Kumar N, et al., Geoinfor Geostat: An Overview 2026, 14:1

Geoinformatics & Geostatistics: An Overview

Research Article

A SCITECHNOL JOURNAL

Applicability of HEC RAS and Microwave Remote Sensing Techniques in Flood Evacuation. A Case Study of Gandak River, Bihar, India

Neeraj Kumar[1*], Deepak Lal[1], Shakti Suryavanshi[4], Vivekanand Rawat[2], Akash Anand[3], Ajaz Ahmad[1] and Mukesh Kumar[1]

[1]Deparment of Agriculture Science, Sam Higginbottom University of Agriculture Technology and Sciences, Naini, Prayagraj, India

[2]Department of Bioresource Engineering, McGill University, Montreal, Canada

[3]Department of Civil Engineering, Aligarh Muslim University, Aligarh, India

[4]Department of Environmental Hydrology, National Institute of Hydrology, Roorkee, Uttrakhand, India

[*]**Corresponding author:** Neeraj Kumar, Deparment of Agriculture Science, Sam Higginbottom University of Agriculture Technology and Sciences, Naini, Prayagraj, India; E-mail: neerajwre@gmail.com

Received date: 26 September, 2024, Manuscript No. GIGS-24-148861;

Editor assigned date: 30 September, 2024, PreQC No. GIGS-24-148861 (PQ);

Reviewed date: 15 October, 2024, QC No. GIGS-24-148861;

Revised date: 03 February, 2026, Manuscript No. GIGS-24-148861 (R);

Published date: 10 February, 2026, DOI: 10.4172/2327-4581.1000445.

Abstract

Emergency evacuation during a flood becomes difficult due to the unavailability of various scientific evidence, tools, and, most importantly, near real-time data. Every year millions of lives are affected due to floods worldwide. In most cases, the preparedness to use inland waterways system is ignored. In India, thousands of river systems are abandoned, and they can be used for evacuation using inland waterways networks. The development of a precise water level information system with operational in both day and night time is highly required for this purpose. The organizations working in this field are facing the same problem of inaccurate depth information. A study has been conducted to develop an information system using near real-time discharge data. The HEC RAS model, along with Sentinel 1 satellite imageries and Glofas discharge data, have been used for this study. The output obtained by the study is useful for identifying the depth of the river for inland waterway navigation. Using the information, it is easy to reach the remote places surrounded by the flood. The method is tested on the ground and easily replicable to other river systems across the world during disaster relief operations.

Keywords: Flood modelling; Disaster management; Glofas data; Flood evacuation

Introduction

Bihar ranks India's one of the most flooded states in India. Every year millions of lives are affected due to floods and poor evacuation strategies. During the flood, the most trusted transportation system *i.e.*, road, railway and airway are totally collapse in North Bihar. There are more than seven main rivers flowing from the Himalayan foothills *i.e.*, upstream and confluences in River Ganga *i.e.*, downstream. These rivers are Gandak, Budhi Gandak, Bagmati, Kamla Balan, Kosi, and Mahanada. Every year during the monsoon these river carries a huge volume of flood water and silt and creates flooding situation in the lower elevation areas [1-3]. In the past few decades, the death and economic losses due to floods have also risen [4]. The reason behind the death and economic losses are anomalous precipitation rate, river siltation, faulty reservoir operation, rise in population density, unavailability of river data, lack of planning and management skills, short term solutions etc. [5]. The situation becomes worst when the embankment made on the rivers breaches or sudden water is released from reservoirs during monsoon [6]. Uncountable death and displacement have been reported by various organizations working in this field [7]. The number is continuously increasing and risen a concern for the researcher and policy maker to find a sustainable method for saving the lives of people and animals in flood-affected areas [8]. Continuous research, based on scientific observation was required to minimize the losses due to flood [9].

The study area has a wide network of perennial rivers that connect the various populated cities of north Bihar. The dense population exists near both banks of the rivers. The habitation mask is not uniform or in a planned manner. The cluster of ten to fifty houses is speared to entire areas. This unplanned cluster of homes becomes a hurdle during disaster relief operations, especially during lifting people from their native places at night time. A lot of losses was reported previously due to delay in disaster relief operations. The flood water inundates the road networks and other village identification footprints such as milestones, shine-boards, maps, etc. During the nighttime, the dark grey muddy water, and undulated terrain create complex invisibility conditions. Most of the time the professionals' divers, evacuating professionals' groups, armies, social workers, etc. are completely unknown to the flooded areas. Due to the unknown depth of water boats are stuck in dense vegetation, electric cables, bamboo poles, etc. in Figure 1. It makes the relief operation more complex and riskier. The identification of habitation masks and connecting networks is a challenging task during evacuation. On the other hand, these river networks are the only source of navigation that saves a thousand of lives during the flood. The entire disaster relief operation is a time-bounded program with priority-based works.

Figure 1: Rescue boat struck in flood plain due to unknown water depth.

In recent days the use of remote sensing and GIS techniques along with hydraulic flood models becomes an essential part of disaster relief operations. The post-flood inundation areas along with the depth of water can be easily identified by using various available methods. These methods are highly accurate and tested over various regions in the world. Normally, these models are based on the stage-discharge relationship. The river discharge data plays an important role in disaster relief operations.

At present the river discharge data is collected by a few organizations named Central Water Commission, Irrigation Department, etc. for Indian rivers. The data is collected at various locations across the rivers in pan India. The availability of these data is for a limited period, especially during floods, and also not available for all rivers. The data request from the organization is a self-complex task. For flood modelling and forecasting, it is necessary to have a time series dataset at frequent intervals. A few space-borne-based river data are available in the public domain, which can be used for the continuous study of river behaviour. The data are widely being used for hydrological and hydraulic modelling using river simulation models. Some research also finds reliability in flood forecasts and early warning systems. The data have some discrepancies which need to rectify before their use for proper flood forecast.

In this study, the GLOFAS river discharge data were used to check its reliability in flood modelling and disaster relief operation. The data is publicly available on a daily basis on the European space agency website for various rivers across the world. These data are used for various purposes such as flood forecasting, disaster management, and hazard assessment. In this study, the data will be used for 1D and 2D flood modelling on the river Gandak to estimate and model the water level and flood extent for the pre and post-flood event.

The validation of flood extent will be done by using Sentinel 1 microwave satellite imageries. The data is reliable to use for estimation of flood extent. The modelling output along with highly precise flood extent and depth of water information will help the flood evacuation process be more convenient.

About the study area

The study area is situated in North Bihar in which the river Gandak flows from the upstream side of the Himalayan foothills to the Ganga river (Downstream). The total length of the river is approximately 630 km in which 292 km falls in Nepal. The Gandak river flows along the six different districts of Bihar state and during the monsoon, it creates a flooding situation among all of them. The location map of the river is in Figure 2.

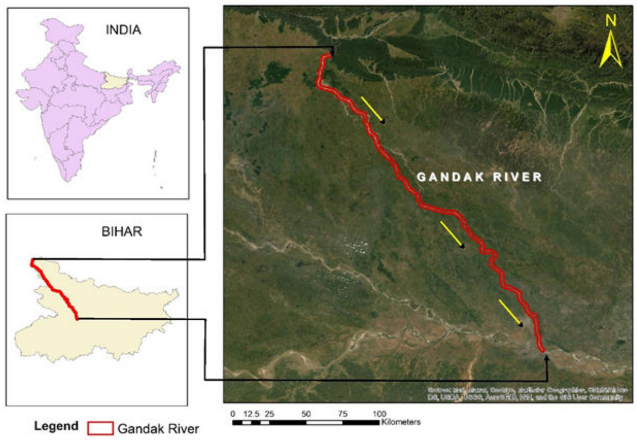

Figure 2: Location map of Gandak river in India.

At the border of India and Nepal, the Gandak barrage is situated. The purpose of the barrage is to divert the water for irrigation. The salient feature of the barrage is depicted in Figure 3. The total catchment area is about 15000 sq. mile, maximum discharge 700000 cusec, minimum 800 cusecs, design discharge is 85000 cusecs, length of the barrage is 2425 feet, total number of river gates 36, HFL 370.90 upstream, 368.70 in downstream, danger level 368.70 upstream and 359 downstream, pond Level 362 feet.

Figure 3: Features of Gandak barrage.

Data and tools requirement for the modelling

About GEBCO bathymetry data: The GEBCO_2022 grid is a global terrain model for ocean and land. It provides elevation data, in meters, on a 15 arc-second interval grid of 43200 rows × 86400 columns, giving 3,732,480,000 data points. The data values are pixel-centre registered, *i.e.,* they refer to elevations, in meters, at the centre of grid cells.

The grid was published in June 2022 and is the fourth GEBCO grid developed through the Nippon Foundation-GEBCO Seabed 2030 Project. This is a collaborative project between the Nippon Foundation of Japan and GEBCO. The Seabed 2030 Project aims to bring together all available bathymetric data to produce the definitive map of the world's ocean floor and make it available to all (Table 1).

Sr. no.	Data's	Type 1	Type 2
1	Bathymetry data	GEBCO Bathymetry data	Observed data
2	River discharge data	Glofas	CWC observed data

3	Flood extent modelling	Sentinel 1	Sentinel 2

Table 1: Data used in this study.

About GloFAS datasets: This dataset contains global modeled daily data of river discharge from the Global Flood Awareness System (GloFAS), which is part of the Copernicus Emergency Management Service (CEMS). River discharge, or river flow as it is also known, is defined as the amount of water that flows through a river section at a given time. This dataset is simulated by using a hydrological modeling chain with inputs from a global reanalysis. Data availability for the historical simulation is from 1979-01-01 up to near real-time (Table 2).

Data description		
Data type	**Gridded**	
Horizontal coverage	Global except for Antarctica (90N-60S, 180W-180E)	
Horizontal resolution	0.1° × 0.1°	
Vertical resolution	Surface level for river discharge	
Temporal coverage	1 January 1979 to near real time for the most recent version	
Temporal resolution	Daily data	
File format	GRIB2	
Conventions	WMO standards for GRIB2	
Versions	Current version-GloFAS v3.1 released 2021-05-26. For more information on versions we refer to the documentation	
Update frequency	A new river discharge reanalysis will be published with every major update of the GLOFAS system. The latest version will always be the version used in operations. For more information on the model versions, we refer to the documentation.	
Main variables		
Name	**Units**	**Description**
River discharge in the last 24 hours	m^3/s	The volume rate of water flow, including sediments, chemical, and biological material, in the river channel is averaged over a time step through a cross-section. The value is an average over a 24-hour period.
Related variables		
Upstream area	m^2	Static file-up area.nc, upstream area for the point in the river network

Table 2: Data descriptions.

About microwave satellite imageries (Sentinel 1): The Sentinel 1 mission is a joint initiative by two different groups *i.e.*, European Commission and European Space Agency. These both agencies work under Global Monitoring for Environment and Security (GMES) programme. The groups are associated with different segments such as ground and space segments at various resolutions. The main aim of the mission is to provide continuous resources for the monitoring of sea ice, marine winds, Land-use change, waves and currents, oil spills, and land deformation among others, and to respond to emergencies such as floods and earth quacks. Sentinel 1 was operational from 2013 until now (Table 3).

Product description	
Lifetime	7 years (consumables for 12 years)
Orbit	Near-polar Sun-synchronous orbit at 693 km altitude; 12-day repeat cycle; 175 orbits per cycle
Mean local solar time	18:00 at ascending node

Orbital period	98.6 min
Maximum eclipse duration	19 min
Attitude stabilisation	3-axis stabilised
Attitude accuracy	0.01° (each axis)
Instrument	Right looking with respect to the flight direction
Steering	Zero Doppler yaw steering and roll steering (−0.8° to +0.8°)
Attitude profile	Geocentric and geodetic
Orbit knowledge	10 m (each axis, 3σ) using GPS
Operative autonomy	96 h
Launch mass	2300 kg (including 130 kg mono-propellant fuel)
Dimensions (stowed)	3900 × 2600 × 2500 mm
Solar array average power	5900 W (end-of-life)
Battery capacity	324 Ah
Satellite availability	0.998
S-band TT and C data rates	64 kbit/s tele-command; 128 kbit/s – 2 Mbit/s telemetry (programmable)
X-band downlink data rate	2 × 260 Mbit/s
Launcher	Soyuz from Kourou

Table 3: Sentinel 1 data descriptions.

Software used

About HEC RAS: HEC-RAS is available on the US Army Corps website. (https://www.hec.usace.army.mil/software/hec-ras/). However, HEC-RAS 6.3.1 (2D) version has been used in this study for flood modelling. HEC-RAS solves the energy equation (Saint Vedant equation), along with an iterative procedure; the standard step method:

$$Z_2+Y_2+(a_2V_{22})/2g = Z_1+Y_1+(a_1V_{12})/2g+he \qquad (1)$$

where Y_1, Y_2=depth of water at cross sections, Z_1, Z_2=elevation of the main channel, V_1, V_2=average velocities (total discharge/total flow area), α_1, α_2=velocity weighting coefficients, g=gravitational acceleration, he=energy head loss.

SNAP 9.0.0 tool box: The SNAP toolbox is software used for analysing Sentinel 1 microwave satellite images. The European Space Agency introduced the software, which is open for public use. It can be downloaded by using the link (https://step.esa.int/main/download/snap-download/). In this study, it has been used to process Sentinel 1 data for the flood extent of Gandak river.

Q GIS: The Q GIS is a geospatial software introduced by Open-Source Geospatial Foundation in 2007. It has a wide application is scientific research and industrial applications. It can be download from the website *i.e.*, https://www.qgis.org/en/site/. In this this study, the software has been used for various analysis and mapping the various features required for the study (Table 4).

Sr. no	Software's	Version	Uses
1	HEC RAS 5.0.7	6.3.1	Modelling
2	SNAP Tool Box	9.0.0	SAR data processing
3	Q GIS	3.24.1	Mapping

Table 4: Software used in the study.

Materials and Methods

Modelling using HEC-RAS and GloFAS datasets

The study is based on one and two-dimensional flood modelling using HEC–RAS 5.0.7 and GloFAS datasets. Further, the extent obtained by the model has been used for the identification of possible inundated areas. Sometimes the modelled flood extent shows some discrepancies so it needs to verify by other sources such as field data or using cloud-free satellite imageries. In this study, the microwave satellite imageries have been used to make the modelling more precise.

Data requirement for modelling

The flood modelling was performed from the downstream of Valmiki barrage made on River Gandak to Gaighat, Patna, Bihar, India. The data required for the modelling consist of the following.

Cross-section of river Gandak: In this study, the cross-section of river Gandak from the Valmiki barrage to the downstream Gaighat Patna has been measured manually at a distance of approximately to 0.5 km.

Discharge and HFL of the river: For the modelling, the GloFAS discharge dataset has been taken. The result obtained by the modeling in the form of water surface elevation has been co-related with observed HFL at the five different locations within the river Gandak.

Data for calibration and validation of model: The discharge and HFL data were provided by the Bihar water resource department.

Selection of Stations for modelling: The station is situated downstream of the Valmiki barrage up to Gaighat Patna. The station is selected on the basis of data observation sites,

Slope of the bed: The slope of the bed has been considered (Normal) *i.e.*, 0.001.

Manning's coefficient: In this study, Manning's coefficient was used from 0.030 to 0.035.

Modelling approach

- The entire methodology has been divided into three categories
- Data collection
- Modelling
- Result interpretation
- Correlation with observed data with model output.

River data collection: The river data collection consists the various step and procedures. The first step of this study was the reconnaissance survey of the study area. In the study area a barrage is made over the Gandak river. The length of the barrage is about 739 m. At present, the river water is distributed for various applications such as domestic, industrial and agricultural use. The river bed has silt and is full of weeds on both sides of the river. The basic information of the study area was collected such as bank conditions, the paved area near the bank, the slope of the river, etc.

Processing of discharge data: The GolFAS discharge data used in this study need a minor processing before its use for modelling. The data comes under NetCDF format which is difficult to direct use. For the extraction of data, it has been further converted into raster format and then raster to point respectively. The point file contains the discharge value of the nearest the discharge observation site. Further it was overlaid to the observation site and the discharge of the river has been found (Figure 4).

Figure 4: The methodology flow chart of the study.

Modelling: The modelling consists of various segments *i.e.*, explained below.

Model setup: In this study, The HEC RAS 5.0.7 model has been used. It can be downloaded from https://www.hec.usace.army.mil/software/hec-ras/download.aspx. The model has some default values which has to be adjust before its use for the modelling such as unit system, projections etc.

The river reach: In this study, the river reach has been created by using HEC RAS. The river reach starts from the downstream side of Gandak barrage (Gate) to the distance of 282 km towards the downstream side of the river. The layer has been exported to HEC RAS for further use.

Cross-section: The cross-section data for this study has been collected by the river survey (manually) at the various observation sites at a distance of 0.5 km on both the upstream side and downstream side of the flow. The rest of the cross-section has been generated using GEBCO gridded bathymetry data. The interval between one cross-section to another was approximately 500 m. The detailed procedure for cross-section generation has been adopted.

Discharge: The GloFAS discharge data has been used in the model. In this study, the discharge from the month of June to December has been taken for the modelling. The reason behind taking this date was that a severe flood event has been recorded during this duration.

Boundary condition: In this study, the slope of the river bed has been selected. The slope value of 0.001 has been taken.

Manning's coefficient: Manning's roughness coefficient used in this study was 0.030 and 0.035. The reason behind using this value was that the river bed is silty and also has weeds and algae near the banks.

Model run: The data inserted into the software was run for the various plan within steady-state conditions with various plans (discharge).

Interpretation of HFL: The result obtained by the modelling in the form of HFL has been used to co-relate with the observed dataset. The reason for the co-relation is to check the feasibility of the data for the flood modelling for a large area.

Discharge monitoring sites: The discharge monitoring sites on river Gandak are used for the monitoring of daily discharge of the River. In this study area, a total of five sites have been identified. The daily river discharge by both observed and satellite-based discharge has been used and co-related for these site only (Table 5).

Sr. no	Site no.	Downstream length in km
1	Gandak barrage	0
2	Sohagi Barwa sanctuary	24
3	Gohni forest area	36
4	Gandak bridge at Bidhunpur	75
5	Bangraghat bridge at Jadopur	75
6	Sahahpur village	90

Table 5: Discharge monitoring sites along Gandak river.

Calibration of the model: Model calibration is one of the essential tasks to make the model more accurate using various parameters. In this study, the model calibration has been done by using Manning's roughness coefficient at a few locations near observation sites.

Validation of the model: The validation of the model has been done using the GolFAS discharge datasets (Figure 5).

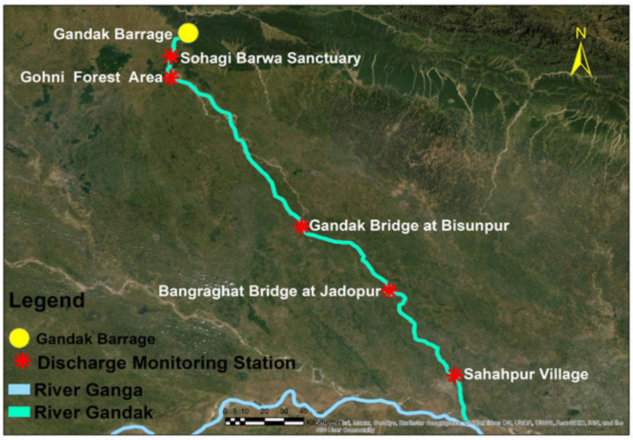

Figure 5: Discharge monitoring sites at Gandak river.

Results and Discussions

In this study, various models and datasets have been used. The main objective of the study was to know the applicability of GloFAS, GFMS, GEBCO bathymetry data, and the HEC RAS model in flood modelling and evacuation planning for the areas of North Bihar. The result of GloFAS and observed discharge datasets used in the study. The detailed observation of the datasets is described below (Figure 6).

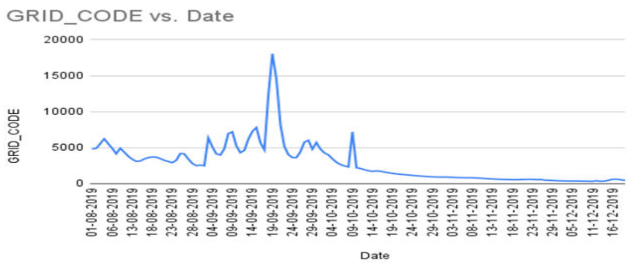

Figure 6: GloFAS discharge of 2019 monsoon season.

Peak flood analysis

In this study area, the flood occurs from June to September. In 2019, the GloFAS discharge data were available from August to December only. The flood occurs in September. The maximum discharge obtained by the GloFAS discharge was about 12286 m^3/sec on 18/09/2019. The discharge is maximum in 24 hours. At the same time, the observed discharge is approximately 6000 m^3/sec, shown in Figure 7.

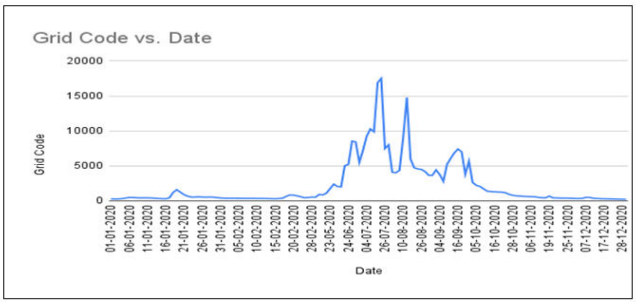

Figure 7: GloFAS discharge of 2020 monsoon season.

In the year 2020, the GloFAS discharge datasets were available from January to December. After the analysis of the data, it has been found that the two different flood events occurred in the month of July and August and on the dates 21/7/2020 and 13/8/2020. The discharge of the first event was 17492 m^3/sec and for the second was 14790 m^3/sec but the observed discharge on the same event was 12360

m^3/sec for the first and 5932 m^3/sec for the second events shown in Figures 8 and 9.

Figure 8: Discharge measurement on 24/12/2020 at Gandak barrage.

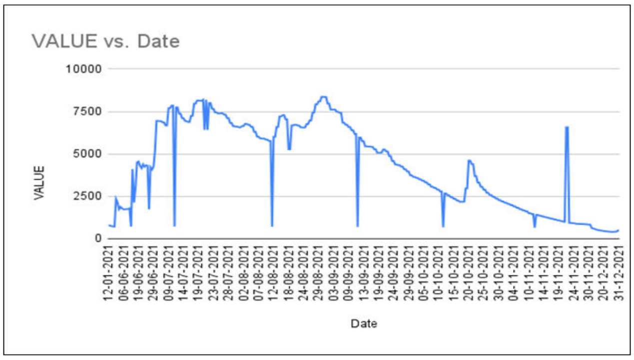

Figure 9: GloFAS discharge of 2021 monsoon season.

In the year 2021, the discharge data were available from January to December. The flood event occurred during the month of August. The discharge on 30/08/2021 was 8364 m^3/sec, but the observed discharge on the same date was 10126 m^3/sec (Figure 10).

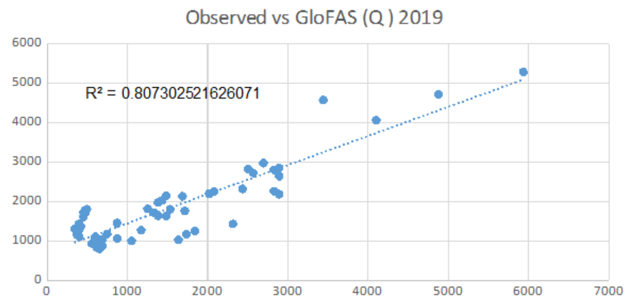

Figure 10: Observed *vs.* GloFAS discharge of 2019 monsoon season.

The correlation of GloFAS discharge *vs.* observed datasets for the years 2019, 2020, and 2012 has been estimated. The discharge of the peak flood event of 2019 has been analyzed. The main reason for this analysis was to check the difference between observed discharge and GloFAS discharge for using these data in flood modelling and evacuation planning. The correlation between observed and GloFAS datasets for the month of August to December for the year 2019 is approximately 0.8 (Figure 11).

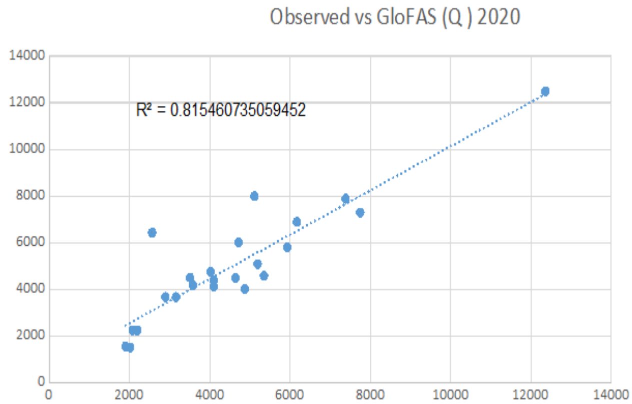

Figure 11: Observed *vs.* GloFAS discharge of 2020 monsoon season.

The same steps have been adopted to estimate the correlation of observed *vs.* GloFAS discharge for the year 2020 only for the peak flood season *i.e.*, near about 0.8 (Figure 12).

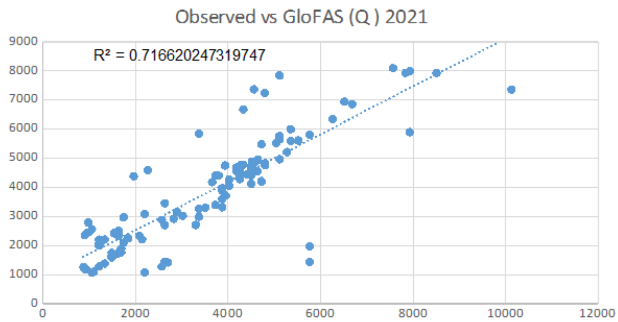

Figure 12: Observed *vs.* GloFAS discharge of 2021 monsoon season.

The discharge correlation for the monsoon season in 2021 has been estimated. It was approximately 0.7 using the Glofas discharge data to the HEC RAS model to estimate the depth of the water during peak floods for the years 2019, 2020, and 2021 (Table 6).

Sr. no	Data ID
1	S1A_IW_GRDH_1SDV_20190915T122126_20190915T122151_029032_034B39_0235
2	S1A_IW_GRDH_1SDV_20190915T122151_20190915T122216_029032_034B39_9F2D
3	S1A_IW_GRDH_1SDV_20200728T122938_20200728T123007_033655_03E688_1501

4	S1B_IW_GRDH_1SDV_20200717T122100_-20200717T122129_022511_02AB9D_A86D
5	S1A_IW_SLC__1SDV_20210831T001954_20210831T002021_039466_04A9B8_DEB0
6	S1A_IW_SLC__1SDV_20210831T002019_20210831T002046_039466_04A9B8_1C90

Table 6: Microwave satellite imageries acquisition date.

About sentinel data processing

In this study, Sentinel 1 microwave data has been used to estimate flood extent and check the accuracy of the entire modelling. A few basic steps have been used to process Sentinel 1 data.

Apply orbiting: This step is used for positioning satellite imagery. The satellite images (Sentinel 1) are generally not in the correct position. They need to be adjusted to their proper locations, so this step is required in the SNAP toolbox model (Figure 13).

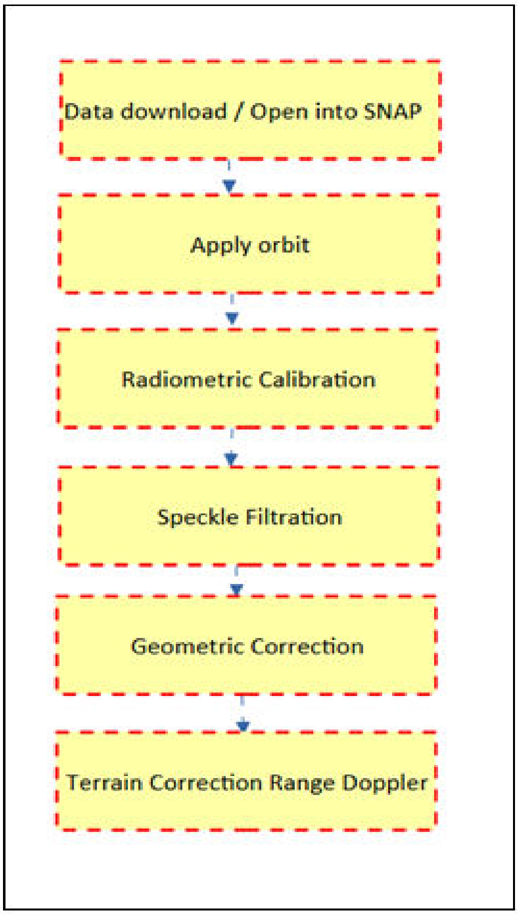

Figure 13: Flowchart Sentinel 1 image processing.

Radiometric calibration: Radiometric calibration is used to convert the digital number *i.e.*, recorded by the satellite into physical units.

Speckle filtering: Speckle filtering is the process to reduce the speckle. Basically, it is a grainy texture (salt and pepper) in an image.

Geometric correction: During the image acquisition the image doesn't have a proper position with reference to the earth's surface. Geometric correction is used to place the entire image in its real position.

Terrain correction: Terrain correction dissolves the elevation difference from the image (Figure 14 and Table 7).

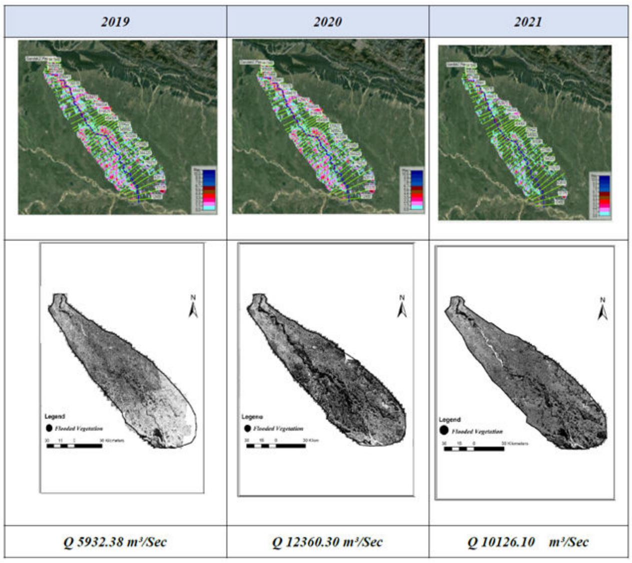

Figure 14: Flood depth and inundated areas in Gandak flood plain area.

Year	Date	GloFAS (m³/sec)	Observed (m³/sec)	Difference (m³/sec)
2019	18/09/2019	8092.16	5932.379	2159.781
2020	21/07/2020	18508.11	12360.3	2147.806
2021	30/08/2021	12364.08	10126.1	2237.974

Table 7: Date acquisition date and discharge.

Validation of modelled flood extent using microwave satellite imageries: The modelled output needs to validate because the bathymetry data used for the modelling has a resolution of four hundred fifty meters. Sometimes the inundated areas are slightly different than the near real-time inundation areas. Microwave satellite imagery is one of the best solutions for the mapping of inundation areas. In this study, the microwave satellite imageries of post-flood events have been taken and processed into SNAP Esa software. The image acquisition date of the Sentinel 1 satellite image is in Table 5 and the processed flow chart is shown in Figure 15.

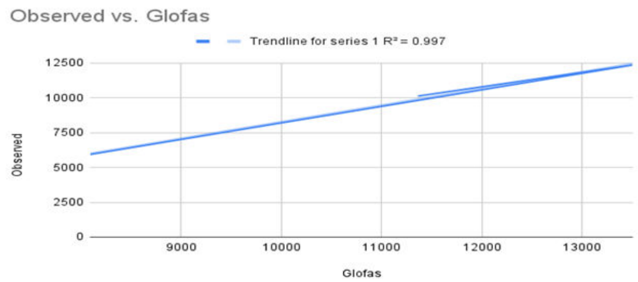

Figure 15: Trend line observed *vs.* GloFAS discharge data.

Application in flood evacuation especially in inland waterway development during disasters

At present, approximately twenty million people are living in flood-risk areas of the Gandak river basin. Almost every year the flood hits the population living near the river. During the flood, the disaster relief operations are conducted by the smallest boat *i.e.*, dinghy its capacity of intake is only 6-8 people at a time. Food and emergency medical supply badly affect the reason. A large population needs to evacuate from the remote areas. It requires a big development in evacuation programs and technical capacity building. The study informs that in this area some huge boats or vessels can be used despite dinghies. The depth requirement along with available water depth is depicted in Figure 16. The modelling approach also informs that the navigation of big vessels in the river is also possible in the river. It can provide support to millions of people during floods (Figure 17).

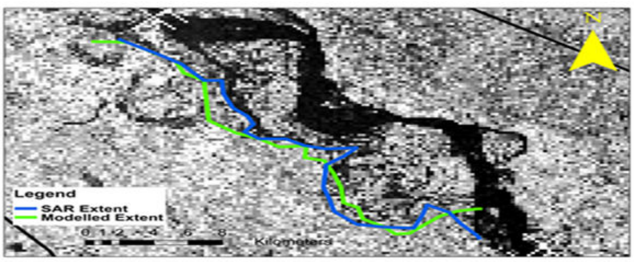

Figure 16: The modelled and real flood extent 2020 flood in Gandak basin.

Figure 17: Depth of water during flood in Gandak river basin area.

Depth requirement of boats and vessels

There are various kinds of boats and vessels used for disaster relief operations. According to their performance and demand the selection of these boats is done. In the Gandak river basin and various other river basins where flood is a common disaster these boats and vessels can also be used for life-saving. The required depth of water for the boats is Dhingy from one to two feet, and for daysailers, three to five feet deep water is required. For the large and mega evacuation drive the catamarans and trawlers will be useful. The depth required for these vessels is two to eight feet only (Figure 18).

Dinghy	*Day Sailers*	*Catamarans*	*Trawlers*
			
1-1.5 Feet	*2-3 Feet*	*02-04 Feet*	*08 -10 Feet*

Figure 18: Depth of water required for the navigation.

Inland waterways navigational route and planning

The inland waterways navigation using remote sensing and GIS techniques provides powerful decision-making and execution support to reach out to remote areas during flood evacuation and other logistic support in disaster relief operations. The unique advantage of using the HEC RAS model is that it also estimates the depth and inundates areas apart from the river. In this study, the use of remote sensing and GIS tools and models also helps to understand the extent of water used to plan several evacuation routes in flood-affected areas. The navigation route is depicted in Figure 19 with the various navigation depth of water and connectivity to populated areas.

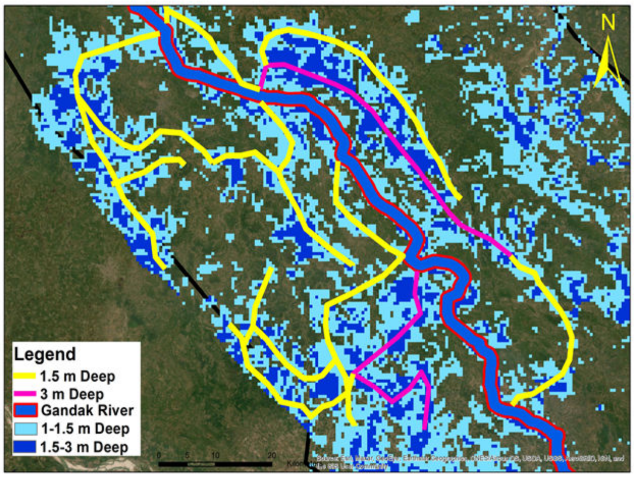

Figure 19: Route for inland waterways navigation in Gandak river basin.

Conclusion

The present study has been conducted to estimate the approximated depth of flood and extent by using various remote sensing and GIS tools, including models. The aim of the study was to develop a navigational route for inland waterways to evacuate people living in flood-affected areas. The method used in this study will help in planning, execution along with disaster management during floods. The entire methodology is based on open-source data and platforms, which can be highly useful without dependency on data, license, and technology transfer during disaster relief operations.

Acknowledgment

The team at ARSET, Applied Remote Sensing Training (NASA), is acknowledged by the authors for providing helpful training in the area of flood and disaster studies. The authors further thank SHUATS Prayagraj's Centre for Geospatial Technologies for providing appropriate facilities as well as helpful advice and support. We also want to thank all the government and non-government organizations that contributed different datasets for the study.

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