Paper:

Flood Hazard Assessment of Bago River Basin, Myanmar

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Flood hazard mapping is an effective non-structural measure for sustainable urban planning, protecting human properties, lives, and disaster risk reduction. In this study, flood hazard assessment for the Bago river basin was performed. The flood inundation map of the Bago river basin was developed by coupling a hydrological and hydraulic model with geographical information systems. Flood hazard maps with different return periods were developed. The flood hazard map can be utilized to enhance the effectiveness of disaster risk management activities.

Keywords: Bago river basin, flood hazard map, disaster risk management

1. Introduction

Large-scale flooding is a global phenomenon that causes widespread devastation, economic damage, and loss of human lives [1]. Flooding is one of the major natural disasters affecting many parts of the world, including developed countries. One of the methods to prevent and reduce losses is to provide reliable information to the public about flood risk through a flood inundation map [2]. By identifying future flood-prone areas, flood inundation maps can be useful in rescue and relief operations related to disaster risk mitigation. Identifying flood-prone areas is one of the key solutions in flood mitigation.

In order to develop effective flood inundation maps to support the decision-making process in flood risk mitigation and basin-wide planning, the following three objectives are set in this article:

1 To improve a coupled hydrological and hydraulic model considering dams and actual cross-sections

2 To validate the simulated flood inundation areas using SAR images

3 To produce flood hazard maps in various return periods.

In this work, the Bago river basin, a flood-prone basin in Myanmar where two severe floods occurred in 2011 [3, 4], is used as the study area. Flood inundation maps in the Bago river Basin have been proposed by Win et al. (2015) [3] and Bhagabati and Kawasaki (2017) [5]. Considering serious data scarcity in the study area, the previous inundation maps have accuracy and reliability issues because of its simplified process with limited validation of results. Previous study of [3] analysed 2004 to 2011 flood events and compared the simulated 2006 flood inundationmap with an 2006 July ALOS PALSAR image.

Therefore, we conducted an intensive cross-section survey along the river from upstream to downstream in more than 60 locations. Then, an improved coupling hydrological and hydraulic model considering the three newly constructed dams was developed in this study to improve the accuracy and reliability of inundation maps. Then two SAR images were used for validation, and flood hazard maps in various return periods were developed to support the decision-making process in flood risk mitigation in the basin. Flood hazard maps should be promoted as a primary measure in developing countries because it is less time consuming, effective, and has long-term benefits for land use. The process we propose in this article can be applicable to other data-scarce basins for producing flood inundation maps.

2. Study Area and Data

The Bago river basin is a flood-prone area in Myanmar. In 2011, two severe floods occurred in the Bago river basin in July and August [3, 4]. Considering rapid urbanization and climate change, flood risk is considered to increase in the basin [6].

The data used in this study primarily consisted of data sets, such as the SRTM DEM, 10m DEM, Sentinel-1: SAR image, PALSAR image, meteorological and hydrological data provided by the Department of Meteorology and Hydrology (DMH), rating curve developed by the Irrigation and Water Utilization Department (IWUMD), rainfall data and outflow data of dam sites provided by IWUMD, and outflow data at Zaungtu dam provided by the Department of Hydropower Implementation (DHPI).

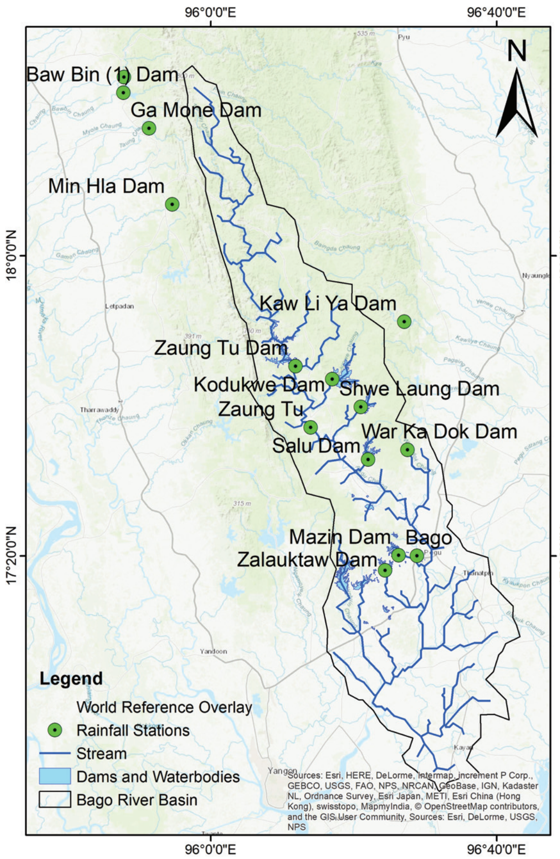

Fig. 1. Location of study area and existing dams within catchment.

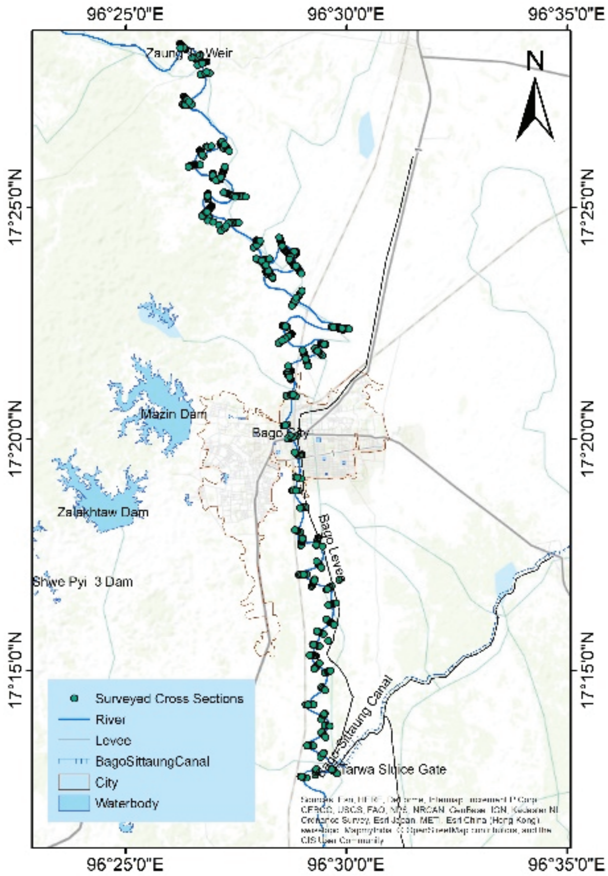

Fig. 2. Available survey cross-sections.

The limited amount of available cross-sectional profiles consists of 68 cross-sections for approximately 50 km reach of the lower part of the Bago river. The distance between consecutive cross-sections varies from 0.5 and 1.5 km, and all of them cover the main channel and the flood plain to some extent.

The location of the study area and existing dams within the catchment area is shown in **Fig. 1**. The channel slope ranges from 4.4 m/km to 0.56 m/km, with an average value of 2.81 m/km along the entire Bago river. The average value of the floodplain slope is 0.56 m/km. **Fig. 2** shows the available survey cross-sections.

3. Materials and Methods

3.1. Flood Modeling

Typically, flood modeling comprises two components, i.e., hydrological simulation, which quantifies the size, duration, and probability of the flood event, and hydraulic simulation, employing the propagation of the flood wave across the river channel and the mapping of inundated areas. Inherent uncertainties regarding multiple aspects are present in the above approaches, involving the model structure, model parameters, boundary conditions, and input data. However, most of these uncertainties that may be surprisingly large, even in small basins [7], are usually ignored. In fact, in most applications, particularly in everyday engineering practice, flood models are considered as fully deterministic tools, in which the unique expression of uncertainty is the return period of rainfall [8].

Hydrological simulation is performed through a rainfall–runoff model that quantifies flood peak discharges or a flow hydrograph in the given return period. The hydraulic analysis is conducted using a one-dimensional hydraulic model in a steady state condition or an unsteady one-dimensional or two-dimensional flood routing algorithm for the accurate spatially distributed evaluation of flow and velocity dynamics [9].

The hydrological–hydraulic modeling procedure for flood mapping is characterized by three main issues: (1) availability of detailed topographic information; (2) choosing an appropriate flood propagation hydraulic model; and (3) the impact that the hydrological forces has on flood mapping results (i.e., design hydrograph estimation). The first two issues benefit from latest technological advancements, in particular, increasing accuracy, availability, and usability of high resolution Lidar DEMs and 2D hydraulic models [10, 11].

The selection of rainfall events is a critical step for event-based hydrological models and model calibration/verification. In this study, hydrological modeling was conducted up to Tarwa outlet across a catchment area of 2,800 km^2. HEC-HMS 3.5 was used as the hydrological model in this research, which is linked to GIS environment using HEC-GeoHMS extension. HEC-HMS was widely applied in many water resource studies and provides reliable results. An initial and constant method and SCS unit hydrographs are selected for the loss and transform methods, respectively. Recession and lag methods were assigned to the base-flow and routing methods, respectively. In the routing process, we used outflow structure routing. First, we conducted many simulation runs and compare the outflow results and observed flow. Next, the optimization process was continued.

Four flood events between 2012 and 2015 were selected for the calibration and validation process. During the calibration procedure, six parameters, initial loss, constant rate, base-flow rate, base-flow threshold ratio, recession constant, and SCS lag, were adjusted. The calibrated parameters of different events were used in validation process. The Nash and Sutcliffe [12] efficiency (NSE) was used to quantify the goodness of fit between the simulated and observed flows.

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,i} - \overline{Q}_{obs}\right)^2}, \quad . \; . \; . \; . \; . \quad (1)$$

where NSE= Nash and Sutcliffe efficiency, $Q_{obs,i}$ = observed discharge; $Q_{sim,i}$ = simulated discharge; $\overline{Q}_{obs}$ = mean of the observed discharge; and n = number of observed or simulated data points.

Flood routing models have received much attention by researchers in the last decades [13–15], with the development of one-dimensional (1D), two-dimensional (2D), or coupled 1D/2D (also referred as quasi-2D) numerical solutions, for steady and unsteady flow conditions. The comparison between these models has obviously intrigued the scientific society [16–18]. The resulted differences are assigned mostly to the quality of topographical and input data [19, 20] and less to the complexity of the phenomenon itself [21].

The more complex and detailed 2D models developed in the past suffer from limited amounts of data and computational issue. However, latest 2D models, overcoming these limitations, are now increasingly used as the new standard approach for accurately simulating spatial and temporal dynamics of the flooding process [22, 23].

HEC-RAS is a widely used hydraulic software tool developed by the U.S Army Corps of Engineers, which is usually combined with the HEC-HMS platform for hydrological simulations (hec.usace. army.mil). HEC-RAS employs 1D flood routing under both steady and unsteady flow conditions by applying an implicit-forward finite difference scheme between the successive sections of flexible geometry. Because of the 1D nature of the model, the discharge is distributed within the whole cross-section in the longitudinal direction.

This can lead to difficulties when multiple flow directions are required or when the flow exchange between the channel and floodplain cannot be neglected. However, it can sufficiently represent the topography as it is not raster-based. Further, it has a low computational cost and it is very powerful for simulating 1D steady flows [24].

In the HEC-RAS model, two boundary conditions are required, which are usually set at the upstream end of the channel through an imposed inflow, as well as assuming uniform water depths at the upstream and downstream ends (kinematic wave condition). The steady flow scheme is based on the solution of the 1D energy equation (for gradually varied conditions) or the momentum equation (for rapidly varied conditions) between two successive cross-sections:

$$\Delta Y + a_2\frac{{V_2}^2}{2g} - a_1\frac{{V_1}^2}{2g} = L\overline{S}_e + C\left|a_2\frac{{V_2}^2}{2g} - a_1\frac{{V_1}^2}{2g}\right|, \quad (2)$$

$$b_2\frac{Q_2}{A_2} - b_1\frac{Q_1}{A_1} + g\frac{(A_2\overline{Y}_2 - A_1\overline{Y}_1)}{\overline{A}L} = g(S_o - S_e), \quad . \quad (3)$$

where Y is the water surface elevation and ΔY is the residual between the upstream and downstream cross-sections; Q_1, A_1 and Q_2, A_2 are the discharge and wetted areas of the upstream and downstream cross-sections; a_1, b_1 and a_2, b_2 are velocity and momentum correction coefficients (for a non-uniform distribution); L is the flow-weighted reach length; S_e is the representative energy slope between two cross-sections; and C is the expansion or contraction loss coefficient (representing the magnitude of the loss of energy between two expanding or contracting cross-sections).

The HEC-RAS model solves the full Saint Venant equations by using an implicit Preissmann four-point scheme of finite differences [25]. The finite differences equations are linearized and solved through Gaussian elimination by using the Skyline storage scheme [26].

It is well-known that the roughness coefficient is one of the most difficult parameters to estimate in hydraulic modeling. A major issue is the different sensitivity of each model against the roughness assigned to the channel and floodplain. In general, we expect flood inundation to exhibit a larger sensitivity to channel friction compared with that of the floodplain coefficient, as the wave is carried primarily by the channel while the floodplain acts merely as additional storage [25, 27]. The well-known HEC-RAS 4.1 1D hydrodynamic model was used for river flow routing along the main river reaches in this study.

3.2. Coupling Hydrological and Hydraulic Models

Flow calculated by the hydrological model is used as input at the upstream boundary condition of the hydraulic model. The output of the HEC-HMS model, the flood hydrographs, were used as input in the HEC-RAS model for calibrating and validating with the known water levels. Floodplain mapping is a sequential process, starting with a hydrological analysis, followed by a hydraulic analysis and geospatial processing with spatial analysis tools such as geographic information system (GIS) and remote sensing. Many researchers have developed flood inundation mapping by coupling a hydrological model and a hydraulic model [3, 9, 28–30]. The inundation models are mainly constrained by upstream river discharges or water

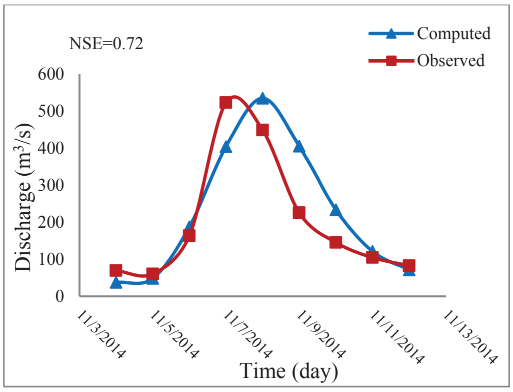

Fig. 3. Calibration result for 2014 flood event at Bago station.

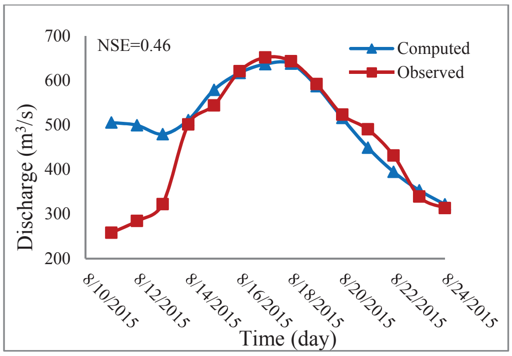

Fig. 4. Calibration result for 2015 flood event at Bago station.

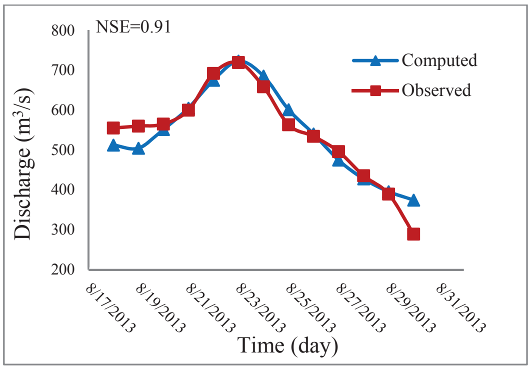

Fig. 5. Validation result of 2013 flood event.

level boundary conditions. Uncertainties in flood inundation mapping arise from many sources such as model mathematical background and configuration, model assumption, boundary condition, model parameters, input data, design discharge, topography, grid cell size, flow condition, water surface elevation, the gradients of the channel and floodplain, and Manning's roughness coefficients.

4. Results and Discussion

No available discharge was observed for the upstream boundary condition for the calibration period in HEC-RAS, and it was simulated with the distributed hydrological model HEC-HMS. There are 20 sub-basins for the catchment area of the outlet at Tarwa. The calibrated results of the flood events of 2014 and 2015 are shown in **Figs. 3**, and **4** respectively. In 2015 event, it was noticed that computed discharge of initial stage differs from observed discharge. Although we gave smaller initial moisture storage, we found that there was no significant change in that event. It depends on quality of rainfall data too. In the 2014 flood event, it is seen that the observed peak date is one day earlier than the simulated peak date. In the daily-based calibration process, we could not differentiate this issue. In the 2015 flood event, it is seen that model result did not match the observed value in the initial stage. The detail of the 2015 Myanmar flood is described in Kawasaki et al. (2017a). The HEC-HMS validation result of the 2013 flood event is shown in **Fig. 5**. A reasonable fit was achieved, with the NSE ranging from 0.46 to 0.91.

Flow routing along the modeled river network was simulated with the HEC-RAS hydraulic model. The inlet section of the Bago river in the Zaungtu region was considered as the upstream boundary condition. The Tawa station, approximately 17.2 km downstream from Bago, was taken as the downstream boundary condition of the modeled network, considering the energy slope parallel to the average bed slope.

Although the detailed cross-sectional survey of the Bago river is available, this data set is insufficient to represent river hydraulics, as the cross-sectional profiles are limited to the main channel and do not extend along the wide range in the floodplains. Composed profiles were created using the elevation data from DEM to represent floodplains combined with the main channel cross-sections. Interpolation was performed for combining detailed cross-sectional data related to the main channel and elevation values from the DEM, in order to extend the profiles along the floodplain.

For each river segment, the corresponding n values (channel and floodplain) were manually varied to determine the best agreement between the observed and calculated hydrographs at the downstream control point. The initial n estimates were adopted as a constant value of 0.035 for the channels and 0.1 for the floodplains. Moreover, owing to data scarcity related to the channel cross-sections, the variation in roughness values of the Bago river was restricted, for which there were few cross-sectional data sets available. Following the calibration process, the final values of the Manning's coefficients varied from 0.025 to 0.035 for the main channel and from 0.045 to 0.06 for the flood plain. The simulated flow data with the time series of flood event were used for calibrating the model. Normal depths were defined as the boundary conditions.

In general, the HEC-RAS model was found to fit satisfactorily, as the NSE ranged from 0.50 to 0.65 for the events. The validation result for the 2011 flood event is shown in **Fig. 6**.

Before 2011, there was no proper dam operation within the basin. After the 2011 flood, three new dams, namely,

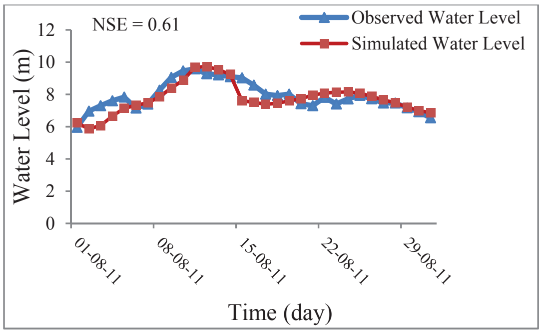

Fig. 6. HEC-RAS validation result for the 2011 flood event at Bago station.

Table 1. Peak discharge and flood inundation area with related return period.

Return Period [Year]	Peak Discharge [m^3/sec]	Total inundation area [km^2]
2	975	38.7
10	1109	47.1
25	1243	49.9
50	1422	53.7
100	1549	55.9

the Kodukwe, Salu, and Shwelaung dams were constructed. Besides, water released from the Zaungtu dam was properly controlled by the Department of Hydropower. Moreover, the flood diversion channel from Zaung Tu weir to Moeyongyi lake was also completed in 2012. Floods were frequent in Bago before the construction of the three dams. The occurrence of floods reduced after the construction of these new dams. It is significantly affected by doing structural measures of flood mitigation measures. The development of flood inundation maps are non-structural measures of flood damage mitigation. Firstly we did rainfall frequency analysis for different return periods. Then we determined design storm (10 day duration) for related return periods. Then we put these values in HEC-HMS and from the resulted hydrographs we got peak discharges of related return period. **Table 1** describes the peak discharge and flood inundation areas for different return periods. Simulated flooded area for the 2015 August flood using HEC-RAS is shown in **Fig. 7**.

After the construction of the three new dams, there was flood in Bago in 2014. However, we could not obtain high resolution images for 2014 flood verification. Thus, we used Sentinel-1: C-band Synthetic Aperture Radar (SAR) 2015 August for comparing model results. Using "Filter function" from earth engine, images with VV and VH dual polarization are achieved. We used VH dual polarization image. Further, the backscatter value was taken as −17.5 for the most reasonable inundation threshold. Then, "focal median and smoothed" functions were used to reduce noise and extract the waterbody in the image. The result layers were added to the GIS software (ArcMap), and the raster was converted to vector by using the conversion function 'raster to polygon' for the flood

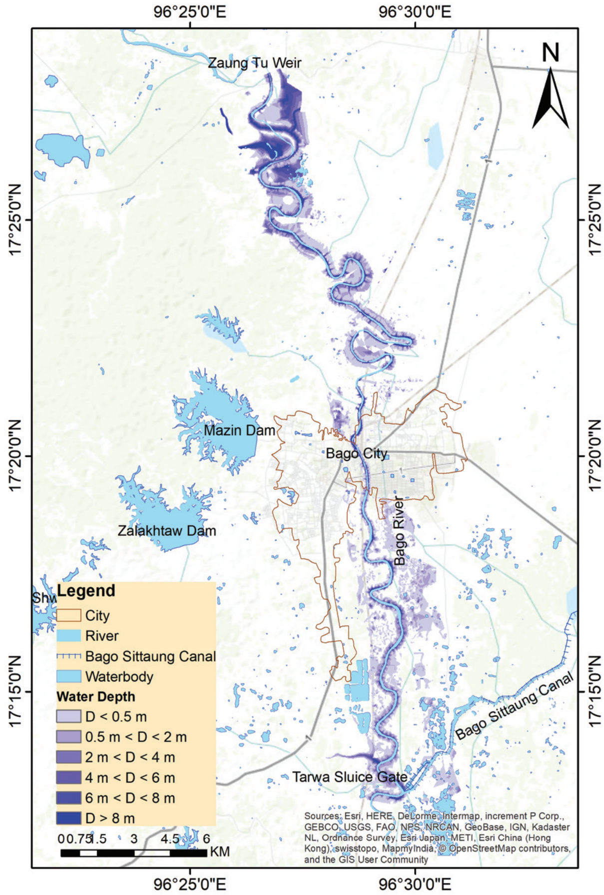

Fig. 7. Simulated flooded area for 2015 August flood using HEC-RAS.

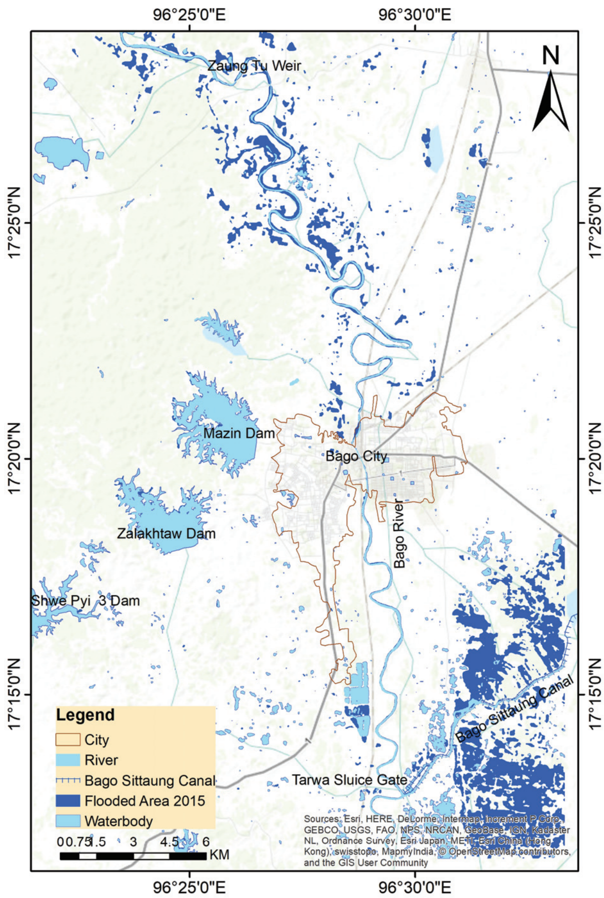

Fig. 8. Flood inundation extent predicted from 2015, August SAR image.

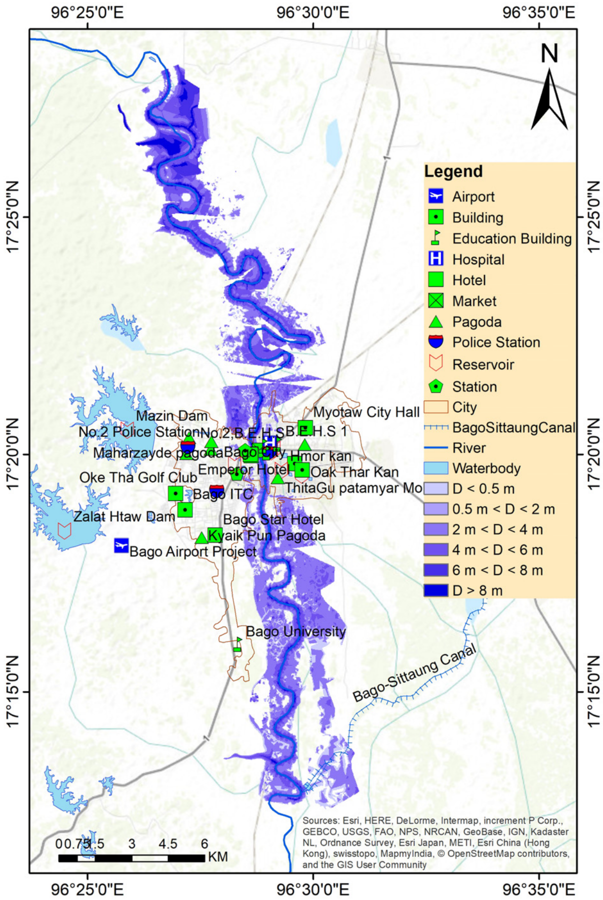

Fig. 9. Flood hazard map for 100-year return period.

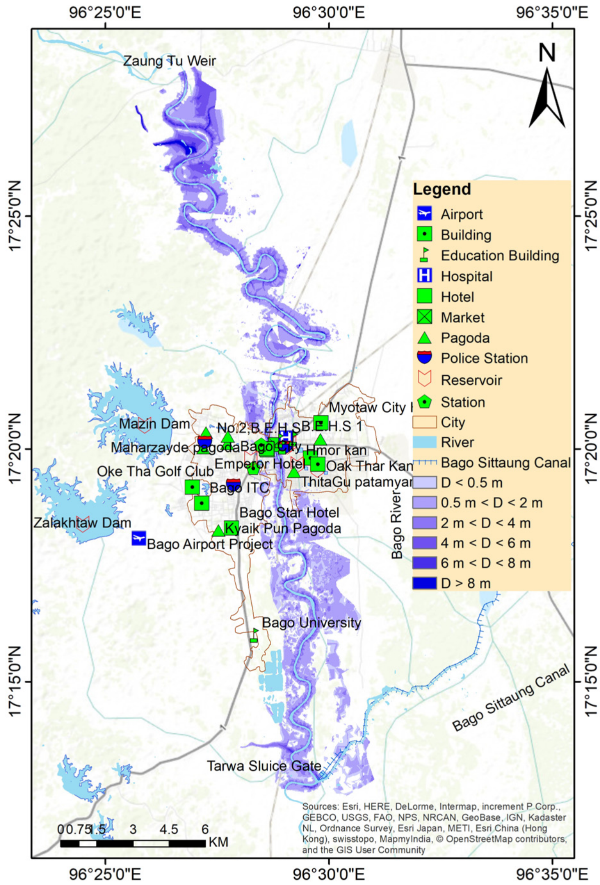

Fig. 10. Flood hazard map for 10-year return period.

layer and before flood layer. After that, the flood layer is erased with the before flood layer to remove the permanent water body. Finally, we obtain the flooded area, and it is shown in **Fig. 8**.

In this study, we do not have the survey data of Bago–Sittaung canal, and thus, the model output could not provide flood inundation area around Bago–Sittaung canal.

Flood hazard simulation requires meteorological and hydrological data, tidal data, and topographical data, including river cross-section, land use data, and records of past inundation. These data are essential in formulating and calibrating simulation models. However, the current modeling is formulated based on limited information from ground observation; therefore, satellite global data are complementarily used in areas where ground observed data are scarce or unavailable. Such data are useful for developing a basic level of hazard analysis. Data to be collected include base maps, water depth, inundation area, evacuation routes, and other relevant information. However, in this study, the flood hazard map of the Bago river basin is developed with limited available data.

The flood hazard map for a 100-year return period and 10-year return period are shown in **Figs. 9** and **10**, respectively. Parameters such as flood depth, inundation area, land use, population density, and road networks were used for flood hazard evaluation. In this study, flood depth and inundation area were used for developing a flood hazard map. The developed flood hazard map includes not only inundation areas and depth but also information structures such as pagodas, schools, hospitals, roads, and public buildings.

5. Summary and Conclusions

There are some difficulties such as data deficit, communication mechanism, public will, implementation agencies, and administrative organizations in the development of flood hazard maps in developing countries such as Myanmar. The accurate delineation of flood extent and depths are essential for proper flood management. This study deals with the development of flood inundation maps and flood hazard maps for the Bago river basin. The flood inundation map of the Bago river basin was developed by coupling hydrological and hydraulic model with GIS such as HEC-GeoHMS and HEC-GeoRAS. Two parameters, namely, the flooding area and depth, were considered for flood hazard assessment of the Bago river basin.

Flood hazard maps, extracted from hydraulic simulation models, may have multiple uncertainties, which are often ignored or misinterpreted. These issues should be carefully taken into account in flood risk studies. To reduce uncertainty, the sophisticated approach is extremely demand in terms of data and computational resources. Further study should be performed on a comprehensive integrated approach by considering tidal effects and the Bago–Sittaung canal operation.

Acknowledgements

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- "Long-term Changes in Annual Precipitation and Monsoon Seasonal Characteristics in Myanmar," Hydrol Current Res, Vol.8, p. 271, 2017.

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