MODELLING THE FLOOD BEHAVIOR OF UPPER MEGHNA RIVER

by

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LIST OF ABBREVIATIONS

AMSR	Advanced Microwave Scanning Radiometer
BWDB	Bangladesh Water Development Board
BIWTA	Bangladesh Inland Water Transport Authority
DEM	Digital Elevation Model
DTM	Digital Terrain Model
EOS	Earth Observing System
GBM	Ganges Brahmaputra Meghna
MODIS	Moderate Resolution Imaging Spectroradiometer
SRTM	Shuttle Radar Topography Mission
TM	Thematic Mapping
TRMM	Tropical Rainfall Measuring Mission
RADARSAT	Radio Detection and Ranging Satellite
WB	World Bank

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ABSTRACT

Floods are probably the most recurring, widespread, disastrous and frequent natural hazards of the world. Bangladesh is one of the worst flood-affected countries due to its unique geographical and geological condition. Geographically Bangladesh is surrounded by India from north, east and west and by Bay of Bengal from south. Geologically Bangladesh is situated in a depression area which is called Bengal Basin. This is why all major rivers meet in this basin. This is the one of the main reason of flood in Bangladesh. The north east zone of Bangladesh is one of the most susceptible areas which are prone to flooding. Flood forecasting and flood warning, flood hazard mapping and flood risk zoning are quite effective non-structural procedures in managing floods that decreases the risks and disasters which floods may cause.

In view of this an attempt has been made in the present work to simulate flood inundation for Upper Meghna River and also to verify the inundation with RADARSAT imagery. Flood patterns and inundation behavior has also been derived from satellite imagery. This study introduces the verification of inundation from 1D-2D hydrodynamic modeling and flood inundated area mapping for Upper Meghna River. Time series analysis of satellite imagery and model output has been analyzed to look for the inundation behavior in Upper Meghna River. DEM of 300m resolution is used to generate the various maps for the floodplain depended on Upper Meghna River. SOBEK 1D and 2D hydrodynamic module have been used for floodplain inundation modelling.

Results indicate that upstream of the Upper Meghna River in Brahmanbaria and Kishoregonj is more vulnerable to flooding compared to downstream. Flooding in the Upper Meghna follows a common pattern except 1998 flood. Brahmanbaria in the study area is vulnerable to flood inundation compare to other district.Model results also show that the upstream of the Upper Meghna River in Brahmanbaria and Kishoregonj is susceptible to flooding. Both model and satellite images show that left bank of the Upper Meghna River is vulnerable to flood inundation.

Chapter 1 Introduction

1.1 Background

South Asian country Bangladesh is located between 20°34´ to 26°38´ north latitude and 88°01´ to 92°42´ east longitude, with an area of 147,570 sq km. It has a population of about 156.6 million (WB, 2013). It has a border on the west, north, and east with India, on the southeast with Myanmar, and the Bay of Bengal is to the south (Figure 1.1). Geologically, Bangladesh is a part of the Bengal Basin, one of the largestgeosynclinals in the world. The Basin is bordered on the north by the steep Tertiary Himalayas; on the northeast and east by the late Tertiary Shillong Plateau, the Tripurahills of lesser elevation, and the Naga-Lusai folded belt; and in the west by the moderately high, ancient Chotanagpur plateau. The southern fringe of the basin is not distinct, but geophysical evidence indicates it is open towards the Bay of Bengal for a considerable distance. The formation and growth of the Bengal Basin is directly related to the origin and morphology of the Indo Gangetic trough, which itself is overlaid and filled by sediments thousands of metres thick (Rahman, et al., 1994). The broad geological features of the Bengal Basin and its prominent tectonic elements are Indian platform, Bengal foredeep, Arakan Yoma folded system, and the Sub-Himalayan Foredeep (MoEF, 2001). Other features are Rangpur Saddle, Dinajpur slope, Bogra slope, Hinge Zone, Barisal High, and Troughs of Sylhet, Faridpur and Hatiya, etc. The floor of the Bengal Basin consists of quaternary sediments deposited by the Ganges, the Brahmaputra, and the Meghna rivers, known together as the GBM river system, and their numerous tributaries and distributaries. The sediments are washed down from highlands on three sides of the Basin, particularly from the Himalayas, where the slopes are steeper and the rocks less consolidated. Over 92 per cent of the annual runoff generated in the GBM catchment area flows through Bangladesh, although it comprises only about 7 per cent of the total catchment (Coleman, 1969). This causes flood almost every year in Bangladesh.

1.1 Floods in Bangladesh

Bangladesh is a riverine country criss-crossed by around 405 (BWDB, 2012) rivers, situated in the confluence and delta area of the Ganga, the Brahmaputra and the Meghna rivers (Figure 1.1). A flat, low-lying topography is the most characteristic geomorphological feature: 60 per cent of the country lies below 6 mMSL (USAID, 1988). The average river gradient in the delta is as small as 6 cm/km (GOB, 1992a). The whole country consists of mainly low and flat land, except for the hilly regions in the northeast and southeast. Over 92 per cent of the annual runoff generated in the GBM catchment area flows through Bangladesh, although it comprises only about 7 per cent of the total catchment (Coleman, 1969). The country has to drain water from an area 12 times its own size (Miah, 1988) and (Bingham, 1991).The amount of water that annually reaches Bangladesh from outside the country would form a lake of the size of the country and of 10.3 meters depth (Ahmend, 1989). Therefore, the particular physical features of Bangladesh can be well understood only by looking over the national boundaries into the whole basin of the three major rivers. These are

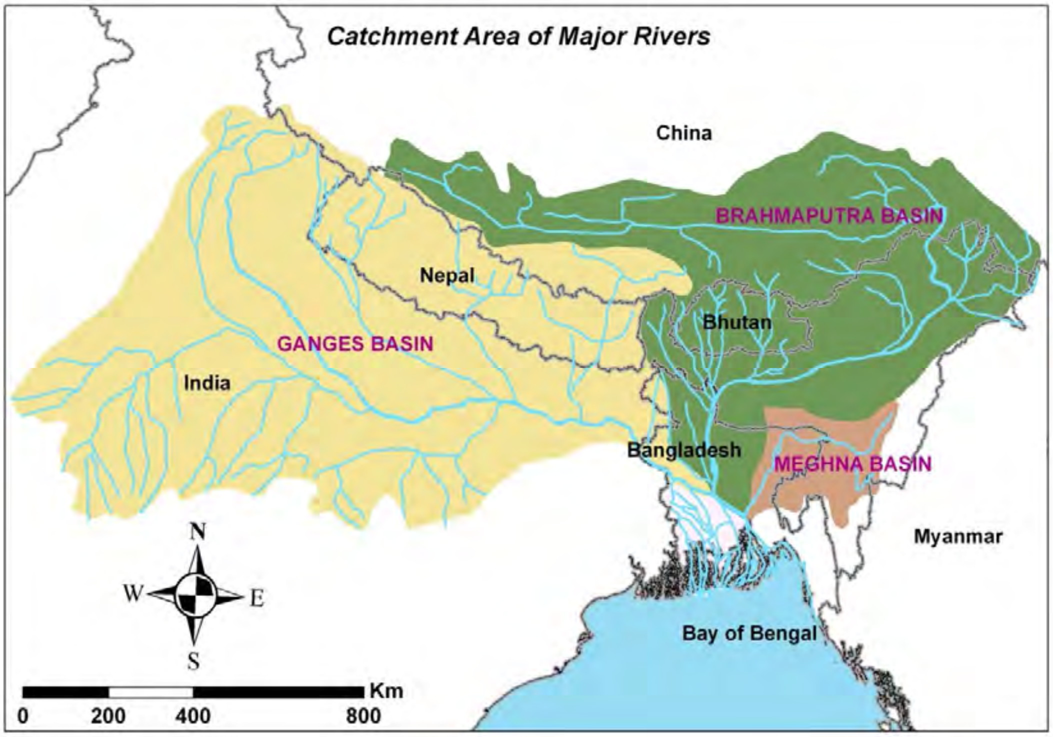

Figure 1.1: Catchment of major rivers. (Source: CEGIS)

the main reason of flooding which makes our country prone to flood. This why Bangladesh experiences flood almost every year and the flood inundation is about 26,000 km^2(around 18% of the country) each year(MDMR, 2013).During severe floods the affected area may exceed up to 75% of the country, as was seen in 1998(Hofer, et al., 2006). The floods have caused devastation in Bangladesh throughout history, especially during the years 1966, 1987, 1988 and 1998. The 2007 South Asian flood also affected a large portion of Bangladesh. In the other hand small scale flooding in Bangladesh is required for ground water replenishment, to sustain the agricultural industry; flood water fertilizes the land by the deposited sediment. The flood water is required to grow crop, so natural flooding replaces the requirement of artificial irrigation. Salt deposited on fields from high rates of evaporation is removed during floods, preventing the land from becoming infertile. The benefits of flooding are clear. But now flood events appear to become more extreme.

1.2 Scope of the Study

Upper Meghna River controls the flood in north east region of Bangladesh. It is one of the rivers that join with others to contribute to the development of the Ganges Delta and is an integral part of the Surma-Kushiyara River system. Upper Meghna River is a major river which drains out the flood water in north east region of Bangladesh. The large and seasonally deeply flooded basin in this region has significantly different physical environment than the plains of other regions of Bangladesh, is draining an area which generates the highest rainfall in the world through an outlet at south. Instead of saucer shape, Sylhet basin can be better described by the shape of a bathtub (CEGIS, 2011). The basin bottom is elongated in north south direction, with a deeper bottom and very steep slopes at northern edge (Figure 1.2). Slopes of both east and west edges are milder and vary from 15 to 30 cm/km with a flat bottom having several kilometers width. The rivers from east and west are entering into the basin flowing over the side slopes in east-west direction and these river turn towards the south while they are flowing over the flat bottom of the basin. Base level of this outlet, however, is governed by the monsoon flow of the Brahmaputra-Ganges, one of the largest river systems in the world. 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. The geological, hydrological and geographical settings generate a unique hydro-ecological environment in this region (CEGIS, 2011).Deep flood basin in this north east region of Bangladesh is called Haor (CEGIS, 2011). The main outlet to drain out the huge flow from these Haors is the Upper Meghna River.

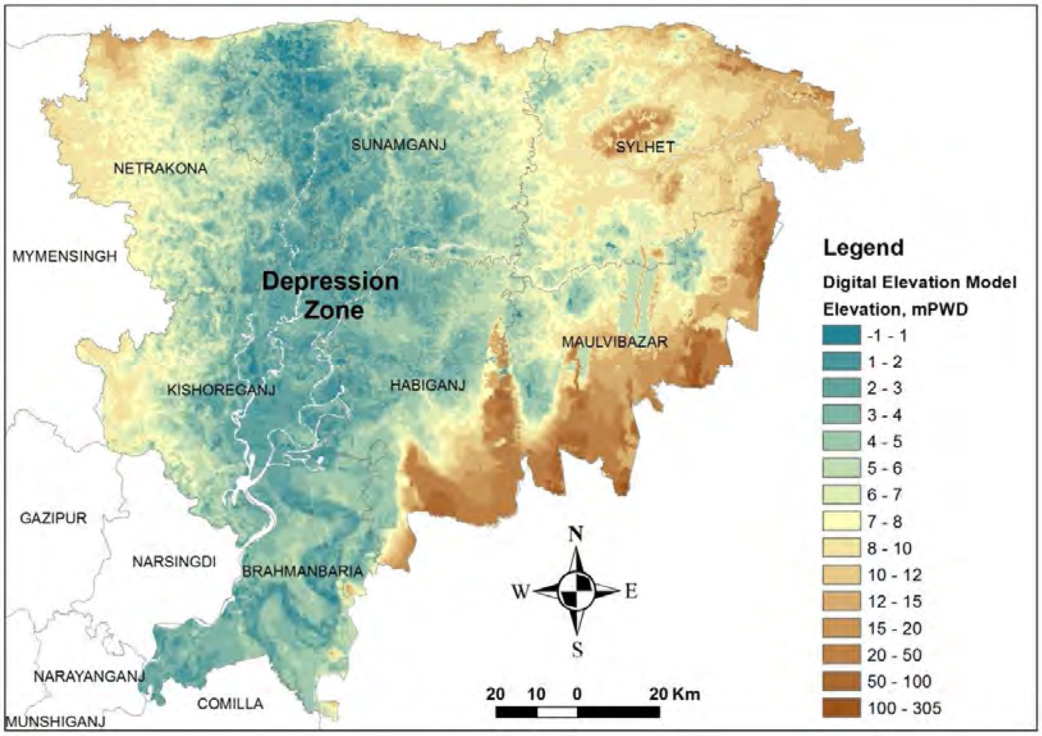

Figure 1.2: Depression Zone in North Eastern region.(Source: CEGIS, 2011)

Mathematical modeling is a method of simulating real-life situations with mathematical equations to forecast their future behavior. It is also an established, habitual, logical, or prescribed practice or systematic process of achieving certain ends with accuracy and efficiency, usually in an ordered sequence of fixed steps. Mathematical modelling allows finding out the most essential characteristics of the object studied and abstracting away from non-essential ones. Mathematical Modelling gives a possibility to formulate hypotheses and to receive new knowledge about the object which were unavailable before. Mathematical model can be used almost every sector in water resources engineering. Ground water model, Rainfall runoff model, Climate model, Underground drainage system model etc. are the model used in various sector in water resources engineering.

SOBEK 1D and 2D module have been used to simulate the flood of Upper Meghna River. It is a very unique tool to simulate overland flow. SOBEK's numerical solution scheme is very strong (Deltares, 2013) that's why the model simulates quickly and gives convenient results no matter how complicated the simulation is. It also takes less time to simulate model compared to other model available for over land flow modeling.

Radarsat satellite image will be used to analyze and compare flooding extant of Upper Meghna River. Radarsat satellite emits microwave energy pulse directly towards the earth surface and the SAR sensor measures the amount of energy which returns to the satellite after it interacts with the Earth's surface. Radarsat's microwave energy penetrates clouds, rain, dust, or haze, and acquires images regardless of the sun's illumination, enabling Radarsat to collect data under most atmospheric condition. Flood depth map for Upper Meghna River basin is a significant way to analyze flood behavior of Upper Meghna River. Flooding in different year will be modeled and flood depth map from the output of calibrated and validated model will provide the idea about flooding behavior of Upper Meghna River. All flood maps will be compared with the available Radarsat satellite image.

1.3 Objective of the Study

The objectives are as follows-

1. Analysis of flooding behavior of Upper Meghna River by using Radarsat satellite images of different year.
2. Setup of 1D and 2D hydrodynamic numerical model for Upper Meghna River and calibration and validation of the model.
3. Preparation of flood depth map of the study area from model output and comparison of the flood extent with Radarsat satellite images.
4. To observe the flood scenario in Upper Meghna River considering upstream withdrawal of water.

1.4 Organization of the Thesis

The whole thesis has been presented in six chapters are follows

Chapter 1 introduction discusses the current situation of the flooding problem in Bangladesh; scope, objective, possible outcomes of the study.

Chapter 2 contains the literature review which is the summary of all study conducted in connection with the study has been accumulated in this chapter.

Chapter 3 involves the detail of theory and the methodology required to conduct the study.

Chapter 4 is the description of the study area where the study has been conducted and also the important physiographic unit which lies within the study area.

Chapter 5 is results and discussion. All results and discussion from the analysis has been described in this chapter.

Chapter 6 is conclusion. Concluding remarks and recommendations have been listed in this chapter.

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Chapter 2 Literature Review

2.1 General

The Ganges River drains the Indian Shield and southern slope of the Himalayas; the Brahmaputra River flows through the northern slope of the Himalayas, and the Meghna River drains the western slope of the Indo-Burman Mountain Ranges. Ascending from the Indo-Gangetic plain (Quaternary deposits), from south to north, these units are (1) the Sub-Himalaya, representing the Miocene to Pleistocene molasses deposits of the Siwalik belts (Figure 2.1); (2) the Lower or Lesser Himalaya, composed of Precambrian and Paleozoic sedimentary rocks, crystalline rocks, and granites; (3) the Higher Himalaya, composed of schists, gneisses, and granites; and the (4) Tethys Himalaya and Trans-Himalaya, representing fossiliferous Cambrian to Eocene sedimentary rocks (shallow-water deposits, such as limestone, calcareous sandstone and dolomite), batholiths and volcanic rocks.

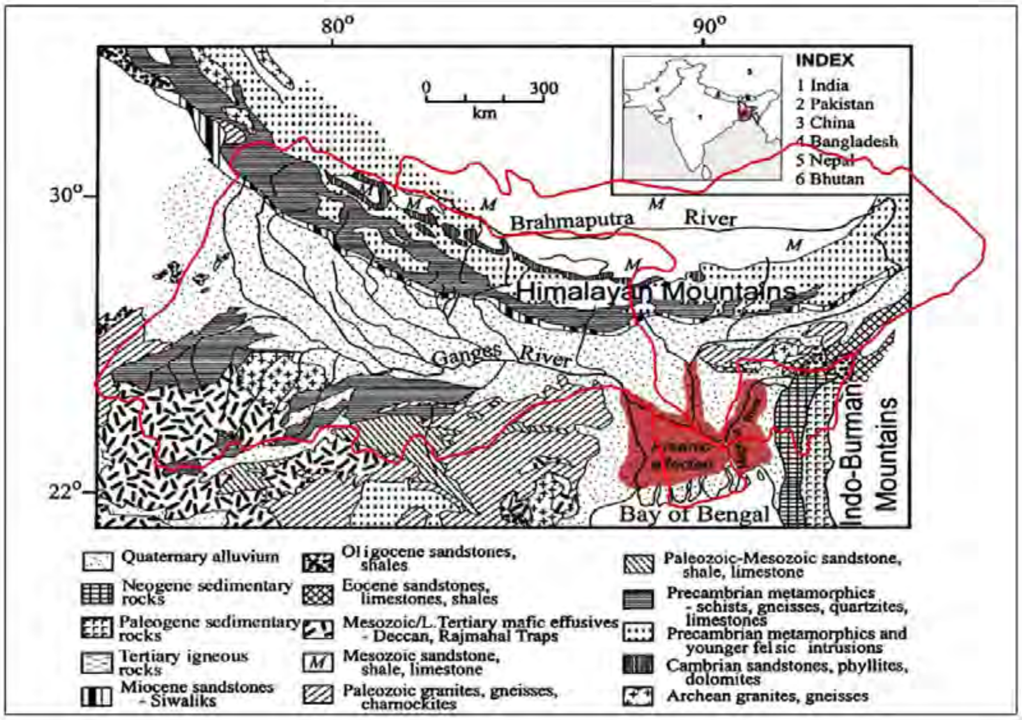

Figure 2.1: Generalized geological map. (Source: Uddin, et al., 2011)

Bangladesh is surrounded by India on the west, north, and east, on the southeast with Myanmar, and the Bay of Bengal is to the south. Bangladesh is a part of the Bengal Basin. There are four geomorphic and morphostratigraphic units e.g. the Tertiary Hills, the Pleistocene Uplands, the Tippera Surface and the Young Flood Plains and the Delta Surface (MORGAN, et al., 1959). Later on (Alam, et al., 1990) delta surface is divided in to 7 units (Figure 2.2) in Bangladesh.

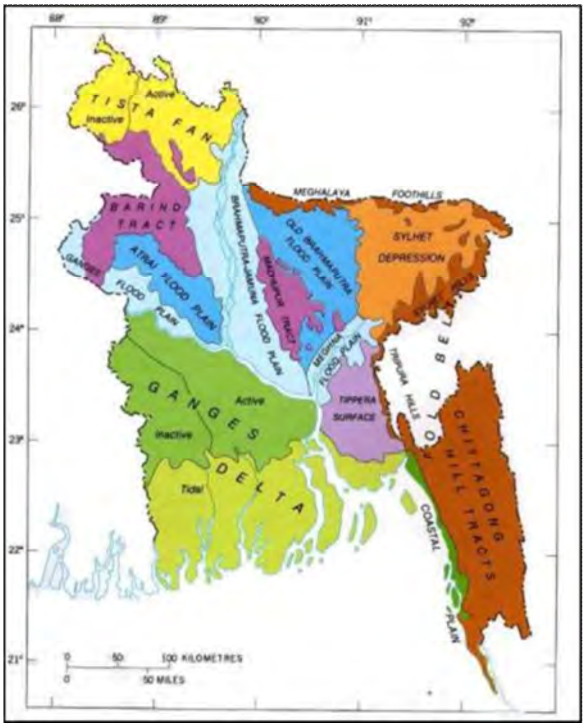

Figure 2.2: Geomorphic divisions of GBM delta, Bangladesh. (Source: Alam, et al., 1990)

2.1 Physiographical Setting

In order to understand the flooding conditions in Bangladesh, a short presentation of the principal physiographical units of the country is necessary (Figure 2.3). The following discussion of these units is compiled from (Islam, 1995) and (Brammer, 2000):

Hills:

Hills, tertiary and older, exist only in the east and south-east of the country, in the Comilla and Chittagong areas, with maximum elevations of approximately 700 mMSL. The folded Chittagong Hill Tract Ranges are densely forested and sparsely populated. Shifting cultivation is a typical agricultural feature in the area.

Pleistocene upland:

There are two major areas of pleistocene sediments within the Bengal basin. One is located to the north of Dhaka (Madhupur tract), with maximum elevations of approximately 15 mMSL, the other west of Bogra (Barind Tract), with maximum elevations of around 30 mMSL. These areas remain above the active floodplains and are usually not flooded during the rainy season.

The floodplain:

This land category occupies a large part of the country. The areas close to the major rivers host young alluvial lands with mixed sandy and silty soils. These lands continually change in extent and elevation owing to river bank erosion and new alluvial deposition. They are subjected to annual flooding by the rivers.

The deltaic plain:

The deltaic plain is drained by innumerable distributaries off the Ganga. It is characterized by a gentle slope and a complex river system, the river courses criss-crossing each other. The topographic features are similar to those of the floodplains.

Tidal floodplains:

These consist of almost level lands with numerous tidal rivers and creeks, and predominantly clayey soils. ‘‘Under natural conditions, the land can be mainly shallowly flooded with silty river water at high tides, either throughout the year near the coast or only in the monsoon season further inland. Flooding is by fresh water inland and in the monsoon season near the coast, but in the dry season by saline water near the coast. Following the empolderment of much of the land, flooding is now mainly by ponded rainwater’’ (Brammer, 2000).

Piedmont plains:

These areas are gently sloping alluvial plains at the foot of the hills, generally subject to flash flooding. They often have complex sandy and loamy soil patterns on higher land, grading into more silty and clayey soils in depressions.

Coastal plains:

The coastal plains in the Chittagong area occupy a narrow strip of land between the Chittagong Hills and the sea. The area is often subjected to shallow flooding and flash floods from the hills. It is also exposed to tropical cyclones and the associated storm surges. Ingress of saline water at high tides is a major handicap for agriculture.

The country consists of low and flat land formed mainly by the sediments carried by the Ganges and the Brahmaputra River systems except for the hilly regions in the north-eastern and south-eastern parts. From physiographic point of view, about 80 per cent of the land is floodplains with very low mean elevation above the sea level with the rest made up of hills and elevated lands (Ahmed, 2006). Topography of the country is characterized by very low differences in the elevation between adjoining ridge tops and depression centers, which range from less than 1 meter on tidal floodplains, 1 to 3 meters on the main river and estuarine floodplains, and up to 5 to 6 meters in the Sylhet Basin in the north-east (Rashid, 1991). Only in the extreme north-west land elevations exceed 30 meters above the mean sea level. There are two uplifted land blocks, known as the Madhupur and the Barind tracts, which generally have higher elevation: within 1 and 5 meters above the adjoining floodplains. In some places, however, they reach up to 25 meters higher than the adjoining floodplains. Hills are located along the northern and eastern borders of the country. These tertiary hills have higher elevation, some reaching over 1000 meters above MSL(Ahmed, 2006). These generally consist of very steep slope, but there are some areas with moderate or gentle slopes. Based on these physiographical units, it is evident that, large parts of the territory of Bangladesh are potentially flood-affected areas and that the flooding characteristics need to be regionally differentiated.

The range of the flood dimension in different years is surprising. According to the Bangladesh Water Development Board, in 1994 only 419 km^2 of flood-affected area

(0.28 per cent of the country) was reported, whereas in 1998 the area under floods exceeded 100,000 km^2 (68 per cent of the country).

Table 2.1: Return period of different flood dimensions in Bangladesh

Return period (years)	Affected area (% of the country)
2	2
5	5
10	10
20	20
50	50
100	around 60
500	around 70
Return period of 1998 flood: around 400 years	
Return period of 1988 flood: around 100 years	
Return period of 1987 flood: 20 years	
Return period of 1974 flood: 10 years	

(Source: Hofer, et al., 2006)

2.2 Types of Flood

The term ‘flood’(*bonna*) and ‘flooding’ (*barsha*) is two different word (Brammer, 2000). ‘Flood’ implies abnormal submergence of land, which may cause damage or loss of crops, property or lives (Brammer, 2000).The term flood is generally used when the flows in the rivers and channel cannot be contained within natural or artificial river banks. By spilling the river banks, when water inundates flood plains and adjoining high lands to some extent or when the water level in the river or channels exceeds certain stage, the situation then termed as flood (Rahman, et al., 2007). Floods can results from abnormally early of late inundation, abnormally high water levels, or unusually rapid rates of rise or flow of water on the land. On the other hand the ‘flooding’ merely implies submergence of land by water, such as floodplain inhabitants except in normal years and on which farmers base their cropping patterns (Brammer, 2000). The distinction is between floodwater (whether from rivers, rainwater or the sea) which is liable to cause damage and that which is not (Brammer, 2000).

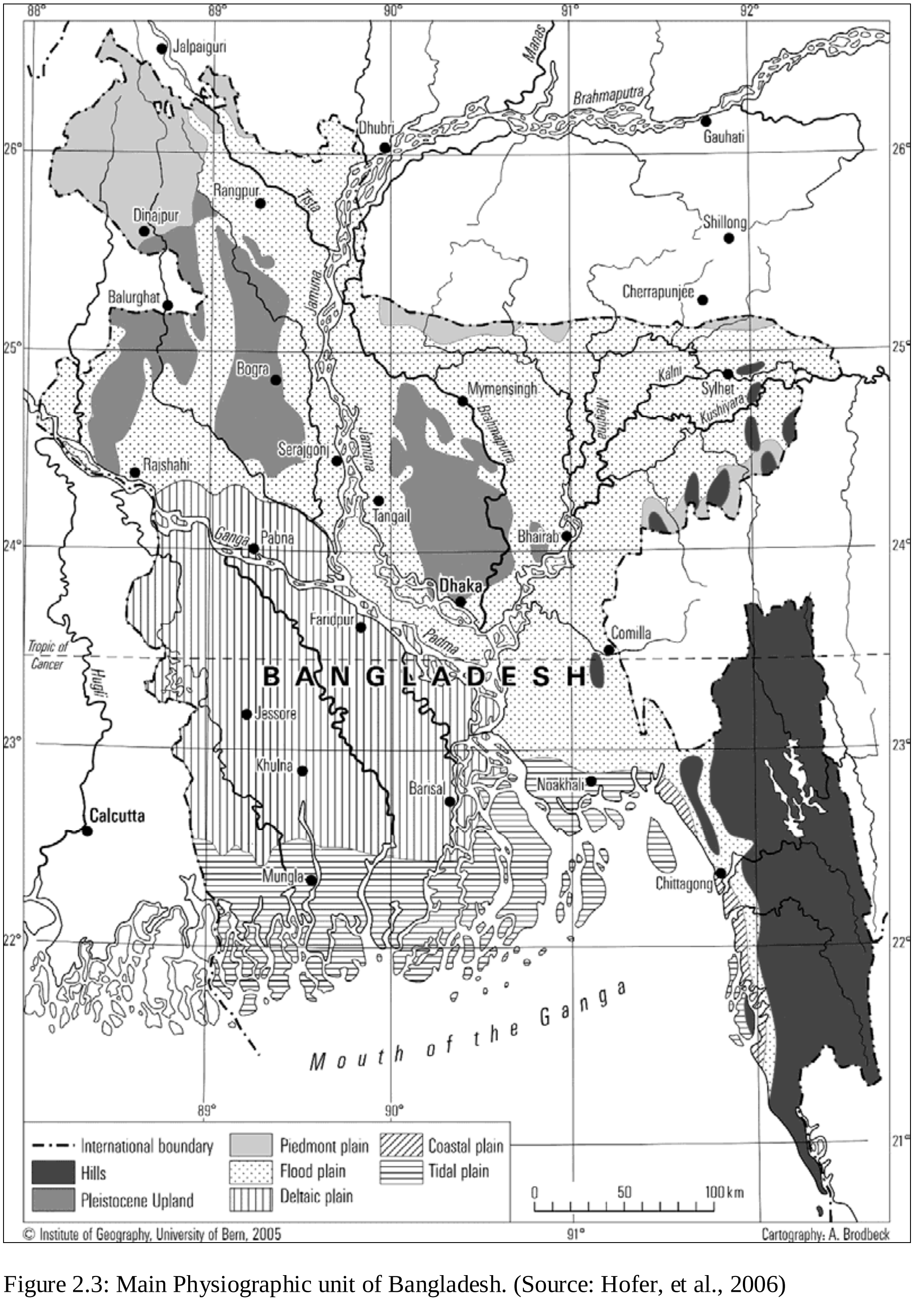

Figure 2.3: Main Physiographic unit of Bangladesh. (Source: Hofer, et al., 2006)

Generally four types of flood occur in Bangladesh (Brammer, et al., 1993). Normal monsoon floods of major rivers occurs with the water level showing a slow rise and fall with pulsations. River flood is a common phenomenon in the country caused by bank overflow. Of the total flow, around 80% occurs in the 5 months of monsoon from June to October (WARPO, 2004). A similar pattern is observed in case of rainfall also. As a consequence to these skewed temporal distribution of river flow and rainfall, Bangladesh suffers from abundance of water in monsoon, frequently resulting into floods and water scarcity in other parts of the year, developing drought conditions (IEB, 1998). Climatologically, the discharge into Bangladesh, from upper catchments, occurs at different time of the monsoon. In the Brahmaputra maximum discharge occurs in early monsoon in June and July whereas in the Ganga maximum discharge occurs in August and September. Synchronization of the peaks of these rivers results in devastating floods. Such incidents are not uncommon in Bangladesh.

Flash floods, where hydrographs rise and fall sharply. Flash flood prone areas of the Bangladesh are at the foothills. Intense local and short-lived rainfall often associated with mesoscale convective clusters is the primary cause of flash floods. These are characterized by a sharp rise followed by a relatively rapid recession. Often with high velocities of on-rush flood damages crops, properties and fish stocks of the wetland. Flash flood can occur within a few hours. In the months of April and May flash floods affect the winter rice crop at the harvesting stage, and are common in the districts of Northeast and Southeast regions of the country.

Floods owing to excessive rainfall is a flood generally occurs in many parts of the country but is mainly prevalent in the south-western part of the country. This kind of flood also occurs in the flood plains where natural drainage systems have been disturbed either due to human interferences e.g. construction of unplanned rural roads and encroachment of river courses etc. or due to gradual decay of the natural drainage system. When intense rainfall takes place in those areas, the natural drainage system cannot carry the run-off generated by the storm and causes temporary inundation in many localities. This kind of rain-fed flood is increasing in the urban areas.

Tidal floods as a result of cyclones and storm surges (Figure 2.4).This kind of flood mostly occurs along the coastal areas of Bangladesh over a coastline of about 800 km at the southern part. Continental shelves in this part of the Bay of Bengal are shallow and extend to about 20-50 km. Moreover, the coastline in the eastern portion is conical and funnel like in shape. Because of these two factors, storm surges generated due to any cyclonic storm is comparatively high compared to the same kind of storm in several other parts of the world. In case of super-cyclones maximum height of the surges were found to be 10-15 m, which causes flooding in the entire coastal belt. The worst kind of such flooding was on 12 Nov 1970 and 29 April 1991 which caused loss of 300,000 and 138,000 human lives respectively (FFWC, 2005). Coastal areas are also subjected to tidal flooding during the months from June to September when the sea is in spate due to the southwest monsoon wind.

Major portion of the land of Bangladesh is rain water flood zone. Besides the hilly region, north east region is mostly rain water flood zone. Moreover, northeast region is vulnerable to normal monsoon flood and flash flood (Figure 2.5). That means northeast region gets inundated every year. The main river in this region which drains all the flood water is Upper Meghna River. Upper Meghna River is an anastomosing river according to the criteria (Rosgen, 1994) of anastomosing river. The river has a tidal influence at the downstream. All river in northeast zone in turns meets to the Upper Meghna River. To study flooding in this region, the study should be focused on the Upper Meghna River.

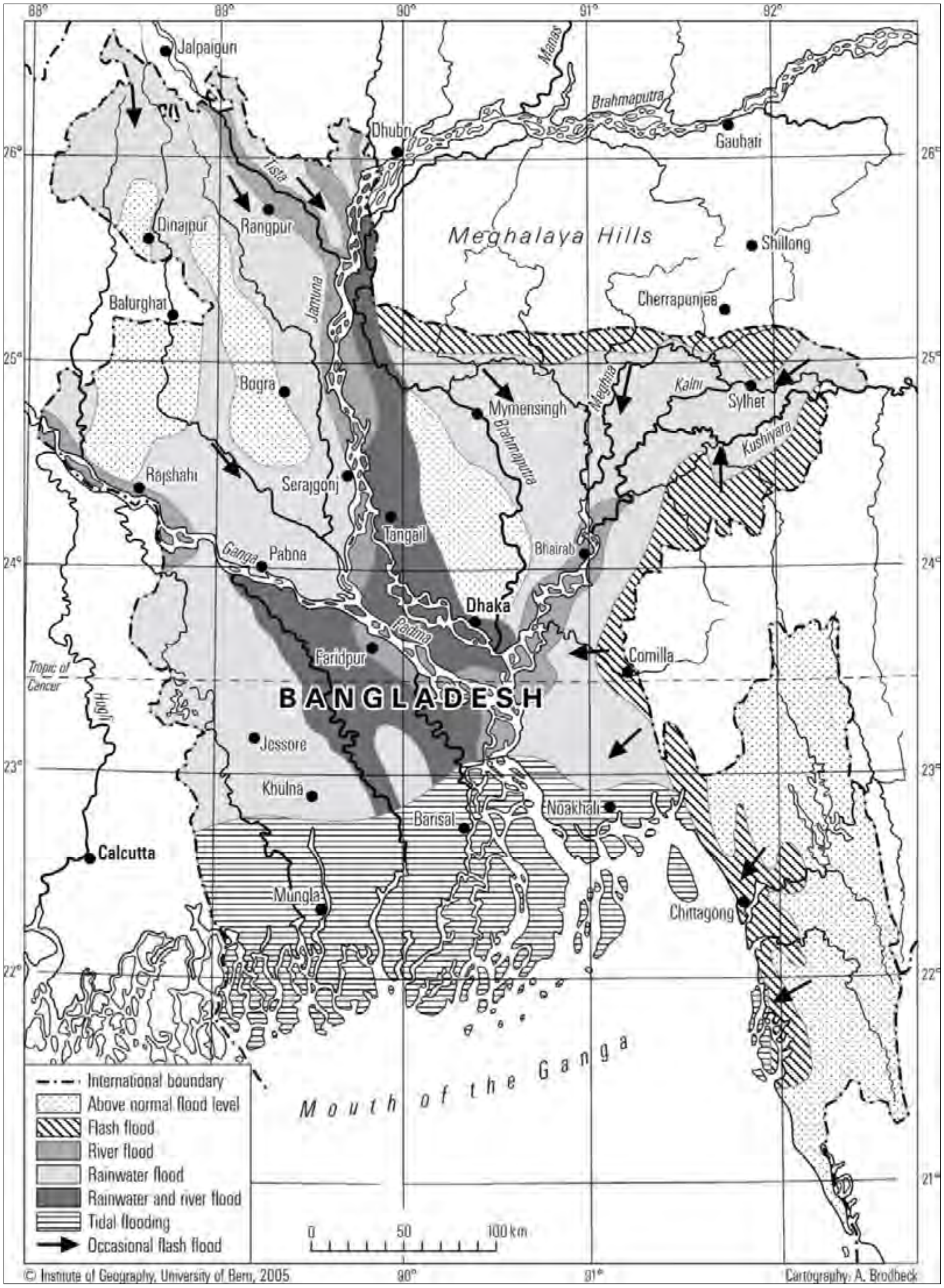

Figure 2.4: Types of flood in Bangladesh. (Source: Brammer, et al., 1993)

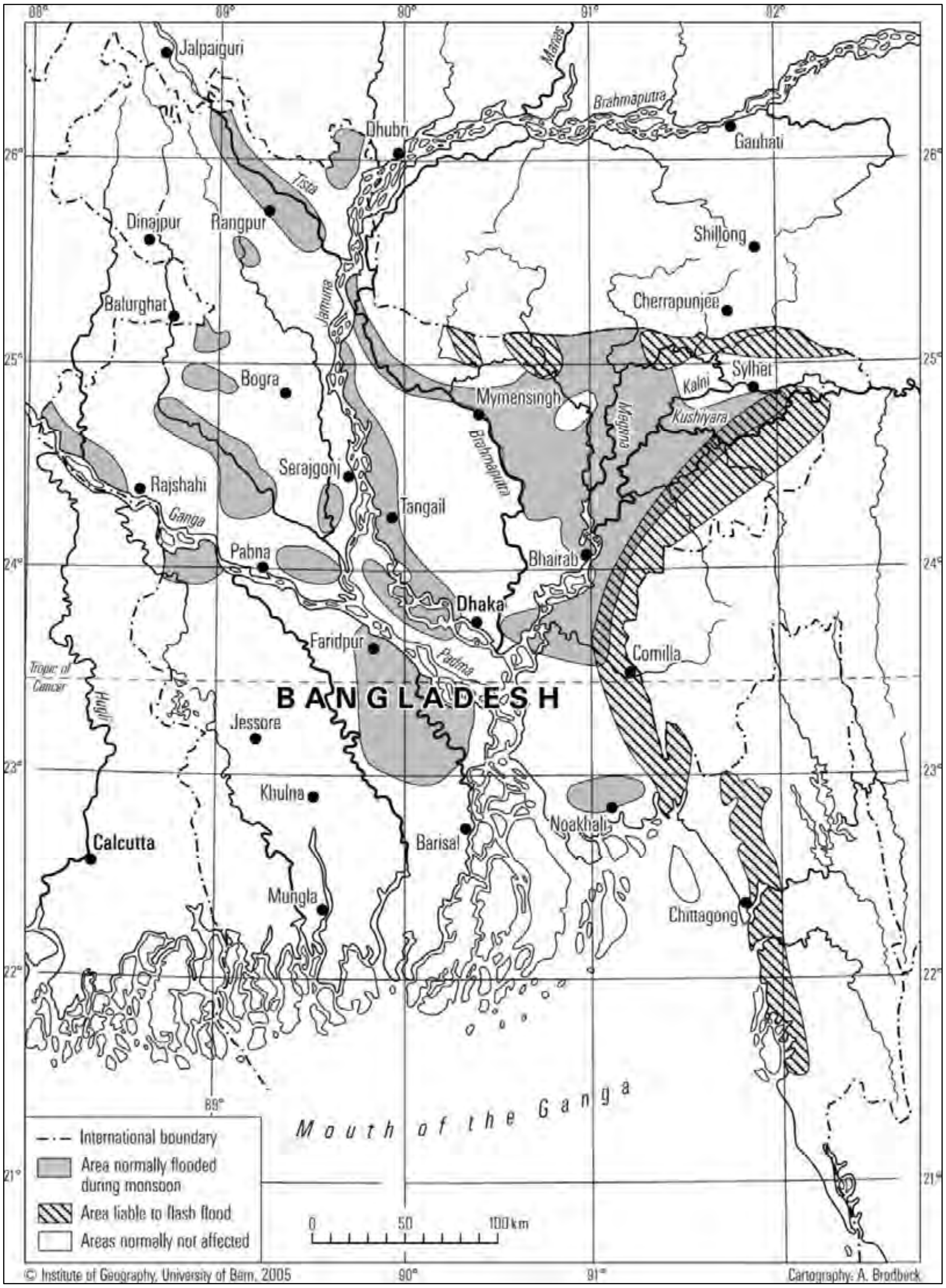

Figure 2.5: Extant of normal flooding in Bangladesh.(Soruce: BWDB, 1991a)

2.3 Remote Sensing

Remote sensing is defined, for our purposes, as the measurement of object properties on the earth's surface using data acquired from aircraft and satellites (Schowengerdt, 2007). It is therefore an attempt to measure something at a distance, rather than in situ. Since we are not in direct contact with the object of interest, we must rely on propagated signals of some sort, for example optical, acoustical, or microwave. While remote-sensing data can consist of discrete, point measurements or a profile along a flight path, we are most interested here in measurements over a two-dimensional spatial grid, i.e., images. Remote-sensing systems, particularly those deployed on satellites, provide a repetitive and consistent view of the earth that is invaluable to monitoring short-term and long-term changes and the impact of human activities (Avery, et al., 1992).

There are various important applications of remote-sensing technology (Schowengerdt, 2007). Environmental assessment and monitoring can be conducted using remote sensing technology. Global change such as atmospheric ozone depletion, deforestation, global warming can be detected and monitored by remote sensing. There are numerous fields where remote sensing technology and technique can be used such as agriculture, nonrenewable resource exploration, renewable natural resources, meteorology, mapping, military surveillance and reconnaissance etc.

2.4 Estimation of Inundation from Satellite Image

Flood inundation maps were developed from vegetation and land water surface indices derived from surface reflectance (Islam, et al., 2009). In this studythe inundation map developed from MODIS data has been compared with a consequent Radarsat image. The estimates show a strong correlation with the inundated area derived from Radarsat products. The products derived from MODIS 500m imagery shows the ability to study flood dynamics and performs similar to Radarsat based flood assessments. Considering that MODIS products have a great advantage in the high-frequent observation, the study concludes that this is a useful method to clarify the entire extent of the temporal floods in Bangladesh.

With the introduction of the earth observing satellites, remote sensing has become an important tool in analyzing the Earth's surface characteristics, and hence in supplying valuable information necessary for the hydrologic analysis. Due to their capability to capture the spatial variations in the hydro-meteorological variables and frequent temporal resolution sufficient to represent the dynamics of the hydrologic processes, remote sensing techniques have significantly changed the water resources assessment and management methodologies. Remote sensing techniques have been widely used to delineate the surface water bodies, estimate meteorological variables like temperature and precipitation, estimate hydrological state variables like soil moisture and land surface characteristics, and to estimate fluxes such as evapotranspiration (Kumar, et al., 2013). Today, near-real time monitoring of flood, drought events, and irrigation management are possible with the help of high resolution satellite data.

The growing availability of multi-temporal satellite data has increased opportunities for monitoring large rivers from space. A variety of passive and active sensors operating in the visible and microwave range are currently operating, or planned, which can estimate inundation area and delineate flood boundaries. Radar altimeters show great promise for directly measuring stage variation in large rivers. It also appears to be possible to obtain estimates of river discharge from space, using ground measurements and satellite data to construct empirical curves that relate water surface area to discharge (Smith, 1997). Extrapolation of these curves to ungauged sites may be possible for the special case of braided rivers.

MODIS data provide the most realistic means to achieve inundation (Ticehurst, et al., 2013), they are often limited by cloud cover during flooding events, and their spatial resolutions (250 – 1000 mpixel) are not always suited to small river catchments. The suitability of MODIS data has been studied in that study for providing daily surface water maps, both spatially and temporally, across a range of Australian catchments. This study shows that MODIS is suitable for capturing both medium and large flood events, but lacks the detail around the edge of a flood or along narrow water features where it tends to underestimate water extent. Compared to a Landsat water map, the MODIS water maps have shown a strong-to-moderate statistical agreement. MODIS surface water maps are sensitive to the dynamics of water movement when compared to flow gauge data. The MODIS sensors can provide useful information for hydrodynamic modelling, and do appear to be the best available product for mapping inundation extent and its change dynamics at large regional/basin scales.

The surface water area, the elevation of the water surface (h), its slope (δh/δx), and temporal change (δh/δt) are now being studied (Alsdorf, et al., 2007). The study suggest a future satellite concept, the Water and Terrestrial Elevation Recovery Mission, will improve upon the SRTM design to permit multi temporal mappings of elevation across the world’s wetlands, floodplains, lakes, reservoirs, and rivers.

A generic algorithm has been developed and tested (Guerschman, et al., 2011) for quantifying water fractions based on MODIS and ancillary data sources. The effects of using different MODIS products for standing water estimation, particularly of flood events and large reservoirs have been determined in that study. The best model obtained from MODIS composited data which has been generated a time-series of standing water for the Australian continent and secondary products such as flood recurrence and flood persistence have also been derived in that study.

A study (Sun, et al., 2011) investigates how to derive water fraction and flood mapping from the Moderate-Resolution Imaging Spectroradiometer(MODIS) onboard the Earth Observing System(EOS) satellites using the linear mixture model and decision-tree approach. MODIS surface reflectance with the matched land cover data in the Midwest prior to the flooding events were used for the training dataset, with the split test mode of 50% for training and the remaining 50% for testing. The derived water fraction maps were evaluated using higher resolution Thematic Mapper (TM) data from Landsat observations. Flood distributions in both space and time domains were generated using the differences in water fraction values before and after the flooding.

mapping monthly flood extent in the lower Mekong Basin (Cambodia and Vietnam); and near-real time mapping of inundation in the lower Condamine-Balonne catchment (South Queensland) has been done in a study by Passive microwave and optical remote sensing data (Ticehurst, et al., 2009). Both optical and passive microwave datasets are sensitive to surface water enabling them to map flood events. For both applications, the higher spatial resolution of the MODIS data is utilized to interpret and develop a set of rules for mapping the mixed pixels in passive microwave data using historical imagery for the same dates. For the Mekong River study, since the flood events gradually occur over a six month period, 37 GHz TRMM imagery was composited into monthly images and flood extent mapped for 1999 to 2002. The MODIS 8-day composite MOD09A1 was used to map flood extent for 2000 to 2002. The focuses on the methods developed from the two case studies to map flood extent using a combination of passive microwave and MODIS imagery.

A near real-time system is described (Gouweleeuw, et al., 2011), which provides spatial information of inland flood extent, using Moderate resolution Imaging Spectrometer (MODIS)optical reflectance and Advanced Microwave Scanning Radiometer (AMSR-E) microwave brightness temperature imagery, and flood volume through combination with a Digital Elevation Model (DEM). This information is an independent and useful addition to point data of gauged river flow at the in- and outlet of floodplains, typically only available with some latency, if at all. Comparison of satellite-derived volume estimates with those estimated from flow gauges for flood events on the lower-Balonne floodplain, South- Queensl and, indicates flood volumes generally compare quite well atthe onset of the flood events, but start to deviate at the peak flow into the flood recession. This is possibly explained by a combination of ungauged outflows, soil infiltration, evaporation and diversion of flood water into many large open reservoirs for crop irrigation.

A study (Ticehurst, et al., 2014), with the MODIS sensor for identifying flood events through comparison with stream flow and rainfall measurements at a number of sites during the wetseason in Northern Australia, has been conducted. The results showed that removing pixels containing less than 6% water can eliminate most commission errors when mapping surface water. Using only MODIS OWL pixels with a low view angle, or a range distance of less than 1000 km, also improves the results and minimizes multi-temporal errors in flood identification and extent. Given these limitations, MODISOWL surface water maps are sensitive to the dynamics of water movement when compared to stream flow data and does appear to be a suitable product for the identification and mapping of inundation extent at large regional/basin scales.

2.5 Estimation of Inundation from 2D Hydrodynamic Model

To understand flow pattern and flood wave characteristics of Haor areas, it is necessary to simulate 2D model as one dimensional typical modeling is not quite capable of generating flows. In this context, Delft3D has been selected to represent flow process of the Haor areas (Paul, et al., 2013). In this study, FLOW module of Delft3D has been used to derive floods with a return period of 50years during the monsoon season (June to August). Simulation has been started from April to provide spin-up period of two months before actual monsoon season. It is found that flood inundation depth increases with time and reaches to the maximum level at the end of the third week of July. The Kushiyara-Kalni system overspills only at the upper reach of the river. By this time, the floodplain of the Darain, Surma and Kalni River gets deeply flooded. At that time, flow of Dirain and Surmanriver systems are converged towards the Kushiyara River at Madna. However, with the road in place, the obstructed flood flow would pass from north to the south mostly parallel to the road along both sides of the road.

Three types of topography data was used in study (Wilson, et al., 2005)to predict flood inundation for an event in the United Kingdom in 1998 using the two-dimensional model LISFLOOD-FP. The contour dataset was different in spatial character (overly smooth) to the DGPS dataset and resulted in substantial differences in the timing and extent of flood inundation. However, results demonstrate potential problems with the use of satellite remotely sensed topographic data in flood hazard assessment over small areas.

The detailed DTM has been generated in a study (Tennakoon, 2004) in urban area under a data scarce situation from different elevation datasets. Optimum raster resolution has been identified in that study to incorporate roads, building and other physical structures inside the DTM looking at accuracy and hydrodynamic modeling requirements. In addition to that, a GIS model of the urban built up area has been developed to serve as an input for the 2D Hydrodynamic model. Moreover, a flood hazard map has been derived by incorporating kinetic energy, depth and duration of inundation. The effect of model results with the change of spatial resolution in the 2D model has also been investigated in that study.

Reconstruction of a high-magnitude flood outburst in 2D hydrodynamic model using SOBEK consist (Carrivick, 2005) of the calculations of high-magnitude fluvial flow characteristics within an anastomosing network of simultaneously inundated channels, including; sheet or unconfined flow, simultaneous channel and sheet flow, flow around islands, hydraulic jumps, multi-directional flow including backwater areas, hydraulic ponding and multiple points of flood initiation.

Impact of Tipaimukh Dam has been analyzed by IWM in a study Study of "Tipaimukh Dam Project of India on Bangladesh". Different scenario have been simulated and analyzed with MIKE FLOOD (IWM, 2005).

2.6 Combination of Satellite Image and 2D Hydrodynamic Model

The application of hydrodynamic modelling in conjunction with remote sensing to estimate flood inundation and discharge in a sparsely monitored and topographically complex tropical catchment has conducted in Western Australia (Karim, et al., 2011). Two dimensional flow model with a Shuttle Radar Topographic Mission (SRTM) derived 30 m digital elevation model (DEM) has been used in that study. Laser altimetry has been used at a number of locations to improve the resolution of key features within the topographic model. The model was calibrated using a combination of gauge water heights and remotely sensed inundation extent maps. The inundation maps were combined with SRTM derived 30 m DEM to obtain estimates of inundation depths across the floodplain. The method described in this study would help to address the problem of data deficiency in calibrating hydrodynamic models and provides improved estimates of flood discharge (Karim, et al., 2011).

A method for modeling the extent and depth of flooding in a complex river system is determined in a study (Penton, et al., 2007)of the River Murray. Hydrodynamic models require river cross-sections, accurate high resolution digital elevation models (DEMs) and extensive calibration. Therefore, the study has developed a technique for predicting the depth of water on floodplains from high-resolution digital elevation data and satellite imagery. The technique involves combining flood masks from Landsat imagery with a very high resolution DEM. The result is a set of very high resolution flood maps for river flows observed at gauging stations. The model enables users to visualize and analyze the inundation of floodplains along the River Murray.

Flood hazard zones are usually generated based on the basis of flood depths and velocities. However, the computer based flood modelling result does not give any integration of velocity and depth to produce flood hazard maps. Therefore, a study (Ediriweera, 2007) is aimed to develop a GIS based framework to produce hazard zones. At the sametime this study approaches to asses and visualize the tangible and intangible flood damages by manipulating thousands of data with different formats such as polygons, poly line, point, raster, etc, on one GIS based platform. Further to that, this research demonstrates the capabilities of traffic planning and evacuation strategies, with the help of network analysis tool on the same GIS based framework to minimize the flood damages in future.

Flood modeling often provides inputs to flood hazard management. A study have been conducted (Tarekegn, et al., 2010)to analyze the flooding characteristics in the data scarce region of the Lake Tana basin at the source of the Blue Nile River. The study required to integrate remote sensing, GIS with a two-dimensional (2D) module of the SOBEK flood model.

2.7 Summary

There are a lot of studies in Bangladesh and worldwide to determine flood inundation from 2D hydrodynamic modeling. But research for Flood inundation derived in combination of 2D hydrodynamic model and satellite imagery in Bangladesh context is very little. While this technique is very reliable and accurate to determine flood inundation

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Chapter 3 Theory and Methodology

3.1 General

Upper Meghna River is the only way of draining the floods of the North East Hydraulic Region. Major portion of North East hydraulic region of Bangladesh flooded in monsoon every year. Moreover, flash flood is also a common phenomenon for this region. In addition to that, the unique characteristics of Haor makes the flooding different compared to the flooding of other hydraulic region. The purpose of this chapter is to give a brief description of the related theories regarding flood, Satellite images (Landsat and Radarsat), inundation from satellite image, Mathematical Modeling and SOBEK.

3.2 Land Sat

Landsat represents the world's longest continuously acquired collection of space-based moderate-resolution land remote sensing data. Four decades of imagery provides a unique resource for those who work in agriculture, geology, forestry, regional planning, education, mapping, and global change research. Landsat images are also invaluable for emergency response and disaster relief. As a joint initiative between the U.S. Geological Survey (USGS) and NASA, the Landsat Project and the data it collects support government, commercial, industrial, civilian, military, and educational communities throughout the United States and worldwide. As with previous partnerships, this mission continues the acquisition of high-quality data that meet both NASA and USGS scientific and operational requirements for observing land use and land change.

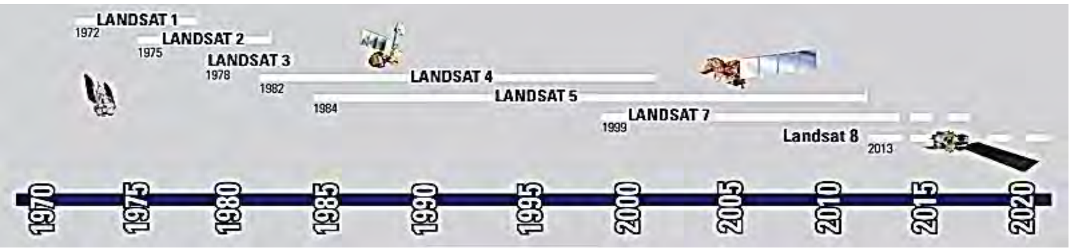


Figure 3.1: Landsat History

- Landsat 1: Launched July 23, 1972; originally named ERTS-A (Earth Resources Technology Satellite); renamed to Landsat 1; 80m ground resolution.

- Landsat 2: Launched January 22, 1975; originally named ERTS-B (Earth Resources Technology Satellite); renamed to Landsat 2; 80m ground resolution.

- Landsat 3: Launched March 5, 1978; also known as Landsat-C; 40m ground resolution.

- Landsat 4: Launched July 16, 1982; also known as Landsat-D; 30 m reflective, 120 m thermal resolution.

- Landsat 5: Launched March 1, 1984; exceeded its three-year design life, collecting imagery for over 27 years and decommissioned in 2013; 30 m reflective, 120 m thermal resolution.

- Landsat 6: Launched October 5, 1993; did not achieve orbit; 30 m reflective, 120 m thermal.

- Landsat 7: Launched April 15, 1999; first panchromatic band on a Landsat satellite; 30 m reflective, 60 m thermal.

- Landsat 8: Launched February 11, 2013; improved sensors and technology; 9 spectral band with 15 to 30 resolution and 2 thermal band with 100 m resolution.

3.3 Radarsat

The Radarsat constellation is a pair of Canadian Remote Sensing satellites. The constellation consists of:

- Radarsat-1, launched 1995
- Radarsat-2, launched 2007

Radarsat-1 is Canada's first commercial Earth observation satellite. It utilized synthetic aperture radar (SAR) to obtain images of the Earth's surface to manage natural resources and monitor global climate change. As of March 2013, the satellite was declared non-operational and is no longer collecting data.

Radarsat-1 used a synthetic aperture radar (SAR) sensor to image the Earth at a single microwave frequency of 5.3 GHz, in the C band (wavelength of 5.6 cm).[1]

The SAR support structure was designed and manufactured by Northrop Grumman Astro Aerospace and deployed to 15 metres (49 ft) in length on orbit. Unlike optical satellites that sense reflected sunlight, SAR systems transmitted microwave energy towards the surface and recorded the reflections. Thus, RADARSAT-1 imaged the Earth, day or night, in any atmospheric condition, such as cloud cover, rain, snow, dust or haze.

Radarsat-2 is an Earth observation satellite that was successfully launched December 14, 2007for the Canadian Space Agency by Starsem, using a Soyuz FG launch vehicle, from Kazakhstan's Baikonur Cosmodrome. RADARSAT-2 was previously assembled, integrated and tested at the David Florida Laboratory near Ottawa, Ontario before the start of its launch campaign.

Radarsat-2 is follow-on to Radarsat-1 which mission terminated in April 2013. It has the same orbit (798 km altitude sun-synchronous orbit with 6 p.m. ascending node and 6 a.m. descending node). Some of the orbit characteristics are 24 days repeat cycle (=343 orbits), 14.29 orbits per day, each orbit being 100.75 minutes duration. It is filling a wide variety of application, including sea ice mapping and ship routing, iceberg detection, agricultural crop monitoring, marine surveillance for ship and pollution detection, terrestrial defense surveillance and target identification, geological mapping, mine monitoring, land use mapping, wetlands mapping, topographic mapping.

3.4 Inundation Extraction from Satellite Image

There is several ways to extract Inundation from satellite images. One of them is thematic image classification. Thematic image classification is an effective way to extract feature; not only inundation but also spatial distribution of identifiable earth surface features. Image classification is the process used to produce thematic maps from imagery. The themes can range, for example, from categories such as soil, vegetation, and surface water in a general description of a rural area, to different types of soil, vegetation, and water depth or clarity for a more detailed description. A number of factors can cause confusion among spectral signatures, including topography, shadowing, atmospheric variability, sensor calibration changes, and class mixing within the GIFOV. Some of these effects can be modeled, some cannot (with any reasonable amount of effort), and so they must be treated simply as statistical variability. Traditionally, thematic classification of an image involves several steps, as shown in (Figure 3.2).

Feature extraction: Transformation of the multispectral image by a spatial or spectral transform to a feature image. Examples are selection of a subset of bands, a PCT to reduce the data dimensionality, or a spatial smoothing filter. This step is optional, i.e., the multispectral image can be used directly, if desired.

Training: Selection of the pixels to train the classifier to recognize the desired themes, or classes, and determination of decision boundaries which partition the feature space according to the training pixel properties. This step is either supervised by the analyst or unsupervised with the aid of a computer algorithm.

Labeling--Application of the feature space decision boundaries to the entire image to label all pixels. If the training was supervised, the labels are already associated with the feature space regions; if it was unsupervised, the analyst must now assign labels to the regions. The output map consists of one label for each pixel.

3.5 Mathematical Modeling

Mathematical models are, abstraction of reality, representation of a particular thing, idea or condition, as a whole a simplified representations of some real world entity. Mathematical models are characterized by assumptions about: variables (the things which change), parameters (the things which don’t change), functional forms (the relationship between the two). There are several situations in which mathematical models can be used very effectively in all relevant aspects.

Mathematical models can help people understand and explore the meaning of equations or functional relationships. After developing a conceptual model of a physical system it is natural to develop a mathematical model that will allow one to estimate the quantitative behavior of the system. Quantitative results from mathematical models can easily be compared with observed data to identify a model’s strengths and weaknesses. Many modeling packages are available which can simulate hydrodynamic phenomena: HEC-RAS, SOBEK, MIKE11, MIKE 21C, MIKE FLOOD, Delft 3D etc.

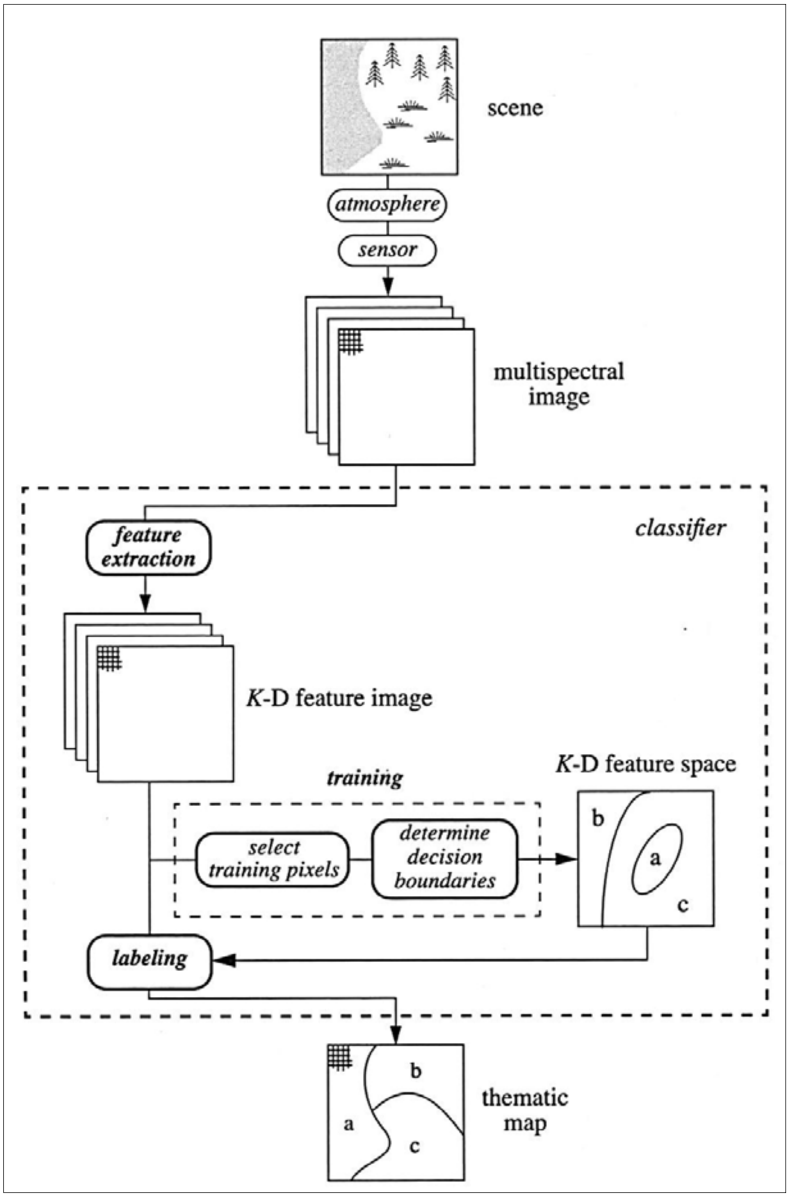


Figure 3.2: Image classification steps. (Source: Schowengerdt, 2007)

3.6 SOBEK

SOBEK is an integrated software package for river, urban or rural management. Seven program modules work together to give a comprehensive overview of waterway systems keeping you in control. Its integrated framework also means that SOBEK can link river, canal and sewer systems for a total water management solution. The flow in one dimension is described by two equations: the momentum equation and the continuity equation. The continuity equation is-

$$\frac{\partial A_f}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \tag{3.1}$$

And the momentum equation is

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right) + gA_f\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2RA_f} - \omega_f\frac{\tau_{wind}}{\rho_w} = 0 \tag{3.2}$$

Where,

Q	Discharge (m^3/s)
A_f	Wetted Area (m^2)
t	Time (s)
x	Distance (m)
g	Acceleration due to gravity (≈ 9.8 m/s^2)
h	Water level with respect to the reference level (m)
τ_{wind}	Wind share stress (N/m^2)
w_f	Cross sectional width at water level (m)
ρ_w	Water density (kg/m^3)
C	Ch´ezy coefficient ($m^{1/2}/s$)
R	Hydraulic radius (m)

The flow in two dimensions is described by three equations: the continuity equation, the momentum equation for the x-direction and the momentum equation for the y-direction. The continuity equation reads:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0 \tag{3.3}$$

Where,

u	velocity in x direction (m/s)
v	veloctiy in y direction (m/s)
h	Total water depth (m)
d	Depth below plane of reference (m)
ζ	Water level above plane of reference (m)

The continuity equation ensures the conservation of fluid.

For two dimensional flow, two momentum equations are calculated, together with the continuity equation 2D. The momentum equations read:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} + g\frac{u\left|\vec{u}\right|}{C^2 h} + au|u| = 0 \tag{3.4}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial x} + g\frac{v\left|\vec{u}\right|}{C^2 h} + av|v| = 0 \tag{3.5}$$

Where

u	velocity in x direction (m/s)
v	veloctiy in y direction (m/s)
$\left\lvert\vec{u}\right\rvert$	velocity magnitude (= $\sqrt{u^2 + v^2}$) (m/s)
ζ	water level above plane of reference (m)
C	Chezy coefficient ($\sqrt{m/s}$)
d	Depth below plane of reference (m)
h	total water depth (= d+ζ) (m)
a	wall friction coefficient (1/m)

They consist of acceleration terms, the horizontal pressure gradient terms, convective terms, bottom friction terms and wall friction terms. These equations are non-linear and they are a subset of the well-known shallow water equations, that describe water motion for which vertical accelerations are small compared to horizontal accelerations (this applies to tidal flow, river flow, flood flow).

3.7 Methodology of the Study

Upper Meghna River bankline has been delineated from Landsat satellite image of 2010. Study area has been delineated from physiographic unit. Radarsat satellite images are the main basis for flood analysis. Landsat satellite images are not suitable for analysis of flood inundation. Because frequency emitted from landsat satellite can’t penetrate cloud cover. That’s why during monsoon Radarsat satellite images are the best option for inundation calculation. So, flood extant of the study area has been calculated with the help of Radarsat satellite imagery. After that, 1D model for Upper Meghna River has been set up taking Bhairab Bazar discharge station as upstream boundary and Satnal water level station as downstream boundary. This 1D model has been calibrated in Meghna Ferryghat water level station and also validated. Then this calibrated and validated model has been coupled with 2D overland flow model with the DEM of the study area. This 2D overland flow model has been calibrated with the help of Radarsat satellite images, road and embankment alignment. After calibration, validation has also been conducted. This process has been completed with the help of 5 years monsoon satellite images. The whole process can be summarized in Figure 3.3.

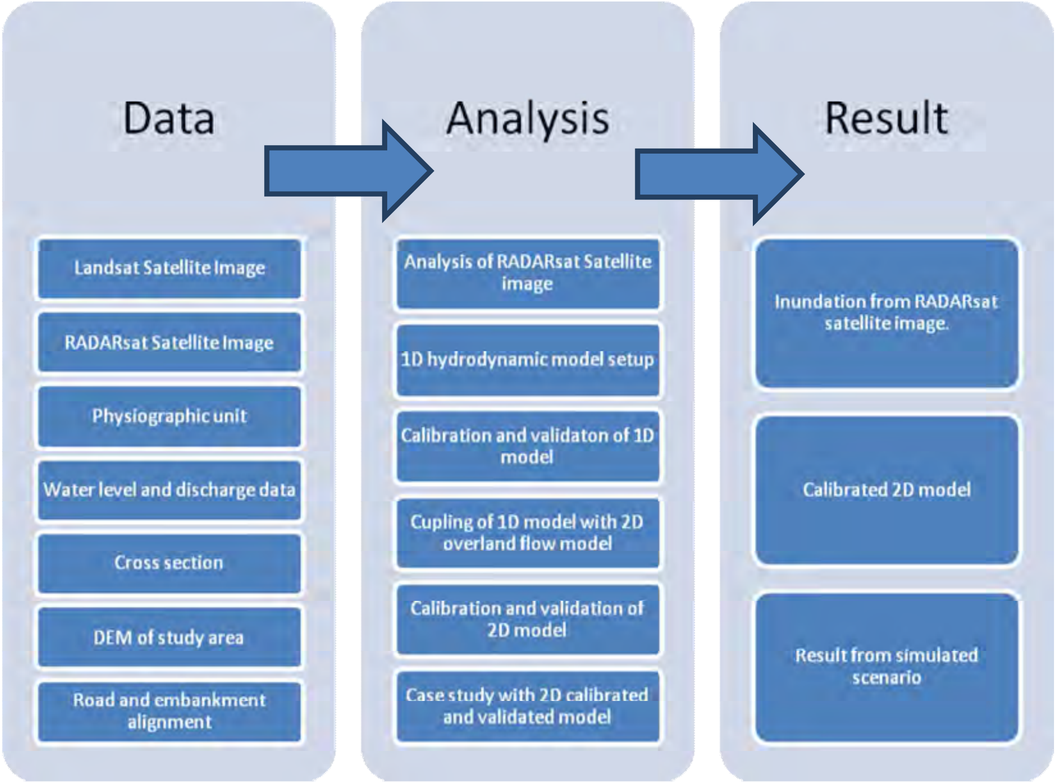


Figure 3.3: Outline of methodology

3.8 Data Used

3.8.1 Satellite Images

Two types of satellite images have been used in this study. Landsat and Radarsat images. Landsat images of 2010 have been used for bankline and land use delineation. Radarsat images have been used for inundation analysis.

Table 3.1: Details of Radarsat satellite images

Date	Resolution
26th August 1998	100m X 100m
6th September 2000	50m X 50m
1st September 2001	50m X 50m
27th August 2002	50m X 50m
22nd August 2003	50m X 50m
9th September 2004	50m X 50m
3rd August 2007	50m X 50m

3.8.2 Water Level and Discharge

Water level data have been used for Satnal station (ID 276). Narsingdi (ID 274). There are two main Tributary of Upper Meghna River, one is Dhaleswari and another is Gomtiriver. Bhairab Bazar (ID 273) discharge staion is used for Upper meghna river. Discharge from Kalagachia (ID 71) station is used for Dhaleswari River and station is used for Gomti River (Figure 4.1).

Table 3.2: Water level and discharge station in study area.

Water level staion		Discharge station	
Satnal (276)	1950-2009	Kalagachia (ID 71)	1965-2006
Narsingdi (274)	1959-2009	Bhairab Bazar (ID 273)	1964-2006
Badyar Bazar (275)	1959-2009	Jibanpur (ID 114)	1964-2006
MeghnaFerryghat (275.5)	1959-2009		

3.8.3 Cross Section

A total of 24 cross sections have been used. In them 15 sections are of Upper Meghna River. Seven section are for Gomti River and 2 sections are used for Dhaleswari River.

Table 3.3: Cross section staion used in model

River	Cross section ID	Year
Upper Meghna	RMM19, RMM17, RMM16, RMM15, RMM14, RMM13, RMM12, RMM11, RMM10, RMM9, RMM8, RMM6, RMM5, RMM4, RMM3	2000
Gomti	RMGTI1, RMGTI2, RMGTI3, RMGTI4, RMGTI5, RMGTI6, RMGTI6.1	2000
Dhaleswari	RMD23, RMD22	2000

3.8.4 Digital Elevation Model

Digital elevation model of 1950 has been used for 2D overland flow model as topography (Figure 3.4). Resolution of the DEM is 300m x300m.

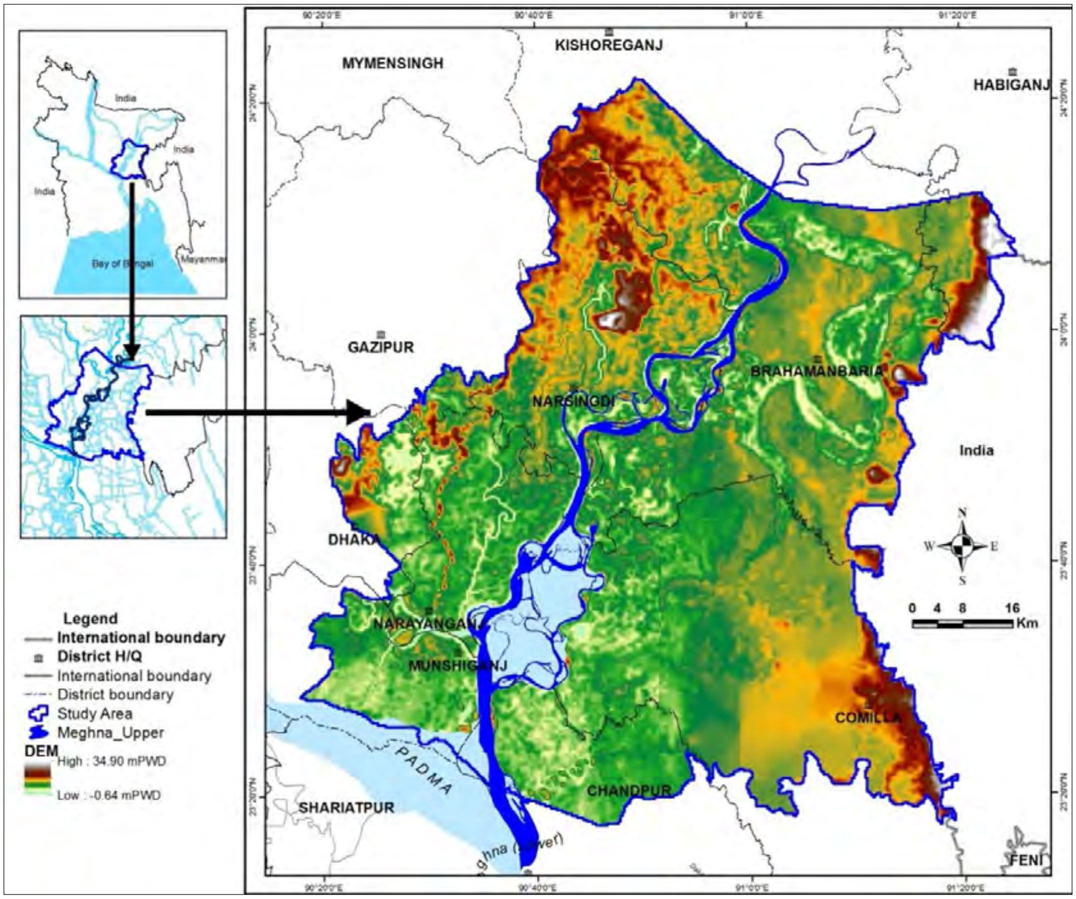


Figure 3.4: Digital Elevation Model of the Study Area

3.9 Summary

This chapter deals with the theories involve in this study such as different types and purpose of satellite images involve with the study. Basic technique of image classification has also been discussed. Mathematical model package and its governing equation have also been discussed. A Brief discussion of the methodology and approaches are also provided in this chapter which includes satellite image classification, model set up and calibration validation both 1D and 2D.

Chapter 4 Study Area

4.1 General

The main river of the study area is Upper Meghna River. It has been an important river of the southeast region of Bangladesh, being a drainage outlet for the north-central, northeast and southeast regions (Figure 4.1). The river has joined with other major rivers to contribute to the development of the Ganges Delta and is an integral part of the Surma-Kushiyara River System. It has been flowing on the abandoned bed of the old Brahmaputra and Meghna rivers. The present river course was developed for transporting much larger flow when the main flow of the Brahmaputra was flowing along the present course of the Old Brahmaputra River about 240 years ago than what the present Meghna has been carrying.

As for its origin, the Barak River has been originated from Assam, and has bifurcated at Amalshid, Zakiganj, Sylhet into the northern Surma and southern Kushiyara branches. These two rivers have reunited at Bajitpur in Kishoreganj district, though under different downstream names, and have proceeded for a while downstream to assume the name Meghna. The Old Brahmaputra River has met the Meghna further downstream of the confluence of the Surma-Kushiyara River and the combined flow meets with the Padma near Chandpur. The river has been propagating from the Lakhai in Habiganj to the UttorMatlab in Chandpur. The major regional river Gumti has been draining into it at Doudkandiupazila of Comilla, substantially augmenting its flow.

Study area has included a part of south east and north central hydrological region. North part of the study area has a portion of north east hydrologic region (Figure 4.1).The common boundary of these two hydrological regions has gone through the study region. Study area has comprised ten districts. Among those the 100%area of Narayanganj and Narsingdi include in study area. The other major areal contributions of district are Brahmanbaria 91%, Chandpur 31%, Comilla 68%, Kishoreganj 23%, Munshiganj 61% and the minor contribution of the district is Habiganj 7%.

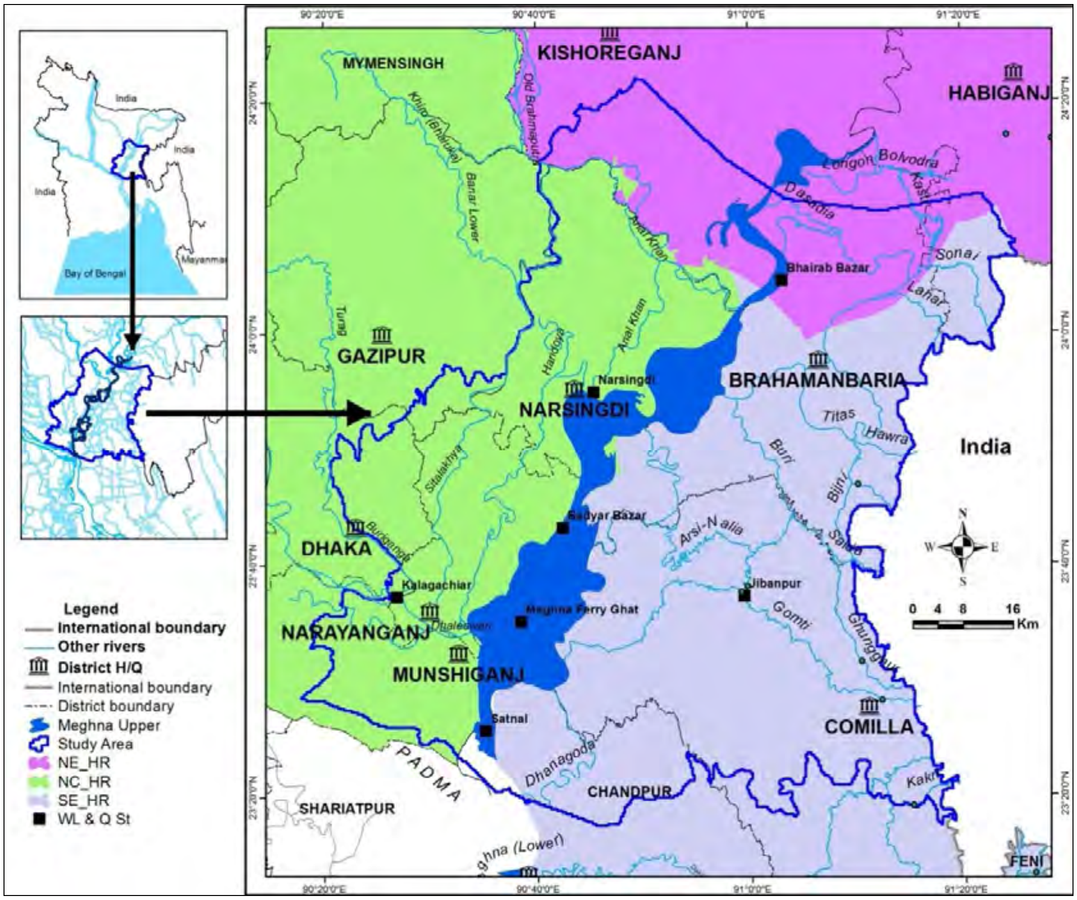


Figure 4.1: Study area

Table 4.1: Area of District in study area

District Name	Study Area (Km^2)	Total Area (Km^2)	Percentage
Brahmanbaria	1748.5	1921	91
Chandpur	518	1697.9	31
Comilla	2086.3	3083.8	68
Habiganj	193	2587.2	7
Kishoreganj	607.5	2611.4	23
Munshiganj	566.	932	61
Narayanganj	701.8	701.9	100
Narsingdi	1157	1167	99
Total	7578.1		

4.2 Study Area Selection

The boundary of the study area has been selected based on the physiographic unit (Brammer, 2000) around the Upper Meghna River. East side of the study area has been chosen the international boundary. South side of the study area is the just upstream of the Padma and Upper Meghna confluence. The south portion of Old Meghna Estuarine Floodplain has been excluded because the south part of this physiographic unit has the influence of Lower Meghna River. The boundary of the west side of the study area has been selected considering the Old Brahmaputra Floodplain which is adjacent to right bank of the Upper Meghna River. The north side of the study area has been fixed considering the Middle Meghna River Floodplain.

4.2.1 Old Meghna Estuarine Floodplain

Smooth, almost level, floodplain ridges and shallow basins. Relief is made irregular locally by man-made cultivation platforms in east of Chandina and in parts of Munshigonj, Sonagaon, Sariatpur.

Soils are relatively uniform within this region, both between adjoining ridges and basins, and between subregions. Silty soils predominate, but there are significant proportions of silty clay of clay basin soils in Dhaka, Madaripur-Gopalpur, Barisal.

4.2.2 Middle Meghna River Floodplain

This Region includes islands – former Brahmaputra chars – within the Meghna River as well as adjoining parts of the mainland. It comprises various kinds of relif : low – lying basins with surrounding low ridges along river banks; areas with low ridges, inter- ridge depressions and old channels; and higher sandy ridges. The Meghna River banks are mainly stable, but bank erosion occurs on a small scale locally.

There are three main kinds of soils in this region. Grey loams and clays developed on ridges and basin in areas of Meghna alluvium. These soils occupy the greater part of the region. Grey loamy ridge soils and dark grey basin soils in included areas of Old Brahmaputra alluvium. Grey sands to loamy sands with compactsilty topsoil, occupying areas of Old Brahmaputra char land which has been only shallowly buried by Meghna alluvium.

4.2.3 Old Brahmaputra Floodplain

Most areas have broad ridges and basins. Relief is locally irregular, especially near old and present river channels. The difference in elevation between ridge tops and basin centers is usually 2-5 meters, but it exceeds 5 meters near the boundary with the Sylhet basin.

Dark gray floodplain soils generally predominate. However ridges have brown floodplain soils, gray valley soils, and varying proportions of gray valley plain soils. Ridge soils are mainly silt loam and silty clay loam. Clays predominate in basins.

The higher ridge soils are rapidly permeable. Lower ridge soils used are slowly permeable, so are basin clays. Moisture holding capacity is high in deep silt loam on ridges, but is moderate or low in more sandy or shallow ridge soils and in basin clays.

4.2.4 Sylhet Basin

The region is mostly smooth. It has broad basins with narrow rims of higher land along rivers. Relief is locally irregular near the rivers. The difference in elevation between riverbanks and adjoining basin centers is 3-6 m or more.

There are two main kinds of soils in this region. Gray silty clay loams and clay with developed profiles occur on the relatively higher land which dries out seasonally. Gray clays with raw alluvium at a shallow depth occupy basins which stay wet throughout the year.

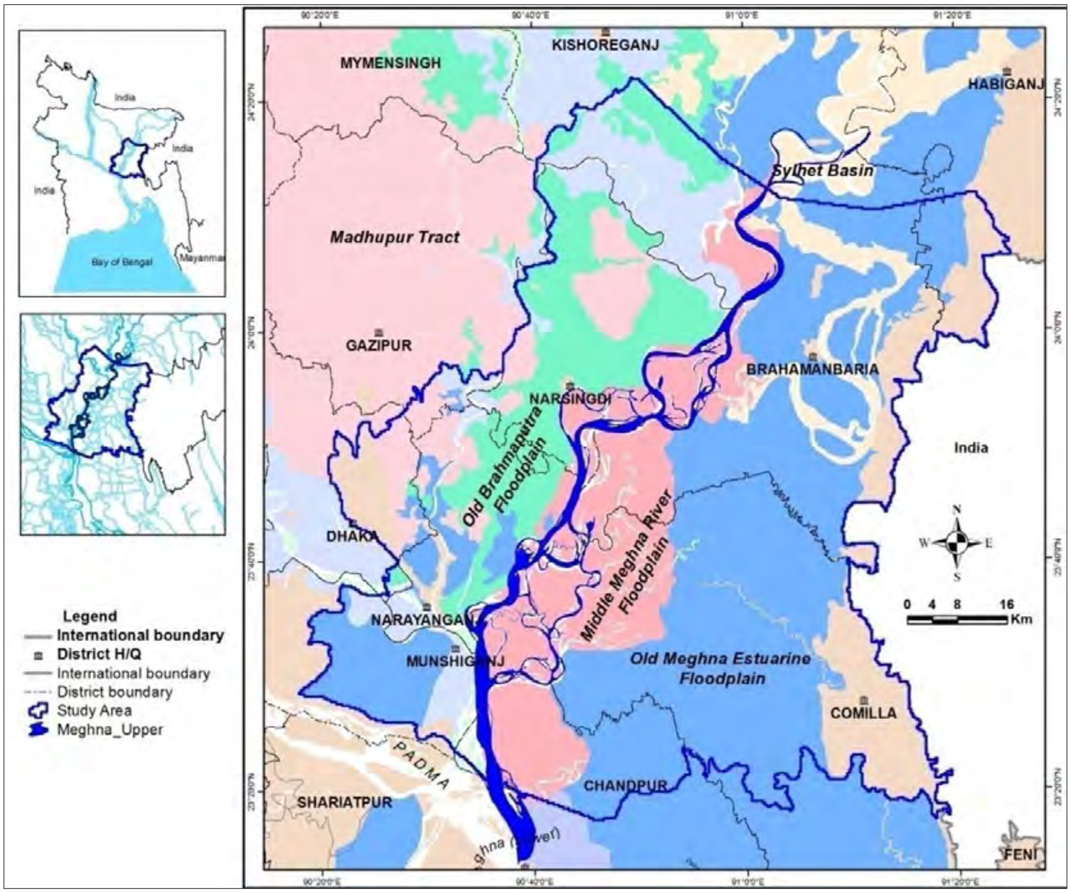


Figure 4.2: Physiographic unit of the study area

4.3 Summary

The main focus of this chapter is brief description of the study river and study area. The study river and study area selection process has also been discussed. The physiographic unit in the study area has also been discussed.

Chapter 5 Results and Discussions

5.1 General

In this study several Radarsat satellite images have been classified and inundation has been extracted and analyzed also. Not only that, numerical model have been simulated with SOBEK 1D-2D package for different flood year. After that, both inundation from satellite images and model have been compared. Finally, a scenario has been developed based on previous study and literature, which has also been simulated. Different type of analysis has been conducted to understand the outcome of simulated model and also from satellite images.

5.2 Flood Inundation from Satellite Image

Flood inundation from Radarsat satellite images of 1998, 2000, 2001, 2002, 2003, 2004 and 2007 have been extracted after image classification. Flooding pattern and the amount of inundation in each satellite images have been extracted first. Afterwards, flood incidence map have been derived by superimposing all the classified images. Then district wise inundation has been tabulated.

The 1998 flood has about 400 year return period (Hofer, et al., 2006), taking inundation into consideration. The inundation of the study area during 1998 flood was about 4444.5 km^2, which is 58.6% of the whole study area. That means about half of the study area was inundated in that flood. But the interesting thing is that about 3128 km^2 of 7572 km^2 study area remains unflooded even in the worst situation. Most of the unflooded zone lies at the downstream part of the Upper Meghna River in the Munshiganj district close to the left and right bank of the river and the physiographic name of this unflooded zone is Young Brahmaputra and Jamuna Floodplain, Old Meghna Estuarine floodplain and Middle Meghna River Floodplain. The downstream floodplain char of the Upper Meghna River is also an unflooded zone, is the part of Middle Meghan River Floodplain. In the upstream of the river there is a distinct unflooded zone. The physiographic name of this zone is Madhupur Tract. This part of the Madhupur Tract is not connected to the main

Madhupur Tract, this part actually splitted from the main part of the tract. As this is the part of Madhupur Tract, which has higher elevation compared to the floodplain, this why this part is not getting any flood. Some part around the Comilla district headquarter also seems unflooded, this is because, the physiographic unit of the area is Low hills and Northern and Eastern Piedmont Plains and also this part is an Urban area. Except this zone and some hill, all the part of the study area is inundated (Figure 5.1). Part of the Sylhet Basin in the study area seems severely flooded. Because this part is situated in the upstream of the Upper Meghna River and all the flood water from North Eastern hydrologic region passes along this part.

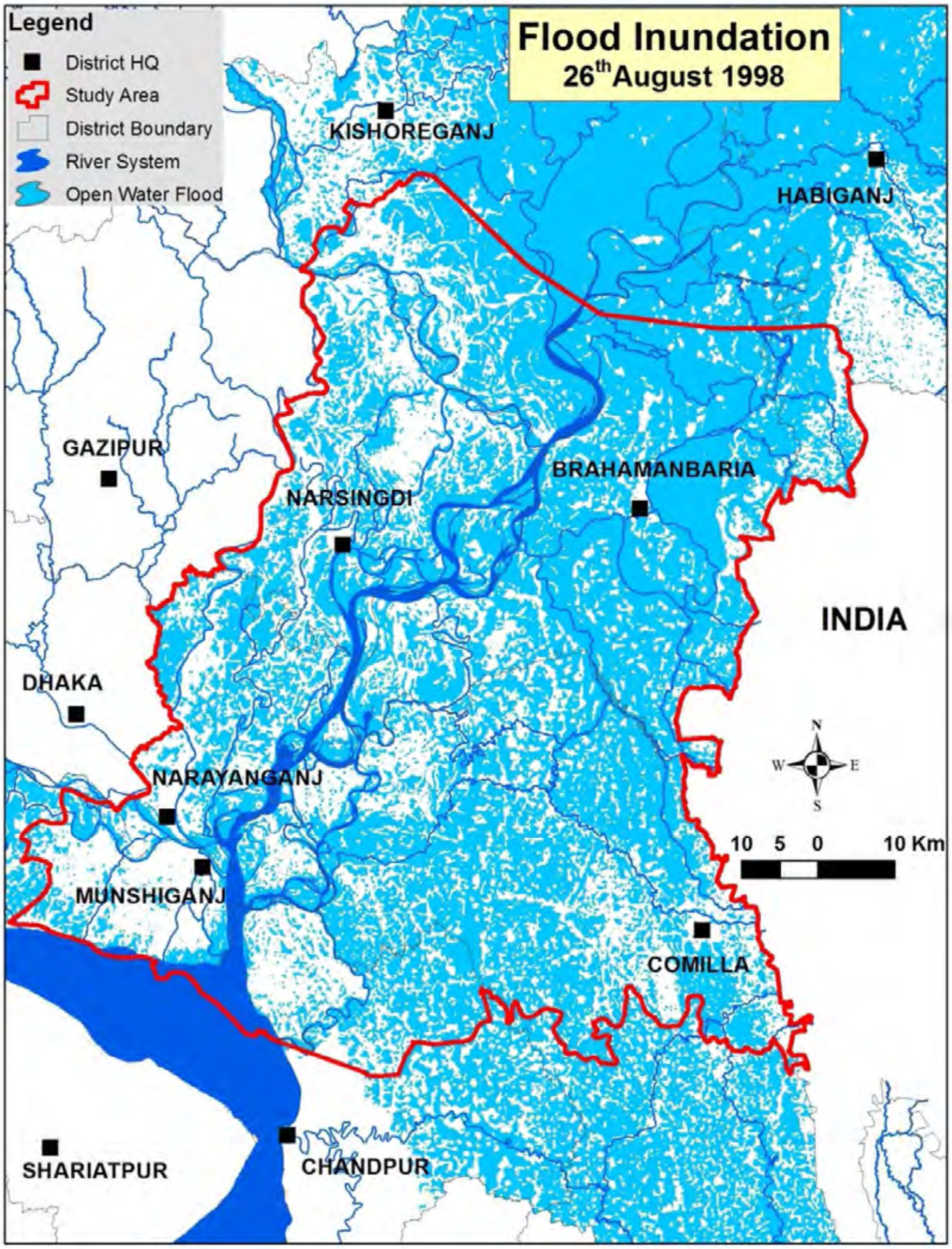


Figure 5.1: Inundation from RADAR sat image of 26thAugust 1998

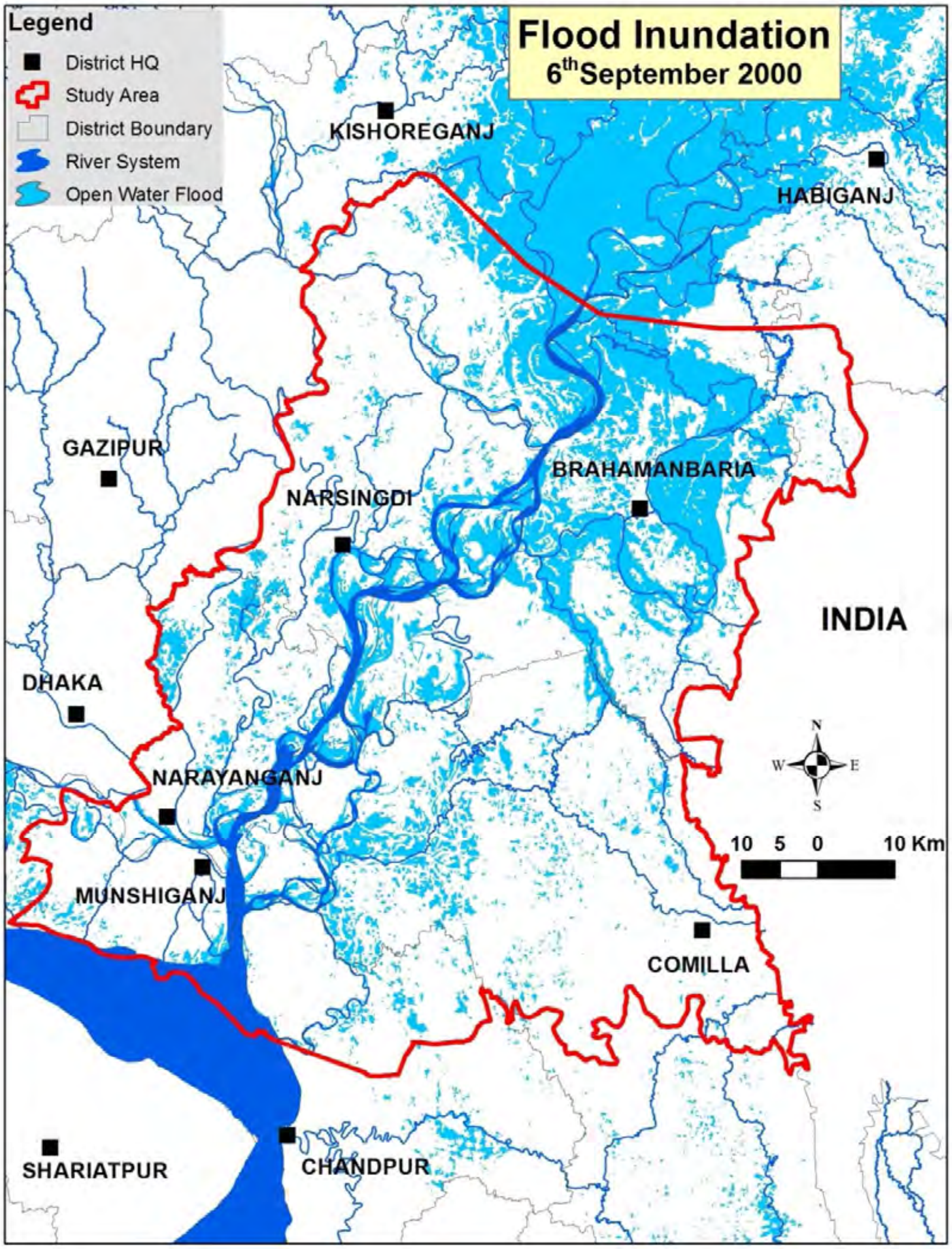


Figure 5.2: Inundation from RADAR sat image of 6th September 2000.

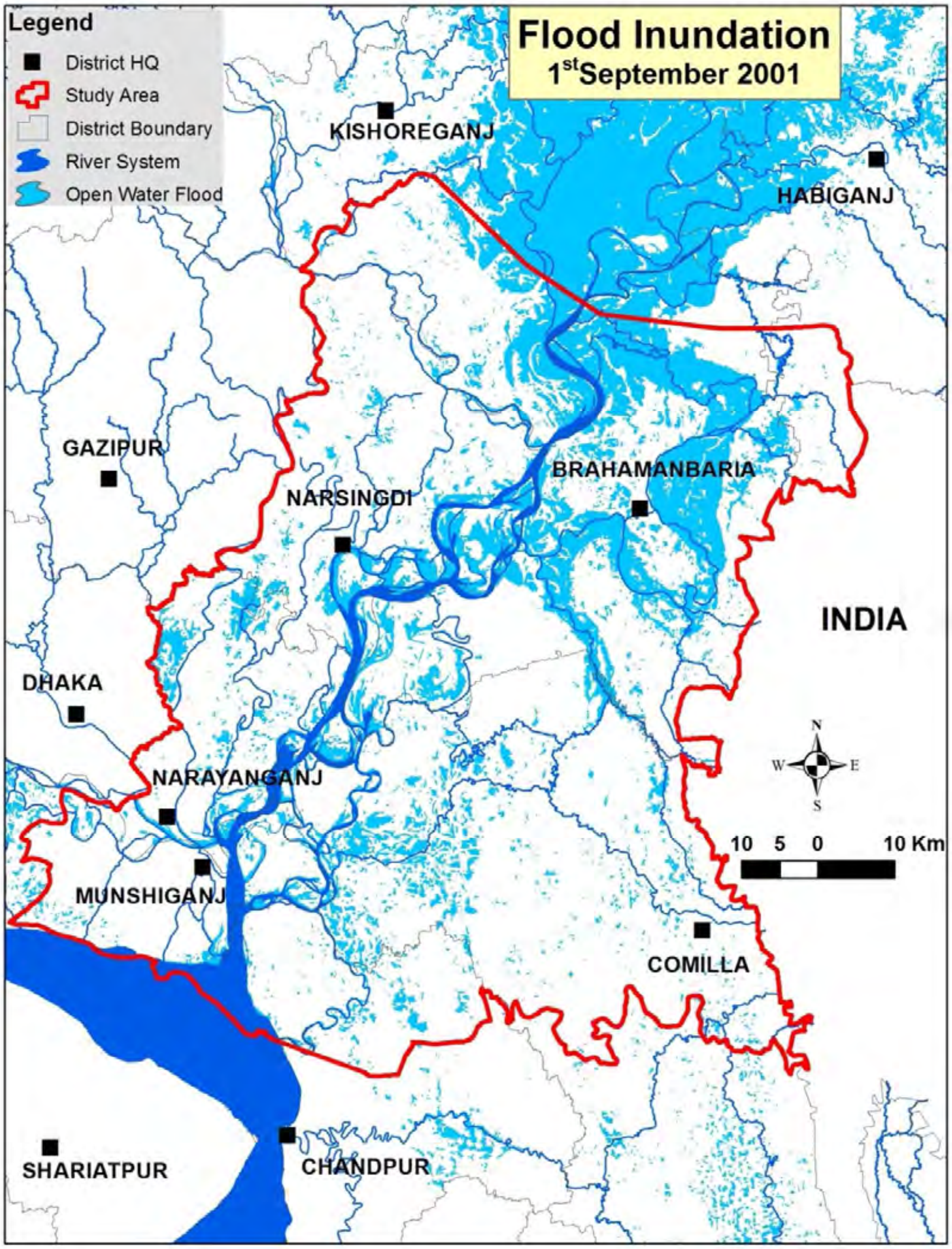


Figure 5.3: Inundation from RADAR sat image of 1st September 2001

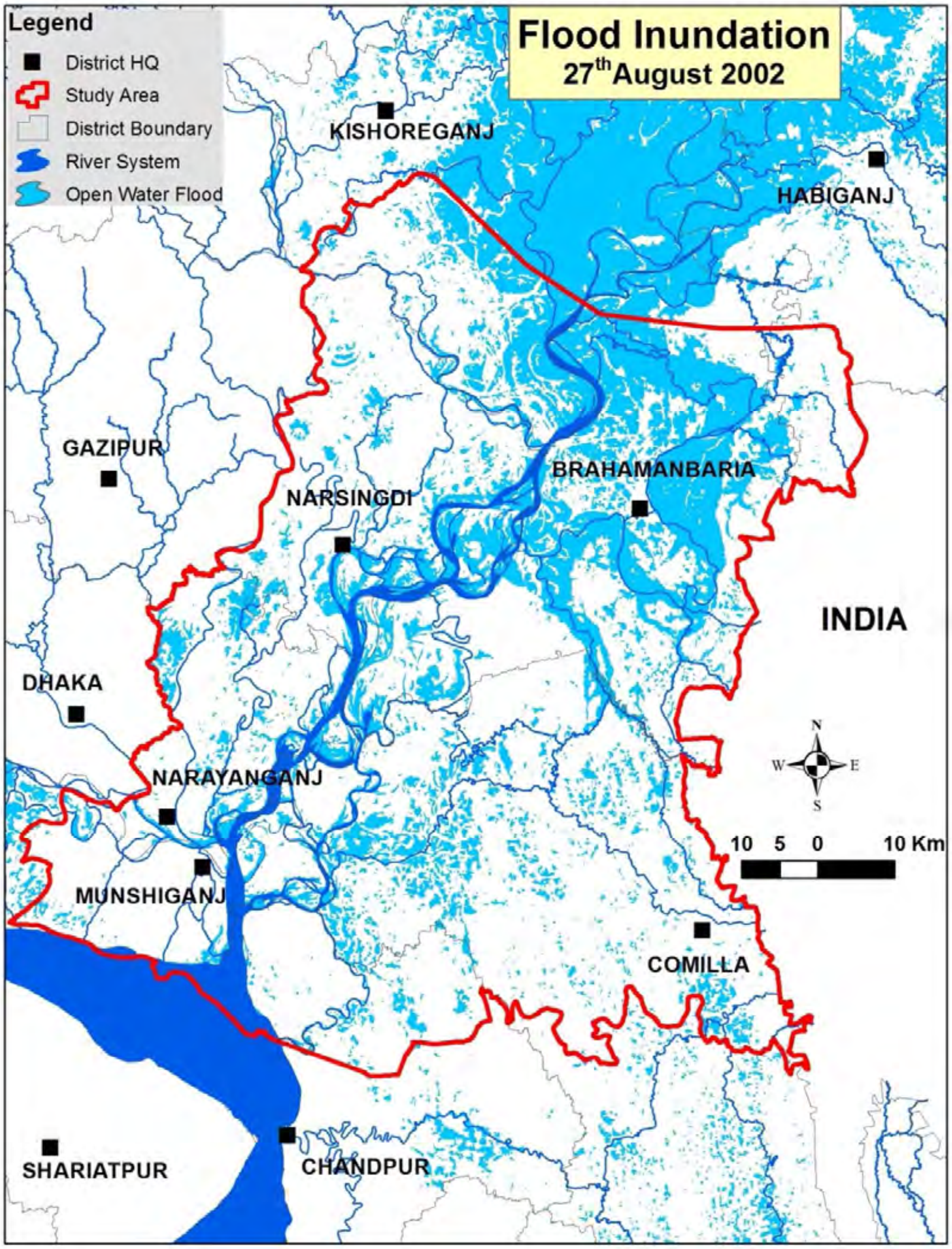


Figure 5.4: Inundation from RADAR sat image of 27th August 2002

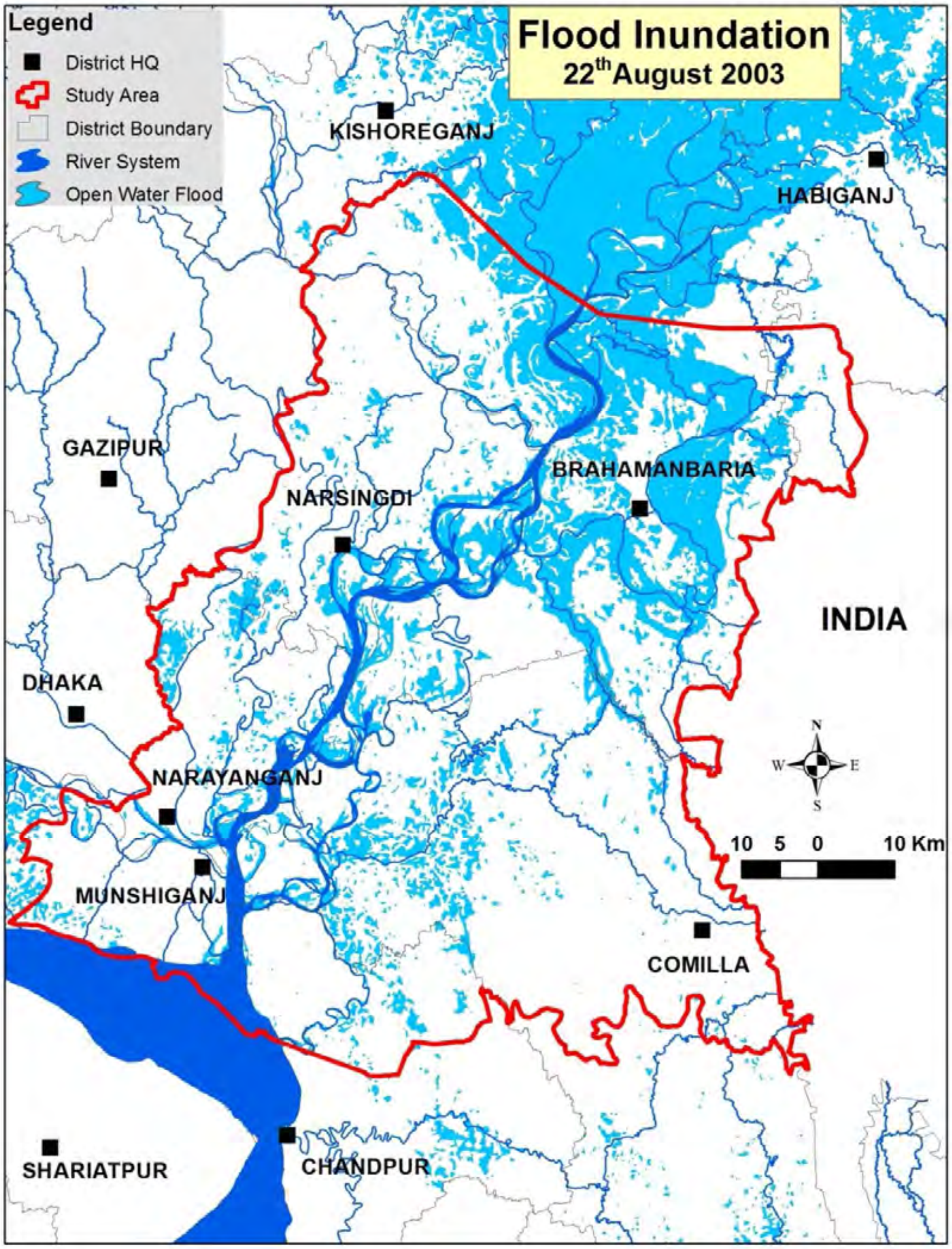


Figure 5.5: Inundation from RADAR sat image of 22nd August 2003

The inundation of the study area during 2000 flood was about 1608 km^2, which is 21.2% of the whole study area. That means about one fifth of the study area was inundated in that flood and about 752 km^2 inundation is found (Table 5.2) in Brahmanbaria only. Inundation is found mainly in the Upper Meghna River, which is obvious and in the part of the Sylhet basin in the study area. Some scattered inundation is found (Figure 5.2) near the main left bank tributary (Gomti River) at outfall to Upper Meghna River.

In 2001 the inundation in the study area is about 1364 km^2, which is about 18% of the whole study area. Brahmanbaria is the most flooded from all about 650 km^2 (Table 5.2 and Table 5.3), as part of the Sylhet basin is situated in the district.

About 1759 km^2 is found from the classified satellite image of 2002 (Figure 5.4) in the study area is, which is about 23% of the whole study area. Brahmanbaria is the most flooded from all about 787.6 km^2 (Table 5.2 and Table 5.3), as part of the Sylhet basin is situated in the district.

In 2003 the inundation in the study area is about 1543 km^2, which is about 20% of the whole study area. Brahmanbaria is the most flooded from all about 744.4 km^2 (Table 5.2 and Table 5.3), as part of the Sylhet basin is situated in the district.

In 2004 the inundation in the study area is about 1873 km^2, which is about 25% of the whole study area. Brahmanbaria is the most flooded from all about 904.5 km^2 (Table 5.2 and Table 5.3), as part of the Sylhet basin is situated in the district.

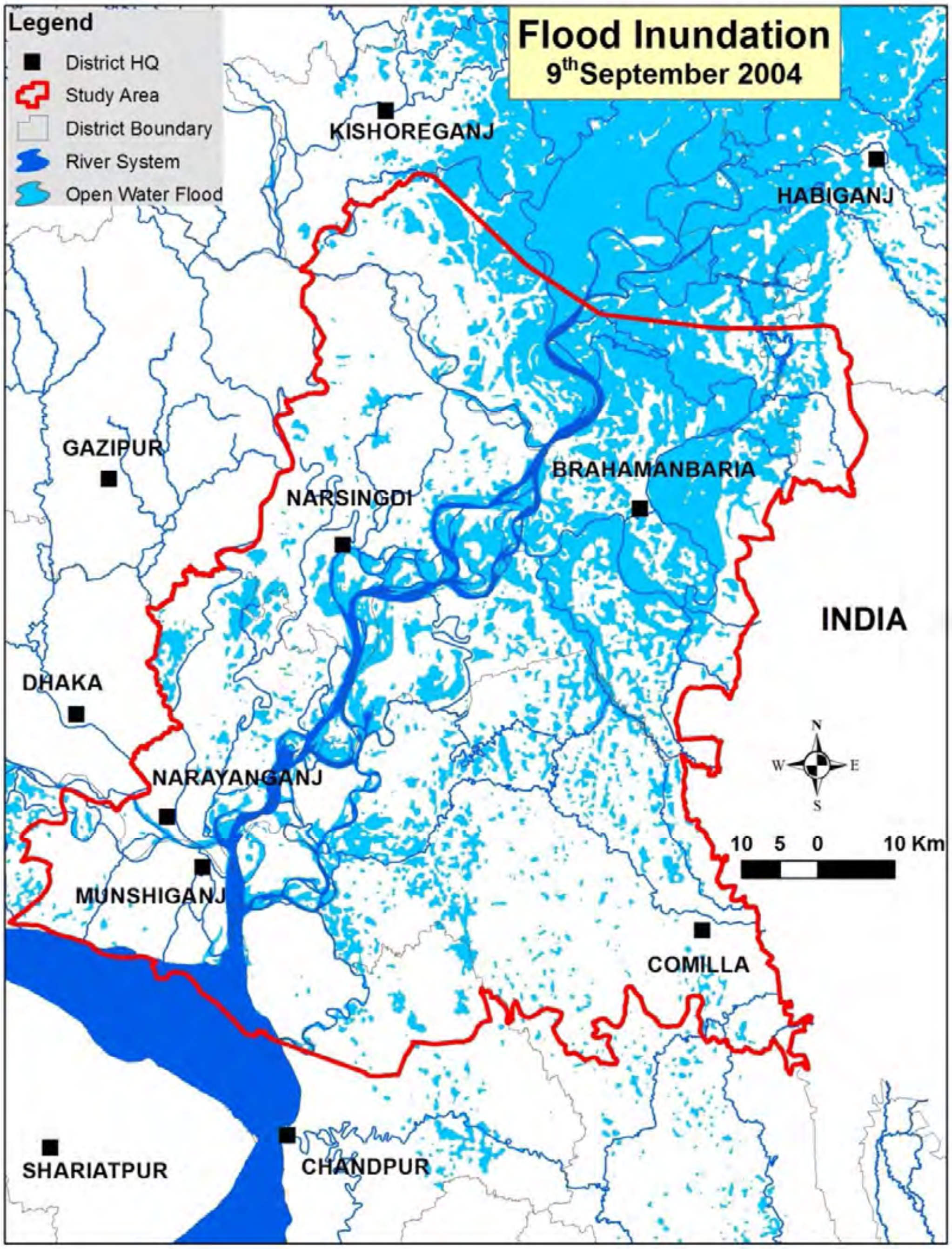


Figure 5.6: Inundation from RADAR sat image of 9th September 2004.

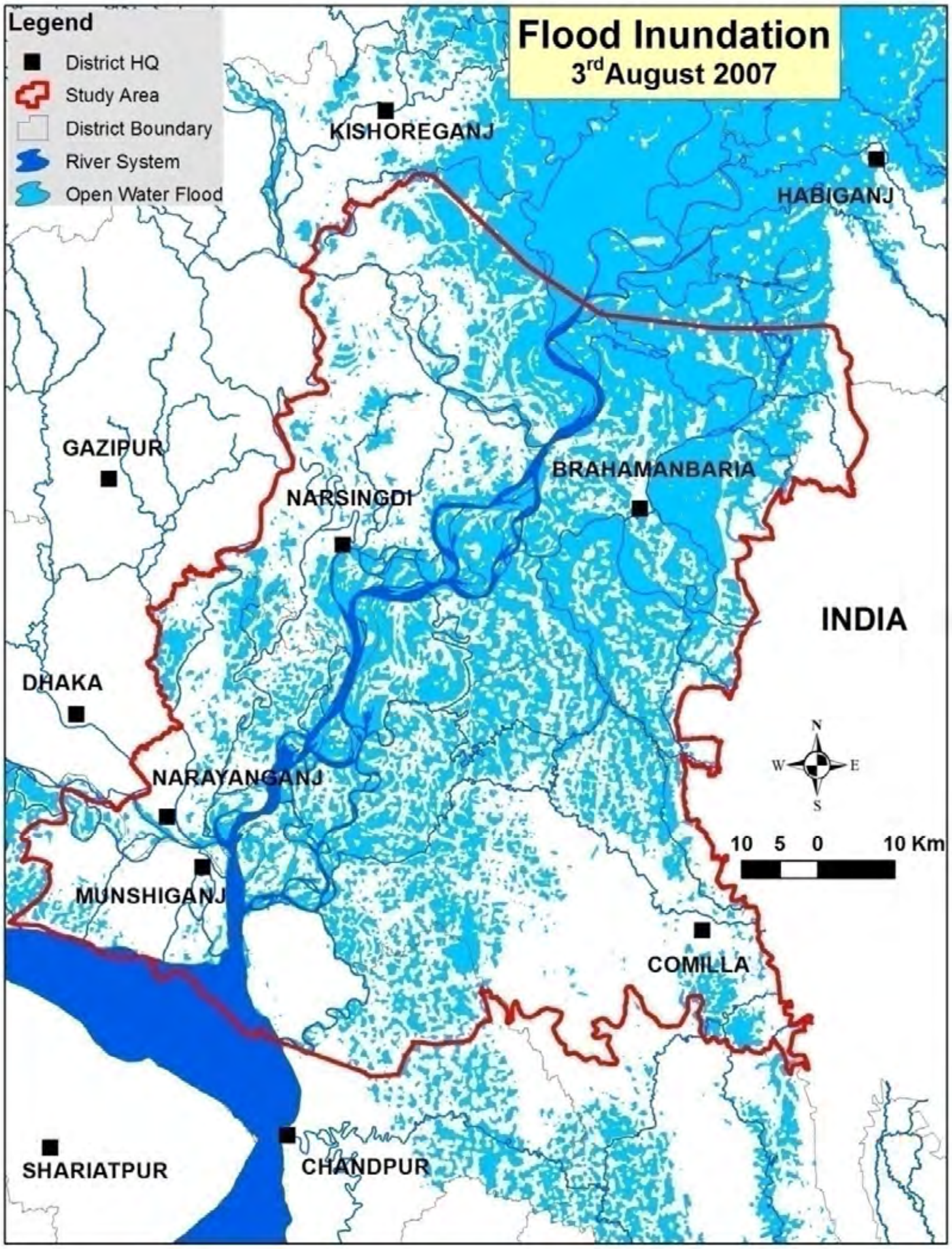


Figure 5.7: Inundation from RADAR sat image of 3rd August 2007

After 1998 flood, the inundation from 2007 is found significant (Figure 5.7) and the inundationin the study area is about 2918 km^2, which is about 38% of the whole study area. Brahmanbaria is the most flooded from all about 1140 km^2 (Table 5.2 and Table 5.3), as part of the Sylhet basin is situated in the district. An interesting this is found from the classified satellite image of the 2007 flood; major part of the Comilla District is found almost unflooded. This clearly states that, Comilla District normally not get the inundation except a flood like 1998. If we quantify the inundation, it says that the part of the Comilla District in the study area about 2086 km^2 and the inundation is about 32% of that part.

Flood incidence has been derived by superimposing all the classified RADAR sat images of monsoon period presented in Figure 5.8.About 1243 km^{2}is 100% flood incidence zone. This means minimum of 1243 km^2 from 1998 to 2007 gets inundated in every monsoon period. In this 100% flood incidence zone excluding river, the physiographic unit named Sylhet Basin has 238 km^2, Old Meghna Estuarine Floodplain has 111 km^2 and Middle Meghna River Floodplain has 96 km^2(Figure 5.10). Among the eight district of the study areaBrahmanbaria has got the most area in the 100% flood incidence zone which is about 584 km^2. Narsingdi has 179 km^2, Kishoregonj has 179 km^2 and Comilla has 121 km^{2}area in the 100% flood incidence zone (Table 5.1).

After analyzing flood incidence map (Figure 5.8) and flood incidence distribution (Figure 5.9) it is evident that about 2569 km^2 in the study area (Table 5.1) never get flooded from 1998 to 2007 which is 0% flood incidence zone. The amount of 100% flood incidence zone is about 1243 km^2 including river. The interesting thing is that after inundation of 100% flood incidence zone, very little area increases with the increase of the flood incidence. That means, when a flood inundates the 100% flood incidence zone, the flooding area doesn’t increase so much with the increase of flood height (Figure 5.10 and Figure 5.11). The Figure 5.11 also reflects the same thing. Because there is very little difference with 100% flood incidence zone with the 71-100% flood incidence zone.

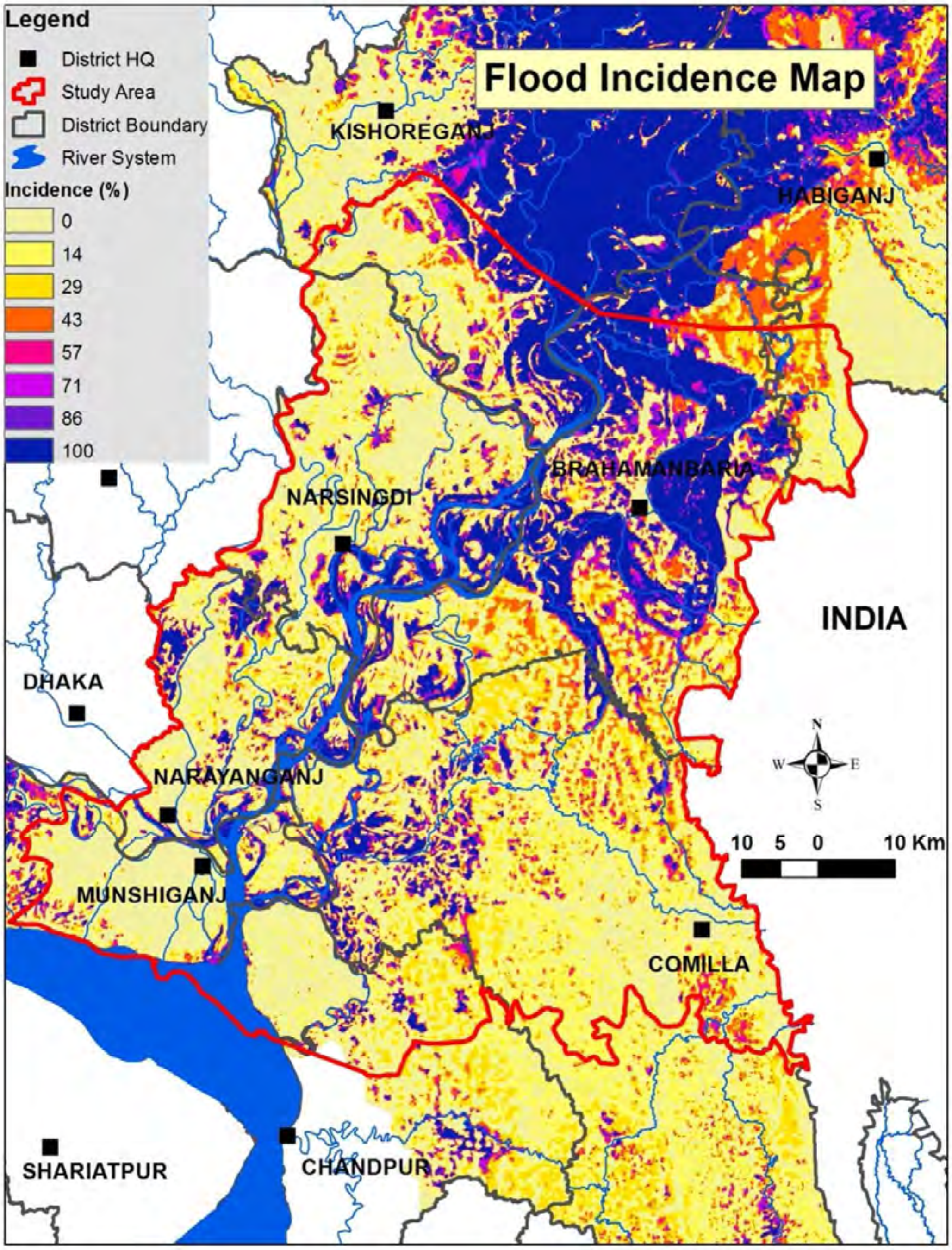


Figure 5.8: Flood incidence map

Table 5.1: District wise area of flood incidence

District	Flood Incidence, %								Study Area (Km^2)
	0	14	29	43	57	71	86	100	
Brahmanbaria (km^2)	308	227	202	151	76	85	112	584	1746
Chandpur (km^2)	228	112	67	16	13	13	14	55	517
Comilla (km^2)	678	671	313	131	71	46	53	121	2085
Habiganj (km^2)	62	56	29	29	6	4	3	5	192
Kishorgonj (km^2)	190	112	46	35	28	26	32	138	608
Munshiganj (km^2)	304	98	35	17	14	13	21	65	566
Narayanganj (km^2)	297	146	69	29	21	19	25	95	701
Narsingdi (km^2)	502	255	82	42	30	30	37	179	1157
Total(km^2)	2569	1676	843	450	258	236	296	1243	7572

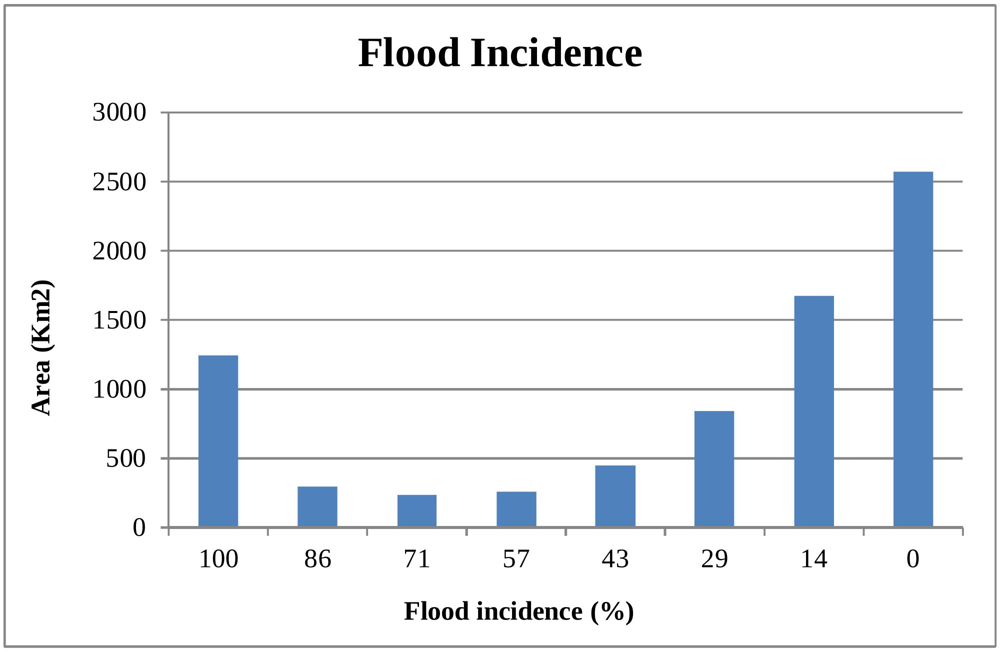
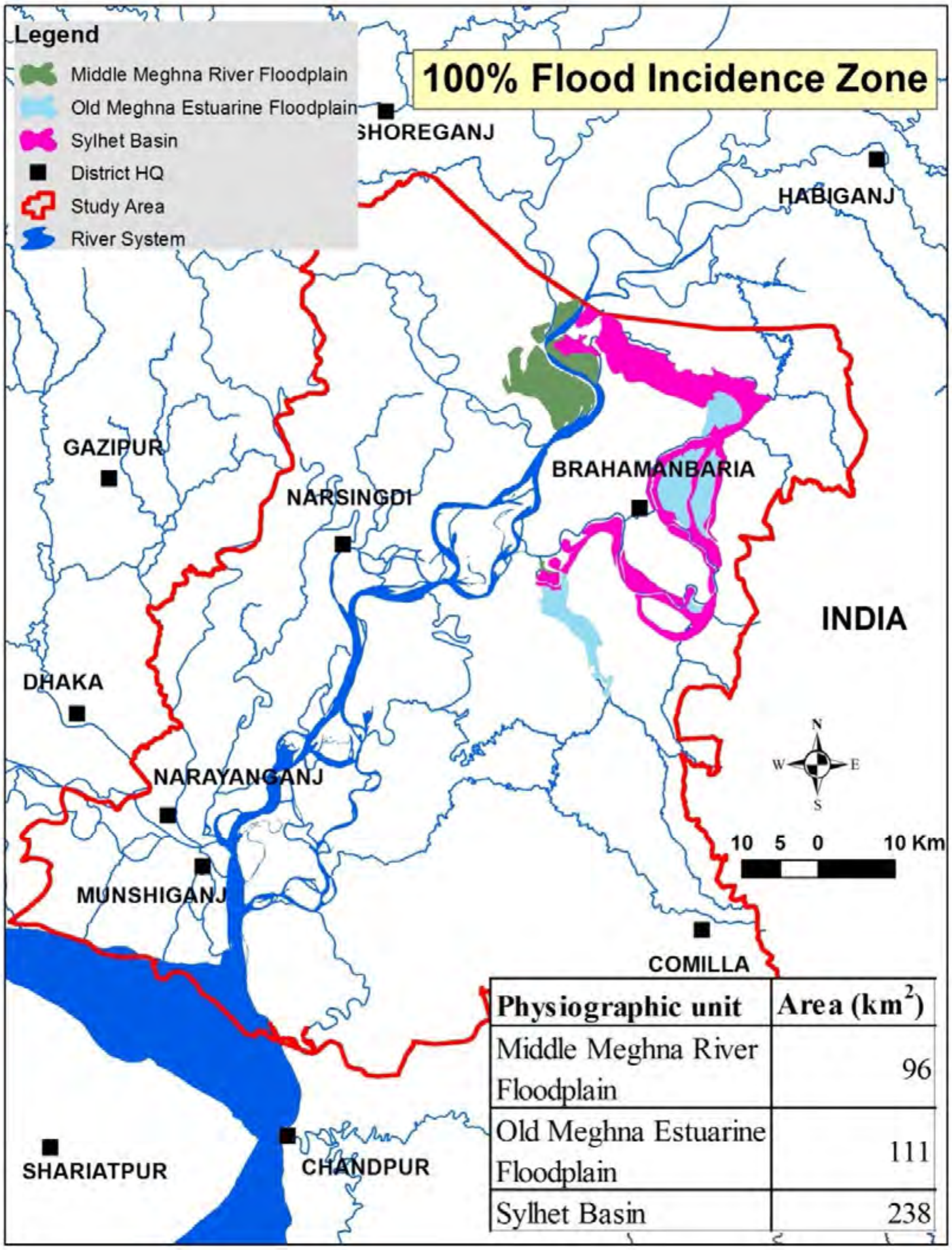


Figure 5.9: Distribution of flood incidence zone



Physiographic unit	Area (km^2)
Middle Meghna River Floodplain	96
Old Meghna Estuarine Floodplain	111
Sylhet Basin	238

Figure 5.10: 100% flood incidence zone

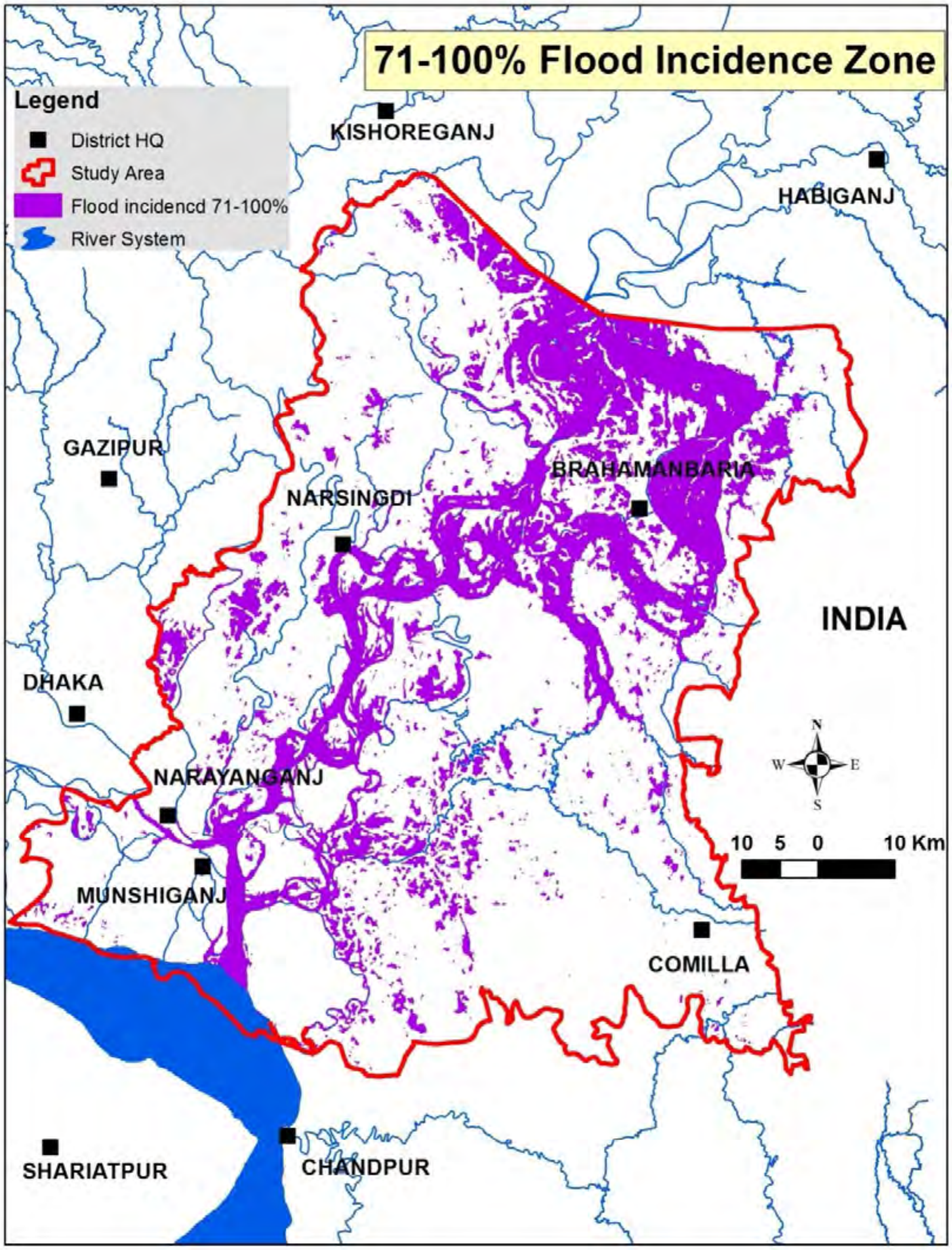


Figure 5.11: 71% to 100% flood incidence zone

RADAR sat satellite images of 1998, 2000, 2001, 2002, 2003, 2004 and 2007 have been used for the calculation of inundation. The flood of 1998 is an extreme case. The return period of 1998 flood is 400 year (Hofer, et al., 2006). About 67.93% of the whole country was in inundated during 1998 flood (Hofer, et al., 2006). From RADAR sat image of 1998 about 58.6% (Table 5.3) of the whole study area was inundated and the amount is about 4444 km^2 (Table 5.2). From 1998 to 2007 the lowest inundation in the monsoon was in 2001, which is about 18%. After 1998 in 2007 about 38.5% of the study area was inundated (Table 5.3) and the amount of inundation is 2919km^2.Figure 5.12 to Figure 5.21 shows that there is an increasing trend in the flooding from 2000 to 2007.Figure 5.1, Figure 5.2, Figure 5.3, Figure 5.4, Figure 5.5, Figure 5.6, Figure 5.7 shows the inundation extant from Radarsat satellite image.

Table 5.2: Inundation from satellite image in the study area

District	Inundation, (km^2)						
	1998	2000	2001	2002	2003	2004	2007
Brahmanbaria	1326.4	752.3	650.7	787.6	744.4	904.5	1139.6
Chandpur	232.5	42.8	41.0	45.4	46.9	41.5	120.5
Comilla	1282.2	229.0	189.7	294.7	203.9	298.7	685.1
Habiganj	125.7	13.3	7.8	12.8	12.6	46.8	74.2
Kishorgonj	387.9	179.2	150.1	218.9	184.0	211.5	268.3
Munshiganj	181.7	73.6	55.4	63.6	65.6	60.6	119.0
Narayanganj	345.9	124.5	103.7	114.8	108.4	111.5	209.6
Narsingdi	562.1	193.1	165.8	221.6	177.0	197.6	302.3
Total	4444.5	1607.9	1364.1	1759.4	1542.8	1872.8	2918.7

Table 5.3:Inundation from satellite image compared to the study area

District	Inundation, (in % compared to amount of study area)						
	1998	2000	2001	2002	2003	2004	2007
Brahmanbaria	75.9	43.0	37.2	45.0	42.6	51.7	65.2
Chandpur	44.9	8.3	7.9	8.8	9.0	8.0	23.3
Comilla	61.5	11.0	9.1	14.1	9.8	14.3	32.8
Habiganj	65.1	6.9	4.0	6.6	6.5	24.2	38.5
Kishoreganj	63.8	29.5	24.7	36.0	30.3	34.8	44.2
Munshiganj	32.1	13.0	9.8	11.2	11.6	10.7	21.0
Narayanganj	49.3	17.7	14.8	16.4	15.4	15.9	29.9
Narsingdi	48.6	16.7	14.3	19.1	15.3	17.1	26.1
Total	58.6	21.2	18.0	23.2	20.4	24.7	38.5

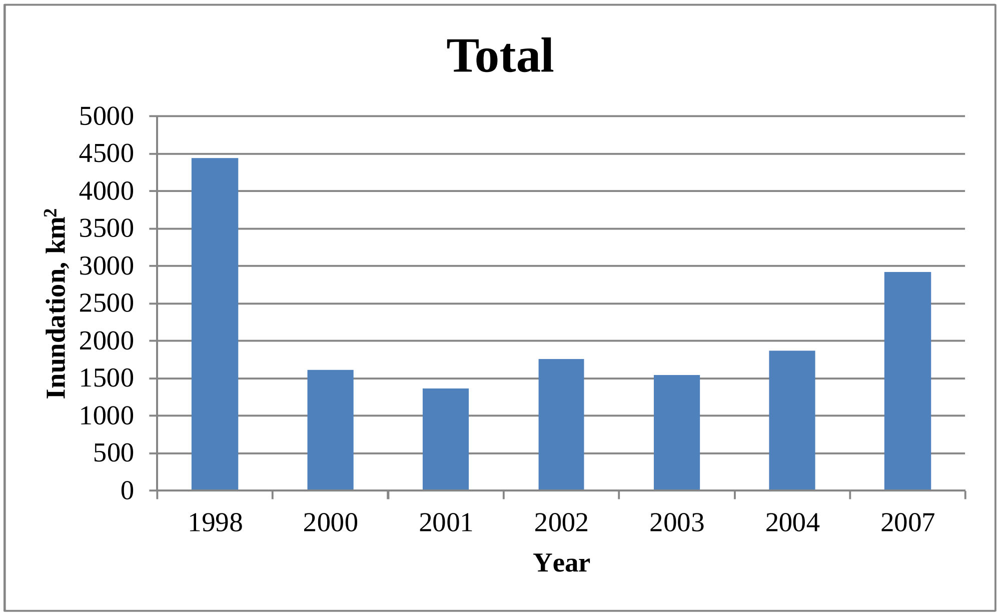


Figure 5.12: Total inundation in the study area from satellite image

Figure 5.13: District index map in the study area

The area of Comilla district is 3083.8 km^2. About 68% of the Comilla district lies in the study area which is 2086.3 km^2 (Table 4.1 and Figure 5.13). In 1998 about 1282 km^2 has inundated by flood which is about 61.5% compared to the portion of the Comilla district in the study area. From 2000 to 2004 the inundation of Comilla district in the study area varies from 189 km^2 to 299 km^2 which is about 9% to 15% of the study area (Figure 5.14). The inundation of 2007 in Comilla district is about half of the inundation compared to that of the 1998 flood, which is about 685km^2 (32.8%) (Table 5.2andTable 5.3).

Habiganj district has about 2587.2 km^2 spatial area and about 7% of the Habiganj district lies in the study area which is 193 km^2 (Table 4.1 andFigure 5.13). The 1998 has inundation on Habiganjabout125.7 km^2, which is about 65.1% compared to the portion of the district in the study area. From 2000 to 2004 the inundation of Habiganj district in the study area varies from 7.8 km^2 to 46.8 km^2 which is about 4% to 24.2% of the study area. The inundation of 2007 in Habiganj district is about 74.2 km^2(38.5%) (Table 5.2&Table 5.3), which is significant after 1998 flood (Figure 5.15).

The area of Brahmanbaria district is 1921 km^2. About 91% of the Brahmanbaria district lies in the study area which is 1748.5 km^2 (Table 4.1 and Figure 5.13). In 1998 about 1326.4 km^2 has inundated by flood which is about 75.9% compared to the part of the district in the study area. From 2000 to 2004 the inundation of Brahmanbaria district in the study area varies from 650 km^2 to 904 km^2 which is about 37% to 57% of the study area (Table 5.2 & Table 5.3). The inundation of 2007 in Brahmanbaria district is about 1139.6 km^2 (65.2%) which is only about 10% less than the 1998 flood. Though the 1998 has greater than 400 year return period (considering inundation), the inundation of 2007 flood is little bit closer to the 1998 flood for Brahmanbaria district. This is because almost half of the left bank of the Upper Meghna River coincide with the district boundary of the Brahmanbaria district (Figure 5.13). So whenever this part of the river overtops the left bank, the very first district to spread out the flood water is Brhamanbaria.

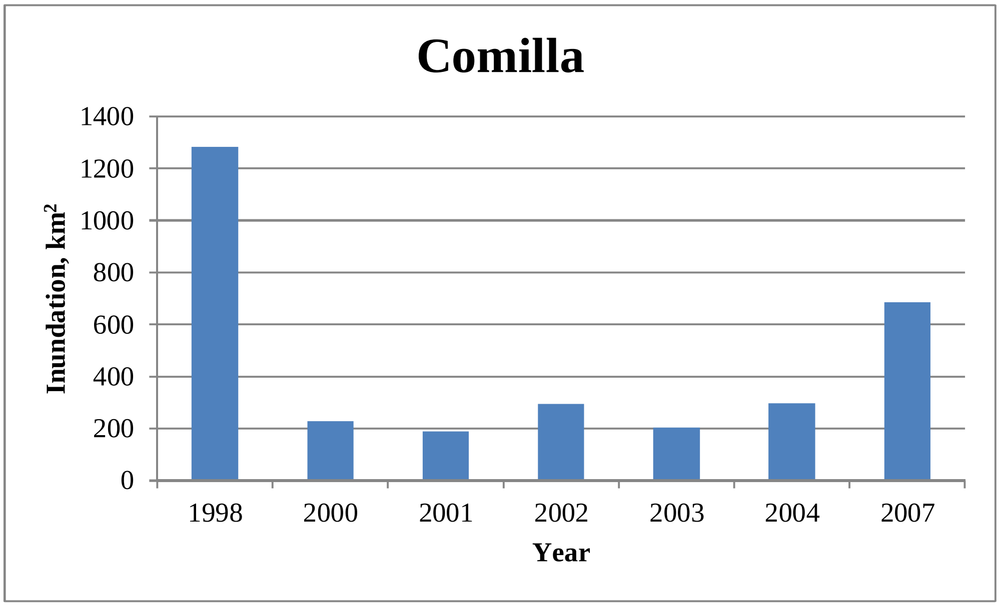


Figure 5.14: Inundation from satellite image in Comilla

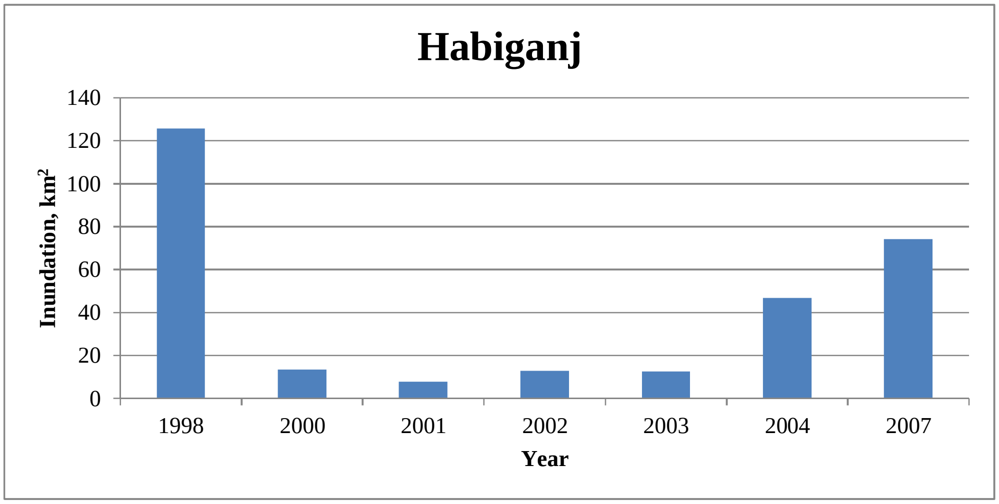


Figure 5.15: Inundation from satellite image in Habiganj

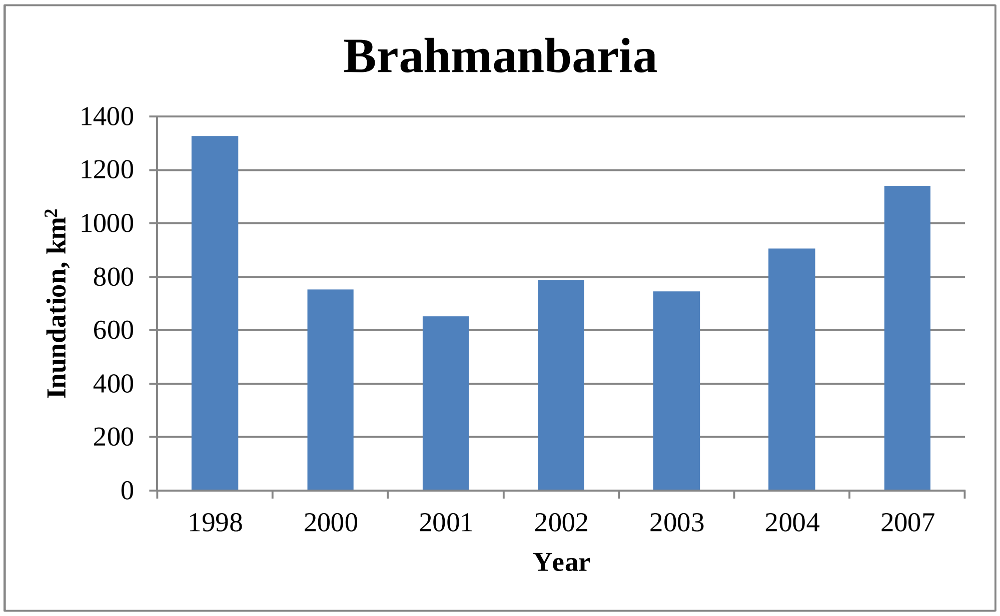


Figure 5.16: Inundation from satellite image in Brahmanbaria

The Kishoregonj district has an area of 2611.4 km^2 and about 23% of the Kishoregonj district lies in the study area which is 607.5 km^2 (Table 4.1 and Figure 5.13). In 1998 about 387.9 km^2 has inundated by flood which is about 63.8% compared the portion of the district in the study area. From 2000 to 2004 the inundation of Kishoregonj district in the study area varies from 150 km^2 to 219 km^2 which is about 24% to 36% of the portion of study area of Kishoregonj. The inundation of 2007 in Kishoregonj district is significant after 1998 flood (Figure 5.18), which is about 268.3 km^2 (44.2%) (Table 5.2andTable **5.3**). This is because, some part of the boundary of Kishoregonj district coincide with the upstream right bank of the Upper Meghna River which has also some influence of the Haor.

The area of Munshiganj district is 932 km^{2}and about 61% of the district lies in the study area which is 566 km^2 (Table 4.1 andFigure 5.13). In 1998 about 181.7 km^2 has inundated by flood which is about 32.1% of the part of study area of the Munshiganj. From 2000 to 2004 the inundation of Comilla district in the study area varies from 55 km^2 to 73.6 km^2 which is about 9% to 13% of the study area in the district. The inundation of 2007 in Munshiganj district is significant after of the 1998 flood (Figure 5.19), which is about 119 km^2 (21%) (Table 5.2 & Table 5.3). There is an important things that the part of the Munshuganj closer to the downstream part of the Upper Meghna River is Old Meghan Estuarine Floodplain (Brammer, 2000) and flood can't reach there even in the extreme event like 1998 flood.

The area of Narayanganj district is 701 km^2 and about 100% of the Narayanganj district lies in the study area which is 701 km^2 (Table 4.1 and Figure 5.20). In 1998 about 345.9 km^2 has inundated by flood which is about 49.3% of the study area in Narayanganj. From 2000 to 2004 the inundation of Narayanganj district in the study area varies from 189 km^2 to 299 km^2 which is about 9% to 15% of the study area. The inundation of 2007 in Narayanganj district is about half of the inundation compared to that of the 1998 flood, which is about 685 km^2 (32.8%) (Table 5.2 and Table 5.3).

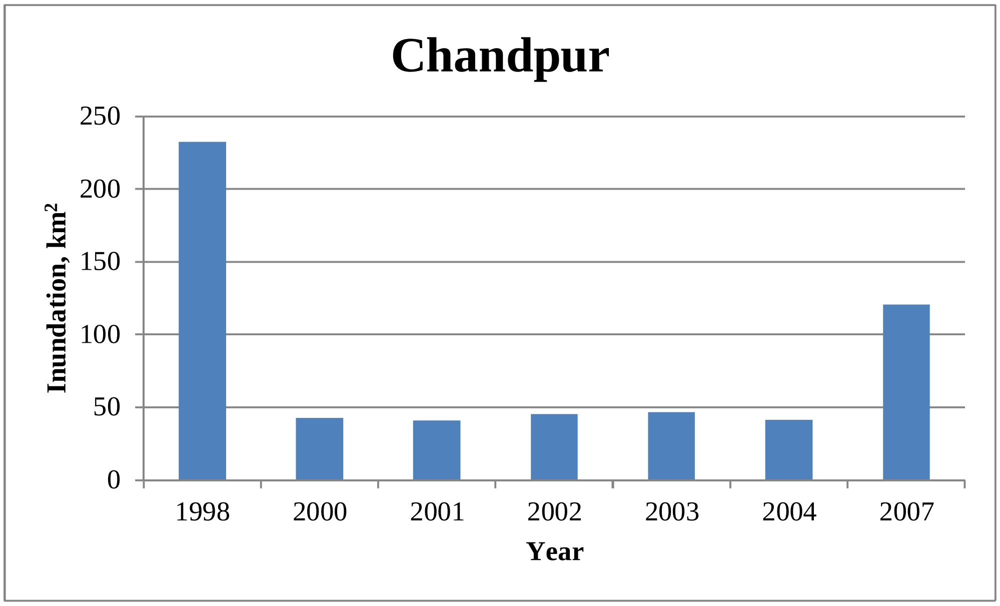


Figure 5.17: Inundation from satellite image in Chandpur

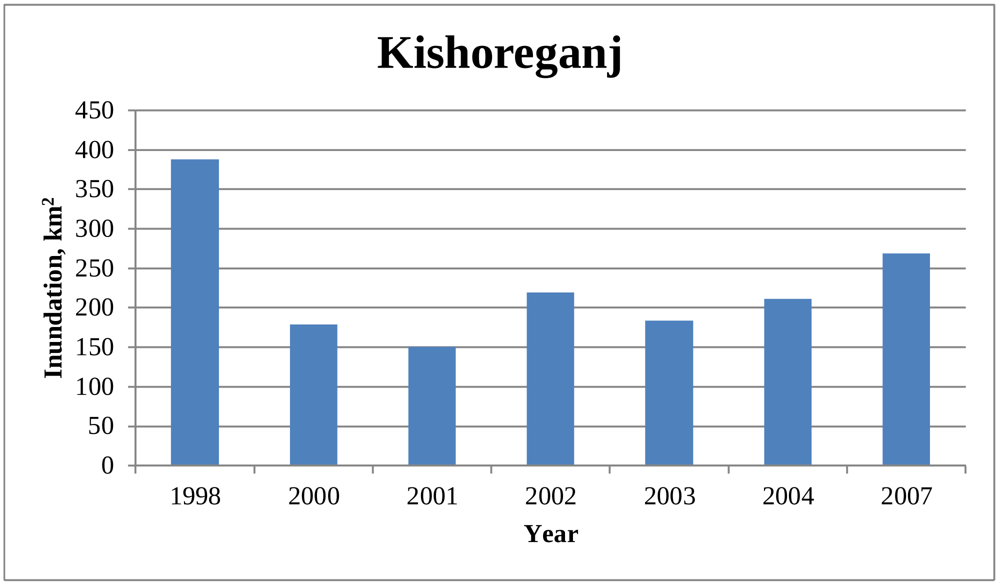


Figure 5.18: Inundation from satellite image in Kishoreganj

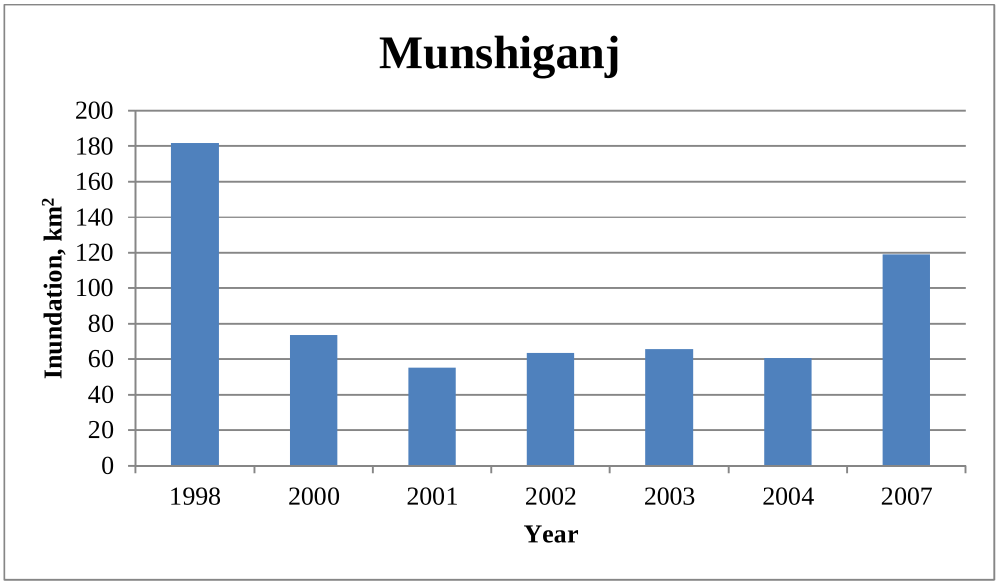


Figure 5.19: Inundation from satellite image in Munshiganj

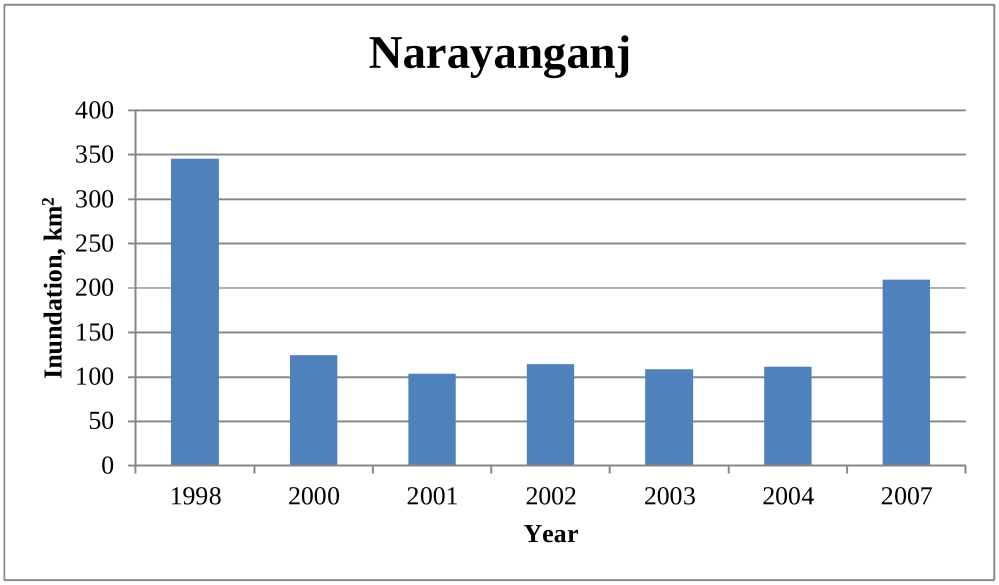


Figure 5.20: Inundation from satellite image in Narayanganj

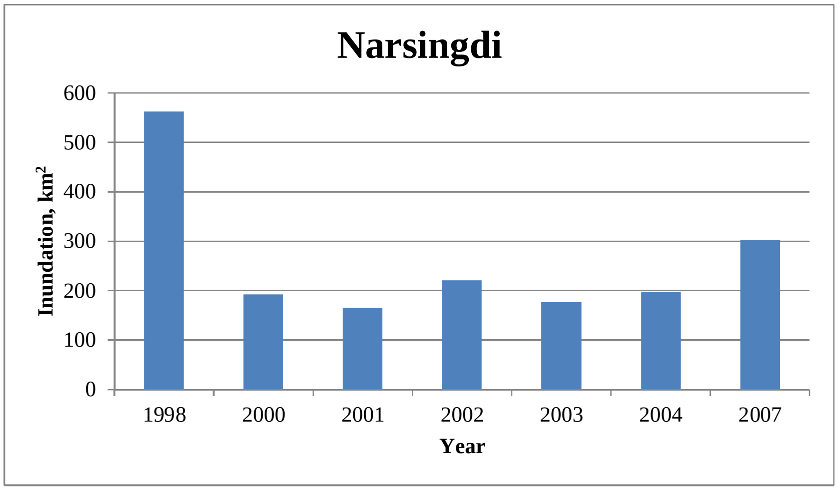


Figure 5.21: Inundation from satellite image in Narsingdi

The area of Chandpur district is 1697.9 km^2. About 31% of the Chandpur district lies in the study area which is 518 km^2 (Table 4.1 andFigure 5.13). In 1998 about 232.5 km^2 has inundated by flood which is about 44.9% compared to the part of the Chandpur in the study area. From 2000 to 2004 the inundation of Chandpur district in the study area varies from 41 km^2 to 47 km^2 which is about 8% to 9% of the study area. The inundation of 2007 in Chandpur district is about half of the inundation compared to that of the 1998 flood (Figure 5.17), which is about 120 km^2 (23.3%) (Table 5.2 and Table 5.3).

The area of Narsingdi district is 1167 km^2. About 99% of the Narsingdi district lies in the study area which is 1157 km^2 (Table 4.1 andFigure 5.13). In 1998 about 562 km^2 has inundated by flood which is about 48.6% of the study area in Narsingdi. From 2000 to 2004 the inundation of Narsingdi district in the study area varies from 165 km^2 to 221 km^2 which is about 16.7% to 19.1% of the study area. The inundation of 2007 in Narsingdi district is significant after the 1998 flood, which is about 302 km^2 (26.1%) (Table 5.2 and Table 5.3).

5.3 Mathematical Model

The adopted modelling approach appears in Figure 5.22. Five sequential steps have been followed to achieve the study objectives: model study plan, data collection and analysis, model setup, calibration and validation and option simulations.

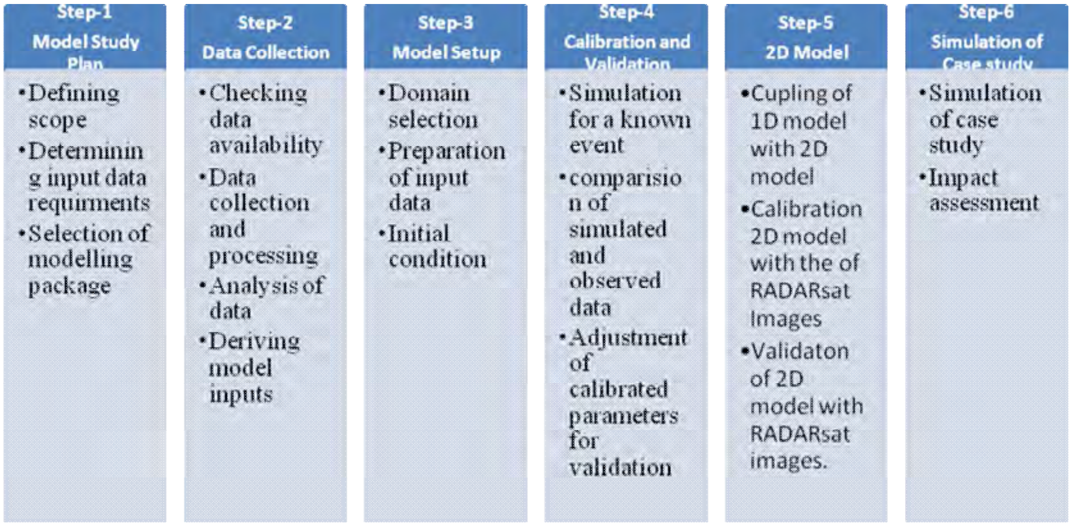


Figure 5.22:Overallmodelling approach

SOBEK 1D model has been used to investigate the hydrodynamic process of the Upper Meghna River. SOBEK is the name of a highly sophisticated software package, which in concise technical terms is a one and two-dimensional open-channel dynamic numerical modelling system, equipped with the user shell and which is capable of solving the equations that describe unsteady water flow, salt intrusion, sediment transport, morphology and water quality. It can be simulated and solved these problems in river management, flood protection, design of canals, irrigation systems, water quality, navigation and dredging. This programme works with the complete de Saint Venant Equations, including transient flow phenomena and backwater profiles (Deltares 2014).

5.3.1 Development of 1D Model

Model Setup

All the collected data has been processed and analyzed to the extent of deriving necessary model inputs. A model domain is then selected from the river network model.

Domain Selection

The domain includes Upper Meghna River which has two tributaries Dhaleswari River and Gomti River. The model domain starts from Bhairab Bazar and continues up to 97.5km downstream to Satnal. Dhaleswari River, which is a right bank tributary of the Upper MeghnaRiver is included in the model domain from Hariharpara to Kalagachia about 16.2 km. In addition to that the 54.5 km of Gomti River, which is the left bank tributary of the Upper Meghna River has also been included in the model domain.

Cross section and Bathymetric data

A cross-section is defined as an input element of SOBEK in which the shape and size of the river profiles perpendicular to the flow is described. In SOBEK model, these cross sections must be given as the relations between the vertical and the width of cross-section. The cross-section data have been collected from BWDB for 2000.The datum of the cross section data is PWD datum.

Along the Upper Meghna River15 cross sections have been taken for model input. In addition to that seven cross sections for the Gomti River and two cross sections for the Dhaleswari River that are obtained from the BWDB have also been used as model inputs.

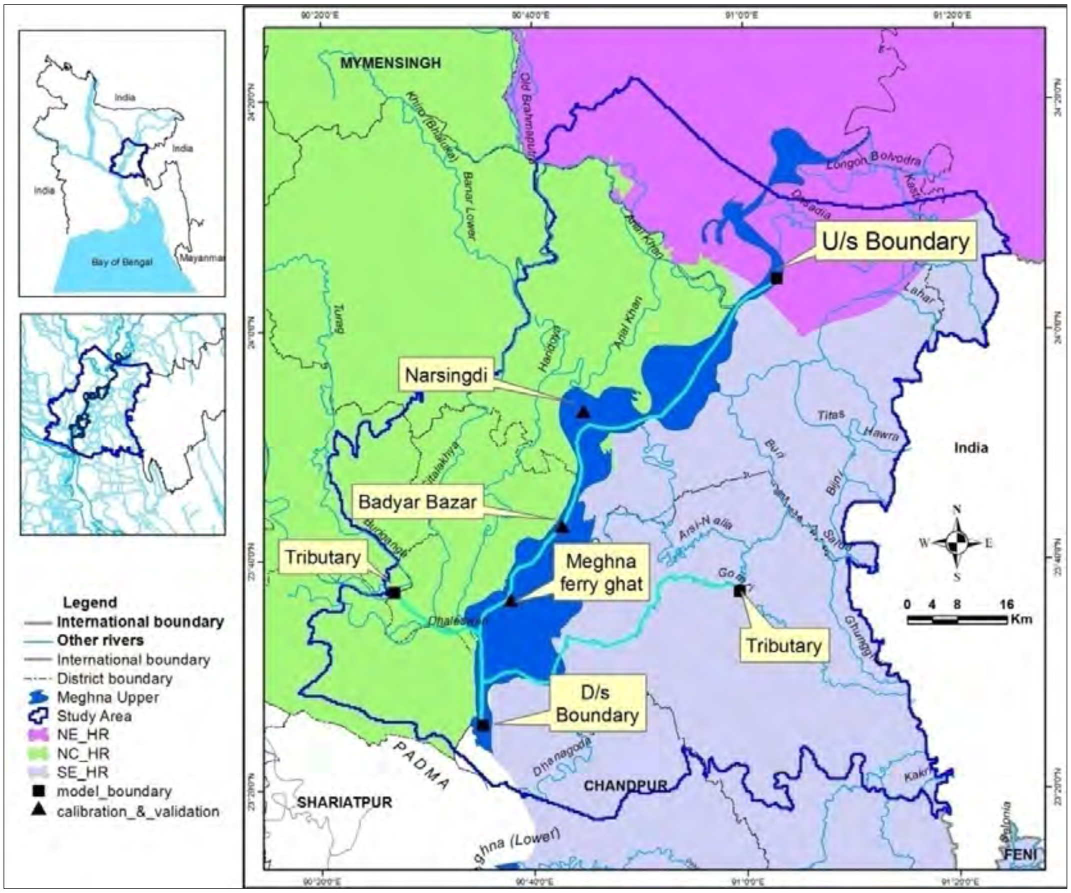


Figure 5.23: Computational domain of the model for Upper Meghna River

Model boundaries

There are two boundaries in the model. Two boundaries are on the Upper Meghna River. Bhairab Bazar station has been taken as the upstream discharge boundary. Downstream boundary has been taken at the Satnal water level station which is situated at the 97.5 km downstream from the upstream boundary.Jibanpur discharge station has been taken as the discharge boundary for the Gomti river tributary and Hariharpurdishcharge station has been taken as another discharge boundary for the Dhaleswari River which is the right bank tributary of Upper Meghna River.

Model Simulation

Based on the availability of the most recent cross section, water level and discharge data, the model has been simulated for year of 2000. The simulations have been conducted for water level, water depth, unit discharge, discharge and velocity. The computational grid points have been placed at every 2000 m interval in the main river and for tributary it has been taken 1000m.

Model calibration and validation

Once a model setup is completed, the model has to be calibrated and validated against observed data to determine its ability to reproduce the actual phenomena observed in the field. Model calibration is a trial and error process in which some model parameters are adjusted and fine-tuned until a reasonable agreement between simulated results and observed data is achieved. The resistance parameter is the major controlling calibration parameter for the hydrodynamic model. Manning's 'n' has been chosen as resistance parameter for the model. After calibration, the model has to be validated another set of observed data different from those used for model calibration.

The model has been calibrated for the period July 2000 to September 2000 for 3months and validated for July 2004 to September 2004. It has been calibrated against BWDB daily water level data at stations of Narsingdi, Badyar Bazar, and Meghna Ferry ghat (Figure 5.23). The calibrated Manning's 'n' value during the model calibration has been given in Table 5.4.

The visual comparison of observed and simulated water level for the above two stations during both calibration and validation have been given in Figure 5.24andFigure 5.26. It is evident that the model results are in reasonable agreement with the observed data for both of the stations during calibration and validation. The model can simulate the water level and discharge in the whole network.

Table 5.4: The calibrated values of Manning's n for different river reaches

Si.	River	Reach	Manning's n
1	Upper Meghna	Bhairab bazar to Narsingdi	0.03
		Narsingdi to Dhaleswari confluence	0.034
		Dhaleswari Confluence to Satnal	0.03
4	Dhaleswari	Hariharpara to Kalagachia	0.03
5	Gomti	Jibanpur to Upper Meghna	0.03

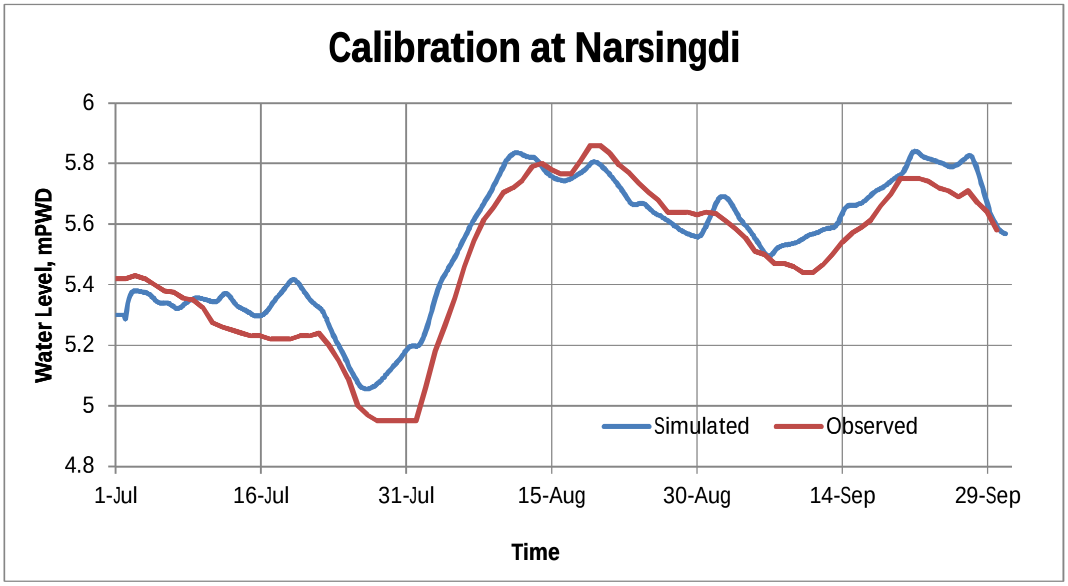


Figure 5.24: Calibration at Narsingdi from July 2000 to September 2000

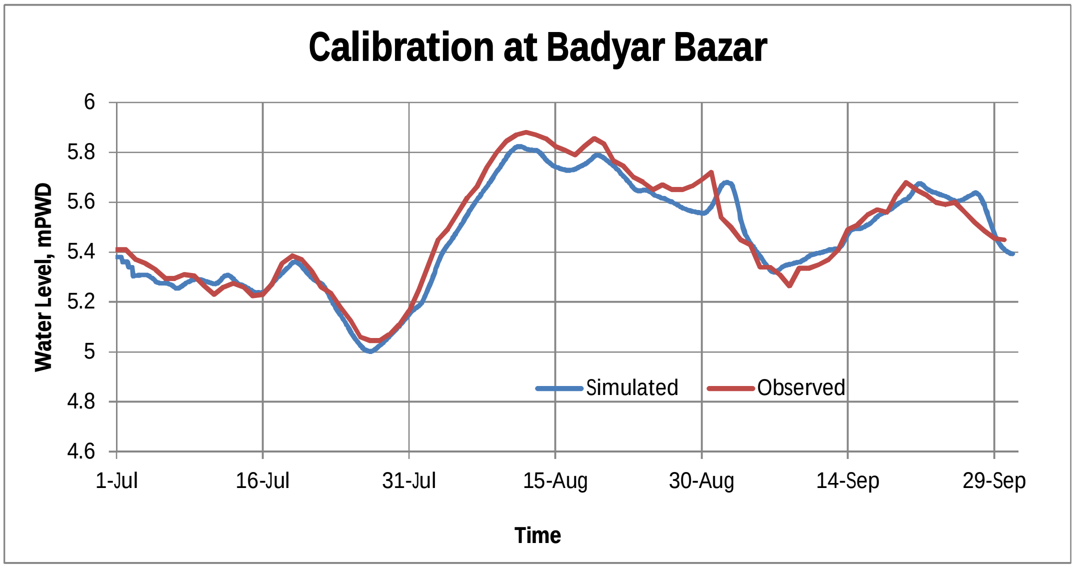


Figure 5.25: Calibration at Badyar Bazar from July 2000 to September 2000

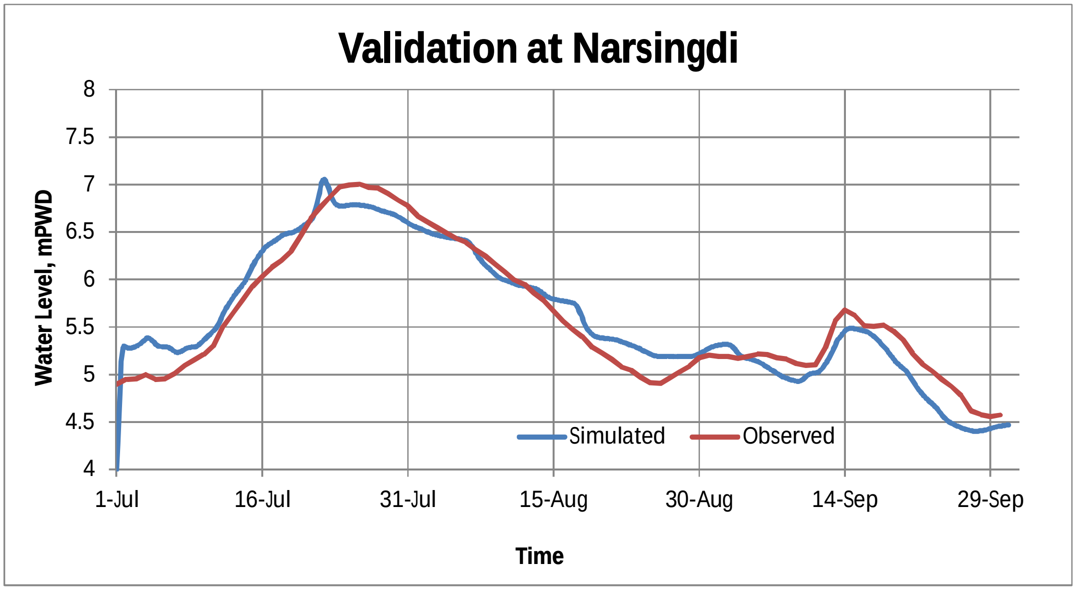


Figure 5.26: Validation at Narsingdi from July 2004 to September 2004

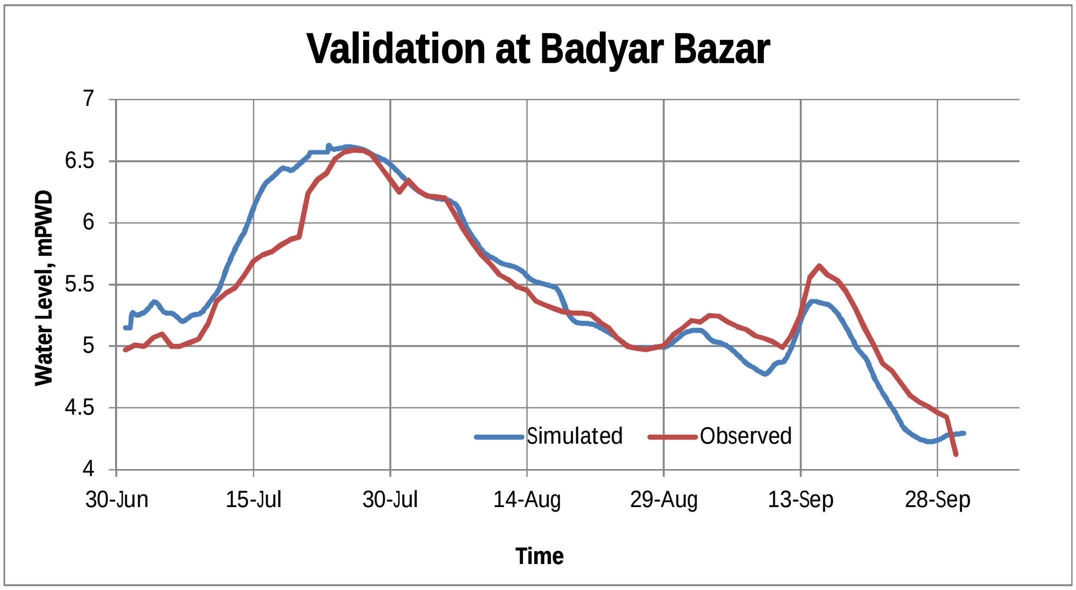


Figure 5.27: Validation at Badyar Bazar from July 2000 to September 2000

5.3.2 Development of 2D Model

2D model domain

The 2D model domain has been set up taking physiographic unit into consideration. The model domain is about 7975.53 km^2. The study area has the areal contribution of 10 districts. The main physiographic unit which are within the study area are Old

Meghna Estuarine Floodplain, Middle Meghna River Floodplain, Old Brahmaputra Floodplain, Sylhet Basin.

Coupling of 1D model with 2D model

Calibrated and validated 1D model has been coupled with 2D overland flow module of the SOBEK modeling package. The time frame of the 2D overland flow model has taken same as the time of Radarsat imagery. For the better flow distribution to the floodplain the 2D overland flow model has been simulated for one month same as the month from the date of satellite imagery.

Model calibration and validation (2D)

Once the2D model setup has completed, the inundation from 2D overland model has to be calibrated and validated against theinundation from Radarsat imagery to determine its ability to reproduce the actual flooding phenomena in the field. 2D Model calibration is a trial and error process in which the main step is to make the 2D surface as same as the in the nature is. The major changes made to the surface is consist of putting roads, embankments and other major floodplain feature which is not present in the 2D surface. The 2D surface of the floodplain has been adjusted and fine-tuned until a reasonable agreement between simulated inundation and results and observed inundation from satellite images have been achieved. After calibration, the model has to be validated with another satellite image different from that used for model calibration.

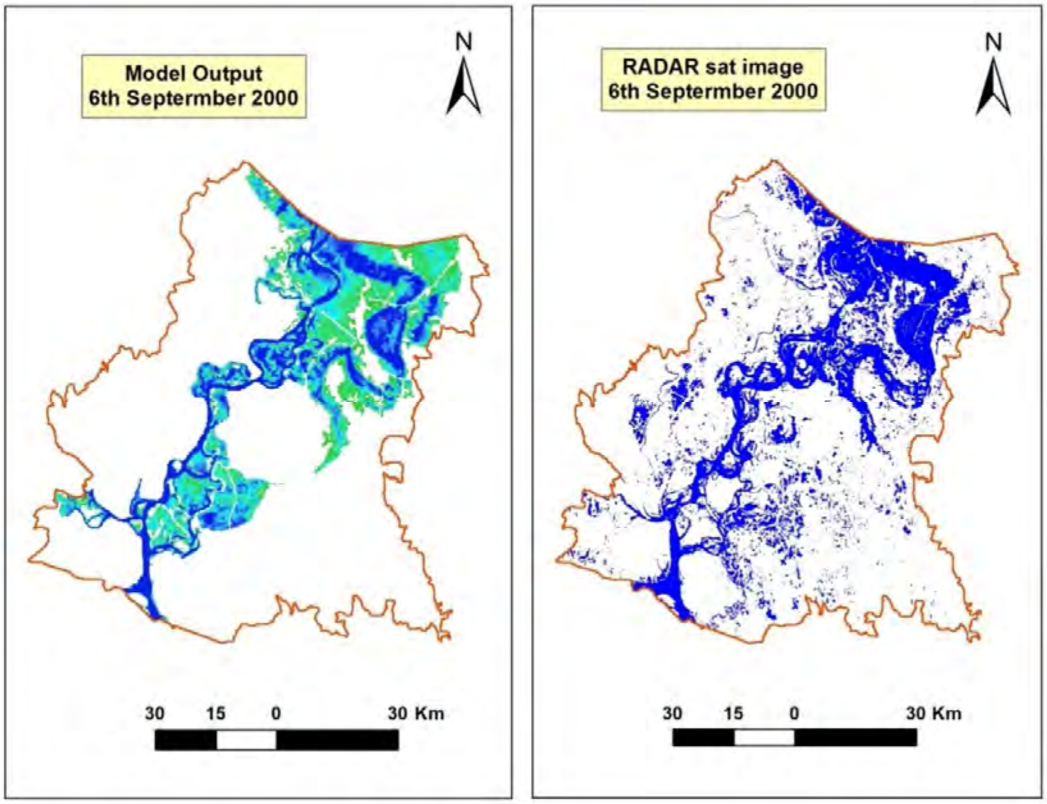


Figure 5.28:Inundation from satellite image and model output

The model has been calibrated for the period 6th September 2000 for one month and validated for 9th September 2004. It has been calibrated and validated against classified Radarsat images.

The visual comparison of observed and simulated inundation both calibration and validation have been given in Figure 5.28 and Figure 5.29. It is evident that the model results are in reasonable agreement with the observed data for calibration and validation. Now the model can simulate the water level, discharge and inundation in the whole network and study area.

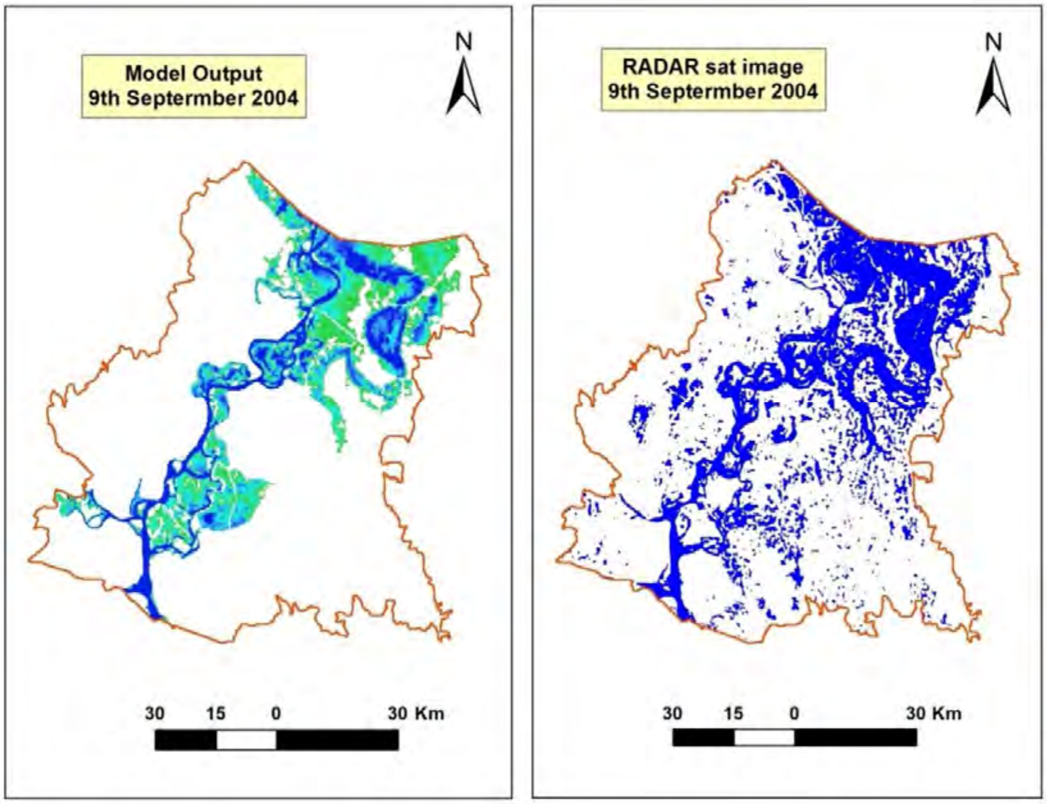


Figure 5.29: Inundation from satellite image and model output

5.4 Model Results

5.4.1 Inundation

Inundation from model has been derived by simulating the model in the time of available satellite image. The calibrated and validated model in both 1D and 2D has been simulated to determine the inundation in 26th August 1998, 6th September 2000, 1st September 2001, 22nd August 2003 and 9th September 2004. As the flood of 1998 is the flood of return period of 400 years (Hofer, et al., 2006), so it is obvious that the inundation of 1998 from model would be extreme about 4975 km^2. The inundation from model varies 1500 to 1800 km^2 from 2000 to 2004 (Table 5.5). The total inundation of 2000 and 2001 in the study area is almost same about 1600 km^2. The amount of F0, F1, F2 and F3 land type is also same in 2000 and 2001 according to model result (Table 5.5).

Table 5.5: Inundation from model output

Land Type	Inundation in Km^2				
	1998	2000	2001	2003	2004
F0 (0-30 cm)	339	171	164	171	190
F1 (30-90 cm)	1085	614	572	570`	634
F2 (90-180 cm)	1511	656	597	697	613
F3 (180-360 cm)	2040	210	180	250	362
Total	4975	1651	1513	1688	1800

Flood inundation of 1998 flood from model is almost similar to model output of 1998 flood simulation (Figure 5.30 and Figure 5.31). There is little bit exception of water body which is not connected to the main stream flow. The disconnected water body from main stream cannot be simulated on model. Disconnected water body observed from satellite image (Figure 5.31) is more or less smaller in quantity if we compare it to the model output of 1998 flood simulation (Table 5.6). The model output of 1998 flood is about 4975 km^2 and the inundation from satellite image is 4445 km^2. The difference is about 12% which is acceptable. The detail comparison of output from model simulation and from satellite image is made in article 5.5

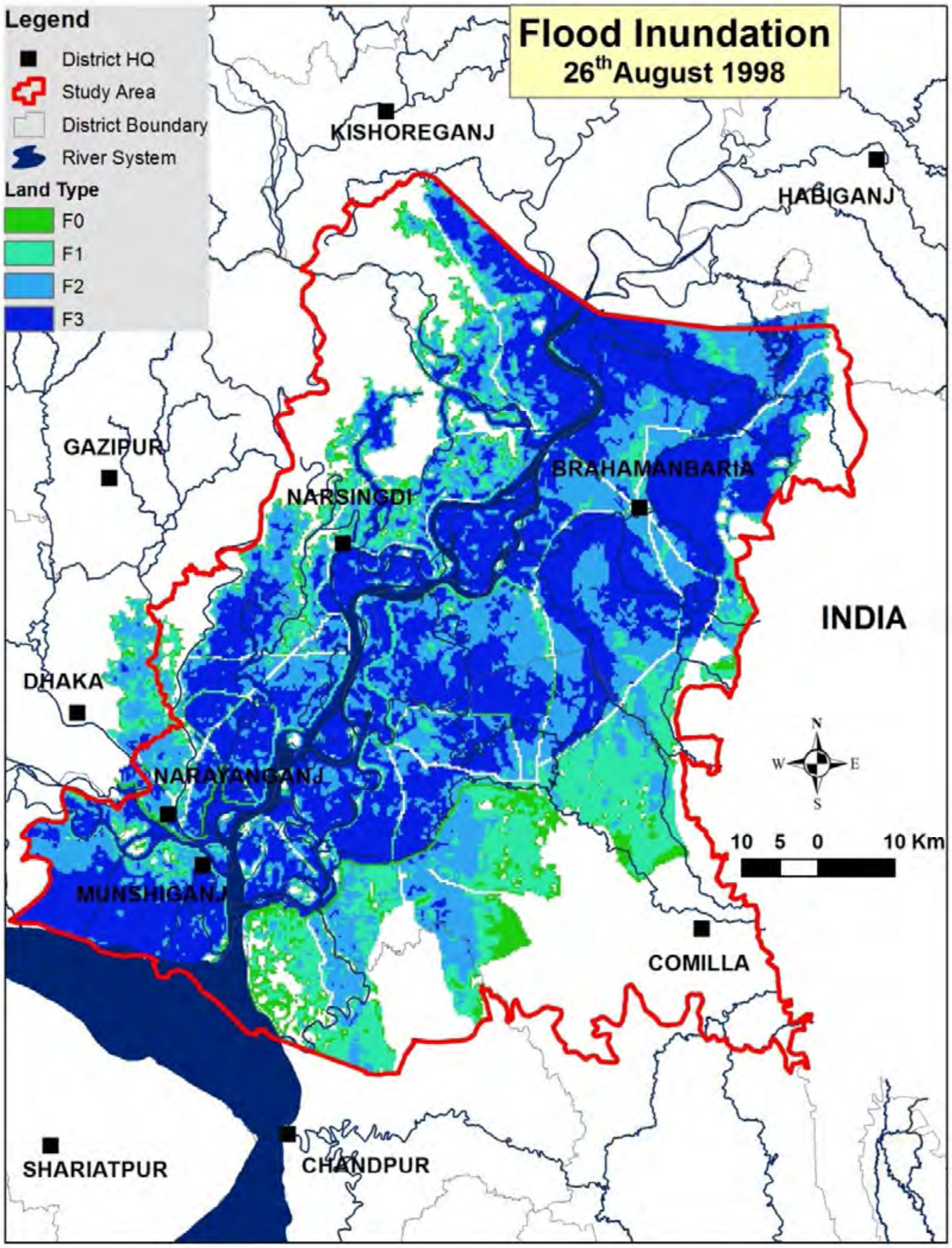


Figure 5.30: Flood depth map of 26th August 1998 from model output

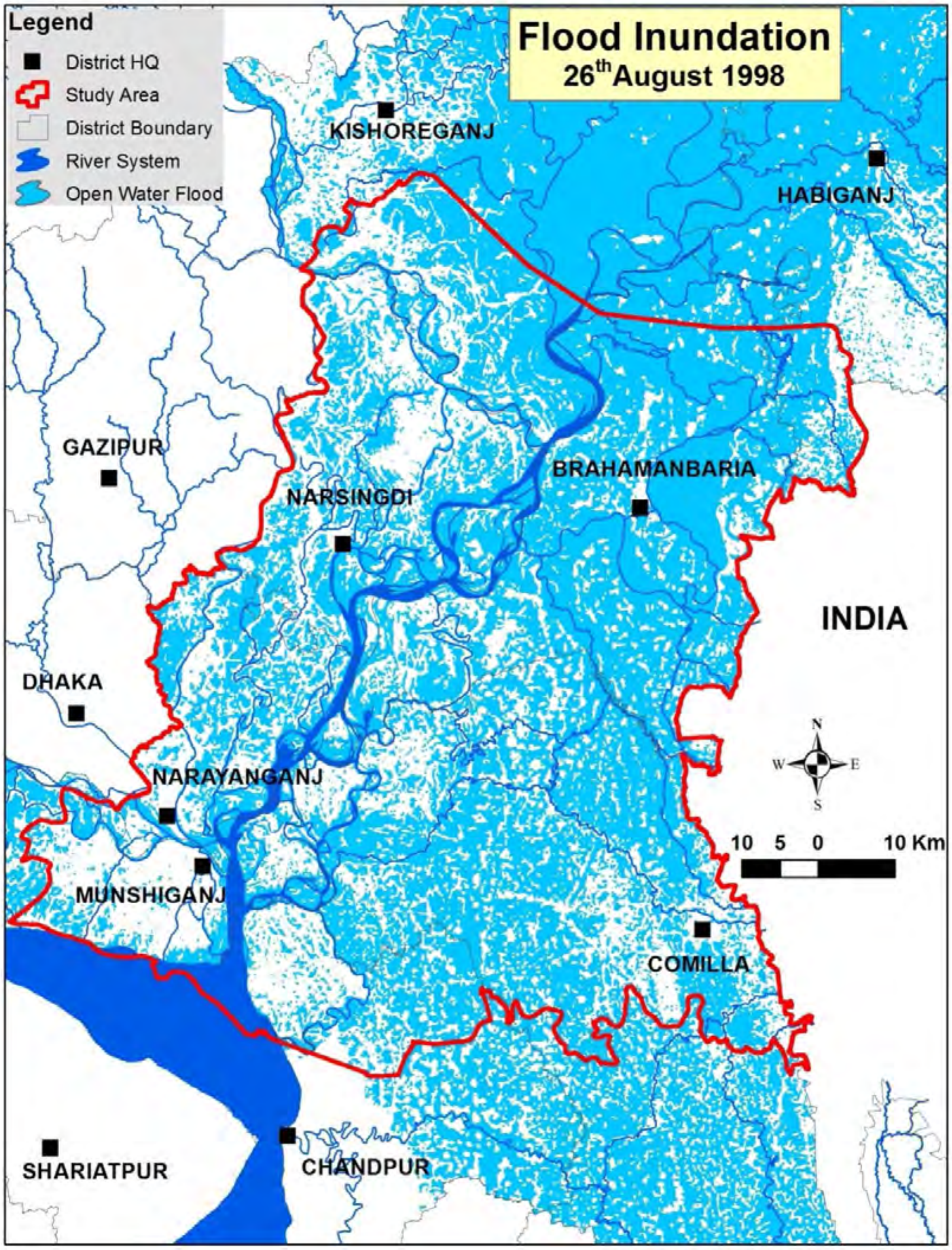


Figure 5.31: Flood Inundation of 1998 from Radarsat satellite image

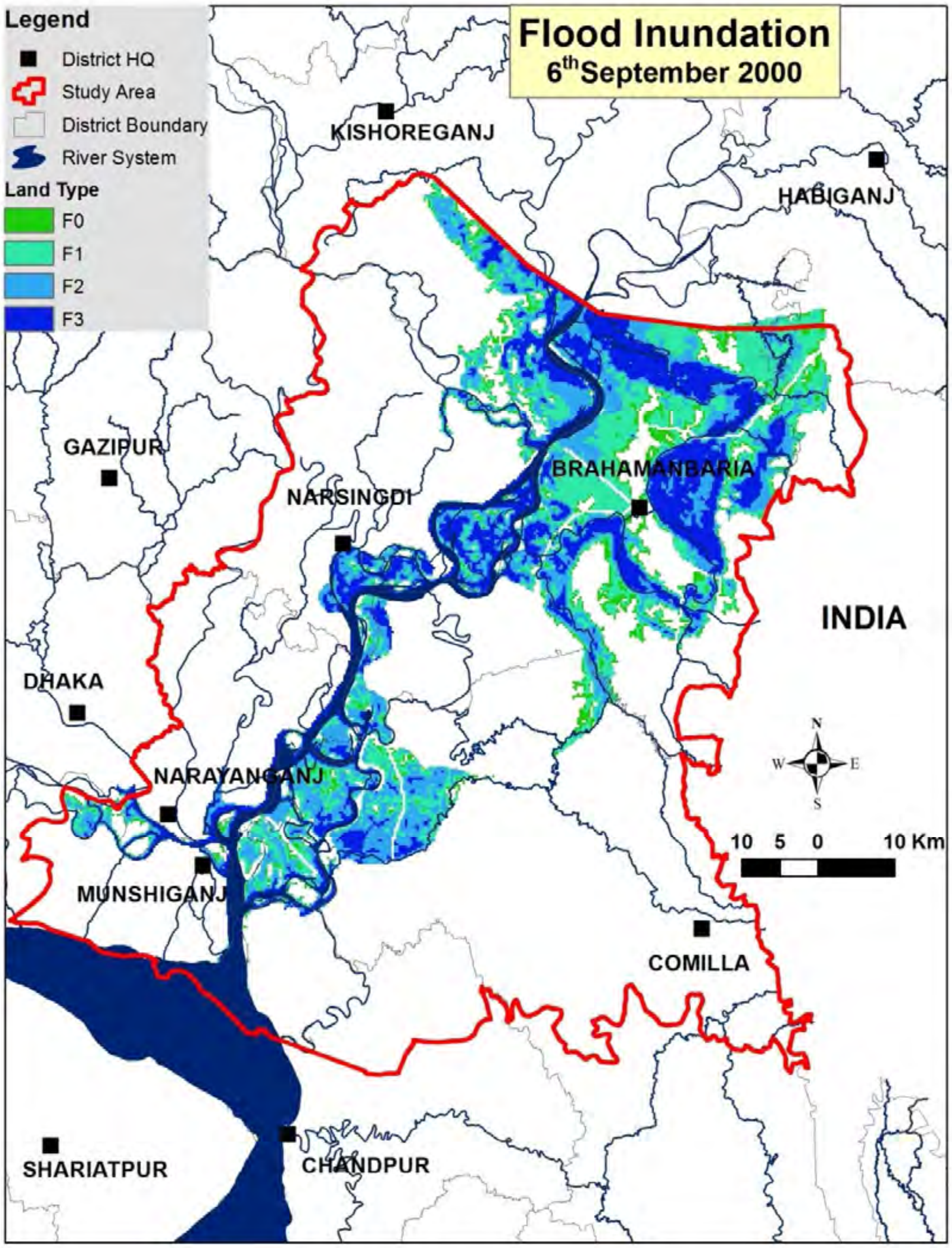


Figure 5.32: Flood depth map of 6thSeptember 2000 from model output

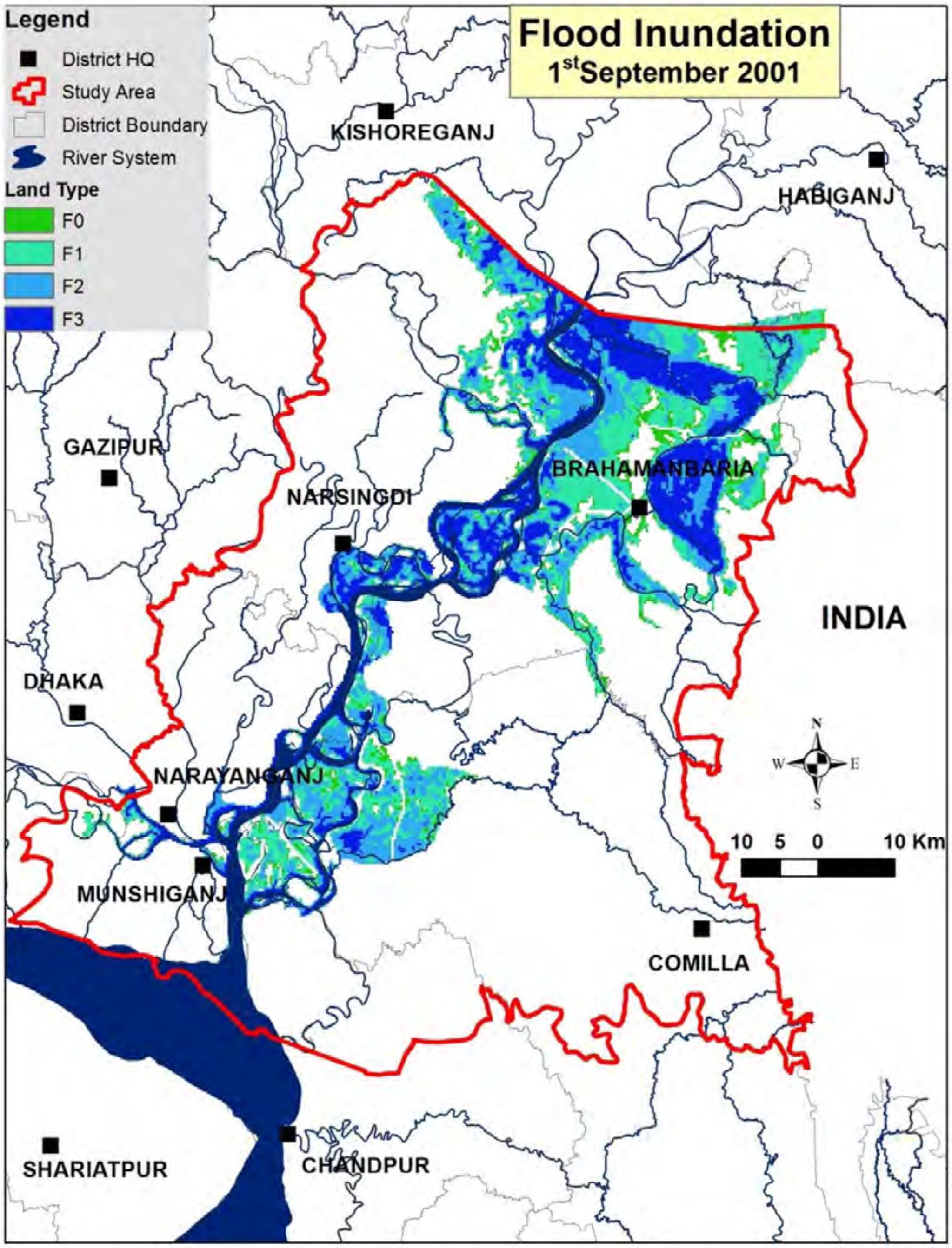


Figure 5.33: Flood depth map of 1stSeptember 2001 from model output

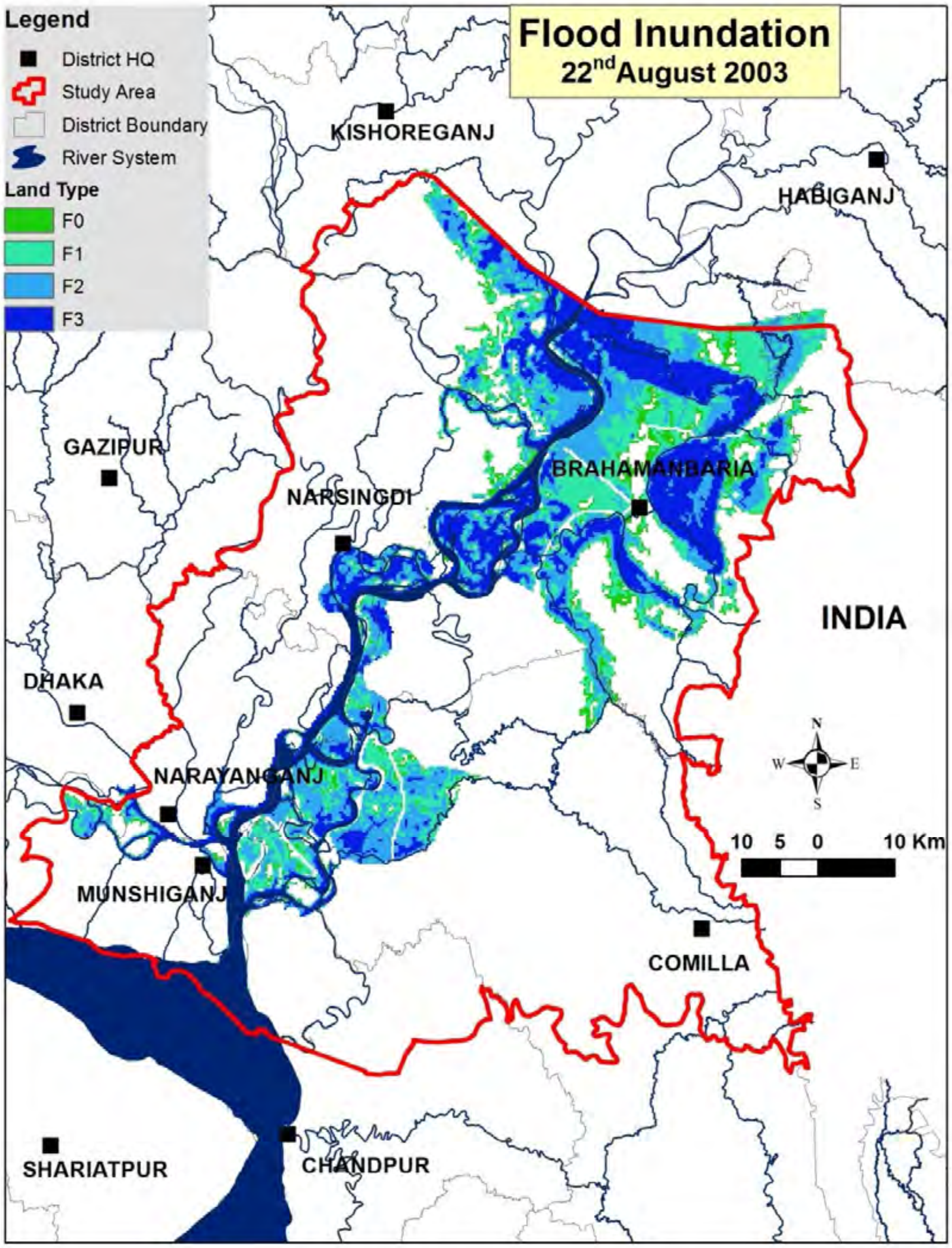


Figure 5.34: Flood depth map of 22nd August 2003 from model output

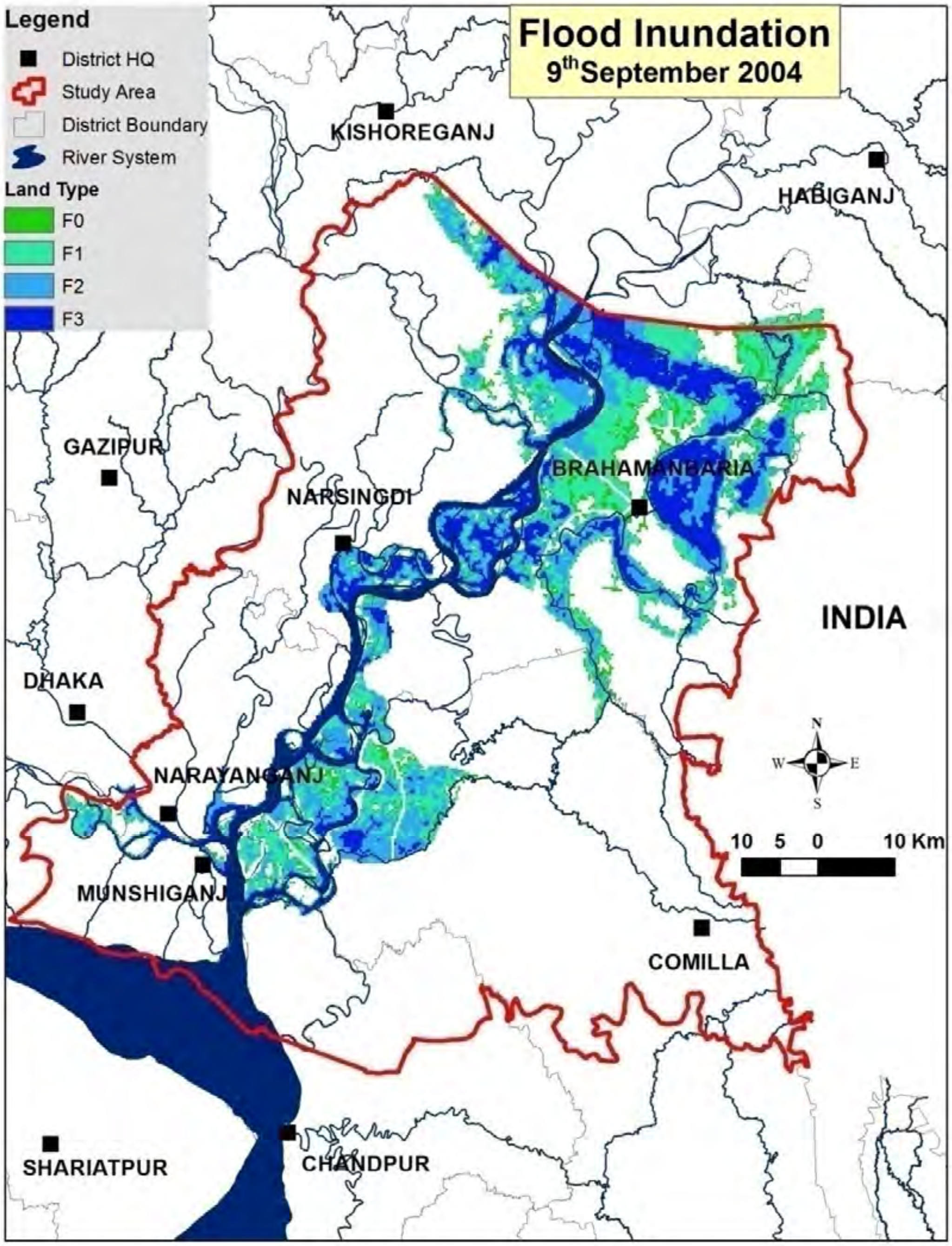


Figure 5.35: Flood depth map of 9th September 2004 from model output

5.5 Comparison of ResultsBetween Satellite Image and Model Output

The model output of 26th August 1998, 6th September 2000, 1st September 2001, 22nd August 2003 and 9th September 2004 has been matched with the Satellite image of same date. The model outputof 26thAugust of 1998 is larger about 12% compared to the satellite image (Table 5.6). The difference of model output compared to the satellite image of 2000, 2001, 2003 and 2004 is 3%, 11%, 9% and -9% respectively. The deviation of 2000 and 2004 is less. This is because the model is calibrated considering the data of 2000 and validated considering the data of 2004. 1D model as well as 2D model is now reflecting result which is more or less closer to the observe situation. 1D and 2D model is now ready to simulate future scenario.

Table 5.6: Comparison of inundation from model output with satellite image

Year	Model output (km^2)	Satellite image (km^2)	Difference (%)
1998	4975	4445	12
2000	1651	1608	3
2001	1513	1364	11
2003	1688	1543	9
2004	1699	1873	-9

5.6 Application of Model to Different Scenario

Scenario has developed considering the withdrawal due to Tipaimukh dam. According to (Bennett, et al., 1994)due to Tipaimukh dam and Fulertal barrage, the wet season flows of the Barak at Amalshid would be decreased by 25% and dry season flow would be increased by 60% during an average flow year. Upstream withdrawal has been considered in average and 5 years return period flood. The flood discharge has been calculated from Gumbel's extreme value distribution (Table 5.7). The maximum discharge of Bhairab Bazar in 1982 was 13500 which are more or less equal to the flood discharge 2.33 year period. Similarly the maximum discharge of 1998 has the return period of 5 years. But 1998 flood is an exceptional case. Because the inundation of 1998 flood was about 68% of the whole country. Whereas the 20 year return period discharge of 1988 has caused the inundation about 63% of the whole country (Hofer, et al., 2006). This is lower than the inundation of 1998 flood. As this study is considering the flood inundation that's why inundation of 1998 flood has been selected for the scenario.

Simulation of the 1998 flood scenario considering upstream withdrawal of about 20% revels an important thing. The total inundation in base and in upstream withdrawal is same which is about 5400 km^2. Low land (F3) in the withdrawal scenario decreases in about 226 km^2 (Table 5.8).Mediumhigh land (F1) increases about 141 km^2 and high increases about 57 km^2. The 30% upstream withdrawal scenario has different situation (Figure 5.39). F0 and F1 land has increased about 191 km^2. Low land (F3) and Medium Low land (F2) has decreased about 467 km^2 and 148 km^2. This tells that, the 30% decrease of upstream discharge will convert some low land to high land.

Table 5.7: Flood discharge in different return period

Return Period (Year)	Discharge (m^3/s)
2.33	13700
5	15800
20	19200

Table 5.8:Land type of 1998 base condition with upstream withdrawal condition

Land Type	Inundation in Km^2			Difference, %	
	Base condition (1998)	20% upstream withdrawal	30% upstream withdrawal	20% withdrawal	30% withdrawal
F0 (0-30 cm)	339	396	530	17	56
F1 (30-90 cm)	1085	1226	1128	13	4
F2 (90-180 cm)	1669	1693	1521	1	-9
F3 (180-360 cm)	2311	2085	1844	-10	-20
Total	5404	5400	5023	0	-7

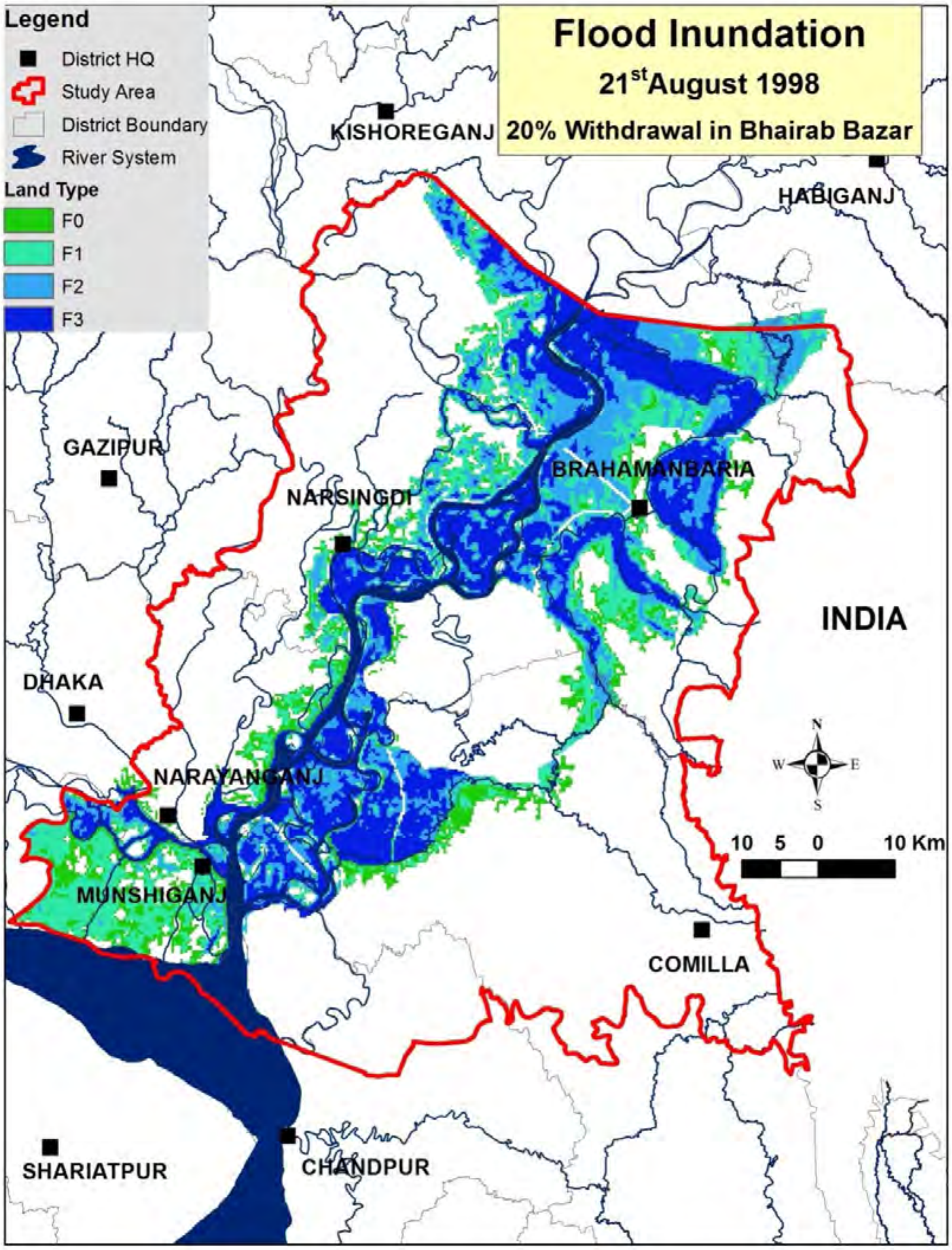


Figure 5.36: Inundation before full flood with 20% upstream withdrawal

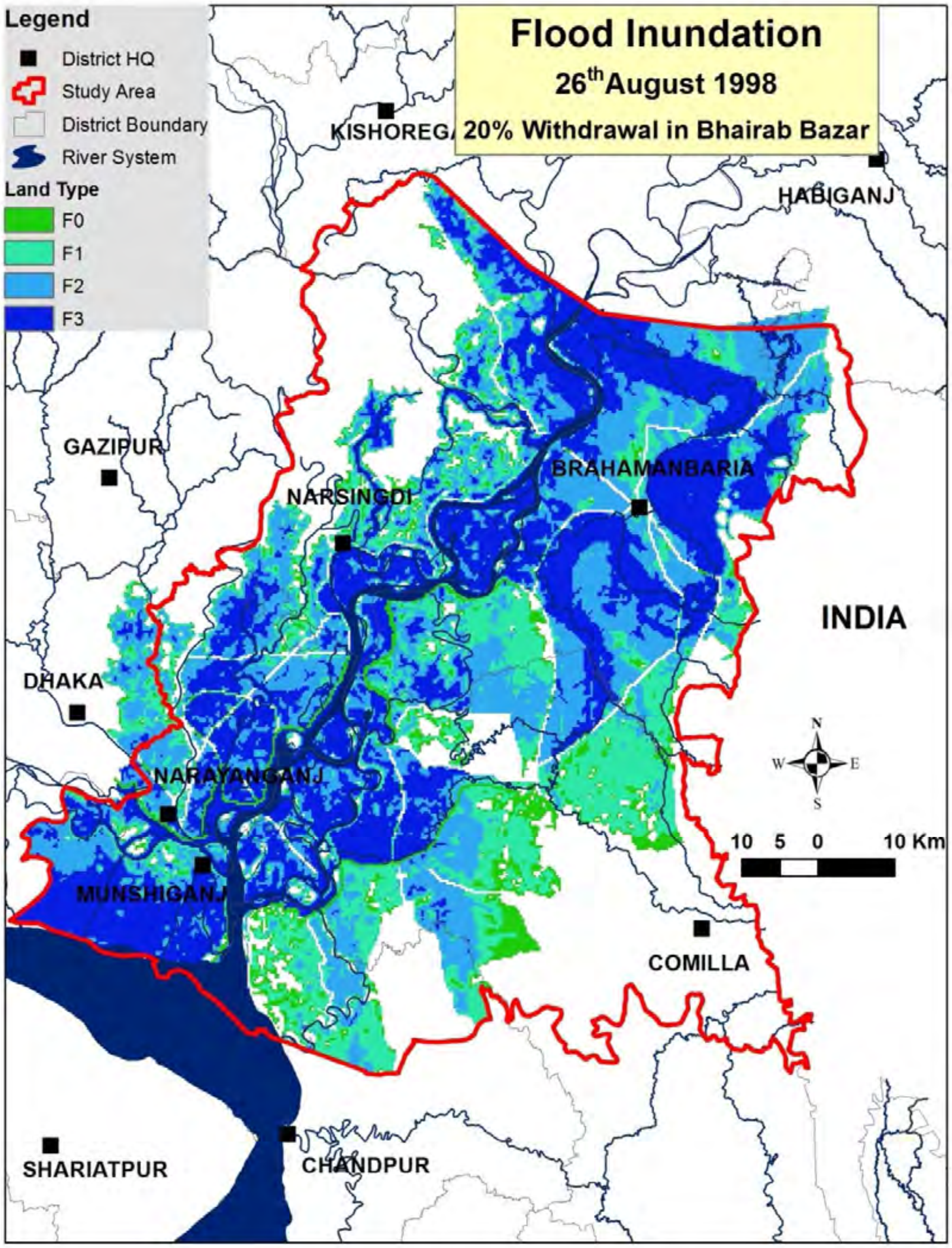


Figure 5.37: Flood inundation of 1998 flood with 20% upstream withdrawal

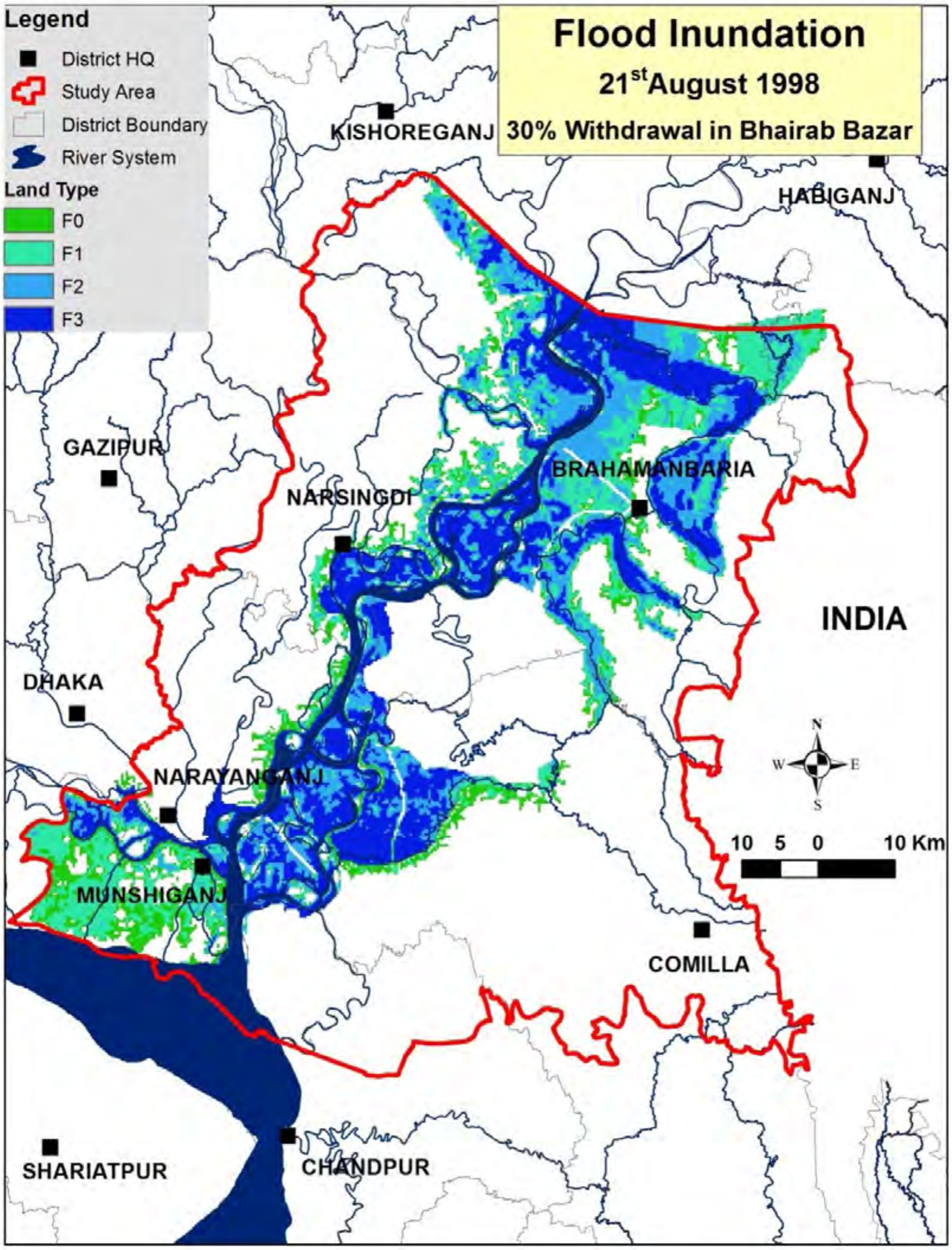


Figure 5.38: Inundation before peak flood with 30% upstream withdrawal

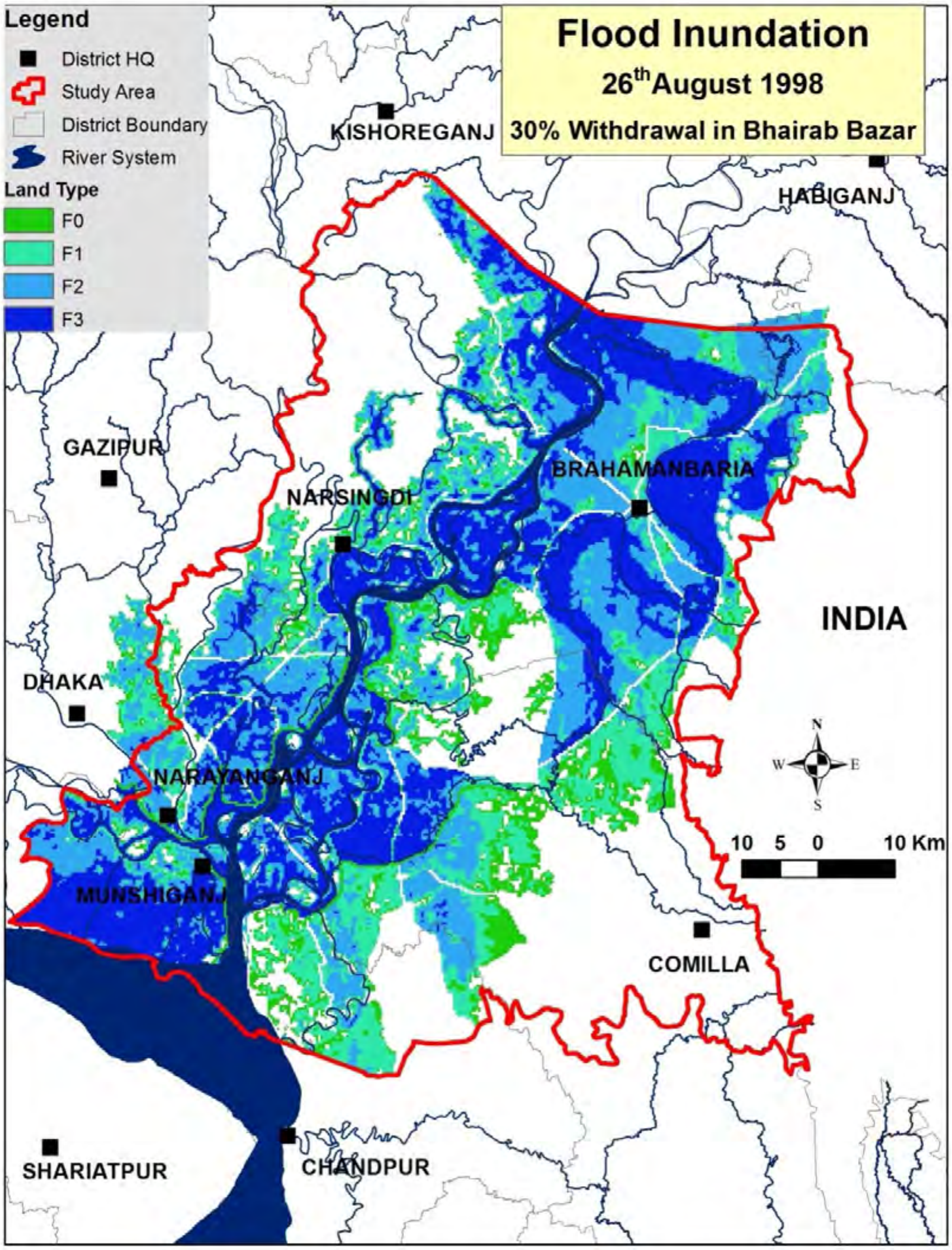


Figure 5.39: Flood inundation of 1998 flood with 30% upstream withdrawal

Another scenario has been developed according to the ICIMOD report (CEGIS, 2013).The report says the discharge of the Meghna basin will increase due to climate change about 10% to 12%. The effect of sea level rise has also been considered. A study of Bangladesh Agricultural University (Khan, et al., 2009) reports that the sea level rise around Meghna will be about 32cm. The model has been simulated considering all these factors.

The total inundation increases about 1483 km^2 and the total inundation is about 6887 km^2. The amount of F3 land is about doubled compared to the 1998 flood. The F0, F1 and F2 land actually decreases (Table 5.9 and Figure 5.40).

Table 5.9: Inundation due to discharge and water level increase.

Land Type	Inundation in Km^2		
	Base condition (1998 flood)	Impact of Scenario	Difference
F0 (0-30 cm)	339	244	95
F1 (30-90 cm)	1085	742	343
F2 (90-180 cm)	1669	1418	251
F3 (180-360 cm)	2311	4483	-2172
Total	5404	6887	-1483

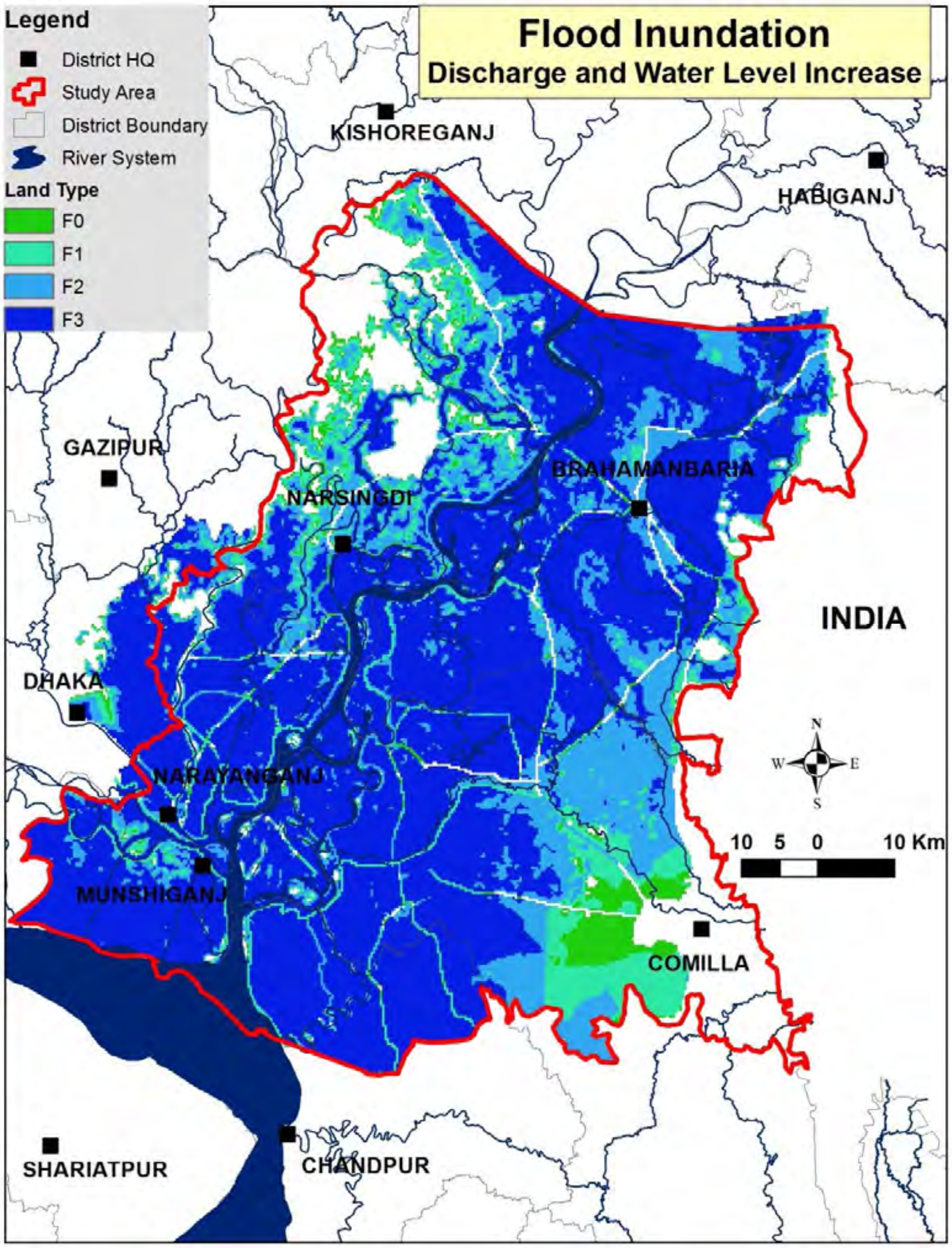


Figure 5.40: Inundation due to increase of discharge and water level.

Table 5.10: Inundation and corresponding water level

Year	Inundation (km^2)		Water Level (mPWD)
	Satellite Image	Model output	
1998	4445	4975	6.3
2000	1608	1651	5.24
2001	1364	1513	4.84
2003	1543	1688	5.22
2004	1873	1699	6.57
2007	2919		

5.7 Summary

Spatial coverage of inundation from flooding has been identified and calculated from satellite images. But depth of inundation can’t be extracted from Radarsat satellite images. Other than satellite image, the easy way to find out the depth of inundation is mathematical modeling. The flood events of the available satellite images have been simulated with a calibrated and validated 2D model. After that inundation extant and depth have been derived from the model. Different land type for different flood has been extracted from simulated model.

Chapter 6 Conclusions and Recommendations

6.1 General

The combination of satellite images and model simulations for flood inundation analysis is not thoroughly adapted. In case of 1D model we calibrate the model with the observe water level or may be with observed discharge. But when it comes to 2D model, the water level and discharge alone cannot be the only criteria to calibrate the model. Because the tern 2D itself explaining 2 dimension event, so the 2D model cannot be calibrated with 1D data (water level, discharge). We must calibrate a 2D model with a 2D observe data such as flood extant from satellite image.

In calibrating 2D model in with 2D data we need the actual surface information from the field. Because, inundation from a flood primarily depends on water level and discharge and also on an important factor, surface features. In this study we have used a 300m X 300m DEM which is not very suitable data to simulate flood accurately. Because in a 300m X 300m cell there are a lot of surface features but the cell represents an average elevation which lowers the higher elevation features in actual case. So it is obvious that we will get more inundation compared to the actual scenario. We have already gotten an evidence of excess flooding from the 2D model output.This excess flooding has been minimized by separately imposing the national highway, feeder road and embankments.

6.2 Conclusions of the Study

The following conclusions can be drawn after summarizing the present study:

1. From the analysis of satellite images it is evident that, unlike the extreme case the flooding of the upper Meghna River shows a common flooding pattern.
2. The 1D-2D model has been set up and calibrated and validated with the observed water level and with the satellite images.

3. The flood depth map prepared from model output is a useful way of flood risk management. The areal extent of the flood depth map is more or less same to the areal extent of flood inundation from the satellite images. The variation is about 10-12%.
4. Flood scenario considering 20% withdrawal of flow at Bhairab Bazar shows no change in total inundation compared to the 1998 base condition, but 30% withdrawal shows about 7% decrease in total inundation compared to the 1998 flood inundation.
5. Flood scenario considering 10% increase of flow at Bhairab Bazar and 32 cm increase of downstream water level shows significant amount of increase in flood inundation of about 7% compared to the 1998 base condition.

6.3 Recommendations for further study

Based on the current research project some recommendations for future study can be as follows:

1. Detail land use can be used for the simulation of the inundation model to find out the more reliable inundation.
2. Detail road and embankment alignment can be used in the model.
3. Fine resolution DEM can be used for further accurate inundation from model simulation.

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