Assessment of the tidal effect on flood inundation in a low-lying river basin under composite future scenarios

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Abstract
Large-scale flooding causing widespread devastation is expected to increase in the low-lying river basin of developing countries. Flood inundation occurring in deltaic environments are caused by both river runoff and tides. Furthermore, flood risk in deltas can be exacerbated by composite driving forces, such as future climate change, land-use change, and sea-level rise. Flood hazard maps have provided one way to visualize flood risk, and are generally created with future projection. However, existing hazard maps have not incorporated the tidal effect and have not assessed the impact of these three future driving factors simultaneously. Here we presented a method to quantify and visualize the tidal effect on flood inundation under current and future scenarios by coupling rainfall-runoff and inundation models, and tide level data. We found simulations of the composite future scenario indicate a 1.27-fold increase in the inundation area, with a two-fold increase in the extent of the tidal effect for the case of a with any return period rainfall event. These achievements can be used to provide flood hazard maps that also visualize the tidal effect. This new information will enhance our understanding of flood risk in low-lying areas and contribute further to disaster risk reduction.

KEYWORDS
coastal, climate change, land use, hydrological modeling

1 | INTRODUCTION

1.1 | Background

Large-scale flooding causing widespread devastation, economic damage, and loss of human life (Jha, Bloch, & Lamond, 2012; Surminski & Oramas-Dorta, 2014) is expected to increase in the future due to climate change, especially in Asia and Africa (Hirabayashi et al., 2013). The Sendai Framework for Disaster Risk Reduction 2015–2030 has highlighted that natural disasters significantly impede progress toward sustainable development (Aitsi-Selmi et al., 2016). Therefore, flood risk management is important, especially in the low-lying areas of developing countries, such as deltas (Berkes, 2007; Syvitski, 2008; Syvitski et al., 2009; Tessler et al., 2015). Flood inundation occurs in such regions as a consequence of the complex interactions between high river runoff due to heavy precipitation and high water levels due to tides or storm surges. Therefore, flood magnitude in deltas is affected by tidal conditions such as water level and timing. Furthermore, flood risk in deltaic
environments can be exacerbated further by composite driving forces, such as future climate change, land-use change, and sea-level rise. Therefore, flood risk assessment should include these potential future changes as a primary step toward disaster risk reduction. Flood hazard maps provide one way to visualize flood risk, and are generally created using a geographic information system (GIS)-based hydrological model (Bhuiyan & Baky, 2014; Ntajal, Lamptey, Mahamadou, & Nyarko, 2017; Rudari, Gabellani, & Delogu, 2014). Although flood hazard maps are beneficial for promoting a public awareness of flood risk, they usually do not show the variation in inundation caused by tidal effect. Visualization of tidal effect will help the residents and policy makers to understand flood risk and further contribute to better evacuation plan or urban planning. Also, research studies that simultaneously assess the impact of these three future driving factors, climate change, land-use change, and sea-level rise, are lacking.

1.2 Previous studies

Risk assessment of fluvial flood requires two models: rainfall-runoff and inundation models. Although a number of distributed hydrological models (DHMs) have been developed, most only include either an empirical estimation of evapotranspiration or a nonphysical description of the land-surface scheme, even though both components are essential for long-term water cycle analysis. The geomorphology-based hydrological model (GBHM) (Yang, Koike, & Tanizawa, 2004) and Simple Biosphere model (SiB2) (Sellers et al., 1996), which is an improved land-surface model that incorporates sparse canopy processes and turbulent flux transfer, have been combined to form the water and energy budget-based distributed hydrological model (WEB-DHM). This model has shown reliable accuracy in simulating the fluxes, discharge, and surface soil moisture in river basins (Wang et al., 2009; Wang, Koike, Yang, & Yang, 2009; Wang, Koike, Yang, & Yeh, 2009). One such inundation model is the rainfall-runoff-inundation (IRI) model (Sayama, Ozawa, Kawakami, Nabesaka, & Fukami, 2012; Sayama, Tatebe, & Tanaka, 2017), which is a one-dimensional (1D)/two-dimensional (2D) hybrid model that simulates RRI processes simultaneously using a diffusion wave model that considers the water surface gradient.

The interaction between the coastal and fluvial components has primarily been studied in the field of coastal engineering (Arns, Wahl, Dangendorf, & Jensen, 2015; Shepard et al., 2012), with most of the studies focusing on storm surges and ignoring the tidal effect. For example, some of the studies physically simulated the interaction between floods and storm surges (Ikeuchi et al., 2017; Karim & Mimura, 2008; Takagi et al., 2016; Teng, Shen, Huang, Ginis, & Cai, 2017; Wahl, Jain, Bender, Meyers, & Luther, 2015; Yang, Wang, Khangaonkar, & Breithaupt, 2012), and others statistically analyzed observed rainfall and surge levels (Karamouz, Ahmadvand, & Zahmatkesh, 2017; Zheng, Westra, & Sisson, 2013). However, the interaction between fluvial flooding and tides has primarily been analyzed in the context of environmental issues, such as sediment transport or salt intrusion, as opposed to flood risk (Alebregtse & Swart, 2016; Fu, Liu, Yu, & Dong, 2017; Leonardi, Kolker, & Fagherazzi, 2015; Passeri et al., 2016; Webster, McGuigan, Collins, & MacDonald, 2014; Yankovsky & Iyer, 2015). Therefore, most of these studies focus on estuarine areas and ignore inundation processes in flood plains. Olbert, Comer, Nash, and Hartnett (2017) analyzed flood inundation under different tidal conditions, with the observed discharge used as upstream river inflow. However, there is currently no study that visualizes and assesses the tidal effect on flood inundation depth.

The Intergovernmental Panel on Climate Change Fifth Assessment Report has indicated that global warming and human activity have undoubtedly been the dominant causes of climate change since the middle of the 20th century. General circulation models (GCMs) and regional climate models (RCMs) have been largely utilized for climate change impact assessments on basin water resources and flooding, with numerous flood risk analyses conducted under various future climate scenarios (Arnell, 2004; Hirabayashi et al., 2013; Milly, Wetherald, Dunne, & Delworth, 2002; Tezuka et al., 2014). Climate change can also increase sea-level rise, resulting in more serious inundation (Birkmann, Garschagen, Kraas, & Quang, 2010; Hunter, Woodworth, Wahl, & Nicholls, 2017; Ikeuchi et al., 2015; Nicholls, Hoozemans, & Marchand, 1999; Pelling, Green, & Ward, 2013; Wassmann, Hien, Hoanh, & Tuong, 2004; Wu, Yarnal, & Fisher, 2002). Land-use change is also a significant factor in developing countries (Brath, Montanari, & Moretti, 2006; Bronstert, Niehoff, & Burger, 2002; Hundecha & Bardossy, 2004). Although each of these three aspects can worsen flooding in the low-lying areas of developing countries, there is currently no attempt to simultaneously model the effects of these factors.

1.3 Objectives

This study aims to quantify the tidal effect on fluvial flood inundation in the low-lying areas of developing countries under composite future scenarios. We set the following three sub-objectives:
(1) To apply and validate coupled hydrological and flood inundation models that incorporate the tidal effect.
(2) To analyze flood inundation under composite future scenarios via the incorporation of climate change, land-use change, and sea-level rise effects.
(3) To quantify and visualize the tidal effect on inundation under different rainfall intensity and tidal conditions.

The novelty of this study can be summarized as the following two points: assessment of tidal effect on fluvial flood inundation and consideration of these future driving factors.

2 | STUDY AREA

Bago River Basin, located in the central part of Myanmar, is chosen as the target basin for this study (Figure 1). This region is located in a tropical monsoon climate and experiences flooding frequently, with an observed increase in the intensity and frequency of flooding events (Htut, Shrestha, Nitivattananon, & Kawasaki, 2014). The most serious flood event since the 1960s occurred in 2011 (Kawasaki et al., 2017; Win, Zin, Kawasaki, & San, 2018a). The upstream area of the river basin is hilly and mountainous, whereas the downstream area is quite flat and low-lying, and the river water level is sensitive to tidal changes. The river mouth is located inside the Gulf of Martaban, a part of the Bay of Bengal. The average tidal range of the river mouth is about 5.85 m at spring tide and 2.55 m at neap tide. The semi-diurnal tides have significant amplitudes owing to the converging effect of the funnel-shaped gulf, shallow bathymetry, and the wide continental shelf (Sindhu & Unnikrishnan, 2013). In this low-lying region, rapid economic growth is accelerating land-use change. Therefore, the devastating impact of flooding will become more severe in the future due to climate change, land-use change, and sea-level rise. Several studies have conducted flood simulations in the Bago River Basin. For example, Zin, Kawasaki, and Win (2015) used HEC-HMS, a semi-distributed hydrological model, and HEC-RAS, a 1D hydraulic model, to map the flood inundation extent. Yonehara, Kawasaki, and Takeuchi (2017) employed the same models and analyzed the impact of future land-use change on stream flow and inundation. Bhagabati and Kawasaki (2017) successfully applied the RRI model to the Bago River Basin. However, these studies did not investigate the tidal effect on flood inundation, and they did not assess climate change, land-use change, and sea-level rise effects simultaneously.

3 | METHODOLOGY

3.1 | General concept

Figure 2 illustrates the conceptual framework of this study. The topography of the basin can be clearly characterized by a hilly terrain in the upstream area and a low-lying area in the downstream area. Therefore, we divide the basin into two areas, with the boundary set at Bago, located in the middle of the basin. We apply WEB-DHM to the upstream area to assess river discharge under given rainfall and meteorological inputs. Then, we employ the RRI model to simulate flood inundation and water level change in the downstream area of the river channel, where the tidal effect is non-negligible, using the discharge derived from WEB-DHM. The observed tide level data at the estuary is used as the downstream boundary condition of the RRI model. In this way, we integrate the
Here, we develop a new method to quantify and visualize the tidal effect on flood inundation. Different tidal conditions are thought to differentiate the inundation depth even though the amount of rainfall is fixed. For example, spring tide will cause more inundation whereas neap tide will cause less inundation. We prepare multiple inputs for tides by shifting the original data by a series of lag times to analyze the maximum possible difference in inundation depth due to the tidal conditions. We term this lag time the lag value, which is defined as the number of hours before (negative) or after (positive) the current tidal condition. First, we considered 51 tide inputs, with lag values ranging from −150 to 150 (6-h interval) and run simulations. Then, we calculate the difference between the maximum and minimum inundation depths among the 51 results for the entire floodplain. We assume this difference value is the tidal effect and produce a map to visualize the tidal effect on the region.

### 3.2 Data

Table 1 lists the data used in this study. Here, we provide a brief description. The DEM was created by Bhagabati and Kawasaki (2017), and is a combination of several products, including USGS HydroSHEDS, ALOS 5-m digital surface model, and river cross-sections. Bago River discharge data at Bago and Zaung Tu were estimated from daily water level data using a rating curve. River water level is measured by the newly installed sensor at Tawa Point from 2017 (Win, Zin, Kawasaki, & San, 2018b). Here we employ these newly obtained water level data for model validation. Daily rainfall data were available at two stations inside the basin. Tide data at Bago River estuary is estimated data based on the measurement in 2011. Figure 1 shows the location of each hydro-meteorological station. The river cross-section data were used to configure the river channel parameters of the RRI model.

| Data                                | Spatial resolution | Temporal resolution | Source                                                                 |
|-------------------------------------|--------------------|---------------------|------------------------------------------------------------------------|
| Digital elevation model             | 15 s               | Static              | USGS HydroSHEDS                                                        |
| Land use                            | 15 s               | Static              | GLCNMO (The global land cover by National Mapping Organizations)        |
| Soil                                | 30 s               | Static              | FAO digital soil map of the world                                      |
| Leaf area index/fraction of photosynthetically active radiation | 1,000 m           | 8 days              | MODIS Terra (MOD15A2)                                                 |
| Meteorological variables            | 0.5625 deg         | 3 h                 | JRA55 (Japan Reanalysis Project)                                       |
| Precipitation                       | 2 stations (Bago and Zaung Tu) | 1 day              | DMH (Department of Meteorology and Hydrology, Myanmar)                 |
| River water level                   | 2 stations (Bago and Zaung Tu) | 1 day              | DMH (Department of Meteorology and Hydrology, Myanmar)                 |
|                                     | 1 station (Tawa)   | 10 min              | IWUMD (Irrigation and Water Utilization Management Department, Myanmar) |
| Dam outflow                         | 1 station          | 1 day               | DHPI (Department of Hydropower Implementation, Myanmar)                |
| Rating curve                        | 1 station          | Static              | DMH (Department of Meteorology and Hydrology, Myanmar)                |
| River cross-section                 | 111 lines          | Static              | The University of Tokyo and Yangon Technological University           |
| Tide level                          | 1 station          | 6 min               | Japan International Cooperation Agency                                 |
in accurately simulating the fluxes, discharge, and surface soil moisture in river basins. A digital elevation model (DEM) is employed to define the basin and sub-basins using the Pfafstetter Coding System. The flow interval, representing the movement and accumulation of water in the river network, is specified for each sub-basin. Flow interval is a minimum calculation unit of discharge, which includes several model grids. Each flow interval is linked by the river network generated from the DEM. The flow routing for the river network in the basin is assumed to be a kinematic wave. The three-layer soil structure for the unsaturated zone, the same as in SiB2, is used for the land-surface processes. See Wang (2007) for more details of the equations used.

WEB-DHM Version 3.0.5 is used in this study. We define a model grid with a 500-m spacing, and divide the river basin into nine sub-basins. Then, each sub-basin is divided into flow intervals, and the remaining static parameters, such as soil and land-use, are defined based on the global dataset. For rainfall input, station-based data was interpolated via the Thiessen polygon method. Other dynamic parameter inputs, such as meteorological variables, leaf area index (LAI) and fraction of photosynthetically active radiation (FPAR), are down-scaled to a 500-m grid that meshes with the WEB-DHM model grid.

WEB-DHM has seven calibration parameters: saturated surface hydraulic conductivity, root zone hydraulic conductivity, groundwater hydraulic conductivity, hydraulic conductivity anisotropic ratio, maximum surface storage, slope roughness, and river roughness. These parameters are manually calibrated based on the estimated discharge data at Bago station in 2011, when serious flooding occurred (Figure 3). The Nash Sutcliffe efficiency (NSE) and coefficient of determination ($R^2$) are also used to evaluate the model performance, with $NSE = 0.94$ and $R^2 = .87$.

### 3.4 RRI model

The RRI model is a 2D grid-based hydrodynamic model capable of simulating both rainfall-runoff and flood inundation processes (Sayama et al., 2012; Sayama et al., 2017). Each grid cell receives rainfall, and the model tracks the flow based on the 2D diffusion wave equations, regardless of topography (i.e., including both hill slopes and flood plains). This 2D model also simulates vertical infiltration based on the Green–Ampt model and saturated subsurface flow in the mountainous areas to provide better representations of rainfall-runoff processes. The flow inside a river channel is computed using the built-in 1D diffusion wave model, which is coupled to a 2D land model to estimate the lateral inflow and outflow or overbank flow. See Sayama et al. (2017) for a detailed explanation. Here, we employ RRI model Ver. 1.4.2. The river basin is delineated from the DEM created by Bhagabati and Kawasaki (2017), and the river network is automatically created.

Figure 4 and Figure 5 show validation results of RRI model. We adopt two different simulation periods in both the dry and rainy season, since the observed water level has different characteristics in dry and rainy seasons. Calibration was conducted using river channel parameters. We used the river width for calibration, with the river...
depth and bank height estimated from the actual cross-section data. Also, the simulation is conducted for two cases: with and without tides. We can see in Figure 4 and Figure 5 that the inclusion of tide level data improves the reproducibility of tide-induced periodicity.

3.5 Future scenario projections

We consider climate change, land-use change, and sea-level rise to conduct an impact assessment of composite future driving factors. Here, the target year for future scenarios was set to 2100. We employ GCMs in Coupled Model Intercomparison Project Phase 5 (CMIP5), which is a standard experimental protocol for studying the output of coupled GCMs from more than 20 modeling groups worldwide. In this study, DIAS CMIP5 tool (Kawasaki et al., 2017) was used for GCM selection, bias corrections, and future projections. Although the GCM output has a coarse resolution compared to RCMs, it is still useful for a preliminary assessment at a basin scale. First, we select several GCMs by statistically assessing their reproducibility of past climate based on results by Htut et al. (2014), used in a climate change impact assessment of the Bago River Basin. Table 2 shows selected GCMs (BCC-CSM1.1, BNU-ESM, CCSM4, FGOALS-g2, MIROC5, and MRI-CGM3). Then, we employ a bias correction with the quantile mapping method (Nyunt et al., 2013; Nyunt, Koike, & Yamamoto, 2016). In addition, we run a future projection under the RCP8.5 scenario, with a 2080 to 2100 target, to determine the extreme case. Figure 6 shows the projected rainfall intensities for different return periods in Bago and Zaung Tu. We computed the extreme rainfall under each return period and calculated their mean value. Subsequently, we performed constant multiplication of the 2011 rainfall event so that the peak rainfall corresponded with the return period rainfall obtained. Figure 7 shows the land-use change scenario under the assumption that the entire deciduous forest area (Category 2 and 4) will change to a sparse forest area (Category 6). For sea-level rise scenario, we employ a constant 1-m increase to the tide data based on the IPCC report value (0.98 m).

4 RESULTS AND DISCUSSION

4.1 Inundation extent analysis

The inundation process is simulated under both the current and future scenarios. First, we fix the lag value to zero and conduct a simulation with a 100-year rainfall event. Figure 8 shows the inundation depth resulting from a 100-year rainfall event under the current and future scenarios, as well as their difference. We select three points along the river channel (P1, P2, and P3) to discuss the inundation depth changes. This result illustrates the effect

| Model name   | Resolution (Lat. × Lon., layers) | Source                                           |
|--------------|----------------------------------|--------------------------------------------------|
| BCC-CSM1.1   | 2.8° × 2.8°, L26                 | Beijing Climate Center (China)                   |
| BNU-ESM      | 2.8° × 2.8°, L26                 | College of Global Change and Earth System Science (China) |
| CCSM4        | 0.94° × 1.25°, L26               | National Center for Atmospheric Research (USA)   |
| FGOALS-g2    | 2.8° × 2.8°, L26                 | LASG-CESS (China)                                |
| MIROC5       | 1.4° × 1.4°, L40                 | MIROC (Japan)                                    |
| MRI-CGM3     | 1.1° × 1.1°, L48                 | Meteorological Research Institute (Japan)        |
of compound future scenarios on inundation extent, with a 1.27-fold increase in inundation area for this case. More precisely, the increase in inundation depth of the downstream part including P3 is thought to be caused by sea-level rise. On the other hand, the upstream and middle part including P2 and P3 is mainly affected by climate change and land-use change, not sea-level rise.

4.2 | Tidal effect analysis

Inundation is simulated for the 51 lag values of each rainfall input, as shown in Figure 9. Figure 10 illustrates the simulated inundation depths at P1, P2, and P3 for different return periods and lag values. Our results illustrate the effect of rainfall and tides on inundation depth. For example, the Bago city (P1) rainfall largely increases inundation depth whereas the tidal effect is almost negligible. However, the P2 inundation depth is affected by both tides and rainfall, and the P3 tidal effect is more significant than rainfall. The difference in inundation depth due to rainfall intensity (i.e., difference between the 2- and 500-year rainfall events) is estimated as 1.5 m at P1, 0.8 m at P2, and 0.7 m at P3. A lag value of 30 to 40 yields the minimum depth while a lag value of −130 to 140 yields the
maximum depth, with little variation between these minimum and maximum values. These results indicate that the monthly spring-neap tidal cycle has a bigger impact on flood inundation than the daily tidal cycle. We can also see the inundation depth difference due to tides (i.e., difference between spring and neap tides) is estimated as 0 m at P1, 0.2 m at P2, and 0.3 m at P3. Furthermore, we select one point and one rainfall event to investigate the tidal input that causes serious inundation. Figure 11 shows the input discharge for a 2-year rainfall event and the input tides that maximize and minimize the inundation depth at P3. The maximum depth occurs when the spring tide corresponds to the timing of peak discharge whereas minimum depth occurs when the neap tide corresponds to the timing of peak discharge.
Figure 12 shows the spatial distribution of this value for the 2- and 100-year rainfall events under the current scenario and the 100-year rainfall event under the future scenario. This result indicates the spatial extent and range of the tidal effect. While the tidal effect is constant for the different rainfall intensities, there is a two-fold increase in the extent of the tidal effect around the estuary area, including P2 and P3, under the future scenario. We can conclude that the extent of the tidal effect is limited to the 50 km zone surrounding the estuary even under sea-level rise. We demonstrate that the timing of high tide is critical to inundation depth, especially near the estuary. This information can be utilized for future land-use planning. Although most of the basin is currently developed for agriculture, much of the region, including P2 and P3, is expected to be urbanized in the near future.

4.3 | Limitation

This study aimed at: (a) application of coupled hydrological and flood inundation models with the tidal effect; (b) analysis of flood inundation under composite future scenarios; and (c) visualization of the tidal effect under current and future conditions. The limitations are mentioned below.

Regarding WEB-DHM validation, the timings of peak discharge are well captured by our simulation. However, there are some gaps between the simulation and observation. These deviations are partly due to the temporal and spatial resolution of data: rainfall, discharge, and dam outflow. We used only two rainfall stations due to poor data availability. Accuracy of discharge and dam outflow data is also limited because these are based on manual observation. Moreover, discharge data has uncertainty because it is estimated from water level data by using rating curves. Simulations can thus be improved by enhancing data availability and quality. On the other hand, the amplitude of water level simulated by the RRI model has deviation especially during neap tide. It is partly because the RRI model assumes that the river channel has a rectangular shape and it may neglect the actual geometry.

There is room for further consideration about future projections. The relative contribution of each driving factor to flood risk should be clarified. It will enable us to evaluate the effectiveness of various kinds of countermeasures such as levee construction, land-use control and so
on. In this case, more simulations with and without each component are needed. This study showed only the worst scenario since the primary objective is to establish the method to assess tidal effect. This will be the next step to be accomplished.

5 | CONCLUSIONS

This study quantifies and visualizes the tidal effect on flood inundation under current and future scenarios via an integration of rainfall-runoff and inundation models, and tide level data. Specifically, we employ WEB-DHM and RRI models to simultaneously simulate river flow and tides. Moreover, we developed a method to assess the tidal effect by considering multiple tide inputs. This new information will help us to understand flood risk in low-lying areas. Our major findings are summarized as follows.

1. Our coupled WEB-DHM and RRI model reproduces the observed river water level of a tidal river. The tidal effect on flood inundation is visualized using this newly developed method, which conducts multiple simulations with shifted tide inputs.

2. Simulations of the composite future scenario for climate change, land-use change, and sea-level rise indicate a 1.27-fold increase in the inundation area, with a two-fold increase in the extent of the tidal effect for the case of a 100-year rainfall event. There is also a two-fold increase in the extent of the tidal effect for the case with any return period rainfall event.

3. Rainfall intensity does not affect the tidal effect extent. The inundation depth difference due to tides is mainly dominated by the monthly spring-neap component whereas the daily tidal cycle has little effect.

The limitation of this study is data availability and further consideration of future scenarios. Model performance can be enhanced by improving meteorological inputs and collecting more water level data for validation. Although this study considered a single composite scenario, the relative contribution of each driving factor should be assessed by expanding simulation cases.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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