Assessment of Tropical Cyclone Remal Induced Inundation in Patuakhali and Barguna Districts of Bangladesh Using Sentinel Satellite Images

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ABSTRACT: Tropical cyclones are common natural phenomena that affect both natural and human environment. They often cause significant flood inundation in coastal regions. Tropical Cyclone Remal, which struck the southern coast of Bangladesh in May 2024, caused significant flooding and damage across multiple districts of the country. This study aims to assess the inundation caused by Tropical Cyclone Remal in the central coastal districts of Patuakhali and Barguna of Bangladesh using both Sentinel-1 SAR and Sentinel-2 data. Additionally, it identifies the land use and land cover (LULC) classes affected by the inundation. To find the extend of inundation, Sentinel-1 SAR data was processed using binarization techniques on images taken pre- and post-cyclone. On the other hand, Sentinel-2 optical imagery was used to map the different LULC classes in the study area. By overlaying the LULC and inundation maps, the study calculated the LULC classes affected by the inundation. Sentinel data were useful in the whole process especially sentinel-1 for its capacity of penetration though cloud. The results of this study highlight the significant impact of Cyclone Remal on the central coastal districts of Patuakhali and Barguna in Bangladesh. Patuakhali is the most affected district in terms of total area (835 sq. km) inundated whereas in terms of severity of inundation, Barguna affected severely. Most of these inundated areas were agricultural lands. The cyclone hit during the harvesting time of kharif-1 crops and the crops were damaged by prolonged inundation of the agricultural lands. This study will be helpful to the policy makers in case of informing about the severity of tropical cyclones in coastal districts of Bangladesh especially Patuakhali and Barguna district.

Keywords: Tropical Cyclone; Cyclone Remal; Coastal Inundation; Landuse-Landcover; Sentinel-1 SAR; Sentinel-2

INTRODUCTION

The atmosphere of the Earth is an ever-changing structure that may create influential natural phenomena like cyclones (Patra et al., 2024). It causes devastating events like extreme flooding, damaging winds, affecting drainage system and destroying coastal ecosystem (Feng et al., 2019; Brown et al., 2017; Hadipour et al., 2018). For example, in 2012, 8.5 million households suffered the disruption of power supply and economic losses exceeding USD 50 billion were made in US due to the Hurricane Sandy (Blake et al., 2013). Cyclone Fani, which hit eastern India in 2019, delivered wind leading 200 km/h, tremendous rainfall, and substantial storm surge, resulting in at least 64 deaths and over 28 million people affected (Chatterjee, 2020). Tropical Cyclones like *Gorki* in 1991 caused the death of 147,000 people and *Sidr* in 2007 caused 4500 deaths in Bangladesh (Alam, 2023). Moreover, cyclone endangers life by contaminating surface and groundwater of the affected area with heavy metals, salt water intrusion and bacteria (Roca et al., 2019). It also affects fisheries, agriculture and vegetation. Bangladesh, a south Asian country, is the 7th most distressed country in the world due to the frequent and severe cyclones that hit the country between the time span of 2000 to 2019 (Eckstein et al., 2021). Tropical cyclones in Bangladesh mostly occur from October to May. Almost 70% of its people are at the risk of being victim to them (World Bank, 2018). The flat terrain of the country, huge rainfall and anthropogenic causes along with Sea Level Rise (SLR) significantly amplifies the impact of cyclones in Bangladesh. Cyclone in Bangladesh is mostly associated with the storm surges and floods (Chakma and Akter, 2021). Every year cyclone induced storm surges inundates the coastal districts specially the Barisal and Khulna Division (Chakma and Akter, 2021). Agriculture is one of the major sectors severely affected by tropical cyclones as 70% of the country's land is used for agricultural purposes (Singha et al., 2020). Long-time inundation

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of the agricultural field causes damage to the yields and salinity intrusion in the crop field affects crop production by delaying germination and reducing rice production (Rahman et al., 2024). Although advance technology, mass awareness and the intervention of NGOs and local government have succeeded in reducing the death tolls due to cyclone (Alam, 2023) but such impacts on agriculture significantly affects food security. Efforts to mitigate these impacts are essential for sustainable management and overall development of the country.

Understanding the nature and characteristics of cyclone induced inundation is important for damage analysis and further management. The data required for this work can be acquired both from fieldwork and satellite imagery (Jensen, 2013). The use of satellite imageries for mapping flooding over a large area is more preferable as satellite imageries have a wide coverage, cost-effective and highly accessible (Clement et al., 2017). Several studies had been conducted on this regard where satellite images were used for flood mapping and identifying the inundated areas to determine extent of damage due to the flood in different areas (Anusha and Bharathi, 2020; Pramanick et al., 2022; Elstohy and Ali, 2023). There are various satellites that help in flood mapping and researchers all over the world used various methods in accomplishing this work. Such as Lee and Li (2024) used deep active learning for mapping the flood inundated areas, Huang et al. (2014) used MODIS imagery for this work in Australia's Murray-Darlin Basin, Tanguy et al. (2017) used RADARSAT-2 images and Auynirundronkool et al. (2012) used both RADARSAT and MODIS imageries in the Central Thailand. Microwave satellites, particularly those equipped with Synthetic Aperture Radar (SAR), are ideal for flood mapping as they can work in all-weather situation including cloud, fog and rain. In this case, Sentinel-1 SAR data could be very useful for flood inundation mapping (Pramanick et al., 2022) as it provides high resolution data even in cloudy weather conditions. It is also easy to acquire and available at free of cost (Islam and Meng, 2022; Jamali et al., 2024). Again, classifying the Land Use and Land Cover (LULC) is also important to quantify the extent of flooding in different LULC types. Various satellite imageries are used for LULC mapping such as Landsat-8 (Mohith and Karthi, 2022; Jombo and Adelabu, 2023), Sentinel -2 (Puttinaovarat et al., 2023; Makandar and Kaman, 2021; Gao et al., 2022), MODIS (Thenkabail et al., 2005) and so on. Sentinel-2 MSI data provides high resolution images (10-60m) and it has 13 spectral bands. Which gives clear identification of the features of the earth surface. Moreover, it is free to use. GIS-based overlay analysis is essential for synthesizing several spatial data layers to obtain practical insights, allowing the merging of various outcomes instead of illustrating them independently (Bourjila et al., 2024; Arumugam et al., 2023; Walke et al., 2011). So, it is important to conduct a overlay analysis combining the layers of Flood map and LULC map to quantify the flood extent in different LULC types.

The central coastal area in Bangladesh which mostly includes some of the districts Barishal Division faces cyclone induced storm surges almost every year. This area faced Sidr in 2007 which was a category-4 tropical cyclone (Haque and Hoyanagi, 2021). This area also suffered Cyclone Komen, Cyclone Roanu, Cyclone Mora, Cyclone Fani, Cyclone Amphan, Cyclone Yaas, Cyclone Sitrang and Cyclone Remal in the year 2015, 2016, 2017, 2019, 2020, 2021, 2022 and 2024 respectively (Akon and Mia, 2024). These causes loss to the people, animal, agriculture and eventually hampers the economy (Medha et al., 2021).

Several approaches have been made to assess the risk of cyclone-induced flooding in the coastal areas of Bangladesh (Hasan et al., 2023; Rahman and Akter, 2024) and also to evaluate the resulting damages (Liu et al., 2023; Medha et al., 2023). Moreover, various studies with various methodologies were found with an attempt to assess the flood extent in the Bengal Basin. Islam, Bala, and Haque (2010) assessed the spatio-temporal extent of flooding in Bangladesh during 2004 and 2007 using water and vegetation indices with the help of MODIS and RADARSAT data. Bhattacharya, Mazzoleni, and Ugay (2019) conducted flood mapping in the trans-boundary Brahmaputra basin, Again, Tripathi, Pandey, Parida, and Kumar (2020) mapped the flood extend and assessed the impact of 2017 flood in Bihar, India using SAR data. However, very few studies were found that have focused on flood mapping of the central coastal areas of Bangladesh in response to cyclone-induced storm surges. The primary objective of this research is to generate cyclone Remal induced flood inundation map for central coastal districts of Patuakhali and Barguna of Bangladesh. The work also analyzes the distribution of inundated areas across different land use and land cover classes. A Remote Sensing (RS) and Geographic Information System (GIS) based approach have been undertaken to fulfill such objective by utilizing openly available Sentinel-1 and sentinel-2 data. Such studies will help the policy makers to identify high-risk areas, inform flood mitigation strategies, and develop preparedness plans, ultimately supporting informed policies to reduce flood risks and enhance disaster response, protecting lives and property. Moreover it will work as an input in dynamic geospatial portal for flood monitoring and damage assessment and help in efficient water management which is an important point in Sustainable Development Goals (SDGs).

CYCLONE REMAL

The coastal region of Bangladesh is highly susceptible to cyclones due to its geographical location. It experiences cyclone almost every year. In May 2024, the region experienced a tropical cyclone named Remal (BDRC, 2024). Forming on 24 May, 2024, Remal had a landfall in West Bengal of India and the coastal districts of Bangladesh on 26 May, 2024 (BDRC, 2024; FAO, 2024). The maximum wind speed of the cyclone was recorded 111 km/h on 27 May, 2024. This wind, along with massive tides from the sea, produced flooding of 5-8 feet above sea level in coastal areas (IFRC, 2024). As a result, the coastal districts of Bangladesh including Satkhira, Bagerhat, Khulna, Barguna, Patuakhali, Bhola, Noakhali, Feni, Chattagram, Cox's Bazar, Pirojpur, Lakshmipur, Cumilla was severely flooded (ECHO, 2024). During the field survey, local people has remarked Cyclone Remal as more severe than Cyclone Sidr in 2007. However, the death toll of Remal is lesser than Cyclone Sidr (Alam, 2023; AFP, 2024). Cyclone Remal entered from the southwest of Bangladesh through Satkhira district in Khulna Division on 26 May, 2024 with severe cyclonic storms, later the wind became weaker and changed its direction towards Dhaka as depression. Later it left the territory of Bangladesh through Sylhet district at the northeast of the country in 28 May, 2024 (BMD, 2024b). It flooded 19 districts in the country (The Daily Star, 2024b) among them 6 districts (Satkhira, Bagerhat, Khulna, Patuakhali, Barguna and Bhola) was specially warned (Prothom Alo, 2024).

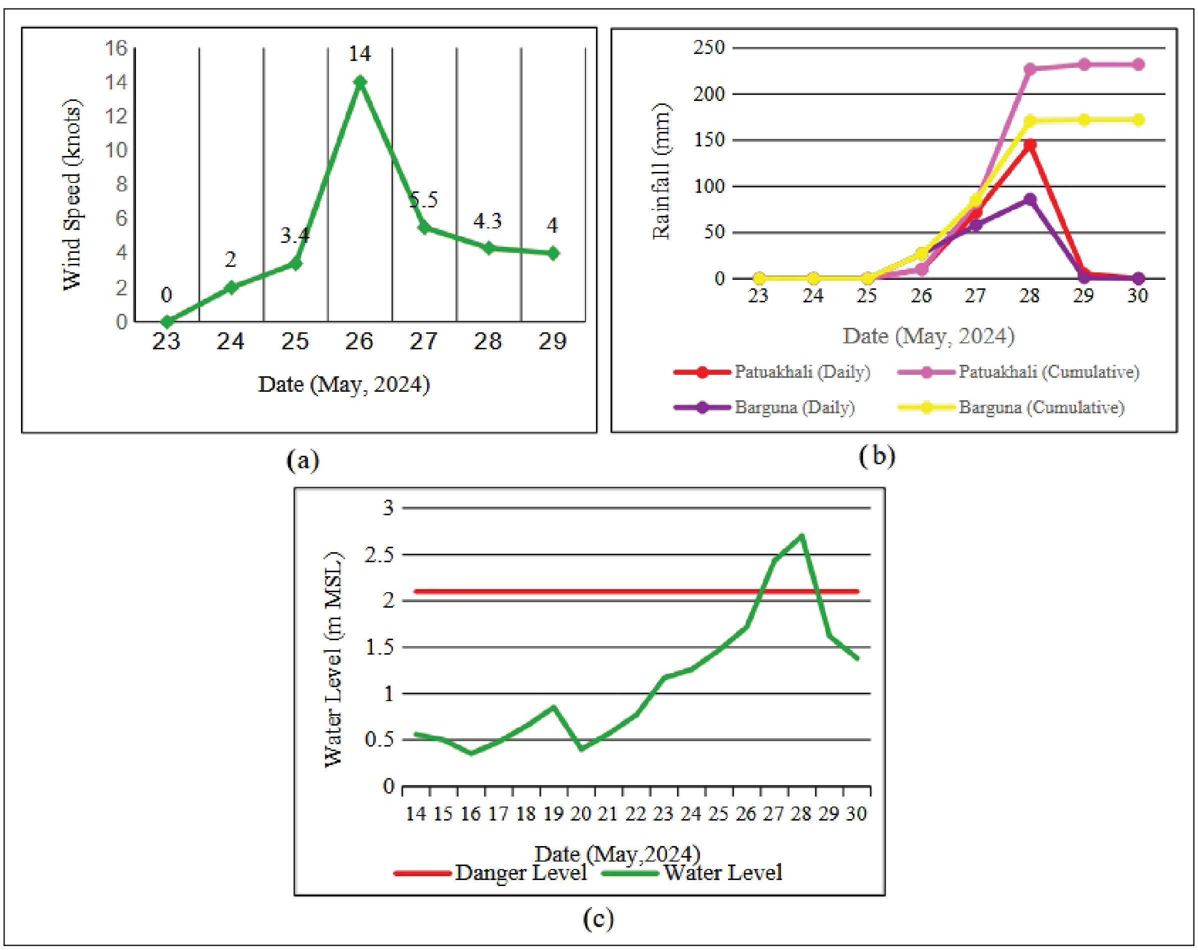

Figure 1: Recordings of (a) Wind Speed (b) Rainfall (c) Observed Sea Level

Rainfall during the situation ranged from 44-289 mm at the western and central coastal areas and 200-350mm rainfall was seen in the northeastern coastal areas and hill tracts (BDRC, 2024). As a result, the whole country witnessed from heavy to very heavy rainfall all over the period. Daily rainfall data from the Bangladesh Meteorological Department (BMD, 2024a) has been shown in Fig. 1 (b) for May 23 to May 30, 2024, at Patuakhali and Khepupara stations. There was a sudden rise in rainfall in both stations from 25 May, 2024, coinciding with Cyclone Remal*'s* landfall. The highest rainfall was 127 mm in Patuakhali and 86 mm in Khepupara on May 28.

Daily maximum wind speed at both the stations of Patuakhali and Khepupara also shows a sudden rise to 14 knots (Southeast) (25.928 Km/hr) on May 26, 2024 (Fig. 1 (b)), during Cyclone Remal's landfall (BMD, 2024). This increase is due to wind moving from high to low-pressure areas caused by the cyclone (Nugroho et al., 2019).

Storm surges are marked by unusual water level rises (Lun et al., 2011). Data from the Flood Forecasting and Warning Centre (2024) showed fluctuating water levels in Barisal from May 14 to May 30, peaking at 2.1 m MSL on May 27-28 (Fig. 1 (c)). The water level rose significantly after Cyclone Remal formed on May 24 *(BDRC, 2024)*.

Cyclone Remal affected more than 37 lakh people and more than 35 thousand houses were completely devastated and more than 1 lakh houses were partially damaged leaving its dwellers homeless (The Daily Star, 2024b). There is a debate on the specific number of deaths due to Cyclone Remal. AFP (2024) in "Prothom Alo" reported 17 deaths because of the cyclone in Bangladesh and 65 combinedly with India, where The Daily Star (2024a) reported 10 deaths. Again, according to Islam (2024) in The Business Standard the death toll in 14. But it is sure that Cyclone Remal took the lives of at least 10 people in Bangladesh.

STUDY AREA

Bangladesh is one of the most vulnerable country to natural disaster due to its geographic location (Rahman et al., 2024) especially the coastal zone due to frequent struck of cyclone and cyclone-induced storm surges (Akter et al., 2024). Southern districts of Patuakhali and Barguna of Bangladesh in the central coastal region of the country are chosen as study area for this study (Fig. 2). These areas are susceptible to frequent cyclones every year (Haque et al., 2022). Although Cyclone Remal landfall in Bangladesh through Satkhira district but Satkhira and Bagerhat is surrounded by Sundarbans, worlds largest mangrove forest, in the south which acts as a "shelter belt" during cyclones (UNESCO, 2024). But Patuakhali and Barguna district has no such shield rather these are floodplain lands where people live very close to the sea. Again, due to their location at the south-central part of the country, Patuakhali and Barguna faces the impact of both cyclones coming from the southeast (Cyclone Mora) and southwest (Cyclone Aila) (BMD, 2024c). All these factors influenced the researchers to select Patuakhali and Barguna as the study area. The geographical location of Patuakhali district is 22°19' 60" N and 90°19' 60" E (Bangladesh National Portal, 2024a). And the geographical coordinates of Barguna district is 23°04′10" N and 21°50′5" S (Bangladesh National Portal, 2024b). Geologically the study area is situated in the Hatiya trough (Eva et al., 2020) and falls into Barisal Gravity High tectonic element (Alam et. al., 2023). The physiographical setting of the study area includes delta plain in most of the area and large inland lakes or haors and beels in some parts of Barguna and Patuakhali district (Hasan et al., 2007). As a low-lying area in the southwestern part of the country, Patuakhali & Barguna is situated in the Ganges Tidal Basin (GTB) where it faces frequent tides from the Bay of Bengal (Aziz et al., 2022).

The study area expanded to 5052.62 sq. km (BBS, 2023) having floodplain land and flat topography (Roy and Zahid, 2021). Patuakhali and Barguna is inhabited by 27,37,785 people (BBS, 2023). This area surrounded by numerous Small and large River and Chars. *Payra* river and *Bishkhali* river flows through the study area with the funnel shape Bay of Bengal in the south. There are vegetation scattered all over the study area specially surrounding the households. Moreover, a little part of Sundarbans Mangrove Forest is situated in the southwest part of the study area known as Fatrar *Char*. In Patuakhali there are three large urban agglomerations in Patuakhali Sadar, Dumki and Kalapara. And in Barguna district there are urban agglomerations in Barguna Sadar, Amtoli and Patharghata. Moreover, there are small urban centers in all urpazila. There is an abundance of agricultural land in the study area and there are open spaces mostly along the sea shores in the south.

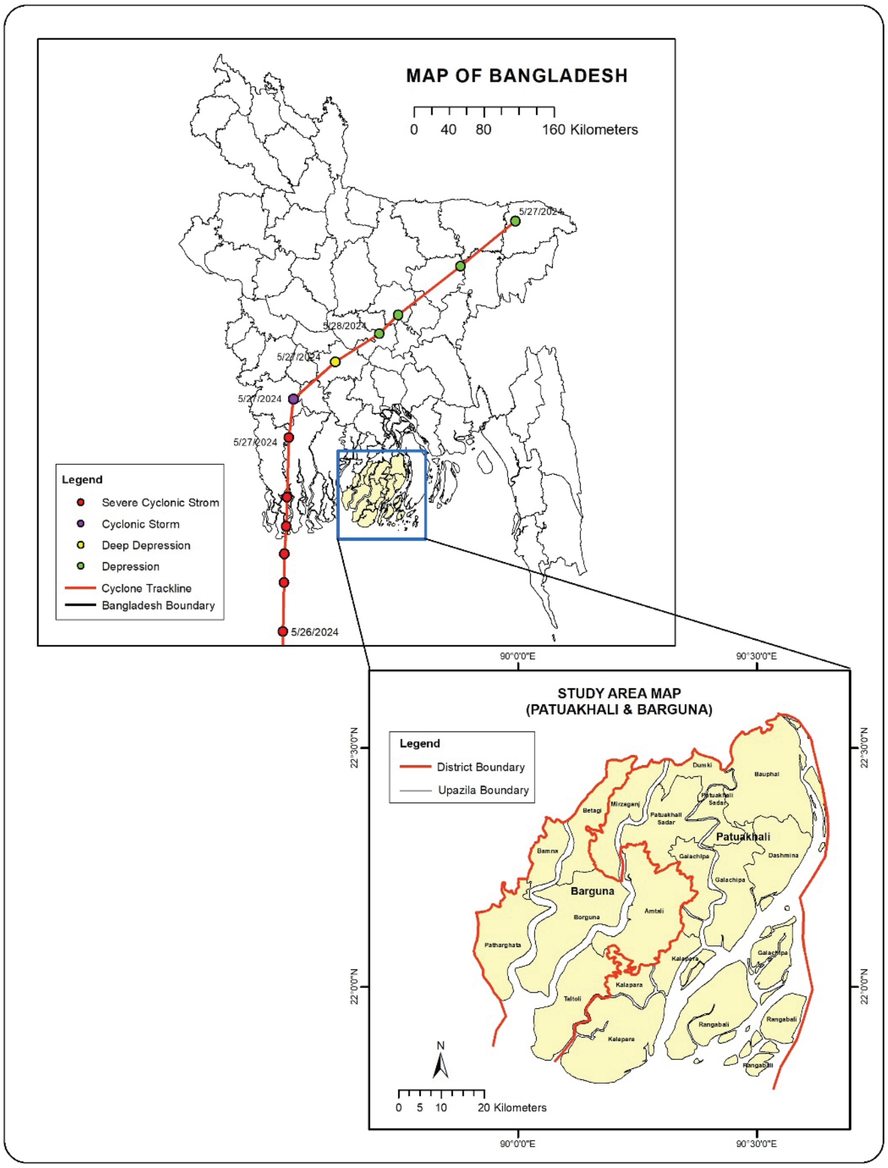

Figure 2: Study Area Map (Patuakhali and Barguna) with Cyclone Remal Track (Source: BMD, 2024)

MATERIAL AND METHODS

Data

Both Sentinel-1 SAR data and Sentinel-2 optical images were used in this study. Sentinel-1, launched by European Space Agency (ESA) in 2014, is basically a group of 2 satellites which has an orbit cycle of 12 days (ESA, 2014a). The C-SAR instrument in Sentinel-1 provides high resolution data in every weather condition as it is an active satellite which sends microwave rays to the earth that can penetrate through clouds (ESA, 2014a; Hall, 2024). On the other hand, Sentinel-2 is a passive satellite that works with the help of the reflected light from the sun and have a 10 days orbit cycle (ESA, 2022b). The Multi-Spectral Instrument (MSI) of Sentinel-2 provides 13 bands of optical data at 10m, 20m and 60m resolution, among these Band 2,3,4 and 8 of 10m spatial resolution were used in the study. Sentinel-2 data was acquired from the Copernicus Data Space Ecosystem on the date 15 April, 2024 and was used in this study. Sentinel-2 data was used for Land Use and Land Cover (LULC) of the study area.

Again, Sentinel-1 SAR data is more suitable for flood inundation mapping (Hall, 2024). In this study Sentinel-1

SAR data was used for determining the inundated areas. Data of the pre-flood condition (18 March 2024) and the flooded condition (29 May 2024) was acquired from the Copernicus Data Space Ecosystem. In this study, each of the date required two images to completely cover the whole study area. Thus, total four images were collected from Copernicus Data Space Ecosystem. The sensor mode used was Interferometric Wide Swath (IW), and the polarization mode used in the study was VV (Vertical Transmit – Vertical Receive). The details about the satellite data is described in Table 1.

Table 1: Information of the Data (Sentinel-2 & Sentinel-1) used in the Study

Mission	Name	Spatial resolution	Bands Used	Acquisition date	Instrument	Product	
Sentinel-2	S2A_MSIL1C_20240415T042711_N0510_R133_T45QZE_20240415T070223.SAFE	10m	2, 3, 4 & 8	15/04/2024	MSI	L1C	
						Sensor Mode	**Polarization**
Sentinel-1	S1A_IW_GRDH_1SDV_20240529T120419_20240529T120444_054086_069394_DAE5.SAFE	10m		29/05/2024	SAR-C	IW	VV
Sentinel-1	S1A_IW_GRDH_1SDV_20240529T120444_20240529T120509_054086_069394_43C4.SAFE	10m		29/05/2024	SAR-C	IW	VV
Sentinel-1	S1A_IW_GRDH_1SDV_20240318T120418_20240318T120443_053036_066C05_8C78.SAFE	10m		18/03/2024	SAR-C	IW	VV
Sentinel-1	S1A_IW_GRDH_1SDV_20240318T120443_20240318T120508_053036_066C05_38E0.SAFE	10m		18/03/2024	SAR-C	IW	VV

Land Use and Land Cover Mapping

In this study Sentinnel-2 optical data was used for the LULC mapping of Patuakhali and Barguna districts. Both 10 meter and 20 meter spatial resolution bands of sentinel-2 data were used in the study. Band 2, 3, 4, and 8 of sentinel-2 images have a spatial resolution of 10m whereas band 5, 6, 7, 8A, 11 and 12 have a spatial resolution of 20m (Li et al., 2020). At first, all the bands were converted into a same spatial resolution of 10m. To do so, resampling technique was performed on the bands with 20m resolution. Nearest Neighborhood method was used for resampling as it was the most suitable method for such purpose. Then all the bands were converted into a single image by stacking. As the orbital swath width of Sentinel-2 is 290 km so the area of the study area was extracted from the whole image with the help of clip tool. All these steps are done using ArcGIS 10.8 software (ESRI, 2020).

After preprocessing of the stacked image, Supervised Classification was performed based on the spectral reflectance of different land use and land cover (LULC) types (Gadrani et al., 2018). In doing so, training data were collected form the image by selecting representative samples for each LULC type Erdas Imagine 2015 software was used for image classification. In the Signature editor tool in Erdas Imagine 2015, more than 100 samples were taken for each land use and land cover types except waterbodies. There were 5 main land use and land cover types in the image which were Waterbodies, Bare Land, Vegetation, Built-up Area and Agricultural Land. Accuracy assessment is an integral part of mapping as it helps to the minimize the error in the data (Alqurashi & Kumar, 2013). The accuracy of the LULC Map is assessed in GIS environment by generating total 397 random points on the study area. The random points were validated by ground truthing during fieldwork. A classification error matrix was used to calculate the user's accuracy, producer's accuracy, overall accuracy and kappa statistics. The overall accuracy of inundation mapping is 85.14% and the Kappa Coefficient is 0.9899. Further details are shown in table 2.

Table 2: Accuracy Assessment Result of LULC Map

Class	Vegetation	Built up Area	Barren Land	Agricultural Area	Waterbodies	Total	User Accuracy	Kappa
Vegetation	81	0	0	8	3	96	84.375	0
Built up Area	2	6	0	2	0	10	60	0
Barren Land	1	0	14	1	4	20	70	0
Agricultural Area	12	2	2	126	5	147	85.714	0
Waterbodies	5	0	0	12	111	128	86.718	0
Total	101	8	16	149	123	397	0	0
Producer Accuracy	80.198	75	87.5	84.563	90.243	0	85.138	0
Kappa	0	0	0	0	0	0	0	0.989

Flood Inundation Mapping

The Flood Inundation Map (FIM) was created with the help of SNAP 10.0.0 (Pramanick et al., 2022). Flood mapping with SAR data in SNAP involved several steps. First, Sentinel-1 SAR data is acquired from the Copernicus Data Space Ecosystem. The preprocessing of the collected data was done at the very first stage. At first Orbit File is applied to the images to correct satellite positioning. Subsequent steps included removing thermal noise and calibrating the data to Decibel (dB) format. The VV band of the images were used in the process. Speckle filtering method of the Lee Sigma Filter is then applied to reduce noise of the image. At last, the terrain was corrected with using using the digital elevation model (DEM) and by applying Bilinear Interpolation Method.

After correcting terrain geometry, the processed images of the same dates were mosaicked together into a single image. As mentioned earlier, total four images were collected to cover whole study area with each two representing the image of a single date. After mosaicing, binarization techniques had been used to distinguish between water and non-water areas in the images. In this process a threshold value is used to differentiate between water and non-water pixels. The threshold value for binarization was determined with the help of the histogram of the image in Color Manipulation box of ESA SNAP 10.0.0 (Serco Italia SPA, 2018). The waterbodies in the binarized image of 18 March, 2024 depicted the permanent waterbodies of the study area whereas waterbodies in the the binarized image of 29 May, 2024 depicted both the inundated areas and permanent waterbodies. In GIS environment, both the images were converted into polygon and the inundated areas were separated by erasing the permanent waterbodies.

After completing the Map, the accuracy of the map was assessed by comparing the classified data with data obtained from the field. A total 400 random points were generated in GIS environment . The points were validated by the field survey conducted immediately after the flood in Patuakhali and Barguna districts. The overall accuracy of inundation mapping is 80% and the Kappa Coefficient is 0.723. Details are given in table 3.

Table 3: Accuracy Assessment Result of Flood Map

Class Name	Inundated Areas	Permanent Waterbodies	Uninundated Areas	Total	User Accuracy	Kappa
Inundated Areas	120	4	76	200	60	0
Permanent Waterbodies	0	84	0	84	100	0
Uninundated Areas	0	0	116	116	100	0
Total	120	88	192	400	0	0
Producer Accuracy	1	95.455	60.417	0	80	0
Kappa	0	0	0	0	0	0.723

Inundated Area Calculation

To quantify the extent of inundation of different land use types in the study, at first the area of the geometry of each land use type was calculated using GIS. Then an overlay analysis was conducted between both landuse types and inundated layers to calculate the inundated areas of specific land use type (Uddin et al., 2024). The whole workflow is given in Fig. 3.

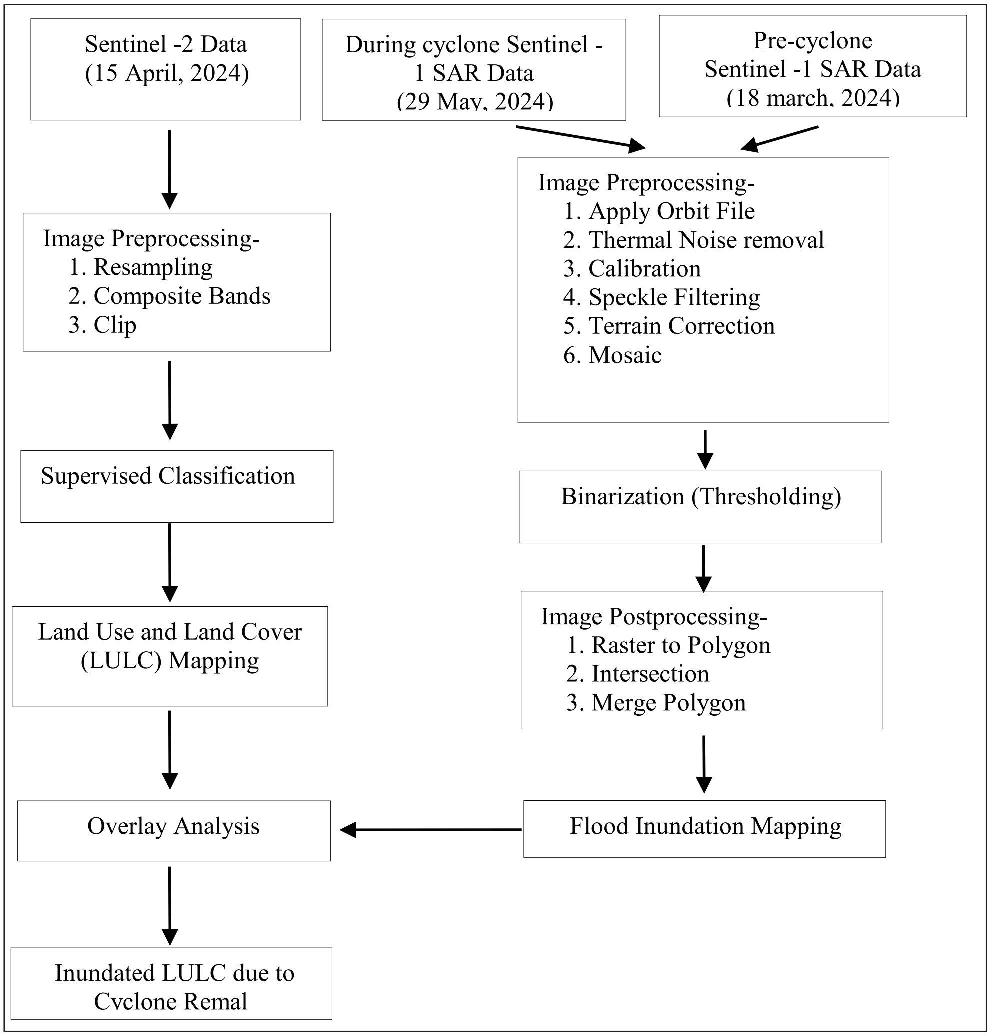

Figure 3: Methodology of the Study Illustrating the Whole Workflow of the Research Including LULC Mapping, Flood Inundation Mapping and Lastly Overlay Analysis

RESULT

LULC of the Study Area

Most of the study area is agricultural land accounting almost half of the study area followed by water body and vegetated areas (Fig. 4). The LULC classification of the study area reveals that agricultural land, vegetation, built up area, barren and water body cover a percentage of 48.55, 21.82, 4.95, 1.55 and 23.13 of the total study area respectively (table 4).

The total area of Patuakhali district is more than double of the area of Barguna. The LULC classes of agricultural land, vegetation, built up area, barren and water body of Patuakhali district cover an area of 46.23, 22.29, 4.83, 1.90 and 24.75 percent of the total area of the district respectively, while that of Barguna district covers 53.27, 20.87, 5.19, 0.83 and 19.84 percent.

Table 4: Land Use and Land Cover of the Study Area Including the Total Area of Each Land Use and Land Cover Type and Occupying Percentage of Total Area of the Districts

LULC type	Area (square kilometer) Patuakhali (% total area of the district)	Barguna (% total area of the district)	Total	Percent of the study area
Agricultural Land	1491.62 (46.23%)	843.56 (53.27%)	2335.18	48.55
Vegetation	719.18 (22.29%)	330.43 (20.87%)	1049.61	21.82
Built up Area	155.77 (4.83%)	82.31 (5.19%)	238.08	4.95
Barren Land	61.37 (1.9%)	13.1 (0.83%)	74.47	1.55
Water body	798.46 (24.75%)	314.24 (19.84%)	1112.7	23.13
Total	**3226.4 (100%)**	**1583.64 (100%)**	**4810.04**	**100**

Flood Inundated Areas

The total area of the present study is 4810 square kilometer (sq. km) which includes both Barguna and Patuakhali district (Fig. 4 (a)) in central coastal area of Bangladesh. Total area inundated of the study area is about 1451.46 sq. km which is about 30% of the total area and about 39.26 % of the total landmass excluding waterbody. It was found that, 48.35% (613.72 sq km) out of the total landmass in Barguna district was inundated due to Cyclone Remal. In Patuakhali district, the amount of inundated area was 837.74 sq km which is 34.5% of the total landmass of the district (table 5).

There are 8 upazilas or subdistricts in Patuakhali district: Patuakhali Sadar, Dumki, Kalapara, Galachipa, Rangabali, Dashmina, Bauphal and Mirzaganj (Bangladesh National Portal, 2024a). Among them, in terms of severity of inundation, Mirzaganj is the most affected sub-district as 48.9% of its landmass was inundated due to flood. The second most affected sub-district is Kalapara where 45.17% of its landmass was inundated. The least inundated sub-district is Dashmina (22.4%). Other sub-districts are Patuakhali Sadar (35.8%), Dumki (37.9%), Galachipa (26.81%), Rangabali (32.16%) and Bauphal (33.98%). In terms of total inundated area, Rangabali (130.23 sq. km) is the most inundated upazila.

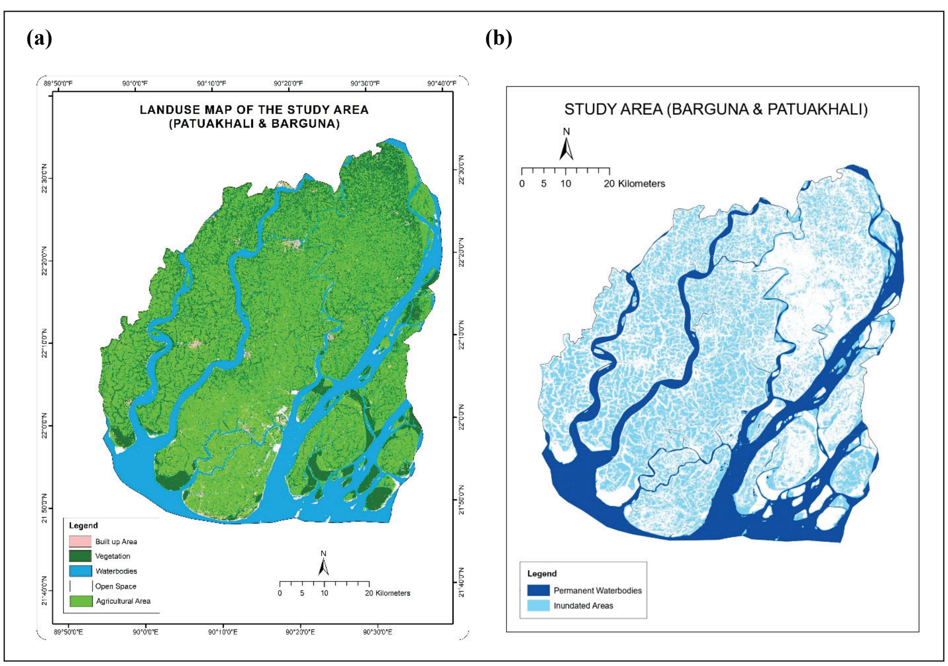

Figure 4: (a) Land Use and Land Class Map of the Study Area (2024); (b) Flood Inundation Map of the Study Area

There are six upazilas or sub-districts in Barguna district: Barguna Sadar, Betagi, Bamna, Patharghata, Amtoli and Taltoli (Bangladesh National Portal, 2024b). Among them, in terms of severity of inundation, Amtoli is the most affected upazila where 147.52 sq. km, more than half of its total land area, was inundated. The second most affected upazila is Taltoli which is situated right at the south of Amtoli and near to the Bay of Bengal. In this sub-district 107.07 (49.92%) area was inundated. Patharghata upazila was the least inundated compared to other sub-districts of Barguna district. Even though 45.3% of this sub-district was inundated. The percentages of inundation of other upazillas are 47.4% of Barguna Sadar, 45.97% of Betagi and 45.7% of Bamna upazila. In terms of total inundated area, Barguna Sadar (148.27 sq. km) is the most inundated upazila in Barguna. Both Patuakhali and Barguna is situated in the floodplain low-lying area but not all places are equally developed. Some places are guarded by polders which saved the area from severe effects of the flood for example Dashmina sub-district in Patuakhali. Again, polder and dams were broken in many areas which hugely affected the area. This caused a variation in the flood extent among the sub-districts in the study area. Again, Cyclone Remal first hit the mangrove forest Sundarbans in Bangladesh which is located right beside Barguna at the west. So, Barguna district had more flooding than Patuakhali district because to its proximity to the cyclone track.

Table 5: Total Landmass and Inundated Areas in Different Sub-districts of Patuakhali and Barguna District

Patuakhali District			**Barguna District**		
Upazila Name	**Total Landmass excluding water bodies (sq. km)**	**Inundated Area (Sq.km)**	**Upazila Name**	**Total Landmass excluding water bodies (sq. km)**	**Inundated Area (Sq.km)**
Patuakhali Sadar	323.87	116.18	Barguna Sadar	312.83	148.27
Dumki	90.55	34.34	Betagi	150.06	68.98
Kalapara	407.89	184.23	Amtoli	279.71	147.52
Galachipa	421.47	112.98	Taltoli	214.48	107.07
Rangabali	404.91	130.23	Bamna	84.85	38.77
Dashmina	236.92	53.08	Patharghata	227.56	103.11
Bauphal	392.46	133.36	**Total**	**1269.4**	**613.72**
Mirzaganj	149.87	73.34			
Total	**2427.94**	**837.74**			

Flood Inundated LULC Classes

The inundation of different LULC class shown in table 6 shows that about 54.77% of the agricultural land of the study area has been inundated by cyclone Remal whereas about 43.69% of barren land and 22.86% of the built-up area are also inundated. Total area under different LULC class has been shown earlier in table 3.

From the table 6 it is clear that the agricultural lands were the most affected land use type due to flooding of Patruakhali district (Fig. 4 (a) and (b)). 47.55% (709.26 sq. km) of its agricultural fields were inundated in the flood. Usually, the agricultural lands in Patuakhali and Barguna district are comparatively lower areas surrounded by roads, households and other settlements having higher elevation. This can cause waterlogging in the agricultural lands during flood. Again, 8.1% (58.25 sq. km) of its land covered with vegetation were inundated. The microwave of SAR-C band cannot fully penetrate the canopy of dense vegetation and that's why it created limitation while analyzing the inundated vegetation areas (Meyer, 2019). In case of built-up area, which have comparatively high elevation than other land use and land cover types, the number of inundated areas were 37.54 sq. km (24.10 % of its built-up areas) and in case of barren Land, it is 27.99 sq.km (45.61% of its barren lands).

In case of Barguna district (Fig. 4 (c) and (d)), the majority of its area is covered with (843.56 sq. km) is covered with agricultural land. Due to flood, 67.53% (569.66 sq. km) of its agricultural went under water. 5.8% (19.16 sq.km) of its vegetation, 20.51% (16.88 sq. km) of its built-up area and 34.73% (4.55 sq. km) of its total barren land was inundated due to flood induced by Cyclone Remal.

Table 6: Inundated LULC Classes

LULC class	Patuakhali		Barguna		Study area total	
	Inundated Area (sq km)	**Percent of LULC class**	**Inundated Area (sq km)**	**Percent of LULC class**	**Inundated Area (sq km)**	**Percent of LULC class**
Agricultural Land	709.26	47.55	569.66	67.53	1285.64	54.77
Vegetation	58.25	8.1	19.16	5.8	77.41	7.24
Built up Area	37.54	24.10	16.88	20.51	54.42	22.86
Barren Land	27.99	45.61	4.55	34.73	32.54	43.69
Water body	798.88	---------	314.84	---------	1113.72	---------

Impact of Inundation on Land Use Classes

It is evident from the above discussion that dominant LULC class of the study area is agricultural land. These lands are extensively used for agriculture throughout the year. The cropping pattern in the region is diverse with Single T. Aman, Single Boro and Mungbean−Fallow−T. Aman as the dominant cropping patterns (Ibrahim et al., 2018). Mungbean and Maize are the main crops that is produced in the region during the growing season Kkarif specifically during Kharif 1 which extends from last week of March to end of May. Cyclone Remal hit the region during this period. It hit the region during the period of harvesting of kharif 1 crops from the fields. Though harvesting has started earlier and a considerable percentage of the crops had been harvested, still some crops damaged during the stuck of the cyclone. It is observed during the fieldwork that most of the crops went under water and damaged. The runoff of chemicals from agricultural fields affected finishers of the rivers and ponds and killed fish community.

Fatrar Char, part of the Sundarbans mangrove forest, is located in the south of the Barguna district. Cyclone Remal impacted the vegetation in these forests. During the field survey, numerous uprooted trees were spotted throughout the research area (Fig 5). Moreover, 2 crore plants and 27,300 hectares of forest land was destroyed in the study area due to the cyclone (The Daily Star, 2024c).

Remal had a destructive impact on the infrastructures of Patuakhali and Barguna district. Many roads were fully or partially destroyed, resulting in the loss of connectivity between two areas. Several dams were destroyed in various places, causing widespread flooding in inland areas. For example, the dam at the west of Baithakata Union in Amtoli Upazila, Barguna district got breached during the cyclone which caused huge inundation in the adjacent areas. Many places were spared the worst of the flooding thanks to the strength of polders, dams, and highways built by local governments. But, people residing on the coastal side of these roads were subjected to the maximum impact of the storm, which damaged countless homes and displaced many residents. However, some major urban agglomerations in the study area such as Patuakhali City, and Kalapara were shielded from the strong winds of the cyclone but these areas suffered highly due to the waterlogging caused by excessive rainfall during the timespan.

DISCUSSION

Tropical cyclone Remal had profound impacts on the coastal areas of Bangladesh. This study aimed at assessing cyclone Remal induced inundation in coastal districts of Patuakhali and Barguna of Bangladesh. Geospatial technique is employed in the process and the study helped in better understanding the spatial extend of cyclone induced flood and it's impacts on land use.

Tropical cyclone is a common phenomenon in Bangladesh and the southern coastal districts of Bangladesh are mostly vulnerable to them. The country's low-lying topography, combined with its location in the Bay of Bengal makes it highly vulnerable to cyclonic storms and storm surges (Rezaie and Haque, 2022). The elevation of the area is just few meters above the mean sea level and thus it gets inundated too quickly with small rise in water level due to storm surge. Apart from that the area experiences huge torrential rainfall every year especially in the months of summer. Cyclone induced storm surge and associated rainfall results in extensive flooding during any stuck of cyclone. Inundation of extensive coastal areas also caused by breaching earthen dikes and overflowing coastal defenses during the stuck of cyclones (Islam et al., 2019). The area also held extensive agricultural land where different types of crops are grown. These crops are regular victims of such natural disaster and affects the food security in the turns. Cyclones also affect human lives and infrastructure. During the field observation, it is also being noticed that various infrastructure such as poulders, roads and houses were also being damaged by the cyclone. Inundation of extensive areas and the impacts consistent with findings from other studies that show that coastal regions with poorly maintained infrastructure and high population densities are especially vulnerable to flooding during cyclones (Jakobsen et al., 2006; Dube et al., 2009).

(Source: The Authors, 2024)

Figure 5: Impact of Cyclone Remal on Vegetation and Settlements of the Study Area

The findings also shows that multispectral and radar imagery data of remote sensing technology is highly effective in monitoring cyclone induced inundation in the study area. Similar findings are also seen in the previous studies (Mondal et al., 2020). However, challenges such as accurately identifying inundated areas in complex geomorphological settings and atmospheric interference during cyclones are limitations. Real-time field verification and unavailability of satellite images during peak flooding also pose challenges.

While the study contributes to mapping inundation and affected land use, further investigation into the long-term impacts on agriculture, infrastructure, and ecosystems is needed. The findings of this study have critical policy implications for disaster preparedness and response in cyclone-prone coastal areas of Bangladesh. In the face of increasing frequency and intensity of tropical cyclones, more robust disaster mitigation measures are required. Vulnerability of agriculture, infrastructure and coastal ecosystem to cyclone focused integrated land use planning is essential in this context. In addition, creating early warning systems that are integrated with geospatial technologies could improve disaster preparedness and provide timely information to communities at risk.

CONCLUSIONS

In conclusion, the inundation mapping of Cyclone Remal is a vital step toward understanding the severity and extent of cyclonic impacts on coastal Bangladesh. The study showed how freely available open-source data can contribute in mapping inundation accurately and quickly. Its a powerful method of inundation assessment and can be used in assessing other natural hazards like, flash flood, riverine flood. The results also shows that both Patuakhali and Barguna district faced huge inundation due to Cyclone Remal. About 837.74 sq. km area in Patuakhali district and 613.72 sq. km area in Barguna district were inundated due to the cyclone induced flooding. Total 1285.64 sq. km of agricultural land was inundated in the whole study area causing huge damage to the crops. The results have shown a comparatively low extent of flooding in vegetation as the microwaves sent by sentinel-1 SAR-C band are not capable to penetrate through dense vegetation. Both excessive rainfall and storm surge is responsible for the inundation in the study area. 145 mm was the highest amount of rainfall observed by BMD from Patuakhali station and 86 mm from Khepupara station. While the study provides valuable insights into cyclone induced inundation dynamics, it also highlights the need for improved methods to address the complexities of land use and environmental degradation in post-cyclone recovery. Moving forward, future research should focus on refining remote sensing techniques and exploring the cumulative impacts of cyclone-induced flooding on agricultural systems and ecosystems. Furthermore, effective disaster management policies, based on scientific data, are essential to mitigate the impacts of future cyclones and enhance the resilience of coastal communities.

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