



Flood Simulation Studies with Rainfall-Runoff-Inundation (RRI) Model, Over Yangon City, Myanmar

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Abstract. Flood risks are increasing due to climate change and human activities in river basins. Flooding is one of the most common disasters in Myanmar, as well as in many other countries. The floods occur during the southwest monsoon season, which is from May to October. Yangon City is at risk of flooding when heavy monsoon rainfall coincides with high tides. In this study, the Yangon area was used as a case study, and the Rainfall-Runoff-Inundation (RRI) model was applied. The RRI model is one of the models that has been applied in various river basins to estimate river discharges and flood inundation from rainfall data. The model is a two-dimensional model capable of simulating rainfall-runoff and flood inundation simultaneously. This study aimed to clarify the characteristics of the model's parameters, such as lateral saturated hydraulic conductivity k_a and soil depth h_d , for a flat river basin in Yangon. Eighty numerical simulations were conducted for four flood events in 2011, 2012, 2013, and 2014, with six soil depths h_d and five different k_a values in the Bago River. The discharge hydrographs with different k_a and soil depths h_d values for this river basin were compared. The results show that k_a and soil depth h_d values significantly differ between Myanmar and other countries due to the geological characteristics and climate zones of the countries.

1 Introduction

According to a global disaster database, flood and storm are the primary causes of disasters in Myanmar (World Meteorological Organization, 2011). Flooding is one of the most devastating natural phenomena in the world. It occurs when the watershed system experiences heavy or continuous rainfall events, causing the water flow rate to exceed the channel's capacity. There are three types of flood characteristics: pluvial floods, fluvial floods, and coastal floods (storm surges). Yangon City, located in the center of Lower Myanmar, which encompasses the coastal lowlands and the confluence of the Bago River and Hlaing River, is prone to fluvial and pluvial floods. These frequently occur during each rainy season. Fluvial floods in Yangon happen when the water levels in the surrounding rivers or canals are higher than those in areas within the city. Pluvial floods can also occur even at low tides in some locations due to blockage of the drainage system by solid waste. Flood inundations, with over 0.5 m and a duration of 3 to 5h, occurs 6 to 10 times per year. Based on records from 1947 to 2008, there is a 3.2 % annual probability that Yangon City has been affected by a tropical cyclone and a 6.7% probability that a storm surge has occurred in nearby coastal areas (Asian Development Bank, 2016). Severe flood events occurred in the city in 1973, 1974, 1976. 1988, 1991, 1997, 2002, 2004, 2007, and 2014. The flood event in Yangon in 2014 was different from previous floods, and this happened in the Yangon area in June and July due to continuous heavy rainfall. Nearly all the rivers and creeks overflowed, and the inundation lasted for more than seven days. The heavy rainfall in 2014 led to flooding in 14 townships in Yangon City, causing significant damages to infrastructure and economic losses for the residents.

Access

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There is a strong need for an available model that simulates rainfall-runoff, and flood inundation models have been developed and successfully applied to river basins in many parts of the world (Bates and De Roo, 2000; Leandro et al., 2014; Liu et al., 2015). A one-dimensional analysis method is generally used for predicting flood flows through the rivers in rainfall runoff analysis (Collection of Hydraulic Formulas, 2019). To consider the rainfall distribution and topography, a distributed runoff model can be used. Recently, the Rainfall-Runoff Inundation (RRI) model was developed to analyze the processes of rainfall runoff, flooding, and inundation in an integrated manner using rainfall as input conditions (Sayama, 2014). The RRI model has also been developed and applied to evaluate river discharges and flood inundation depths in flood-prone areas (Shimizu et al., 2021a, b). In this paper, we selected part of the Bago River Basin, specifically the downstream section that includes Yangon City, as our case study area to investigate the rainfall and runoff characteristics of floods in Yangon City. In the Bago River basin, other researchers have previously applied the RRI model to both the upper and lower Bago River (Bhagabati and Kawasaki, 2017). They analyzed the applicability of the RRI model to a flat river basin and confirmed the model's performance by comparing the results with satellite-based data from UN-OSAT (United Nations Satellite Centre). However, the basin area in this study differs from the previous research. Furthermore, the effect of parameters in the model on the discharge hydrograph has not been revealed for this basin. This paper discusses the applicability of the RRI model to a flat river basin to understand the runoff characteristics of floods in Yangon for future research considerations. The objectives of this study include understanding the rainfall and runoff characteristics of the 2014 flood in Yangon and clarifying the RRI parameters, specifically lateral saturated hydraulic conductivity k_a values and soil depth h_d for the large, flat river basin in Yangon.

2 Background of the Study Area

Yangon City is located in the eastern part of the Ayeyarwady Delta, with a patchwork of rivers, creeks, and canal drains around the area. Yangon is 794.43 km² in land area, and is situated at approximately 96.141762° longitude and 17.132582° latitude. Yangon has a tropical climate. The average annual temperature is around 26 °C, and the average annual rainfall is 93.5 in. (237.49 cm) (Asian Development Bank, 2016).

The area of the Yangon model basin is 22 700 km², with approximately 1100 grid cells. The upper boundary of the catchment area is formed by the Hlaing River and Bago River, while the lower boundary is defined by the Yangon River and the coastal line. The location Map of the Yangon Basin Model is shown in Fig. 1. This map was generated 70 using ArcGIS Pro 3.2 (https://pro.arcgis.com/en/



Figure 1. Location Map of the Yangon Basin Model.

pro-app/latest/getstarted/download-arcgis-pro.htm, last access: 6 March 2024).

This basin area comprises of eleven townships: Yangon, Kungyangon, Kyauktan, Thongwa, Hlegu, Hmawbi, Htantabin, Taikkyi, Kawkhmu, Hinthada, and Bago. Among these, Yangon City is the largest.

3 Methodology

Rainfall-Runoff-Inundation (RRI) model

The RRI model was developed to simulate the water flow mechanism between slope grid cells and river grid cells (Sayama, 2014). The continuity equation (Eq. 1) is solved to calculate the temporal variation in water volume within the grid of watershed slopes.

$$\frac{\partial z_s}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = r - f \tag{1}$$

where, z_s = water level, q_x , q_y , = unit width flow rate in the x, y direction, r = rainfall intensity, f = vertical penetration intensity. The unit width flow rates are divided into surface

Compare Accumulative Rainfall Data of 2011, 2012 and 2013 and 2014 3000 Sep - Dec May - Aug Jan - Apr 2500 Simulation Tin 2000 1500 ainfa 1000 500 182 -500 Day of yea Acc 2012 Year Acc 2013 Year Acc 2014 Year cc 2011 Year

Figure 2. Comparison between the Accumulative Rainfall data of 2011, 2012, 2013 and 2014.

flow and penetrating flow. Generally, the unit width flow rate in the x and y directions is described by the shallow water equation as:

$$\begin{cases} \frac{\partial uh}{\partial t} + \frac{\partial u^2 h}{\partial x} + \frac{\partial uvh}{\partial y} = -gh\frac{\partial z_s}{\partial x} - \frac{\tau_{0x}}{\rho} \\ \frac{\partial vh}{\partial t} + \frac{\partial uvh}{\partial x} + \frac{\partial v^2 h}{\partial y} = -gh\frac{\partial z_s}{\partial y} - \frac{\tau_{0y}}{\rho} \end{cases}$$
(2)

where, g = gravitational acceleration, τ_{0x} , $\tau_{0y} = \text{shear stress}$ terms in x, y directions which can include other flow resistance such as vegetation. In the RRI model, a diffusion wave is assumed for surface flow, in which the convection terms in Eq. (2) are ignored. In this study, Eq. (3) was used to calculate the surface flow flux (Shimizu et al., 2021a, b).

$$u = \frac{1}{n}h^{\frac{2}{3}}\frac{\partial z_s}{\partial x}S^{-\frac{1}{2}}, \quad v = \frac{1}{n}h^{\frac{2}{3}}\frac{\partial z_s}{\partial y}S^{-\frac{1}{2}},$$
$$S^2 = \left(\frac{\partial z_s}{\partial x}\right)^2 + \left(\frac{\partial z_s}{\partial y}\right)^2 \tag{3}$$

where, n = the roughness coefficient of Manning. The flow in the ground was divided into the basin slope, the plain area, and the mountainous area. In the mountainous area, vertical seepage flow was not considered (f = 0), and lateral seepage flow was calculated using Darcy's law as shown in Eq. (4).

$$q_x = -k_a (h_d + h) \frac{\partial z_s}{\partial x} + uh,$$

$$q_y = -k_a (h_d + h) \frac{\partial z_s}{\partial y} + vh$$
(4)

where q_x and q_y = unit width flow rate in the *x*, and *y* direction, respectively k_a = saturated hydraulic conductivity, and h_d = water depth in the soil layer, where the lateral infiltration flow is saturated and surface flow occurs.

4 RRI model Calibration and Validation

Calibration was performed using known rainfall data and observed river discharge data, adjusting selected model parameters in the model to match the model's outputs with the

Table 1. The calibration parameter values base on three land areas.

Calibration Parameters	Mountain	Flat Plain Area	Urban Area
Ns River	0.03	0.03	0.03
Ns slope	0.4	0.4	0.4
Soil depth h_d	1, 1.5, 2, 2.5, 3, 3.5	1	0.5
φ	0.463	0.501	0.475
k_{sv}	3.670×10^{-6}	1.000×10^{-6}	1.000×10^{-7}
Sf	8.890×10^{-2}	1.668×10^{-1}	3.163×10^{-1}
k _a	0, 0.025, 0.05, 0.1, 0.2	0	0

Table 2. The best Nash-Sutcliff efficiencies in calibration process for different event with different k_a value and soil depth h_d .

Sr	Events	k_a (m s ⁻¹)	Soil depth $h_{\rm d}$ (m)	Nash Sutcliffe Efficiency
1	2011	0.05	1.5	0.89
2	2012	0.05	2.5	0.93
3	2013	0	3	0.89
4	2014	0	3	0.89

observed values. Generally, the calibration procedure consists of a combination of manual and automated calibrations. In this study, finding acceptable parameters was based on manual calibration through trial and error. Table 1 shows the calibrated parameters, and Table 2 shows the best Nash-Sutcliff efficiencies for each rainy season's flood event of 2011, 2012, 2013, and 2014. The simulation period, from 7 June to 23 August, was selected based on the accumulative rainfall data, as shown in Fig. 2. For the initial condition of the simulation, the water depth was set to zero after the dry season. The calibration process was conducted for different soil depths h_d and different lateral saturated hydraulic conductivity k_a values in the Bago River basin on a daily flow basis. These values were considered to depend on the soil texture and particle size distribution. The soil depth $h_{\rm d}$ values depend on how much water can be stored in the soil conditions and the size of sediment materials in the basin area. As indicated in Eq. (4), the subsurface velocity of flux varies with the gradient of the water level. If large values of k_a are used, the water can pass through the river in the earlier stages before saturating the soil. When the water depth exceeds the soil depth above an impermeable layer, such as bedrock, infiltration stops, and the surface water flows as described in Eq. (3). If the soil depth h_d is high in the calculation, a large amount of water enters the river with $k_a = 0$, and only surface water goes into the river. On the other hand, if large values are used, the soil has storage space, and then the water slowly move into the river that the discharge will be decreased. This is the effect of k_a and soil depth h_d . Therefore, the depth of soil depth h_d and lateral saturated hydraulic conductivity k_a are important parameters for fixing these calibration events.



Figure 3. Simulated Hydrographs with different k_a values and calibrated soil depth h_d for each year.

A total of 80 numerical runs were conducted with perturbations of these parameters.

5 Results and Discussion

In this study, the discharge hydrographs with different k_a values and soil depths h_d for this river basin were compared between Myanmar and other countries. The simulated hydrographs with different k_a values and calibrated soil depth h_d are shown in Fig. 3. For each year, increasing the k_a value decreases the simulation discharge in the early stage but increases it in the late season because the river basin is already saturated. As a result, the water flows through the river on the water surface flows. If large values are used, the water can pass through the river in the earlier stage before saturating the soil. However, if very small k_a values are used, the ground becomes saturated in the early rainy season.



Average Rainfall 🚽 Sim Q (Soil 1) 🛶 Sim Q (Soil 1.5) 🛶 Sim Q (Soil 2) 🛶 Sim Q (Soil 2.5) 🛶 Sim Q (Soil 3.3) 🛶 Obs

Figure 4. The Simulated Hydrographs with different soil depth h_d values and calibrated k_a for each year.

The simulated hydrographs in different soil depth h_d values and calibrated k_a are shown in Fig. 4. When larger soil depth h_d values are used for year, the discharge becomes close to the observed discharge because the soil depth is high in the calculation, allowing a large amount of water to enter the river.

According to the simulation results, Table 3 shows the calibrated values for k_a and soil depth h_d for a mountainous area in Japan, Myanmar, and other countries. When calculated using the Nash Sutcliffe Efficiency value, which indicates a close relationship between the observed and simulated flow, the model performance is good. As a result, the best Nash Sutcliffe Efficiency values for the 2011 event were found to be soil depth $h_d = 1.5$ m and $k_a = 0.05$ m s⁻¹, $h_d = 2.5$ m and $k_a = 0.05$ m s⁻¹ for the 2012 event, $h_d = 3$ m and $k_a = 0$ m s⁻¹ for the 2013 event, and $h_d = 3$ m and $k_a = 0$ m s⁻¹ for the 2014 event, indicating a close correlation between the observed and simulated flows. In Japan's

Parameter	Japan (Subarctic & Subtropical)	Myanmar (This study) (Subtropical)	Oman (Arab Country) (Subtropical)	Thailand (Tropical)	Indonesia (Tropical)	Pakistan (Continental)
Lateral saturated hydraulic conductivity (k_a)	0.03–0.53	0-0.05	0.05	0.1	0.1	0.1–0.4
Soil Depth (h_d)	0.5–2	1.5–3	0.7–2	0.3	1.0	0.1

Table 3. Comparison of the differences in k_a values and soil depths h_d among different countries.

case, for the mountainous area, the values of lateral saturated hydraulic conductivity k_a ranged from 0.03 to 0.53, and the soil depth h_d values ranged from 0.5 to 2 (Sayama et al., 2020; Shimizu et al., 2019; Yagi et al., 2020). In Myanmar's case, for the mountainous area, the lateral saturated hydraulic conductivity k_a values ranged from 0 to 0.05, and the values for the soil depth h_d ranged from 1.5 to 3. In Oman's case, for the mountainous area, the values of lateral saturated hydraulic conductivity k_a is 0.05, and the soil depth h_d values ranged from 0.7 to 2 (Abdel-Fattah et al., 2018).

In Thailand's case, for the mountainous area, the values of lateral saturated hydraulic conductivity k_a is 0.1, and the soil depth h_d value is 0.3 (Sayama et al., 2017; Try et al., 2020). In Indonesia's case, for the mountainous area, the values of lateral saturated hydraulic conductivity k_a is 0.1, and the soil depth h_d value is 1.0 (Nastiti et al., 2018). In Pakistan's case, for the mountainous area, the values of lateral saturated hydraulic conductivity k_a ranged from 0.1 to 0.4, and the soil depth h_d value is 0.1 (Sayama et al., 2012).

Therefore, the values of lateral saturated hydraulic conductivity k_a of Myanmar are smaller and the soil depth h_d values are larger than those of other countries.

The best parameter range values and sensitive parameters will change for different countries due to the climate zone, geographical features, flood characteristics, river morphology and sediment size of the basin area.

According to the table, the parameter values for soil depth h_d in Myanmar have a larger range than those in other countries, and the values of k_a are smaller. When the gap between the soil and the sediment materials size is large, water can easily flow into the ground layer. In Myanmar's case, the size of the sediment materials is not too large, hence; water cannot easily flow into the ground layer.

6 Conclusions

In this study, the RRI model was applied to rainfall and flooding events that happened in Myanmar in 2011, 2012, 2013, and 2014. The hydrographs were created, demonstrating acceptable performance in simulating flood events and are closely related to meteorological hydrographs observed, indicating the usefulness of the RRI model for flood inundation analysis. In summary, this study investigated the differences in values of lateral saturated hydraulic conductivity k_a and the soil depth h_d between Myanmar and other countries. However, in terms of Myanmar's river basin, the k_a value ranges from 0 to 0.05, and the soil depth h_d ranges from 1.5 to 3. In this study, considering these two parameters, the evaluation of this model's simulation focuses on the infiltration process. Infiltration parameters vary with rainfall, soil porosity, and the topography of the study area. The rate of infiltration depends on measurable soil properties, such as hydraulic conductivity, and the soil depth h_d . The effects of the parameters of lateral saturated hydraulic conductivity k_a and the soil depth h_d were investigated within the optimal range of $k_a = 0$ to 0.05 and $h_d = 1.5$ to 3, which indicate deep and compacted soil layers compared to other countries. Therefore, these two parameters were used to provide satisfactory output for measured data, and those coefficients closely match what is expected from the study basin area in Myanmar. Apart from that, the difference in these two parameters indicates the geographical features of Japan, Myanmar, and other countries where sediment deposits are deeply in large flat areas. As a result, Japan, and Oman's values range of k_a and the soil depth h_d are very close to Myanmar's case because they are in the same climate zone. More detailed investigation of the differences in parameters and geographical features is required for future research avenues.

Code availability. The RRI model is accessible on the International Centre for Water Hazard and Risk Management (ICHARM) website: https://www.pwri.go.jp/icharm/research/rri/index.html (Sayama, 2024).

Data availability. Meteorological and Hydrological data were provided by the Department of Meteorology and Hydrology (DMH) in Myanmar. The data sets are not publicly accessible.

Author contributions. PPP designed, planned, collected the data, systematized the processing and analysis of meteorological data, and wrote the original manuscript in consultation with TU. TU supervised the project, provided research tools, and edited the manuscript.

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