Title: Assessing performance of porous pavements and bioretention cells for stormwater management in response to probable climatic changes

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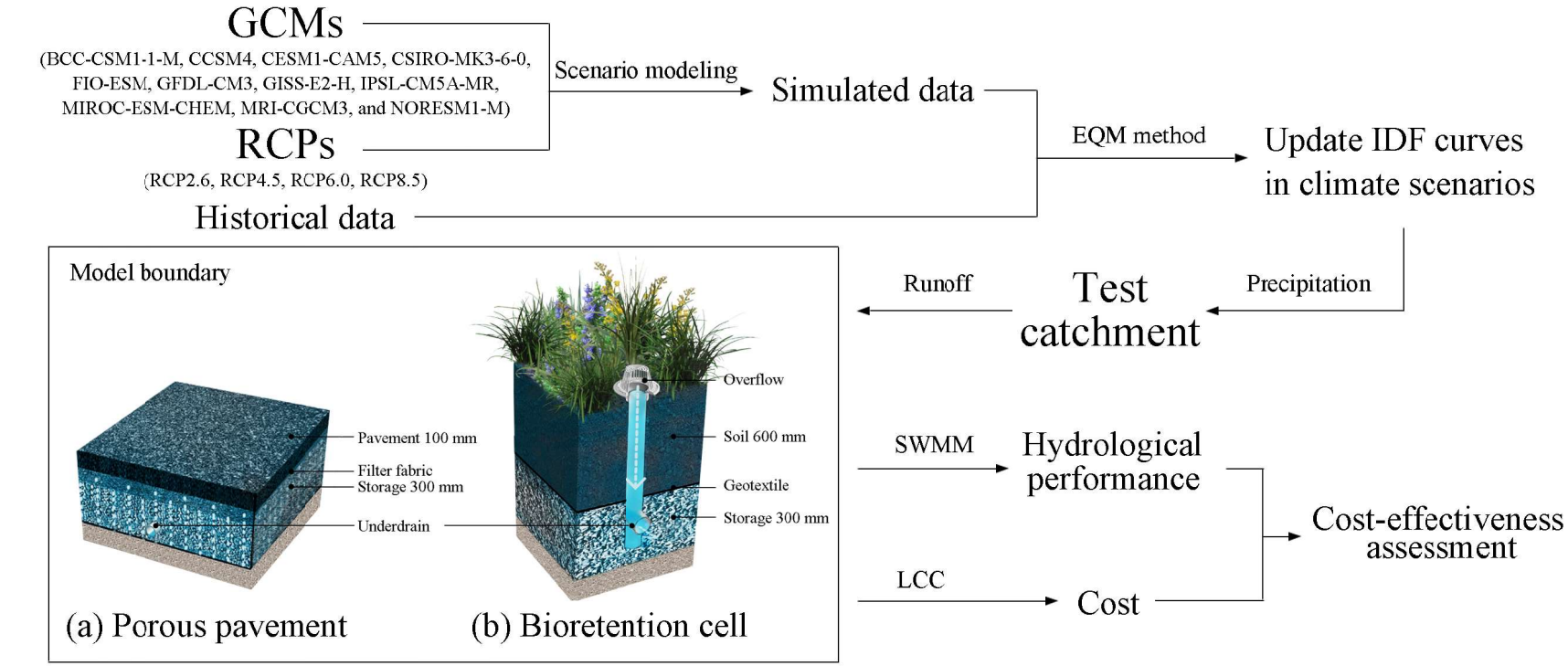
Graphical Abstracts



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Highlights

- Hydrological responses investigated under climate scenarios
- Cost-effectiveness of PP and BC analyzed based on LCC and hydrological indices
- PPs and BCs could be more effective in response to small storms
- Optimizing PP and BC proposed for adapting potential climate change

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Title: Assessing performance of porous pavements and bioretention cells for stormwater management in response to probable climatic changes

ABSTRACT

~~Investigation of t~~The effectiveness of porous pavement~~s~~ (PP~~s~~) and bio-retention cells (BCs) under the influence of potential climate change~~s~~ was ~~conducted~~ investigated based on representative concentration pathways (RCPs). A case study ~~based on~~of a test catchment in Guangzhou illustrated changes of peak runoff under various climate scenarios. There were distinct increases in runoff volume and peak discharge in response to RCP8.5 but only marginal increases in response to RCP2.6 (compared with ~~that under the~~ present conditions). The performance~~s~~ of PP~~s~~ and BCs ~~expressed~~ in terms of percentage reduction of runoff volume and peak discharge ~~were~~ was examined for 1-, 10-, and 100-year return period and 1- and 6-hour-duration storms under various climate scenarios ~~using Storm Water Management Model~~. The effectiveness of PP~~s~~ and BCs ~~was found to vary~~varied non-linearly with the extent of PP and BCs adopted. In general, the fluctuation of hydrological performance of PP is greater than that of BCs in RCP2.6 and RCP8.5 (e.g., peak flow reductions range from –60% to 69% and from –22% to 9%, for 5% area of PP and BCs, respectively). And PP is more cost-effective for frequent storms using life cycle costing analysis. ~~Based on the findings of the study, it was concluded~~We find that PP~~s~~ and BCs could ~~provide~~ significantly ~~impact~~ reduce ~~on the~~ runoff volume and peak discharge in response to rainfall events with ~~low~~ short return period, but ~~failed to do so~~not for heavy storms with ~~larger~~ longer return period. ~~It was further concluded that use of PPs and BCs~~

~~could not replace conventional runoff management practices but could be incorporated with the latter to form an integrated storm water management system.~~

Keywords: Porous pavement; bioretention; stormwater; climate change; representative concentration pathways; low-impact development~~low impact development~~

1. Introduction

Global warming due to increasing atmospheric concentrations of greenhouse gasses has already caused significant changes in the frequency and patterns of storms (Shaw et al., 2016; Wiel et al., 2017). More frequent storms may have severe consequences, especially in high-density urban areas (Ma et al., 2018; Wang et al., 2018a). Consequently, projections of climate change are relevant to~~play a relevant role in~~ risk assessment ~~of~~ in urban stormwater management. A number of studies based on climate-change scenario modeling have ~~been carried out to~~ investigated the impacts on rainfall patterns (Ault et al., 2014; Jhong and Tung, 2018; Prudhomme et al., 2014). Bacmeister et al. (2018) conjectured that extreme storms will become more common under future global warming scenarios. In climate scenario modeling, representative concentration pathways (RCPs), which reflect different possible future scenarios based on radiative forcing levels, ~~are offering~~offer an important basis for climatic change projection (Rogelj et al., 2012). Fix et al. (2018) projected that precipitation extremes will increase over the contiguous United States between 2005 and 2080 under RCP4.5 and RCP8.5. Lee et al.~~,~~ (2014) projected that the frequency and variability of extreme storms will increase by 24.0% and 31.5%, respectively, in East Asia under RCP8.5. ~~Zou and Zhou (2013) analyzed the potential changes of summer precipitation over China under RCP8.5 in the~~

~~period of 2015 to 2040.~~ Schewe et al. (2014) reported that climate change would likely exacerbate regional and global water scarcity considerably according to selected RCPs. At present, a large number of adaptation and/or mitigation approaches, such as low-impact development (LID) (Palla and Gnecco, 2015) and water-sensitive urban design (Lu et al., 2019), as well as some novel mitigation approaches for reducing CO_2 emissions, such as membrane bioreactors (Sepehri et al., 2018), have emerged to address the challenges of climate change. Such climate scenario projections could provide valuable inputs to better understand ~~the adaptation and/or mitigation~~effective measures ~~in~~ to response to the uncertainty arising~~potential uncertainty arisen~~ from climate change.

~~Low impact development (LID)~~LID practices, including porous pavement (PP) and bioretention cells (BCs), are decentralized drainage designs to control storm runoff, and have become increasingly attractive solutions to restore predevelopment hydrological processes by promoting infiltration, retention, and adsorption (Huang et al., 2018). PP~~s~~ with pervious materials and BCs with shallow depressions have been implemented to combat runoff from small catchments for multiple hydro-environmental benefits, such as reducing outflow volume, peak flow, and pollutant loads (Liu et al., 2015; Mei et al., 2018). A growing number of studies have evaluated the hydrological performance of PP~~s~~ and BCs based on ~~the findings of~~ field and laboratory experiments (Zhang et al., 2018; Turco et al., 2017; Glaister et al., 2017; Wang et al., 2018b) and hydrological models, such as the Storm Water Management Model (SWMM) and SUSTAIN (Huang et al., 2018; Lee et al., 2012). Wu et al. (2018) assessed the effectiveness of PP~~s~~ for urban waterlogging mitigation under different rainfall-runoff scenarios. Winston et al. (2016) showed that runoff from regular rainfall may

be controlled, and the initial part of surface runoff from storms can be adequately retained through storage volumes of BCs. Zahmatkesh et al. (2015) evaluated the impacts of PP and BCs on urban storm runoff under different precipitation scenarios in New York. Also, many studies have reported that ~~BCs and PPs~~PP and BCs can effectively mitigate peak runoff ~~in~~ from various rainfall events (Garcia-Cuerva et al., 2018; Chui et al., 2016). Some other studies have examined both the hydrological effects and the cost-effectiveness of PP and BCs (Liu et al., 2016). For example, Liao et al. (2014) analyzed the hydrological effects and also life cycle costs (LCC) of PP~~s~~ and BCs under different design storms in Shanghai.

Climate change is a dynamic process which makes longer~~-~~-term design and planning of stormwater management difficult. However, there is some information on the hydrological cost-effectiveness of LID practices in response to uncertainties ~~arisen~~ arising from climate change. Liu and Chui (2017) simulated the hydrological performance~~s~~ of PP~~s~~ under two long-term climate scenarios. Hathaway et al. (2014) found that BCs could be incorporated to adapt to the uncertainty based on climate scenarios in North Carolina, USA. Some researchers have investigated runoff water quality and quantity with control of BCs in urban catchments based on future scenario modeling (Borris et al. 2016; Wang et al., 2017, 2018c). The studies illustrated the potential for PP~~s~~ and BCs to be used as resilient landscaping features to mitigate some of the adverse ~~influences~~ effects of climate change on urban hydrological processes. There are still opportunities for further advancement ~~on~~ in the application of PP~~s~~ and BCs under climate change, in terms of reduction of runoff volume and peak flow, hydro-environmental performance and cost-effectiveness.

The objectives of this study are: (1) to analyze the potential ~~influences~~ effects of climate

change on storm runoff in urban catchments; (2) to examine the hydrological benefits of PPs and BCs under climate change; and (3) to investigate the cost-effectiveness of PPs and BCs to meet different hydro-interests based on climate scenarios. The methodology developed here could be applied to develop options for LID as the relevant and appropriate adaptation/mitigation measures for climate change under local conditions.

2. Methodology

Climate scenarios were simulated to examine their impacts on surface runoff in an urban catchment in response to various changes in probable storm characteristics and distributions. Then, hydro-modeling simulation was used to assess the hydro-environmental benefits of PPs and BCs under the corresponding different climate scenarios. Then LCC were calculated, and the cost-effectiveness of PPs and BCs for different scenarios was examined. Finally, the suitable sizes of PPs and BCs to meet different performance interests (in response to the uncertainty of future changes) were derived (**Fig. 1**).

2.1 Conceptual study site

The hypothetical catchment was located in Guangzhou, China (22°95′ N; 113°35′ E), a high-density, subtropical city with around 1,600 mm of annual precipitation and 77% annual mean relative humidity. The urban areas in Guangzhou are threatened by waterlogging due to the uneven spatio-temporal distribution of rainfall events (Wu et al., 2014). Zhang et al. (2017), used using selected climate models and emissions scenarios, projected an increase in extreme storms in Guangzhou over the periodin 2020-50, as compared to the period

1970-2000.

Due to their flexibility of size, PP~~s~~ and BCs' positive life-cycle benefits can be readily and effectively integrated into dense urban areas ~~readily~~ (Xie et al., 2017; Li et al., 2017; Liu et al., 2018; Wang et al., 2018d). PP~~s~~ and BCs have been widely applied in urban areas through strong support from local governments, such as in the Sponge City program (Liu, 2016). It is critical to develop a comprehensive design and planning approach to support effective PP and BC adoption in Guangzhou in response to climate change.

The hypothetical catchment was based on a typical low-lying area~~low lying rea~~ in Guangzhou, and is assumed to be rather flat (average slope 1%), small in size (5,000 m^2), and 50% impervious (paved and clayey silty top soil layer) ~~according to~~, per previous studies (Chui et al., 2016; Wang et al., 2016). Climate scenarios were established using the current climate conditions as the baseline response. Depending on the management targets, various design storms (various intensities and durations) need to be simulated. The design storms were clustered into six groups based on representative ~~recurrence intervals~~return period (P—1 y, 10 y, and 100 y)~~(RI) (1 y, 10 y, and 100 y)~~ and durations of storms (1 h and 6 h). The local storm intensity distribution for Guangzhou is ~~as shown in Eq. (1).~~

$$i = \frac{a}{(t+b)^{\mathrm{n}}} = \frac{A(1+\mathrm{c}\log(\mathrm{P}))}{167*(t+b)^{\mathrm{n}}} = 14.52\,(1+0.533\times \lg RI(\mathrm{P}))\Big/(t+11)^{0.668} \quad (1)$$

where i is the storm intensity (mm/min), ~~RI~~P is the return period (y~~ear~~), and t is rainfall duration (h~~our~~), ~~as well as~~and a, b, and c are the parameters ~~in~~ for Guangzhou~~.~~: a = 14.52 (1 + 0.533 × lg~~RI~~(P)), A=2424.17, b = 11, c = 0.533, and n = 0.668.

Hyetographs of the different design return periods were determined according to a rainfall pattern closest to the actual observed condition using the formulae for synthetic Chicago storms (Keifer and Chu, 1957).

The formulae for Chicago storms synthetic rainfall patterns are

$$i(t_{b1}) = \frac{a[\frac{(1-n)*t_b}{r}+b]}{\left(\frac{t_b}{r}+b\right)^{1+n}} \quad (2)$$

and

$$i(t_{a0}) = \frac{a[\frac{(1-n)*t_a}{1-r}+b]}{\left(\frac{t_a}{1-r}+b\right)^{1+n}} \quad (3)$$

Where $i(t_0)$ and $i(t_1)$ ~~$i(t_a)$ and $i(t_b)$~~ are the storm intensity (mm/min) after and before the peak ~~time point,~~ respectively, and the parameter r ~~refers to~~is the time-to-peak factor. According to previous studies (Jia et al., 2014; Mei et al., 2018), this value ranges from 0~~–~~ to 1 of the storm duration, and a reasonable range for r is 0.3–0.5. ~~Short of~~Lacking any other information ~~available~~, a value of 0.5 was chosen in this study. Here a, b, and n are parameters from Eq. (1).

The calculated synthetic hyetographs for the baseline condition in Guangzhou are shown in **Fig. 2**.

2.2 Climate scenarios

Climate change scenarios ~~refer to a~~are descriptions of potential developments of anthropogenic climate change at ~~a certain~~designated times in the future (O'~~-~~Neill et al., 2014). The scenarios ~~could~~ can be used to test and identify the effectiveness of various adaptation

~~and/~~or mitigation strategies (Leng et al., 2016; Andersson-Sköld et al., 2015). An ce~~E~~quidistance quantile-matching (EQM) method, which ~~integrated~~ integrates spatial and temporal downscaling, was used to quantify the variations in rainfall intensity and update i~~I~~ntensity-d~~D~~uration-f~~F~~requency (IDF) curves in climate scenarios (Li et al., 2010; Srivastav et al., 2014). The Gumbel distribution is widely used as the standard distribution for rainfall frequency analyses and was selected for the EQM method in this study (Langousis et al., 2009). The IDF_CC tool, developed by Simonovic et al.~~,~~ (2016), allows users to generate IDF curves based on historical data and projected data using GCMs and RCPs simulating various climate scenarios that affect local storm patterns. ~~11~~ Eleven GCMs (BCC-CSM1-1-M, CCSM4, CESM1-CAM5, CSIRO-MK3-6-0, FIO-ESM, GFDL-CM3, GISS-E2-H, IPSL-CM5A-MR, MIROC-ESM-CHEM, MRI-CGCM3, and NORESM1-M) and 4 RCPs (2.6, 4.5, 6.0, and 8.5) (Yu et al., 2018; Liu et al., 2018) were assessed at the chosen location (22°95′ N; 113°35′ E), and the results were used as projected climate change. A scenario period from 2040 to 2059 was adopted in view of the life cycle of PP~~s~~ and BCs, which have useful service life of 30 years (Vineyard et al., 2015). Table 1 gives a summary of the variations in rainfall intensity in these climate scenarios.

2.3 Hydrological model

The Storm Water Management Model (SWMM) has been widely used for analysis, planning, and design of various LID practices, including PP~~s~~ and BCs in small urban catchments (Rossman and Huber, 2016; Hamel et al., 2013). SWMM ~~(~~version 5.1~~)~~ was used to assess the hydro-performance of LID practices in this study. In SWMM, PP is~~PPs in~~

~~SWMM are~~ represented as structures including (from top to bottom) ~~including~~ pavement layer, filter fabric, storage, and drainage layer; BCs are represented as structures including a surface layer, soil layer, geotextile, storage, and drainage layer, as well as outflow structures (**Fig. 1**). The detailed LID parameters of PP and BCs are shown in **Table 2**. Total impervious areas are directly connected with ~~LIDs~~low-impact designs, and all surface runoff from the test catchment ~~are~~ is treated by PP~~s~~ or BCs. In SWMM, infiltration estimation is established using the Horton model; percolation is modeled using Darcy's law; and dynamic wave routing is used to solve the one-dimensional ~~Saint~~ Saint-Venant flow equations for flow routing (Rossman, 2010). The hypothetical catchment was established to simply emulate representative characteristics of a dense urban surface in Guangzhou. Nevertheless, the authors attempt to demonstrate the validity of the current approach of SWMM and climate change scenario modelling by making reference to a ~~reported~~ study by Zhu et al. (2016), as the approach and methodology used for the hydrological modelling were identical. Zhu et al. (2016) carried out the study of calibration and verification for SWMM in an urban catchment in Guangzhou. They used rainfall–runoff events during 2013 and 2014 to calibrate the parameters and applied ten other events to validate the model satisfactorily. Nash-Sutcliffe~~Nash–Sutcliffe~~ efficiency (NSE) and Kling-Gupta efficiency (KGE), used as the goodness-of-fit measurements between the observed and simulated events (Pushpalatha et al., 2012; Gupta et al., 2009) were up to 0.7 in different rainfall events, and the relative peak errors were less than 10% in parameter calibration. In the model validation analysis, the NSE and KGE of rainfall events were above 0.6, and the relative peak errors were less than 10% ~~similarly~~. Thus, the calibrated parameters with ~~high~~good-fit features were selected for the test

catchment in this study (**Table 3**). After completion of simulation, SWMM exports the summary statistics and time series into a report file (.rpt) and output files (.txt or .dat).

2.4 Performance metrics

2.4.1 Hydrological performance calculation

The effectiveness of PP~~s~~ and BCs can be evaluated in terms of hydrological performance indices. ~~Both indices, including percentages~~ Percentages reductions of outflow volume and peak flow~~,~~ were selected for this study in accordance with other studies (Palla and Gnecco, 2015). Here, outflow volume refers to the total amount of discharge at the outlet, and peak flow refers to the highest flow rate from the test catchment.

The reduction of outflow volume based on event i ~~($R_{OV(i)}$)~~ is defined as the difference in outflow volume between event i and that for the baseline scenario (without LID), ~~and~~ expressed as a percentage:

$$R_{OV(i)} = {(V_b - V_i)}/{V_b} \times 100 \quad (4)$$

where V_b is the total outflow of rainfall event in the baseline scenario (without any LID measures~~) implemented~~, and V_i is the surface outflow of event i.

The reduction of peak flow ~~($R_{PF(i)}$)~~ was calculated in a similar way ~~as follow~~:

$$R_{PF(i)} = {(P_b - P_i)}/{P_b} \times 100 \quad (5)$$

where P_b and P_i are the peak runoff ~~based on~~in the baseline scenario ~~without any LID measures implemented~~ and ~~based on~~ event i, respectively.

2.4.2 Life cycle costs calculation

~~In this study, an assessment of~~This study also assessed the capital costs~~,~~ and operation and maintenance (O&M) costs for PP~~s~~ and BCs using life cycle cost~~s (LCC)~~ analysis over an assumed design service life of 30 years (Vineyard et al., 2015; Xu et al., 2019), based on the model framework (~~see~~ **Fig. 1**) ~~was carried out~~. The construction~~s~~ of PP~~s~~ and BCs ~~are~~ is assumed to take place at year 0, while O&M are incurred from year 1 to year 30. A present value (PV) exercise was performed by compiling all LCC. The LCC of PP~~s~~ and BCs were calculated as ~~follows~~:

$$LCC = C_{\text{capital}} + \sum_{t=1}^{n} PV_{O\&M} \quad (6)$$

$$PV_{O\&M} = {}^{FV_{O\&M}}/_{(1+i)^n} \quad (7)$$

where C_{capital} is the capital cost of LID, $PV_{O\&M}$ is the present value of O&M costs, $FV_{O\&M}$ is the future value of O&M, i is the discount rate, and n is the years of service.

2.4.3 Cost-effectiveness analysis

In this study, the present value of benefit (PVB) and the present value of LCC were applied to analyze PP and BC cost-effectiveness, represented here by the ~~Benefit~~benefit/~~Cost~~ cost ~~(B/C)~~ value based on quantized values ~~calculated using Eq. (8).~~:

$$B/C = {}^{PVB}/_{LCC} \quad (8)$$

where PVB is an index that reflects the combined hydrological performance of PP~~s~~ ~~or~~ and BCs, which can be calculated as:

$$\text{PVB} = {}^{(R_{\text{OV}(i)} + R_{\text{PF}(i)})}/_{2} \quad (9)$$

~~where it~~It is assumed that both indices are equally important in the evaluation of storm runoff

management, so PVB (unit: %) ~~in this study~~ was ~~casted as~~taken to be the arithmetic mean of ~~both indices adopted in this study~~the two.

3. Results and discussions

3.1 Impacts on storm runoff caused by climate change

Climate change is intensifying the global hydrological cycle, notably making the peak flow increasingly stronger in urban catchments, with increased frequency and severity of waterlogging, especially in dense urban areas with high imperviousness of surface (Hu et al., 2017). Average changes of peak runoff for the test catchment in response to climate change scenarios compared to the baseline scenario are summarized in **Fig. 3**. The simulation showed similar trends across different climate scenarios. In almost all scenarios modeled, the events which showed dramatic variations corresponded to those with higher peak flows.

Peak flows become significantly larger in ~~response to the~~ climate change scenarios. Especially in RCP8.5, the average peak runoff increases by ~~31.68~~32% for 1 y ~~RI~~ storms with 1 h duration (dramatic challenges to adaptation and mitigation of climate change ~~by~~ from high emissions). The variations of peak flow in RCP2.6 were clearly smaller due to the relatively slight variations in climate (RCP2.6 is a relatively low-emissions scenario). The average peak flow increased by 3~~.37~~% for 100 -y ~~RI~~ storm events, with 6 h duration. As may be expected, RCP4.5 and RCP6.0 ~~scenarios~~ showed increases ~~which lie intermediate~~ between RCP2.6 and RCP8.5, since rainfall intensity increased moderately in these scenarios. Other works focusing on projection of climate report~~s~~ similar findings based on RCP scenario~~s~~ modeling (Riahi et al., 2017; O'Neill et al., 2016).

For storms with different ~~RI~~return period, the changes (absolute value) of peak flow were higher for the 10 y and 100 y ~~RI~~ storms than ~~that~~ for 1 y ~~RI~~ storms. This is ~~supported by and~~ consistent with other studies which found that climatic change may lead to more serious impacts particularly for storms with longer ~~RIs~~return periods, at least in the mid-latitudes (Kim and Choi, 2011). However, comparing the ratios of changes, the variation of peak flow for longer return periods is smaller than for shorter return periods~~RIs~~. For example, in RCP8.5 with 6 h events, the average increase in peak flow (~~18.00~~18%) for the 1 y ~~return period~~storms is larger than for 10 y (~~13.13~~13%) and 100 y (~~10.38~~10%) events. Thus, uncertain future changes will lead to larger adverse ~~influences~~ effects on the quantity of runoff during relatively low-frequency rainfall events. The findings of this study are supported by similar findings ~~reported based on future scenario modeling~~ by others based on future scenario modeling (Wang et al., 2016; Borris et al., 2016). Wang et al. (2016) illustrated that the risk of adverse effects of climate change for 2 y storms is worse than for 10 y storms in Singapore since the uncertainty in rainfall intensity for shorter-return-period storms is obviously greater than for longer-return-period storms in GCMs. Comparing the 1 h and 6 h storms, the variations in peak flow in ~~shorter duration~~briefer storms are larger than ~~those with longer durations~~in longer ones, whether in absolute value or as a ratio ~~compared~~ to the baseline scenario. This finding is supported by Noor et al. (2018) and Uraba et al. (2019), who found that more drastic intensification is expected in rainfall intensity for shorter duration, because shorter duration rainfall tends to be associated with bursts and is highly non-uniform both in space and time. Whereas longer duration rainfall tends to be associated with wider spatial coverage and more voluminous rain clouds, and hence are more uniform in both space and

time. Consequently there would be higher variation in 1 h rainfall compared to 6 h storm. For example, in RCP8.5 with 10 y ~~RI~~ events, the average increase in peak flow for 1 h storms (~~20.01~~20%) is larger than ~~in~~ for 6 h storms (~~13.13~~13%). And~~,~~ the variation in 1 h storms is ~~11.81~~12 % more than that in 6 h storms. Some other studies have found that the biggest increases are more likely in ~~those corresponding to~~ brief rainfall events, which implies higher frequency and greater intensity of flash floods (Westra et al., 2015). Dense urban catchments with a high percentage of impervious surfaces would be seriously challenged by such events; the drainage systems in high-density urban catchments will be put under higher stress due to the much larger scale of increase caused by more frequent heavy storms (Wang et al., 2018a).

3.2 Performance of PP~~s~~ and BCs in climate scenarios

3.2.1 Outflow volume reductions

The outflow volume reductions (R_{OV}) ~~in~~ from PP~~s~~ and BCs ~~with~~ of various sizes were calculated using Eq. (4), and the required sizes of PP~~s~~ and BCs to meet specific levels of R_{OV} were then estimated. Generally, the ~~size~~ area of PP~~s~~ and BCs should be increased as better performance ~~would be~~is needed (Qin et al., 2013). The authors selected RCP2.6 and RCP8.5 as representative scenarios in the comparative analysis because they correspond~~as RCP2.6 and RCP8.5 corresponded~~ to the minimum and maximum variations caused by climate change (Srivastav et al., 2014).

~~The authors found that~~ R_{OV} displays similar trends across various scenarios in the test catchment. R_{OV} increases with the size of PP~~s~~ and BCs, and the performance~~s~~ on R_{OV} of PP is clearly better than that of BCs (**Fig. 4**). This ~~finding~~ is consistent with the findings of Mei et

al.~~,~~ (2018). The effectiveness of PP~~s~~ and BCs in reducing outflow volume shows only minor changes across scenarios for ~~a~~ 1 y ~~RI~~ storms. With 5% area of PP~~s~~, and in response to a 1 y–1 h storm,~~1y-1h storm~~ for example, the simulated outflow volume~~s~~ reduction was ~~92.08~~92%, ~~87.90~~88%, and ~~76.71~~77% for the baseline scenario, RCP2.6, and RCP8.5, respectively. Meanwhile, for the same 1 y-1 h storm and with 5% BC area, the simulated ~~reduced outflow volume were~~reduction was much smaller, at ~~57.23~~57%, ~~50.62~~51% and ~~49.33~~49% for the baseline scenario, RCP2.6, and RCP8.5, respectively. However, there was an obvious decrease in the effectiveness of adopting ~~BC and PP~~PP and BCs in response to longer-return-period~~longer return period~~ (e.g., 100 y–1 h storm~~100 y-1h storm~~) events. This is because retention volumes are depleted during extreme storms (Yang and Chui, 2018a; Guibaz and Kazezylimaz-Alhan, 2016). For instance, the reduction achieved with 5% area of PP~~s~~ was ~~56.81~~57% in the case of baseline storm, and the corresponding value were only ~~8.73~~9% and ~~6.93~~7%, respectively, under RCP2.6 and RCP8.5, with 100 y-1 h storm events. Meanwhile, the reduction ~~values were~~was 27~~.24~~%, ~~15.5~~16%, and ~~14.63~~15% in the case of baseline storm, RCP2.6, and RCP8.5, respectively, for the same area of BCs. These ~~lower %~~smaller reductions in volume outflow emphasize the storage capacity of PP and BCs in handling larger volumes of flow within the same period of time.

It was also noted that the incremental runoff volume reduction decreases with increasing areal coverage of BCs (Eckart et al., 2018). Referring to **Fig. 4**, one ~~could~~ can see the distinct non-linear rate of decrease in reduction percentage with ~~increase~~ increasing percentage of PP and BCs (see the interface between the blue and orange-yellow shaded area). This trend clearly indicates that there is diminishing benefit and increasing cost with more adaptation

measures, and more so with BCs than PP.

R_{OV} is ~~40.49~~40% and ~~35.87~~36% respectively, with 20% ~~of~~ PP and BC coverage in RCP8.5 for a 100 y–6 h~~100y–6h~~ storm (~~see~~ **Fig. 4** ~~(100y-6h: RCP8.5)~~). In contrast, there is complete control with 7% ~~of~~ PP and 12% ~~of~~ BC coverage in the baseline for a 1y–1 h~~1y-1h~~ event (~~see~~ **Fig. 4** ~~(1y-1h: Baseline)~~). The difference may be due to the limited capacity of PP~~s~~ and BCs to cope with large storms (Ahiablame et al., 2012). In addition, the performance~~s~~ of PP~~s~~ and BCs ~~are~~ is slightly better with ~~shorter duration of~~ briefer storms than those ~~with~~ of longer duration. These results suggest that PP~~s~~ and BCs may not be able to fully retain runoff volume, especially during larger storms, in climate change scenarios.

3.2.2 Peak flow reductions

Several studies ~~had~~ have reported that the performance of PP~~s~~ and BCs ~~for~~ in reducing peak runoff to mitigate ~~the~~ flood risk~~s~~ could vary ~~distinctly~~ strongly with ~~different~~ storm ~~intensities~~ intensity (Baek et al., 2017; Yang and Chui, 2018b). Peak runoff reductions (R_{PF}) provided by various extents of PP~~s~~ and BCs corresponding to different scenarios and design storms were calculated using Eq. (3). Surface runoff from the test catchment ~~were~~ was apportioned and stored in PP~~s~~ and BCs, ~~thus~~ reducing ~~the~~ peak runoff. However, retention volumes within PPs and BCs may be depleted rapidly during heavy storms; after that there could be but very slight reduction in rate of flow of the surface runoff (Chui et al., 2016). Therefore, depending on the time when the storage capacity of the PP and BCs is depleted, the temporal and spatial distribution of the hydrograph, and hence the time to peak and peak flow rate, could be affected~~modified accordingly~~ (Yang and Chui, 2018a).

The performance of PP~~s~~ and BCs for reduction of peak runoff is shown in **Fig. 5.** Three climate scenarios ~~including~~ were considered: baseline ~~scenario~~, RCP2.6, and RCP8.5 ~~were considered~~. If relatively frequent storms with short duration, such as ~~1 y 1h~~1 y–1 h rainfall are of interest, one would need ~~to utilize~~ 8% areal coverage with PP or 14 % areal coverage with BCs to achieve better than 80% reduction in peak runoff for the baseline, RCP2.6, and RCP 8.5 scenarios. The reason is that continuous infiltration ~~limited the~~limits peak flow due to the high permeability of PP~~s~~. This finding is consistent with previous studies ~~on the comparison of~~comparing the hydrological performance~~s between~~ of PP and BCs ~~(Chui et al., 2016)~~. Chui et al. (2016) found that the performance of peak flow reduction of PP is better than BCs by comparing the optimal areas of two LID practices implemented for 2 y and 50 y storms in Hong Kong and Seattle, because of the high permeability of surface and storage layer, allowing continuous infiltration during the rainfall events. One can also deduce from **Fig. 5** that peak flow rate reduction is achieved only with~~effectively only for if~~ larger areal coverage of PP~~s~~ and BCs ~~are used~~. Furthermore, if not designed appropriately, PP and BC can *increase* peak runoff instead, as indicated by the *negative* reduction rates in **Fig. 5**.~~**Fig. 5** also indicates that PP and BC, if not designed appropriately could lead to rise in peak runoff instead such as those shown with negative "reduction rate" in **Fig. 5.**~~ All in all, one may safely conclude that PP and BCs may not be a cost-effective LID solution for peak discharge reduction for low-frequency, long-duration storms.~~low frequency and long duration storm. One can also deduce from **Fig. 5** that~~ LID measures based on PP and BCs are probably more effective ~~in the case of~~ for more frequent and ~~shorter duration~~briefer rainfall, and less effective ~~they are very much ineffective~~ for less frequent, heavier and longer-duration storms~~longer duration~~

~~storm~~ (Pyke et al., 2011). One may conclude that LID based on PP and BCs alone is not recommended. PP and BCs should ~~at best~~ be an integrated part of a bigger LID scheme.

3.3 Cost-effectiveness analysis

The LCCs of PP and BCs were calculated using the method described in Section 2.4.2. Land costs were not considered~~It is worth noting that the land costs of PPs and BCs were not considered in LCC calculation~~ (Chui et al., 2016). The construction costs of PP~~s~~ and BCs in Guangzhou are shown in **Table 4**. Itemized construction costs are estimated for each LID practice for each scenario based on ~~the~~ material quantity, and it is assumed that all costs are linearly related to the quantity. In Guangzhou, the annualized O&M costs are expressed as a percentage of the capital costs~~—~~, 4% for PP and 8% for BCs (Houle et al., 2013). To calculate the construction and O&M costs for ~~BC and~~ PP and BCs, the original unit construction and O&M costs were converted to bench mark on 2017 US ~~Dollar~~ dollar using consumer price index (CPI) and inflation rates for Guangzhou data according to the Guangzhou Investigation Team of the National Bureau of Statistics of China (~~-~~http://gjdc.gz.gd.gov.cn). The unit LCCs of PP and BCs were set as $~~37.30~~ 37.30/$m^2$ and $167.68/~~-~~$m^2$, respectively (**Table 4**).

Fig. 6 presents the B/C values of PP~~s~~ and BCs under various scenarios. The B/C value decreases with increasing climate change and the ~~RI~~ return period of storms. In the budget of LCCs from $10,000 to $35,000, the B/C values of PP are obviously better than those for BCs for most climate scenarios, except for RCP2.6 and RCP8.5 with the design storm of 100y RI. In frequently occurring storms, the ~~difference in the~~ B/C values of PP ~~is~~ are quite ~~close to one another~~similar for the various scenarios considered. However, for ~~the~~ extreme storms, the B/C

values of PP are significantly reduced.

Fig. 7 gives a~~A~~ set of look-up curves for selecting rational sizes (e.g. 3%, 5%, and 7%) of PP~~s~~ and BCs to provide B/C values of R_{OV}, R_{PF}, and PVB among various climate scenarios under the six design storm events ~~are presented in **Fig. 7**~~. For PP (**Fig. 7a**), the B/C values decrease~~s~~ in ~~the following~~this order: ~~Baseline~~ baseline (1 h) > ~~Baseline~~ baseline (6 h) > RCP2.6 (1 h) > RCP2.6 (6 h) > RCP8.5 (1 h) > RCP8.5 (6 h), and ~~it~~ they decrease~~s~~ with ~~increasing rain storm~~longer return period and duration of storms. For BCs (**Fig. 7b**), the B/C values in baseline (1 h) are the highest; but ~~compared. However,~~ the B/C values of other scenarios are ~~close to each other~~similar. ~~In addition, t~~The B/C value~~s~~ of R_{OV} in 3% ~~of~~ LID implementation appeared to be the best; but~~. However,~~ the value~~s~~ of R_{PF}/LCC is inconclusive. With respect to PVB/LCC, the range of values is widest for 3% LIDs, and narrowest for 7% LIDs~~most volatile for 3% of LIDs, while the volatility is the lowest for 7% of LIDs~~. For the various climate scenarios, the greater the proportion of LID applications, the more stable the performance is, ~~and is~~ especially ~~so~~ for PP.

PP~~s~~ and BCs have potential for use~~the potential to be incorporated~~ as ~~part of~~ LID elements in an urban catchment. Before developing a master plan for LIDs to manage runoff, it is important to design for different hydro-interests, to consider the uncertainty of climate change and to maximize the hydro-environmental benefits based on limited resources and costs. Based on the findings of this study, a set of multi-look-up curves for sizing ~~the~~ PP and BCs in a LID development could be developed by integrating the various single-objective~~single objective~~ look-up curves (e.g. R_{OV}, R_{PF}, or PVB versus ~~to~~ LCC or sites of LIDs) for ~~the~~ Eq. (4) ~~to~~ through Eq. (9).

~~As~~ Because LIDs could provide sufficient effects in response to frequent rainfall events ~~as aforementioned deliberation~~, frequently occurring storms (1 y–1 h~~1y-1h~~ design storms) could be selected as the input and storm runoff (peak and volume) as the management objectives. A work example to analyze the performance~~s~~ of PP~~s~~ and BCs in various climate scenarios based on single- and multi-objective~~single and multi-objectives~~ runoff management is shown in **Fig. 8**. For the budget of $20,000 for LID implemented over a service life of 30 years, the R_{OV}, R_{PF}, and PVB are almost 100% in all scenarios for PP~~s~~, while the performance~~s~~ of BCs ~~are~~ is not satisfactory (~~see~~ **Fig. 8a)**. In addition, to ensure at least 80% of the R_{OV}, R_{PF}, and PVB in all climate scenarios, more than 7.5% ~~of~~ PP~~s~~ should be provided, ~~while~~ and there must be at least 13.8% ~~of~~ BCs in the development (~~see~~ **Fig. 8b)**. ~~In addition, it is worth noting~~Also, the B/C values of LIDs are not absolute. ~~In order to~~To apply a more comprehensive indicator to represent the benefit, both R_{OV}~~,~~ and R_{PF}~~–~~ were selected, and they were ~~set~~ given equal weight in this study. The ~~weightage~~ weighting may be selected differently in other applications, since the opinions of various stakeholders should be considered for a more practical ~~weight allocation~~weighting of ~~the~~ indices for performance evaluation based on the specific circumstances.

4. Conclusions

Climate scenarios and the ~~subsequent~~ resulting storm runoff were simulated and investigated to assess the performance of PP~~s~~ and BCs in a high-density urban catchment. Storms with short return period and short duration are found to have more significant impacts than ~~other~~ less frequent and longer~~–~~ duration storms. The influence is more extreme in

RCP8.5, while it is relatively mild in RCP2.6.

~~Based on the findings of the study, the authors observed that o~~Optimum extent (areal coverage) of PP~~s~~ and BCs in an LID scheme can be determined based on a single objective~~single objective~~ (i.e., outflow volume ~~and~~ or peak flow reduction) ~~and~~ or multiple-objectives (i.e., a combination of the single objectives) for ~~–~~runoff management ~~(i.e., a combination of the single objectives) functions~~ and in response to various ~~potential~~ amounts of climate change~~s~~ using climate scenarios and appropriate hydrological modeling tools. ~~The~~ This case study of Guangzhou shows that PP~~s~~ and BCs are relatively effective at managing the volume of runoff and peak flow. BCs are more effective in controlling peak runoff during small and brief storms~~It was also noted that the capacity of BCs in controlling peak runoff is more effective in small and short duration storm~~. The performance of PP~~s~~ for less frequent, longer-duration storms~~for less frequent and large storm duration less frequent~~ is less satisfactory.

5. Recommendation

Despite the uncertainty in climate change scenarios and modeling, studies such as this are necessary to understand the resilience of practices to adapt to probable future changes. In future studies, predictions of future climate changes and their effects should be refined through advanced modeling techniques such as scenario modeling, integrated big data technology, and machine learning algorithms.

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Figure
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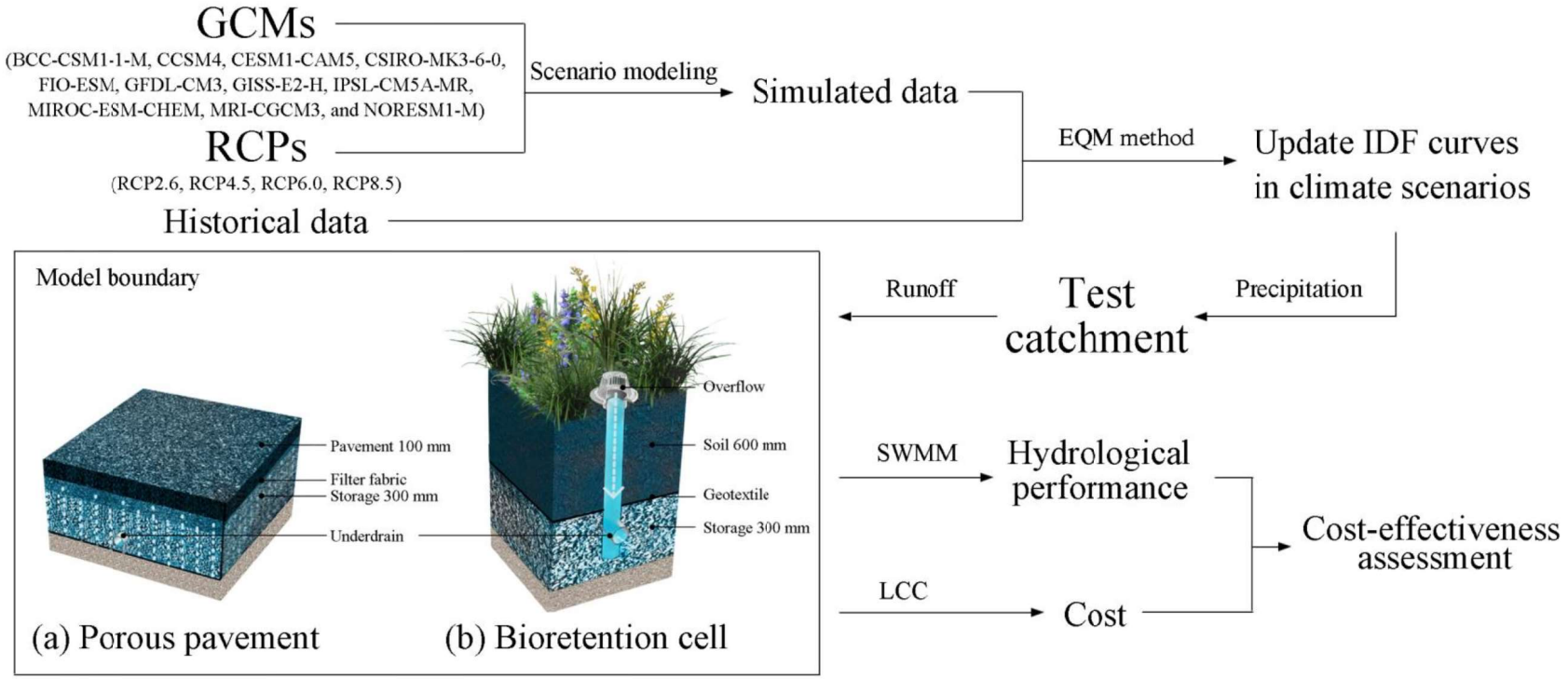
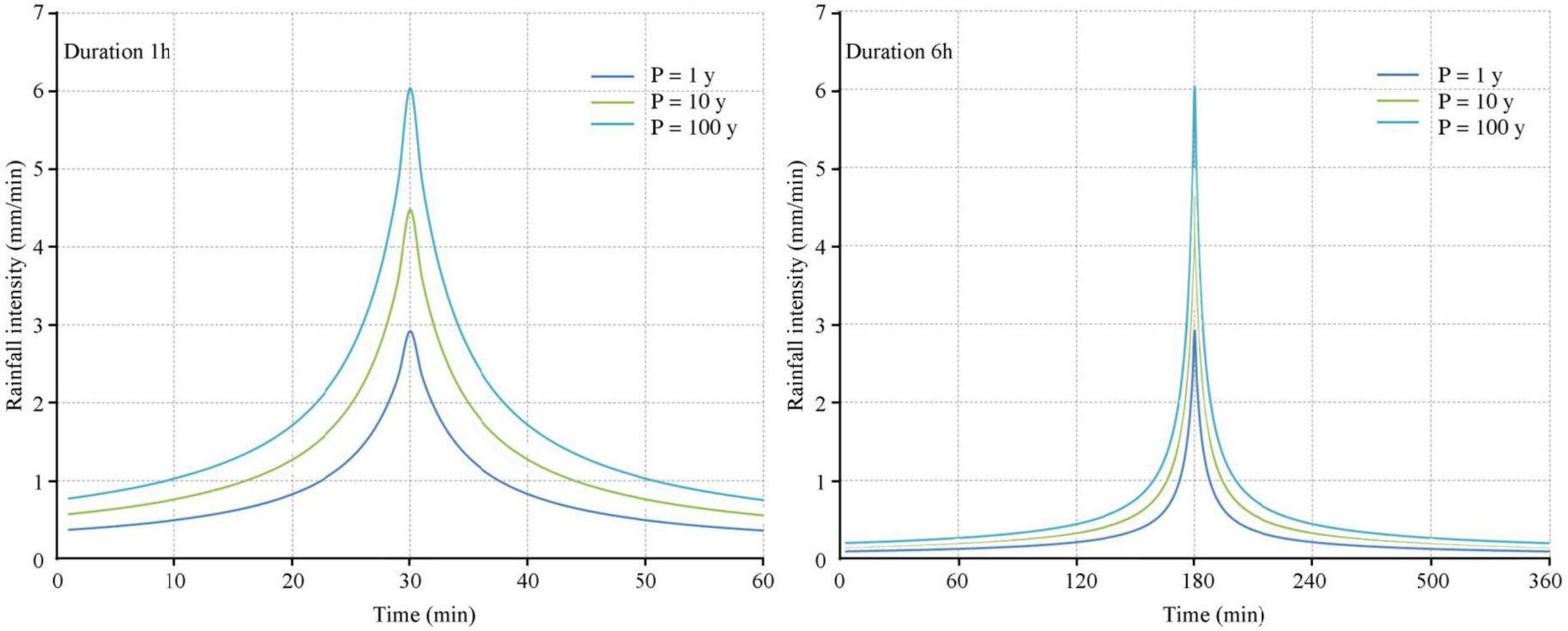


Fig. 1. The framework of cost-effectiveness assessment for porous pavement and bioretention cell based on climate change and scenario modelling. Notes: GCMs = General circulation models; RCPs = Representative concentration pathways; EQM method = Equidistance quantile-matching method; IDF curves = intensity-duration-frequency curves; SWMM = Storm Water Management Model; and LCC = Life cycle costs.


Duration 1h
P = 1 y
P = 10 y
P = 100 y
Rainfall intensity (mm/min)
Time (min)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
Duration 6h
P = 1 y
P = 10 y
P = 100 y
Rainfall intensity (mm/min)
Time (min)
0
60
120
180
240
500
360

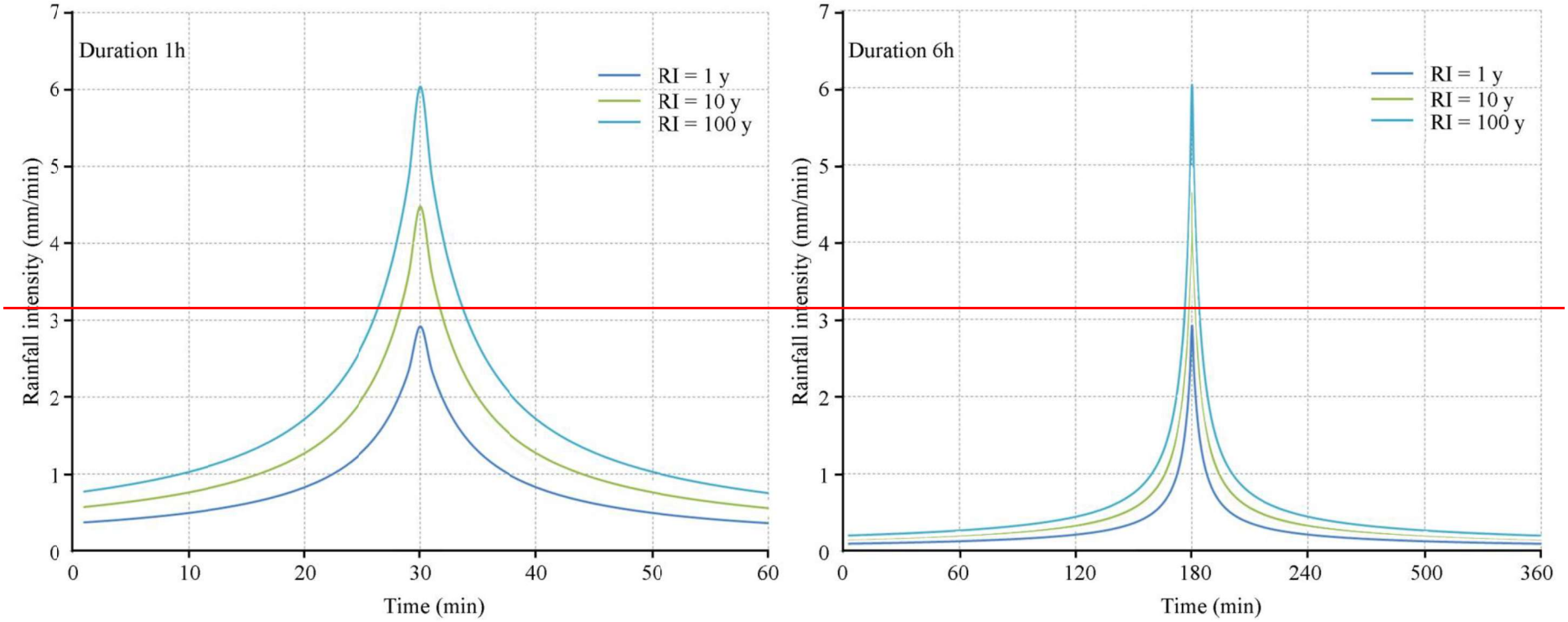


Fig. 2. Synthetic hyetographs of six design rainfall events (baseline scenario in Guangzhou) used in this study.

Notes: P = return period.

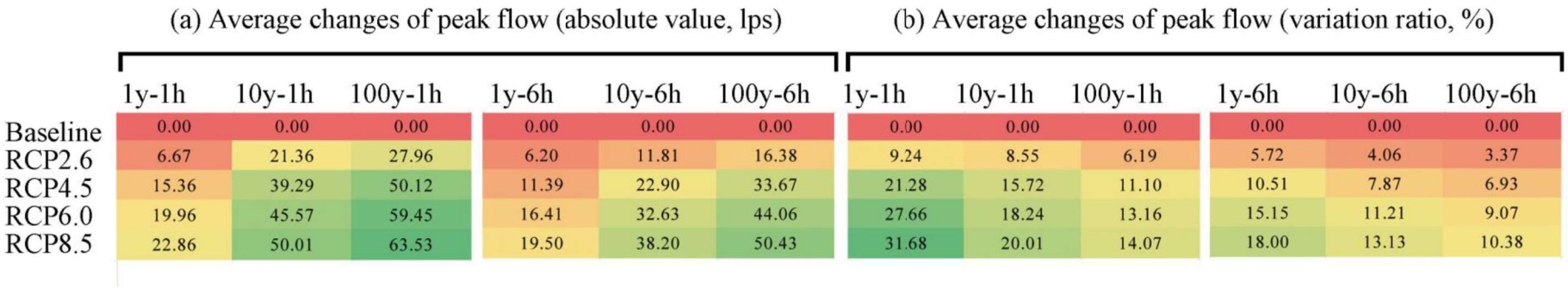


Fig. 3 Average changes of peak runoff for the test catchment in climate change scenarios compared to the baseline scenario.

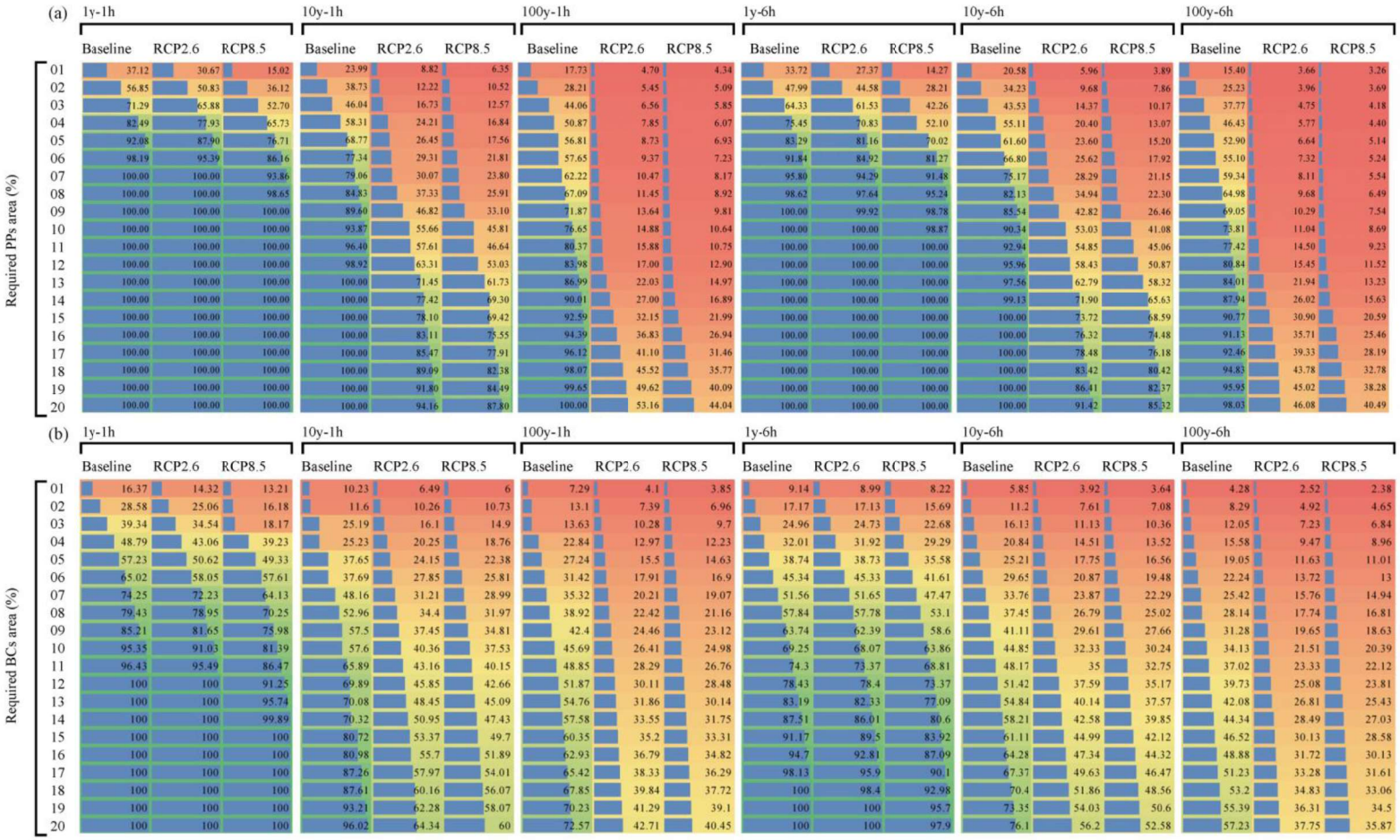


Fig. 4 (a) Reduction rates of outflow volume for PPs simulated in baseline scenarios, RCP2.6, and RCP8.5 scenarios; (b) Reduction rates of outflow volume for BCs simulated in baseline scenarios, RCP2.6, and RCP8.5 scenarios.

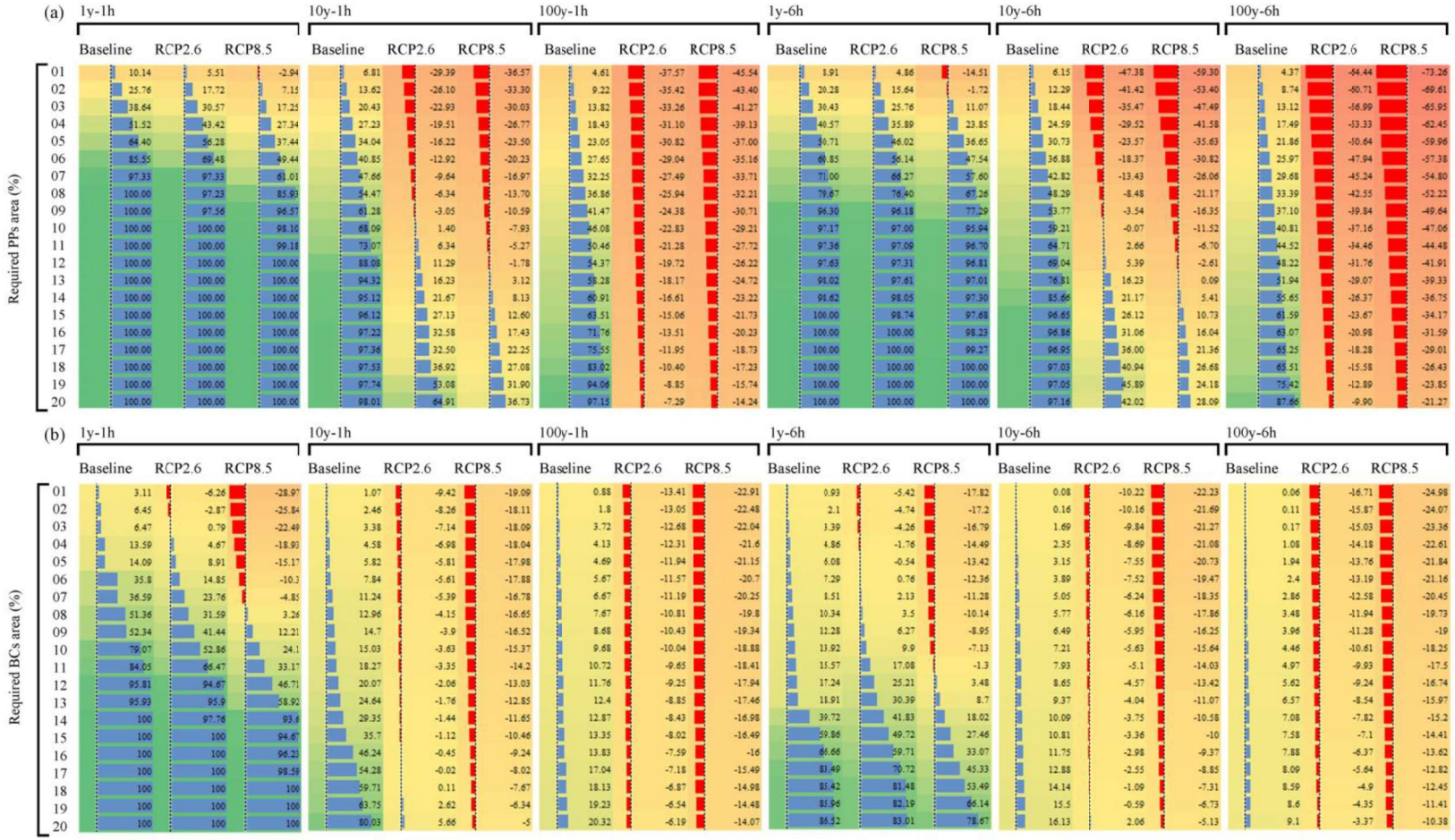


Fig. 5 (a) Reduction rates of peak flow for PPs simulated in baseline scenarios, RCP2.6, and RCP8.5 scenarios; (b) Reduction rates of peak flow for BCs simulated in baseline scenarios, RCP2.6, and RCP8.5 scenarios.

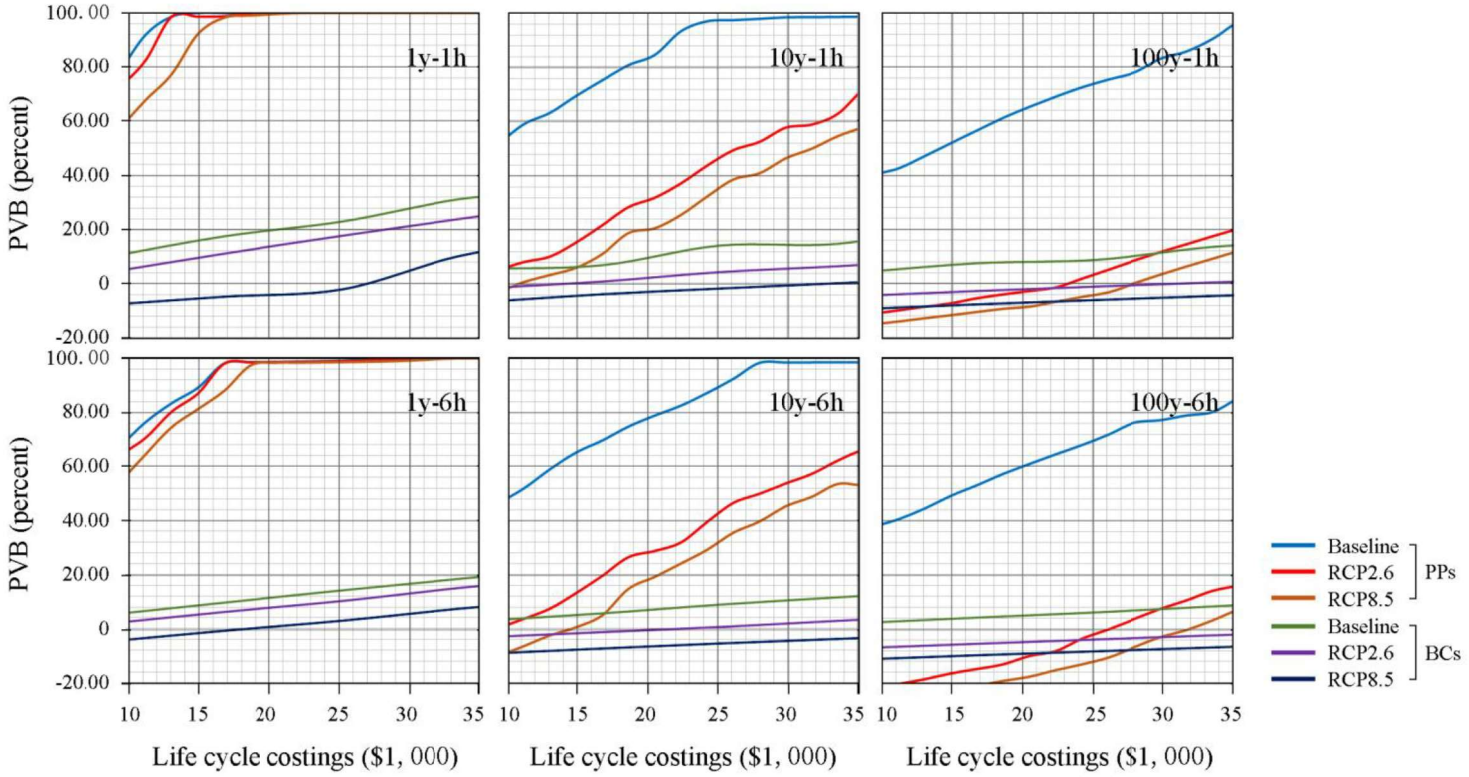


Fig. 6 ~~The~~ B/C values of PP~~s~~ and BCs under Baseline scenarios, RCP2.6, and RCP8.5.

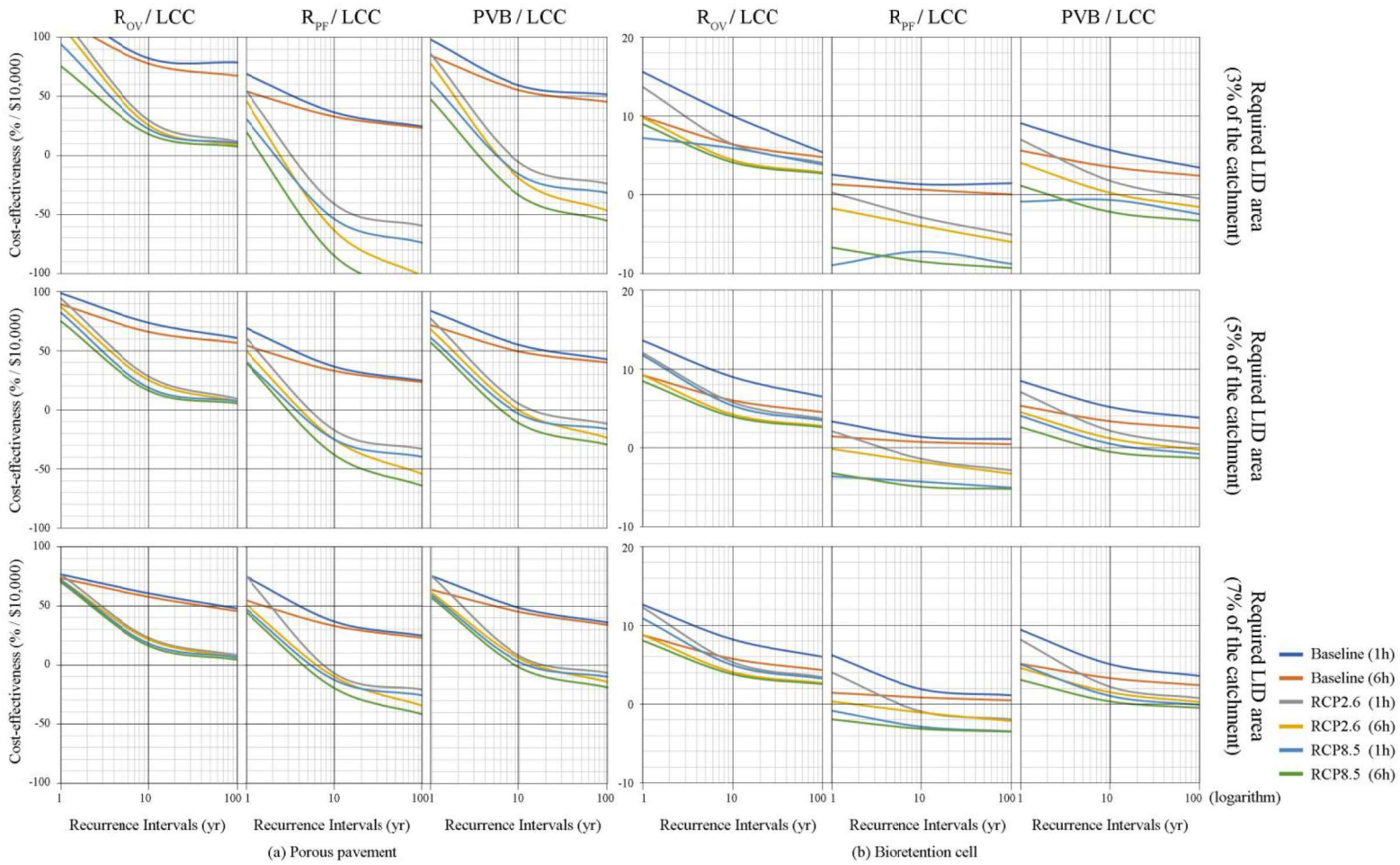


Fig. 7 ~~The c~~Comparison~~s~~ of ~~the~~ B/C values for PP~~s~~ and BCs under different climate scenarios.

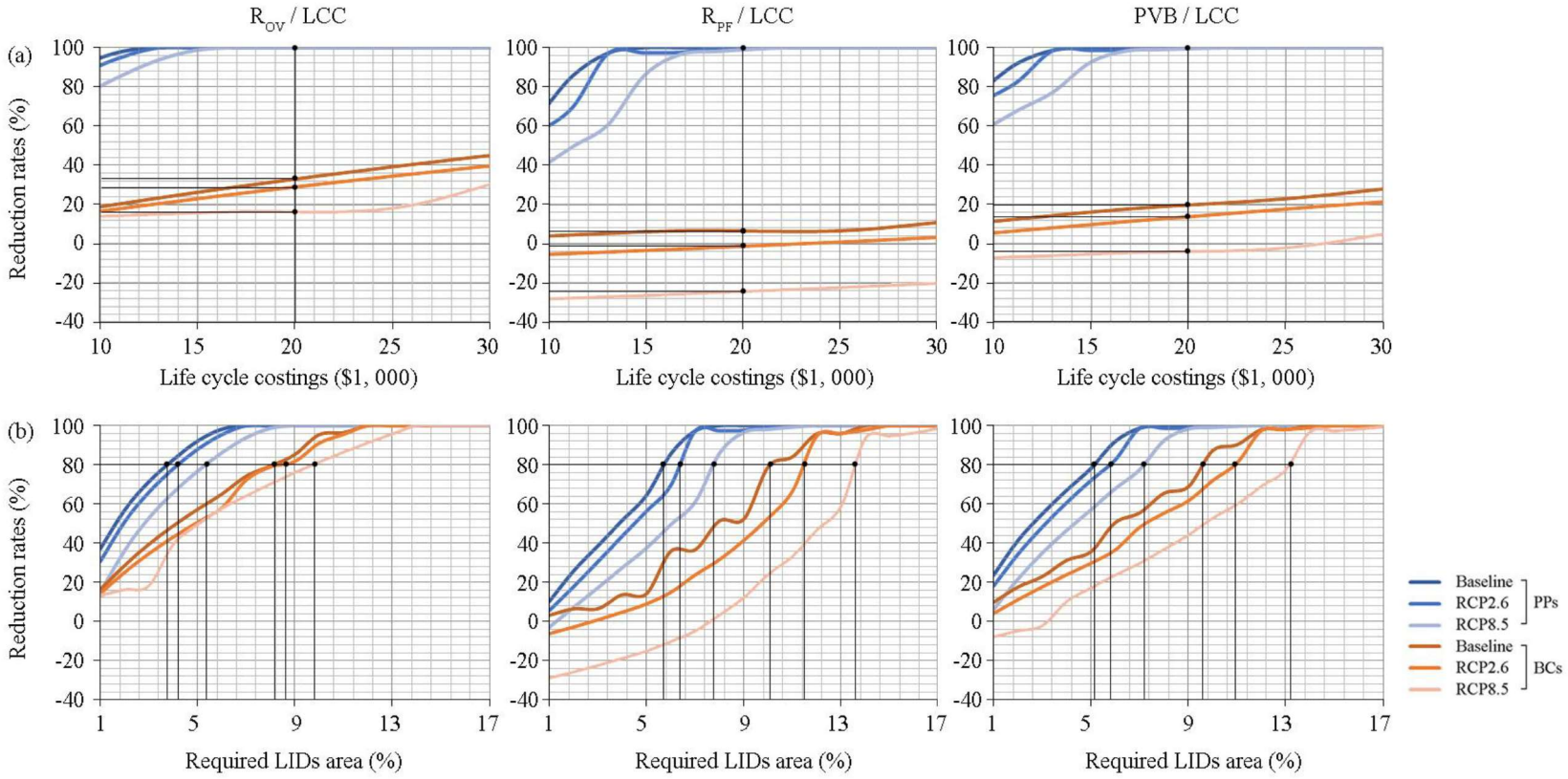


Fig. 8. ~~The~~ B/C values of PP~~s~~ and BCs in 1 y–1 h~~1y–1h~~ storms under various climate scenarios.

Table

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Table 1 Average changes (%) ~~of~~ in rainfall ~~intensities~~ intensity compared to the baseline for 4 RCPs in Guangzhou from 2040 to 2059.

Guangzhou （N=11）	1y-1h	1y-6h	10y-1h	10y-6h	100y-1h	100y-6y
RCP2.6 (%)	4.86	3.88	4.19	2.92	3.28	2.29
RCP4.5 (%)	11.43	7.38	9.21	6.07	7.09	5.33
RCP6.0 (%)	14.81	10.82	11.13	8.96	8.67	7.32
RCP8.5 (%)	16.92	12.88	12.12	10.52	9.38	8.17

Notes: source of information published by the China Meteorological Data Service Center (data.cma.cn [accessed 22 April 2018]), and Guangzhou Meteorology (www.tqyb.com.cn [accessed 7 May 2018], and Climate Change Knowledge Portal of the World Bank Group for Guangzhou, China (sdwebx.worldbank.org/climateportal/ [accessed 15 March 2018])).

Table 2 The characteristic parameters ~~characteristics~~ of porous pavement and bioretention cells considered in this study.

LID	Parameter	Porous pavement	Bioretention cells
Surface	Berm height (mm)	0	150
	Vegetation volume fraction (m^3/m^3)	0	0.1
	Surface roughness (Manning's n)	0.012	0.1
	Surface slope (%)	0.5	0.5
Soil	Thickness of soil (mm)	-	600
	Porosity (m^3/m^3)	-	0.5
	Field capacity (m^3/m^3)	-	0.2
	Wilting point (m^3/m^3)	-	0.1
	Conductivity (mm/hr)	-	250
	Conductivity slope	-	10
	Suction head (mm)	-	87.5
Pavement	Thickness	100	-
	Void ratio (Voids/Solids)	0.15	-
	Impervious surface fraction	0	-
	Permeability (mm/hour)	500	-
	Clogging factor	0	-
Storage	Thickness of storage (mm)	300	300
	Void ratio (voids/solids)	0.4	0.75
	Seepage rate (mm/hour)	750	750
	Clogging factor	0	0
Underdrain	Flow coefficient of drain	0.5	0.5
	Flow exponent of drain	0.5	0.5
	Offset height of drain (mm)	100	150

Note: ~~Parameters of bioretention cell are s~~Summarized from Prince George's County (2002), Rossman (2010) and Hinman (2012). Parameters of porous pavement ~~are~~ summarized from Rossman (2010) and Hinman (2012).

Table 3 Best-fit~~ted~~ model parameters of the test catchment.

Parameter~~s~~	Description	Recommended parameter range (Rossman, 2010)	Value of parameter used (Zhu et al., 2016)
N-imperv	Manning's roughness of impervious	0.001 – 0.1	0.015
N-perv	Manning's roughness of pervious	0.01 – 0.5	0.4
Dstore-imperv (mm)	Depression storage of impervious	1	1
Dstore-perv (mm)	Depression storage of pervious	3 – 10	10
MaxRate (mm/h~~our~~)	Maximum infiltration capacity	25.4 – 127	103.81
MinRate (mm/h~~our~~)	Minimum infiltration capacity	0.25 – 30	11.44
Decay constant (h~~our~~)	Decay coefficient	2 – 7	2.75
Drying time (day)	Regeneration coefficient	2 – 14	7.00

Table 4 Construction costs and O&M costs of bioretention cells (100 m^2) and porous pavements (100 m^2) in this study.

Cost		Size		Unit price	Value ($)	
		Bioretention cells	Porous pavement		Bioretention cells	Porous pavement
Construction costs	Plant	100 m^2	-	25 \$/m^2	2500	-
	Asphalt pavement	-	10 m^3	150 \$/m^3	-	1500
	Soil	60 m^3	-	45 \$/m^3	2700	
	Gravel	30 m^3	-	40 \$/m^3	1200	
	Pipe	10 m	10 m	15 \$/m	150	150
	Filter fabric	-	100 m^2	2 \$/m^2	-	200
	Geotextile	100 m^2	100 m^2	1 \$/m^2	100	100
	Excavation	105 m^3	40 m^3	4 \$/m^3	420	160
	Disposal	90 m^3	40 m^3	5 \$/m^3	450	200
	Capital costs	100 m^2	100 m^2	-	7520	2310
Annual O&M costs		100 m^2	100 m^2	-	601.6	92.4
$PV_{O\&M}$		100 m^2	100 m^2	-	9248	1420
LCC		100 m^2	100 m^2	-	16768	3730
LCC unit		-	-	-	167.68	37.30

Note: The data is are mainly from a local inquiry internet platform for engineering materials (www.gldjc.com [accessed 27 June 2018]); discount rate 5%; project life: 30 years; annual O&M costs are 8% and 4% of capital cost for bioretention cells and porous pavement, respectively.