Development of flood inundation extent libraries over a range of potential flood levels: a practical framework for quick flood response

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ABSTRACT
The aim of the present study is motivated to build an inundation library for a range of gauge heights, which can be used by decision-makers to anticipate the likely extent of inundation and provide quick response towards warning the habitations at threat. In the present study, two approaches for developing a series of static flood-inundation extent libraries for a range of potential flood levels using historical satellite images, gauge heights and digital elevation model (DEM) are demonstrated. First method is based on the geotagging of gauge height data with corresponding satellite observed inundation extent and the other method supplements the first method in the absence of adequate satellite data-sets by simulating inundation using gauge data and DEM for a range of gauge heights. Simulated inundation extents are validated with the satellite-derived reference inundation extents using spatial statistics, which measure the correspondence between the estimated and observed occurrence of events like probability of detection (POD), false-alarm ratio, and critical success index (CSI). A good correlation between the simulated inundation and satellite-derived inundation extents, with POD varying between 87% and 94%, CSI between 75% and 80% is observed.

KEYWORDS
Floods; satellite; DEM; inundation library; FLDPLN model

1. Introduction
Floods are the most frequent and catastrophic natural disasters occurring worldwide (Berz et al. 2001; ISDR 2004) and affecting societies and economies globally (Schumann & Moller 2015). Global annual average losses occurring from flood disaster is assessed to be about US$104 billion (GAR 2015). In the last decade of the twentieth century, about 100,000 persons are reported to have lost their life and about 1.4 billion people are estimated to have been affected due to flood disasters, (Jonkman 2005). Flood disasters have maximum impact on the poorest people in the developing countries. Due to high population density, poor infrastructure development, poverty and illiteracy, the developing countries are more vulnerable and less equipped to withstand the damaging effects of the hazards (Irtesema 2002). One of the most effective ways to improve the flood preparedness and response is to model flood events to anticipate the area to be flooded and provide alerts to habitations in danger. However, due to the scarcity of hydrological observations from well-distributed network of gauge stations and poor availability of fine resolution digital elevation model (DEM) (Sanyal & Lu 2005; Sanyal & Lu 2006), land use and land cover information, software for inundation modelling and technically trained manpower to run the model and interpret the results.
meaningfully, flood early warning becomes a difficult task in developing countries. Long-term spatio-temporal data with good positional accuracy required for carrying out hydrodynamic modelling is not available in least developed countries and also for some developing countries (United Nations Framework Convention on Climate Change 2007). Even the basic flood hazard maps are not available for many developing countries (Rabindra et al. 2008) which can provide basic support and help response and rescue agencies to coordinate their efforts in response to flooding events (Hagen & Teufert 2009). Most of the hydrological and hydraulic models used for identification of flood-risk areas are based on the complex algorithms and multiple data requirements like detailed fluvial section data and topographic surveys that are difficult to collect (Hagen et al. 2010). Dependence on calibration and lack of available input hydrologic parameters has prevented the widespread application of hydrodynamic models for flood extent prediction (Nobre et al. 2015).

Considering the potential catastrophic impact of floods to life and economy, it is imperative to evolve methods to equip the planners with easy approaches which can be used readily in times of emergency to warn the population in advance of the impact. Attempts have been made to use active and passive remote sensing data to estimate water surface area, stage and discharge (Smith 1997; Usachev 1983). Technique of mapping of water surface area using a variety of passive and active sensors operating in the visible and microwave range are by far the best developed and operationally used. However, techniques of using radar altimeters for measuring stage variation in large rivers and obtaining of estimates of river discharge from space, using ground measurements and satellite data to construct empirical curves that relate water surface area to discharge techniques are largely in their infancy and not yet used operationally for flood disaster response. Bales and Wagner (2009) have suggested developing a library of modelled flood extents for communities over a range of potential flood levels. Voigt et al. (2007) have used flood stage as the input variable for the production of flood inundation libraries that could be accessed during flood events to produce real-time flood extent estimates. USGS website under USGS Flood Inundation Mapping Science page (water.usgs.gov/osw/flood_inundation/focus-staticmap.html) also demonstrates the concept of linking flood hydrograph data to inundation map libraries to estimate inundated areas, hours to days in advance.

Taking forward the idea of inundation libraries, an attempt is made in the present study to develop comprehensive spatial inundation static libraries over a wide range of gauge heights, using historical satellite images, gauge heights, DEM and FLDPLN (flood plain) model which could aid decision-makers towards quick flood response during flood disasters. The present study is also motivated by the fact that flood warnings in India are generally communicated in the form of gauge heights (vertical elevation) and if the gauge height warnings can be translated to spatial dimension, decision-makers can better anticipate and understand the impact of flood disaster and accordingly take steps to alert and evacuate the population likely to get affected. The inundation library can be used by decision-makers to have a preliminary idea about the extent of inundation that may take place at various gauge heights and accordingly take steps to alert and evacuate the population likely to get affected. Two approaches are demonstrated for developing a database of flood-inundation extent libraries for a range of potential flood levels using historical satellite images, gauge heights, DEM and FLDPLN model for Sabari River, a tributary of Godavari River (India).

2. Study area

For the present study, Sabari River, a tributary of Godavari River passing through Khammam district of Telangana (erstwhile Andhra Pradesh), was selected. Sabari River is one of the main tributaries of Godavari River, which originates from the western slopes of Eastern Ghats in Odisha state from Sinkaram hills 1370 m above mean sea level (msl). The Sabari River enters into Telangana state near Kalleru village of Khammam district and flows for about 35 km before merging with the Godavari River near Kunavaram. Sabari River witnesses recurrent flooding during monsoon season. The elevation within the study area varies between 13 and 764 m, the higher elevation representing the
hills located on both sides of Sabari River. The point where Sabari River enters Telangana has an elevation of 36 m and at the point of confluence with Godavari River the elevation drops down to 20 m. Central Water Commission (CWC) has two gauge discharge sites established along the river at Konta upstream and Kunavaram downstream side. Figure 1(a—d) shows the location map of the selected study area, its environs and elevation.

3. Materials and method

3.1 Data-sets used

Fourteen historical Radarsat-1 and Radarsat-2 satellite images available with National Remote Sensing Centre (NRSC) were used for extraction of satellite-based inundation extent, geotagging
inundation extent with gauge height information and for validation of the simulated inundation extents. The details of satellite data-sets used are provided in Table 1. Gauge height data for 2002, 2005, 2006 and 2010 years for Konta gauge station is available from CWC is used for present analysis. CWC is the national nodal organization which carries out the flood forecasting activity on the major rivers and has fixed warning level (WL) and danger level (DL) at important sites. FLDPLN model (Kastens 2008) is used to simulate the inundation extents as a function of floodwater depth relative to nearby stream surface elevation (Figure 2). Elevation information is derived using Shuttle Radar Topographic Mission (SRTM) DEM.

### Table 1. Details of satellite data-sets used for the study.

| S No. | Date            | Satellite     | Mode       | Polarization | Swath (km) | Incidence angle (deg) |
|-------|-----------------|---------------|------------|--------------|------------|-----------------------|
| 1     | 1 September 2000| Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 2     | 22 September 2005| Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 3     | 7 August 2006   | Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 4     | 10 August 2007  | Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 5     | 30 July 2010    | Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 6     | 7 August 2010   | Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 7     | 8 August 2010   | Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 8     | 9 August 2010   | Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 9     | 10 August 2010  | Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 10    | 5 September 2011| Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 11    | 9 September 2012| Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 12    | 23 August 2012  | Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 13    | 20 July 2013    | Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |
| 14    | 6 August 2013   | Radarsat-2    | Scan SAR   | HH           | 500        | 20°—59°               |

3.2 Methodology

The aim of the present study is to use the generated comprehensive library of inundation extents for different gauge heights using satellite data and DEM and without involving hydrodynamic modelling during flood disasters. Such studies are limited but there are examples where DEM and gauge height data are used as proxy indicators for identification of flood inundation extent. Two approaches (1) correlating gauge height with available historical satellite-based inundation extent inundation library is developed and (2) using FLPDPLN model to simulate the inundation for

![Figure 2. FLDPLN model flooding mechanism of backfill and spillover flooding (Kastens 2008).](image-url)
different heights, to supplement inundation extent information in absence of adequate satellite data. Simulated inundation extents derived for different gauge heights have been validated wherever historical satellite-based observations are available.

The main steps involved in this process of developing flood-inundation extent libraries are (a) extraction of inundation extent from satellite data, (b) geotagging of satellite-based inundation extents with observed gauge height data, (c) simulation of inundation extents based on gauge height and DEM using FLDPLN model, and (d) validation of simulated inundation extents.

3.2.1 (a) Extraction of inundation extent from satellite data

Satellite images acquired from microwave Synthetic Aperture Radar (SAR) were used in the present study due to their ability to penetrate cloud cover and provide information on the inundation extent, which otherwise is hampered by the cloud-covered conditions in case of optical data. SAR sensors can not only penetrate through clouds but are also useful in detecting standing water through emergent aquatic plants and forest canopies (Smith 1997). The satellite images were pre-processed using ERDAS IMAGINE software (version 2013). SAR images were pre-processed for generation of beta naught (dB) image and then computation of sigma naught (dB) and incidence angle (degrees) images. Subsequently, filtering of the images was carried out to suppress speckle using enhanced Lee adaptive filter. The enhanced Lee adaptive filter is an efficient tool for reducing SAR image speckle by removing high-frequency noise while preserving edges or shaper features in the image (Zhengao & Fung 1994). The speckle-suppressed images were then geometrically corrected with master reference images to a defined projection system for positional accuracies. In SAR images, water surfaces being smoother than the surrounding land, act as a specular reflector, reflecting nearly all the incident radiation away from the sensor and the weak return from the signal is represented by dark tonality on radar images of the standing water (Brivio et al. 2010). Variable incidence angle threshold technique was used for the extraction of inundation layer, which is based on the principle that the radar backscatter from a feature decreases with increase in its incidence angle (Baghdadi et al. 2001). Thresholding is one of the most frequently used techniques to segregate flooded areas from non-flooded areas in a radar image (Townsend & Walsh 1998). Backscatter response at river cross-sections and flood pockets in near and far ranges is evaluated by drawing the transect lines and an average backscatter range is chosen. From the average backscatter profiles generated, it is observed that the backscatter of water is in the $-18$ to $-25$ dB range. Using a variable incidence angle threshold model, intensities within these ranges are regarded as water, whereas pixels with intensities above the threshold are regarded as non-flooded. To extract the flood inundation layer, a mask which comprises the water bodies, river channel, waterlogged areas and hill boundaries is applied to the output layer derived from thresholding process. Mask layer is prepared from pre-flood data and land-use/land-cover data. Further refining of the flood inundation layer is carried out by grouping and removing the stray pixels using the clump and sieve tools. Finally, using recode command a single bit flood inundation layer is generated containing flooded (grid code = 1) and non-flooded (grid code = 0) classes. Using the method above explained, 14 historical satellite images were processed for extraction of spatial extent of flood inundation.

3.2.2 (b) Geotagging of gauge height and inundation extent

The inundation extent delineated from satellite-based analysis is correlated with the corresponding same day observed gauge height information based on the flood hydrographs. In the present analysis, four historical (7 August 2006, 9 August 2010, 10 August 2010 and 22 September 2005) SAR images representing different magnitudes of flood for which gauge height data (46.26, 42.07, 40.79 and 40.16 m, respectively) is available are geotagged. Figure 3 shows the inundation extent derived from satellite data analysis for four cases and each layer being geotagged with the observed gauge heights. Satellite data-sets for the rising limb of the hydrographs have only been considered in this process. The satellite data-sets if selected from receding limb may show more area under inundation for a lower gauge height. Flood inundation pattern, extent and inundated area observed for a
particular gauge height arising from first wave of a flood season and second flood wave of the season may not be similar. This is due to the fact that before the onset of the flooding, the soil will be unsaturated and will allow more infiltration compared to overland flow. However, with first wave of flood, the underlying soil gets saturated and more overland flow happens compared to the infiltration. Therefore, when geotagging, gauge heights flooding resulting from similar hydrographs should be compared i.e. first wave flood gauge height with data acquired during first flood wave and so on and this way, we can have scenarios for different flood waves also to have a comprehensive library for all type of scenarios. In future, with availability of more satellite data, the inundation scenarios for all stages of river from the time river starts to be in flooding stage to high flood levels can be used to enrich the existing database.
3.2.3 (c) Simulation of inundation extents using gauge heights and DEM

The satellite-based information in the absence of adequate satellite data-sets to represent complete inundation scenarios from bank full stage to high flood level (HFL), FLPDPLN model (Kastens 2008) was used to simulate the extents. FLDPLN model is basically a static 2D hydrologic model that requires only DEM data as input. Nobre et al. (2015) have also used the height above the nearest drainage (HAND) terrain model to develop a simple static approach for mapping the potential extent of inundation. Using simple surface flow properties, FLDPLN identifies the depth-varying floodplain in reference to the input stream network. The model consists of three GUI modules, i.e. stream segmentation tool, FLDPLN model tool and depth-to-flood (DTF) tool. This model has earlier also been used by Voigt et al. (2007), Dobbs (2010) and Williams et al. (2013) for flood extent

Figure 3. (Continued)
prediction. After standard fill, flow direction and flow accumulation procedures are applied to DEM, this model utilizes an iterative two-step, backfill and spillover procedure. Figure 2 shows the two-step backfill and spillover procedure, wherein point P can be flooded by water originating from point P by backfill (swelling) and spillover (overland flow) flooding. In this process, each stream pixel is flooded to a specified depth (iteration \times step size), so that all upstream, connected pixels, as specified by the corresponding flow direction layer, are assigned a DTF reflecting elevation differences between the stream pixel in question and the identified flooded pixels. This is followed by a spillover step that address discontinuities created by flow divided and allows for the creation of new floodwater paths. These steps are repeated in small vertical step-size increments to create a DTF map from which library of inundation extents can be derived.

3.2.3.1 Initial processing. SRTM DEM was initially hydrological conditioned for removing all the depressions in the DEM using the ‘Fill sink’ procedure. Depressions in the DEM data create uncertainty in the determination of flow directions (e.g. Garbrecht & Martz 1997; Jenson & Domingue 1988). This procedure fills all depressions (local minima) in the DEM surface to ensure that all cells (pixels) in the DEM can route through the watershed’s mouth without requiring any uphill flow. The Fill tool uses the equivalents of several tools, such as Focal Flow, Flow Direction, Sink, Watershed and Zonal Fill, to locate and fill sinks. Fill sinks operation reduces local depressions (single and multiple pixels). The height value of a single-pixel depression is raised to smallest value of the eight neighbours and height values of local depression consisting of multiple pixels are raised to the smallest value of a pixel that is both adjacent to the outlet for the depression, and that would discharge into the initial depression. As a result of DEM hydro-processing, we have a hydrologically consistent raster-based elevation representation. Using depressionless DEM as input surface flow direction is determined.

Flow direction raster is derived using flow direction tool which takes the processed DEM surface as input and outputs a raster showing the direction of flow out of each cell. The direction of flow is determined by the direction of steepest descent, or maximum drop, from each cell (maximum drop = change_in_z-value/distance \times 100). The distance is calculated between cell centres. There are eight valid output directions relating to the eight adjacent cells into which flow could travel. This approach is commonly referred to as an eight-direction (D8) flow model and follows an approach presented in Jenson and Domingue (1988). Flow accumulation raster is derived from the flow direction raster as input. Flow accumulation in its simplest form is the number of upslope cells that flow into each cell. The Flow Accumulation tool calculates accumulated flow as the accumulated weight of all cells flowing into each down slope cell in the output raster. The depressionless DEM, flow direction and flow accumulation are used as inputs for running the three tools i.e. Stream Segmentation tool, FLDPLN tool and DTF tool of the FLDPLN model for further simulation. The hydrological processing of DEM, generation of flow direction and flow accumulation, is carried out using Spatial Analyst extension containing Hydrology Tools of ARC GIS software (version 10.0).

3.2.3.2 Stream Segmentation tool. Stream Segmentation tool takes the standard D8 flow direction and flow accumulation raster’s developed using Arc Hydro Tools flow as input. Then a minimum catchment size is defined to delineate a stream (drainage channel) network and partition it for use with the FLDPLN Tool. In the present case, a threshold of 30,000 (number of pixels) is taken. Using this catchment size, all pixels with flow accumulation values greater than or equal to the taken value are found to comprise the stream network. Cells with a high flow accumulation are areas of concentrated flow and used to identify stream channels. There are two outputs from the Stream Segmentation tool, the segment information file and the segment ID raster. The segment information (MATLAB ‘.mat’) file is for internal use and is required for the other two tools to be run subsequently. The segment ID raster (BIL or FLT format) is provided so that the user can visualize the resulting stream network and associate individual stream segments with their respective ID values.
3.2.3.3 FLDPLN and DTF tool. FLDPLN tool uses the filled DEM raster, the flow direction raster, output from the Stream Segmentation tool and user-specified maximum flood depth (gauge height) values for each stream segment and flood depth step size to construct a ‘depth-to-flood’ (DTF) database that can be used to map the valley floor surrounding the processed segments. Under this module, each stream segment is processed independently and each pixel in the identified floodplain area is assigned a DTF value, which indicates the minimum local stream gauge height (relative to the stream surface representation in the filled DEM), required for inclusion of the pixel in the floodplain. Flood depth (gauge height) information indicates which stream segments are to be processed, and to what maximum DTF value (gauge height) each of these segments is to be processed. In the present case, the gauge height is taken as 30 m and flood depth step size is fixed to about 1. Smaller values offer more spillover flooding opportunities, which can produce expanded flooding in spillover areas and mitigate spatial discontinuities in DTF values. Smaller values also require more processing time. Output from the FLDPLN Model Tool consists of segment-specific data files (MATLAB ‘.mat’ internal files that cannot be viewed or manipulated) containing floodplain extent information. These internal files are required to create DTF maps using the DTF Map Maker tool. The DTF Map Maker tool uses output from the Stream Segmentation tool; the DTF database produced using the FLDPLN model tool, and user-specified, segment-specific flood depth (gauge height) values to generate a custom DTF raster floodplain map. In the DTF output, each DTF 1 to DTF-25 corresponds to a range of gauge height. The DTF’s generated were then validated with observed inundation extents from satellite data and gauge heights and assign each DTF a corresponding range of gauge height.

3.2.4 (d) Validation of simulated inundation DTF layers and development of library of inundation extents

The FLDPLN model-derived simulated inundation spatial extents (DTF-1 to DTF-25) were compared with the available historical satellite-derived inundation spatial extents. Validation was done through visual matching by superimposing observed and simulated inundation patterns, comparing spatial inundation area statistics and using categorical verification statistics, which measure the correspondence between the estimated and observed occurrence of events like probability of detection (POD), false-alarm ratio (FAR) and critical success index (CSI).

Four events where gauge height and satellite-based inundation extents were available were compared with the simulated inundation extents. Figure 3 shows the comparison of the inundation pattern derived from satellite data analysis and through simulation using FLDPLN model. From perusal of Figure 3, it can be observed that inundation pattern observed on 7 August 2006 closely matches visually with simulated DTF-15 layer, when the recorded gauge height is 46.26 m. Following similar approach, it is observed that inundation pattern observed from satellite image of 9 August 2010, when gauge height is 42.07 m, matches with simulated DTF-11 layer. Simulated DTF-10 inundation layer shows similar inundation pattern to that derived from satellite image of 10-Aug-2010, when gauge height is 40.79 m. Further, simulated DTF-9 inundation layer shows similar inundation pattern to that observed from satellite image of 22 September 2005, when gauge height is 40.16 m. In addition to the close match in spatial pattern of flood inundation through visual method for four cases, match for area inundated statistics between observed and obtained through simulation was also carried out. It is observed that at gauge height 46.26 m (7 August 2006), inundated area obtained from satellite data analysis is 10,289 ha and through simulation method, it is estimated to be 11,979 ha, having a match of about 84%. Similarly, at 42.07 m (9 August 2010) gauge height, inundated area estimated from satellite analysis is 7325 ha and from simulation is 7585 ha, having a match of about 97%. At a gauge height of 40.79 m (10-Aug-2010), inundated area estimated from satellite analysis is 5796 ha and from simulation is 7585 ha, having a match of about 97%. For the fourth event for a gauge height of 40.16 m (22 September 2005), inundated area estimated from satellite analysis is 4814 ha and from simulation is 5265 ha, having a match of about 91%. Table 2 shows the match between the observed and simulated inundation area for the four
cases considered for validation. A match of more than 84% in the estimated and simulated area for all the four cases considered is observed.

The FLDPLN-simulated inundation spatial extents were compared with the satellite-derived flood inundation extents using categorical verification statistics, like POD, FAR and CSI. These indexes have been used (Hong et al. 2008; Khan et al. 2011) to measure the correspondence between the estimated and observed occurrence of events. The POD indicates what fraction (pixels) of the observed inundation extent matches correctly with that of the simulated extent. The POD is sensitive to hits, but ignores false alarms. The FAR indicates what fraction of the simulated inundation extent (pixels) actually did not occur. The CSI takes into account hits, false alarms and missed events, and is therefore a more balanced score. It indicates how well the simulated events did correspond to the observed events. It is sensitive to hits and penalizes both misses and false alarms.

\[
\text{POD} = \frac{\text{hits}}{\text{hits} + \text{misses}} \quad (1)
\]

\[
\text{FAR} = \frac{\text{false alarms}}{\text{hits} + \text{false alarms}} \quad (2)
\]

\[
\text{CSI} = \frac{\text{hits}}{\text{hits} + \text{misses} + \text{false alarms}} \quad (3)
\]

Using the above-mentioned indices, it can be observed that the simulated inundation extent has a close match with that of the reference satellite image-derived inundation extents for the four flood events considered. Table 3 summarizes the spatial statistics between satellite image and FLDPLN-derived inundation layers. With satellite imagery as a baseline, inundation extent obtained through FLDPLN simulations produced inundation extents with high PODs (0.94, 0.88, 0.91, 0.89, 0.87 and 0.89). Similarly, CSI also ranges between 0.75 and 0.80. Figure 4 shows the hit—miss—false alarm map for the simulations carried out for 7 August 2006, 9 and 10 August 2010, 22 September 2005,

Table 2. Comparison of inundation derived from satellite and simulated using FLDPLN model.

| S No. | Date          | Satellite | Water level (m) | Satellite | Simulated | % match |
|-------|---------------|-----------|-----------------|-----------|-----------|---------|
| 1     | 7 August 2006 | Radarsat  | 46.26           | 10,289    | 11,979    | 84      |
| 2     | 9 August 2010 | Radarsat  | 42.07           | 7325      | 7585      | 97      |
| 3     | 10 August 2010| Radarsat  | 40.79           | 5796      | 6440      | 89      |
| 4     | 22 September 2005 | Radarsat  | 40.16           | 4814      | 5265      | 91      |

Table 3. Summary of the spatial statistics carried out for validation of simulated inundation extents from the FLDPLN model when related to satellite reference inundation.

|                    | 7 August 2006 | 9 August 2010 | 10 August 2010 |
|--------------------|---------------|---------------|---------------|
| False alarm        | 7554          | 3738          | 1440          |
| Miss               | 2550          | 3828          | 672           |
| Hit                | 40,656        | 27,394        | 6547          |
| Total              | 50,760        | 34,960        | 8659          |
| POD                | 0.94          | 0.88          | 0.91          |
| FAR                | 0.16          | 0.12          | 0.18          |
| CSI                | 0.80          | 0.78          | 0.76          |

|                    | 22 September 2005 | 20 July 2013 | 6 August 2013 |
|--------------------|-------------------|--------------|--------------|
| False alarm        | 3873              | 941          | 4307         |
| Miss               | 2161              | 1040         | 3172         |
| Hit                | 17,920            | 7052         | 26,825       |
| Total              | 23,954            | 9033         | 34,304       |
| POD                | 0.89              | 0.87         | 0.89         |
| FAR                | 0.18              | 0.12         | 0.14         |
| CSI                | 0.75              | 0.78         | 0.78         |
20 July 2013 and 6 August 2013. Using satellite-derived inundation extents as reference, FLDPLN-simulated inundated extents have in general overestimated the inundation extent as observed by more false alarm pixels than missed pixels.

Validation of simulated extents was also assessed by observing the relation between the increase and decrease in the gauge heights and corresponding DTF layers. This observation is explained with the help of an example. For example, for gauge height of 46.26 m matching simulated inundation extent is DTF-15. If the gauge height lowers to 42.07 m (decrease of 4.19 m from previous gauge height of 46.26 m) then the DTF matching at this gauge height should also decrease by four levels. It is observed that for gauge height of 42.07 corresponding matching simulated layer is DTF-11. Similar relationship is observed for other three cases wherever historical satellite images are available.

From this analysis of relationship established between the gauge height and simulated DTF layers, the remaining DTF layers can be attributed to a gauge height range wherever data is not available to build the complete inundation library. Table 3 shows the generalized DTF ranges and gauge heights and Figure 5 shows the match between the simulated inundation pattern for a particular gauge height range and corresponding satellite images having similar inundation pattern.

It was observed from the analysis of inundation extents derived that gauge height variations within 1 m did not show much significant changes in inundation statistics and pattern. For ease of

![Figure 4. Hit-miss-false alarm map for validation of simulated inundation extents from the FLDPLN model.](image-url)
operating in operational environment, gauge heights were therefore generalized and inundation library with 1 m increment interval was developed from bank full to high flood gauge height. The incremental changes in inundation pattern were verified before implementing. For example, inundation pattern observed from the analysis of satellite data-sets of 8-Aug-2010 and 6-Aug-2013, when gauge height data is 41.9 and 41.3 m respectively, matched with simulated inundation of DTF-11. Figure 5 shows match between the simulated inundation pattern for a various gauge height ranges and corresponding satellite images having similar inundation pattern.

4. Results and discussion

In India, during the monsoon season daily forecasted gauge height and also flood warnings are provided by CWC for all major river systems in India. CWC is the national nodal organization which carries out the flood forecasting activity based on more than 945 hydrological observation stations established on the major rivers. Flood warnings are issued when the river gauge height exceeds the fixed WL and DL. A river is said to be in flood when its gauge height touches or exceeds DL at that particular site; when the gauge height is 1 m or more above DL, it is known as major flood (Dhar & Nandargi 2000; Nandargi & Dhar 2003). However, these warnings are only in the form of gauge height values (vertical elevation), non-spatial in nature and difficult in anticipating the likely inundation extent (spatial dimension) which may be caused at different gauge heights. If warning in the form of gauge height values can be translated to spatial dimension, decision-makers can better anticipate and also visualize the possible inundation due to flood disaster and accordingly take steps to alert and evacuate the population likely to get affected at different gauge height forecasts. The library can be generated with minimal inputs like historical satellite images, gauge height data and DEM,
unlike hydrological modelling which requires a large number of inputs. From the analysis it is observed that for Sabri River, DTF-6 i.e. 36–37 m is the gauge height range when flooding is observed to initiate along Sabri River. At this gauge height area affected is about 2053 ha and about 11 villages are likely to get submerged. DTF-15 i.e. 45–46 m represents a scenario which

Figure 6. The inundation library from flooding initiation at gauge height between 36 and 37 m to HFL between 50 and 51 m and possible inundation scenario at 5 m above observed HFL i.e. between 55 and 56 m.
corresponds to the maximum spatial extent of inundation recorded from the available historical satellite images. As per CWC records on 7-Aug-2006, the gauge height recorded for River Sabri at Konta gauge station is 46.26 m and at this level, about 11,979 ha of land and 47 villages are likely to get affected. For highest flood level of 50.13 m recorded at Konta gauge station on 16-Aug-1986, which corresponds to DTF-20 i.e. 50–51 m and under this scenario, about 17,250 ha of land and 59 villages get submerged. Considering, in future if the present HFL record is also crossed by the river, five more levels of scenarios ranging between DTF-21 (51–52 m) to DTF-25 (55–56 m) have also been simulated to have an idea of the inundation impact. With an increase of say plus 5 m to the existing HFL (50.13 m) i.e. DTF-25 (55–56 m) range, about 22,720 ha and 70 villages can get inundated. Figure 6 shows the entire range of inundation scenarios and Table 4 shows the area and villages likely to get affected under various ranges of gauge heights 36–37 m (DTF-6) to 55–56 m (DTF-25). From the analysis of the flood hydrographs generated, it is also understood that the Sabri region witnesses high flood situation during month of August in general and this library can be very useful during that time.

The inundation library can be very useful in cases (a) when cloud-free satellite data is not available during monsoon season, (b) when area of interest is partially covered by satellite, (c) when daily satellite coverage is not available over flood affected region and (d) to provide daily likely inundated area scenario based on forecasted gauge heights. These layers can also be integrated with the respective land use/land cover, roads and rail and key installations likely to get submerged and arrange within the library database in spatial format (shape file and kmz format) as well as tabular format (dbf format) data like list of the villages, length of roads/rail and name of key installations to get affected. With availability of such readily available information like inundation pattern, area statistics and villages to get affected at various gauge heights, the decision-makers can have good time to respond to the flood disaster to alert and evacuate the population likely to get affected. A more practical operational framework of the inundation extent library for flood disaster management by decision-makers could be that if the inundation library database can be developed into an information system, with basic GIS functionalities wherein during the flood season as the flood forecasts are received, the system using automated procedures reads the gauge location (basin name, station name, district and state name) and forecasted gauge heights. This information is then arranged into a database and used for matching and fetching the corresponding inundation extent and other related layers available in the library. The layer fetched then can be visualized over the base

| DTF | Water level (m) | Area affected (ha) | Villages inundated (numbers) |
|-----|----------------|--------------------|-----------------------------|
| 6   | 36–37          | 2053               | 11                          |
| 7   | 37–38          | 3047               | 13                          |
| 8   | 38–39          | 4024               | 18                          |
| 9   | 39–40          | 5265               | 22                          |
| 10  | 40–41          | 6440               | 26                          |
| 11  | 41–42          | 7588               | 30                          |
| 12  | 42–43          | 8723               | 34                          |
| 13  | 43–44          | 9797               | 38                          |
| 14  | 44–45          | 10,903             | 43                          |
| 15  | 45–46          | 11,979             | 47                          |
| 16  | 46–47          | 12,741             | 49                          |
| 17  | 47–48          | 13,803             | 50                          |
| 18  | 48–49          | 14,921             | 51                          |
| 19  | 49–50          | 16,148             | 56                          |
| 20  | 50–51          | 17,250             | 59                          |
| 21  | 51–52          | 18,414             | 61                          |
| 22  | 52–53          | 19,540             | 63                          |
| 23  | 53–54          | 20,638             | 65                          |
| 24  | 54–55          | 21,674             | 68                          |
| 25  | 55–56          | 22,720             | 70                          |
information in freely earth visualization portals like ISRO’s Bhuvan portal (bhuvan.nrsc.gov.in) or Google Earth. The prototype for the entire process in an automated web environment is shown in Figure 7. The entire process in automated environment may not take more than 10—15 minutes and thus help decision-makers to visualize and take preparedness measures accordingly for warning of habitation to likely to be affected, planning relief and rescue operations. The library may also help administrators in better flood mitigation and flood management planning strategies by allowing visualizing inundation scenarios for different magnitudes of flood and associated likely damage for various gauge heights.

5. Conclusions

The approaches explained through the present paper can be made use of because of the simplicity of implementation, both in terms of time and cost-effectiveness compared to modelling options. Long-term historical satellite images and simple models like FLDPLN based on basic hydrological inputs like flow direction and flow accumulation derived from DEM’s can be used to build exhaustive static flood inundation map libraries linked to gauge heights. FLDPLN model can be applied to any number of stream segments and flood water depths, with the resulting floodplain maps able to be merged seamlessly. Developing a library of modelled flood extents for each stream segment over a range of potential flood levels can offer a resource that can be easily accessed and, when combined with addition geospatial data, can provide valuable information that can be used to guide critical, time-dependent decision-making. The static map inundation library can be automated as a workflow, invoked as a web service and executed dynamically wherein with the available forecasted gauge height will
fetch the concerned inundation layer integrate with villages, land use and other infrastructure data-
sets to generate spatial and tabular information on the extent and likely damage.

The major limitations of the inundation library method using FLDPLN model is that it is a static
library based on past observed inundations and may not be helpful in case of flash floods, embank-
ment breaches and dam failures and river stretches which are embanked. The proposed method can-
not be considered a substitute for hydrodynamic modelling where the flow rates, water levels and
extent are dynamically computed. However, when given gauge heights (water levels), the model can
be a good proxy predictor of the extent of flooding. Because SRTM DEM is available for most of the
areas globally, this methodology can be useful for areas especially where calibrated hydraulic models
are not available. Hydrodynamic models provide a realistic dynamic representation of the flood
extent but the complexity of the involved numerical computations and the need for data-intensive
calibrations make their utilization difficult (Horritt & Bates 2001; Hunter et al. 2007). The FLDPLN
model used does not require the discharge data which remains classified and also long-term historical
data from well-distributed gauge stations is not available for many regions. This model is also
useful in areas of rivers or sections that do not have detailed bathymetry data required for running
hydrodynamic models.

The approach explained is only a basic tool and provides a quantitative approach to evaluating
the potential risk to village, land use and infrastructure for preliminary early warning and investiga-
tions for regions which lack data for detailed hydrologic and hydraulic simulations. This method
has operational advantages because of its simplistic approach. However, it cannot be considered as
an alternative to standard hydrological and hydraulic simulation modelling.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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