EO aided comprehensive flood management for the Brahmaputra and Barak river basin in NE India

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Abstract

Floods are among the most frequent and devastating natural disasters globally, affecting over 94 million people annually. In Northeast India, particularly in Assam, recurrent floods caused by excessive rainfall, silt deposition causing reduction in river depth, rapid urbanization, and settlements in floodplains lead to significant economic and human losses. The Brahmaputra and Barak river basins with its complex hydrology, faces escalating flood risks due to climate change, highlighting the need for robust flood management systems. This study outlines a comprehensive flood management strategy for these basins integrating early warning systems, flood hazard zonation, and embankment breach monitoring. A Weather Research and Forecasting (WRF) model was employed to generate high-resolution rainfall forecasts, which was validated with satellite-based rainfall datasets. Hydrological modeling using HEC-HMS was conducted for all major tributaries, combining meteorological inputs to estimate river discharge and predict flood probabilities, achieving 80% to 90% success rate with a lead time of 36 to 48 hours. Alerts are disseminated to the authorities through emails and SMS. Embankment breach monitoring using satellite data identified vulnerable points along Assam's rivers, aiding authorities in proactive flood mitigation. Additionally, flood hazard zonation maps prepared using remote sensing could delineate high-risk areas, supporting long-term structural planning. These efforts demonstrate the effective use of earth observation data, numerical modeling, and in situ measurements in flood mitigation. Despite limitations in meteorological and hydrological models, this system provides critical early warnings, minimizing flood impacts. This integrated approach serves as a model for flood-prone regions globally, emphasizing the importance of advanced technologies and timely interventions in disaster management.

Keywords: Brahmaputra, Barak, Flood

1. Introduction

Floods are a significant natural disaster with widespread impacts on people and property worldwide. According to international data, floods occur more frequently than other disasters, affecting over 94 million people annually. In North East India, Assam experiences more than three flood waves each year primarily during the monsoon season, causing severe damage. Contributing factors include heavy upstream rainfall, complex terrain, shallow river channels, silt deposition causing reduction in river depth, inflow from nearby catchments, and urbanization in flood plains. The state of Assam in India incurs huge financial loss every year due to floods, with about 70 lives lost each year. The Brahmaputra and Barak river basins covering almost entire Assam, is the most affected. While the impact of flood on property and lives continue to increase over the years, climate change is expected to exacerbate extreme flood events.

Effective flood mitigation requires both structural and non-structural measures. Flood forecasting, a key non-structural measure, has gained prominence since the 20th century. A robust flood management strategy includes actions in all stages of flood disaster, i. e. pre-disaster, during disaster, and post-disaster. Early warning systems could be one of the most effective actions towards reducing flood damage that should include generation of warning with actionable lead time, timely dissemination of the warning to the vulnerable communities, keeping communities informed on the near real time conditions. Such effective early warning forms the basis for an effective response and recovery system as well. Advances in meteorological and hydrological monitoring, numerical models, space-based systems, internet access, and communication technologies have enabled the development of comprehensive flood management systems that could significantly reduce the damage and save very important human and cattle lives. The advent of space technology has also paved way for making effective preparedness towards building a flood resilient infrastructure; get finer details about river morphology, etc. However, the Brahmaputra and Barak basins, owing to their complexities and vastness, pose a major challenge to develop comprehensive flood management systems including flood early warning.

2. Study Area

The comprehensive flood management system comprising of the Early warning, flood hazard zonation, monitoring of the status of flood mitigation structures, etc. is developed for both the Brahmaputra and Barak river basins in the NE India (Figure 1). The Brahmaputra basin originates from the Kailash ranges of the Himalayas. The great river traverses from the Tibetan plateau via Arunachal Pradesh to the alluvial plains of the state of Assam and into the Bangladesh. The slope of the river channel ranges between 4.3 to 16.8 m/km in the gorge section upstream of Pasighat and the gradient becomes flatter at 0.1 m/km, near Guwahati area (Anonymous, 2012). The drastic difference in slope along the river channel of the Brahmaputra river, makes Assam highly vulnerable to the effect of flooding due to extreme flow events. The geomorphic topography of the entire region, especially the Brahmaputra Valley, is shaped by the Brahmaputra River and its vast network of tributaries. Major tributaries on the North bank include the rivers Subansiri, Jiadhal, Ranganadi, Jiabharali, Dhansiri (North), Puthimari, Pagladiya, Beki, Manas-Aei, Saralbhanga, Sonkosh, and Champamati. In contrast, the main tributaries on the Brahmaputra's south bank include the rivers Buridehing, Dikhow, Kopili, Dhansiri, Krishnai, Disang, Bhogdoi, and Jinari. The Barak river originates from the hill near Mao at the border of Nagaland and Manipur, southern of japvo peak. The Barak flows through state of Assam, Manipur and Mizoram. Its important contributing tributaries in the right bank include Makru and Jiri in Manipur, Labak, Dalu, Madhura,

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Jatinga and Larang in the Barak plains. Whereas, the Irang, Tuivai in Manipur, and Sonai, Rukni, Kathakal, Dhaleswari, Singla, Langai in Cachar plains form the important tributaries in the left bank.

Rainfall in the basin primarily depends on the southwest monsoon, which lasts from June to September. The region is a prime location for both localized and large-scale floods due to the unpredictable temporal scale of rainfall in the spatial domain, which occurs in enormous volumes with significant volatility (Varikoden and Revadekar 2020; Zahan et al. 2021; Bora et al. 2022). The Brahmaputra River receives most of its drainage from heavy rainfall, which ranges from 250 to 510 cm in the Brahmaputra floodplain and from 510 to 640 cm in the Abor and Mishmi highlands of Arunachal Pradesh (Murthy, 1981; Dhar and Nandargi, 2000). In contrast, Meghalaya recorded 26,461 mm of rainfall between August 1860 and July 1861, the most in the world (Jennings 1950; Murata et al., 2007; Prokop and Walanus, 2015). The paper contains details about one such complex basin only.

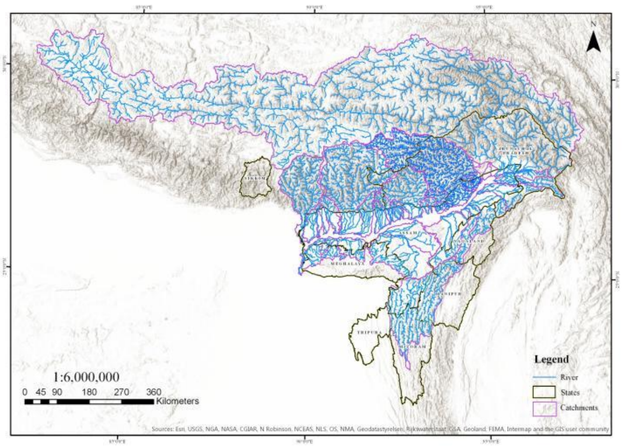

Fig 1: Study area showing the Brahmaputra and Barak basin

3. Flood Early Warning

3.1. Meteorological model: Generation of rainfall forecast

Rainfall is one of the most crucial components towards developing successful flood forecasting system. The Weather Research and Forecasting (WRF) Model is one of the mostly used Numerical Weather Prediction models in the weather forecast community because of its highly developed physics schemes and better time integration method to give improved output at shorter duration. It features multiple dynamical cores, a 3-dimensional variational (3DVAR) data assimilation system, and a software architecture allowing for computational parallelism and system extensibility. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. In this study, the Weather Research and Forecasting (WRF) model was used to generate the rainfall forecast for 48 hours over the entire study region at spatial grid size of 9 km X 9 km and temporal resolution of one hour. The initial and boundary conditions were obtained from the Global Forecast System (GFS). The evaluation of WRF showed that when compared to GPM (Global Precipitation Mission) rainfall products, there is a good performance over most part of the study region, except some parts of the high altitude regions within the study area. Figure 2 provides a typical accumulated rainfall forecast over the NE region of India that was used as input for hydrological model and computation of basin-wise runoff. The numerical model based forecast was also supplemented by a synoptic scale analogue rainfall forecast prepared using the synoptic weather analysis done using real/near real time meteorological parameters. First the successive growth of cumulative clouds is observed by analyzing the INSAT 3D/3DR/3DS TIR (thermal infrared) images and confirm the vertical water vapor availability by analyzing WV (water vapor) channel images. Potentiality of cloud growth with respect to the area of interest is analyzed from 3 hourly 850mb relative vorticity products. At the same time cloud movement are observed from lower and upper level atmospheric motion vector. Past 24 hours precipitation is monitored from Doppler weather radar products, AWS (automatic weather station) and quantitative precipitation estimator. Parallely, IMD (India meteorological department) daily weather advisory issued by regional meteorological centre, Guwahati for north east sector are also studied. Based on all the above mentioned inputs decisions on probable quantitative rainfall for the next 12 hours over the concerned catchment area is taken. The synoptic scale forecast helped taking critical decision when there were severe over-estimations in the numerical weather forecast. Figure 3 shows the sample synoptic weather analysis during September 17, 2024.

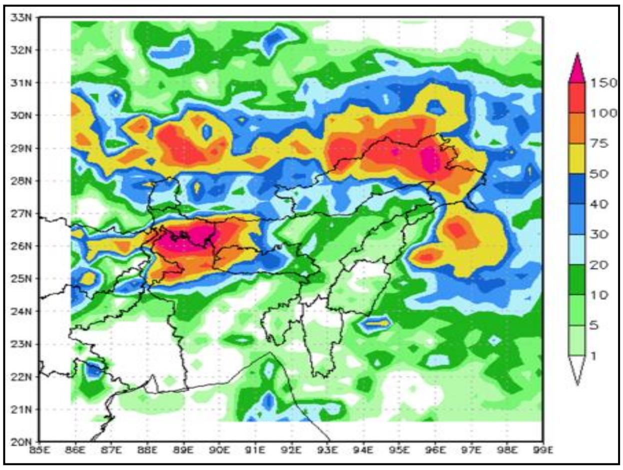

Fig 2: Rainfall forecast over NE India using the WRF model

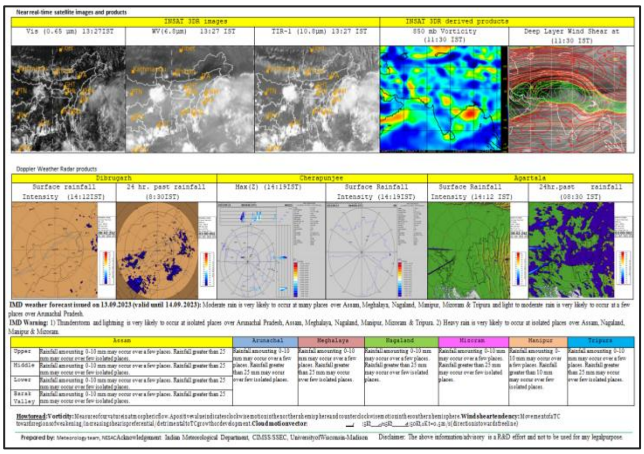

Fig 3: Sample synoptic weather analysis

3.2. Hydrological model: Generation of discharge forecast

Rainfall-runoff modeling is focused on quantifying the runoff occurrence, without necessarily looking into the processes of runoff generation. Runoff at the spatial and temporal scale for a basin is generally obtained by direct in-situ discharge measurements or indirect techniques involving ‘lumped’ or ‘distributed’ hydrologic models. As the conventional method is at times faces constraints with resources and time frame, etc., hydrologic rainfall-runoff modelling is increasingly used for computing runoff and thereby put into many usages viz., flood simulation, catchment level water management, water balance computation, and many more. Hydrological models play an important role in predicting the system behavior and understand various hydrological processes. A wide range of physical parameters, such as rainfall, air temperature, soil characteristics, terrain, vegetation, and hydrogeology, are used as inputs in a number of models that have recently been developed worldwide (Devi et al., 2015).

The discharge forecast component in flood early warning is a combination of a good number of basin level quasi-distributed hydrological models built in a GUI based hydrological software platform known as HEC-HMS (Hydrologic Engineering Centre’s – Hydrological Modeling System). The core frame of this modeling system is a combination of rainfall to runoff model and a hydrologic flow routing model. The HMS model has been used in a number of studies, showing that it can be used to simulate the rainfall-runoff processes of dendritic watershed systems in event-based rainfall-runoff simulations and peak flood discharge estimations (Natarajan and Radhakrishnan, 2019); evaluate the effects of rainfall products and satellite-based rainfall products on streamflow (Nhi et al., 2019); and assess the hydrologic impacts of climate change (Meenu et al., 2013). Typically, the loss models in HEC-HMS determine the runoff volume by deducting the amount of precipitation from the volume of water that is transpired, evaporated, intercepted, infiltrated, and stored (Tassew et al., 2019). For the study; the Soil Conservation Service (SCS) Curve Number (CN) loss model that uses cumulative rainfall, soil cover, land use, and antecedent moisture to determine precipitation excess was employed. Soils and CNs are closely related where each soil evaluated is grouped into one of four categories (A, B, C, or D) (Hawkins et al., 2008). The values of the dimensionless runoff index CN vary from 1 to 100. As per USDA (1986), higher CN values correspond to high runoff potential. Also, the Soil Conservation Service Unit Hydrograph method that averages the rainfall from the watersheds was chosen as a transform method to calculate the actual surface runoff. The SCS unit hydrograph method makes use of a dimensionless, curvilinear unit hydrograph to route excess precipitation to the sub-basin outlet (Cronshey, 1986). This transformation approach is based on the utilization of the time of concentration (Tc) and the lag time (minutes). Lastly, the Muskingum-Cunge method, also referred to as a "variable coefficient" method, that combines the continuity equation with a simplified version of the momentum equation is used in this study for channel flood routing. The use of this method in HEC-HMS requires the initial condition, the reach length (ft or m), the friction slope (ft/ft or m/m), Manning's n roughness coefficient, a space-time interval method and value, an index method and value, and a cross-section shape and parameters/dimensions (HEC, 2022). Figure 4 shows the overall methodology of flood warning to the concerned authority.

Both the spatio-temporal datasets and in-situ measurements form an integral part in the development of accurate hydrological models (Zhao and Liu 2020; Sivapalan and Blöschl 2019; Beven and Binley 2021; Krajewski and Smith 2022). The Cartosat Digital Elevation Model (CartoDEM) V3 generated by Indian Space Research Organization (ISRO) was used to derive the drainage networks, catchment related parameters, and catchment boundary delineation. The CartoDEM was obtained using the Augmented Stereo Strip Triangulation (ASST) method, which is indigenously developed by Space Application Centre, ISRO.

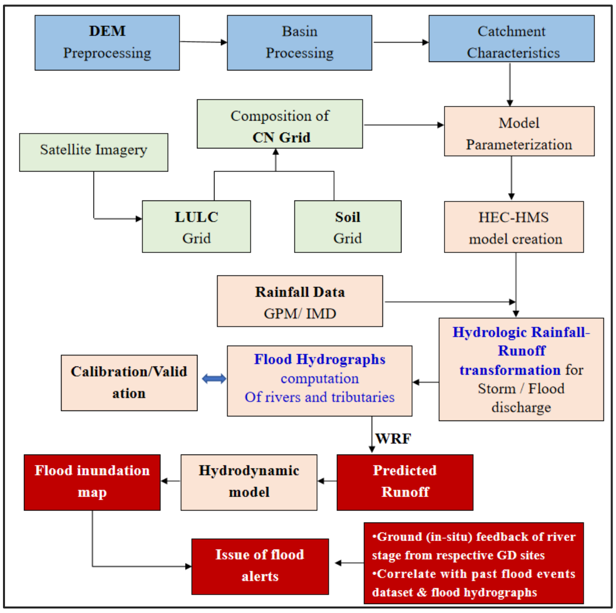

Fig 4: Overall methodology of flood early warning system

To cater to the uncovered sections in the upstream catchments, Shuttle Radar Topography Mission (SRTM) DEM, was used. The high resolution Resourcesat LISS IV imagery, having a spatial resolution of 5.8 m, was used for generation of land use land cover map. The soil data representing the Hydrological Soil Group (A, B, C and D) was obtained from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), where HSG – A has low runoff potential (>90% sand and <10% clay) and HSG – B has high runoff potential (<50% sand and >40% Clay) , HSG-C has Moderately High runoff potential (<50% sand and 20-40% clay) and D has High runoff potential (<50% sand and >40% clay). It is a known fact that rainfall and other meteorological variables in-situ measurements are quite important and yet there is a lack of coverage in terms of large or trans-boundary basins or even in most of the smaller catchments, especially in North-Eastern Himalayas, where rough terrain is pre-dominant. Therefore, the remote sensing based Global Precipitation Measurement (GPM), equipped with the first-ever advanced Ku/Ka-band Dual-Frequency Precipitation Radar (DPR) and a multi-channel GPM Microwave Imager (GMI), was used in the study along with the in-situ rainfall data from IMD wherever is available. This satisfies the need for rainfall-runoff simulation cover for the entire basin. Development of rainfall-runoff model is incomplete without the comparison of the simulated flow with the observed flow. This data is however obtained from the Central Water Commission (CWC) as well as from the state Water Resources department. The detail of the data used is shown in Table 1.

For instance, a HEC-HMS model developed using the spatio-temporal data for the Ranganadi basin in the upstream of Assam, having a catchment area of 1883 km^2 is shown in Figure 5. Figure 6 shows the comparison of the simulated discharge against the observed discharge for Ranganadi basin for the monsoon season of 2021. The qualitative model performance evaluation shows that there is a good match between the observed flow and the simulated flow. This indicates the model parameters are well calibrated.

Table 1: Data used in the study

Data	Spatial Resolution	Purposes
Land Use Land Cover (LULC)	1:10,000	CN-Grid Generation
Soil data	1:50000	CN-Grid Generation
CartoDEM v3 and SRTM	10 m and 30 m	Generation of drainage network and catchment delineation
Rainfall data	0.1^0 X 0.1^0	Runoff estimation
Discharge/stage data	Daily	For calibration and validation of models

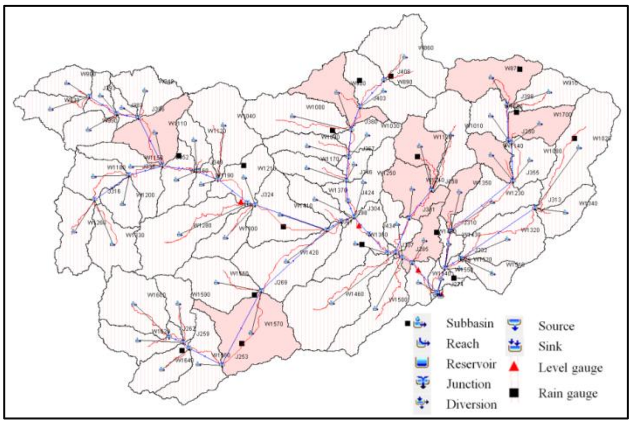

Fig 5: HEC-HMS model for the Ranganadi basin

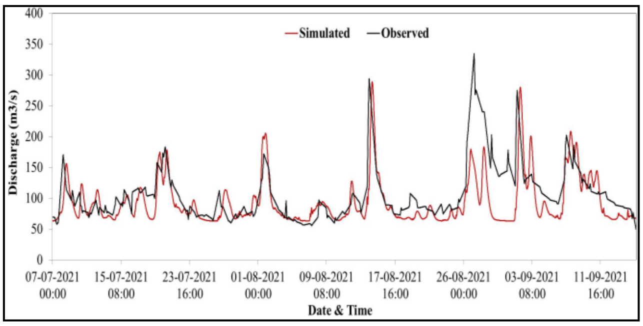

Fig 6: Time series plot between simulated and observed discharge in Ranganadi basin for the monsoon season in 2021

3.3. Hydrodynamic model: Generation of inundation map

For the precise spatial distribution of the flow and velocity dynamics, flood hydrodynamic modeling is typically done using a 1-D or 2-D or coupling 1D-2D flood routing method that is based on different modified versions and solutions of St. Venant's equations. In this study, HEC-RAS model was used to simulate the probable inundations in the floodplains. The HEC-RAS model can solve either 2D Diffusion Wave equations or the 2D Shallow Water equations, with the option to incorporate momentum for turbulence, wind forces, mud and debris flows, and Coriolis effects (HEC, 2012). For flood simulation, the HEC-RAS flood model employs the 2D Saint-Venant and 2D diffusive wave equations through an implicit finite-volume solution (HEC, 2021). The 2D diffusion wave solver was chosen to make use of more stable numerical solutions and shorten the computation time for the current situation. HEC-RAS have wide range boundary conditions that are made up of internal boundary conditions, global boundary conditions (meteorological data), and external boundary conditions along the 2D area's perimeter (i.e., precipitation, wind, etc.). A high resolution DEM of 5 m spatial resolution along with high scale LULC for generation of Manning's coefficient (n) and the unsteady flow data from the simulated hydrological model, are used for simulating the flood inundation. The resulted HEC-RAS inundation map can be viewed and extracted from RAS-Mapper. Using a hydrodynamic model that takes boundary conditions, river geometry, and channel roughness into consideration the flood simulation for the flood-concerned Ranganadi River is examined to check the floodplain impacts, water surface elevations, and flow conditions as shown in the Figure 7.

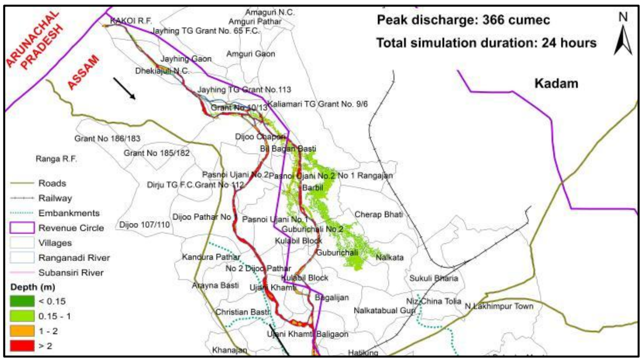

Fig 7: HEC-RAS simulation for Ranganadi flood discharge

The flood alert generation is based on the combination of meteorological and hydrological modeling outputs along with the inundation map generated from the hydrodynamic model. The output obtained from the WRF model is being taken as input to all 43 HEC-HMS models built for the flood prone tributaries of the Brahmaputra and Barak basins. For each of the basins, the discharge is estimated. The real-time stage and discharge data are obtained from the in-situ measurement from the concerned authority. Based on the estimated discharge through the HEC-HMS model simulation, current level of water in a river, synoptic weather conditions, the decision of impending flood is taken. Once the probability of flood is likely, the state level disaster managers are alerted through e-mail and SMS service about the likelihood of flood with the probable severity level in terms of low flood, moderate flood, high flood and very high flood. A map showing the areas that are likely to be impacted are also provided to the authorities to take timely and effective decision on evacuation, relief planning, etc.

The accuracy of the flood alert was validated with reports generated by the Govt. of Assam as well as using field level information shared by the concerned disaster authority. The mean monsoonal alert success score for the year 2012 to 2023 is shown in Figure 8. The mean combined score of both absolute and partial success is about 88 % during 2012 to 2023, which highly appreciated by the user agency.

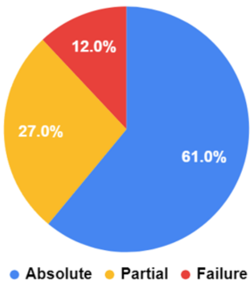

Fig 8: Mean monsoonal alert success score (2012-2023)

Where, Absolute success accounts to actual flood occurrence and the validity of flood alert is valid, partial success implies to the substantial rise in water levels reaching the danger level though flood have not actually occurred during the alert validity and failure is when the alert is issued to a river but there was no rise in water level or flood inundation. In year to year basis, the alert success score vary from 80 % to 90 % with a lead time of 24 to 48 hours.

4. Monitoring of embankment breach

Most of the tributaries in Assam are protected by embankments on both sides of the river. Such embankments are often very old and are subject to erosion and being damaged by anthropogenic activities. Many of embankments are also damaged every year by breaching. Plugging of such breaches is very essential well in advance to stop flood in those areas. As part of this comprehensive flood management initiative, mapping the existing embankments in major flood prone districts of Assam are done and all breach points are identified using temporal satellite data. For instance, in 2022 there was around 19 embankment breach in Assam, leading to flood inundation in nearby areas. Pre- and post-flood Sentinel-1 and Sentinel-2 data of 2022 is used to identify the embankment breach locations due to the floods that occurred in the year 2022. With both datasets, nineteen breach locations were identified in 8 districts of Assam. The embankment breach location caused by Baralia River in Kamrup district as seen on satellite data (in False Color Composite) is shown in Figure 9.

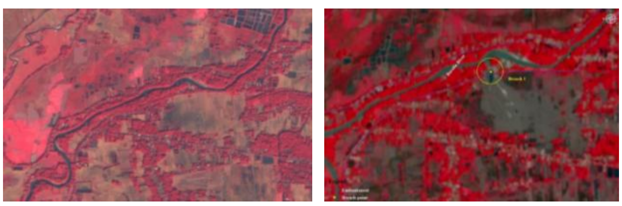

Fig 9: Pre-flood image in January 2022 (left) and post-flood image in June 2022 (right) caused by embankment breach near Baralia River

This input has been found very effective by the authorities towards preparedness for flood mitigation. A report is provided to the authorities with details on each of the embankment breach locations, based on satellite imagery every year (post flood) so that it can be rectified and reconstruct before the onset of another monsoon flood events.

5. Flood Hazard Zonation

Preparation of the flood hazard zonation forms another component towards the comprehensive flood mitigation initiative in Assam. Although the entire Assam is prone to flooding, except a few high altitude areas, there is significant spatial variability on the frequency as well as the intensity of flooding. Flood hazard maps are prepared using satellite data on inundation for more than two decades. A typical flood inundation extent in Nagaon district in Assam is shown in Figure 10. The maps are used effectively for making structural mitigation plans to reduce the impact of flood in most vulnerable areas.

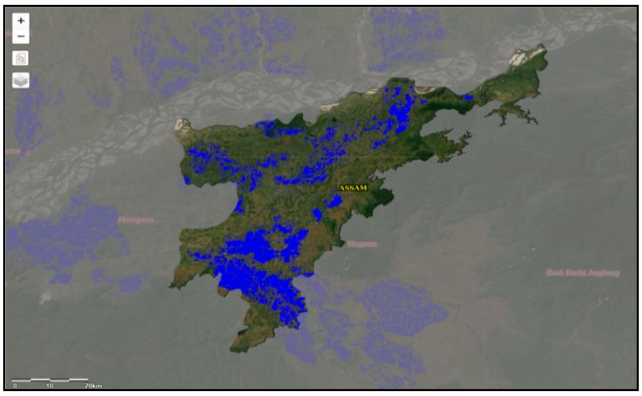

Fig 10: Flood inundation map of Nagaon district in Assam

Another approach for generation of Flood Hazard Zonation maps over the entire Assam state is by utilizing the most widely used Multi-Criteria Decision Analysis (MCDA), Analytic Hierarchy Process (AHP) technique (Miminoski and Luthfi 2020; Maji and Bar 2019; Mandal and Ray 2017) . The primary objective is to establish a robust framework that accurately identifies and delineates areas at high risk of flooding, serving as a vital component for effective disaster management and mitigation strategies in the state. To achieve this objective, advanced geospatial data layers and cutting-edge remote sensing techniques are leveraged within a state-of-the-art Geographic Information System (GIS) environment. These data layers encompass crucial factors such as Land Use Land Cover (LULC), Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI), Digital Elevation Model (DEM), slope information, breach records, and confluence locations. By incorporating this wide array of geospatial data, the study aims to capture diverse elements influencing flood hazards and enable a comprehensive assessment of flood-prone areas. To enhance the accuracy and significance of the analysis, a meticulous process of reclassification is performed on the geospatial data layers, assigning them to distinct classes based on their importance in determining flood hazard zones. By effectively categorizing the data layers, the study optimizes their utility and relevance in evaluating flood susceptibility across the study area. Furthermore, to gauge the interrelationships between the reclassified layers and ascertain their combined influence on flood hazard identification, a comprehensive confusion matrix is developed using Saaty's scale (Saaty, 2002). This matrix provides a quantitative measure of agreement or disagreement among the reclassified layers, facilitating a deeper understanding of their individual contributions to flood hazard mapping. Building upon the insights gained from the reclassification and confusion matrix analysis, the study employs the MCDA AHP methodology to generate highly informative and detailed flood hazard maps. The AHP technique systematically analyzes and prioritizes the relative importance of each reclassified layer, considering their unique roles in identifying areas at higher risk of flooding. By leveraging the results obtained through the AHP analysis, the study produces comprehensive flood hazard maps that accurately delineate vulnerable areas across the various districts in Assam. Figure 11 shows the flood hazard map categorized in very low, low, moderate, high and very high for the Cachar district of Assam.

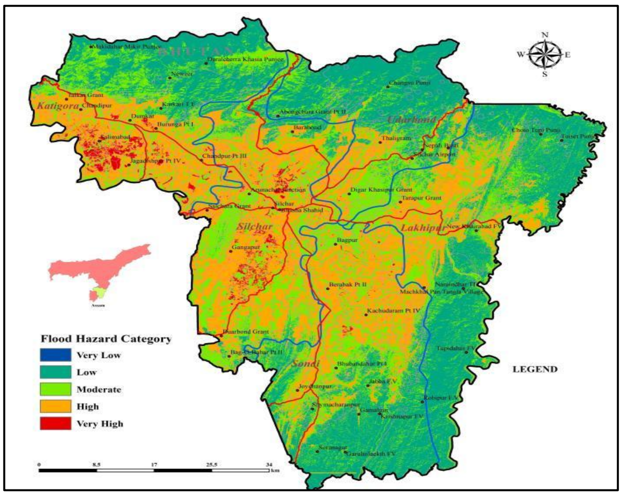

Fig 11: Flood Hazard Zonation map of Cachar district

The accuracy of the generated hazard map is assessed with the flood hazard zonation map generated by the National Remote Sensing Centre (NRSC) using the performance matrix known as the Receiver Operating Characteristic - Area Under the Curve (ROC-AUC), to evaluate the quality of a binary classification model (Chakraborty and Das 2020). Figure 12 shows the AUC curve for Cachar district with respect to high flood zone and it is observed that an overall 89 % accuracy is achieved.

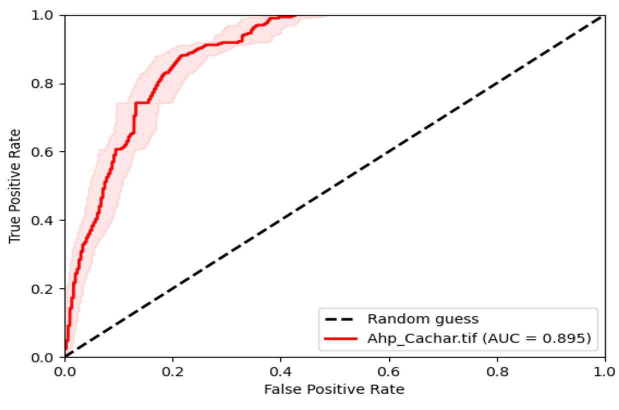

Fig 12: ROC-AUC for high flood zone of Cachar district

6. Conclusion

This study highlights the effectiveness of earth observation data towards developing a comprehensive flood management plan for the Brahmaputra and Barak basins in Assam. A space data aided hydrological and meteorological model combined with in situ measurements has been developed and the system is supported by flood hazard zonation, embankment monitoring system, etc. to deliver an effective flood management strategy. The warnings are disseminated through web, e-mails, and SMS services to ensure proper and timely action are taken. The early warning component has some limitations both in the meteorological modeling as well as hydrological modeling. However, this has been proven effective to take timely decision to minimize the flood damage and mitigate flood in many areas of Assam.

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