Consideration of the rainfall-runoff-inundation (RRI) model for flood mapping in a deltaic area of Myanmar

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Abstract:

Formulating countermasures to flooding risks is important, especially in areas where data are scarce. Numerical modeling techniques may enable hydrologists to model flooding events and access flood risk. Many flooding-inundation models have been developed and successfully applied to many areas. The rainfall-runoff-inundation (RRI) model is one such model that has been applied in various places to estimate river discharges and flooding-inundation depths. However, its applicability to flat river basins is in question. Here, we evaluate the applicability of RRI model to a flat river basin in a data-scarce region. Using the Bago River basin, Myanmar, as a case study, we analyzed past extreme flooding events and developed flooding-inundation maps. The model was calibrated with observed discharge data for a 2011 flooding event and validated for flooding events in 2014 and 2015. The model produced reasonable hydrographs (both peak and base flows). Although the simulated discharges showed good agreement with observed data, the simulated inundation extent showed some discrepancies due to lack of data. Our results indicate that the RRI model may be applicable to flat river basins (short-term analysis). However, for long-term flood simulation, the model may not be the ideal choice as it does not include any land-atmosphere interactions.

KEYWORDS hydrological modeling; flood inundation; RRI; flat river basin; Bago River basin

INTRODUCTION

Floods are among the most devastating natural disasters. According to Hirabayashi et al. (2013), flood risks are expected to increase in the years to come. Almost every country is affected by floods, but the damage is most significant in developing countries in Asia and Africa, especially in their deltaic regions, as existing countermeasures are currently not strong enough. Hence, flood-risk assessments in those regions are crucial.

To estimate flood risks in affected areas, it is essential to calculate the immersed area within a short time after the disaster. Hydrological models can do this, but modeling becomes complicated in countries where data, especially meteorological data, are scarce (Hanasaki et al., 2014; Tomkratoke and Sirisup, 2015). The scarcity of data coupled with the geometry of a deltaic river basin makes it difficult to develop flooding models and simulate inundation areas in areas of very low topography.

Several flooding-inundation models have been developed recently and have been applied to river basins in various parts of the world (Bates and De Roo, 2000; Leandro et al., 2014; Liu et al., 2015). One such model is the Rainfall-Runoff-Inundation (RRI) model (Sayama et al., 2010, 2012), which provides modeled river-discharge data, water depths, and inundation maps. The RRI model may predict the progress of a flooding event by considering the effects of discharge and inundation. The model was developed to address the issue of simulating inundation areas especially in low-lying regions.

The RRI model has been applied to flat river basins. Sayama et al. (2015) applied the RRI model to the Chao Phraya River basin in Thailand. However, the Chao Phraya basin’s characteristics are unique: (1) It is a very flat basin with a slope ranging from 1/10,000 to 1/15,000, and (2) the downstream area of the basin is highly urbanized, especially near the river mouth as it passes through the Bangkok metropolitan area (Komori et al., 2012). In many deltaic regions, the downstream region is usually cultivated land. Apart from that study, there has not been much research to confirm whether the RRI model can be applied to other deltaic river basins.

The purpose of this paper is to (1) verify whether the RRI model can be used for a flat river basin by doing short-term event-based simulations, and (2) to check the accuracy of the modeled inundation maps produced for data-scarce regions by comparing with some satellite-based data. We chose Myanmar’s Bago River basin as the study area because it covers a small area and its bed slope ranges from 1/300 to 1/3,000. Apart from a few cities and towns along the river, most of the mid-to-downstream region consists of paddy fields. The river-flow characteristics differ from those of the Chao Phraya River. Myanmar is also a data-scarce country, so there are limited meteorological and topographical data available for the Bago River basin. Even though Myanmar is flooded almost every year, there has been limited scientific research conducted on the flooding, especially at a basin scale (Zin et al., 2015). Most of the past studies were conducted on the effects of Cyclone Nargis (Fritz et al., 2009; The United Nations Human Settlements Programme [UN-Habitat], 2011). Due to the limited availability of data, developing a flooding-inundation
model in Myanmar is a challenge.

Using the RRI model, we simulated past extreme flooding events and generated inundation maps. We also modeled the spread of flood waters at different time steps. This paper also focuses on detecting and comparing the inundated areas using satellite products.

OVERVIEW OF THE BAGO RIVER BASIN

The Bago River is 335 km long. It originates from the Bago Yoma mountainous region, flows into the Yangon River, and finally drains into the Gulf of Mottama. The river basin, which is a historically flood-prone area of Myanmar, has a catchment area of 4,893 km² and is one of the most populous regions (Htut et al., 2014). Many seasonal wetlands are present in the downstream part of the basin. Figure 1 shows the Bago River basin (16°55′N to 18°22′N, 95°54′E to 96°42′E).

In 1996, the Zaungtu Dam was constructed on the Bago River for hydropower generation. A diversion weir was constructed in 1998 solely for irrigational purposes. In 2012, three earthen dams (Salu, Kodukwe, and Shwelaung Dams) and a flood-diversion channel from the weir at the Zaungtu Dam to Moeyongyi were built. Additional construction activities have recently taken place in the basin. The region contains few artificial reservoirs.

Only two meteorological stations (Bago and Zaungtu) are located inside the basin. As of 2010, there were three other meteorological stations (Kabaraye, Shwegyin, and Tharawady) in close proximity of but not within the Bago River basin. The average annual total rainfall at the Bago station is around 3,000 mm. The Bago River basin suffers from flood damage every year. In 2015, a large-scale flood occurred in the Bago River basin and inundated most of the low-lying area, causing tremendous structural and non-structural damage and some loss of life in cities and towns in the basin.

As seen in Figure 1, there is a big difference in the topography between the upper and lower parts of the basin. The upper basin is hilly and mostly covered with forest, whereas the lower basin is mostly farmland and is relatively flat, with a very gentle gradient. The average gradient ranges from 1/300 in the upper basin to 1/3,000 in the lower basin. Hence, the basin also experiences a daily tidal fluctuation as far as 50 km from the river mouth.

METHODOLOGY

The RRI model is a two-dimensional (2D) model capable of simultaneously simulating rainfall runoff and flood inundation (Sayama et al., 2012). The model treats data on slopes and river channels differently. The RRI model has been successfully applied to several regions of the world to simulate flooding events with good performances in all cases (Sayama et al., 2010; Sayama et al., 2012; Nastiti et al., 2015). One of the advantages of RRI model is that it can be applied to a flat river basin, such as the Bago River basin.

Rainfall intensity and distribution are the most important input parameters for the RRI model. The daily rainfall data from the following five meteorological stations were obtained from Myanmar’s Department of Meteorology and Hydrology: Bago (17°20.250′N, 96°29.082′E; 15 m AMSL), Zaungtu (17°37.812′N, 96°13.734′E; 36 m AMSL), Tharawady (17°39.396′N, 95°46.962′E; 20 m AMSL), Kabaraye (16°51.882′N, 96°9.252′E; 20 m AMSL), and Shwegyin (17°55.464′N, 96°53.394′E; 40 m AMSL). With stations both inside and outside the basin, the overall spatial distribution of stations is good; however, rainfall data in the northern hills were not available due to the lack of observation stations, so there is a possibility that the absence of data might affect the overall performance of the model. Thiessen polygon method was used to prepare the rainfall data. All the datasets used in the study are listed in Table I.

The RRI model provides three outputs: the water depth on the slope (m), the water depth of the river (m), and the river discharge (m³/s). The RRI model was initially run for the year 2011. The model was then calibrated by using the observed data for the flooding event that occurred between August 1 and August 20 that year.

Earth’s water is constantly moving in a continuum of time and space. There is exchange of energy when water undergoes phase changes. These phase changes are the result of interactions with radiation and atmospheric circulation. These water and energy fluxes are important elements of the water and energy cycles and constitute the water and energy budgets respectively. Accurate estimation of these fluxes can result in better hydrological models. The RRI model is a simple inundation model where the flow in
slopes is calculated by using a 2D diffusive wave model and the river routing is calculated using a 1D diffusive wave model (Sayama et al., 2012). The model uses the following mass balance equation:

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = r - f$$

where $h$ is the height of water from the local surface, $q_x$ and $q_y$ are the unit width discharges in $x$ and $y$ directions, $r$ is the rainfall intensity and $f$ is the infiltration rate. The model lacks any land-atmosphere interactions, such as energy transfer among the soil, vegetation, and the atmosphere. For a small flooding event (1–2 days), these energy-budget components can be neglected. However, for long-duration flooding, they cannot be neglected and should be considered for better modeling results.

RESULTS AND DISCUSSION

Floods are annual events in Myanmar, with the most recent severe floods occurring in 2011 and 2015. During these events, almost all the rivers and streams flooded, inundating more than 500 km$^2$ of paddy fields. Both events lasted more than four days and caused massive property losses and a few human fatalities.

Figure 2 shows the comparison of the two hydrographs (observed and simulated) after calibration was done. The observed peak discharge (1,199 m$^3$/s) occurred on August 11, but the simulated peak discharge (1,204 m$^3$/s) occurred on August 10, so the simulated discharge was ahead by one day. The observed and simulated discharges, however, showed a good relation, as indicated by a Nash–Sutcliffe efficiency (NSE) value of 0.94 and a coefficient of determination ($R^2$) value of 0.93. The difference in the peak time can be explained by the rainfall distribution pattern. As mentioned in the previous section, rainfall data of the northern hill is not available. Thiessen polygon interpolation method was used for generating the rainfall distribution. In Figure 2, the inverted vertical axis shows the basin average rainfall. On August 9 and 10, high rainfall was observed around the mid basin (Zhaungtu station and Tharawady station). Since there is no station (to interpolate) on the northern side of these stations, this high rainfall has been mapped onto the northern hills. Hence the prepared input data has high rainfall for August 9 and 10 in the northern part of the basin, resulting in slightly higher discharge. A similar explanation can be given for the validation cases.

As a validation, the model was also run for flooding events in 2014 and 2015. Figure 3 shows the comparison of observed and simulated hydrographs for those years using data from the Bago station. The NSE and $R^2$ values for these events were 0.84 and 0.89, and 0.81 and 0.91 for

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Table I. Datasets and their sources for the Bago River basin, Myanmar

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Dates</th>
<th>Sources</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily precipitation</td>
<td>2006–2015</td>
<td>Department of Meteorology and Hydrology</td>
<td>Stations: Bago, Zaungtu, Kabaraye, Shwegyin Tharawady</td>
</tr>
<tr>
<td>Daily water level</td>
<td>2006–2015</td>
<td>Department of Meteorology and Hydrology</td>
<td>Station: Bago</td>
</tr>
<tr>
<td>Rating curve for Bago station</td>
<td>2009</td>
<td>The European Space Agency’s GlobCover</td>
<td>Resolution: 1 km</td>
</tr>
<tr>
<td>Land cover map</td>
<td>2003</td>
<td>Food and Agriculture Organization (FAO) of the United Nation’s global dataset</td>
<td>Resolution: 9 km (approximately)</td>
</tr>
<tr>
<td>RADARSAT-2 flood-water extent analysis map</td>
<td>September 8, 2015</td>
<td>United Nations Institute for Training and Research (UNITAR)’s Operational Satellite Applications Programme (UNOSAT)</td>
<td>Water bodies detected from Radarsat-2 data</td>
</tr>
<tr>
<td>River cross sections</td>
<td>2014</td>
<td>The University of Tokyo and Yangon Technological University</td>
<td>Surveyed point data</td>
</tr>
<tr>
<td>HydroSHEDS digital elevation model (DEM) (edited)</td>
<td></td>
<td>U.S. Geological Survey (USGS), World Wildlife Fund (WWF)</td>
<td>Resolution: 90 m (approximately)</td>
</tr>
</tbody>
</table>

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Figure 2. Comparison of observed and simulated hydrographs of river discharges (after the calibration process) for the 2011 flooding event at the Bago meteorological station, Bago River basin, Myanmar
2014 and 2015, respectively, which means that there was a good correlation between the observed and simulated discharges at the Bago station. For 2014, the simulated peak discharge (1,066 m$^3$/s) occurred on August 7, one day ahead of the observed peak discharge (1,084 m$^3$/s). For 2015, however, both the observed peak discharge (943 m$^3$/s) and the simulated peak discharge (1,032 m$^3$/s) occurred on August 31.

Figure 4 shows the spatial distribution of the peak flooding heights during the simulation period. The result suggests a large-scale inundation in the lower Bago River basin. The peak was observed on August 31, 2015. For this particular flood event, published inundation information from only one source—United Nations Institute for Training and Research (UNITAR) Operational Satellite Applications Programme (UNOSAT)—was available. And the satellite product published by UNOSAT (Table I) was only available for August 9, 2015 (UNOSAT, 2015). As seen from Figure 3(b), the river flow started to decrease beginning on August 4, 2015. Because there was a gap of 8 days between the simulated peak and the satellite product, they did not match well. Although the river flow was reduced, the flood waters remained longer due to the relatively flat flood plain, which can be seen in the UNOSAT product in Figure 4. Unfortunately, the UNOSAT satellite product doesn’t contain inundation depth information, and hence inundation depth comparison of the model output and the UNOSAT product was not possible.

Figure 5 shows the simulated inundation depths of the lower Bago River basin at four different time steps (2 days apart) in 2015: (a) July 28, (b) July 30, (c) August 1, and (d) August 3. The inundation and flood water can be better understood by studying these images. Figure 5(a) illustrates the onset of the flood; 5(b) illustrates the period almost at the peak of the flooding event, where almost the entire lower basin is flooded; 5(c) illustrates the period when the flood waters began to recede; and 5(d) indicates that a large part of middle Bago River basin is no longer flooded. Hence, it is safe to assume that the flood water started to recede on August 3.

Figure 3. Comparison of observed and simulated hydrographs of river discharges in the validation process for (a) the 2014 flooding event and (b) the 2015 flooding event at the Bago meteorological station, Bago River basin, Myanmar

CONCLUSIONS

Every year, outflow from the Bago River causes flooding in the middle and lower parts of the Bago River basin. Model simulations provide a large amount of data about the flooding processes both in the river channel and in the floodplain, which can be used to mitigate damage to life and property in frequently flooded basins such as the Bago River basin. In this study, the RRI model has been applied to simultaneously simulate rainfall runoff and flood inundation. Flooding-inundation maps of the Bago River basin were simulated for 2011, 2014, and 2015 and were validated with observed discharge data. For the 2015 event, the modeled data were also validated by comparing them with observed data from the UNOSAT satellite product. The modeled hydrographs showed acceptable performance in
simulating flooding events, and the modeled discharge hydrographs correlated well with the observed discharge hydrographs. Also, the replicability of the generated inundation data was acceptable. Hence, from this analysis, we can state that the RRI model may be applicable to flat river basins such as the Bago River basin.

In most flat river basins of Asia and Africa, paddy fields are predominant. One characteristic of flat basin floods is that because they are most likely to occur in coastal deltaic regions, the flood water takes much longer to drain out (recede) into the sea; thus, large areas stay inundated for a longer period of time. Hence, the effect of the energy-budget component (soil-vegetation-atmosphere interactions) is large and cannot be neglected. As seen in Figure 4, there is a discrepancy between the simulated data and the observed data from the satellite product. Although this discrepancy is primarily due to the time difference, we suspect that the results may be improved by including the energy-budget component.

The RRI model is suitable for short-term flooding-inundation mapping. To determine the inundation area with higher accuracy in the case of a long-term event, the energy-budget component should be included. However, for long-term simulations, the RRI model alone is not enough to estimate when flood waters will recede or dry up. Therefore, the next step of this research should include the energy-budget component for precise flooding-inundation mapping.

Several other factors may help improve the RRI model: (1) more precipitation data, (2) a consideration of dam operations, and (3) higher-resolution elevation data. As mentioned earlier, accurate precipitation data are the most important in implementing the model. Even though precipitation data from five stations were used, only two stations (Bago and Zaungtu) were inside the Bago River basin.

Hence, installing a dense network of meteorological stations may further improve the results of this analysis. In 2012, new dams were constructed in the Bago River basin. Currently, the RRI model does not consider the dam operations, but as a next step in this research, dam operations may be considered. Finally, more cross-sectional data and subsequently higher-resolution DEM data may provide a more accurate representation of the floodplain, which may then be used to improve the flooding-inundation mapping.

The results of this study may be used to estimate potential flood damage for the Bago River basin. Moreover, such well-calibrated models may be used to predict the discharge of rivers almost in real-time, which may be used for flood forecasting, early warning systems, flooding-inundation potential maps, and estimates of flood vulnerability.

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