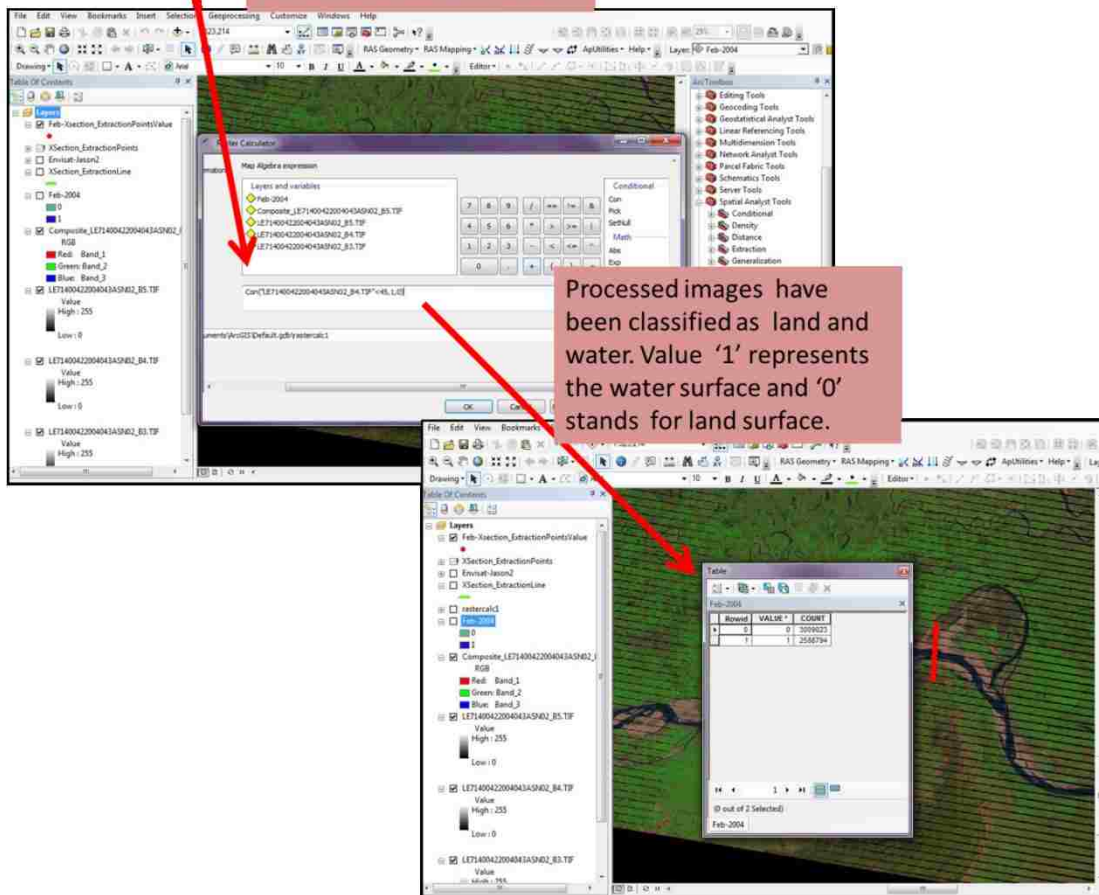
Figure 2.22 : Graphical representation of LANDSAT image classification technique

The generated output has shown in the Figure 2.23 where blue part represents the water body (parallel black line has occurred due to partial failure of LANDSAT-7 sensor quoted by NASA). This unsupervised classification of LANDSAT images have done for certain points. For

the same points, Envisat satellite based water level data were acquired to establish relationship

between LANDSAT generated river width versus ENVISAT satellite estimated water level data.

In addition, the satellite water heights provided an independent way to validate the performance

of the hydrodynamic model at upstream locations.
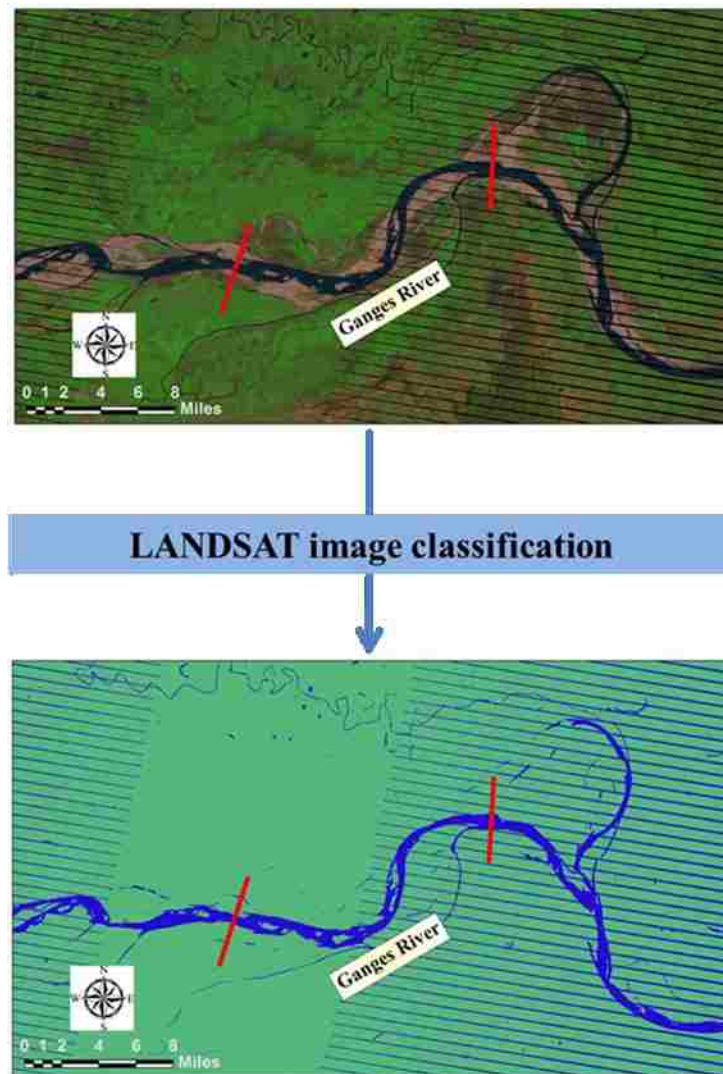
Figure 2.23: Classification of Landsat image on the basis of land-water classification mask
The upper panel shows the Landsat image in tiff format. And the lower panel shows the classified image where the thick blue curve line represents the Ganges River. Red lines indicate the location where the cross-sections have been extracted. Parallel blue lines are satellite sensor generated disturbance which causes some difficulties to measure the width of the river.

3. CHAPTER 3 – RESULTS & DISCUSSION

3.1   Hydrodynamic Models Result

The study has been conducted systematically to evaluate the performance of progressively developed three different versions of model setups on HEC RAS platform. The models were simulated for the hydrological year 2004 and model outcomes were tested at known downstream points with observations. For the calibration purpose most influential model parameter known as Manning's roughness coefficient has been applied within certain range. In this study, the values of Manning's roughness coefficient mostly varied in between 0.018 to 0.035. With the advancement of model development work one after another for the three different versions of model setups, the model outcomes also show systematic improvement from the previous one.

As we mentioned earlier three version of models are named as a) Non-SRTM RAS Model with Factorized Boundary Flow Data; b) SRTM RAS Model with Factorized Boundary Flow Data; c) SRTM RAS Model with Hydrologic Model based Boundary Flow Data. Initial model (Model 'a') development work has been done by extending the base model (Only Bangladesh domain) river network for the entire GBM basin. Later, bathymetry data was incorporated by 'backward' extension of river bed slope measured inside Bangladesh. Boundary data for newly developed model has been generated from the base model of Bangladesh by applying sub basin wise multiplying factor. For the second model setup (Model 'b') SRTM DEM derived adjusted bathymetry data have been applied keeping the same boundary data. In the final setup (Model 'c') VIC hydrological model simulated sub basin wise rainfall generated flow data have been used for hydrodynamic model boundary data.

3.1.1 Non-SRTM RAS Model with Factorized Boundary Flow Data

To ensure smooth model simulation this setup has very closely spaced river bathymetry data. Most of the cases river cross sections spaced at 20 km interval. The model has been simulated with computational time step 10 minutes and it has generated hydrograph at three hours interval. Simulated model results have been compared with the gauging stations observed water level data located at Hardinge Bridge and Bahadurabad within Bangladesh.

Figure 3.1 : Comparison of HEC-RAS simulated and observed river levels for model scenario a) Non-SRTM RAS model with Factorized Boundary Flow Data. [Note: river 'Jamuna' is the local name for Brahmaputra inside Bangladesh]

The Figure 3.1 shows the comparison plot for these two stations. For the Ganges part, simulated water level shows significant mismatch with the observed water level data. Basically model result failed to capture the trend of the recorded data. On the other hand, although model result for Brahmaputra basin area capture the trend well but it has systematic error in estimation. The model results can be outlined as underestimation for the Hardinge Bridge station whereas it showed overestimation for the Bahadurabad station. The root mean squared error (RMSE) values of river level simulation for Hardinge Bridge and Bahadurabad locations were 3.12 m and 1.002 m, respectively. The corresponding correlation values were 0.806 and 0.639.

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3.1.2 SRTM RAS Model with Factorized Boundary Flow Data

In order to improve the model performance more reliable river bathymetry data (SRTM) have been used in this setup. The model has been simulated with computational time step twenty minutes and it has generated hydrograph at three hours interval. The comparison plot between observed water level and model simulated water level has shown in the Figure 3.2.
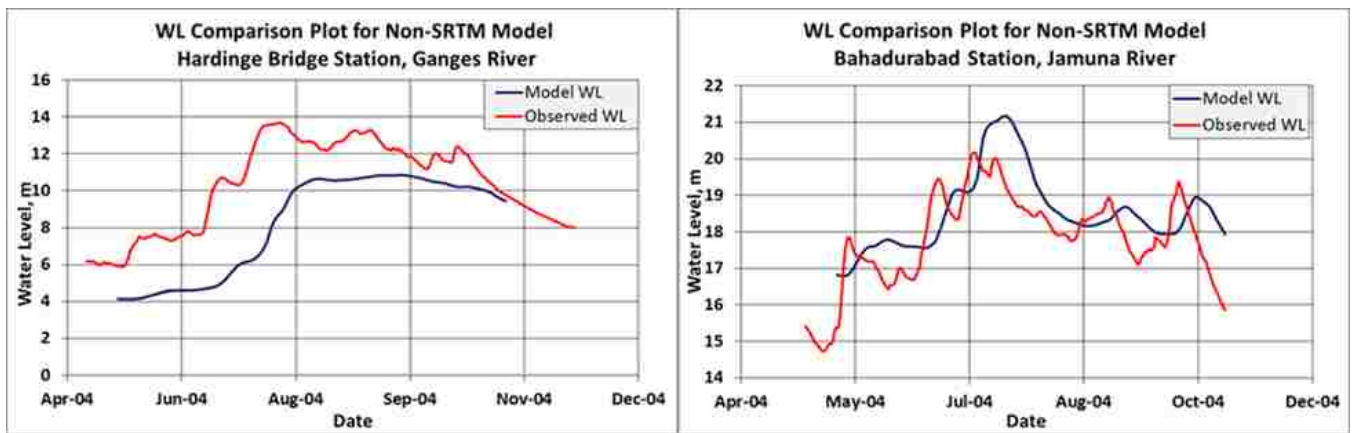

Figure 3.2 : Comparison of HEC-RAS simulated and observed river levels for model scenario b) – SRTM RAS model with Factorized Boundary Flow data that uses more realistic river bed slopes

Although the model has been simulated keeping the same boundary data, the new model setup has shown modest improvements in river water levels matching with observations. For Bahadurabad station (Brahmaputra river), the model result has shown almost similar pattern with the observed water level. RMSE for the both stations have been estimated. For the Hardinge Bridge station, calculated RMSE was 2.621m whereas for Bahadurabad station the RMSE was 0.944m. Table 4 shows the calculated RMSE and correlation value at the river locations for the model set ups a) and b).

Table 4 : RMSE and Correlation between model output and gauging station data for model scenarios a) and b)

Case	MODEL	Station	RMSE (m)	Correlation
Before (model a)	Non-SRTM RAS model with factorized boundary	Hardinge Bridge	3.12	0.806
		Bahadurabad	1.002	0.639
After (model b)	SRTM RAS model with factorized boundary	Hardinge Bridge	2.621	0.660
		Bahadurabad	0.944	0.703

3.1.3 SRTM RAS Model with Hydrologic Model Derived Boundary Flow Data

This is the third and final iterative setup where VIC hydrologic model generated sub basin wise flow data were applied as upstream tributary junctions for the SRTM based RAS model. The model outcome showed greatest improvement as it captured the dynamic nature of the flow much more accurately. The Figure 3.3 shows the comparison plots of simulated and observed river levels for model scenario 'c'. Model results captured the trend very well for both
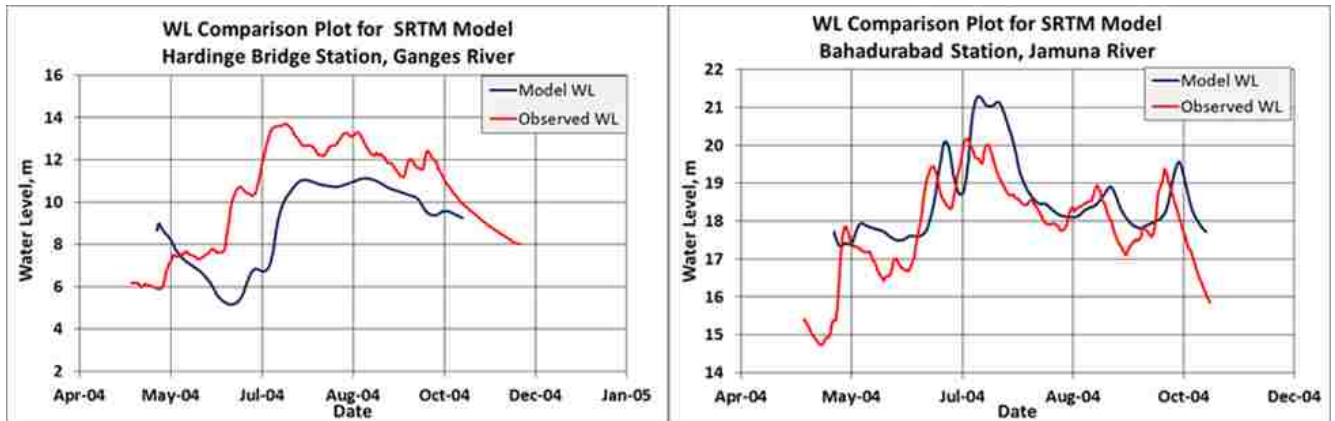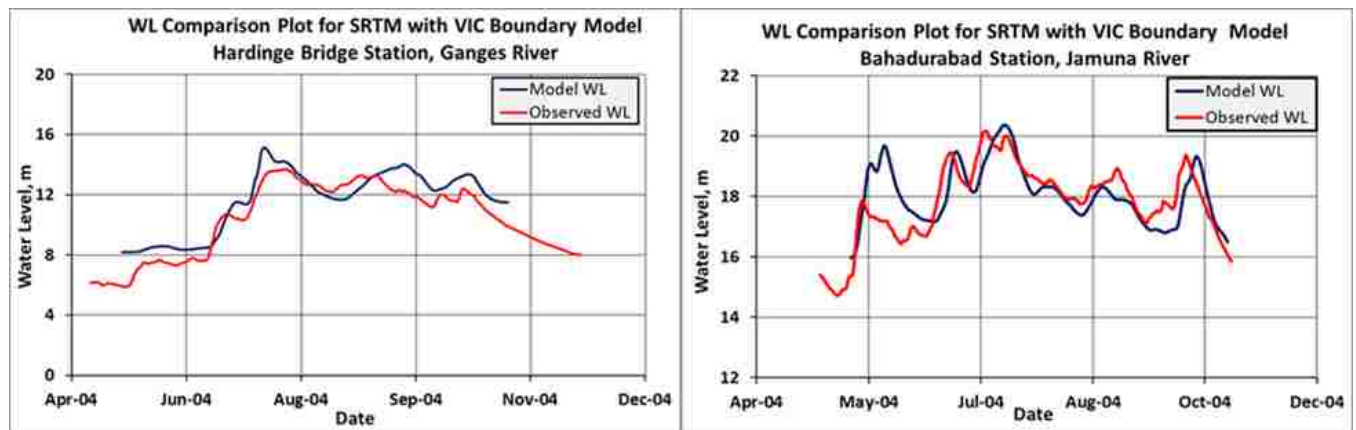

Figure 3.3 : Comparison of HEC-RAS simulated and observed river levels for model scenario c) - SRTM RAS Model with Hydrologic Model Derived Boundary

the stations. For the Bahadurabad station, the model result showed initial sharp rise compared to observed water level. This is likely an artefact due to the use of satellite precipitation data in the hydrologic model where false alarms (estimating precipitation during dry periods) or high bias

are common for the region. For further details on the performance of satellite precipitation accuracy, see Siddique-E-Akbor et al., 2014). Table 5 shows the calculated value of RMSE and correlation.

Table 5 : RMSE and Correlation between model output and gauging station data for model scenarios b) and c)

Case	MODEL	Station	RMSE (m)	Correlation
Before (model b)	SRTM RAS model with factorized boundary	Hardinge Bridge	2.621	0.660
		Bahadurabad	0.944	0.703
After (model c)	SRTM RAS model with hydrologic Model derived Boundary	Hardinge Bridge	1.066	0.934
		Bahadurabad	0.817	0.646

3.2 Comparisons at Ungauged River Locations with Satellite Observations

Although the model has been simulated for the entire GBM basin, its performance was evaluated only gauged location within the Bangladesh region. As a result, model performances for the vast upstream and ungauged basin area remain unknown. To address this issue, one set of radar altimeter satellite known as Envisat data have been collected. The data set consist of river heights for the period of 2002 to 2010. This data has been utilized to evaluate the performance of RAS model at upstream transboundary locations by comparing it with the model simulated water level.

Figure 3.4 shows the locations where the RAS model generated water level has been compared with the Envisat estimated water level. Envisat water level and RAS simulated water level data were not measured from the same datum. In order to make the comparison independent of the datum differences, anomalies were calculated. Anomalies of river heights

were calculated from the annual average river level and expressed in the form of percentage change relative to the maximum anomalies observed in the time series (positive indicates higher than average; negative indicates lower than average). The outcomes have been plotted in the Figure 3.5 and it showed anomalies agree reasonably consistent for the selected ungauged locations. Although the existence of systematic bias has been identified for some locations but the rising and receding trends of water levels appear to be picked up consistently. Overall, the

Figure 3.4 : Location of Envisat data points on the river Ganges in upstream (transboundary) region of India where in-situ data is unavailable.

anomalies tell us that a data assimilation framework that assimilates satellite altimeter height in the RAS model should achieve more accurate estimates of river height estimates at ungauged locations.

Another investigation was conducted to develop a relationship between water level and river width by utilizing Envisat satellite data. Initially, LANDSAT satellite images have been downloaded and processed to generate land water classified images. From the

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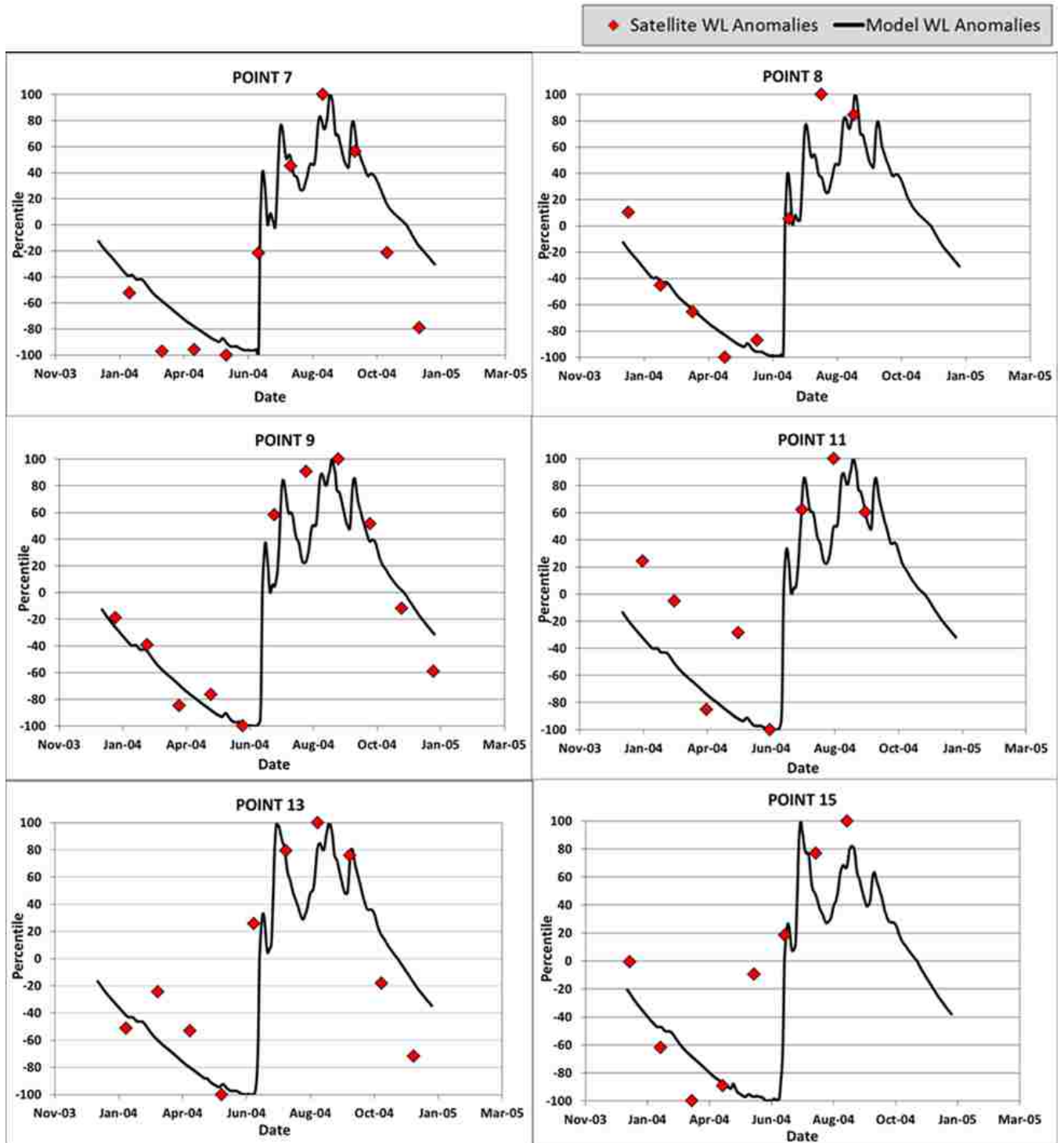
Figure 3.5 : Anomalies between Envisat (satellite) based water level and RAS model generated water level for the SRTM based VIC simulated model output data

processed LANDSAT images river width has been extracted at the same locations for which we

have Envisat estimated water level data. The river widths were acquired from images and plotted

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against the coincident water levels estimated by Envisat (here 'coincident' is defined as the 'closest in time'). This investigation has been conducted with a view to exploring the possibility of a relationship between LANDSAT derived river width and Envisat estimated water level. A consistent relationship would indicate that the two sensors with different orbit and sampling

Figure 3.6 : Relation between LANDSAT river width (x-axis) and Envisat water level (y-axis) estimation. Height is relative to the local geoid (EGM08)

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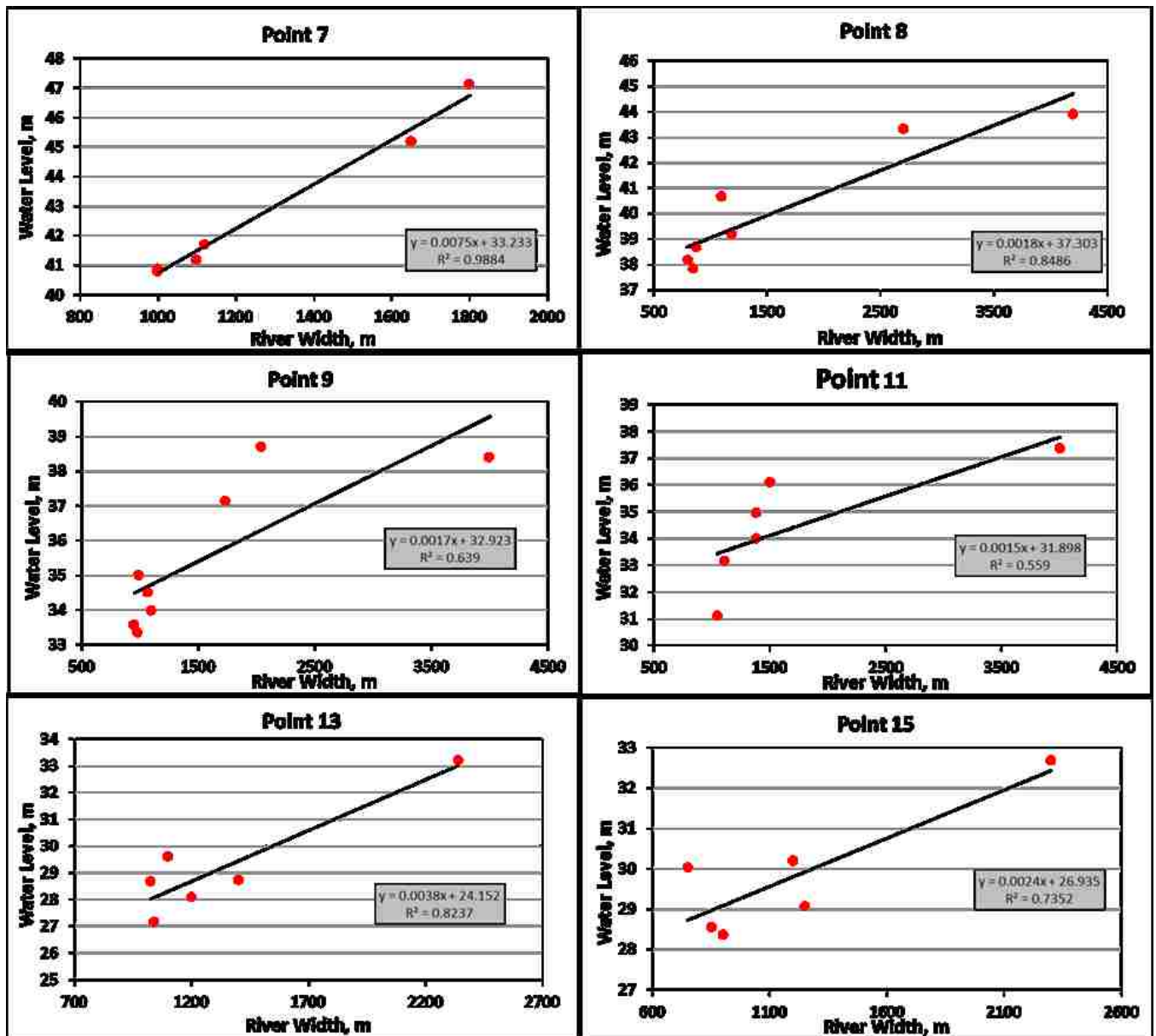patterns could be utilized as a 'team' to derive one hydraulic parameter like height (width) from the other, like width (height) and thereby enhance the RAS models even further at ungauged locations. The processed data have been plotted showing linear relationship with a view to justify trapezoidal relationship although some points have showed little variations. The outcomes of our study have been plotted in the Figure 3.6. Majority of the plots show very consistent relationship at many locations indicating very linear relationship (trapezoidal type cross section at points 7 and 8) and deep channels with wide floodplains (points 9 and 11). This correlation together with the previous agreement observed in height anomalies between Envisat and RAS model specify that satellite based height and width information from a visible and microwave constellation of sensors can be integrated routinely in a river modeling system.

4. CHAPTER 4 – CONCLUSIONS

4.1 Findings of the Study

Outcomes of our hydrodynamic model revealed that it is possible to progressively improve a hydrodynamic model set up with remote sensing data and lower the RMSE of water simulation significantly. It was noticed that the adjusted river bed slope by utilizing SRTM elevation data and hydrological model generated boundary flow data can significantly improve the simulation of downstream river levels. Hardinge Bridge Station located on the Ganges river yielded significant improvement by reducing the Root Mean Square Error from 3.12 m to 1.066 m whereas for the Bahadurabad Station located on the Brahmaputra river, RMSE reduced from 1.002 m to 0.817 m.

Simulated model results for SRTM RAS model with factorized boundary (model b) showed slight improvement compare to the Non-SRTM RAS model with factorized boundary (model a). These outcomes give the feeling that the importance of incorporation of SRTM bathymetry data has no significance. But calculations of water level anomalies over the vast ungauged region for the selected points have justified the importance of utilization of SRTM river bathymetry data.

SRTM RAS model with hydrologic Model derived Boundary (model c) simulated water level showed a sharp pick for the month of May whereas this trend was not visible within the observed water level data. An investigation was conducted to identify the reason behind this error. It has been identified that VIC simulated model results have the same false pick during that period and responsible for such deviation.

LANDSAT satellite images based estimated river width and Envisat measured water level data for selected locations have been plotted showing linear relationship with a view to justify trapezoidal relationship although some points have showed little variations. To develop more representative relationship more data need to process where plots can be drawn more accurately. The lessons learned in this study can be useful and replicable to other ungauged large river basins with populated river deltas. The following step by step rules are outlined below for a successful start to hydrodynamic modeling using remote sensing data.

RULE ONE – Utilize available historical facts, river morphology, local knowledge of rivers to factorize upstream flows at boundary conditions. Sub basin wise distribute (multiplying factor) the flow at upstream.

RULE TWO – Use extensive observed data or LANDSAT images (or any other platform in the visible wavelength –such as IKONOS/QuickBird) to verify and correct the river network.

RULE THREE – Apply SRTM (or any satellite) based surface elevation slope (along the river) to adjust river bed elevation and to correct river cross section profiles in the model setup.

RULE FOUR: Use 'coincident' height and width estimates from different satellites (radar/visible and later SWOT) to infer river cross section at ungauged locations. This can be a useful proxy for inferring river cross section shape and data assimilation of multiple satellites in river models.

RULE FIVE – Apply hydrologic model (rainfall-runoff model) simulated flows generated from sub basin as boundary flow for large basin and keep simulation period longer (>1 month) to address the rainfall-runoff transformation issues.

Scientists and researchers are currently working for many years to develop new techniques for acquisition of precise and reliable data from space. The way satellite technology is advancing makes us optimistic to find more practical ways to measure river discharge and water level data. Transboundary rivers and lakes which consist of more than 60% of global fresh water are desperately in need for a reliable and practical techniques to estimate upstream ungauged flow and water level to ensure durable water resource management. It is expected that the level of accuracy attained in this study could be further improved by integrating future satellite missions that will provide more comprehensive estimates or river height (altimeters; e.g. JASON-3, IceSat-2, Sentinels 3A and 3B), widths (LANDSAT, MODIS) or both (Surface Water and Ocean Topography Mission, Alsdorf et al., 2007). Future work should focus on how best to leverage these multiple satellites as a 'team' to advance surface water modeling where it is fundamentally impossible otherwise using in-situ data.

Another area of future studies is that of upgrading of river models for ungauged river basins using data assimilation of satellite-derived heights and widths as well as interpolation of river bathymetry by utilizing the hydrodynamic model. Data assimilation techniques should strive to develop practicable ways that agencies can apply while recognizing the diverse levels of sampling, data format, uncertainty and spatial coverage. In this study, a big focus was on developing simple and robust techniques that allow flood forecasting agencies to operate independently. As a result, it is hoped that this study will experience further advancement in technology transfer to impact the developing world if the above areas of further study are addressed.

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APENDICES

APPENDIX A

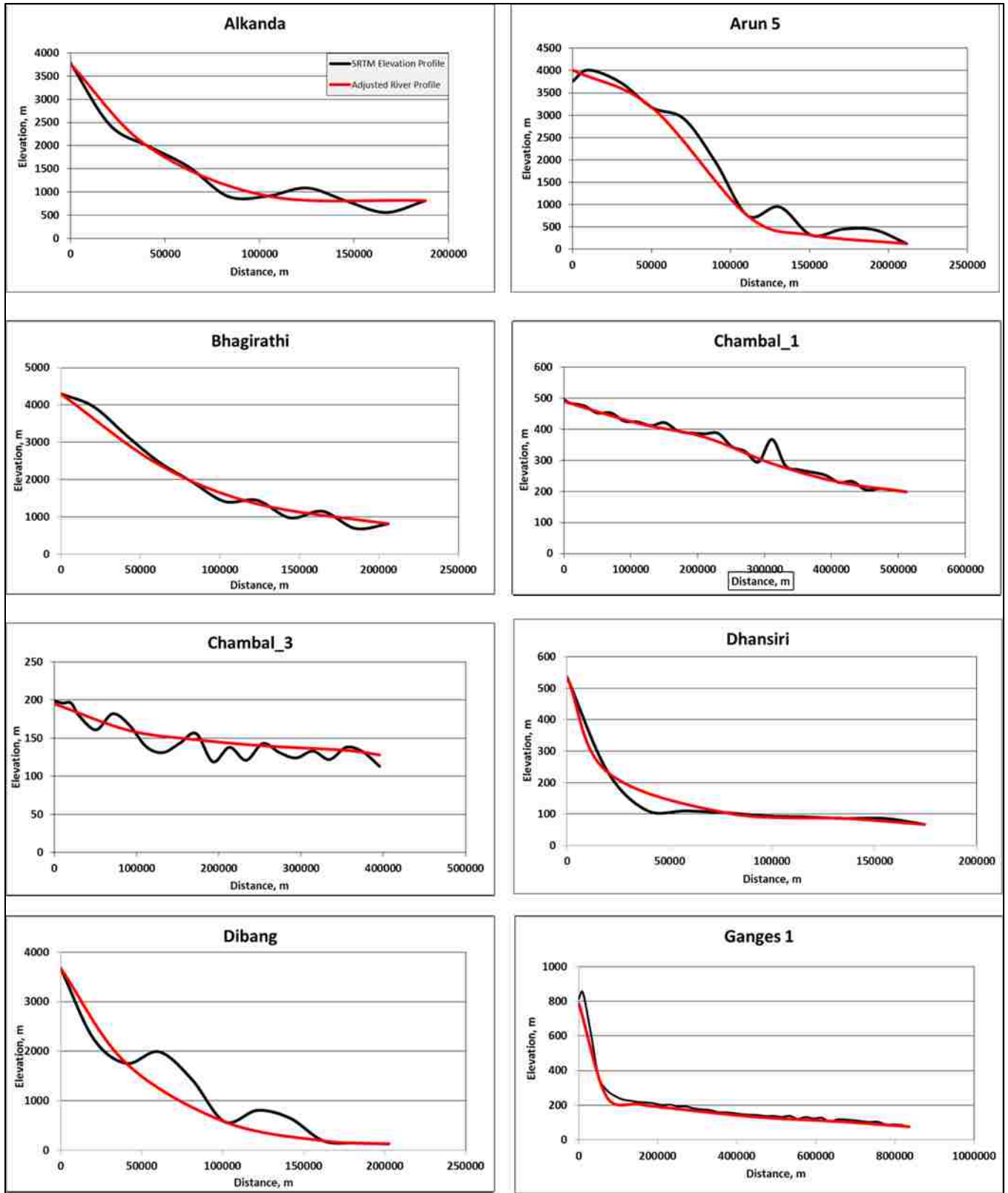# RIVER SLOPE EXTRACTED FROM SRTM DEM

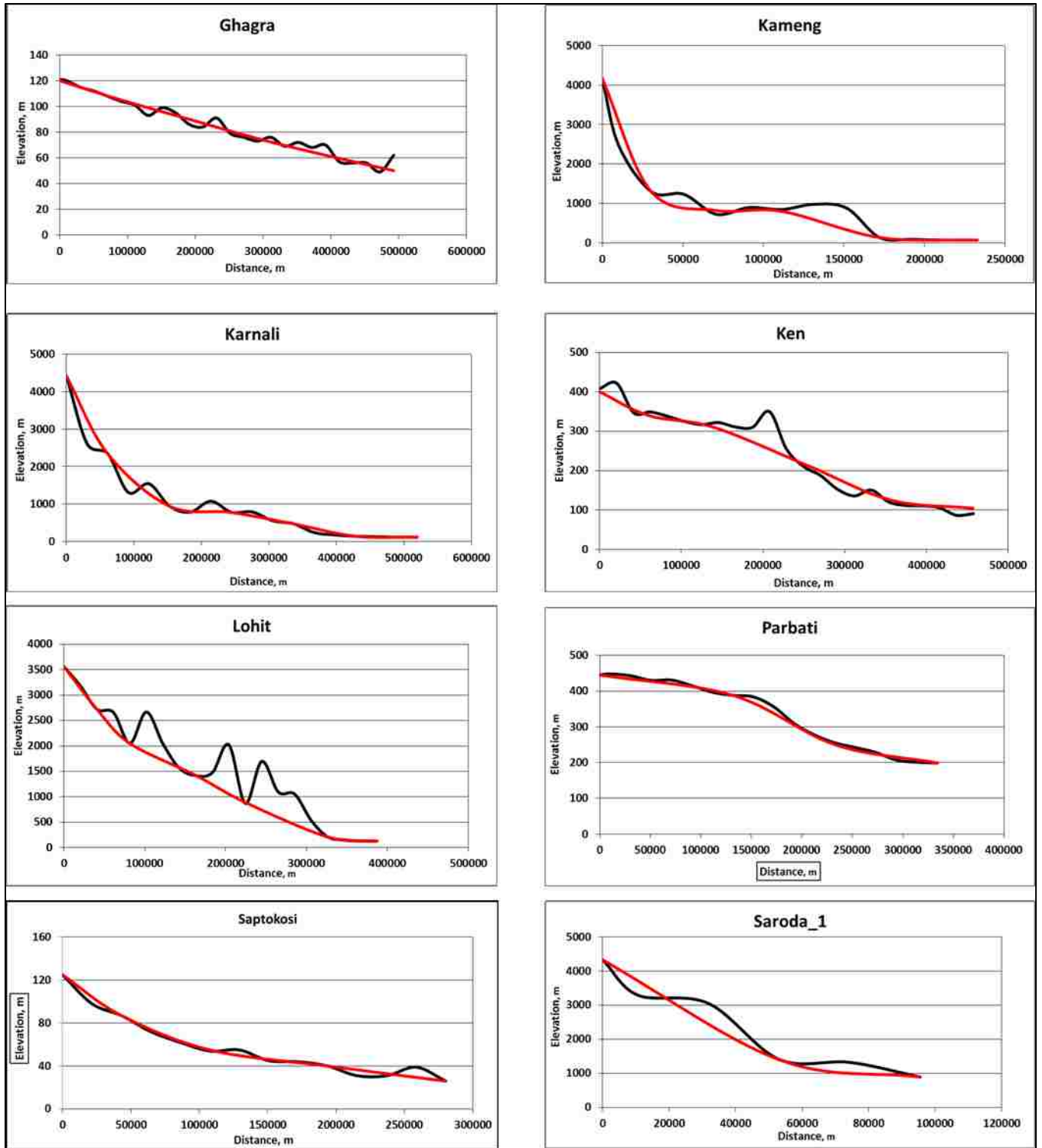Figure A1: Adjusted river profile for the GBM basin rivers

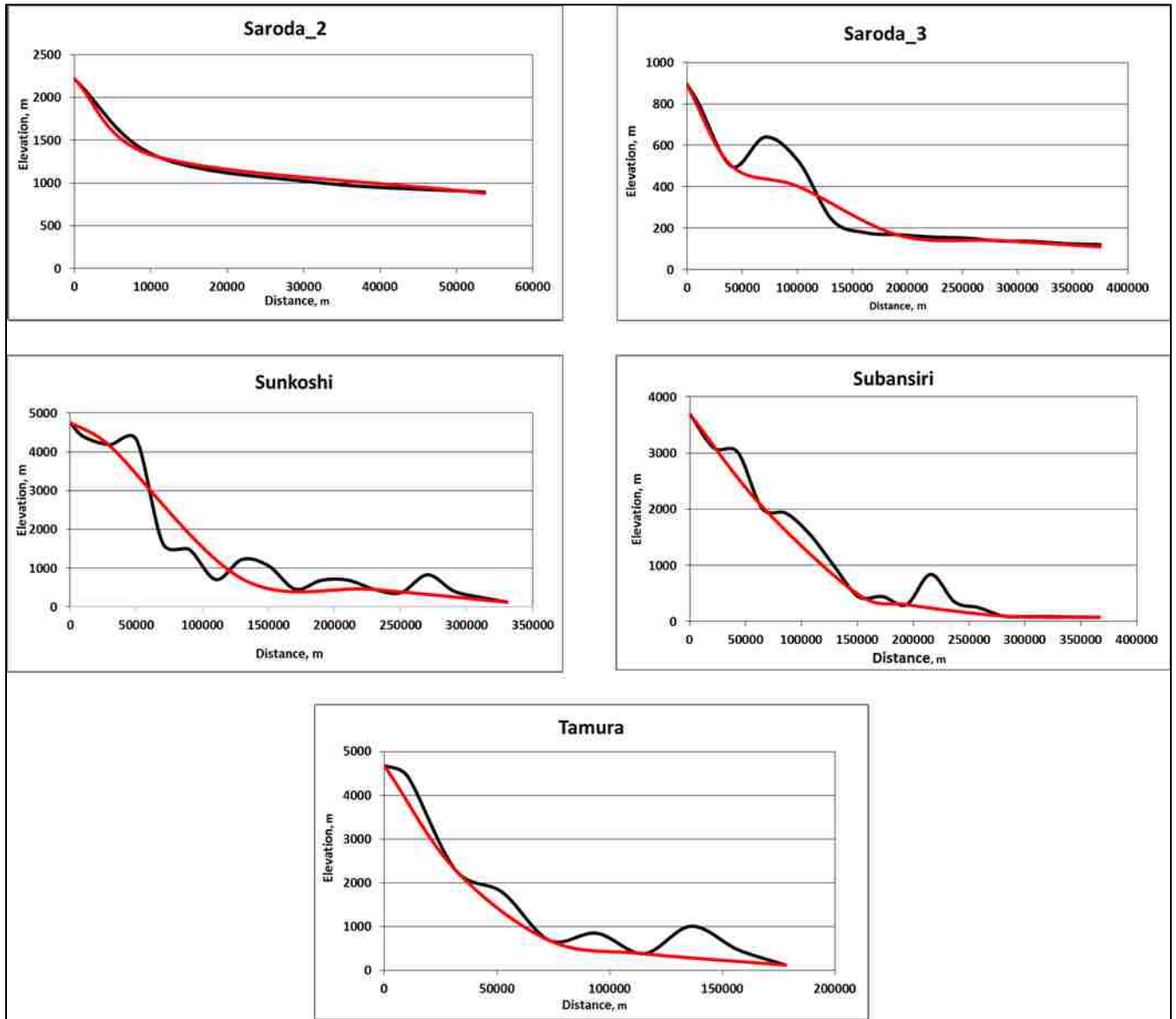Figure A2: Adjusted river profile for the GBM basin rivers

Figure A3: Adjusted river profile for the GBM basin rivers

APPENDIX B

**SUB BASIN RUNOFF GENERATED BY VIC MODEL AND MANNING'S
ROUGHNESS VALUE**
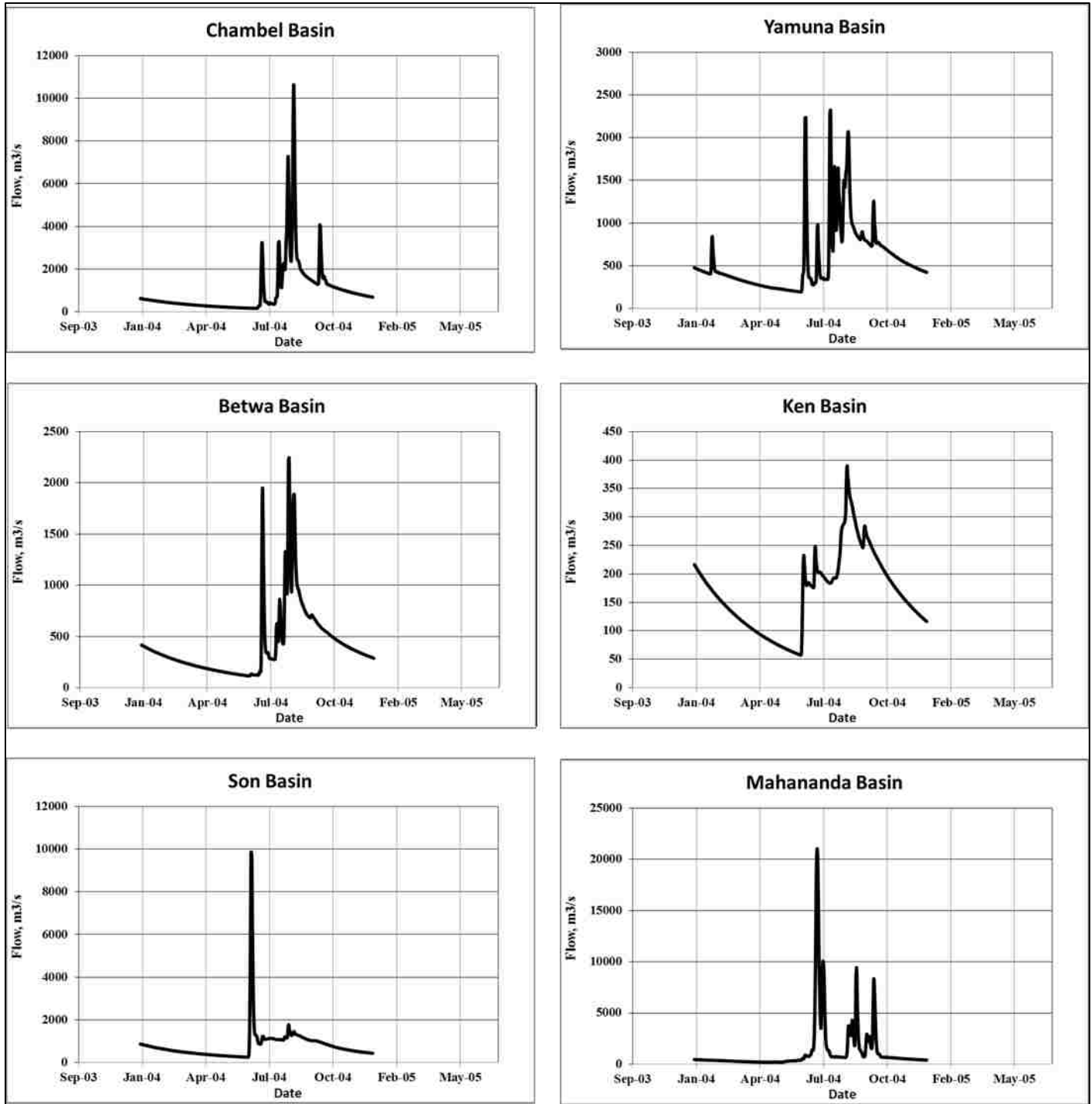
GANGES BASIN

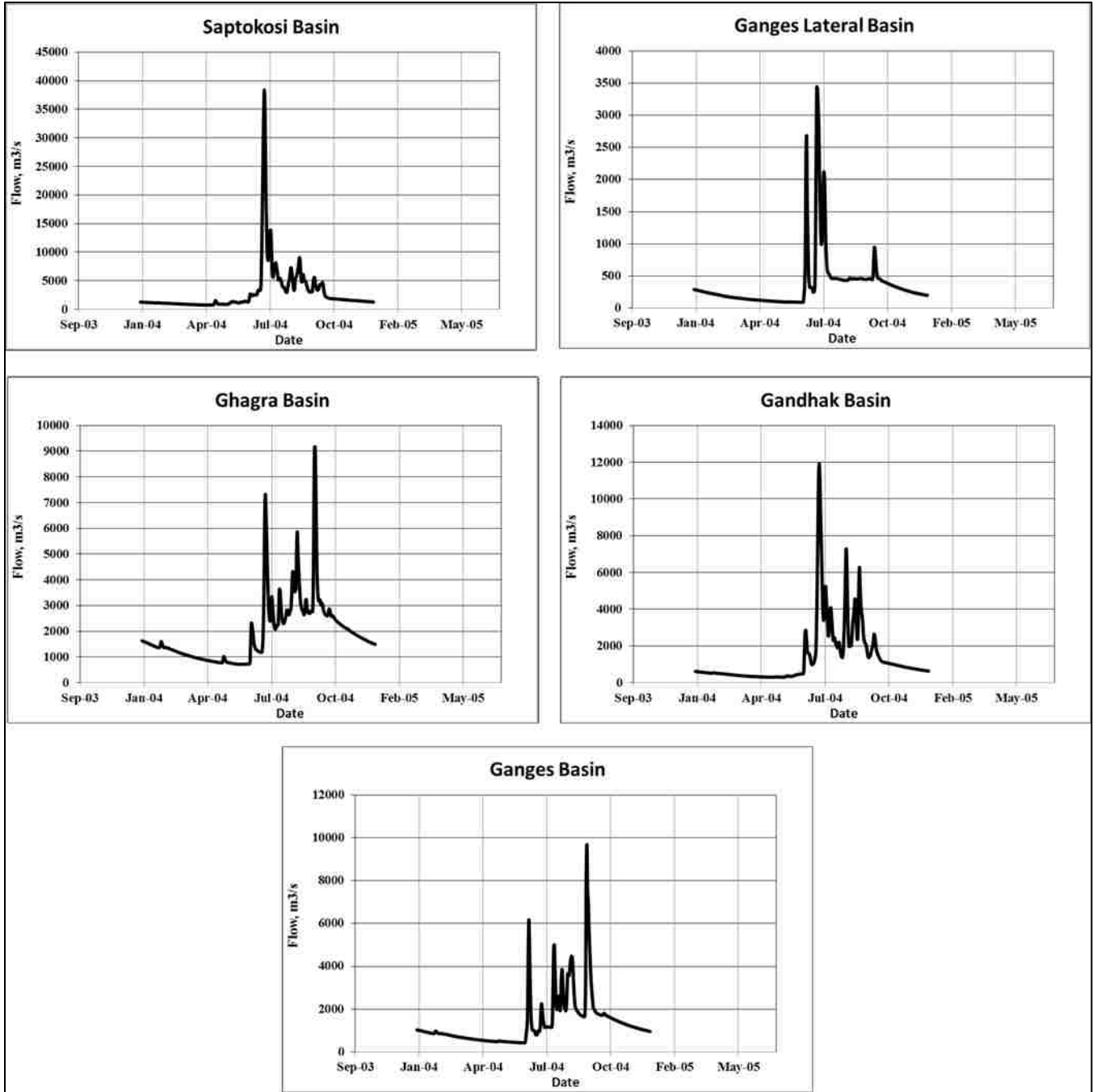Figure B1: Sub basin wise flow hydrograph for the Ganges Basin

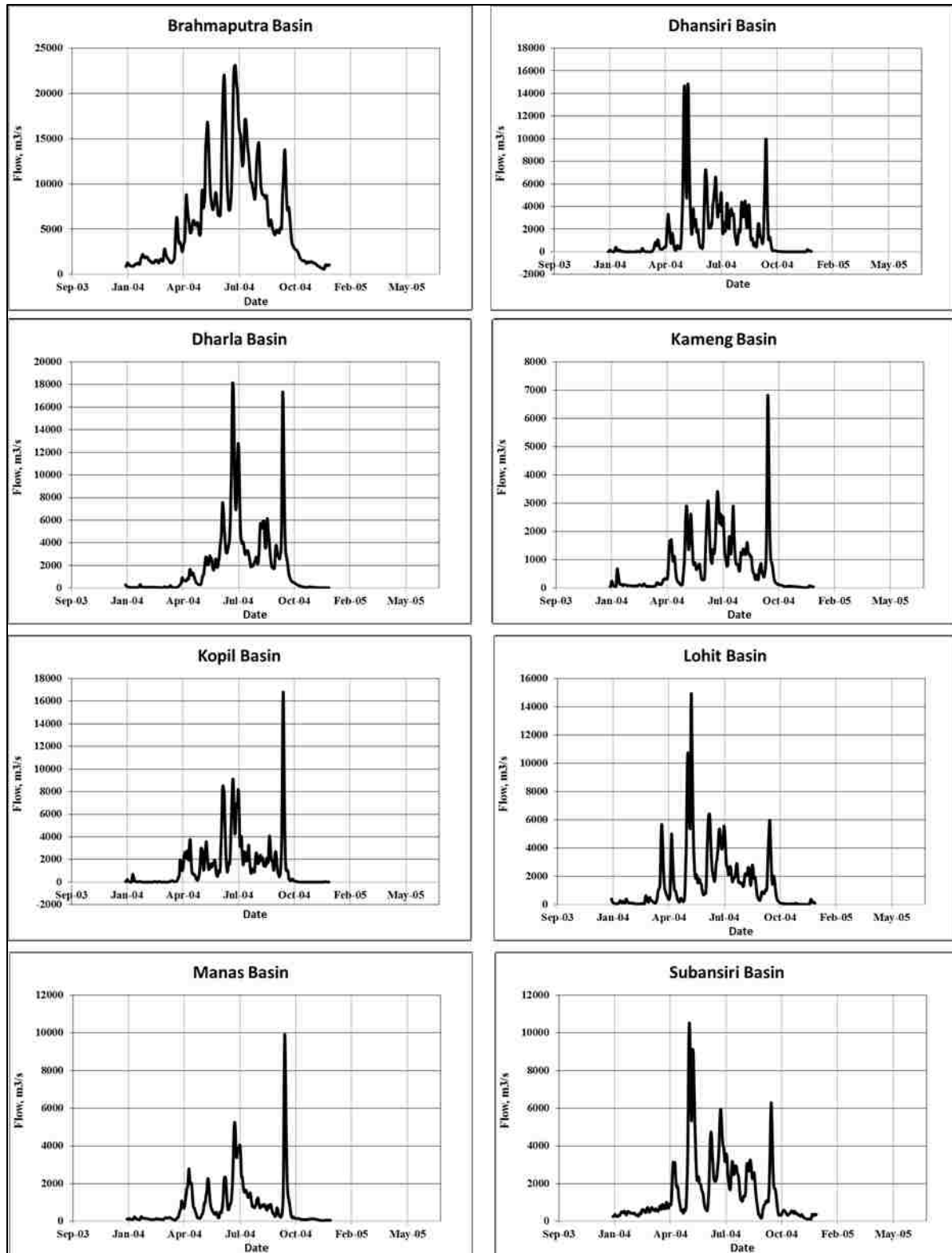Figure B2: Sub basin wise flow hydrograph for the Ganges Basin

Brahmaputra Basin

Figure B3: Sub basin wise flow hydrograph for the Brahmaputra Basin

Table 6 : Sub basin area for Ganges basin based on VIC model output

Name of the Sub Basin	Sub Basin Area (sq km)
Chambel	178260
Yamuna	80946
Betwa	68637
Son	120073
Mahananda	32141
Saptokosi	92846
Lateral	23716
Ghagra	182277
Gandhak	57591
Ganges up	107036
Ken	36236

Table 7: Sub basin area for Brahmaputra basin based on VIC model output

Name of the Sub Basin	Sub Basin Area (sq km)
Brahmaputra	312101
Lohit	72334
Subansiri	38541
Manas	40536
Kameng	20321
Dharla	55156
Dhansiri	38124

Table 8: Manning's roughness value (Manning's n) for the GBM basin rivers

River Name	Manning's n
Ganges	0.02 - 0.035
Yamuna	0.02
Chambal	0.02
Betwa	0.02
Ken	0.02
Son	0.035
Ghagra	0.02
Gandhak	0.035
Saptokosi	0.02
Brahmaputra	0.018 - 0.03
Subansiri	0.03 - 0.035
Kameng	0.03 - 0.035
Manas	0.02
Dharala	0.02
Kopili	0.025 - 0.035