Nat Hazards (2011) 57:525–548
DOI 10.1007/s11069-010-9638-y

ORIGINAL PAPER

Flood monitoring, mapping and assessing capabilities using RADARSAT remote sensing, GIS and ground data for Bangladesh

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Received: 5 January 2010 / Accepted: 28 September 2010 / Published online: 20 October 2010

Abstract Remote sensing is the most practical method available to managers of flood-prone areas for quantifying and mapping flood impacts. This study explored large inundation areas in the Maghna River Basin, around the northeastern Bangladesh, as determined from passive sensor LANDSAT data and the cloud-penetrating capabilities of the active sensors of the remote imaging microwave RADARSAT. This study also used passive sensor LANDSAT wet and dry images for the year 2000. Spatial resolution was 30 m by 30 m for comparisons of the inundation area with RADARSAT images. RADARSAT images with spatial resolution of 50 m by 50 m were used for frequency analysis of floods from 2000 to 2004. Time series images for 2004 were also used. RADARSAT remote sensing data, GIS data, and ground data were used for the purpose of flood monitoring, mapping and assessing. A supervised classification technique was used for this processing. They were processed for creating a maximum water extent map and for estimating inundation areas. The results of this study indicated that the maximum extent of the inundation area as estimated using RADARSAT satellite imaging was about 29, 900.72 km^2 in 2004, which corresponded well with the heavy rainfall around northeast region, as seen at the Bhairab Bazar station and with the highest water level of the Ganges–Brahmaputra–Meghna (GBM) Rivers. A composite of 5 years of RADARSAT inundation maps from 2000 to 2004, GIS data, and damage data, was used to create unique flood hazard maps. Using the damage data for 2004 and the GIS data, a set of damage maps was also created. These maps are expected to be useful for future planning and flood disaster management. Thus, it has been demonstrated that RADARSAT imaging data acquired over the Bangladesh have the ability to precisely assess and clarify inundation areas allowing for successful flood monitoring, mapping and disaster management.

Keywords Monitoring · Mapping · Assessing · LANDSAT · RADARSAT · GIS

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1 Introduction

In one sense, one can consider remote sensing as a term used to describe a study that does not make actual contact with the object of interest. That is, one is using data transmitted from an orbiting satellite in to an individual station located on the surface of the Earth. In this way, one can measure properties from a remote distance (Eric 1997).

During the last two decades, satellite-borne Synthetic Aperture Radar (SAR) with its cloud-penetrating capability has been used with considerable success for mapping the areal extent of flooding in some of the major floodplains and river basins of the world (Wilson and Rashid 2005). Accurate and precise delineation of flood-prone areas using remote sensing data have received considerable attention in the last couple of decades (Dewan et al. 2006).

It is well known that Asian summer monsoon is accompanied by abundant rainfall (Matsumoto 1997). The floods in India and Bangladesh appear in the headlines of the media (Hofer and Messerli 2006). In terms of the impacts of floods on the affected people, flood monitoring, mapping and estimate of the extent of inundation are very important parameters that are usually not documented using remote sensing and GIS over Bangladesh.

This study attempts to utilize the satellite image data derived from the passive sensor LANDSAT and the active sensors RADARSAT. These are used to identify the inundation area and to test the capabilities of satellite images for the purpose of flood monitoring, mapping, and assessing of the Meghna River Basin around northeastern Bangladesh. Unfortunately, the passive sensor LANDSAT does not work well over Bangladesh, during the monsoon season due to the heavy cloud cover. Consequently, the SIR-B RADAR was used as it penetrated the latent monsoonal cloud cover to reveal hydrological conditions on the ground during severe weather conditions (Imhoff et al. 1986). The use of the SAR system as a solution to the cloud cover problem has shown great promise (Imhoff et al. 1987).

Previous studies have been devoted to flood monitoring mapping and assessment over Bangladesh and many other countries, (Ali et al. 1989; Blasco et al. 1992; Badji and Dautrebande 1997; Chowdhury and Sato 1996; Chowdhury and Ward 2004; Dewan et al. 2006; Hofer and Messerli 2006; Imhoff et al. 1986, 1987; Oberstadler et al. 1997; Otsubo et al. 2000; Rasid and Pramanik 1990, 1993; Matsumoto et al. 1996; Matsumoto 1997; Smith 1997; Sakamoto et al. 2007; Wilson and Rashid 2005) etc.

Many methods have been used to estimate the extent of inundation and a review of how remote sensing was applied to mapping the inundation area (Imhoff et al. 1986). Sir-B RADAR data were acquired over the Peoples Republic of Bangladesh. Examined for their ability to penetrate cloud cover, storm front, vegetation and provide a set of image data over the flood plains Eastern and Central Bangladesh. The RADAR images were processed digitally using spatial filters to bring out image patterns that were not visible in the raw data. They applied radar data measurements to the flooded and non-flooded land surfaces of Central Bangladesh. They also identified SIR-B RADAR penetrated cloud cover, with its ability to penetrate vegetation. This has proved useful for mapping flood boundaries. These radar images were used to measure flood water and assess damage.

To make the index more physiological, Imhoff et al. (1987) utilized SAR and LANDSAT MSS images to make comparisons. They suggested that the LANDSAT was a tremendously useful tool for analyzing the Earth and its environment. The L-band radar can also be a very useful tool for monitoring flood boundaries during the monsoon periods in Bangladesh. Ali et al. (1989) examined the applicability of NOAA/AVHRR imaging to monitor river floods and associated hydrological conditions in Bangladesh. However, they only demonstrated the potential usefulness of the Advance Very High Resolution Radiometer (AVHRR) data. Their study, however, could not be supplemented with conventional data of surface measurements. Rasid and Pramanik (1993) also applied AVHRR satellite imaging data to estimate the areal extent of the 1988 flood in Bangladesh. One limitation was that cloud-free images were not available for the peak flood period. They compared the satellite estimates with information from a government of Bangladesh source and news papers reports. They identified that the actual extent of flooding was larger than the satellite images suggested. Smith (1997) used a variety of passive and active sensors to estimate water surface and discharge. He showed that the Radar (SAR) sensor could penetrate cloud and detect standing water. Cloud penetration is particularly important for monitoring flood events, as they commonly occur during period of extended rainfall. The high-resolution visible/infrared sensor LANDSAT provided good delineation of flood extent where cloud and trees did not obscure the water surface. However, he also reported that river flow velocity cannot be directly measured from space. Oberstadler et al. (1997) adopted a traditional mapping method and satellite data analysis. They conducted a visual interpretation and an automatic classification of surface conditions, using various filter steps to derive the flood boundary. A cost and benefit analysis using the operational GIS system with ERS-1 SAR data is still under investigation. Islam and Sado (2000) applied such a method of flood hazard mapping using NOAA-AVHRR and GIS technology. Flood depth and the frequency of flood-affected areas are considered central for the evaluation of flood hazards. Hazard assessment ranks from normal to severe.

Otsubo et al. (2000) applied a method that allowed for inundation and damage assessments around the Lower Mekong Basin using RADARSAT-SAR images. RADARSAT can take images of specified locations and on specific dates. The intention of their study was to develop time-series flood maps that can be valuable for flood damage. They also reported that it is, thus, quite possible to create maximum inundation flood maps by overlaying the time-series of the inundation images. Rahman et al. (2005) investigated the hydrological aspects of 2004 flood using ground data and MODIS satellite images around Dhaka, Bangladesh. They also identified the northeast region, which was heavily damaged in the 1998 and 2004 floods, but they did not analyse the northeast region in general. Wilson and Rashid (2005) monitored and assessed the delineation of flood boundaries of the 1997 Red River Valley flood with a selected number of RADARSAT images. They compared RADARSAT images with hydrologic characteristics and demonstrated that there were some inconsistencies between the hydrologic regimes of the flood and areal extent of flooding. For example, the imagery of the 27 April (1997) did not accurately display the over-bank inundation. In contrast (Dewan et al. 2006) evaluated the utility and accuracy of using C-band RADARSAT SAR data to develop the 1998 flood map and estimated flood-prone areas of Dhaka, Bangladesh. They obtained fairly good results of the flooded and non-flooded areas. These images were digitally extracted using a supervised Maximum Likelihood Classification (MCL) technique.

There is a wide range of satellite research activity available in developed countries in contrast to developing countries such as Bangladesh. The majority of previous studies focused mainly on frequent monitoring and mapping of the ground surface using variety of satellite image data that were limited to the sensors available at the time. Several previous studies have dealt with the extent of inundation mapping around the Dhaka City and limited to only one specific flood year (Imhoff et al. 1986, 1987; Ali et al. 1989; Rasid and Pramanik 1990, 1993; Rahman et al. 2005; Dewan et al. 2006). However, it became clear that the growing flood hazard around northeastern Bangladesh have not been analyzed for the purpose of flood monitoring, mapping and assessing using RADARSAT satellite data.

2 The study area

Bangladesh belongs to the Asian tropical monsoon system lying within 88.05–92.74°E and 20.67–26.63°N (Fig. 1). The land of Bangladesh is very flat. In the southeast, the elevation is lower than 200 m which has a border with Myanmar. In the northeast, the elevation is lower than 100 m and is located on the southern slope of the Meghalaya Plateau and 10 km from the border with north eastern Bangladesh (Pant and Kumar 1997). Rainfall in the Meghalaya Plateau is a major determinant for the flooding processes in Bangladesh (Matsumoto et al. 1996).

Bangladesh is one of the most flood-prone countries in the world as well as one of the most densely populated countries (Islam and Dhar 1998). The country has an area of approximately 147,570 km^2 and is shared by 150 million inhabitants, Bangladesh Bureau of Statistics (BBS 2009). The country's economy is dominated by agriculture. The flood-prone nature of its geomorphology and the size of its population make Bangladesh one of the most difficult ecosystems in the world to manage. During the winter, precipitation is limited by the Siberian high pressure system, and during the summer months, flooding occurs as the major river systems, swollen with the Himalayan snowmelt, are further fed by heavy monsoon precipitation (Imhoff et al. 1987).

Geologically, a major part of Bangladesh is occupied by one of the largest deltas on earth. Bangladesh and the Ganges–Brahmaputra–Meghna River Basin (hereafter the GBM system) as a whole are dominated by the Asian monsoon system (Hofer and Messerli 2006). There are three prominent seasons in a year, namely winter, summer and the monsoon. In this region, the monsoon period is further divided into three periods: (a) pre-monsoon (March–May), (b) monsoon (June–September), and (c) post-monsoon (October–November). June to September is well known as the peak-monsoon months.

Historically, the northeast region is endowed with the major river Meghna and two tributaries, which are the Surma and Kushiyara Rivers. The Meghna River originates in

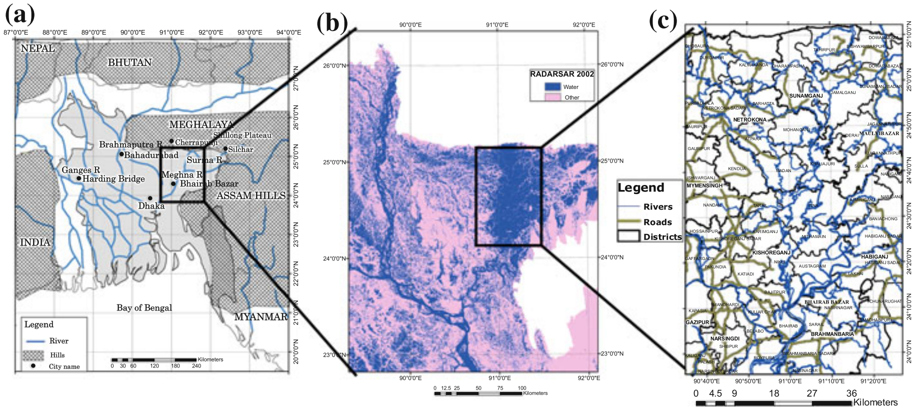


Fig. 1 **a** Geographical location of Bangladesh along with observation stations. **b** RADARSAT image focus study area. **c** Base map of study area illustrates six districts

one of the world's rainiest regions, the Cheerapunji region, in the state of Meghalaya, India (Blasco et al. 1992). Topographically, the northeastern regions are hilly areas, located between Latitude 23–26°E and Longitude 90–92°N. Population here is 193–386 persons per km^2 (BBS 1993).

Matsumoto et al. (1996) delineated the summer monsoon as two heavy rainfall zones in the northeastern subcontinent of India. One is coastal region in India and the other is northeastern Bangladesh. Matsumoto et al. (1996) also reported that in the northeastern regions the mean rainfall ranges from roughly 1,000 to 3,000 mm per year. Tsushima et al. (2009) they experienced about 4,000 mm annual rainfall of which 70% occurs during the monsoon. The results of this study show that the annual rainfall exceeded 5027.0 mm (Fig. 7) in 2004 in the Meghna River Basin at the Bhairab Bazar station, which is higher than previous studies.

The heavy rainfall in 2004 caused severe flooding in the Meghna Basin in the districts of Bhairab Bazar, Sunamganj, Sylhet, Habiganj, Moulvibazar, Kishoreganj and Netrokona. These areas suffered from extensive flood damage. In 1998, the flooded area exceeded 70% of the country, while about 40% of the area was flooded in 2004 (Rahman et al. 2005). This flooding has caused enormous economic loss to the country. It destroyed its infrastructure, standing crops, livestock, human lives and road networks.

3 Objectives

The floods from 2000 to 2004 were specifically investigated. Data drawn from the satellite activity for inundation mapping around northeastern Bangladesh have not been analyzed in previous studies. The northeastern region is an important area for flood hazard analysis, which is major interest here. Therefore, this study attempts to develop a methodology for flood monitoring and mapping. Also attempts to explicitly delineate flood damage by providing unique flood hazard maps that have also not been utilized in previous studies have been made. Mapping of accurate flood-prone areas is not only helpful to prevent flood-induced losses but also important for the evaluation of the extent of damage and for emergency management. Identification of exact flood-prone areas is necessary to communicate timely flood disaster information to the concerned authorities as well as to the public at large (Dewan et al. 2006).

Therefore, this study analyzes the northeast region from 2000 to 2004 and addresses why northeast region is extremely important for flood hazard. This study also presented a unique method of flood hazard mapping. The four main objectives of this study are (1) to demonstrate the capability and usefulness the RADARSAT remote sensing for flood monitoring, mapping and assessing of the northeastern Bangladesh flood zone from 2000 to 2004; (2) to check for data inconsistency in the estimates derived from the LANDSAT 7 ETM+ wet and dry images for 2000; (3) to evaluate the utility and accuracy of the RADARSAT data and compare the results with rainfall, water level and damage data of the Meghna River Basin from 1998 to 2005; and finally (4) to create a composite dataset of 5 years RADARSAT satellite images and develop unique flood hazard maps.

4 Data and methodological approaches

The passive sensor LANDSAT and the active sensors of the microwave RADARSAT remote sensing data were used in this study for flood monitoring mapping and assessing the flood zone terrain. The wet and dry season images of LANDSAT in 2000 were used for comparison with the RADARSAT images. The inundation area and dry areas were digitally extracted and the images classified using the supervised MCL technique. The LANDSAT 7 ETM+ wet and dry season images were acquired for 2000-10-25 and 2000-02-28, respectively. These satellite images were then classified into four groups: water, vegetation, soil, and clouds. Other basic information was acquired: Path: 137; Row: 043; Areal extent: 185 by 185 km^2 and spatial resolution: 30 m by 30 m. These data were derived from the: (1) Center for Environmental and Geographic Information Services (CEGIS), Dhaka, Bangladesh and (2) Global Land Cover Facility of University of Maryland at http://glct.umiacs.umd.edu.

The Canadian RADARSAT provides one of the most effective tools currently available for flood mapping and available from http:www.rsi.ca. The CEGIS received the RADARSAT raw data from the Canada Centre of remote sensing. A digitally supervised classification technique is necessary to view the actual image data. As part of the requirements of flood mapping using RADARSAT data, it is necessary to also use GIS data of the same region. GIS plays an important role for identifying the area of interest and helps to create a very detailed inundation map. The RADARSAT can provide flood image data in all kinds of weather conditions. The RADARSAT data used were derived from the CEGIS, Dhaka, Bangladesh.

The RADARSAT images, spatial resolution of 50 m by 50 m, were used for frequency analyses of floods from 2000 to 2004 and time series images on 5th June, 24th July and 9th September in 2004. The inundation areas and dry areas were extracted using the MCL technique and classified using CEGIS. The RADARSAT satellite images were classified into two groups: (1) maximum extent of water body in blue color and (2) other surface conditions in pink color. From the RADARSAT images, water and land areas can easily be separated due to their distinct tonal variation. From the extraction of the flood-prone areas, a maximum water extent map was created and used to estimate the inundation areas and the dry areas. These results were then compared with the passive sensor LANDSAT for 2000.

To depict the hydrological characteristics of the 2004 flood, the three major river systems were analyzed. Using the water level and rainfall data from 95 stations (1998 to 2005), a time series was generated of the water level along the Ganges–Brahmaputra–Meghna (GBM) river system. The Ganges River station is at Harding Bridge, the Brahmaputra River station is at Bahadurabad; and the Meghna River station is at Bhairab Bazar. Hydrographs of the three major rivers were plotted and their characteristics scrutinized. Precipitation data, as measured by the 35 gauging stations around Bangladesh, were received from Bangladesh Water Development Board (BWDB), Flood Forecasting and Warning Center (FFWC), CEGIS and NOAA.

The distribution of annual rainfall anomaly maps around Bangladesh from 2000 to 2005 was also used. The monthly and annual changes in rainfall around Bhairab Bazar from 1998 to 2005 were also analyzed. In addition, the rainfall of Cherrapunji and Bhairab Bazar for 1998 and 2004 was compared. This precipitation data source was from the CEGIS and NOAA.

The information of the study area was illustrated with the GIS data (from the CEGIS) by overlaying the images for the selection of training areas and subsequent accuracy assessment. Using the GIS data, inundation maps, a base map, damage maps and hazard maps of the northeastern Bangladesh from 2000 to 2004 were created. GIS technology helped recognize the appropriate region such as the district and Thana basis [Thana = Police Station = Sub District]. The GIS data precisely indicated the flooding area.

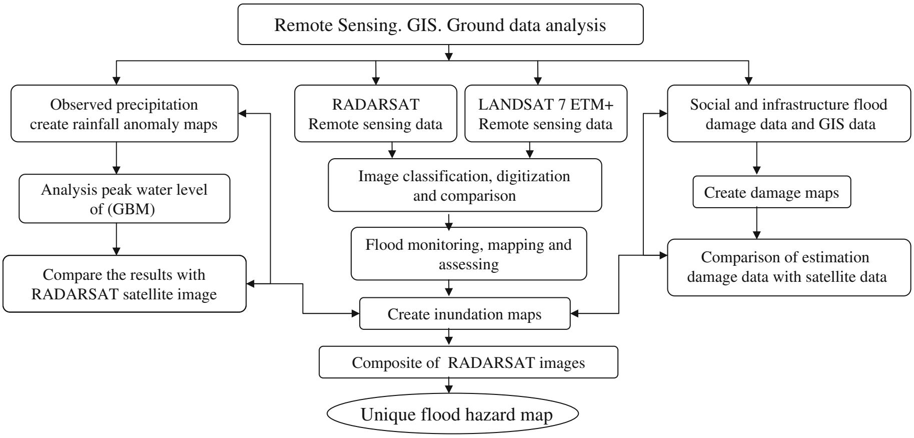


Fig. 2 Flowchart of the methodology

Social and infrastructure flood damage data from 2004, at the district level, were received from the Ministry of Agriculture, Dhaka, Bangladesh**.** Damage data from six districts: Bhairab Bazar, Netrokona, Brahmanbaria, Sunamganj, Moulavi Bazar and Habiganj (District is shown in Fig. 1c) was received. Flood damage data were from the 14th to 31st of July 2004. The relationship between the maximum extent of the flooding estimates from the government of Bangladesh and the RADARSAT satellite images corresponds quite closely in northeastern Bangladesh for 2004. The flow chart of the methodology is shown Fig. 2.

5 Results of satellite image data

5.1 Detection of the flood inundation areas for the northeastern region using RADARSAT remote sensing images from 2000 to 2004

The RADARSAT data were found to be acquired over Bangladesh. It is revealed that very often and all kinds of weather condition RADARSAT satellite provide image data. The RADARSAT satellite images can be taken at specified locations on specified dates and are very useful for inundation mapping. In the case of the Bangladesh floods, the high resolution of RADARSAT imagery proved to be particularly useful. It is proved that RADARSAT has the ability to precisely assess and clarify inundation areas allowing for successful flood monitoring and mapping. Cloud penetration is particularly important for monitoring flood events, as they commonly occur during the period of extended rainfall over Bangladesh. In this reason, the RADARSAT satellite data were found very useful in monsoon country like Bangladesh. The visual interpretation of the RADARSAT images showed good comparison with the ground data interpretation. The RADARSAT imaging system is capable of allowing for flood delineation.

Figure 3 illustrates the progress of the monsoon flood for the northeast region in Bangladesh from 2000 to 2004. It was monitored by the RADARSAT imaging. As stated earlier, the inundation areas detected by RADARSAT image, water and land areas can easily be separated due to their distinct tonal variation. These maps clearly depicted the

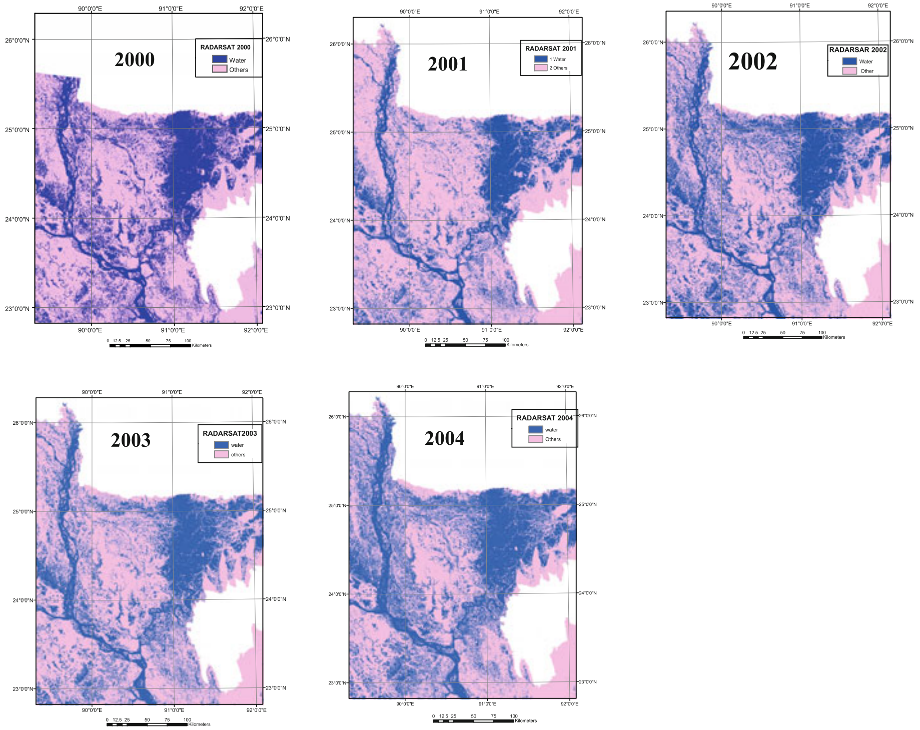


Fig. 3 The RADARSAT inundation map illustrates flooded area around northeastern part of Bangladesh from 2000 to 2004. *Blue part* of the map indicates water and *pink part* indicates other surface conditions. Visual interpretation of the RADARSAT 2004 image data demonstrated that the inundation area was extremely large and estimate of the maximum extent of the inundation area was approximately 29,900.72 km^2. In 2004, the maximum extent of the inundation area was found to be larger than in other years

extent of flooding from 2000 to 2004. The RADARSAT images were digitally processed and analyzed. Polygon data and calculations provided values for the average inundation area in northeastern Bangladesh (annual rainfall shown in Fig. 7; water level shown in Fig. 10).

Visual interpretation of the RADARSAT images for 2000 suggests that the extent of the inundation area was extremely large over the northeastern Bangladesh. The Meghna River Basin at the Bhairab Bazar station illustrates over the bank flooding. The districts of Bhairab Bazar, Sunamganj, Mymensingh Kishoreganj and Netrakona were completely submerged, while the southern side of the district Habiganj Maulvibazar Sherpur showed incomplete inundation. Based on digital analysis of the RADARSAT 2000 image, the maximum extent of inundation area was estimated at 23,678.55 km^2. A comparison with satellite data, the time shift between the highest rainfall and the water level with its acquisition date has to be carefully considered. In 2000, the annual rainfall indicated a lowering of 1598.0 mm, while the peak water level was found to be 6.5 m on 21st August at Bhairab Bazar station.

Visual interpretation of the RADARSAT images of the 2001 data is depicted over bank flooding of the Meghna River Basin. Estimate of the maximum extent of inundation area was 20,956.14 km^2. The Bhairab Bazar, Sunamganj, Mymensingh Kishoreganj and

Netrakona districts were flooded. In 2001, the annual rainfall was found to be 2916.0 mm and the peak water level was found to be 6.03 m on 12th August at Bhairab Bazar station. Therefore, based on the satellite image interpretation and the ground data, it can be deduced that the 2001 flood was not so significant.

Visual interpretation of the RADARSAT 2002 image data demonstrated that the six districts of the northeast region were completely submersed. Estimate of the maximum extent of the inundation area was 27,478.04 km^2. The annual rainfall exceeded 3155.3 mm and the peak water level was found to be 6.55 m on 11th August. Consequently, it can be deduced that the 2002 flood was also severe.

Visual interpretation of the RADARSAT 2003 image data suggested that the Meghna River Basin and Bhairab Bazar, Netrokona, Sunamganj, Moulavi Bazar and Habiganj districts were severely flooded. Estimate of the maximum extent of inundation area was about 25,417.91 km^2. The annual rainfall was found to be 2167.7 mm, while the peak water level was found to be 6.5 m on the 25th July. Therefore, it reveals that 2003 flood was not so significant.

Visual interpretation of the RADARSAT 2004 image data also demonstrated that the inundation area was extremely large, and estimate of the maximum extent of the inundation area was approximately 29,900.72 km^2. The RADARSAT images illustrated that flooding of the Meghna River Basins and that the Sunamjang, Habiganj and Maulvibazar districts and those on southern side, Sherpur, Mymensingh and Netrakona districts were completely submerged. The annual rainfall exceeded 5027.0 mm and the peak water level was found to be 7.87 m on 24th July at Bhairab Bazar station and water level of three major rivers GBM had shown coincidently synchronized their peaks on 24th July in 2004 (Fig. 11), resulting in an extremely severe flood around northeast region. RADARSAT imagery also suggested that the surrounding dry area had been submerged in both 2002 and the 2004 floods. In 2002, the inundation area was 27,478.04 km^2, while in 2004, it was 29,900.72 km^2. In certain situations, the RADARSAT images clearly captured the effect of flooding (Fig. 4).

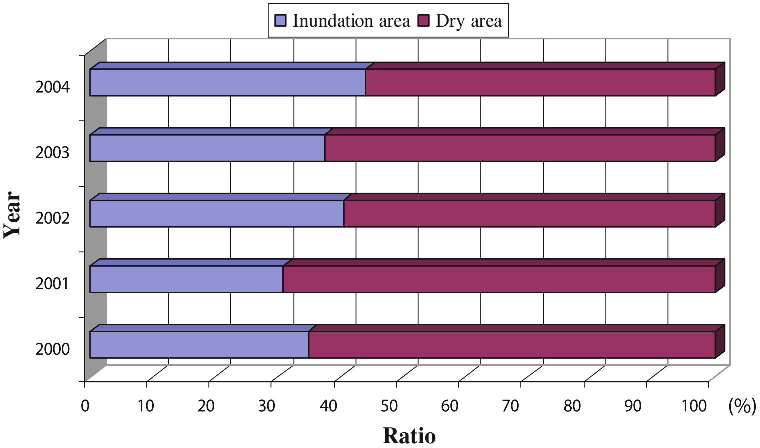


Fig. 4 *Blue line* indicates inundation and *purple line* indicates dry area ratio in (%), using RADARSAT data from 2000 to 2004

5.2 Time series of RADARSAT inundation maps around northeastern Bangladesh for 2004

The use of synoptically acquired RADARSAT image data can revolutionize planning and development activities in third world countries prone to monsoon flooding or continual cloud cover. For flood boundary delineation, the RADARSAT imagery proved exceptional. RARADSAT data were acquired over for Bangladesh. The time series of the RADARSAT inundation map proved to be extremely useful for monitoring, mapping and assessing the inundation area during the monsoon season. Time series analysis of RADARSAT inundation maps allow for visualization of the progress of monsoon flooding in northeastern Bangladesh for 2004 (Fig. 5).

According to the visual interpretation of the RADARSAT image for the 5th June 2004 illustrated that rain water and river water gradually increased and filled the Meghna River Basin including the northeastern part of Bangladesh. The images illustrates water body is blue color and pink color indicates dry land. The images suggested that Sunamganj, Bhairab Bazar, Brahmanbaria, Habiganj and Maulvi Bazar district are heavily flooded, while the western side Gazipur and Mymensings district shown non-flooded in 5th June. Moreover, the image suggested there was enough dry land until the 5th June. It seems that upper Meghna is much flooded than the lower Meghna. The upper level Maghna Basin is river flooding area (Brammer and Khan 1991). It is revealed that in the western side inundation is largely dominated by the rain and river water, while in eastern side rainfall together with river water and the water flows from upper level catchment could be the main issue for worsen flood situation. The certain situation the RADARSAT images clearly demonstrated that the water bodies were raising rapidly and the Meghna River Basin

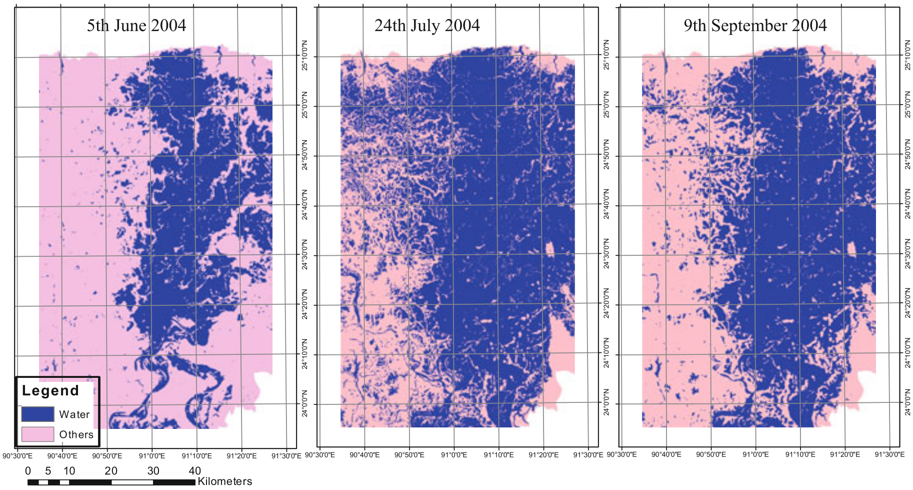
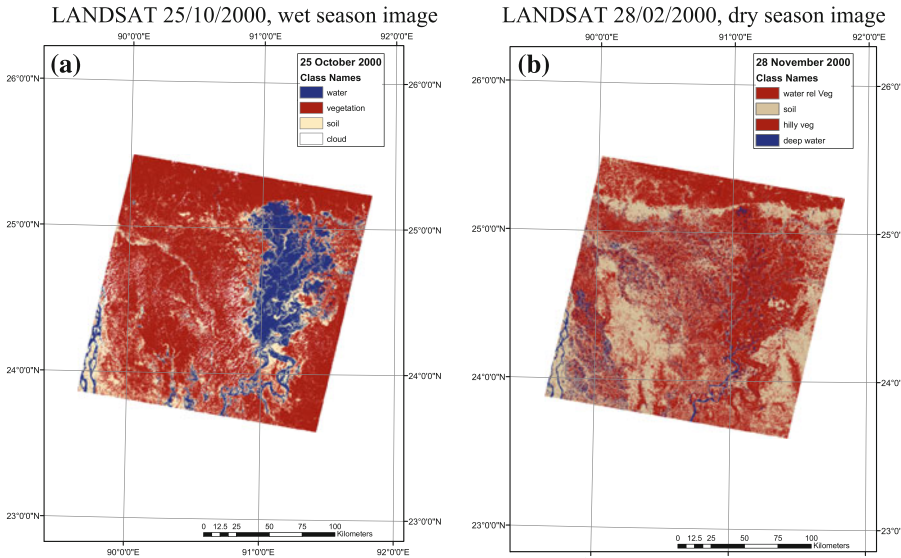


Fig. 5 Time series analysis of the RADARSAT inundation maps illustrates allowed for the visualization of the progress of monsoon flooding from June, July, and September in 2004. *Blue part* of the map indicates water and *pink part* indicates others surface conditions. The RADARSAT image for the 5th June illustrates that rain water and river water are gradually increasing. The RADARSAT image for the 24th of July illustrates that extensive flood water prevailed around the northeast region and 40% of the country was inundated. The RADARSAT image 9th September illustrates that the flood water was gradually decreasing, but a large part of flood water was still present in central region

showed over bank flooding. Approximately, 30% of the area was inundated on the 5th of June 2004.

The visual interpretation of the RADARSAT image on the 24th of July 2004 illustrated the large topographic depression in the northeast region appears extensively flooded. Vast areas of the northeast region are under water. Flooding around northeast region was extremely severe. The Meghna, Surma, and Kushiyara Rivers in particular illustrate overbank flooding. Visual inspection of the imagery shows that western side non-flooded area also submerged on 24th of July. In particular areas, the home, road, embankment network appears completely under water. It is interesting and important for Bangladesh that the ability to observation that the rivers channel course changes apparently can be monitored during summer season with RADARSAT images data. The RADARSAT observation may provide an important basis for flood and river forecasting within Bangladesh. In 2004, rainfall exceeded 5027.0 mm at Bhairab Bazar station and the Ganges–Brahmaputra–Meghna Rivers (GBM) system water level coincided on 24th of July (Fig. 11) resulted in severe flooding with 40% of the country inundated. These results are corresponds well with the RADARSAT images for the 24th July.

The visual assessment of RADARSAT image on the 9th September 2004 showed that the flood water was gradually decreasing. Comparing to the 24th July flood image and the 9th September image, it seems that only western side flood water is slowly decreasing, but a large part of flood water was still present in central region. It is to be noted that it takes



Wet image October 2000
Source: University of Maryland

Dry image November 2000
Source: University of Maryland

Fig. 6 The LANDSAT wet and dry season images illustrate inundation area and dry area around northeastern part of Bangladesh. Acquisition date of **a** 25th October and **b** 28th February 2000. *Blue color* illustrates water, *red* is vegetation, *white* is cloud, and *brown* is soil. The LANDSAT wet season image illustrates that the northeast region was inundated by both river and rain water. The image suggested that the inundation extent was still extensive. The LANDSAT dry season image demonstrated that the water body was gradually drying out. The LANDSAT images will provide flooding information when the weather is clear. Unfortunately, this is not the case during the monsoon season, because of the cloud cover. *Source* University of Maryland long time to dry out this area. Until October, this area is inundated shown in LANDSAT (Fig. 6a). Dramatic change of this area will be seen in end of November in LANDSAT image that flood water is dry out (Fig. 6b). The RADARSAT time series data revealed that the flood in the northeast region occurred early and that the flood water stayed longer than in other region of Bangladesh. The results of the northeast region show that the area was affected by the flood.

5.3 Use of visible/infrared sensor LANDSAT

Accurate information on the extent of water bodies is a prerequisite for flood disaster management. The LANDSAT provides good delineation of the flood extent where clouds, trees or floating vegetation does not obscure the water surface, Smith (1997). Such conditions, however, rarely occur in the rainy season of Bangladesh. Consequently, LANDSAT cannot provide images during the monsoon season due to the cloud cover. As a result, this study used wet and dry season images of LANDSAT, instead of monsoon season image. Examination of the classified images showed that water bodies are well captured by LANDSAT (Fig. 6). The LANDSAT image data is very useful for properly monitoring the flood-prone areas. Using the LANDSAT satellite images of northeastern Bangladesh, a clear picture of the wet season (25th of October, 2000) and the dry season (28th of February, 2000) was obtained. Wet and dry season images of LANDSAT were visually assessed to identify the extent of the four classes as originally defined: water bodies, soil, vegetation, and clouds. A supervised classification technique was again used for this processing.

The visual interpretation of the LANDSAT wet season image illustrated that the northeast region was inundated by both river and rain water flooding. The LANDSAT wet season image suggested that the inundation extent was still extensive in northeastern Bangladesh on 25th of October, 2000. The visual interpretation of LANDSAT dry season image on 28th of February 2000 demonstrated that the water body was gradually drying out. Utilizing the LANDSAT images, river lines, hilly vegetation, floating vegetation and soil could be easily detected, using the supervised classification technique.

LANDSAT can only provide these data during cloud-free intervals (Imhoff et al. 1986). Islam et al. (2009) reported that this is a long-term water body (never drying out). Assessment of the LANDSAT dry season image showed that in the winter season certain areas almost drying out.

6 Uses of ground data

6.1 Seasonal and annual change of rainfall around Bhairab Bazar from 1998 to 2005

Peak rainfall is located at Cherrapunji Meghalaya and northeastern Bangladesh also has abundant rainfall (Matsumoto et al. 1996). It is well known that onset of the summer monsoon generally occurs by the end of May. In 2004, during the pre-monsoon season, unusual rainfall occurred in April, and rainfall exceeded the monthly average from May to September. The highest rainfall was found to be 916.2 mm in August, and the annual rainfall was found to be 5027.0 mm in 2004 (Table 1). Likewise in 1998, rainfall occurred from April and the highest rainfall was found to be 647.0 mm in July. The annual rainfall was found to be 2230.0 mm (Fig. 7). In 2004, the annual precipitation at Bhairab Bazar was heavier than in 1998 event. Heavy rainfall played a significant role in worsening the

Table 1 Rainfall scenarios for Bhairab Bazar in 1998 and 2004 (Unit: mm)

Month	Monthly maximum	Monthly average	Observed in 1998	Observed in 2004
January	21.5	3.3	19.0	21.5
February	120.2	29.4	22.0	12.2
March	193.5	50.5	52.0	193.5
April	388.8	167.7	295.0	388.8
May	801.0	379.9	424.0	801.0
June	674.6	327.4	87.0	674.6
July	695.4	395.4	647.0	695.4
August	622.0	314.5	298.0	916.2
September	634.8	293.9	239.0	634.8
October	365.1	153.7	19.0	365.1
November	159.0	25.5	128.0	159.0
December	164.9	12.7	0.0	164.9
Annual total	5440.8	2153.9	2230.0	5027.0

Monthly maximum and average are calculated from 1970 to 2000

Source BWDB, Dhaka, Bangladesh

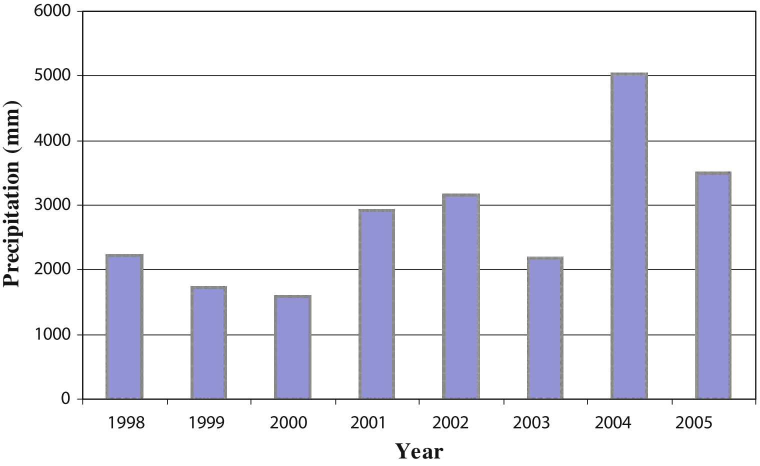


Fig. 7 Seasonal and annual change of rainfall for the Meghna River Basin at the Bhairab Bazar station from 1998 to 2005. In 1998, annual rainfall was found to be 2230.0 mm. While, in 2004, annual rainfall was found to be 5027.0 mm. It was higher than other years. Heavy rainfall played a significant role in worsening the flood situation during the 2004 deluge, particularly in the northeast region

flood situation during the 2004 deluge, particularly in the month of August. The results suggest that precipitation around Bhairab Bazar was a principal factor in the flood of 2004. Distribution of excessive rainfall causes rain water to flood, and devastating floods have occurred frequently causing misery to vast areas of the country (Hoque et al. 2007).

6.2 Rainfall comparison between Cherrapunji in India and Bhairab Bazar from 1998 to 2004

The Cherrapunji is well known as the world's heaviest rainfall zone. Murata et al. (2007) stated that as Cherrapunji is located on the southern slope of the Meghalaya plateau, most

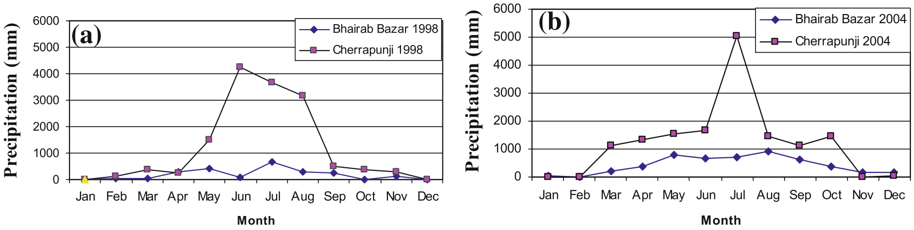


Fig. 8 Rainfall comparison between Bhairab Bazar and Cherrapunji in **a** 1998 and **b** 2004. In 1998, the annual rainfall in Cherrapunji was found to be 14536.9 mm, while the annual rainfall in Bhairab Bazar was found to be 2230.0 mm. In 2004, the annual rainfall was found to be 14816.8 mm at Cherrapunji. In contrast, the annual rainfall was found to be nearly 5027.0 mm in Bhairab Bazar. The Cherrapunji plays a major role in the heavy rainfall and early flood around the northeastern region

of the rain flows directly down into Bangladesh. To assess the rainfall situation of Cherrapunji and Bhairab Bazar, a comparison was made between the 1998 and 2004. Figure 8a, b display the amount of rainfall in both years. In 1998, the annual rainfall in Cherrapunji was found to be 14536.9 mm, while the annual rainfall in Bhairab Bazar was found to be 2230.0 mm. In 2004, however, the highest rainfall was found to be 5040.6 mm in July, and annual rainfall was found to be 14816.8 mm at Cherrapunji. In contrast, the highest rainfall was found to be 916.2 mm in August and annual rainfall was found to be nearly 5027.0 mm in Bhairab Bazar. This result suggested that the 2004 rainfall was considerably higher than that in 1998 at both stations. Thus, the Cherrapunji plays a major role in the heavy rainfall and early flood around the northeastern region (Fig. 9).

6.3 Annual summer monsoon rainfall anomaly maps from 2000 to 2005

Based on the precipitation data, average annual rainfall anomaly maps for the years 2000 to 2005 were created. The rainfall anomaly map for 2000 shows that Bangladesh had less rainfall, only in the northern part was their little rainfall. In 2001, the western and southern parts had shown little rainfall. In contrast, the rainfall anomaly map of 2002 illustrates significant rainfall in Bangladesh; while in 2003, the rainfall anomaly map again shows less rainfall. The rainfall anomaly map for 2004 illustrates extremely high rainfall throughout the country. The annual rainfall for 2004 at Bhairab Bazar station was found to be 5027.0 mm (Fig. 1). The 2005 rainfall anomaly map indicates again less rainfall in Bangladesh. These rainfall anomaly maps clearly depict that 2002 and 2004 were exceptionally high and prolonged rainfall years. Similar results were found for the RADARSAT 2002 and 2004 inundation maps. Analysis of inter-annual rainfall variations showed that anomalous rainfall was found around northeast region. In 2004, significant precipitation was observed from May to September. Heavy rainfalls were observed at the upper reach catchment in India at Cherrapunji and in the northeast region in Bangladesh (Hoque et al. 2008).

6.4 Seasonal and annual changes of water levels around Bhairab Bazar and the GBM River system

For the year 2004 (Fig. 10), the water level of the Meghna River at Bhairab Bazar station recorded its highest peak water level on the 24th of July, approximately 7.78 m. The danger water level was at 6.25 m. While in 1998, highest water level was found to be

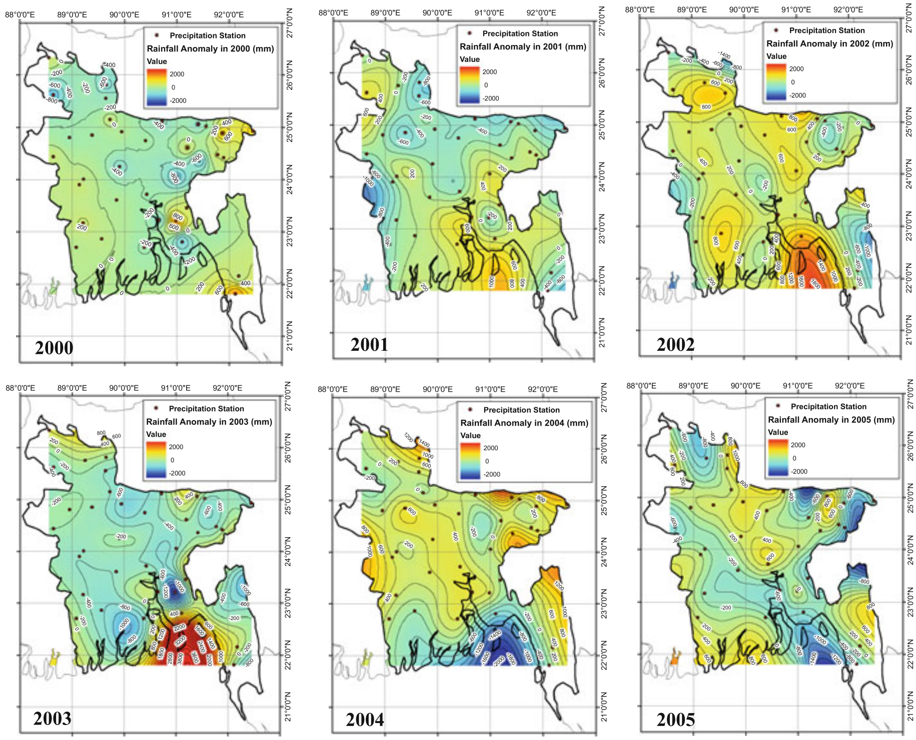


Fig. 9 Annual summer monsoon rainfall anomaly maps from 2000 to 2005 (orange part of the map illustrates 2000 mm rainfall and blue part of the map illustrates −2000 mm rainfall). These rainfall anomaly maps clearly depict that 2002 and 2004 were extremely high rainfall. The rainfall anomaly map for 2004 illustrates exceptionally high and prolonged rainfall years

7.33 m. Thus, in 2004, it was significantly higher than in the 1998 flood event. The water levels of the three major river system GBM stations (Fig. 11) show that water level is extremely high from 2001 to 2005. Moreover, it becomes apparent that the three rivers GBM coincidently synchronized their peaks simultaneously on the 24th of July in 2004, resulting in severe flooding. Occurrences of simultaneous flood peaks in the three major rivers are not historically unusual events, but when they arise they cause widespread flooding and extensive damage.

7 The flood damage maps

Drastic fluctuation in water level is, unfortunately characteristic of much of Bangladesh and causes severe property, agricultural and infrastructural damage (Imhoff et al. 1986). Due to lack of sufficient flood damage data, we present six flood damage maps from written above six districts. The data are based on 18 days from the 14th to the 31st of July 2004 for the northeast region in Bangladesh.

Flood-affected *families* in the Habiganj district are displayed in Fig. 12a. A total of 1,590,425 families were affected by the severe flooding. On the map, red parts indicate the number of flood-affected families, which is estimated at 116,769–176,548. The map indicates that many of the families that suffered from severe floods moved out from the

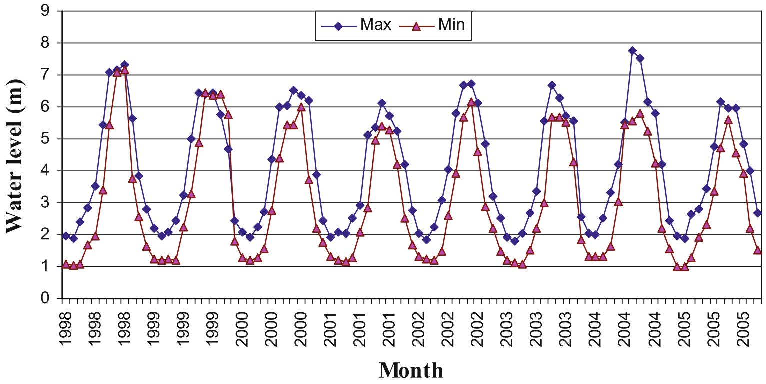


Fig. 10 Maximum and minimum water level of the Meghna River at Bhairab Bazar station from 1998 to 2005. In 1998, highest water level was found to be 7.33 m in September. While in 2004, the highest peak water level was found to be 7.78 m on 24th of July. The danger water level was found to be 6.25 m. It was significantly higher than in 1998 event

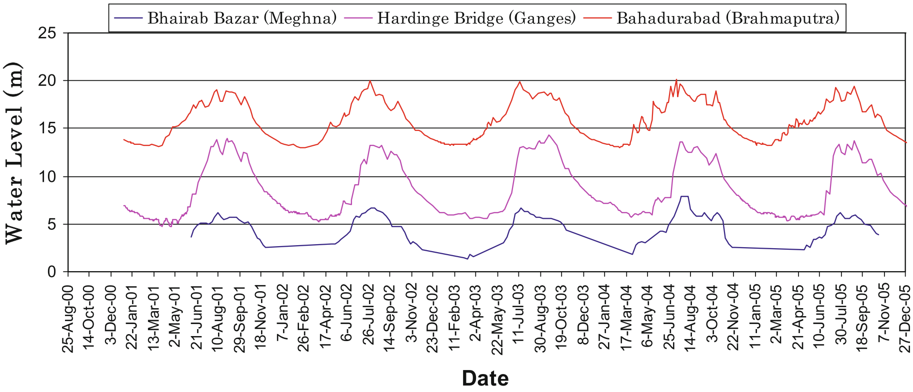


Fig. 11 Daily water level of three major rivers (GBM) the Ganges River at Harding Bridge, the Brahmaputra River at Bahadurabad and the Meghna River at Bhairab Bazar station shown water level is extremely high from 2001 to 2005. It becomes apparent that the three rivers GBM coincidently synchronized their peaks simultaneously on the 24th of July in 2004, resulting in severe flooding. Simultaneous flood peaks in the three major rivers are not historically unusual events, but when they arise they cause widespread flooding and extensive damage

inundation area. Nevertheless, a large number of families continued to live in the inundation area, in spite of the fact that this area is not habitable during flooding.

Flood-affected *people* in the Bhairab Bazar and Sunamganj districts are shown in Fig. 12b. A total of 6,583,912 people were affected. Again, the blue part of the map indicates that the number of flood-affected people is estimated at 313,081–475,000. The flood damage especially affected those with a lower standard of living. Those who were affluent were less affected. Those with incomes of less than $ 1 US per day lost their belongings including their livestock. Those who managed to live in a machang (an elevated platform usually made of bamboo) were able to stay in their houses.

Population deaths are shown in Fig. 12c. Within 18 days of flooding, a total of 317 deaths were recorded. The orange part of the map indicates that in the Bhairab Bazar, Brahmanbaria and Mymensingh districts, 18–84 deaths were documented. The causes of deaths were water-related diseases, such as diarrhea and dysentery. During flooding, acquiring pure drinking water is always a serious problem. People also died as a result of low-quality food at their disposal. This had a far reaching effect on the number of deaths recorded after the flood. Figure 12d illustrates *cattle head deaths*. The blue part of the map estimates a total of 558–1,020 cattle died in the Sunamganj district. A total of 8,466 cattle head died, in the Bhairab Bazar and Moulavi Bazar districts. Livestock farming is a major source of income. While people can move out of an inundation area, it remains difficult to find enough dry land for cattle and poultry during the flood season.

Crop damage is shown in Fig. 12e. Fully damaged crops average a total of 177,842 hectares and 90,160 hectares were partially damaged. The blue parts of the map indicate the crop damage area was estimated at 7,551–11,855 hectare around the Bhairab Bazar, Brahmanbaria and Sunamganj districts. Unusually heavy rainfall occurred in April, the beginning of crop plantation and harvesting periods, with the result that agricultural land became submerged. The Boro rice crops were completely damaged.

The damage to *embankments* is illustrated in Fig. 12f. The blue part of the map illustrates that the 7,836–18,550 km^2 of *embankments* were completely destroyed around Habiganj district. It was discovered that 171,783 km^2 of embankments were completely destroyed around the northeast region. The embankment damage was a natural feature of the Meghna River and the two tributaries the Surma and Kusiyara Rivers.

8 The flood hazard maps

Composites of the five RADARSAT inundation maps from 2000 to 2004, the GIS data and damage data in 2004 allowed the creation of unique flood hazard maps. Five-year hazard zones can be classified based on the number of years affected by floods. Hazard maps covered the northeast region, but damage data focused only on written above six districts. The Hazard maps illustrate that the very vulnerable and risk zone areas are Bhairab Bazar, Sunamganj, Habiganj, Netrokona, and Moulavi Bazar, respectively.

The red part of the map (Fig. 13) illustrates the 5-year flood hazard zone and blue part illustrates the no hazard zone. On the hazard map, green circles indicate the severity of flood damage and risk zone area (large to small) along with damage numbers is showing. Six hazard maps are presented here, which focus on the severity of the flood hazard of northeastern Bangladesh in 2004.

Fully damaged *housing* is displayed in Fig. 13a. A total of 276,516 homes were fully damaged. One green circle illustrates 25,000 homes that were completely damaged in Bhairab Bazar. Note that there were no hazard zones around the Brahmanbaria district. One green circle indicates that even for a no hazard zone 2,544 homes were completely damaged. Those flood affected took shelter with their relatives or left for other areas. Villagers, who stayed, managed to survive by making machangs.

Partially damaged *housing* is displayed in Fig. 13b. A total of 1,032,401 homes were partially damaged. Again, there were no hazard zones around (24.10°N and 91.22°E) the Brahmanbaria district where one green circle indicates that 13,664 homes were partially damaged. This number also indicates that the hazard zone was increasing. Homes in this area are being continually destroyed by the long duration flooding occurring every year.

Damage to *brick roads* is shown in Fig. 13c. A total of 4,489,044 km^2 brick roads were completely destroyed in 2004. The damage to *muddy* roads is displayed in Fig. 13d. A total of 6,190,936 km^2 muddy roads were completely destroyed around the Hobiganj district in

Fig. 12 Damage map illustrates **a** Flood-affected *family*; on the map, red parts indicate the number of flood-affected *families*, which is estimated at 116,769 to 176,548 in the Habiganj district. And **b** Flood-affected *people*; the blue part of the map indicates that the number of flood-affected *people* is estimated at 313,081 to 475,000 in the Bhairab Bazar and Sunamganj districts. **c** Deaths of *people*, the orange part of the map indicates that in the Bhairab Bazar, Brahmanbaria and Mymensingh districts, 18–84 deaths were documented. And **d** *Cattle head deaths,* the blue part of the map estimates a total of 558–1020 cattle died in the Sunamganj district. **e** Damage *of crops,* the blue parts of the map illustrates the *crop* damage area was estimated at 7,551–11,855 hectares around the Bhairab Bazar, Brahmanbaria and Sunamganj districts. And **f** Damage of *embankments,* the blue part of the map illustrates the 7,836–18,550 km^2 of *embankments* were completely destroyed around Habiganj district ▶

2004. While a no hazard zone (24.10°N and 91.22°E) applied to the Brahmanbaria district, two green circles indicate that 5,294.0 km^2 brick roads and 258.0 km^2 muddy roads were completely destroyed. Thus, damaged roads are a common feature in northeast region, making it very difficult to commute during flooding conditions. The government of Bangladesh, therefore, tries to repair these roads during the winter season.

The flood-*affected* areas are shown in Fig. 13e. No hazard zone was in the Brahmanbaria district and one green circle indicated that 26,633 km^2 districts were also affected by the flood. It seems that the RADARSAT images could not capture certain areas. An estimate of the inundation area using the RADARSAT images was about 29,900.72 km^2 in 2004. Comparisons between the flood-affected area using damage data and satellite data showed that the flood-affected area was larger than what was shown on the flood hazard map. Moreover, the hazard map depicts that the flood-affected areas are increasing daily.

Flood-*affected villages* are illustrated in Fig. 13f. A total of 2,358 villages were affected by the flood hazard. Damage data indicate a number of affected villages around the Bhairab Bazar district. The hazard maps show that the Bhairab Bazar district is not conducive for living during flooding. Moreover, the hazard map also indicates that the Meghna River Basin is unfit for life during flooding. This requires that villagers are frequently moved from the hazard zone.

In sum, it is to be noted that the no hazard zone covers a region around 91.22°E and 20.67–24.10°N, as shown with the green symbol (Fig. 13). This clearly indicates the possibility of severe damage and also that the hazard zone is increasing daily. For certain areas, RADARSAT images could not captured.

9 Discussion and conclusions

A number of factors that are essential for the understanding of flooding in northeastern Bangladesh were examined. These include data such as rainfall, water levels using ground data, flood monitoring, mapping and assessments using RADARSAT and LANDSAT images as well as GIS data. In addition, the effects of flooding using damage data were analyzed. The use of these various factors provided new methods for the creation of damage and hazard maps. These suggest the following conclusions:

1. High-resolution visible/infrared sensor LANDSAT images provide good delineation of the extent of flooding. Thus, LANDSAT images are very useful for monitoring flood-prone areas. Using the LANDSAT satellite images, a clear picture of the wet season (25th of October, 2000) and the dry season (28th of February, 2000) was obtained. LANDSAT images will provide flooding information when the weather is, clear.

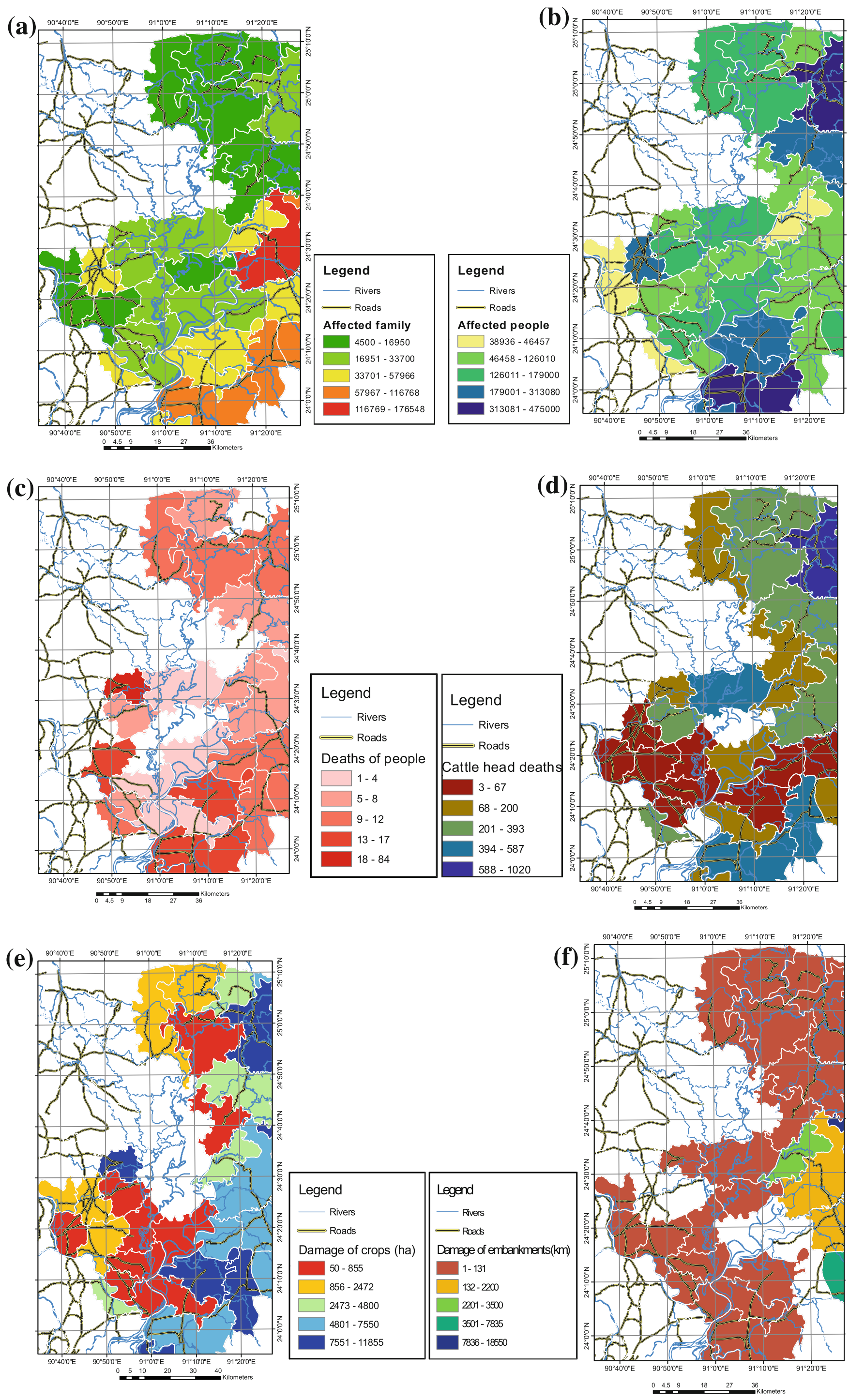

(a)
Legend
Rivers
Roads
Affected family
4500 - 16950
16951 - 33700
33701 - 57966
57967 - 116768
116769 - 176548
(b)
Legend
Rivers
Roads
Affected people
38936 - 46457
46458 - 126010
126011 - 179000
179001 - 313080
313081 - 475000
(c)
Legend
Rivers
Roads
Deaths of people
1 - 4
5 - 8
9 - 12
13 - 17
18 - 84
(d)
Legend
Rivers
Roads
Cattle head deaths
3 - 67
68 - 200
201 - 393
394 - 587
588 - 1020
(e)
Legend
Rivers
Roads
Damage of crops (ha)
50 - 855
856 - 2472
2473 - 4800
4801 - 7550
7551 - 11855
(f)
Legend
Rivers
Roads
Damage of embankments(km)
1 - 131
132 - 2200
2201 - 3500
3501 - 7835
7836 - 18550
90°40'0"E
90°50'0"E
91°0'0"E
91°10'0"E
91°20'0"E
25°10'0"N
25°0'0"N
24°50'0"N
24°40'0"N
24°30'0"N
24°20'0"N
24°10'0"N
24°0'0"N
0 4.5 9 18 27 36 Kilometers
0 5 10 20 30 40 Kilometers

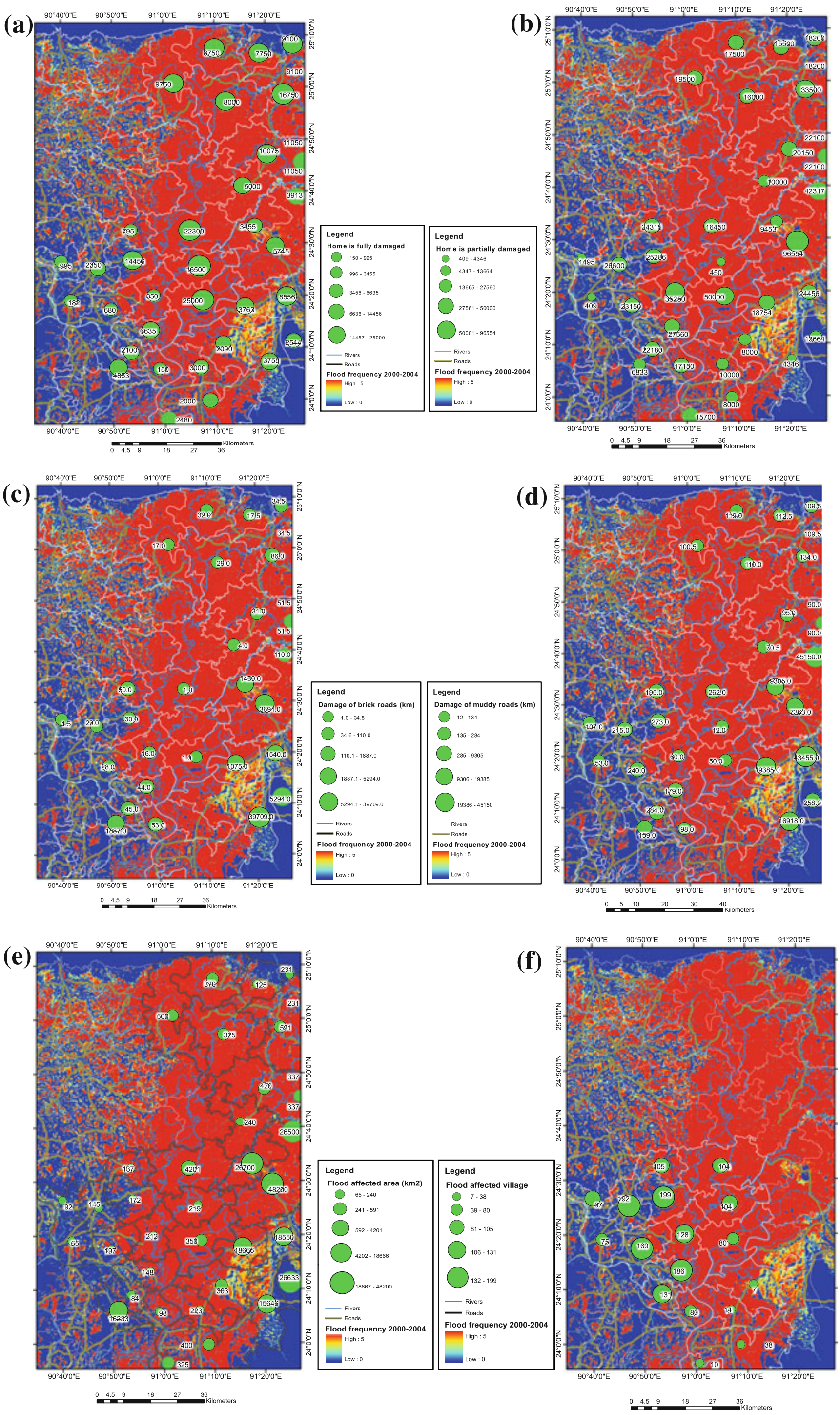
Fig. 13 Hazard map in 2004 illustrate **a** *Home* is fully damaged, a total of 276,516 homes were fully damaged. One green circle illustrates 25,000 homes that were completely damaged around Bhairab Bazar. And **b** *Home* is partially damaged, a total of 1,032,401 homes were partially damaged. No hazard zone around (24.10°N and 91.22°E) the Brahmanbaria district where one green circle indicates that 13,664 homes were partially damaged. Certain areas RADARSAT images could not captured. **c** Damage of *brick roads,* a total of 4,489,044 km^2 *brick roads* were completely destroyed. And **d** Damage of *muddy roads,* a total of 6,190,936 km^2 muddy roads were completely destroyed around the Hobiganj district. While a no hazard zone around (24.10°N and 91.22°E) applied to the Brahmanbaria district, two green circles indicate that 5,294.0 km^2 brick roads and 258.0 km^2 muddy roads were completely destroyed. **e** Flood-affected *area;* no hazard zone one green circle indicated that 266,33 km^2 areas were also flooded around (24.10°N and 91.22°E). It seems that the RADARSAT images could not capture certain areas. And **f** Flood-affected *village;* a total of 2,358 villages were affected by the flood hazard. The hazard maps show that the Bhairab Bazar district is not conducive for living during flooding ▶

Unfortunately, this is not the case during the monsoon season, because of the cloud cover.

2. This study identified that a vast area of the northeast region was inundated and the Meghna, Surma and Kushiyara Rivers in particular illustrate overbank flooding. Certain situation was monitored by the active sensor RADARSAT remote sensing imaging. The RADARSAT images clearly depicted the progress of the monsoon flooding. The maximum extent of the inundation area was successfully estimated using RADARSAT satellite image. In 2004, inundation area was found to be larger than in other years. The RADARSAT data were found to be a very useful tool for clearly identifying flooded and non-flooded areas. The RADARSAT data have the ability to allow flood monitoring, mapping and assessing of inundated areas and other surface conditions. The RADARSAT has the capability of penetrating cloud cover and the heavy precipitation occurring during the monsoon period.

In 2004, the annual rainfall exceeded previous record, and water level of the GBM river system coincidently synchronized their peaks on 24th July in 2004, resulting in extremely severe flooding. The RADARSAT images clearly captured this event. It can be deduced that precipitation around northeast region was a principal factor for the flood in 2004. One can conclude that the relationship between the RADARSAT data and the ground data corresponds quite closely.

3. Time series analysis of the RADARSAT inundation maps allowed for the visualization of the progress of monsoon flooding in 2004. The RADARSAT images for the 24th of July 2004 showed that extensive flood water prevailed around the northeast region and 40% of the country was inundated. The western side inundation is largely dominated by the rain and river water, while in the eastern side, rainfall together with river water and the water flows from an upper level catchment presumably is responsible for the flood situation. The river records indicated that the maximum water level around the GBM river system coincided on 24th July, resulting in the severe flood. It is assumed that the RADARSAT data and the river gauging data coincided on the 24th of July in 2004. For flood monitoring, mapping and assessing, the RADARSAT data is an effective tool. Remote sensing and GIS can play a major role in identifying precisely mapping and estimating flood-prone areas in developing countries like Bangladesh. Consequently, to obtain accurate results of monsoon flooding, monthly time series of RADARSAT images data are crucial. In Bangladesh, there are numerous inadequacies in the availability and access to data and the information required for effective management of this highly sensitive environment subject to extensive flooding.


(a)
(b)
(c)
(d)
(e)
(f)
90°40'0"E
90°50'0"E
91°0'0"E
91°10'0"E
91°20'0"E
25°10'0"N
25°0'0"N
24°50'0"N
24°40'0"N
24°30'0"N
24°20'0"N
24°10'0"N
24°0'0"N
Legend
Home is fully damaged
150 - 995
996 - 3455
3456 - 6635
6636 - 14456
14457 - 25000
Rivers
Roads
Flood frequency 2000-2004
High : 5
Low : 0
Legend
Home is partially damaged
409 - 4346
4347 - 13664
13665 - 27560
27561 - 50000
50001 - 96554
Rivers
Roads
Flood frequency 2000-2004
High : 5
Low : 0
Legend
Damage of brick roads (km)
1.0 - 34.5
34.6 - 110.0
110.1 - 1887.0
1887.1 - 5294.0
5294.1 - 39709.0
Rivers
Roads
Flood frequency 2000-2004
High : 5
Low : 0
Legend
Damage of muddy roads (km)
12 - 134
135 - 284
285 - 9305
9306 - 19385
19386 - 45150
Rivers
Roads
Flood frequency 2000-2004
High : 5
Low : 0
Legend
Flood affected area (km2)
65 - 240
241 - 591
592 - 4201
4202 - 18666
18667 - 48200
Rivers
Roads
Flood frequency 2000-2004
High : 5
Low : 0
Legend
Flood affected village
7 - 38
39 - 80
81 - 105
106 - 131
132 - 199
Rivers
Roads
Flood frequency 2000-2004
High : 5
Low : 0
0 4.5 9 18 27 36
Kilometers
0 5 10 20 30 40
Kilometers
9100
8750
7750
9750
8000
16750
11050
10075
5000
3913
795
22300
3455
5745
995
2350
14456
16500
182
680
850
25000
3763
8556
6635
2100
2000
2544
4853
150
3000
3755
2480
18200
17500
15500
19500
16000
33500
22100
20150
10000
42317
24315
16450
9453
96554
1495
26600
25286
450
409
23150
35260
50000
18754
24456
27560
13664
22180
8000
6833
17150
4346
15700
34.5
32.0
17.5
17.0
86.0
29.0
51.5
31.0
4.0
110.0
1450.0
50.0
1.0
3691.0
1.5
29.0
30.0
16.0
1540.0
28.0
1075.0
44.0
5294.0
45.0
39709.0
1887.0
53.0
109.5
119.0
112.5
100.5
134.0
110.0
90.0
95.0
70.5
45150.0
9306.0
195.0
262.0
7363.0
407.0
215.0
273.0
12.0
53.0
240.0
60.0
50.0
19385.0
43455.0
179.0
258.0
284.0
16918.0
159.0
98.0
231
370
125
500
325
591
337
420
240
26500
137
4201
26700
48200
92
145
172
219
65
197
212
350
18550
18666
148
303
26633
84
16233
98
223
15646
400
105
104
97
192
199
75
169
128
80
186
131
7
14
38
10

4. The damage map illustrates six types of damages that are present. The damage map clearly illustrates the number of families affected by flood, how many people were killed, how much hectares of crops were damaged as a result of the flood, etc. It clearly illustrates that the damage of crops was extremely severe around northeast region.
5. It is possible to create unique flood hazard maps, where one can jointly display the flood hazard zone and the social and infrastructural flood damage. Five-year hazard zones can be classified based on the number of years affected by floods. Hazard maps clearly illustrate that the northeast region was severely inundated for 5 years, where one can easily understand that red part of the map is hazard zone. On the hazard map, the green circle focuses on the number of damages. It illustrates the number of flood damages to homes, roads and area.

These results also indicated that estimates of the inundation area using RADARSAT satellite data and ground data had some inconsistencies. Using social and infrastructure of flood damage data with RADARSAT data, it can be deduced that inundation area and flood damage is larger then the hazard map indicates. These results were found to be similar to those of Wilson and Rashid (2005). They made a comparison between RADARSAT images and the hydrologic characteristics. They demonstrated that there were some differences between the hydrologic regimes of the flood and areal extent of flooding. This inconsistency was re-enforced in that the imagery of 27 April 1997 did not represent overbank inundation accurately. One cause for this discrepancy might be that the timing of the image data and the damage data were different. Nevertheless, results of this hazard map found to be somewhat similar to those of Rasid and Pramanik (1993). They identified that the actual extent of flooding was larger than the satellite images suggested. The hazard map of this study illustrate hazard zone increasing daily. This method is very useful as it increases interpretability using RADARSAT data in Bangladesh and elsewhere. The main advantage of satellite imagery is that an instant picture of the flood scene can be obtained in real-time.

Consequently, the results presented in this paper suggested that the RADARSAT image data provide useful information for mapping the extent of inundation around northeast region. These results are not same as the previous studies like Imhoff et al. (1986, 1987); Wilson and Rashid (2005); Rahman et al. (2005) and Dewan et al. (2006). This study first analyzed northeast region from 2000 to 2004 and estimated inundation area, presented a unique method of flood hazard mapping, which are different from previous studies. The results of this study also suggest that the conditions in the northeast region are considerably more severe than for other regions, in that heavy rainfall and flooding occurs earlier.

The main objective of this study was to demonstrate the capability and usefulness the RADARSAT remote sensing and GIS for early identifying the potential inundation area, which in turn will allow flood forecasting and warning center to identify regions of flooding. It can be deduced that RADARSAT data is acquired over the northeast region. It is revealed that very often and in all kinds of weather condition, RADARSAT satellite provides images data. Therefore, we can conclude that the RADARSAT data have the ability to clarify questions relating to the inundation area, flood monitoring, mapping, and assessing. For the inundation areas and for the severity of flood damage, the RADARSAT data can be objectively mapped. Thus, this study clearly demonstrated that the impact that RADARSAT satellite-based measurements of water body in conjunction with ground data generates confidence that the results are useful for flood disaster management. Finally, the results achieved here could also be expected to be very useful for flood disaster management, and hazard mapping services, which may reduce the cost of a general survey.

Acknowledgments We gratefully acknowledge the Center for Environmental and Geographic Information Services (CEGIS) Bangladesh, for providing the RADARSAT and LANDSAT satellite images and the GIS data. The authors are very thankful to the Flood Forecasting and Warning Center (FFWC) and the Bangladesh Water Development Board (BWDB) for providing the ground data. We wish to thank Dr. Rezaur Rahman, of the Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology (BUET) for his generous assistance. We are also grateful to Dr. Pete E. Lestrel for valuable comments.

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