Impact of temporal rainfall patterns on flash floods in Hue City, Vietnam

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Abstract

Urban flooding is a perennial problem, especially in developing countries with relatively weak infrastructure under ever-increasing stress due to climate change and human activities. We simulate the temporally variable flood-water depth and inundation area under four designed rainfall patterns in the typical tropical rainforest city of Hue, Vietnam. The four rainfall types are R1 (peak at fifth hour), R2 (peak at 20th hour), R3 (peak at first hour), and R4 (peak at 13th hour). Results show that temporal rainfall pattern R4 with peak rainfall in the middle of the total period yielded the maximum water depth of 1.88 m. R3, with peak rainfall in the first hour, yields the shallowest maximum water depth and the largest inundation extent. When the water depth for R3 is 0.1–0.2 m, the inundated area caused by R3 is 3–4 times that of the other three patterns. Analysis of urban flood inundation in Hue provides a management tool to facilitate flood risk management in the context of extreme rainfall.

KEYWORDS
Flo-2D model, flood inundation, inundation area, synthetic rainfall, temporal rainfall pattern

1 | INTRODUCTION

As extreme rainfall and urban flood inundation exacerbated by climate change and urbanization have led to large losses of life and property, these topics drive current research in water resources management (Ballesteros-Cánovas et al., 2014; Borga, Stoffel, Marchi, Marra, & Jakob, 2014; Luo et al., 2020). Changes in atmospheric

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Funding information
Excellent projects for science and technology activities of overseas staff in Shaanxi Province, Grant/Award Number: 2018038; Fundamental Research Funds for the Central Universities of China, Grant/Award Number: 300102299302; International Collaborative Research of Disaster Prevention Research Institute of Kyoto University, Grant/Award Number: 2019W-02; National Key R&D Program of China, Grant/Award Number: 2018YFE0103800; National Natural Science Foundation of China, Grant/ Award Number: 41501552; Natural Science Foundation of Jiangsu Province, Grant/Award Number: BK20161612

Received: 16 March 2019 Revised: 31 July 2020 Accepted: 12 September 2020
DOI: 10.1111/jfr3.12668

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J Flood Risk Management. 2021;14:e12668. wileyonlinelibrary.com/journal/jfr3
conditions drive increasingly extreme and frequent rainfall events (Donat, Alexander, Herold, & Dittus, 2016; Kunkel et al., 2013; Lehmann, Brench, Gebhardt, Schaller, & Sibauer, 2015; Plattner & GianKasper, 2014; Sarr, 2012). The Clausius-Clapeyron equation describes a rate of change of saturation vapour pressure of approximately $7\%\ C^{-1}$ at typical surface temperatures, and thereby sets a scale for increases in precipitation extremes (Trenberth, Dai, & Rasmussen, 2010). The world’s urban population reached half of the world’s total in 2008 and by 2050 it will exceed 60% (Litvovet et al., 2014). The most prominent impact of urbanization is on land use and land cover, with increasing impervious cover in urban areas driving dramatic changes in rainfall infiltration and storage capacity (Moglen & Glenn, 2009; Palla & Gnecco, 2015; Zhang et al., 2020). Natural disasters in developing countries are the cause of widespread economic losses and human casualties (Dan, 2010; Temmerman et al., 2013) and urban inundation is projected to continue to rise, particularly given the effects of global warming and extreme rainfall (Milly, Wetherald, Dunne, & Delworth, 2002; Wang, Hagen, & Alizad, 2013; Zevenbergen, Veerbeek, Gersonius, & Herk, 2010). Urban inundation will be particularly acute in coastal areas and low-lying terrain, where extreme rainfall will cause river overbanking exacerbated by sea level rise (Yang, Wang, Voisin, & Copping, 2015).

Although conventional approaches are increasing urban drainage capacity (Liao, Hejia, & Yang, 2015; Smits, Nienhuis, & Saejjs, 2006), flood management strategies have expanded to include soft infrastructure and strategic planning using flood risk maps (Bladé, Gómez-Valentin, & Sánchez-juny, 2008; Diaz-Nieto, Lerner, Saul, & Blanksby, 2012; Gain & Hoque, 2013; Luo, Kang, Apip, Lyu, & Aisyah, 2019; Price & Vojinovic, 2008). Scenario analysis and numerical simulations have become important methods for flood prediction, assessment, and management (Bubeck, Aerts, de Moel, & Kreibich, 2016; White & Greer, 2006). From the 1970s to the present, researchers have developed a variety of flood inundation models, including InfoWorks (Schmitt, Thomas, & Ettrich, 2004), MIKE (Zoppou, 2001), STROM (Roesner, Nichandros, & Shubinski, 1974), and UCURM (Papadakis & Preul, 1972). Two-dimensional models are increasingly used for flood simulations as they provide more detailed spatio-temporal detail of inundation depth and extent. The main principle of the two-dimensional model lies in the establishment of different boundary conditions, for example using the Saint-Venant equation, the runoff coefficient and infiltration curve methods were used to calculate runoff generation, and the confluence was calculated by hydrologic or hydrodynamic methods (Meierdiercks, Smith, Baek, & Miller, 2010; Mejia, Alfonso, & Moglen, 2009; Ogden, Pradhan, Downer, & Zahner, 2011). Geographic factors that affect urban flooding include soil conditions, climatic conditions, and land use, all of which can be represented easily using modern simulation models (Bartel, 2011; Faulkner, Francis, & Lamb, 2012). Remote sensing (RS) and geographic information systems (GIS) are widely used together for flood prediction (Bhan & Team, 2001; Dewan, Islam, Kumamoto, & Nishigaki, 2007; Giardino, Perotti, & Lanfranco, 2012; Rahman, Kumar, Fazal, & Bhaskaran, 2011; Werner, 2001). The Hydrologic Engineering Center river analysis system (HEC-RAS) and GIS have likewise been combined to obtain the inundation range and water depth of urban floods (Nut & Plermkamon, 2015).

Many studies focus on the effects of rainfall duration and intensity, while ignoring the role of temporal rainfall patterns on urban floods. Forestieri, Caraccio, Arnone, and Noto (2016) used the Topography based probability Distributed Model (TOPDM) to study early warning mechanisms of rainfall and floods under different temporal rainfall patterns in Sicily. Pedrozo-Acuna et al. (2017) used a 1D hydrological model for Tabasco, Mexico to simulate the urban inundation caused by different temporal rainfall patterns of different recurrence periods. Luo, Aipip He, Duan, Takara, and Nover (2018) established the area intensity-duration frequency (AIDF) curve by analysing rainfall data of the Kamo River and designed rainfall patterns based on extreme rainfall events under different return periods to represent distribution of rainfall intensities of certain duration.

The Storm Water Management Model (SWMM) is among the most widely used software for simulating rainfall-runoff in urban areas (Lee, Hewa, Pezzaniti, & Argue, 2008; Sun, Hall, Hong, & Zhang, 2014; Abdul-Aziz & Al-Amin, 2015; Yu, Huang, & Wu, 2014). SWMM is a physical model, whose runoff module deals with precipitation, runoff, and pollution load of each sub-basin. The SWMM model in present version poorly represents the spatial resolution of urban inundation conditions. Flo-2D is a physical model that calculates changes in surface velocity, water depth, and influence range caused by rainfall over time by establishing mass and momentum conservation equations in differential forms and solving them via the explicit central difference method. The Flo-2D model has been used widely in the simulation of two-dimensional debris flows. However, some researchers have used the Flo-2D model to simulate spatial urban flood conditions. Hu et al. (2017) used the Flo-2D model to simulate the flood condition at a single area in Nanjing, China, finding that two different measures of Low Impact Development (LID) construction can effectively reduce urban waterlogging in the event of extreme
Vu and Ranzi (2017) used the Flo-2D model to simulate flooding in Quang Ngai province in central Vietnam based on different storm types. However, little research focuses on the spatiotemporal dimensions of urban flood conditions and the way flooding is affected by rainfall type in Hue City.

This study uses historical rainfall data and Google Earth images, digital elevation models (DEM), soil data, land use data and Flo-2D to simulate urban inundation under four different temporal rainfall patterns for Hue, Vietnam. Vietnam is appropriate for a case study as global warming is driving extreme rainfall in an infrastructure-poor context, leading to serious and complex floods. We present maximum water depth as well as inundation area on an hourly basis under different temporal rainfall patterns and inundation maps of the study area. This study is also designed to address the relationship between peak rainfall timing and subsequent spatial flooding. Simulations of urban flooding provide a scientific basis to guide urban flood risk management.

2 | STUDY AREA AND DATA PROCESS

2.1 | Study area

Hue, Vietnam’s ancient capital, is in central Vietnam at latitude 16°20‘-16°45‘ and longitude 107°00‘-108°15‘. It covers an area of 150 km² and has a population of about 340,000. On the west side of Hue is Truong Mountain, where the elevation ranges from 5 to 1760 m. At the north of Hue is Bach Ma Mountain and south of Hue is the Dong Sea. The Huong River, the largest of four in around the city, passes through Hue, dividing Hue City into two parts. Our study area is in the southern reach of the Huong River (Figure 1). Hue has a typical tropical rain forest climate with maximum temperature of about 35–40°C during March to August. The average temperature from August to January is about 20°C. Hue is located in the tropical monsoon region with average annual rainfall from 2,500 to 3,500 mm. The rainy season, and therefore the flood season, runs from October onward.

Flood risk in Hue has increased in recent years as economic development and urbanization have advanced in Vietnam. November 2007 floods caused over 155 deaths, November 2013 floods caused more than 40 deaths, and October 2016 floods caused more than 30 deaths (Table 1). At the Vietnam Venture Financing Conference, the World Bank reported that about 60% of the country’s land and 71% of the population are exposed to the risks of typhoons and floods. The economic losses caused by floods and typhoons are about 0.8% of Vietnam’s GDP and the World Bank forecasts that Vietnam will lose more than US $6.7 billion due to flooding in the next 50 years.

2.2 | Data processing

This study employs high-resolution Google Earth images with resolution of 1 m. The Environment for Visualising Images software (ENVI) is used to classify Google Earth screenshots. Classification yields land-use maps of the research area. The current land uses in the research area

Figure 1 Location of Study area in the central area of Hue city
are divided into water (20%), road (15%), forest (5%), urban land (38%), and open land (22%). The Manning coefficient is determined for each of the five land-use types obtained through supervised classification. The Manning coefficient of a flooded area depends on many factors such as the structure and type of the ground cover, the cross-sectional area of the river, the degree of meandering, and urban impervious areas. This coefficient is mainly used to describe the retarding of floods by different land types, as determined by the reference values given in the Flo-2D manual. The main road system is extracted based on the resolution of the image and the accuracy of the software. DEM and land use maps are shown in Figure 2. Soil data were sourced from the Global Soil Data Types Library, Soil Map Based Harmonised World Soil Database (HWSD) on the Food and Agriculture Organisation of the United Nations (FAO) website (http://www.fao.org/home/en/), and soil data were processed in ArcGIS. The soil type called Acrisol-AC, homogenous across the city, is obtained from 8 km resolution HWSD data. The 30 m DEM is derived from the USGS (United States Geological Survey) website (http://www.usgs.gov/). Study site elevations ranged from 1 to 24 m. Historical maximum daily rainfall of 977.6 mm was found for Hue from the Vietnam National Center for Hydro-Meteorological Forecasting (NCHMF) (http://www.nchmf.gov.vn/web/vi-VN/43/Default.aspx). All design storms have the same peak rainfall of 97.76 mm/hr. In this study, we set the total rainfall period within 24 hrs. The design storms have stable increasing rainfall intensity before the peak, and stable decreasing rainfall intensity after the peak. Figure 3 shows the distribution of rainfall for the four different temporal rainfall patterns considered in this study. Four extreme temporal rainfall patterns were chosen for this study based on historical temporal rainfall patterns of Hue and the temporal rainfall patterns proposed by Luo et al. (2018). The first temporal pattern of rainfall (R1) shows a rapid increase within 5 hrs, reaching peak rainfall in the fifth hour and slowly decreasing from the sixth hour to the twenty-fourth hour. The second temporal pattern of rainfall (R2) shows a slow increase from the first hour to the twentieth hour, reaching the peak rainfall in the twentieth hour, and rapidly decreasing from the twentieth hour to the twenty-fourth hour. The third rainfall pattern (R3) reaches peak rainfall in the first hour and decreases from the first hour to the twenty-fourth hour. The fourth rainfall pattern (R4) reaches peak rainfall in the middle of the thirteenth hour.

### METHODOLOGY

#### 3.1 Flo-2D model

The Flo-2D model was developed by Flo-2D Engineering Inc. (https://www.flo-2d.com/) to calculate two-dimensio
nal flow combining river and pavement based on the Newtonian fluid model and the central finite difference numerical method. The basic equations of the model include continuity equations and equations of motion, where the continuous equations of the model are given in Equation (1). When a flood occurs, the continuity equations are calculated to control the mass conservation of the flow.

\[
\frac{\partial h}{\partial t} + \frac{\partial h}{\partial x} V_x + \frac{\partial h}{\partial y} V_y = i
\]

(1)

The equation of motion is calculated as follows, which is a momentum balance equation for the flow of water and predicts the flooded area.

\[
S_{fx} = S_{sx} (\frac{\partial h}{\partial x} V_x) - V_y (\frac{\partial V_y}{\partial x}) - (\frac{\partial}{\partial t}) (\frac{\partial V_y}{\partial t})
\]

(2)

\[
S_{fy} = S_{sy} (\frac{\partial h}{\partial y} V_y) - V_x (\frac{\partial V_x}{\partial y}) - (\frac{\partial}{\partial t}) (\frac{\partial V_x}{\partial t})
\]

(3)

where \(h\) is water depth; \(i\) is rainfall intensity; \(t\) is time; \(g\) is acceleration due to gravity; \(V_x\) and \(V_y\) are average flow velocities in the \(x\) and \(y\) directions; \(S_{sx}\) and \(S_{sy}\) are slope of the bed in the \(x\) and \(y\) directions; and \(S_{fx}\) and \(S_{fy}\) are the energy gradients in the \(x\) and \(y\) directions.

The Flo-2D model provides three methods for ground infiltration, including Green-Ampt infiltration, Horton infiltration, and the Soil Conservation Service (SCS) curve infiltration method (Mishra, Jain, & Singh, 2004). We used the SCS curve method for computational efficiency. The value of the curve number (CN) method from the SCS curve is taken from the reference table in the manual of Grid Developer System (GDS) pro.

**FIGURE 3** Four designed temporal rainfall patterns (a) Rainfall NO. 1 (R1), (b) Rainfall NO. 2 (R2), (c) Rainfall NO. 3 (R3), (d) Rainfall NO. 4 (R4)
3.2 | Research framework for urban flood inundation

The 30 m resolution DEM is input to the Flo-2D model, Google images of Hue are added, and the study area border is defined. After setting up the calculation area, elevation values in each grid cell are determined by interpolation. The model assigns the rainfall for each hour of the first extreme temporal rainfall pattern in the rain module. The CN value for each grid cell and SCS values for the infiltration model considering land use and soil type are assigned based on the Flo-2D manual reference table for Manning coefficients for land types and CN reference tables for SCS infiltration curves. We simulate the hourly inundation up to 30 hrs based on the 24-hrs designed rainfall. We select the sixth hour, twelfth hour, eighteenth hour, twenty-fourth hour, and the maximum water depths and inundation area of each storm under the four temporal rainfall patterns. Our results demonstrate the impact of different temporal rainfall patterns on urban inundation and suggest management implications. Pipe systems are not included in our simulation due to lack of available data, but we increase the infiltration value instead of the pipe system for the urban area. Simulations are based on the urban area with the red boundary in Figure 1. Water flow to the rivers is precluded as the riverbank is higher than the urban area in our boundary conditions. Flow from the riverbank is not considered in this research. Although the period of designed rainfall is 24 hrs, our total simulation period is 30 hrs to check the flow conditions in the final stage. The detailed research framework is shown in Figure 4.

4 | FLOOD INUNDATION RESULTS UNDER DIFFERENT TEMPORAL RAINFALL PATTERNS

The area of maximum water depth and the inundation area under different water depths are shown in Table 2. The water depth and inundation area per hour under the four temporal rainfall patterns are shown in Figure 5, and the maximum water depth at each point in the study area is shown in Figure 6. To make the submergence display more intuitive, we set the minimum water depth for the visualisation tool in Flo-2D at 0.1 m. When the water depth exceeds 0.1 m, road inundation becomes more severe. Table 2 shows the maximum submergence depths of the four temporal rainfall patterns of 1.84, 1.85, 1.75, and 1.88 m, respectively. The maximum water depth of R4 (highest rainfall intensity at the center of the storm duration) is greater than R1 (highest rainfall intensity at the fifth hour), R2 (highest rainfall intensity at the twentieth hour) and R3 (highest rainfall intensity at the beginning of the storm). The maximum water depth for R3 is the lowest of the rainfall types, but the inundation area is the largest for all rainfall types. The maximum water depth of R4 is the highest with 1.88 m, but the inundation area occupied by the different water depths is the smallest.

The maximum water depth and inundation area of R1 is shown in Figure 6. To describe the maximum water depth of the study area in detail, we divide the study area into four parts: north, south, east and west. In the northern part of the study area, the flood depth reaches 1.02 m. In the southern part of the study area, the inundation area is large, but submerged areas are
scattered. The water depth in this area is generally between 0.47 and 0.75 m. Inundation in the eastern part of the study area is continuous and relatively shallow with water depth between 0.2 and 0.5 m. The eastern part of our study area is of lower elevation and the flooding range is therefore larger. In the west, during the entire storm, the inundation near the Xiang River, which passes the city center, is the most seriously inundated area with the highest water depth of 1.88 m. The average water depth on the east side of the Xiang River is close to 1 m. This water depth is much higher than that of the inundation in the urban area. Based on DEM and satellite images, the dykes on the west side of the main channel have higher elevation, meaning that inundated water cannot flow into the Xiang River. Extreme rainfall causes the water level in the Xiang River to rise so that flood water in the urban area cannot discharge into the river through the sewage system. The water depth and inundation area under R2 is quite similar with that of R1. R3 yields different results in terms of water depth and inundated area. In the southern part of our study area, many inundation points are added, and many of these inundation points are connected, forming a new inundation area.

**TABLE 2** Inundation conditions at the maximum water depth statement under four extreme temporal rainfall patterns

|           | Maximum water depth | 0.1–0.2 m | 0.2–0.3 m | 0.3–0.4 m | 0.4–0.5 m | >0.5 m |
|-----------|---------------------|-----------|-----------|-----------|-----------|--------|
| R1        | 1.84 m              | 9.05%     | 11.07%    | 4.70%     | 0.95%     | 1.10%  |
| R2        | 1.85 m              | 9.00%     | 10.46%    | 4.55%     | 0.95%     | 1.05%  |
| R3        | 1.75 m              | 12.78%    | 15.36%    | 5.45%     | 1.12%     | 1.02%  |
| R4        | 1.88 m              | 8.93%     | 10.76%    | 4.36%     | 1.12%     | 1.12%  |

*Note: The percentage is the inundation area divided by the total area at different water depths.*

**FIGURE 5** Inundation area under each hour at different water depths
We took the water depth and inundation area of the sixth, twelfth, eighteenth, and twenty-fourth hour, as shown in Figures 7, 8, 9 and 10 to better understand the process of urban inundation under different extreme storms. In the case of R1 (Figure 7), flooding reached a maximum near the sixth hour of rainfall, as seen in the maximum water depth map. At the 12th, 18th and 24th hours, the inundation area and water depth decrease with decreasing rainfall intensity. The rainfall pattern dictates the inundation conditions in the urban area. The inundation area of water depth from 0.1 to 0.2 m increases significantly in the third hour compared with that in the second hour (Figure 5). In the fifth hour, the inundation area of water depth above 0.2 m increases significantly, but inundation area for water depth from 0.1 to 0.2 m is less than that in the other hours. Figure 8 shows the inundation area for R2, with some inundation area for the sixth hour and little inundation area for the 12th hour. However, there is significant inundation area at the 18th and 24th hours. Compared with the inundation area at the 18th hour, the inundation area of the last hour is reduced significantly. As peak rainfall is reached in the 20th hour, rainfall from the first to sixth hour does not cause flooding in urban areas. Figure 3 and Figure 5 show that maximum water depth was reached after the peak rainfall. Maximum inundation area and water depth occur in the 20th hour. For R3, the rainfall intensity decreases with time, and the rainfall peaks in the first hour (Figure 9). The inundation area with water depth of 0.1–0.3 m occupies 20% of the entire study area. The water depth of 0.2–0.3 m reached 10.43% of the total area in the second hour (Figure 5). The short duration of heavy rainfall caused the maximum water depth to rise drastically in a short period. With decreasing rainfall intensity, the inundation area of 0.1–0.2 m and 0.2–0.3 m is like that of R1 in the 12th hour. At the same time, the inundation area with water depth > 0.5 m is above 0.6%. For R4, due to the peak of its temporal rainfall pattern, the maximum water depth and inundation area appear in the 13th hour. Figure 10 shows that
during the period from the first hour to the sixth hour of rainfall, no flooding occurs in the study area. According to Figure 5, when the peak rainfall arrives, the water depth of 0.2–0.3 m increases significantly with 10.56% of the total area in the 13th hour. As the rainfall intensity decreases, the inundation area gradually decreases.

5 | DISCUSSION

Vietnam is flood-prone due to weak infrastructure, low-lying topography, long rainy seasons, and extreme rainfall. We use Flo-2D to simulate the inundation conditions under four synthetics rainstorms and explore the influence of temporal rainfall patterns on urban flood inundation. Rainfall pattern R3 yields a wide inundation area compared to the other temporal rainfall patterns. Maximum water depth occurred after the time of peak rainfall, and the rainfall shapes have a strong impact on water depth and inundation area. At the same time, we find that the essence of different temporal rainfall patterns is the difference in the temporal position of the peak of rainfall. The rain peak position coefficient is the ratio of the time of peak rainfall divided by the total duration hours: for example, the fifth hour is the peak rainfall, it is 5/24 which is 0.208. The rain peak position coefficients of the four temporal rainfall patterns are 0.208, 0.833, 0.042, and 0.542, respectively. As the position coefficient of the rain peak increases, the peak rainfall appears later in time. The interval time between the peak rainfall and the occurrence of the maximum water depth decreases continuously meaning that the peak rainfall comes later as the maximum flood water depth comes earlier. If we collect the total surface runoff from rainfall, the total amount of surface runoff increases as the rain peak position coefficient is lower. When the rain peak position

FIGURE 7  The water depth and inundation area of sixth, 12th, 18th and 24th hour under the R1
coefficient is smaller, the inundation area is larger (the inundation area of R3 is 35.73%, that of R1 is 26.87%, that of R4 is 26.29%, that of R2 is 26.01%). Hou, Guo, and Wang (2017) studied the location coefficient of rain peak and urban flood in Xi’an, China, and concluded that under the 20 years return period storm, earlier peak rainfall corresponds to larger inundation areas. Flanagan, Foster, and Moldenhauer (1988) showed that the peak rainfall position has a significant impact on the peak runoff rate for air-dried soil. Frauenfeld and Truman (2004) identified the fact that changes in rainfall patterns have a large impact on runoff intensity. The effects of rainfall intensity on flooding were analysed in detail in the Hanoi central area of Vietnam (Luo, Mu, et al., 2018). Wen, Zheng, and Yang (2012) found that the total runoff generated under the peak rainfall coming in the central period was 1.12 times than that under the peak rainfall coming in the last hour. Our results show that position of peak rainfall has a significant effect on runoff and flood inundation.

When rainfall intensity is not large, excess water can be removed via conventional drainage networks (Mishra et al., 2004). Extreme rainfall challenges conventional drainage networks. First, rainfall will quickly converge in low-lying areas and eventually exceed the drainage capacity of the drainage network. Second, overwhelmed drainage systems that discharge to surrounding rivers cause downstream flooding. Addressing flood risk associated with extreme rainfall requires changing management strategies and governance approaches and adoption of comprehensive response systems including robust planning and pollution source

**FIGURE 8** The water depth and inundation area of sixth, 12th, 18th and 24th hour under the R2
control, enhanced infiltration, storage, and drainage. The Vietnamese Government is paying careful attention to considering both structural (e.g., dike construction) and non-structural flood mitigation (flood plain management and regulations), flood and disaster-warning systems, emergency preparedness and disaster management (Pilarczyk & Nuoi, 2005) to minimise flood damage. Hue lies on flat terrain in the tropics and close to the coastline. As the groundwater table is high, the measures of infiltration are less effective. Drainage measures require a certain elevation difference, while the Hue terrain is flat, and it is difficult to reform the drainage measures. It is possible to introduce permeable surfaces on both sides of the road and establish rainwater gardens and concave-down greenbelts which let some water infiltrate into the ground. Pump station construction could further alleviate inundation in the city center by moving floodwater to lakes and reservoirs. Rainwater harvesting systems can reduce discharge to the sewer system in densely populated residential areas. Underground water storage systems in flood-prone areas could further reduce flood inundation risk. Our results show that when the peak rainfall comes early, it causes larger inundation areas than under other rainfall types. This result suggests the need to focus on wide flood prone inundation points. When rainfall increases, focus must be placed on the lowest elevation points, and the area with old drainage systems and high building density which may cause higher water depths. Our study provides guidance to reduce cost and improve efficacy of flood warning system for flood risk management.

**FIGURE 9** The water depth and inundation area of sixth, 12th, 18th and 24th hour under the R3
6 | CONCLUSION

We present simulations of hourly water depth, maximum water depth, and inundation area under four designed extreme temporal rainfall patterns in Hue, Vietnam. The spatial flood conditions at the maximum water depth and the sixth, 12th, 18th and 24th hour were displayed with Google maps. The maximum water depths of flood inundation in Hue under the four temporal rainfall patterns occurred after the time of peak rainfall.

Extreme temporal rainfall patterns have a significant impact on the depth and area of urban floods. The following conclusions are drawn through the simulation: (I) The peak rainfall coming in the early hours results that the speed of flow generation and confluence is becoming faster, and the inundation area under this type rainfall is larger than that under other types rainfall. (II) When the peak rainfall is in the middle, the maximum water depth is the largest amount that of all rainfall types.

The temporal rainfall pattern is a major factor influencing spatial inundation conditions of urban floods. Urban floods can be predicted through a combination of meteorological data gathering and modelling simulation. Simulation model results expose flood prone areas which were inundated in the past and suggest target areas for flood risk management. Preventing urban floods requires consideration of urban river water level, discharge gates for urban drainage systems and approaches to drainage. A combination of structural and
nonstructural measures, ranging from rainfall harvesting systems, rainfall gardens, sewage systems, underground water storage systems and cellphone-based information systems can help manage flood risk considering the sub-daily impact of temporal rainfall patterns. Results inform urban flood risk management in significant ways, while further study is needed to improve spatial and temporal resolution and consider different synthetic storm types.

ACKNOWLEDGEMENTS
We received financial support from the National Key R&D Program of China (2018YFE0103800), Fundamental Research Funds for the Central Universities of China (300102299302), National Natural Science Foundation of China (No. 41501552), International Collaborative Research of Disaster Prevention Research Institute of Kyoto University (2019 W-02), Natural Science Foundation of Jiangsu Province (No. BK20161612), One Hundred Talent Plan of Shaanxi Province, the Innovation Training Program for Undergraduate Students of Chang’an University (201610710079), Excellent projects for science and technology activities of overseas staff in Shaanxi Province (2018038), and Special funds of education and teaching reform for the Central Universities of China (310629172112). This work was supported by the National Natural Science Foundation of China (Grants No. 41877232, and 41790444); High-tech research cultivation project (Grants No. 300102299201); Key R & D projects of Shaanxi Province (Grants No. 2020SF-424); Key Laboratory Open Project Fund of State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, CAS (Grants No. SKLQG1909). The authors thank the reviewers for the valuable comments for improving this paper.

AUTHOR CONTRIBUTIONS
D.M. and P.L. wrote original draft preparation; M.Z., J.L., and D.N. wrote review and edited the manuscript; P.L. did supervision; B.H., X.Z., and W.D. did data curation.

CONFLICT OF INTERESTS
The authors declare no conflict of interest.

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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**How to cite this article:** Mu D, Luo P, Lyu J, et al. Impact of temporal rainfall patterns on flash floods in Hue City, Vietnam. *J Flood Risk Management*. 2021;14:e12668. https://doi.org/10.1111/jfr3.12668