DEVELOPMENT OF INTEGRATED HYDROLOGICAL MODELLING FRAMEWORK FOR FLOOD INUNDATION MAPPING IN BRAHMANI-BAITARANI RIVER BASIN, INDIA

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ABSTRACT

To provide aid for operational flood disaster management, this inter-disciplinary research proposes the conceptualized integrated distributed hydrological modelling framework based on the spatially distributed hydrological models such as the Water and Energy Budget-based Distributed Hydrological Model (WEB-DHM) and the Rainfall-Runoff-Inundation (RRI) model for flood inundation mapping and flood hazard assessment in the Brahmani-Baitarani River basin, India. This modelling framework also takes into account the dam operation impact on the flood inundation in the delta region. Furthermore, the attempt has been made to extract the flood extent and flood inundation depth from the MODIS data using GIS based tools such as Modified Gradient Based Method (MGBM) and FwDET 2.0 tool, respectively. These flood inundation maps derived from satellite data products are used to verify the simulated flood extent and flood depth obtained with proposed integrated hydrological modelling framework. These flood inundation mapping results with both above approaches are found promising which warrants its application for the near-real time operational purpose as well as its transfer to large river basin with similar hydro-climatic and topographical conditions.

Keywords: Flood Inundation Mapping, WEB-DHM, RRI, FwDET, Dam Operation.

INTRODUCTION

Flood inundation mapping is very useful and effective non-structural measure in managing flood risk and designing food prevention measures to frame flood disaster risk reduction policies. However , the flood inundation modelling tools for large river basin which are scientifically strong and practically simple for flood hazard assessment in near real-time present great challenges to the disaster planning and management authority. The flood hazard assessment in the coastal areas is very complex due to the presence of multiple reservoirs and irrigation schemes in the river system that control the outflow during the flooding period and presence of tidal backwaters in low-lying areas of the river system. The dam operation in a real-time to achieve flood inundation reduction in the delta region is very challenging task as the existing dam operation are based on the prevailing inflow, storage capacity, pressure to assign high priority to meet out agricultural and other water demands over flood control activities and outdated operational rule curves etc. In order to achieve effective reservoir operations and flood reduction in deltaic regions, mainly three types of approaches seem to be promising: (1) integrated hydrologic

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modelling system to estimate the inflow into and outflow from the water resources controlling structures such as dams; (2) flood inundation modelling system for deltaic region; and (3) short range rainfall forecast system such as qualitative precipitation forecast (QPF) system.

Another major challenge in the costal deltaic region is to identify the flood inundation extent and depth of the flood affected area to plan the disaster management and risk reduction activities during emergency. Nowadays, the various agencies give information on the areal flood extent, but don't provide information on the flood depth, which is very essential for planning evacuation activities as well as flood disaster risk assessment. Taking into account all these difficulties in the prevention and management of flood disaster, this study sets up the following four specific objectives:

(1) To apply the GIS based tools for areal flood extent mapping and flood depth estimation.
(2) To set up integrated hydrological modelling framework for flood inundation mapping.
(3) To evaluate the flood inundation simulation results by the proposed modelling framework with the GIS based flood mapping techniques.
(4) To reduce the flood inundation in low laying area by properly operating dam using the proposed modelling framework.

THEORY AND METHODOLOGY

In this study, the Brahmani-Baitarani River basin laying in the State of Odisha and surrounding Jharkhand and Chhattisgarh has been selected to demonstrate the application of proposed modeling techniques for flood inundation mapping. Figure 1 shows the geographical areal extent of the Brahmani-Baitarani basin and the flood extent in year 2008 to 2010. The basin spreads from 83°55' to 87°3' east longitudes and 20°28' to 23°38' north latitudes. The total catchment area is 51907.45 km^2. On one hand, there are inter-state disputes over water sharing due to reduced water flow in this River basins, which is severely impacting agriculture. On the other hand, most climate projections show the increase of precipitation over Brahmani-Baitarani river basin. The Brahmani-Baitarani river basins fall within the sub-tropical climate zone, characterized by high temperature, high humidity, medium to high rainfall and short mild winter. The basin area receives an average annual rainfall of about 1400 mm with 75 to 80% rainfall occurring during south west monsoon season (June – September).

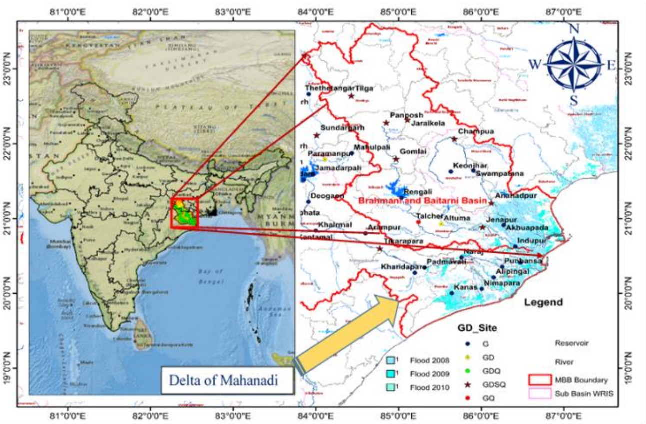

Figure 1: Index map showing the Brahmani-Baitarani River basin.

The upland mountainous river basin area receives very high rainfall over longer duration, which cause intense flooding in the relatively very flat deltaic region. The flood situation further aggravated by the high silt deposition at river mouth, flash floods, poor drainage of flood water into sea, breaching of the embankments and coincidence of flood wave with high tidal waves. In recent years, the Brahmani-Baitarani river basin frequently experienced severe floods viz., flood of 2001, 2003, 2006, 2008, 2011 and 2014 (NWM, 2015). Bedsides the major dams like Rengali and Salandi, there are large numbers of tanks, ponds and lakes. As shown in Figure 1, the Rengali dam (major dam in the Brahmani river basin) having upstream catchment area of 25,250 km^2 plays an important role in controlling floods in the Brahmani-Baitarani deltaic region. However, downstream from this dam around 10600 km^2 area up to Jenapur (where deltaic region start) is fully uncontrolled. It has been observed that runoff from over 50,000 km^2 of catchment area of Brahmani-Baitarani River basin enters the delta, out of which about 50% is fully uncontrolled (NMW, 2015). There is no major diversion channel to control flood in Baitarani river basin and due to dendrite type drainage network it subjects to flashy floods.

In this study, it is proposed to use the Modified Gradient Based method (MGBM) developed by Biswas et al. (2016) for flood extent mapping. The flood water depth estimation tool (FwDET v2.0) developed by Cohen et al. (2019) and applicable to coastal as well as riverine area flood inundation mapping is used to estimate the flood inundation depth using the flood extent extracted by MGBM method and 30 m resolution SRTM DEM of the Brahmani-Baitarani delta region. FwDET v2.0 identifies the floodwater elevation for each cell within the flooded domain based on its nearest flood-boundary grid-cell. Therefore, it eliminates the need to utilize the particular datasets without losing the accuracy and utility. This technique can be used to extract depth from fragmented flood extent map from any source or resolution means its function independent of sensor or platform. The FwDET v2.0 tool can be used in Python or it can be used as add-in in the ArcGIS software.

Further, an integrated hydrological modelling system is conceptualized with in-built capability to simulate the hydrologic response of large river basin to study the spatial and temporal physical processes in the Brahmani-Baitarani river basin, optimization of dam operation and to carry out the flood inundation mapping in the low laying deltaic region (see Figure 2). As shown in Figure 3, the WEB-DHM and RRI model set-up conceptualized for the Brahmani-Baitarani basin. It is proposed to apply the WEB-DHM developed by Wang et al. (2009) to simulate the hydrological response of the upstream catchments in the Brahmani-Baitarani river basin whereas to simulate the flood inundation in the deltaic region the RRI model (Sayama, 2017) developed at ICHARM is applied at the deltaic region. The WEB-DHM model has capability to be applicable for simulation of hydrologic response of the large-scale river basins without compromising the model efficiency. Further, with improved land data assimilation system based on obtained reliable parameters and near-surface soil data from satellite, in-situ observations, the WEB-DHM model is crucial for improving the capability of hazard (Flood and drought) prediction. However, it is based on 1-D Kinematic wave modelling concept, thus it cannot be applicable to low laying area like river delta region. It does not have flood inundation mapping capacity. In order to overcome the limitations of the WEB-DHM model, it is proposed to apply the RRI model, which uses two dimensional diffusive wave approach to route the runoff on the overland and one dimensional diffusive wave approach to route the river discharge, to the delta region. The RRI model is capable to generate the river network and simulate the flood inundation using only the DEM data, which means that it offers simplicity in the modelling. It is important model characteristics where the river network is very complex as in the coastal region.

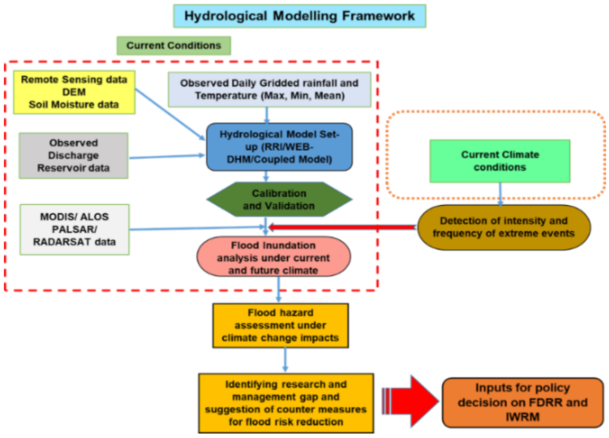

Figure 2: Conceptual integrated hydrological modelling framework for flood inundation

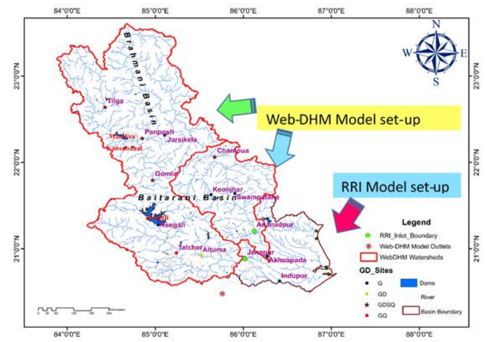

Figure 3: WEB-DHM and RRI model set-up conceptualized for the Brahmani-Baitarani basin

DATA

In order to apply GIS based tools to produce the flood inundation extent and depth map, an 8-day composite MODIS (MOD9A1) satellite images and 30 m SRTM DEM data downloaded from USGS website has been used. To set up WEB-DHM model, three kinds of the input data sets are required to be prepared: namely (a) static data sets; (b) dynamic vegetation forcing, and (c) meteorological forcing. The 30 and 90 m SRTM DEM data is used to for the Baitarani and Brahmani basin, respectively, to generate the static input data sets. Another static input data such as land use and soil parameters data prepared using the USGS (1 km grid size) and FAO (9 km grid size), respectively. All static data sets were resampled to model grid resolution of 500 m. The NK-GIAS software (https://nkgias.com/) is used to prepare all the static data sets. The dynamic vegetation forcing data such

LAI and FPAR is prepared using 8-day composite MODIS Terra (MODI5A2) satellite product with 500 m grid size. In case of the meteorological forcing, the rainfall data is important input parameter in the proposed integrated hydrological modelling framework. In this study, the gridded daily precipitation data at 0.25° from India Meteorological Department (IMD) available for 1960–2015 has been used. Another required Meteorological data (such as wind speed, specific humidity, and downward shortwave radiation) are obtained using JRA55 data sets. All these meteorological datasets are prepared using Data Integration and Analysis System (DIAS). The required topography data sets for set-up of RRI model for delta region are created using the USGS Hydro SHEDS (250 m resolution) DEM data. In order to calibrate and validate the performance of the proposed integrated modelling framework, the daily observed gauge and discharge data from CWC/DoWR at Anandapur, Gomlai and Jenapur (see Figure 3) has been used.

RESULTS AND DISCUSSION

The main objectives of the present study are to demonstrate the application of GIS based tools for areal flood extent and depth mapping and to present the integrated hydrological modelling framework for flood inundation mapping as well as its application for proper operation of the dam and to reduce inundation in the coastal area of the Brahmani-Baitarani River basin.

Figure 4 presents the flood inundation

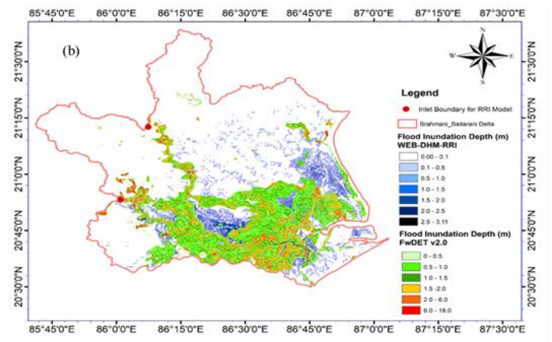

Figure 5. Spatial distribution of flood inundation (27th September, 2011) simulated with the WEB-DHM-RRI model and with GIS based tools in the Brahmani-Baitarani Delta.

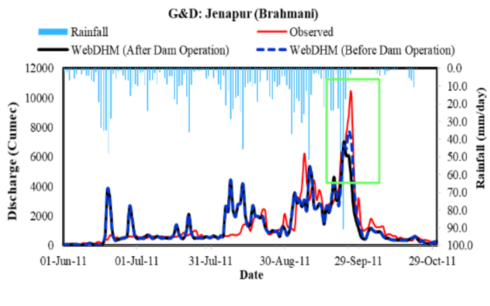

Figure 7. Simulated outflow discharge at the Jenapur site using WEB-DHM Model before and after dam operation.

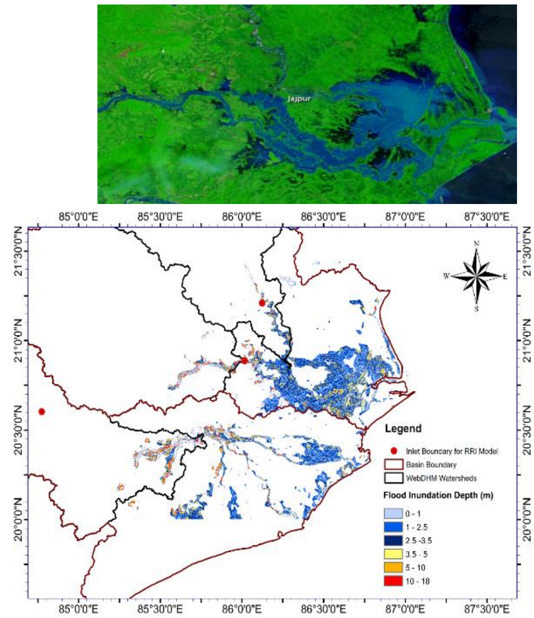

Figure 4. The flood inundation depth estimated using FwDET v2.0 based on flood extent map developed using MBGM method and at top the flood extent map released by NASA (Acquired on 29 September, 2011).

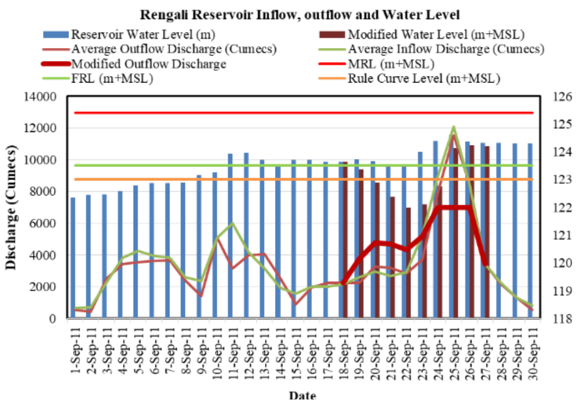

Figure 6. The Actual and modified reservoir water levels, average inflow and outflow from the Rengali dam before and after dam operation.

extent and depth obtained using MGBM method and FwDET v2.0 tools based on MODIS satellite data and 30 m SRTM DEM data. These results are attributed to the capability of the proposed GIS based tools in estimating the flood extent as well as flood depth in the coastal area. The flood depth estimated by the FwDET method suggests that

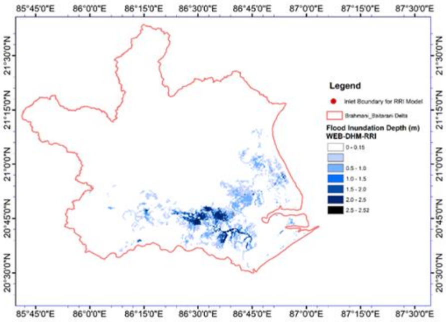

Figure 8. Spatial distribution of flood inundation (on 27 September, 2011) using WEB-DHM-RRI model in Brahmani-Baitarani delta after dam operation

in most of the area, flood depth varies between 1.0 to 2.5 m. In absence of actual observed water level records, it is very difficult to compare the inundation flow depth obtained by FwDET v2.0 method. However, the recent report by National Water Mission, CWC (India) reported that during the flooding in the Brahmani-Baitarani delta region, the flood water depth observed in most of the agricultural land area was ranging between 1.0 to 2.0 m (NWM, 2015). Based on this observation, it could be concluded that the flood depth estimated by the FwDET v2.0 can closely represents the real flood inundation depth in this delta region. The flood inundation mapping results obtained by the WEB-DHM-RRI model for the flood event of 27th September, 2011 is compared with the flood inundation mapping carried out using GIS based tools as shown in Figure 5. From the flood inundation mapping results presented in this Figure 5, it can be seen that the flood inundation mapping in the delta region by the numerical approach and GIS based approach are comparable. However, it should be noted that each approach have its own advantages and limitations.

Further, the conceptualized integrated hydrological modelling framework in above sections is used to demonstrate its capability in planning of the dam operations and to reduce the flood inundation extent as well as depth in the deltaic region. As per existing rule curve for the Rengali dam, the water level throughout the September month should be kept at elevation 123.0 (m+MSL). However, heavy rainfall spell during 2 -9 September, 2011 caused the rising of the reservoir water level not only above the rule curve level but also above the full reservoir level (FRL) of 123.5 (m+MSL) as shown in Figure 6. The second rainfall spell started from 17th September to 23rd September, 2011. Therefore, from the 22nd September, 2011 water level in the reservoir stared building above FRL and on 25th September reached at very high level of 124.61 (m+MSL). On 25th September, the dam authority has left only with option of releasing very huge quantity of water through the dam (See Figure 6). As the result, the discharge of more than 12000 Cumecs was released from the dam which caused the devasting flood conditions in the deltaic region (see Figure 5). Therefore, in the present study, in order to optimize the dam operations, it has been assumed that the rainfall forecast is available three day in advance. By knowing possible heavy rainfall spell (generally very challenging task) in next three days, the dam operations were started on 18th September, 2011 by releasing the volume of water stored above 123.5 (m+MSL) to reduce the reservoir water level approximately 1 m below the rule curve level of 123.0 (m+MSL) within three days. The maximum water discharge released from the dam was kept 7000 Cumecs which is below the recommended discharge of the 8000 Cumecs (See Figure 6). Note that it is a well-known fact that in the Brahmani-Baitarani delta region, the flood discharge below 8000 Cumecs causes only small flood damage (NMW, 2015).

Note that the estimated Nash-Sutcliffe efficiency criteria (NSE) to simulate the hydrograph at Jenapur G&D site using WEB-DHM model as compared to observed data were 0.86 and 0.89 before and after the dam operation. Similarly, the estimated NSE at Anandapur G&D site (Baitarani basin) using WEB-DHM model was 0.74. The outflow discharge hydrographs simulated (for period 1st June, 2011 to 31st October, 2011) at Anandapur (for Baitarani WEB-DHM sub-basin) and at Jenapur (for Brahmani WEB-DHM sub-basin) are used to define upstream boundary conditions for the RRI model for the delta region. Accordingly, the simulated outflow discharges before and after the Rengali dam operation are shown in Figure 7. It can be seen from Figure 7 that during the period 18th to 26th September, 2011 the proposed dam operation resulted in the significant moderation of the peak as well as reduction of peak discharge rate. The simulated flood inundation extent and depth after the dam operation using the proposed WEB-DHM-RRI modelling framework is shown in the Figures 8. The simulated flood inundation extent and depths (as shown in Figure 8) after dam operation are significantly reduced as compared to the flood extent and depths before dam operation (as shown in Figure 5). These results clearly brings out the suitability and necessity of the proposed integrated hydrological modelling framework in the properly operating the reservoir considering the upstream hydro-meteorological conditions to achieve the flood risk reduction in the low laying deltaic region.

CONCLUSION

In present study, an attempt has been made to address the complex problem of flood inundation in the low-lying Brahmani-Baitarani delta (east coastal areas), India. In order to assist in the emergency response activities the GIS based tools such as MGBM method and FwDET v2.0 tools for automatic flood extent and flood inundation depth estimation has been proposed. The proposed GIS based tool found to be highly promising and could be extended for near-real time application provided that the satellite data at high frequency could be available. The proposed conceptualized integrated numerical modeling framework based on spatially distributed WEB-DHM model (to simulate hydrologic response of upstream watershed area) coupled with two-dimensional diffusive wave based RRI model (for flood inundation modelling in deltaic region) is found to be capable to simulate the watershed response in a very large (51, 907 km^2) and complex Brahmani-Baitarani River basins. Further, it was found that this proposed integrated hydrological modelling framework is very valuable tool to operate the reservoir properly and significantly reduce the flood inundation extent and depth in the delta region. Therefore, it is powerful tool to reduce the flood disaster damages and risk.

RECOMMENDATION

In the present study, it is only demonstrated that how the proposed integrated hydrological modelling framework could be used to reduce the flood damages in the deltaic region by planning dam operations well in advance. However, there is a need to develop a dynamic system to support reservoir operators in flood management using real-time observations and weather forecast data.

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