Flood Mapping Tools for Disaster Preparedness and Emergency Response Using Satellite Data and Hydrodynamic Models: A Case Study of Bagmathi Basin, India

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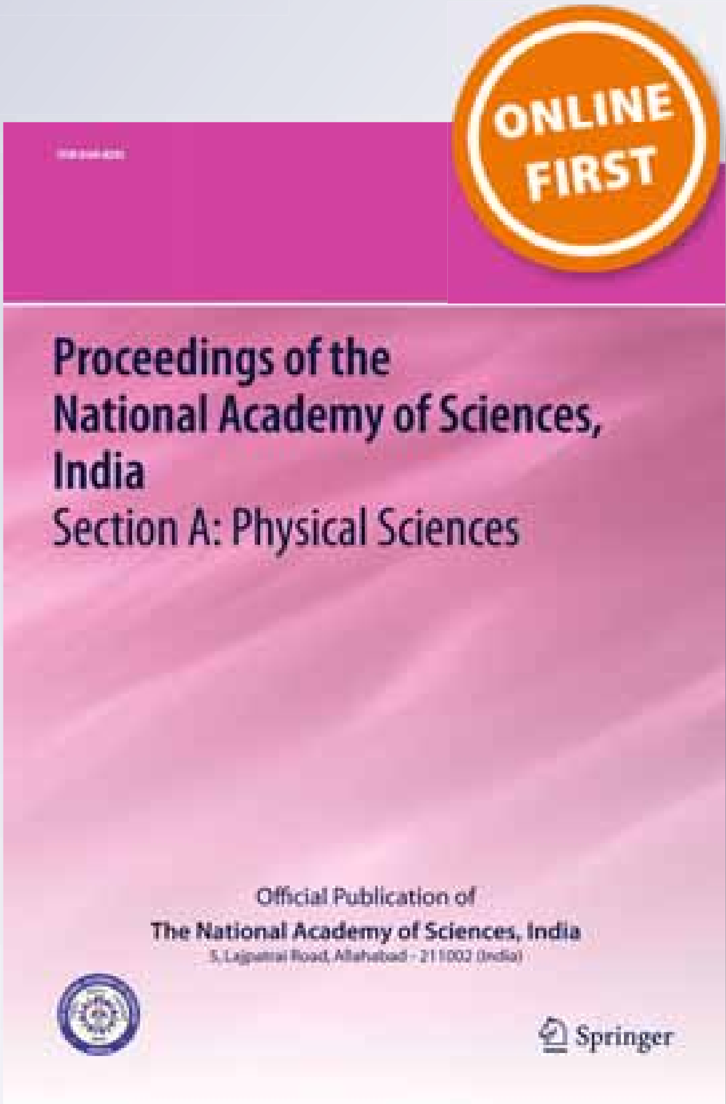

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RESEARCH ARTICLE

Flood Mapping Tools for Disaster Preparedness and Emergency Response Using Satellite Data and Hydrodynamic Models: A Case Study of Bagmathi Basin, India

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Abstract Northern Bihar is one of the major flood prone region in India affecting thousands of human lives and livelihoods during the recurrent floods occurring due to the monsoonal rains. While it is impossible to prevent the occurrence of extreme flood events, disaster planning can help in mitigating its detrimental effects. Monitoring flood extent using satellite observations just after the flood disasters is a core component of rapid emergency response process, which enables the emergency rescue teams to prioritize their efforts in critical areas to save lives and protect health, in addition to providing near real-time flooding information to the decision makers and planners. The main objective of this study is to demonstrate the utility of less data intensive, but equally robust hydrodynamic models to develop flood extent maps in conjunction with freely available remote sensing imageries at different scales. MODIS TERRA satellite data was used to map flood extent from 2001 to 2016 for entire Bihar. Two hydraulic models namely FLDPLN and RRI applied for the Bagmathi basin to evaluate our objectives. Both these models are of varying complexity but generate flood extent patterns with minimum amount of input data. The proposed approach is suited for mapping flood extents to provide an input information in near real time (h) when there is no availability to detailed hydraulic models and satellite datasets. Flood inundation extents from FLDPLN and RRI models were validated with Landsat-7 and MODIS TERRA derived flood extents for model performance. The results show acceptable spatial agreement between model predicted and Landsat-7 observed flood extents, denoting the utility of these tools for flood mapping application in data scarce environments.

Keywords Bihar · Flood mapping · FLDPLN · RRI · MODIS flood extent

Abbreviations

1D	One dimensional
2D	Two dimensional
DEM	Digital Elevation Model
DTF	Depth to Flood
EVI	Enhanced Vegetation Index
FLDPLN	Floodplain
FMISC	Flood Management Information System Centre
GIS	Geographical Information System
HEC-RAS	Hydrologic Engineering Centre's—River Analysis System
HFL	Highest Flood Level
IMD	Indian Meteorological Department
MSL	Mean Sea Level
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
POD	Probability of Detection
RRI	Rainfall Runoff Inundation
USGS	United States Geological Survey
VIC	Variable Infiltration Capacity

Units

km	Kilometre
km^2	Square kilometre
m	Metre
mm	Millimetre

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1 Introduction

Countries around the world are witnessing the increased occurrence and impacts of extreme flood events due to the effect of climate variability, rapid increase in population, unplanned urbanisation, large change in land use patterns, to name a few. Bihar is the most flood-prone state of India with 76% of its population falling in North Bihar is living under the risk of frequent floods [1]. The northern plains of Bihar have experienced devastating floods due to heavy rainfall in the monsoon season as most of the upstream river catchments in Nepal drain through this region. Due to the combination of high flows and sudden changes in gradient from steep mountainous to extremely flat plains, this region is under very high flood risk [2]. In India, the plains of North Bihar have recorded the highest number of floods during the last 30 years [3]. Moreover, both social and economic developments in North Bihar depend to large extent on the agricultural activities, which need to be in tune with the flow of seasons. Frequent flooding disasters in these socio-economically less privileged area increases the vulnerability of the poor by manifold. Bihar has made significant strides in the monitoring and assessment of the flood hazards through setting up Flood Management Information System Centre (FMISC). Stilla map of locally inundated areas produced from less data intensive models and open source remote sensing images in near real time will serve as essential information for emergency response support and relative decision making to manage and mitigate the catastrophic disaster caused by floods. The near real time refers to the period immediately after the occurrence of flood event until the existence of significant inundation in the flood plains.

Traditional methods like ground survey and aerial observation for inundation extent mapping requires huge manpower and high cost. Remote sensing and Geographic Information System (GIS) emerged as the key tool for mapping the inundation extent [4, 5]. Global availability of MODIS, Landsat and the recent Sentinel-2, which is free, and open-source satellite data for deriving flood extent operationally [6–8].Numerous multi-spectral remote sensing based indices have been developed and used to monitor the water and vegetation properties to make use of available optical dataset. Normalized Difference Vegetation Index (NDVI) is the most widely used vegetation index covering large range of applications, and includes distinguishing flood and non-flood pixels [9]. In order to overcome some drawbacks in using NDVI such as its sensitivity to atmospheric aerosols and soil background, other indices like Enhanced Vegetation Index (EVI), Normalized Difference Water Index (NDWI),and Normalized Difference Surface Water Index (NDSWI) were used to improve the observation of flood extents from multi-spectral imageries [10–13]. While the spatio-temporal coverage and free availability of optical remote sensing imageries are unparalleled, discerning valuable information from such imageries affected by cloud cover is difficult, which is particularly the case during the South Asia's monsoon season [14]. In such conditions, all weather capability of space borne radar imagery makes it an ideal platform for use in rapid response emergency operations during extreme flood events.

River hydrodynamic models are often used to mimic the spatio-temporal flood patterns based on hydro-geomorphic conditions of the river channel and flood plains in 1D or 2D. Hydrodynamic models provide a realistic dynamic representation of the flood extent but the complexity of the numerical computations and the need for data-intensive calibrations make their utilization difficult. If suitably represented by the model, the validated hydrodynamic model can be used to predict inundation extent from the forecasted extreme event. Often, hydrologic models are used to convert forecasted rainfall event into discharge values at different sections of the river, which are fed as input to the river hydrodynamic model. Numerous modelling suites, both open source and commercial are available and used widely around the world forflood hazard modelling. Some of the popular modelling suites for flood includes HEC-RAS, TUFLOW, SOBEK, and MIKE FLOOD among others. However, these models require large amount of data representing flow characteristics, river bathymetry, flood plain elevation and land use to adequately model flood dynamics. Often data accessibility restrictions due to trans-boundary nature of the river further complicates the deployment of hydrodynamic models. Even when it is available, such data intensive models may be difficult to operate in large number of river basin in the developing countries particularly during emergency situations. Less data intensive models are currently developed and employed across the world for simulating flood patterns. Rainfall Runoff Inundation model (RRI) and Floodplain (FLDPLN) are two such models of varying complexity but require minimal set of input data (rainfall and water level) for simulating flood plain dynamics and are considered to be amenable during disaster situations [15, 16]. FLDPLN model maps inundation extent as a function of floodwater depth or river stage while rainfall and topographic characteristics forms the main part of RRI model. The performance of FLDPLN model was compared with the HEC-RAS and HAZUS modelling platform and results produced comparable performances [16]. Recently, FLDPLN model was applied to map flood inundation extent and create libraries for range of potential flood levels [17]. RRI is a two dimensional hydrodynamic model which requires only rainfall as hydro-met input, unlike conventional models which need input of measurement of water level and discharge at various points along the stream reach [15].

In this study, we demonstrate the utility of satellite based flood mapping and two modelling tools of varying complexity (RRI and FLDPLN) for use in emergency response and long-term flood management purposes. Application of multi-spectral satellite imagery for flood inundation mapping was demonstrated at regional scale in Bihar, while two sections of the Bagmathi river basin were selected to demonstrate the applicability of these two models.

2 Study Area

Bihar is located between latitude 24°20′10″N to 27°31′15″N and longitude 83°19′50″E to 88°17′40″E with a geographical area of 94,163 km^2. Bihar has a tropical monsoon climate with high temperature and medium to high rainfall. The average maximum and minimum temperature ranges between 24–25 °C and 8–10 °C respectively. The hottest months are during April to June while the coldest are during December to January. Most of the rainfall (80–90%) is concentrated from mid-June to mid-October and these months are very crucial for agriculture in this region as the rainfall distribution makes all the difference between abundant and shortage. Flood extent mapping for the current study was carried out for the entire state of Bihar for the period of 16 years (2000–2016) using MODIS data.

Bagmathi river originates in hilly regions of Nepal and drains through North Bihar before its confluence with the Kosi river. The total length of the river is about 589 km. Unlike other Himalayan rivers, Bagmathi is not fed by perpetual snow and ice. It originates from the Shivpuri range of hills in Nepal at an elevation of 1500 m above Mean Sea Level (MSL). It traverses nearly 195 km in Nepal and rest in Bihar, India. It receives intense rainfall during the monsoon season, thereby flooding settlements and agricultural area along the way from Nepal's hilly region to flat plains of North Bihar. It enters the Indian territory in the village Shorwatia in Sitamarhi district in Bihar and outfalls in the Kosi at Badlaghat. The total catchment area is 14,384 km^2, out of which 6500 km^2 lies in Bihar and the rest in Nepal. The agricultural area in the catchment is 5362 km^2 and the average rainfall is 1255 mm. The main tributaries of Bagmathi are Lalbhekya, Lakhandei and Adhwara. The less data intensive flood models (RRI and FLDPLN) were applied in Bagmathi river basin in North Bihar. Two stretches of the Bagmathi River in North Bihar were chosen for applying the RRI and FLDPLN model mainly owing to different data requirements. FLDPLN model requires a specified water level to be served as an input, while RRI model requires rainfall as the primary input along with Digital Elevation Model (DEM) for simulating flood plain dynamics. The earmarked study area is having an extremely flat topography which makes it more prone to floods.

3 Data and Methodology

3.1 Flood Mapping

MODIS 8-day composite surface reflectance product (MOD09A1) computed from Level 1B land bands with 500 m spatial resolution were used to detect change in the inundation extent at high temporal frequency (every eight day) for the period 2000 to 2016. In total, 730 temporal images covering the state of Bihar were used for this study. Flood mapping has been carried out using NDWI as shown in Eq. 1 by setting the threshold from 0 to 1. NDWI is computed using the near infrared (NIR—MODIS band 2) and the short wave infrared (SWIR—MODIS band 6) reflectance. The IWMI flood mapping tool was used for calculating NDWI from MODIS data and extracting flooded pixels [18]. The resultant flood maps were aggregated at yearly scale to derive the frequency map for 17 years (2000–2016). A similar procedure was used to extract flood extent from Landsat images to be used for comparison with model simulated results.

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR} \quad (1)$$

3.2 Flood Inundation Model (FLDPLN)

FLDPLN model is based on the concept that the flood path from source point to any recipient point can be characterized using two fundamental mechanisms, backfill and spill over flooding. Backfill procedure approximates floodwater swelling and is based on the simple concept that 'water seeks its own level'. Mostly, all the floodplain extents are identified using the backfill procedure. Spill over flooding establishes new floodwater paths in the floodplain and is based on the concept that 'water flows downhill'. These steps are repeated in small step size increments to create a Depth to Flood (DTF) map.

FLDPLN model was used in the present study to bridge the gap between the available limited information and mapping of the inundation extent in near real time. Accuracy of the FLDPLN model depends upon the vertical accuracy of the DEM and the topography of the region. An attempt has been made in the present study to use FLDPLN model for Ekmighat gauge station of the Bagmathi river basin to find out the inundation extent, developed at 1 m interval for 6 different river stages (46–51 m). These stage heights were based on the daily values published by Central Water Commission during the monsoon season, as a part of the flood early warning program. 1arc second DEMwas downloaded from the United States Geological Survey (USGS) earth explorer.

FLDPLN model requires river stage as DTF values and depression less DEM, associated flow direction, flow accumulation and stream network raster, which are the outputs from the Arc Hydro Tools in ArcGIS. FLDPLN model consists of three components namely stream segmentation, FLDPLN model and the DTF map maker. In the stream segmentation tool, flow direction and flow accumulation raster obtained from Arc hydro tool are used as an input, and a user-specified minimum catchment size is used to define a stream network. An individual stream segment represents each headwater-to-confluence and confluence-to-confluence stream path. In the FLDPLN model tool, the filled DEM raster the flow direction raster, output from the stream segmentation tool, and a user-specified maximum flood depth values for each stream segment to construct a DTF database is required as an input. The DTF map maker tool uses output from the stream segmentation tool, the DTF database produced using the FLDPLN model tool, and a user-specified, segment-specific flood depth value to generate a custom DTF raster floodplain map.

3.3 Rainfall Runoff Inundation model (RRI)

Rainfall–Runoff–Inundation (RRI) model is two-dimensional for simulating rainfall-runoff and flood inundation simultaneously [12]. Compared to FLDPLN model, RRI is a complex fully hydrodynamic model which needs representation of slopes and river channels separately. At a grid cell in which a river channel is located, the model assumes that both slope and river are positioned within the same

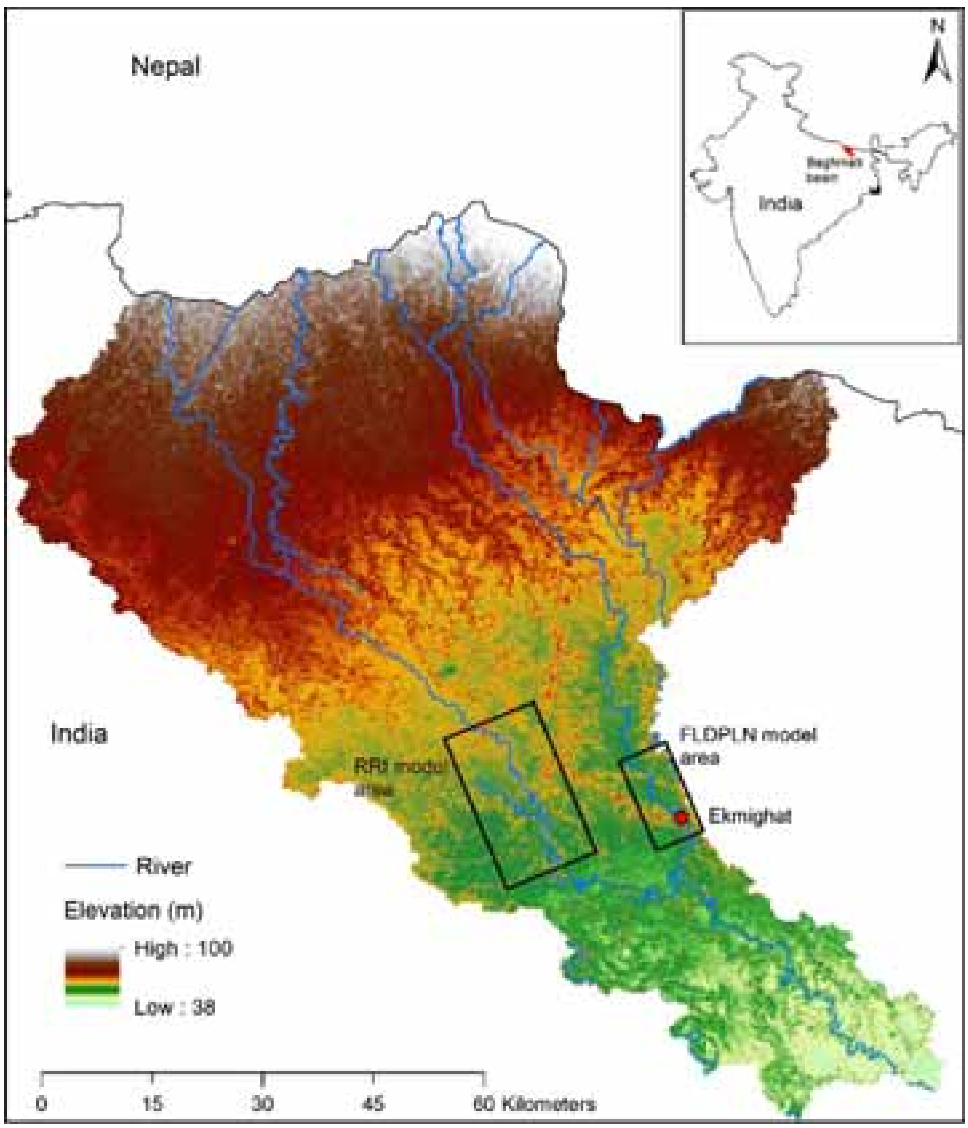


Fig. 1 Map showing the bagmathi river basin covering India. Boxed location highlights river reach in which RRI and FLDPLN models were applied

grid cell. The channel is discretized as a single line along its centreline of the overlying slope grid cell. 1D diffusive wave model is used to calculate channel flow while 2D diffusive wave model is used to calculate the flow in slope grid cells. Like conventional flood models, RRI has the provision to include even the lateral subsurface flow (discharge-hydraulic gradient relationship), vertical infiltration flow (Green-Ampt model) and surface flow. For the study reach shown in Fig. 1, the RRI model set up was created using Indian Meteorological Department (IMD) gridded rainfall data and 90 m hydro sheds DEM as main inputs. The flow at the upstream of selected reach was derived from an existing, calibrated Variable Infiltration Capacity (VIC) model for Bagmathi, available with IWMI to serve as upstream boundary condition. For a catchment scale model, such flow estimates as an input for the RRI model is not necessary.

3.4 Validation

It was very important to test the results generated by the model and validate it before using it for the development of

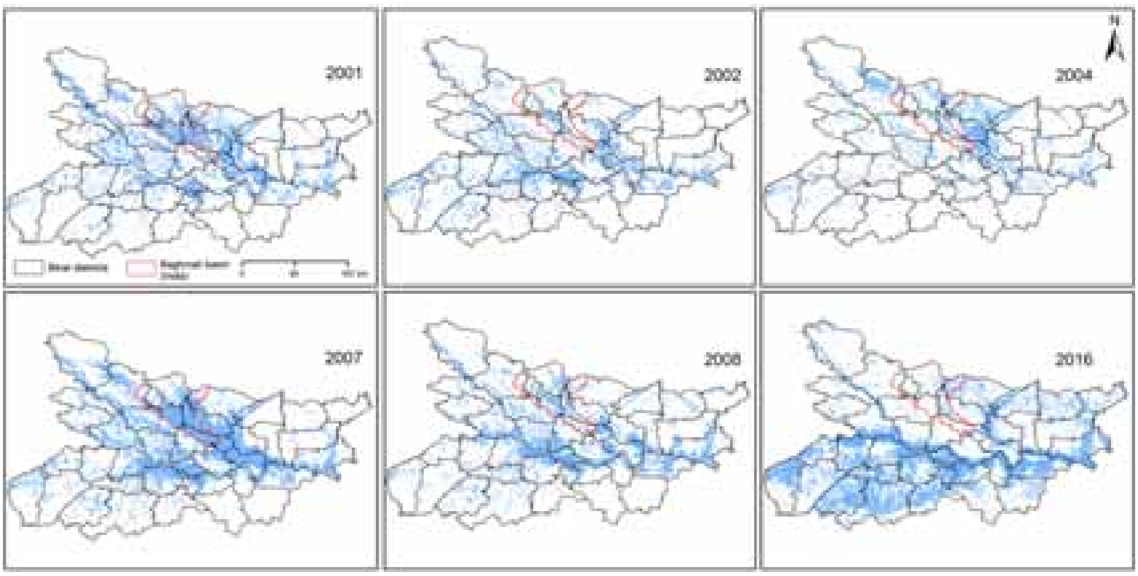
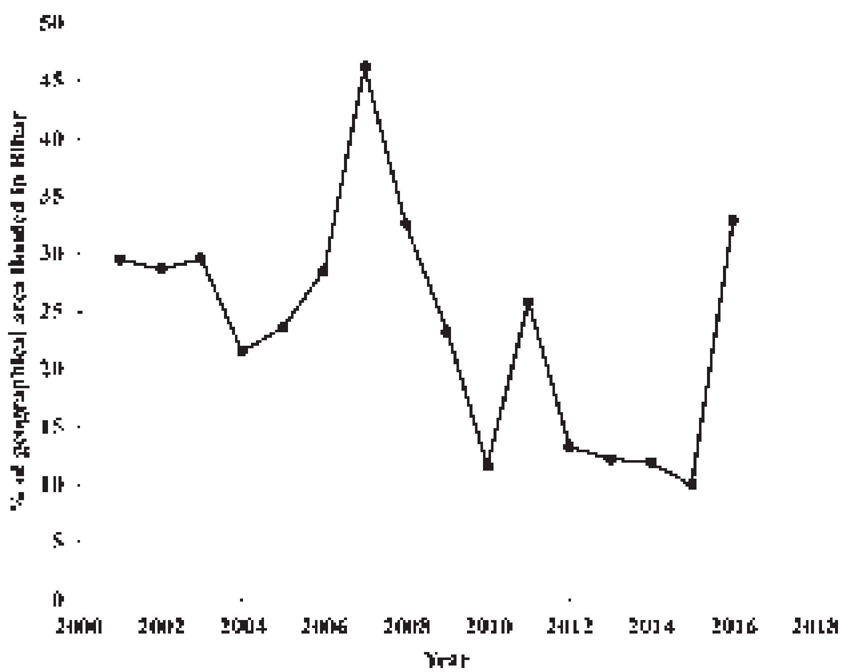


Fig. 2 Flood inundation extent derived from MODIS data for the major flood events from 2000 to 2016 covering the Bihar state, India

Fig. 3 Percentage of flooded geographical area as estimated by MODIS data from 2000 to 2016 in Bihar



a reliable product design. The correspondence between observed remote sensing images from Landsat and simulated inundation extent from FLDPLN model was examined using Probability of Detection (POD) as shown in Eq. 2. POD corresponds to the statistical concepts and parameters between computable and observed data.

$$Probability\ of\ Detection = \frac{Hits}{Hits + Misses} \qquad (2)$$

4 Results and Discussions

4.1 Flood Mapping

In recent decades (2000–2016), Bihar witnessed major floods in 2001, 2002, 2004, 2007, 2008 and 2016 and this can be seen from the MODIS based flood inundation images (Fig. 2). Most of the flood hotspots are concentrated in Northern Bihar around Kosi and Bagmathi river

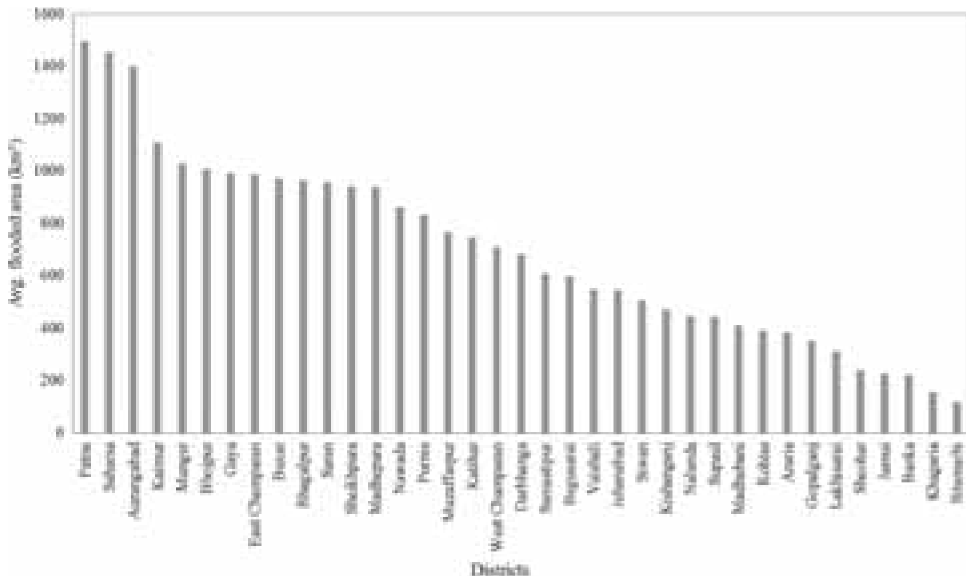


Fig. 4 District wise average flooded area for the time period 2000–2016 using MODIS data

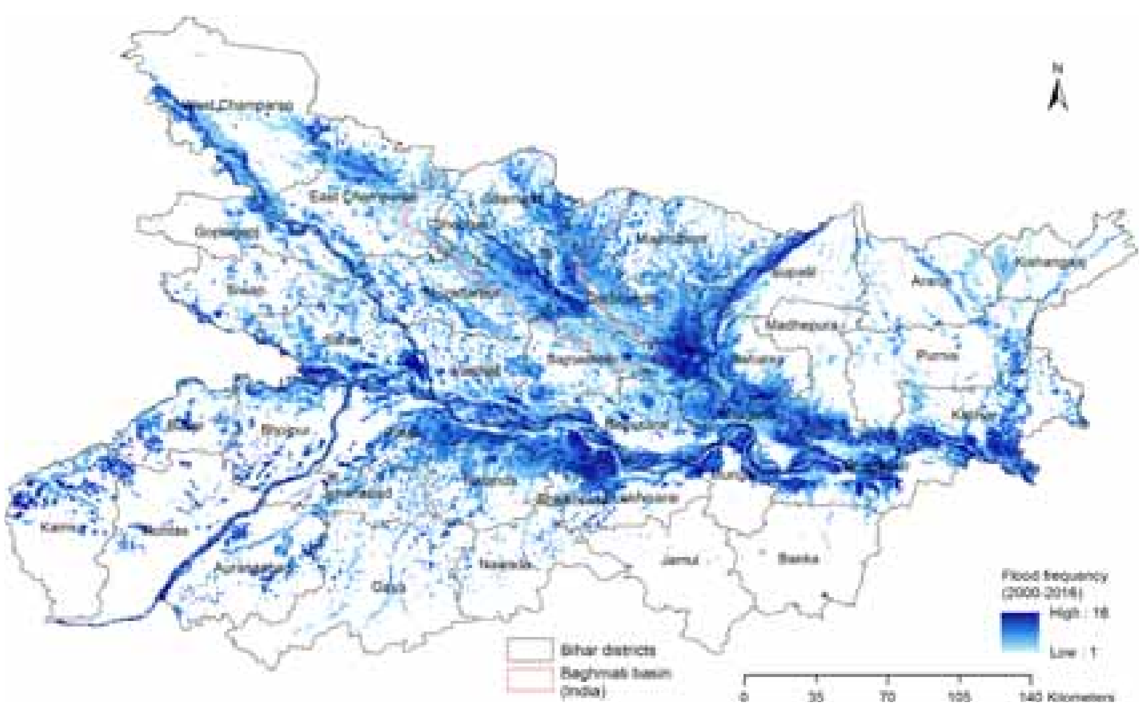


Fig. 5 Flood frequency estimated from aggregated MODIS based flood maps for the time period 2000–2016. Darker blue represents high frequency of flood occurrence and Bagmathi river basin shown in red is one of the hotspots

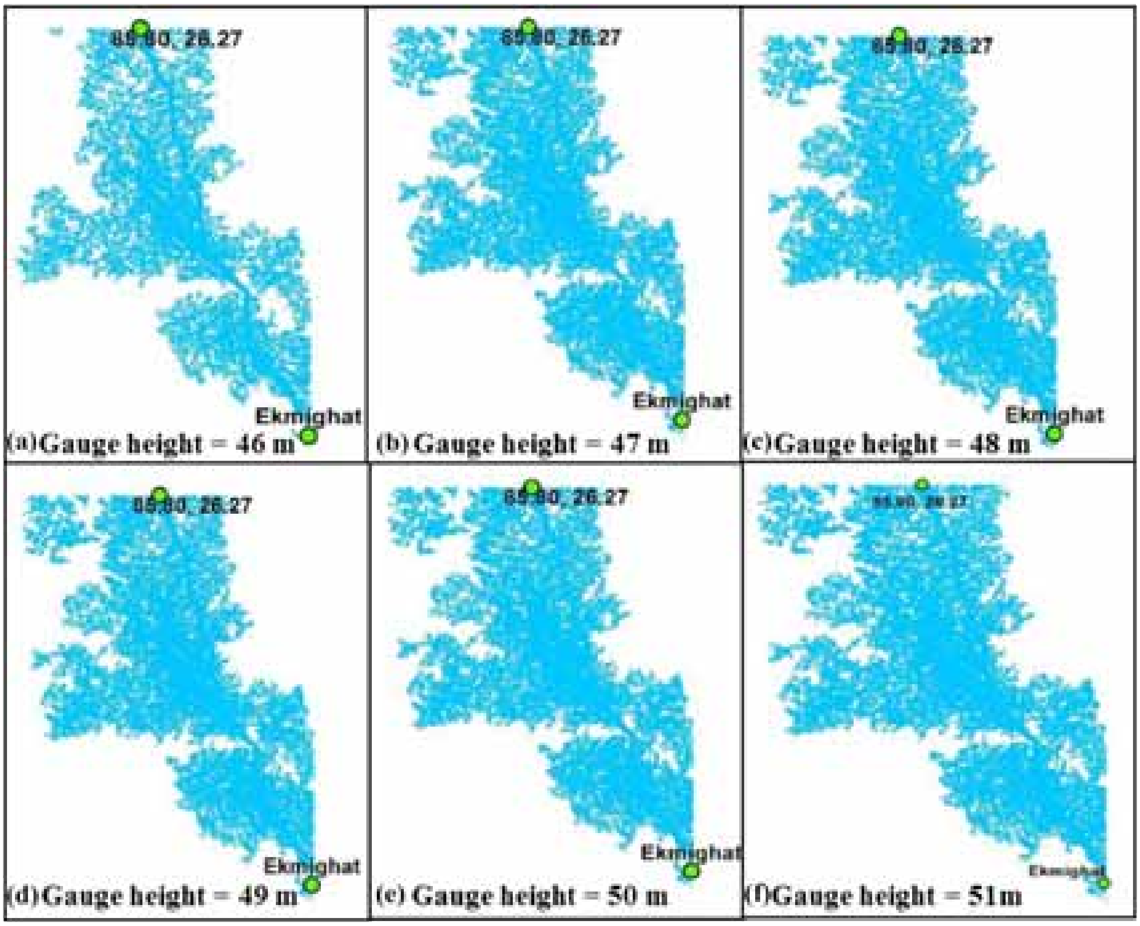


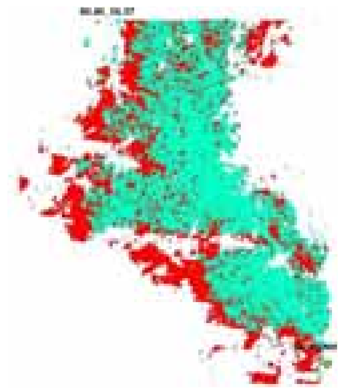
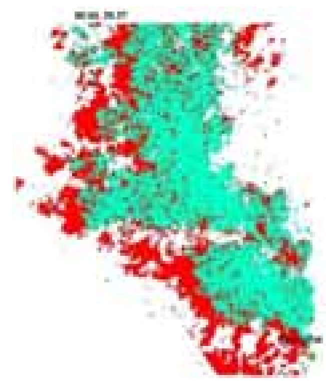
Fig. 6 Flood inundation map from FLDPLN model for different gauge heights at the Ekmighat station

basin. Recurrent flood inundation from Ganges are also clearly seen in the years 2007, 2008 and 2016. Unusually, 2016 witnessed serious flood event in Southern districts of Bihar due to heavy rainfall in upstream catchment area located in other states. The derived flood maps indicate that during the past decade, one-fourth of Bihar's land mass was subjected to flooding every year (Fig. 3). The extreme flood event of 2007 affected close to half of its geographical area. Among other districts, Patna experience large-scale disasters being located on the lower ganges suffered from recurrent flood losses (Fig. 4). However, it should be mentioned that the estimated flood area includes sections of actual rivers within each district and may inflate the resultant flood estimates due to large cross sectional width of water observed from MODIS data. Due to the moderate resolution (500 m) of the data used to derive flood maps, there exists tendency for overestimation of final flooded area. For deriving holistic flood dynamics at the state scale, this resolution is considered adequate. For mapping instances of specific localized flood patterns, data of Landsat (30 m) and Sentinel-2 (10 m) can be effectively used to derive inundation extent. The frequency map developed from aggregated flood images for 16 years is shown in Fig. 5. High flood hazard area corresponds to Kosi and Bagmathi catchments in the North Bihar and districts adjacent to the Ganges river. This flood frequency map can be used to identify and classify area of different risk classes by combining it with socio-economic data to aid in flood mitigation and management activities.

4.2 Modelling Flood Extent Using FLDPLN Model

The main advantage of using FLDPLN model tool is that the river stage data can be transformed to spatial dimension for flood extent mapping. The DTF maps are prepared for different river stages starting from the danger level to the Highest Flood Level (HFL) of the gauge station that is from 46 to 51 m with 1 m interval. Figure 6 shows DTF maps for 6 different river stages. Results from the FLDPLN model are considered to be reasonably acceptable for the 3 flood events dated September 27, 2006, September 17, 2007 and July 27,2011 of Ekmighat gauge stations of the Bagmathi river basin. Validation with the simulated inundation extent from FLDPLN model and remote sensing

Table 1 Validation of inundation extent derived from the FLDPLN model and satellite data

Observed flood event date	River stage (m)	Depth To flood (m)	Gauge station	inundation extent	Simulated inundation extent	POD
27/9/2006	47.70	47	Ekmighat		Hit 18,544 Miss 11,724	0.61
27/7/2011	47.50	47	Ekmighat		Hit 19,402 Miss 14,205	0.58

images from Landsat for different flood events has been made and it indicates that FLDPLN simulated inundation extent shows reasonably good agreement with observed data in terms of POD. POD between 0.58 and 0.61 can be acceptable in the condition when the local model is not available. Comparison of simulated and observed flood extent for flood event has been made and it indicates a reasonably good relationship for observed data dated September 27, 2006 and July 27, 2011 and DTF as 47 m. Table 1 shows the comparison between FLDPLN modelled inundation extent and remote sensing derived inundation extent in terms of POD for the Ekmighat stations of the Bagmathi river basin. Due to the extreme flat topography of the study area and vertical accuracy of the DEM used, the model lacks the ability to count the floodplain extent with desired accuracy. It will be helpful for planners and decision makers to alert the agencies in the near real time for necessary actions. In the present study, flood extent maps for Ekmighat river gauge stations.

4.3 Simulating Flood Extent from RRI Model

The RRI model for the study reach shown in Fig. 1 was used to simulate flood dynamics for the same date of 27 September 2006 as in FLDPLN (Fig. 7). Since no water level or gauge location exists within the selected reach, it provides an ideal condition to apply in the data scarce scenario. The model was calibrated using three sensitive parameters-Manning's roughness for river channel (n_r), roughness co-efficient for flood plains (n_s) and permeability co-efficient (K). The corresponding final calibrated values for the study reach are $n_s = 0.20$, $n_r = 0.10$ and $K = 0.1$. The calibration process was done by comparing the RRI simulated flood extent with Landsat flood extents

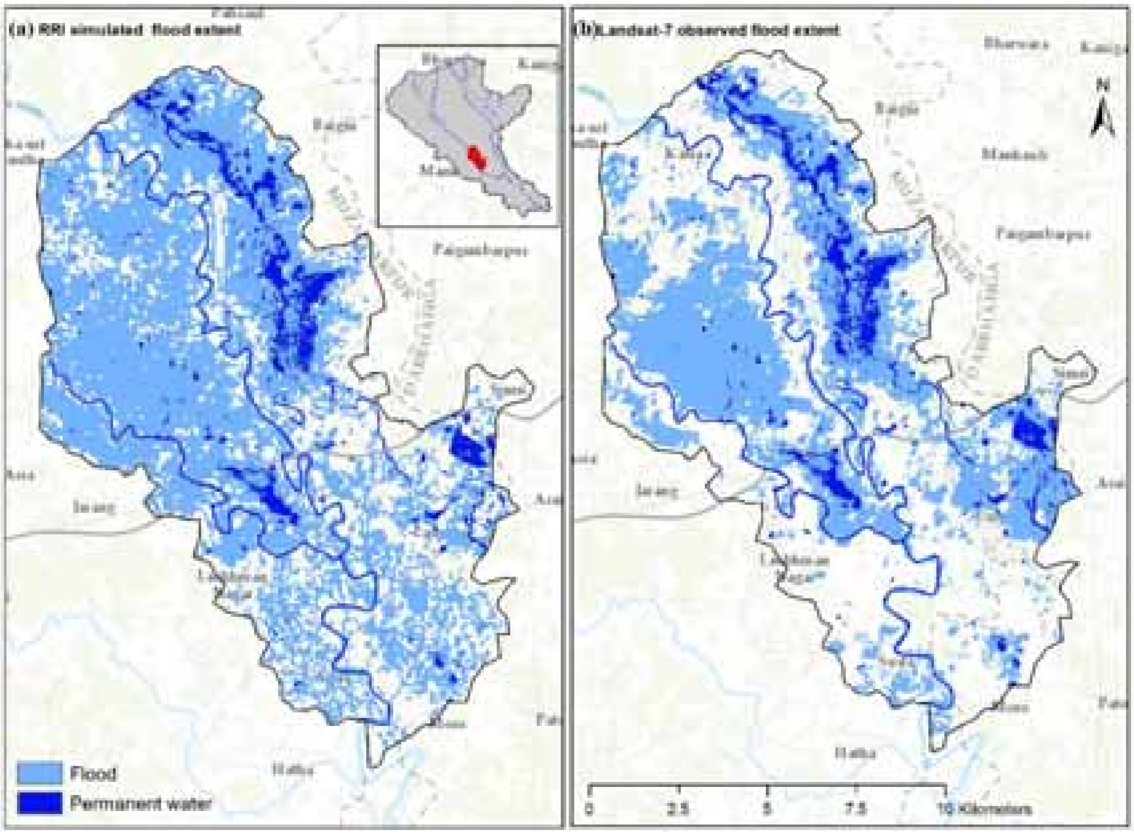


Fig. 7 Comparison of RRI simulated flood inundated area (93 km^2) with Landsat-7 observed inundated area (59 km^2) for the flood event on 27 September 2006 in a reach of Bagmathi river

for the same date. The comparison of RRI flood extent against Landsat flood extent is shown in Fig. 7. RRI model simulated 93 km^2 of flood inundation compared to 59 km^2 estimated from the Landsat-7 imagery.

The pixel by pixel comparison of the two images resulted in POD of 0.66. Considering that the model didn't have any in situ data for calibration, this can be deemed as acceptable. The Landsat derived flood extent indicates that there exits two low lying areas in which serious inundation was concentrated (in-between two channels and right side of the study reach). The pixels in these two locations in the RRI simulated result also corresponds with the observed satellite estimates. The southern section of the study reach was devoid of any inundation but the model predicted scattered number of flooded pixels which is due to the vertical resolution of Hydro sheds DEM (1 m). Even with such low to moderate vertical resolution, the RRI model results indicate that the severity of flooding in simulated places conforms to the Landsat observed data event for an extremely flat terrain such as Bihar. This indicate that RRI model can used for estimating flood inundation extent in catchments where scarcity of flow data is common. However for use in operational conditions, it is highly recommended to calibrate the RRI model for the range of flood conditions with satellite observed flood extents so as to increase its prediction reliability.

5 Conclusion

By combining multi-spectral satellite data and two hydrodynamic models of varying complexities, this study demonstrated the utility of these tools in emergency response and flood management operations using the Bagmathi river basin in Bihar as a case study. The selected location is ideal to demonstrate these tools due to restrictions in data availability and severity of flood damages in North Bihar. Since the demonstrated model uses publicly available sources of DEM with moderate resolution (30 m), estimation of inundation extent and the stream position depends solely upon the accuracy and resolution of the DEM used. The FLDPLN and RRI model can be a good source for predicting the extent of flooding if the agencies can improve employ DEM with higher vertical accuracy. Present approach can be used for preliminary early warning and alerts for regions which lack data for detailed hydrologic and hydraulic simulations. The present study leaves a wide scope for researchers and investigators to explore other aspects of floods by integrating the FLDPLN and RRI model with remote sensing and GIS technology. The study can be helpful in making a flood early warning system which includes preparedness, response and recovery and the parameters from the flood model namely flood duration and flood depth can assist in flood index insurance as innovative tool in enhancing agriculture reliance and flood proofing livelihood.

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