Significant Impacts of Rainfall Redistribution through the Roof of Buildings on Urban Hydrology

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ABSTRACT: Microtopography on a building roof will direct rainfall from roofs to the ground through downspouts and transform the rainfall spatial distribution from plane to points. However, the issues on whether and how the building-induced rainfall redistribution (BIRR) influences hydrologic responses are still not well understood despite the numerous downspouts in the urban area. Hence, this study brings the roof layer into a grid-based urban hydrologic model (gUHM) to quantitatively evaluate the impacts of BIRR, aiming to enhance the understanding of building effects in urban hydrology and subsequently to identify the necessity of incorporating BIRR into flood forecasting. Nine land development strategies and 27 rainfall conditions are considered herein to characterize the changing circumstance. Results indicate that the impacts of BIRR depend on multiple circumstance factors and are nonnegligible in urban hydrology. The BIRR causes not only bidirectional impacts on the hydrologic characteristic values (e.g., peak flow and runoff volume) but also an obvious alteration of the hydrograph. Overall, the BIRR tends to increase the peak flow, and more importantly, the impact will be aggravated by the increase of rainfall intensity with the maximum relative error of peak flow approaching 10%. This study contributes to a better understanding of building effects on urban hydrology and a step forward to reduce the uncertainty in urban flood warnings.

KEYWORDS: Flood events; Precipitation; Hydrology; Hydrometeorology; Radars/Radar observations; Hydrologic models

1. Introduction

Continuous urban expansion and increasing rainfall extremes give rise to frequent flooding and waterlogging (Blair et al. 2014; Yang et al. 2013; Zhang et al. 2018, 2020), leaving behind major casualties in both property damage and loss of lives (Ashley and Ashley 2008; Montz and Gruntfest 2002). With developing science and technology, the death toll due to flooding-induced disasters has been effectively curbed, whereas economic loss geometrically rises because of increasing property exposure to floods (Salman and Li 2018; Wing et al. 2017, 2018). Hence, considerable effort is honed to investigate the induce factors in flooding and the strategies to mitigate flood risks in urban areas. Among them, as a basic facility in cities, buildings significantly alter the hydrological process in the urban area, which has been considered to be a research hotspot (Chen et al. 2012; Huang et al. 2014; Isidoro et al. 2012; Lee et al. 2016; Zhou et al. 2016).

Currently, enormous studies focus on the blockage effects of buildings, where the existence of buildings alters the initial overland flow paths determined by gravity’s direction. To estimate the blockage effects of buildings, various methods in the past are adopted, such as increasing the roughness in localized areas to represent buildings (Connell et al. 2001; Vojinovic et al. 2011), blocking 2D elements or removing them from the simulation grid (Chen et al. 2008; Russo et al. 2012; Zoran 2009) and increasing the bottom elevation of buildings (Brown et al. 2007; Cea et al. 2010; Leandro et al. 2016). McMillan and Brasington (2007) tested the effects of building blockage in urban inundation simulation and demonstrated the necessity of considering building characteristics in each grid unit when a coarse model is adopted. Lee et al. (2016) further emphasized the importance of involving building configuration, and then noted that building blockage effects can alter the shape of hydrographs and the distribution of the urban inundation.

For a developed urban area, the building area generally accounts for a large proportion. Yu et al. (2010) evaluated the building density in downtown Houston using airborne lidar data and an object-based method a decade ago. Results show that more than 40% of hundreds of land lots have a value of building coverage ratio (BCR) larger than 0.5, i.e., over 50% of ground space is occupied by building structures. More importantly, field observation indicates that building roofs typically convert a large proportion of rainfall into runoff, with a ratio of up to 92% (Farreny et al. 2011). Hence, not only the magnitude but the exact footprints of the runoff generated from building roofs is worthy of great attention in urban hydrologic response, considering the diverse surrounding conditions. However, the commonality of the aforementioned studies simplifies the routing process from the roof to the ground, such as disregarding the runoff from roofs (Chen et al. 2008) or force-routing it along the steepest direction, and does not pay more attention to the effects of building downspouts. To simulate the reality, Leandro et al. (2016) and Chang et al. (2015) proposed a novel approach considering the key features in urban flooding simulation and taking into account the effects of downspouts, i.e., forcing the runoff from roof routing into one downspout and then subsequently routing into the drainage system. The research results...
indicate that the existence of downspouts directly connected to the drainage system may cause surpassing drainage capacity within the pipe network in inundation zones, leading to more serious waterlogging. In reality, buildings are generally equipped with more than one downspout, and most downspouts are not directly connected to the drainage system in the urban area (Lee and Heaney 2003; Voter and Loheide 2018; Woznicki et al. 2018). Hence, the runoff from the roof will be allocated to different directions rather than the direction determined by the building bottom elevation. Transforming initial spatial rainfall distribution on roofs into a new concentrated pattern at each building downspout is called building-induced rainfall redistribution (BIRR) herein. However, whether and how the BIRR influences urban hydrologic responses are still less understood.

The current work aims to figure out the following issues: 1) whether the BIRR is negligible in urban hydrology; 2) if not, what the impact of BIRR is and how it responds to the changes of circumstance factors; and 3) why BIRR influences the hydrologic responses. Hence, the roof layer becomes a focal point here and is brought into the distributed urban hydrologic model as described in section 2. Simultaneously, multiple circumstance variables, including rainfall characteristics, building distribution, and the landscape type surrounding the buildings, are incorporated in the numerical simulation scheme, and both dimensional and nondimensional indicators are adopted to quantify the

![FIG. 1. The grid-based urban hydrologic model: (a) the diagram of model three-layer structure and routing relationship between different layers and (b) the flowchart of the calculation module.](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sin_pav</td>
<td>One single building combined with pavement</td>
</tr>
<tr>
<td>2</td>
<td>Low_pav</td>
<td>4-building cluster combined with pavement</td>
</tr>
<tr>
<td>3</td>
<td>Hig_pav</td>
<td>16-building cluster combined with pavement</td>
</tr>
<tr>
<td>4</td>
<td>Sin_law</td>
<td>One single building combined with lawn</td>
</tr>
<tr>
<td>5</td>
<td>Low_law</td>
<td>4-building cluster combined with lawn</td>
</tr>
<tr>
<td>6</td>
<td>Hig_law</td>
<td>16-building cluster combined with lawn</td>
</tr>
<tr>
<td>7</td>
<td>Sin_BRC</td>
<td>One single building combined with BRC</td>
</tr>
<tr>
<td>8</td>
<td>Low_BRC</td>
<td>4-building cluster combined with BRC</td>
</tr>
<tr>
<td>9</td>
<td>Hig_BRC</td>
<td>16-building cluster combined with BRC</td>
</tr>
</tbody>
</table>
impacts (in section 3). Section 4 comprehensively illustrates the impacts of BIRR on various hydrological characteristics under changing circumstance conditions. Subsequently, the causes of why BIRR influences hydrologic responses, the interaction between different circumstance factors, and the attribution analysis for the extreme impacts are further discussed in section 5. The last section provides closure with a set of conclusions.

2. Grid-based urban hydrologic model

A grid-based urban hydrologic model (gUHM), which has been validated repeatedly in a typical urban catchment (Cao et al. 2020a,b; Cao and Ni 2019; Lyu et al. 2018), has been constructed to estimate the hydrologic response in an ideal urban catchment as large as 4 ha. To yield a more realistic description of the complex flow paths and better reflect the effects of buildings, the roof layer is brought into the gUHM besides the traditional layers of surface and sewer network as shown in Fig. 1a. Surfaces are stratified into two categories: roads and non-roads. Grid units of roads are identified: if the grid unit of the surface contains road, the runoff generated from this unit will be routed directly into a sewer network, usually buried in the soil under the road surface; if not, the D8 algorithm (Gangodagamage et al. 2011; Passalacqua et al. 2010) is adopted to compute the direction of overland flow. To approximate the authenticity of reality and ensure the feasibility of study simultaneously, the time step of gUHM is set as 1 min and a series of assumptions are conducted: 1) the buildings are assumed to be regularly rectangular, equipped with downspouts at each of the four corners of the building, and with sufficient drainage capacity to avoid water spilling from the roof; 2) the rainfall falling onto the building roof is assumed to be equally allocated to the four corners of each building, and then flow into the underlying surface through downspouts without time delay.

The model calculation module mainly consists of three parts: runoff generation, overland flow, and sewer flow, as shown in Fig. 1b. To calculate surface runoff, every grid is subdivided into impervious areas and pervious areas. The Green–Ampt method (Brakensiek and Onstad 1977; Green and Ampt 1911; Liu et al. 2020; Huo et al. 2020) is invoked to simulate the infiltration process inside pervious areas. Evaporation during the

FIG. 2. Illustration of the flow field with and without the consideration of the BIRR under different building spatial distribution: (a)–(c) without considering BIRR and (d)–(f) considering BIRR.
The rainfall period is negligible and thus assumed as naught. The nonlinear reservoir algorithm (Rossman and Huber 2015) is employed to estimate the overland flow inside the grid. To accord with the hydrologic characteristics of urban catchment, the slope of grids is uniformly set as the mean value of the campus of Tsinghua University, which has been selected as a typical urban catchment to conduct related research work many times (Cao et al. 2020a; Lyu et al. 2018). The routed flow is then distributed uniformly over the downstream grid. Given the effect of backwater and turbulence in the sewer network, the one-dimensional dynamic wave approach is selected to compute the sewer flow to obtain a better simulation (Rossman and Huber 2017).

3. Numerical simulation scheme and evaluation method

To understand the impacts of BIRR on the hydrologic response, we will investigate it through the following two aspects: 1) different land development scenarios and 2) synthetic rainfall events. For the analysis of the results, we use both dimensional and nondimensional indicators to quantitatively evaluate the impacts on multiple hydrological characteristics including peak flow, runoff volume, and the shape of flood hydrograph.

a. Land development scenarios

To investigate the impacts of BIRR on the hydrologic response, nine development scenarios are designed in a 4-ha area (a residential scale) based on the gUHM, which are obtained by a cross combination of different building distributions and landscape measures (Table 1). All development scenarios are based on an open space surrounded by a looped asphalt road which is equipped with a good drainage system as shown in Fig. 1a; the patterns of building distribution are categorized into three groups: 1) one single building, 2) 4-building cluster (i.e., low discrete distribution), and 3) 16-building cluster (i.e., high discrete distribution), as shown in Fig. 2. Three landscape measures are designed for the study area, inclusive of pavement, lawn, and bioretention cell (BRC). Pavement only can store limited stormwater during the initial stage of rainfall without infiltration capacity, and the lawn is capable of both infiltration and storage. BRC, as a measure of low impact development (LID), is composed of surface layer, soil layer, and storage layer, which has a higher runoff reduction capacity compared to lawn (Lim and Welty 2017; Woznicki et al. 2018) and pavement. The position and distribution of the landscape measures are delineated in Fig. 3, where we take the spatial distribution of the four-building cluster, for example. Considering the general existence of the driveway in front of buildings, the landscapes are thus only adopted at three sides instead of surrounding the whole building.

Considering the focus of the current study, the topography is simply assumed to be generally higher in the northwest and lower in the southeast, and the outlet is located at the southeast corner of the study area as shown in Fig. 2. Therefore, when the BIRR is ignored, i.e., disregarding the existence of downspouts around each building and the microtopography on rooftops, the main routing direction of runoff is from the northwest to the southeast, but local routing directions may be changed obviously due to the blockage of buildings and the drainage of sewer network (Figs. 2a–c). Among them, the runoff routed onto buildings is divided into two parts with different flowing directions and then flows around the edifice barrier due to the blockage effects; the runoff generated from or routed onto the road directly flows into the sewer network due to the existence of stormwater inlets along the road. In contrast, when the BIRR is considered, the runoff generated from the rooftops first flows to each corner of buildings (Figs. 2d–f), and then flows onto the ground through downspouts. Once the runoff

![Diagram of landscape intervention scenario](image)

**Fig. 3.** The diagram of the landscape intervention scenario taking the four-building cluster as an example. The blue arrows show the flow directions in different zones.

<table>
<thead>
<tr>
<th>Land cover</th>
<th>Slope (%)</th>
<th>n</th>
<th>Depression storage (mm)</th>
<th>( K_{\text{sat}} ) (mm h(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>2</td>
<td>0.012</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Concrete pavement</td>
<td>1</td>
<td>0.012</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Asphalt road</td>
<td>2</td>
<td>0.015</td>
<td>1.5</td>
<td>—</td>
</tr>
<tr>
<td>Lawn</td>
<td>1</td>
<td>0.15</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2. Key modeling parameters for different land covers; \( n \) and \( K_{\text{sat}} \) indicate Manning’s roughness and the saturated soil hydraulic conductivity, respectively.
generated from roofs arrives at the ground, it will flow and infiltrate along with the surface topography until reaching the drainage system.

To precisely represent the hydrologic characteristics in an urban catchment to get reliable simulation, specifying the values of key parameters scientifically for a model is another critical step (Krebs et al. 2013; Sun et al. 2014). In this study, the soil is assumed to be uniform in such a 4 ha catchment (Zhang et al. 2019a,b,c). The hydrological and hydraulic parameters of surface, soil, road, and sewer network are determined according to the practice of the relevant urban catchment studies (Awol et al. 2018; Chen et al. 2017; Lyu et al. 2018). Given concrete pavements are generally smoother compared with asphalt road, and thus both lightly reduced roughness and depression storage are supposed. The soil parameters related to infiltration reflect the characteristics of clay loam, with moderate infiltration capacity as is common in many areas. The parameters of each layer of BRC are set according to the relative studies (Mei et al. 2018; Palla and Gnecco 2015; Rossman 2010). The key parameters are summarized in Table 2.

b. Synthetic rainfall events

Given the inherent features of the urban catchment with high impervious rate and fast hydrologic response, urban hydrologic response presents significant sensitivity to the variation of rainfall characteristics (Chao et al. 2018). Therefore, to improve the understanding of the impacts of BIRR on urban hydrology, it is necessary to consider the variation of rainfall characteristics, e.g., rainfall duration, rainfall intensity, and peak ratio. First, the input rainfall intensity is derived according to the regional storm intensity formula (SIF) in Beijing, China (Qiang et al. 2011; Yao et al. 2016), which represents an intensity–duration–frequency (IDF) relationship as follows:

$$p = 12.004 \times \frac{(1 + 0.81 \times \log P)}{(t + 8)^{3/4}},$$

(1)

where $p$ denotes rainfall intensity (mm min$^{-1}$), $t$ denotes rainfall duration (min), and $P$ equals the return period (year) reflecting rainfall intensity. Subsequently, the Chicago Storm Profile (Qin et al. 2013; Yin et al. 2016; Zhou et al. 2018) is used to generate the rainfall hyetograph with different rainfall peak ratios $r$. Peak ratio is a coefficient to describe the relative location of peak rainfall during the entire rainfall duration, ranging from 0 to 1, and the peak ratios of 0.2, 0.5, and 0.8 are adopted herein. Concurrently, the rainfall return periods are designated as 1, 10, and 100 years; the varying

![Fig. 4. Synthetic rainfall hyetograph with varied return periods (1, 10, and 100 years), rainfall durations (60, 120, and 360 min), and peak ratios (0.2, 0.5, and 0.8).](image-url)
rainfall durations are designated as 60, 120, and 360 min. Thus, 27 types of rainfall events are obtained by a cross combination of different rainfall characteristics as shown in Fig. 4, covering different return periods, peak ratios, and rainfall durations. As summarized below in Table 3, the increase of both the return period and rainfall duration will increase the total rainfall amount. While the peak rainfall intensity is only controlled by the rainfall return period. The variation of peak ratio just influences the rainfall temporal pattern with negligible effects on both rainfall amount and peak rainfall intensity.

c. Evaluation indicators

Both dimensionless and dimensional indicators as shown in Table 4 are introduced to quantitatively evaluate the impacts of BIRR under changing circumstances (Yang and Ng 2017).

### Table 3. The characteristic summaries of the synthetic rainfall events.

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Return period (year)</th>
<th>Rainfall duration (min)</th>
<th>Peak ratio</th>
<th>Rainfall depth (mm)</th>
<th>Peak rainfall intensity (mm min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>60</td>
<td>0.2</td>
<td>36.3</td>
<td>2.7</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>120</td>
<td>0.2</td>
<td>46.1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>360</td>
<td>0.2</td>
<td>65.1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>60</td>
<td>0.2</td>
<td>65.7</td>
<td>5.0</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>120</td>
<td>0.2</td>
<td>83.5</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>360</td>
<td>0.2</td>
<td>117.8</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>100</td>
<td>60</td>
<td>0.2</td>
<td>95.2</td>
<td>7.2</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>120</td>
<td>0.2</td>
<td>120.8</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>360</td>
<td>0.2</td>
<td>170.4</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4. Indicators used in this study to evaluate the impacts of BIRR on hydrologic responses; $Q_{10}$ and $Q_{25}$ denote the flow at 10th and 25th exceedance percentiles, respectively.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Unit</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute bias in peak flow</td>
<td>m³s⁻¹</td>
<td>$\text{Bias}_{pk} = \frac{P_K - PK}{PK}$ (2)</td>
</tr>
<tr>
<td>Relative bias in peak flow</td>
<td>—</td>
<td>$\text{RBias}_{pk} = \frac{PK - PK}{PK}$ (3)</td>
</tr>
<tr>
<td>Runoff increment coefficient</td>
<td>—</td>
<td>$I = \frac{(Q - Q) \times 1000}{P \times A}$ (4)</td>
</tr>
<tr>
<td>Bias in very high flows (&gt; $Q_{10}$)</td>
<td>m³s⁻¹</td>
<td>$\text{Bias}<em>{hv} = \sqrt{\frac{1}{T</em>{10}} \sum [F(t) - F(t)]^2}$ (5)</td>
</tr>
<tr>
<td>Bias in high flows (&gt; $Q_{25}$)</td>
<td>m³s⁻¹</td>
<td>$\text{Bias}<em>{h} = \sqrt{\frac{1}{T</em>{25}} \sum [F(t) - F(t)]^2}$ (6)</td>
</tr>
<tr>
<td>Bias in medium–low flows (&lt; $Q_{25}$)</td>
<td>m³s⁻¹</td>
<td>$\text{Bias}<em>{ml} = \sqrt{\frac{1}{T</em>{25}} \sum [F(t) - F(t)]^2}$ (7)</td>
</tr>
</tbody>
</table>
First, peak flow, as a key descriptor of flooding magnitude, is taken into account for both absolute and relative simulation bias [as in Eqs. (2) and (3)]. The term $PK_r$ denotes the simulated peak flow with the consideration of BIRR ($m^3/s$), whereas $PK$ denotes the simulated peak flow without the consideration of BIRR ($m^3/s$). Also, the runoff increment coefficient, i.e., the BIRR induced increment of runoff per unit area for a 1-mm rainfall amount, is another important indicator to identify the impacts of BIRR on the runoff volume [as in Eq. (4)]. The terms $Q_r$ and $Q$ represent the simulated total runoff volume with and without the consideration of BIRR ($m^3$). The term $P$ denotes the total rainfall amount (mm), and $A$ denotes the entire area ($m^2$). Notwithstanding keeping the same peak flow and the same runoff volume, the change of hydrograph (i.e., the flow processes) will also yield different flooding risks and further cause the discrepancy of coping strategies. Therefore, the impacts of BIRR on the hydrograph at the outlet are considered from three flow levels as shown in Eqs. (5)–(7): very high flows, high flows, and medium–low flows ($<Q_{25}$). $Sin$, $Low$, and $Hig$ denote the different building distributions, i.e., one single building, 4-building cluster, and 16-building cluster.

**4. Urban hydrological results analysis**

The impacts of BIRR on hydrologic responses are generally influenced through multiple circumstance factors that can be roughly categorized into two aspects: 1) underlying surface conditions and 2) rainfall conditions. Hence, quantitative analysis is conducted here to investigate whether the impacts of BIRR are negligible and how it varies with the change of circumstance factors.

**a. The impacts of BIRR under different underlying surface conditions**

**1) BUILDING DISTRIBUTION**

Building spatial distribution has been a focus of contemporary research work, due to the tight association with both urban...
hydrology and flood prediction (Bruwier et al. 2020; Lee et al. 2016). Hence, the impacts of BIRR on hydrologic responses are first analyzed under different building spatial distributions. The results show that the impacts of BIRR on hydrologic responses can be detected obviously, where the peak flow tends to be increased but the runoff volume tends to be reduced in general (Figs. 5a–c). The specific impacts are closely associated with the building distribution. Discrete building distribution is inclined to cause aggravated impacts on the peak flow (Figs. 5a,b) but reduced impacts on the runoff volume (Fig. 5c). Despite the limited impacts of BIRR on the medium–low flow process (Fig. 5f), both the very high and high flow processes are significantly influenced by the BIRR (Figs. 5d,f). Interestingly, discrete building distribution can amplify the impacts on peak flow but contributes to maintaining the flow processes (Figs. 5d,e). That is, compared to discrete distribution, concentrated building distribution leads to a smaller increase of peak flow but a significant alteration of the shape of the hydrograph.

2) LANDSCAPE MEASURE

With the emerging concept and technology of stormwater management, various landscape measures are introduced to better serve runoff mitigation at the source. Not only the traditional pavement and lawn, but the measures of low impact development (e.g., BRC) become increasingly common (Li et al. 2019). The results show that the landscape with a higher runoff reduction capacity tends to reduce the impacts of BIRR on peak flow (Figs. 6a,b) but aggravate the impacts on runoff volume in general (Fig. 6c). Overall, the impacts of BIRR on different flow processes all present relatively weak sensitivity to the change of landscape measures (Figs. 6d–f). While the landscape with a strong runoff reduction capacity is inclined to amplify the uncertainty of the impacts of BIRR, especially the impacts on runoff volume (Fig. 6c).

b. The impacts of BIRR under different rainfall conditions

1) RAINFALL RETURN PERIOD

As a key-driven factor of hydrologic response, rainfall conditions deserve special attention. Rainfall return period is an important indicator to represent rainfall intensity, via giving the occurrence frequency of a specific event. The results show that the impacts of BIRR on the peak flow are increased in terms of the absolute bias (Fig. 7a) but almost constant in terms...
of the relative bias (Fig. 7b) with the increase of rainfall intensity. That is, the significant increase in Bias$_{pk}$ is mainly attributed to the increase in rainfall intensity instead of the BIRR. Under heavy rainfall conditions, the impacts of BIRR on the runoff volume tend to be mitigated as shown in Fig. 7c. Besides, the heavy rainfall condition also helps exacerbate both the magnitude and the uncertainty of the impacts on all the flow processes (Figs. 7d–f).

2) RAINFALL DURATION

In general, the impacts of BIRR on the peak flow show little sensitivity to the change of rainfall duration as shown in Figs. 8a and 8b. While long-duration rainfall conditions can slightly curb the impacts on the runoff volume (Fig. 8c). Compared to the impacts on peak flow and runoff volume, the impacts of BIRR on each flow process presents a clear trend with varying rainfall duration as shown in Figs. 8d–f. For short-duration rainfall, BIRR tends to alter the shape of hydrographs to a greater extend.

3) RAINFALL PEAK RATIO

Besides rainfall return period and duration, rainfall peak ratio is another key characteristic, depicting the occurrence time of peak intensity relative to the whole duration quantitatively. It is noteworthy that the impacts of BIRR on Bias$_{pk}$ are nonmonotonic. The Bias$_{pk}$ decreases first then increases with the increase of peak ratio as shown in Fig. 9a. However, the impacts on RBias$_{pk}$ present a clear downtrend with the increased peak ratio as shown in Fig. 9b. This discrepancy can be explained by the different causes of increased Bias$_{pk}$ under different peak ratios. As we know, a large peak ratio tends to yield a larger peak flow due to the higher soil moisture at the time of peak rainfall. Hence, for the events with a large peak ratio, the increase of Bias$_{pk}$ is largely attributed to the increased peak flow that concurrently leads to the reduced RBias$_{pk}$. In contrast to the role of the rainfall return period, an increased peak ratio increases the impacts on runoff volume (Fig. 9c). Figures 9d–f indicate that the impacts of BIRR on all the flow processes present very limited variation with the change of peak ratio.

5. Discussion and future work

Through the analysis in section 4, it has been confirmed that the impacts of BIRR on hydrologic responses are nonnegligible
and influenced by multiple circumstance factors (see Fig. A1 in the appendix). The analysis conducted above mainly focuses on the perspective of overall characteristics and aims to grasp the macroscopic rule of how the impacts of BIRR respond to the change of each circumstance factor. However, the interactions may exist among different circumstances factors, e.g., how the variation of building distribution influences the impacts of BIRR may be inconsistent under different landscape measures. Hence, based on the obtained macro understanding, the interaction between different factors is further analyzed. Simultaneously, the reasons why the BIRR can influence hydrologic responses are discussed from a physically based perspective. Furthermore, the extreme impacts due to BIRR are quantitatively evaluated, and the corresponding attribution analysis is conducted to identify the adverse circumstance factors.

a. The interaction between building distribution and landscape measure

Figure 10a1 indicates that discrete building distribution tends to amplify the impacts of BIRR on peak flow under the cases of lawn and BRC. While this rule is not the same under the case of pavement, where a slightly decreasing trend can be detected. This discrepancy exactly implies the reasons why BIRR influences hydrologic responses: on the one hand, BIRR helps facilitate the converging of stormwater at the position of downspouts and thereby increases the peak flow at the outlet; but on the other hand, BIRR will direct part of roof stormwater to the upstream area where the soil may be still unsaturated and lead to reduced peak flow. Considering the distribution of one single building is conducive to converging more stormwater at one point (i.e., the position of the downspout), hence the impacts on peak flow present a slight increase with the centralization of buildings under the case of pavement where the amount of infiltration is negligible. Simultaneously, centralized building distribution always means lower initial landscape utilization, hence the BIRR is supposed to improve the landscape utilization to a greater extent and thereby to reduce the runoff more largely under the case of lawn and BRC. This also explains the monotonic increase of the blue line in Fig. 10a2, and the divergence phenomenon in Fig. 10b2, i.e., the BIRR leads to reduced runoff volume under the case of centralized building distribution but increased runoff volume under the case of discrete building distribution.

At the same time, the centralized building distribution will aggravate the alteration of flow processes (Fig. 10a3), because the stormwater falling on the roof will be redistributed more...
widely. By contrast, the impacts on BIRR effects induced by the change of landscape measures are consistent under different building distribution. That is, the landscape with strong runoff reduction capacity always tends to cause decreased impacts on the peak flow but increased impacts on the flow process (Figs. 10b1 and 10b3). However, it is worth noting that the uncertainty of BIRR effects due to the changing landscape can be constrained effectively under discrete building distribution.

b. The interaction between different rainfall characteristics

For the cases of different rainfall duration and peak ratio, heavy rainfall always tends to increase the impacts of BIRR on both peak flow and the flow process (Figs. 11a1,a2,a3). While the change of both varying rainfall duration and peak ratio hardly change the impacts of BIRR except under heavy rainfall conditions (Figs. 11b1,11c1,11b3,11c3). In heavy rainfall events, increased rainfall duration leads to decreased impacts on both peak flow and the flow process under the condition of small peak ratio, while increased impacts under the condition of large peak ratio (Figs. 11b1,b3); increased peak ratio tends to decrease the impacts on both peak flow and the flow process (Figs. 11c1,c3). In general, the impacts of BIRR on runoff volume present extremely weak sensitivity to the change of any rainfall characteristic (Figs. 11a2, 11b2, and 11c2). It is because here the statistical analysis mainly focuses on the median of BIRR impacts in all scenarios, with less consideration of the extreme impacts under the BRC scenarios. For both pavement and lawn scenarios, the variation in runoff volume is little relative to the rainfall total in most cases as shown in Fig. 6c, which can be attributed to the limited capacity of runoff reduction.

c. The extreme impacts of BIRR on hydrologic responses

Following the analysis from the perspective of the overall view above, the extreme impacts of BIRR on hydrologic responses are picked up and further analyzed. Aiming at the extreme impacts on $\text{Bias}_{pk}$, $I$, and $\text{Bias}_{vh}$, the three groups of compound conditions are identified from all the designed scenarios. And the corresponding attribution analysis is conducted simultaneously. Figure 12 presents the extremely unfavorable impacts on the hydrologic responses (shown as the red points), where the flood risk is significantly aggravated by the BIRR. Among them, $\text{Bias}_{pk}$ can be up to 0.15 m$^3$/s$^{-1}$, i.e.,
the relative error of approaching 10% according to the statistical distribution of peak flow as the boxplot shown in Fig. 12. When disregard BIRR, it is still likely to constraint the relative error of peak flow within 20% to obtain acceptable results (Kong et al. 2019). While in terms of implementing a perfect simulation, where the RBiaspk should be within 10% (Mateo et al. 2017), the BIRR is nonnegligible and even worthy of double attention especially in densely populated cities that require high-accuracy flood warning. The attribution analysis indicates that all extreme impacts occur under the scenarios of BRC, while about 60% of extreme impacts can be attributed to intensified rainfall and long duration (shown as the radar chart shown in Fig. 12).

d. Future work

The highly heterogeneous building structures pose a great challenge to access precise data of the downspouts in reality. Hence, this study first designs a series of development

![Figure 10. The interaction between building distribution and landscape measure: (a1)–(a3) the response of the BIRR effects to changing building distributions under different landscape conditions; (b1)–(b3) the response of the BIRR effects to changing landscape measures under different building distributions. The solid lines represent the median results; the lower and upper boundary of the shaded area corresponds to the first and third quartile results, respectively.](image-url)
scenarios and considers various meteorological conditions, aiming to identify whether the BIRR deserves more attention in urban hydrology. Although some insights into the building effects in urban hydrology are obtained herein, there still is vast space to investigate the related issues. With the emerging technology of big data and remote sensing, revealing the impacts of BIRR in realistic situations can be realized gradually. A more complicated drainage system and landscape layout can be incorporated into future work, which is likely to further amplify the impacts, due to the increased heterogeneity of routing processes. Concurrently, conducting similar studies on a larger scale to consider the interaction between different rainfall characteristics can provide more comprehensive insights into the BIRR effects.
blocks is suggested to reveal the scale effects of BIRR. Also, for the rainfall input in urban flood forecasting, whether a spatial resolution matching with the building scale to accurately capture the rainfall on roofs is necessary remains to be confirmed.

6. Conclusions

Buildings, as a key component of a city, deserve a great deal of emphasis in urban hydrology. Although the blockage effects of buildings have been studied enormously, the BIRR is still less understood. Therefore, this study constructs a distributed urban hydrological model considering the effects of building roof, aiming to enhance the understanding of the building effects in urban hydrology and subsequently make clear whether the BIRR should be a cause for concern in flood forecasting.

Results indicate that the impacts of BIRR depend on multiple circumstance factors and are nonnegligible in urban hydrology. On the one hand, BIRR helps facilitate the converging of stormwater at the position of downspouts and thereby increases the discharge at the outlet; however, BIRR is also beneficial to make full use of the runoff reduction capacity of the landscape by transmitting more stormwater to the upstream area, which subsequently reduces the runoff. Hence, the BIRR causes bidirectional impacts on the hydrologic characteristic values (e.g., peak flow and runoff volume) and a significant alteration of the hydrograph at the outlet. Overall, BIRR contributes to the increase of peak flow except for part of the BRC scenarios, and more importantly, it can be aggravated by the increase of rainfall intensity with the extreme RBiaspk approaching 10%. From the perspective of the underlying surface, any kind of building distribution may lead to extreme impacts, which relies on the intervened landscape measure. However, it should be noted that the landscape measure with a high runoff reduction capacity is an important driver to exacerbate the impacts of BIRR. From the perspective of rainfall characteristics, heavy rainfall is the basic requirement to control the impacts of BIRR, i.e., the change of rainfall duration or peak ratio only plays a role in the impacts of BIRR under the case of heavy rainfall.
In the context of climate change and rapid urbanization, accurate flood forecasting calls for a better understanding of the hydrologic effects of various urban facilities, especially the building. This study gives a comprehensive illustration of the necessity to fully consider the BIRR in urban hydrologic simulation, via incorporating the roof layer into the traditional model. The improved awareness of building effects contributes to a step forward in the research of urban hydrology and a more robust flood risk warning.

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APPENDIX

Impacts of BIRR on the Hydrograph at the Outlet under Two Typical Compound Conditions

This appendix contains Fig. A1.

REFERENCES
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