Water Resource Management for the Riverine System of Brahmaputra
Case Study of Urban Flooding and Mitigation Management Using Hydrodynamic Models

Meenatchi G
Postgraduate student, IIT Guwahati
meenatchi@mrcfoundationforuda.in

Abstract

Floods represent one of the most widespread natural disasters affecting a significant portion of the global population. In recent times, urban areas have experienced a surge in severe floods due to uncontrolled urbanization and the impacts of climate change. Unfortunately, this trend is expected to continue and even intensify in the coming years. While it may not be possible to prevent such events entirely, technological advancements have made it feasible to identify flood-prone areas through 2D modeling of critical rainfall events. However, the complexity of modeling urban floods arises from the unpredictable flow conditions within urban environments, primarily due to rapid changes in topography and the limited availability of extensive raw data. Consequently, the modeling of urban floods has become a challenging process. Watershed management contributes significantly to solving flood forecasting issues globally. The intricate dynamics of freshwater systems and urban areas can be understood effectively through simulation and modeling. These tools aid decision-makers by simulating physical processes like rainfall, runoff, infiltration, and channel flow to provide an understanding of how water behaves in various settings. This information is crucial for issuing warnings, evacuating at-risk populations, and implementing disaster management plans.

On the Brahmaputra River, the urban watershed of many districts in Assam experiences frequent flooding and other natural disasters. With a crucial route connecting the area with the mainland, it is northeastern India's most important urban and financial center (*Sarmah et al.*). Every moderate to heavy shower causes flooding and waterlogging throughout the urban watershed. HEC-RAS, a freely available 2-D hydraulic modeling software, offers a powerful solution for assessing flood inundation depths and creating risk maps in various rainfall scenarios. By integrating with GIS data, HEC-RAS enables the generation of accurate flood inundation depth information overlaying the underlying terrain. This research describes the need to develop comprehensive risk maps that depict vulnerable areas susceptible to flooding based on different rainfall scenarios. So assessing the flood and flood inundation in the areas of Brahmaputra vicinity is crucial to carry out the appropriate mitigation strategies by municipal authorities.

Keywords: *Hydrodynamic modeling, GIS, Watershed, Brahmaputra*

Introduction

1.1. Background of the study

Urban flooding in the Brahmaputra region of Assam, particularly in Guwahati, is a significant issue that has been affecting the area for many years. The Brahmaputra River, one of the largest rivers in the world, flows through Assam, and its basin is prone to frequent flooding due to heavy rainfall, rapid urbanization, encroachments on floodplains, and inadequate drainage infrastructure. The rapid growth of urban areas in Guwahati and the surrounding regions has resulted in the conversion of natural drainage systems into concrete structures, which has disrupted the natural flow of water. Moreover, encroachments on floodplains and wetlands have further exacerbated the problem by reducing the area available for water storage during heavy rains.

In this research, the major objective is to model urban flooding, which plays a crucial role in watershed management as it helps in understanding the complex dynamics of urban flooding and enables the development of effective flood management strategies. The aim and objectives of urban flood modeling for watershed management include assessing Flood Vulnerability, understanding flood dynamics, evaluating flood mitigation measures, suggesting suitable drainage systems, and proper land use planning. To model urban flooding, GIS-integrated hydrodynamic modeling is used to appraise the flood events that happened in the past in the Brahmaputra region. The final model can be adopted for a global scale with topography and similar urban conditions.

Hydrodynamics modeling plays a crucial role in understanding and predicting urban flooding events. Geographic Information Systems (GIS) and HEC-RAS (Hydrologic Engineering Centers River Analysis System) are two commonly used tools in this field. GIS provides a platform for spatial data management, analysis, and visualization. It allows you to integrate various types of geospatial data such as digital elevation models (DEMs), land use/land cover data, rainfall data, and hydraulic infrastructure information. GIS is used to create a comprehensive database of the study area, including its topography, land cover, and other relevant features.

HEC-RAS is highly helpful for the hydraulic modeling of rivers, streams, and floodplains. It uses a one-dimensional approach to simulate water flow and can be applied to rivers and channels within an urban environment. HEC-RAS can model steady flow, unsteady flow, sediment transport, and water quality. It calculates water surface profiles, flow velocities, and flood extents based on the inputs.

1.2 Motivation

The Brahmaputra River, with more than 50 numbers of tributaries feeding them, causes flood devastation in the monsoon period each year. Flooding from the Brahmaputra and other rivers causes huge devastation in Assam during the monsoon. **40% of the entire State is flood-prone.** Every year, the Brahmaputra Valley in Northeast India experiences devastating floods, resulting in loss of life and widespread destruction. Even before the monsoon season began this year, continuous rainfall over the past week has caused immense havoc, submerging vast areas of Assam, destroying crops, and displacing hundreds of thousands of people.

In previous studies, researchers have explored integrating hydrological and hydraulic models using global datasets to understand better and predict flooding in the Brahmaputra Basin. *Schneider et al. (2017*) conducted a study where they employed a lumped and conceptual hydrological model, NAM, using input data derived from global datasets. The resulting outputs were then utilized in a hydrodynamic model, MIKE HYDRO River, which was calibrated using satellite altimetry data from CryoSat-2. The calibration process involved adjusting cross sections derived from a digital elevation model (DEM) using water level measurements obtained from satellite altimetry. The study demonstrated satellite altimetry data's effectiveness in improving hydrodynamic modeling results' accuracy.

In another study by *Maswood (2015)*, hydrodynamic modeling was performed using two sets of data for river cross sections and boundary flow. One set of cross-sections was generated from survey data, while the other set was derived from satellite observations. For the boundary flow data, one set was based on observed discharges, while the other set was obtained from simulated output generated by a hydrological model. The inputs for the hydrological model were gathered from global datasets and satellite observations. The study found that the combination of satellite-derived cross-sections and boundary flow data from the hydrological model produced the best results, indicating the significance of incorporating both satellite data and hydrological modeling for accurate flood prediction.

These studies highlight the importance of integrating global datasets, satellite observations, hydrological models, and hydraulic models to enhance flood modeling and improve our understanding of flood dynamics in the Brahmaputra Basin. By leveraging such combined approaches, researchers can obtain more reliable flood predictions and contribute to more effective flood management and mitigation strategies in the region.

Accurate modeling and mapping of flood events are essential to effectively manage and mitigate the impacts of urban floods. By simulating and analyzing flood events, we gain insights into flood propagation patterns, flood extent, and water flow behavior through urban areas. This knowledge aids in identifying high-risk areas, evaluating flood mitigation strategies, and improving emergency response planning.

1.3 Novelty

The application of hydraulic modeling for large basins with limited data can greatly benefit from the utilization of freely available global datasets.

One notable innovation in this project revolves around utilizing remote sensing data to assess flood extent by integrating hydrological and hydraulic models, as it helps in understanding how floodwaters propagate through the urban landscape, including the flow paths, inundation patterns, and the interaction between surface water and the drainage network. This understanding is crucial for developing accurate flood forecasting and warning systems. This research represents a novel approach, particularly within the context of the Brahmaputra Basin, where such methods have not been extensively explored before. **And some of the major limitations in consideration of drainage infrastructure and data availability are also addressed here in detail, which can proceed further by other researchers for accurate flood prediction and mitigation strategies and the detailed methodology with novelty also mentioned in the report**. While HEC-RAS is a widely used hydraulic modeling software, its specific application for flood modeling in the context of Assam floods may have limited exploration. Identifying and addressing the unique challenges posed by the complex hydrological characteristics of Assam, such as the Brahmaputra River dynamics and the intricate network of tributaries, can contribute to filling this research gap.

1.4 Research objectives

The aim and objectives of urban flood modeling for watershed management include:

Assessing Flood Vulnerability and Flood Dynamics: The primary aim of urban flood modeling is to assess the vulnerability of an urban area to flooding. This involves analyzing the topography, land use patterns, drainage systems, and hydrological characteristics of the watershed to identify areas at high risk of flooding. Urban flood modeling allows for a comprehensive understanding of flood dynamics in complex urban environments.

Evaluating Flood Mitigation Measures: By simulating different scenarios, such as the implementation of green infrastructure, improved drainage systems, or floodplain zoning, the modeling can provide insights into the potential outcomes and cost-effectiveness of different strategies.

Designing Sustainable Drainage Systems: Urban flood modeling helps in designing and optimizing sustainable drainage systems (SuDS) that can effectively manage stormwater runoff. The modeling can assess the performance of different SuDS components, such as permeable pavements, rain gardens, and retention ponds, in reducing flood risk and improving water quality.

Supporting Land Use Planning: Urban flood modeling provides valuable information for land use planning and development decisions.Accurate flood modeling enables authorities to anticipate the extent and duration of flooding, identify critical infrastructure at risk, and allocate resources effectively.. The modeling results can provide scientific evidence to prioritize investments in flood management, update building codes and regulations, and guide long-term urban planning strategies.

2. Study Area - Brahmaputra Basin

A total of 580,000 km2 make up the Brahmaputra Basin, of which 293,000 km^2 is in China (Tibet), 38,400 km^2 is in Bhutan, 195,000 km2 is in India, and 47,000 km2 is in Bangladesh. It is located between lat 23ºN and 32ºN and long. 82ºE and 97º50'E. The Brahmaputra River is 2880 kilometers long in total. It originated from a glacier mass in Tibet and moved east before turning and entering the Indian state of Arunachal Pradesh. Before it reaches the Assam lowlands, it descends rapidly.

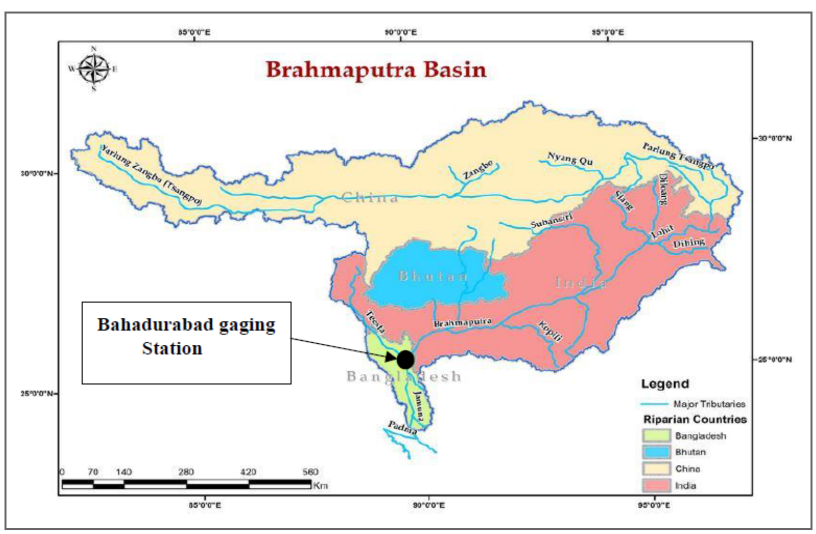


Fig 1. Brahmaputra Basin (Banerjee et al., 2014)

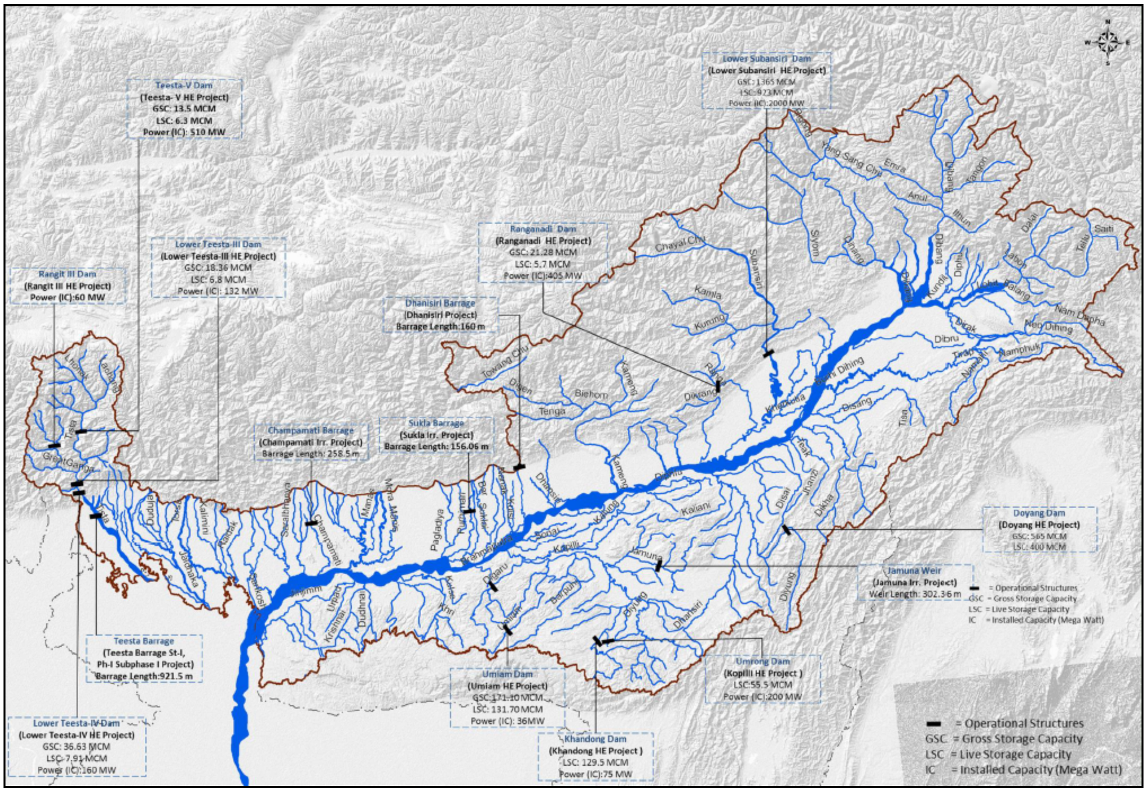


Fig.2 Brahmaputra Basin - Major water resources

3. Data used

To develop a 2D hydrodynamic model in HEC-RAS, Two key types of data are required: hydrological information and geometric information of the river.

Hydrological information refers to data related to the flow of water, such as flow hydrographs. These hydrographs show how the flow rate changes over time at specific locations in the river. It is crucial to have historical hydrological data to simulate and validate the model accurately. By using past events' hydrological data, we can ensure that the model accurately represents real-world flow conditions.

On the other hand, geometric information pertains to the physical characteristics of the river, including elevation data, Manning's roughness coefficient, and normal depth at the downstream section. This information is essential to define the terrain on which the flow simulation will be performed. Elevation data allows us to determine the varying heights along the river channel, while Manning's roughness coefficient helps to quantify the resistance to flow caused by vegetation, roughness elements, and other factors. The normal depth at the downstream section provides a starting point for the simulation, representing the water level under steady flow conditions. Hydrological data from past events are required to accurately simulate and validate the 2D hydrodynamic model. Geometry data, including elevation information, Manning's roughness coefficient, and normal depth at downstream, are necessary to define the river's physical characteristics and provide the basis for the flow simulation.

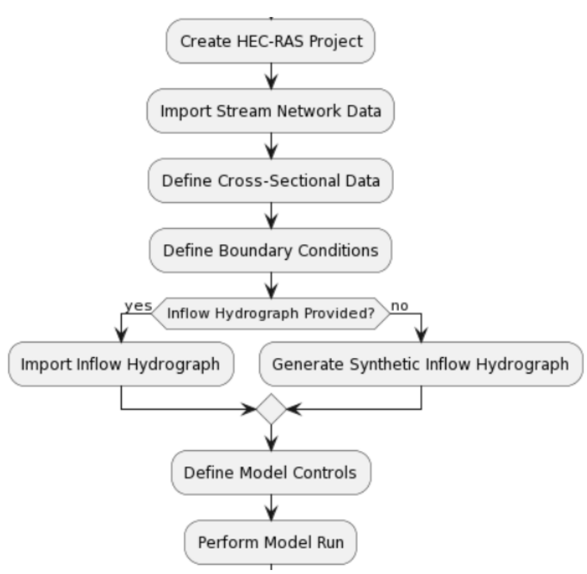
Global Precipitation Data https://gpm.nasa.gov/ State and flow hydrographs - https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest/viewing-results/stage-and-flow-hydrographs Assam flood information - *http://www.asdma.gov.in/reports.html*

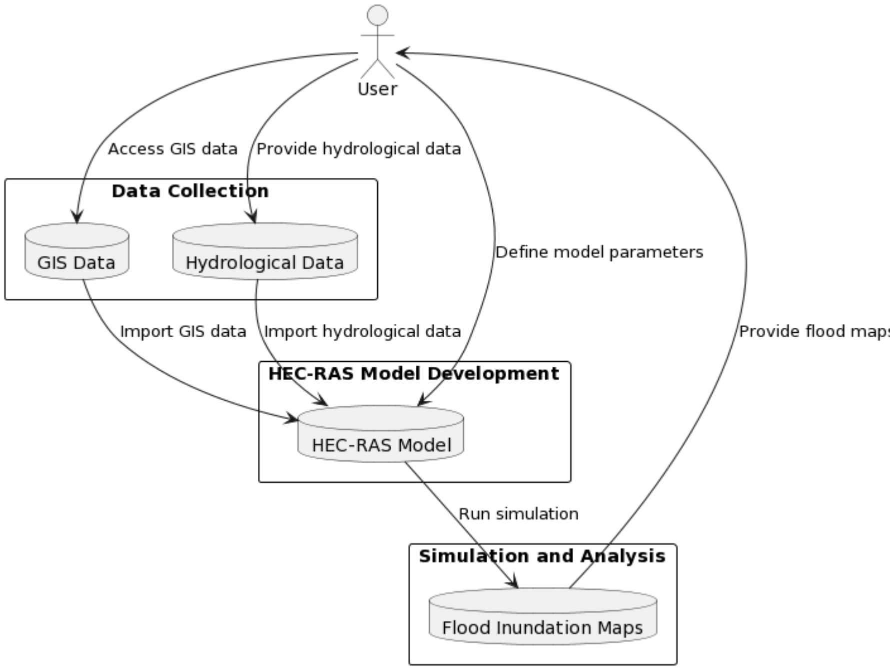
CMIP5 data [https://esgfnode.llnl.gov/search/cmip]. *Huffman, et al.* TRMM Precipitation Data [https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html#detail] - gridded data
GPM IMERG Data Access *https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGHH_06/summary*
Runoffhttps://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=form Sentinel-2 datasets 10m resolution satellite data - https://developers.google.com/earth-engine/datasets/catalog/sentinel-2
SRTM Digital Elevation Model Data
https://portal.opentopography.org/raster?opentopoID=OTSRTM.082015.4326.1

4. Methodology

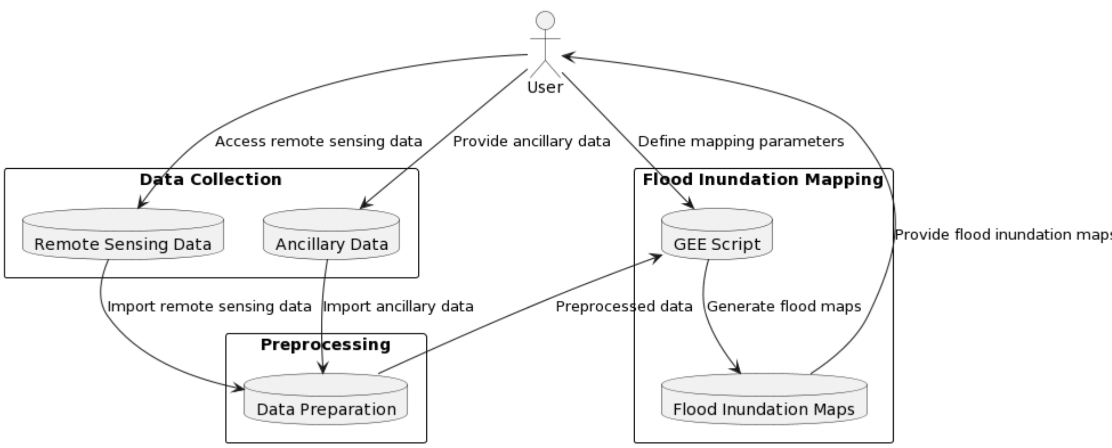
4.1 Hydraulic Analysis: HEC RAS is the software utilized for hydraulic modeling. The entire stretch of the river was not calculated due to computational time constraints; instead, only the flood areas were modeled. HEC Geo RAS was used to build the geometry data in Arc GIS. The hydraulic model's internal and upstream boundary conditions were derived from the flow hydrographs estimated by the hydrological model. The gradient slope was set at 0.007 at the downstream boundary and the gradient slope was set at 0.005 at the downstream boundary, which was set at normal depth. Through HEC DSS Vue, the hydrographs used were linked to the files of the HEC HMS results. The Mannings coefficient was calculated to be 0.02 and 0.035 for riverbeds and floodplains, respectively. From the HEC HMS data, certain flood occurrences were chosen for the hydraulic model simulation. For flood mapping, the HEC RAS output was post-processed in Arc GIS. The maximum water surface in TIN format was created in this stage. The DEM's ground elevation was calculated from the maximum water surface. The final map represented flood conditions for the simulated period or chosen flood event. The resultant flood map was validated with the available satellite datasets at specified flood events.
Based on the results of the activities mentioned above, results were analyzed and conclusions were drawn in relation to the objective of this study. Recommendations for further studies were also made.

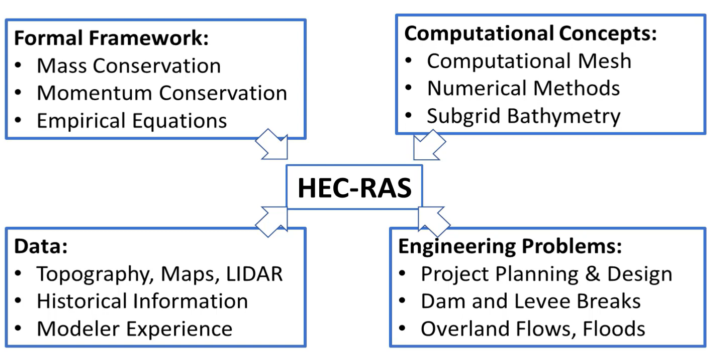
4.2 HEC-RAS Simulation





Methodology Flowchart for flood inundation mapping and hydrodynamic modeling



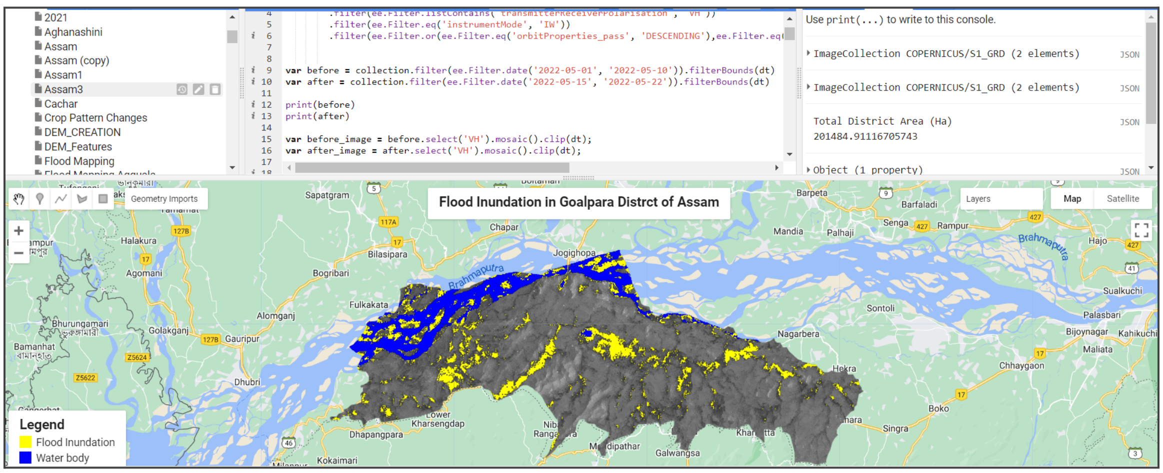


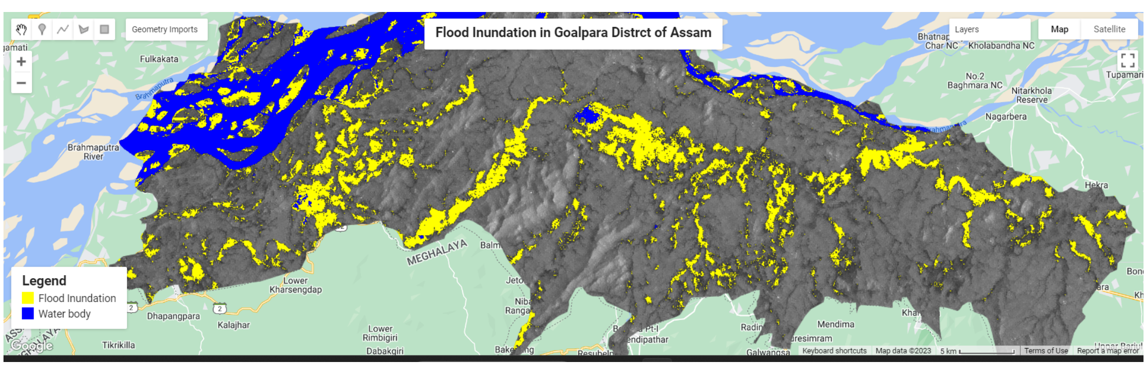
Hydraulic Analysis in HEC-RAS and Google Earth Engine

5. Results

5.1 Google Earth Engine-Based Identification of Flood Extent and Flood-Affected Areas Using Sentinel-1 SAR Data

Mapping of flooded areas by comparing images taken before and after a flood event. Two filtered image collections for the study area have been created: one imagery dataset before the flood and another imagery dataset for the flooding period. For images before the flood event, the date range was from 1 May 2022 to 15 May 2022 and found two images that matched all our criteria. For images during the flood event, images were filtered from 19 June to 28 June 2022 and found two images matched all the criteria, which were for 29 June, which was close to the main impact date, 25 June. These two-image collections for each time period have been mosaiced and clipped for the final analysis purpose. Third, a speckle filter has been applied to suppress noise pixels. In the change detection method, any change in co-registered pixel's backscatter values is calculated in two different time periods to determine changes that occur. In this case, the backscatter coefficient of both pre-flood and flooded imagery of each combination has been calculated. Then the difference of backscatter coefficients at each pixel is calculated using the pixel-based change detection approach.





Flood inundated areas

Applications: Flood mapping using Google Earth Engine (GEE) can be performed both before and after floods. The approach and methods used may differ depending on the specific objective and data availability.

1. **Pre-Flood Mapping:**

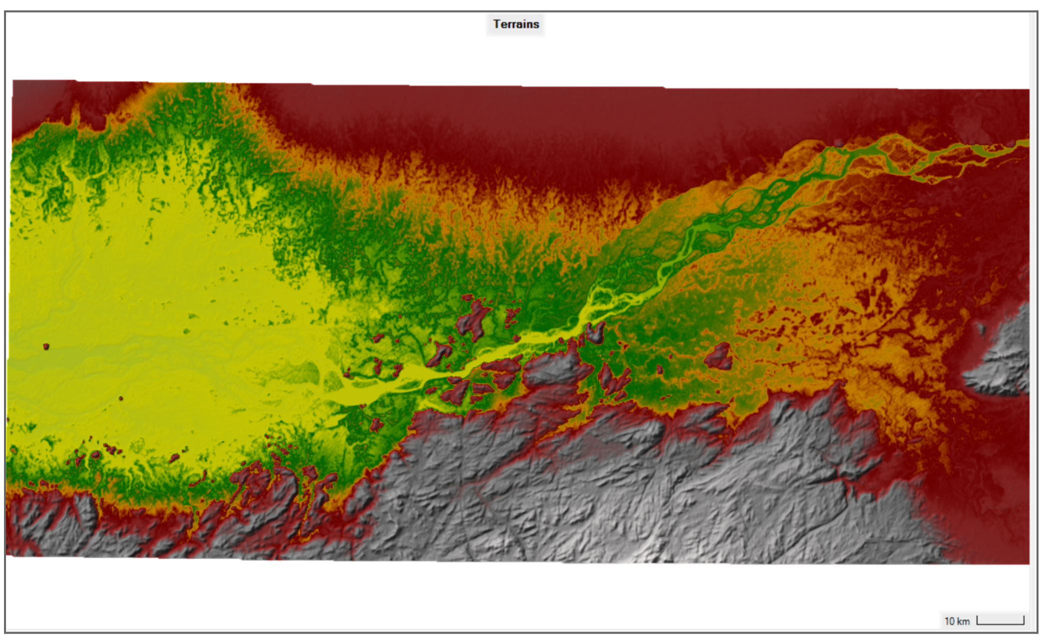
Data Collection: Gathering relevant data such as digital elevation models (DEMs), satellite imagery (e.g., optical, radar), and hydrological information (e.g., river networks, rainfall data).
Image Processing: Pre-processing the satellite imagery to correct atmospheric effects, normalize the data, and enhance relevant features for flood detection.
Hydrological Analysis: Utilizing hydrological models or algorithms to simulate potential flood scenarios based on rainfall data, DEMs, and land cover information.
Flood Extent Mapping: Applying thresholding techniques or machine learning algorithms to classify the satellite imagery and identify areas susceptible to flooding.
Visualization: Displaying the flood extent on a map or generating flood hazard maps to aid in pre-flood planning and risk assessment

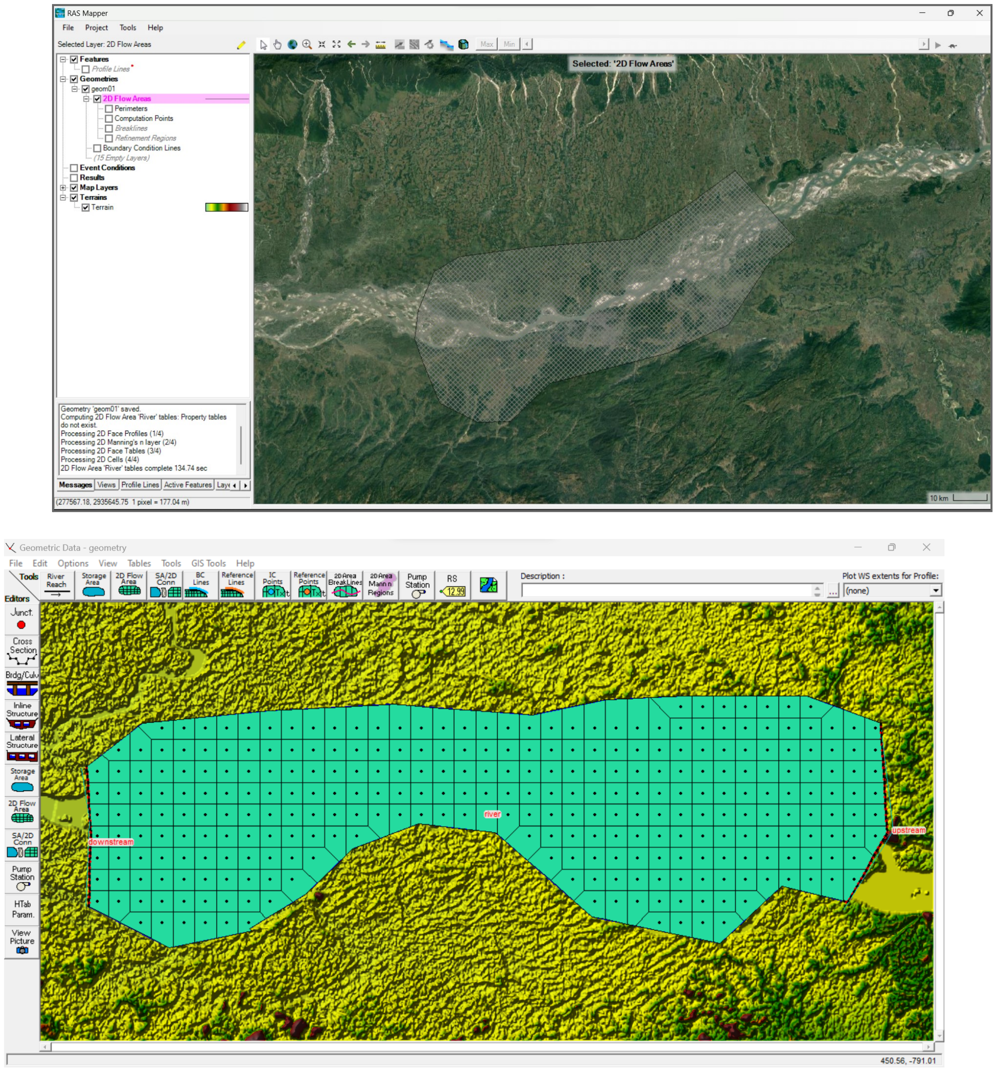
2. Post-Flood Mapping:

Data Acquisition: Acquiring satellite imagery (e.g., optical, radar) before and after the flood event to detect changes in surface water.
Image Differencing: Performing image differencing techniques to identify areas that have been inundated by comparing pre-and post-flood imagery.
Classification: Utilizing machine learning algorithms or thresholding techniques to classify flooded areas based on spectral signatures or radar backscatter changes.
Accuracy Assessment: Validating the accuracy of the flood mapping results by comparing them with ground truth data or other reliable flood extent references.
Visualization and Analysis: Visualizing the flood extent and conduct spatial analysis to assess the affected area, analyze flood dynamics, and support post-flood recovery and response efforts

5.2 HEC-RAS MODELING - RESULTS & ANALYSIS

STUDY AREA - DIGITAL ELEVATION MODEL





3D Computational Mesh

Performing 2D modeling using HEC-RAS involves several steps. And the key steps involved lie in the data preparation:

Obtaining topographic data: Collected elevation data, such as digital elevation models (DEMs), for the area of interest. This data has a sufficient resolution of 30m to capture the details of the urban terrain.

Collecting channel geometry data: Gathered information about the cross-sections, channel banks, and other hydraulic features within the study area.

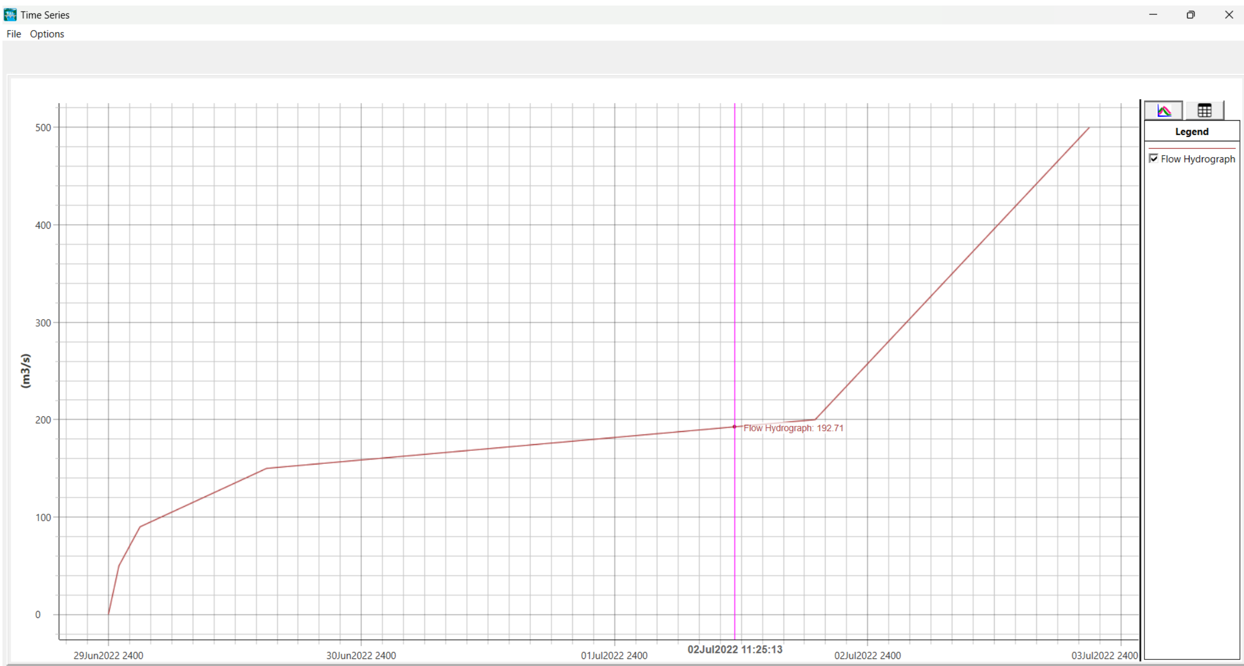
Acquiring hydraulic boundary conditions: Identified the inflow and outflow locations, such as river reaches or culverts, and gathered data on boundary conditions, such as flow rates.

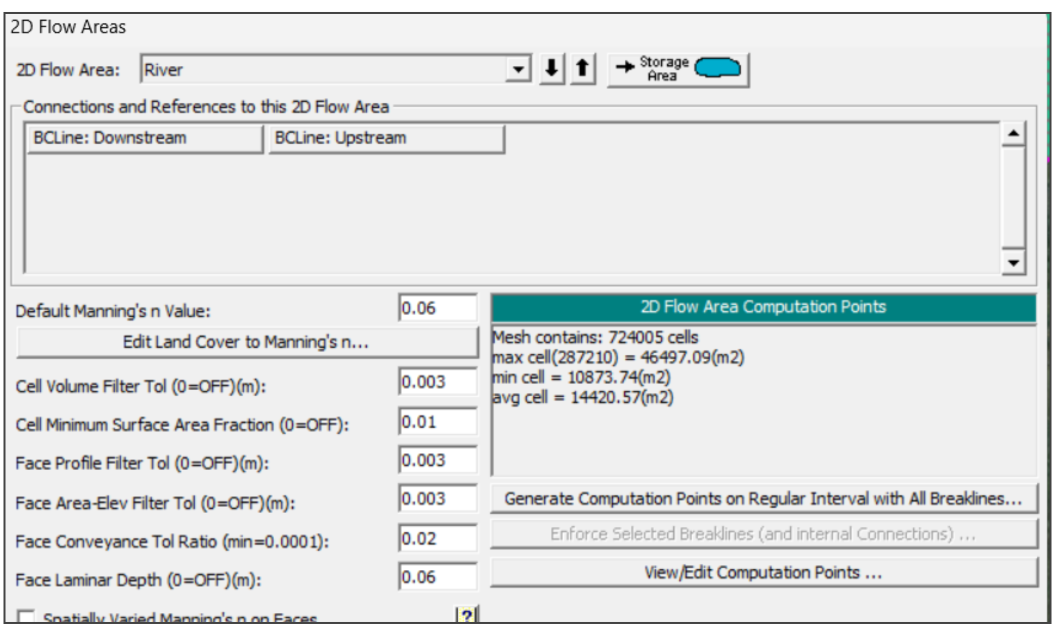
A computational grid covering the study area and mostly the flooding areas has been generated. The mesh density has been adjusted as needed to capture the necessary level of detail. The initial conditions are defined like the initial water levels at various locations, such as river reaches, nodes, or junctions.

The final output

The simulation results help us to calculate the flood propagation and water surface elevations throughout the study area. The generated outputs, such as water surface elevation, flow velocity, and flood extent maps are analyzed. The model results have been compared with observed data. The model's performance is validated by comparing the simulated results with reliable sources of data.

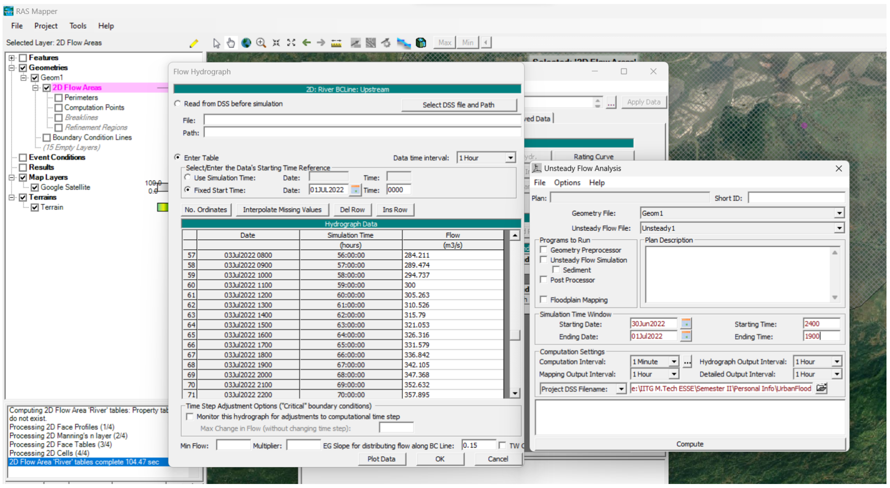
Flow Hydrograph





2-D flow computations

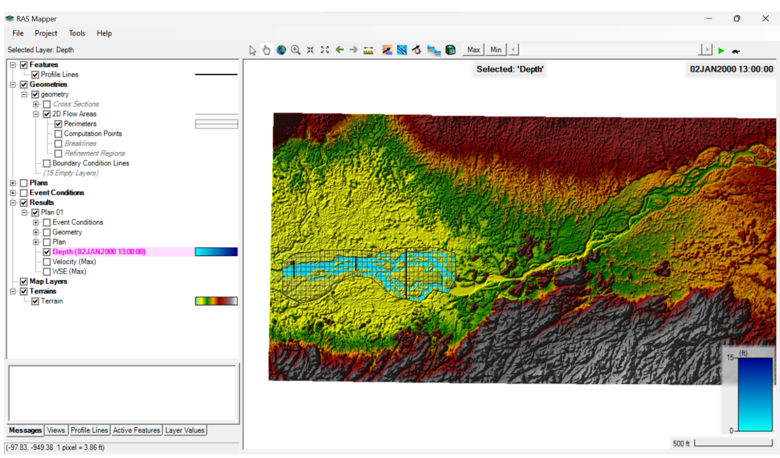
2D flow area in HEC RAS specifies the extent of the area within which 2-D flow calculations are performed. It is marked as a polygon layer for the study area. A computational 2-D mesh is established within a defined 2-D flow area at a cell spacing of 70 which generated 72,4005 computational cells. The boundary condition to initiate the simulations is introduced at a 2-D flow area as time series of event excess rainfall.

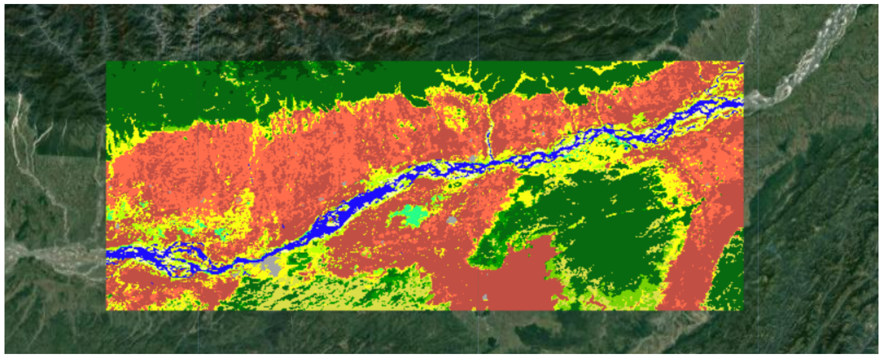


Unsteady flow calculations

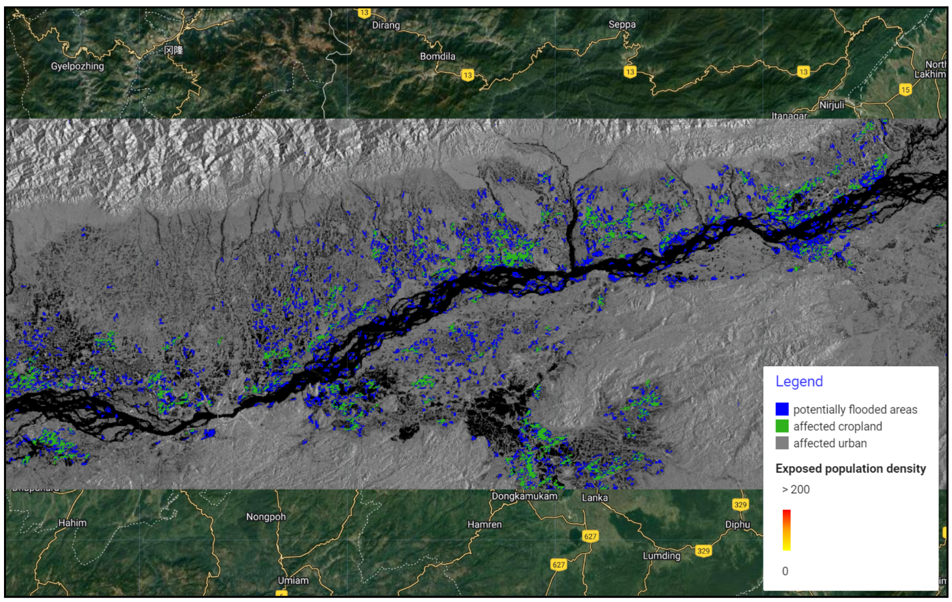
The unsteady flow calculation plan involved specifying the necessary input files, programs to run, and simulation parameters. A si**ngle geometry data file and an unsteady flow data file** were created for the analysis. The chosen programs were the geometry pre-processor, unsteady flow simulations, and the post-processor for result visualization.

The **simulation covered major specific flood events** on June 30, 2022, and July 5, 2021. The time interval for the simulations was set at one day, and the output file directory was designated. Overall, the unsteady flow calculation plan outlined the necessary steps and parameters for the successful execution of the analysis, including input files, program selection, simulation periods, time intervals, and output file management.





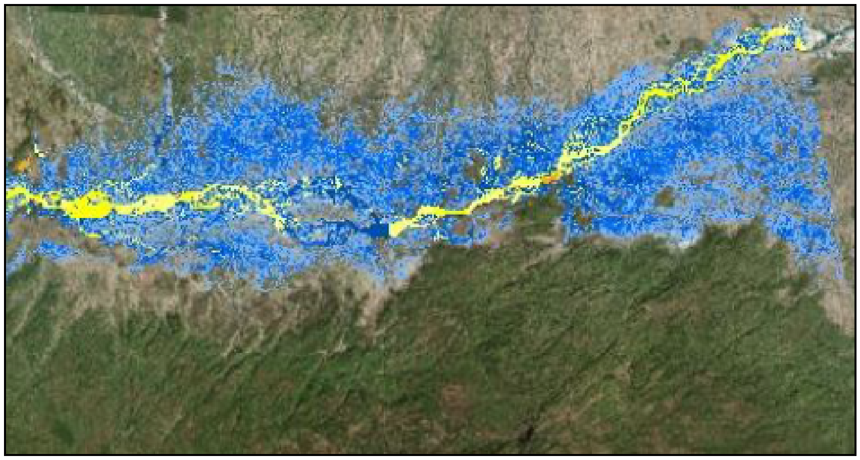
Landuse Land cover for the Study Area. In the map, Blue represents the River channel, Amber color represents the flood plain, green represents vegetation, and pale green represents Urban.



Flood Simulations - Water arrived areas along the study reach for maximum discharge

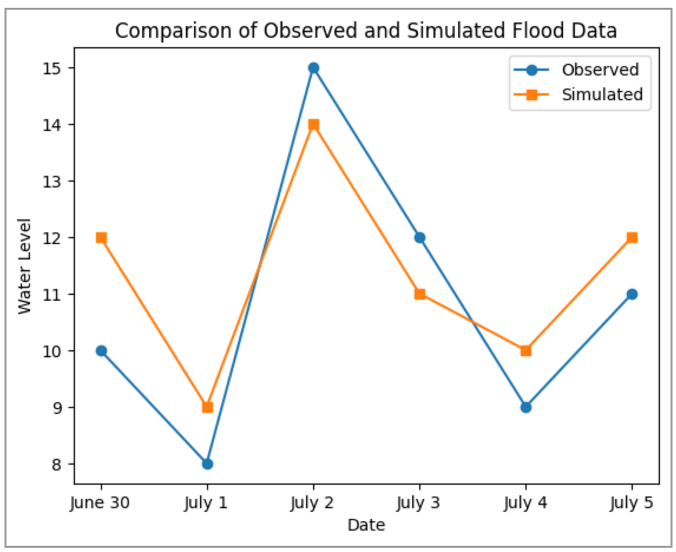
Simulation: A manual calibration of Manning's coefficient was conducted following the simulation. The calibration involved adjusting the coefficient values to improve the accuracy of the model's water level predictions. Specifically, Manning's coefficient in the riverbed was adjusted from 0.04 to 0.02, while in the riverbanks, it was adjusted from 0.045 to 0.025.

A graph was generated to compare the resulting water levels to assess the impact of this calibration. The graph illustrates the observed water levels alongside the simulated water levels with the adjusted Manning's coefficient values.



Satellite Observed Map

The validation of simulated flood inundation maps involves a crucial process of comparing the results obtained from the **simulation with observed flood maps.** These observed maps are generated based on actual historical flood events obtained through satellite observations.



5.3 Way Forward

Limitations to be considered for future work

Lack of Local Calibration: HEC-RAS is a generic hydraulic model that requires calibration to specific local conditions. In the case of the Assam floods, local calibration may be necessary to account for the **unique characteristics of the Brahmaputra River, including its vast catchment area, complex river channels, and changing river morphology.**

Limited Consideration of Drainage Systems: HEC-RAS primarily focuses on river systems and floodplain analysis. It may have limitations in adequately representing and analyzing local drainage systems, such as urban stormwater networks and local surface runoff patterns. These systems play a crucial role in urban flood management and need to be considered in conjunction with HEC-RAS modeling.

Challenges in Incorporating Urban Flood Factors: Assam floods, particularly in urban areas, can be influenced by additional factors such as rapid urbanization, inadequate drainage infrastructure, and local land use patterns. HEC-RAS may not explicitly consider these urban flood factors, necessitating integrating other modeling approaches or incorporating additional data and analysis techniques**.** Complementary modeling approaches such as urban drainage modeling or coupled hydrodynamic models can be considered to incorporate drainage and stormwater management in the context of Assam floods.

Acquiring and integrating detailed data on urban drainage infrastructure, including stormwater networks, culverts, and storage facilities, is crucial.

Utilizing urban drainage modeling software (e.g., SWMM, MIKE URBAN) to simulate the behavior of stormwater runoff in urban areas and its interaction with river systems. It is proposed in this research to couple the urban drainage model with the HEC-RAS model to analyze the combined effects of river flooding and urban stormwater runoff effectively.

6. Conclusions and Recommendations

The presented work combines HEC-RAS flood modeling simulation with flood inundation mapping using GEE. This integration allows for a more comprehensive understanding of flood dynamics and their spatial extent in Assam. By leveraging the strengths of both approaches, we can provide a more holistic assessment of flood risks and generate accurate flood inundation maps.The flood model helps in understanding the intensity and dynamics of the flooding, identifying areas with high velocities and deep water, and assessing potential risks to infrastructure and human safety. But limitations should be considered in the future works. Existing drains should be mapped with detailed field and using UAV/Drone surveys. Four input layers, including the sub-catchments, junctions, conduits, and outfalls, play an essential role in the flood simulations. The conduit dimensions should be provided as per the values obtained during the survey. Impervious and Pervious area, imperviousness rate and average slope should be derived from these sub-catchments. Analysis of land cover and soil characteristics of the sub-Catchment. Developing an urban flood model for Guwahati City is crucial for predicting and mitigating potential flooding events in the present and future years. By considering the rainfall patterns and urbanization trends, we can assess the vulnerability of the city to flooding and devise strategies to enhance flood resilience. The urban flood model will incorporate various factors such as topography, land use, drainage infrastructure, and rainfall data to simulate and predict flood scenarios. By analyzing these scenarios, we can identify high-risk areas and determine the necessary capacities for stormwater drains to mitigate flood impacts effectively. To enhance flood resilience in Guwahati City, the development of a network of stormwater drains with appropriate capacities is essential. The design of the drainage system should consider the projected increase in urbanization and rainfall intensity. This includes evaluating the adequacy of existing drains, identifying areas with insufficient drainage capacity, and proposing new drain networks where necessary.

Implementing a well-designed stormwater drainage network will help mitigate the impacts of urban flooding in Guwahati City. By efficiently channeling and managing stormwater runoff, the city can minimize the risk of inundation, reduce property damage, and protect the lives and livelihoods of its residents. Furthermore, it is essential to continually monitor and update the urban flood model as urbanization and climatic conditions evolve. This will enable proactive planning and adaptation measures to address the changing flood risk landscape and ensure the city's long-term flood resilience. By integrating the urban flood model, predicted flooding scenarios, and a comprehensive stormwater drainage network, Guwahati City can improve its preparedness, response, and overall resilience to urban flooding. These proactive measures will contribute to the city's safety, well-being, and sustainable development in the face of increasing urbanization and potential future flood events.

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