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The influence of Low Impact Development (LID) on basin runoff in a half-urbanized catchment: A case study in San Antonio, Texas

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A R T I C L E I N F O

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A B S T R A C T

Low Impact Development (LID) was promoted as an alternative to conventional urban drainage methods. The effects of LID at the site or urban scales have been widely evaluated. This project aims to investigate the impact of LID implementation on basin runoff at a regional scale in a half-urbanized catchment, particularly the overlap of urban and rural sub-flows at peak times. A SUPERFLEX conceptual model framework is adapted as a semi-distributed model to simulate the rainfall-runoff relationship in the catchment for San Antonio, Texas, as a case study. Scenario analyses of both urban development and LID implementation are conducted. Results show that (1) the infill urban development strategy benefits more from runoff control than the sprawl urban development; (2) in non-flood season, permeable pavements, bioretention cells, and vegetated swales decrease peak runoff significantly, and permeable pavements, bioretention cells, and green roofs are good at runoff volume retention; (3) contrary to the general opinion about the peak reduction effect of LID, for a partly urbanized, partly rural basin, the LID implementation delays urban peaks and may cause larger stacking of rural and urban peak runoffs, leading to larger basin peaks under extremely wet conditions.

1. Introduction

Urbanization brought numerous environmental and hydrological changes to river basins and severely disturbed the natural water processes. Unwanted vegetation is removed for urban development, diminishing vegetation interception and transpiration. Large areas of pervious surfaces are replaced by impervious concrete and asphalt for human convenience, impeding runoff infiltration and subsurface water retention. More environmental issues occur without sufficient and continuous groundwater recharge, such as land subsidence, groundwater shortage, and water quality degradation (Ahiablame and Shakya, 2016). These human activities modify catchments from a relatively robust natural condition to a sensitive and unstable urbanized status, resulting in water scarcity in dry seasons and waterlogging or urban flooding in rain seasons (Gilroy and Mccuen, 2009; Ahiablame et al., 2012).

The conventional urban drainage approach is widely exploited in urban areas to solve flooding problems, adopting the rapid and centralized water transfer strategy. Drainage systems are built to rapidly collect and convey storm and wastewater from impervious urban areas to centralized municipal facilities, nearby water bodies, or downstream rural areas. The conventional approach does not solve water problems such as peak flows and water quality issues, which only shifts the problems to another place to some extent. Low Impact Development (LID or best management practices) is promoted as an alternative to the conventional approach. It seeks environmentally friendly solutions for current urban water problems. Instead of conventional centralized grey infrastructures such as pipelines and reservoirs, LID exploits blue-green practices such as green roofs and permeable pavements to mimic the natural hydrological system and facilitate rainwater detention and natural purification processes. It aims to reduce human impact and control the rainwater at the source (Dietz, 2007; Gilroy and Mccuen, 2009; Bedan and Clausen, 2009; Ahiablame et al., 2012; Ulku et al., 2018).

Since the promotion of the LID concept during the1990s, plenty of LID practices have been designed and introduced to better suit diverse hydrological functions and ecosystem services under different field conditions. The most widely used LID practices include (1) bioretention cells, also known as rain gardens or depressed green, which capture runoff with thick layers of soil and lush vegetation. (2) Vegetated swales,

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shallow and narrow open channels to convey the rainwater, are alternative options for traditional concrete gutters and curbs. (3) Extensive, vegetated green roofs are one of the most popular LID practices because of their claimed advantages, including runoff reduction, house insulation, and ecological and aesthetic benefits. (4) Permeable pavements are a multifunction LID practice, which can be flexibly incorporated into different pavement-needed surroundings.

The effectiveness of LID practices on runoff reduction has been well documented in scientific papers with field tests and simulation investigations (Zhu et al., 2019; Samouei and Özger, 2020; Sheikh and Izanloo, 2021; Yang et al., 2022). Bioretention cells are shown to reduce 48 % to 97 % of the incoming runoff volume (Chapman and Horner, 2010; DeBusk and Wynn, 2011). The runoff reduction proportion of extensive green roofs varies a lot between 6.1 % and 100 %, depending on the roof slope, media type and depth, vegetation species, and the intensity and duration of rain events (VanWoert et al., 2005; Carpenter and Kaluvakolanu, 2011; Soulis et al., 2017). Hunt et al. (2010) monitored the runoff reduction of a vegetated swale for 23 precipitation events and reported that the runoff reduction proportion has a significant difference between 35 % and 100 % for large and small storm events. Permeable pavements can reduce runoff greatly by between 50 % and 93 % (Rushton, 2001; Hunt et al., 2002; Dreelin et al., 2006). Qin et al. (2013) assessed the performance of swales, permeable pavement, and green roofs in a small, urbanized basin using the US EPA Storm Water Management Model (SWMM) model. They found that all three LID practices can retain more flood volume during heavier and shorter storm events. Ahiablame and Shakya (2016) used the Personal Computer Storm Water Management Model (PCSWMM) and found that LID can reduce 3 % to 47 % of total runoff under different LID implementation levels in a highly urbanized watershed.

While the runoff retention performance of LID practices was extensively documented at the site or urban basin scales, few studies illustrated the influence of LID implementation in a half-rural and half-urbanized catchment at a large scale. This research is necessary. Because of the faster runoff response time of urban lands, the urban peak will reach the outlet of the basin before the peak of the rural part arrives. However, implementing LID solutions in city areas may delay the urban sub-runoff and cause more overlap of the urban and rural peaks, resulting in a larger basin peak. For downstream flood safety, the implementation of LID needs to consider the runoff not only in urban areas but also on the whole catchment scale. That is why this research aims to study the influence of LID implementation on the basin peaks for a half-urbanized catchment.

A case study is conducted for San Antonio, Texas, to investigate the peak stacking of rural and urban runoff. The SUPERFLEX conceptual model framework is used to develop to simulate the rainfall-runoff relationship of this partly urbanized catchment. Further urbanization of this catchment is foreseen. To deal with the uncertainty of future urban development, we use a scenario analysis of both LID implementation and urbanization to give a reliable answer to the research question. The specific objectives are to (1) investigate the different rainfall-runoff relationships of urban and rural sub-areas; (2) examine the influence of urbanization on the basin runoff; and (3) assess the influence of LID implementation on the basin runoff, especially the overlap of urban and rural sub-flows at peak times.

The structure of this paper is organized as follows. The study area, hydrological data, and SUPERFLEX model framework are introduced in Section 2. The methods of the scenario design and model setup are illustrated in Section 3. The research results regarding the effects of urbanization and LID implementation on the catchment scale are shown in Section 4. Some discussions concerning the transferability, limitation, and comparative analysis of this research and recommendations for future urban development are in Section 5. Finally, the conclusions are drawn in the last Section 6.

2. Study area, data, and modeling tools

2.1. Study area

San Antonio city is the seventh most populous city in the U.S., with more than 1.5 million residents (Ready and Montoya, 2019). It is also the fastest-growing of the top ten largest cities in the United States (The City of San Antonio - Official City Website, 2020). From 2010 to 2017, San Antonio experienced a population growth rate between 1.5 % and 2.0 %. The city still keeps a stable demographic expansion. With this stable population increase, the urban built-up area in San Antonio is expected to grow at a more or less equal pace.

San Antonio has a transitional humid subtropical climate featuring hot and humid summers and mild to cool winters. The average annual precipitation is 737 mm. The soil in San Antonio is mainly moderately permeable clayey soil. Edwards Aquifer is the most prolific groundwater aquifer in the study area, which is the main source of water for residents. A groundwater recharge project is developed in the north part of San Antonio to release the stress of the Edwards Aquifer by holding back storm runoff in recharge zones. The implementation of LID practices like permeable pavements and bioretention cells can also accelerate natural stormwater infiltration. Other personal stormwater infiltration is not allowed to avoid groundwater pollution (The Edwards Aquifer Website, 2020).

The research catchment is 4544 km^2, which is a sub-basin of the San Antonio River. The city of San Antonio takes 27 % of the research catchment (de Colstoun et al., 2017). The urban built-up area is near the basin outlet (Fig. 1). San Antonio River flows through San Antonio downtown and joins with the Medina River. San Antonio has separate foul sewer and stormwater transportation systems. The precipitation collected by the stormwater pipelines is discharged directly to nearby water bodies without treatment. The wastewater is transported to three major wastewater treatment centers in San Antonio, and the treated water is discharged to nearby rivers (San Antonio Water System, 2020).

2.2. Hydrological data

The time series of precipitation, evaporation, and runoff data for the study catchment from 2017-04-12 to 2018-12-02 (600 research days) are collected from the USGS website (https://www.usgs.gov/). The first 365 days are the calibration period, and the last 235 days are the verification period. We use 30 min time scale hydrological data to reflect the fast runoff response in urban areas.

Precipitation data are retrieved from 10 monitoring stations. Thiessen polygons method is used to calculate the mean precipitation in this catchment. Evaporation data comes from a meteorological station in the research area. The discharge data from the study catchment and two sub-catchments are collected from three streamflow monitoring stations, as shown in Fig. 1. Over 600 research days, the accumulated precipitation, evaporation, and runoff amounts are 1335, 1054, and 166 mm.

2.3. SUPERFLEX model framework

To avoid issues of too complex hydrological models, including high-data requirements, equifinality problem, and model uncertainty, and to distinguish the rural and urban areas in the same catchment, the SUPERFLEX (Fenicia et al., 2011) hydrological modeling framework is adapted to a semi-distributed model in this study. The SUPERFLEX modeling framework uses generic building blocks, such as reservoirs, junctions, and related functions, which provide a platform for hydrologists to test dominant water processes and build tailor-made models. The SUPERFLEX framework has been adapted for different topographical conditions (e.g., plateau, hillslope, and wetland) as the FLEX-Topo model (Savenije, 2010). The DYNAMIT (DYNAmic Mixing Tank) model, proposed by Hrachowitz et al., in 2013, is loosely based on the

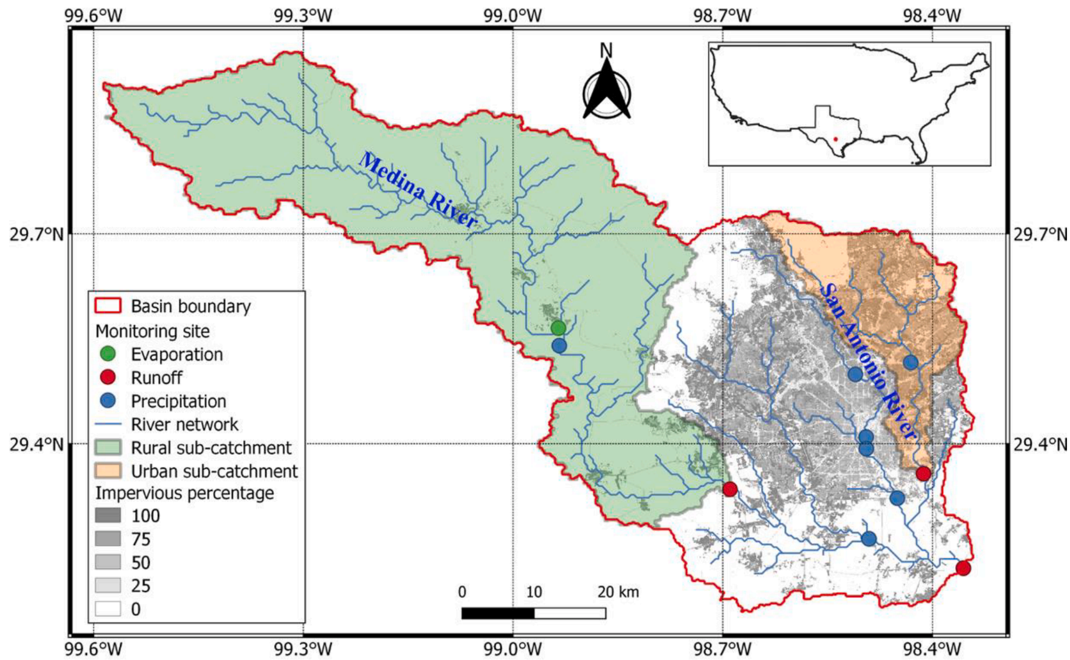

Fig. 1. The built-up condition in the study catchment and two sub-catchments. The rainfall-runoff relationship in the study catchment is simulated by a semi-distributed model, and the rural and urban sub-catchments (colored in green and orange) are used to calibrate two lumped pre-models (section 3.2.1). The eastern impervious area is the city of San Antonio.

FLEX model, the predecessor of SUPERFLEX framework. Furthermore, the FLEXG model is a glacier hydrological model that integrates snow and glacier accumulation and ablation processes (Gao et al., 2018). In Lisflood-FP (Hostache et al., 2018), the output of a SUPERFLEX-based model is combined with a hydraulic model to simulate river discharge. While SUPERFLEX was widely used to simulate the rainfall-runoff relationships under different natural landscapes, it has not yet been applied in a highly urbanized catchment. In this study, several urban water processes as well as four LID modules (bioretention cells, green roofs, bioswales, and permeable pavements) were formulated and added to the SUPERFLEX framework.

3. Method

Because the different lag times and stacking of the rural and urban peaks are key points, this study focuses on the different hydrological characteristics of urban and rural areas. SUPERFLEX conceptual model framework is adapted to a tailor-made semi-distributed model with two hydrological response units for urban and rural surfaces, respectively. The SUPERFLEX model is firstly calibrated for the current rainfall-runoff relationship. The influences of urbanization and LID implementation on the basin runoff are also investigated. To address the research problem, eight scenarios, including three urbanization scenarios (A, B, and C) and five LID implementation scenarios (bioretention cells, permeable pavements, green roofs, vegetated swales, and mixed LID scenarios), are designed to deal with the prediction uncertainty. The design of urbanization and LID implementation scenario is introduced first, followed by the hydrological model setup.

3.1. Scenario design

3.1.1. Urbanization scenarios

According to the urbanization projection from “City of San Antonio: Comprehensive Plan” (2010), there will be 1.1 million new residents in San Antonio by 2040. In this research, the current time is defined as 2017. The expected population growth between 2017 and 2040 is estimated at 0.9 million. The government of San Antonio plans to terminate the unconstrained urban sprawl and adopts the infill urbanization strategy to retrofit existing urban and suburban areas. It could attract more investment in the urban core and save the high infrastructure and utility services costs for newly developed areas.

Based on the information above, three urban development scenarios for 2040 are designed (Table 1). Scenario A offers an extreme infill urban development situation in which city size in 2040 will be the same as it is now. Scenario B is a partial-infill, partial-sprawl urban development situation. In this scenario, 70 % of the new residents will live in current urban areas, while 30 % of new residents will be living in new suburban areas. In scenario C, 50 % of the new residents are assumed to stay in urban expansion areas, while the other 50 % will infill current vacant and underutilized urban areas. Since the infill development strategy may lead to a compact living space, per capita living space for scenario A is assumed to be 0.85 times the current areas, and this ratio is 0.9 for scenario B, while no compact living space is assumed for scenario C.

3.1.2. LID implementation scenarios

According to local regulations, the implementation of LID is not strictly mandatory, and there is great flexibility in the selection of LID practices. Therefore, this research adopts the four most common and typical LID practices to design five LID implementation scenarios based on the conventional urban development scenario C. The first four scenarios assume moderate LID implementations, as 15 % of the precipitation on urban impervious (grey) surfaces will be collected by a single type of LID practice (bioretention cells, vegetated swales, extensive green roofs, or permeable pavements). This will allow us to compare the different hydrological performances of these LID practices.

The last scenario assumes a wide-scale LID implementation, as 50 % of the precipitation on urban impervious (grey) surfaces will be conveyed by mixed LID practices (bioretention cells, 15 %; vegetated swales, 15 %; extensive green roofs, 5 %; permeable pavements, 15 %), to provide an optimistic and flexible LID implementation plan. Green roofs and permeable pavements serve the area where they are constructed. The construction areas of bioretention cells and vegetated swales are smaller, with the ratio of drainage and construction areas as

Table 1
The urban development condition in 2017 and three future scenarios for 2040 (City of San Antonio, 2010).

Scenarios	Total residents [million]	Percentage of new residents following the infill development [%]	Residents in current urban areas [million]	Percentage of new residents following the sprawl development [%]	Residents in urban expansion areas [million]	The compact factor for living space
Current (2017)	1.5	–	1.5	–	–	–
A (2040)	2.4	100	2.4	0	0	0.85
B (2040)	2.4	70	2.13	30	0.27	0.9
C (2040)	2.4	50	1.95	50	0.45	1

1.5 and 3, respectively. Besides, the cascading connections among these LID practices are designed based on realistic construction considerations, as shown in Fig. 2c.

3.2. Hydrological model

SUPERFLEX hydrological modeling framework is adapted into a tailor-made semi-distributed model for the study catchment. The semi-distributed model is calibrated and validated with the observed precipitation, evaporation, and runoff data. Based on the calibrated model for the current condition, the model structure and parameter values are further modified for the simulation of urban development and LID implementation.

3.2.1. Semi-distributed model setup

The hydrological modeling starts from two simple lumped pre-models, one for the rural and one for the urban sub-catchment. The dominant water processes in rural and urban environments are identified from lumped models and inherited by semi-distributed models to simulate the whole study catchment. Six generations of semi-distributed models, ranging from six-bucket to eight-bucket, are built (Sui, 2019). These semi-distributed models are calibrated for the first 365-day period on a 30-minute scale and then validated with the last 235-day data pairs. We use the multi-objective calibration approach in this research. Nash-Sutcliffe Efficiency (NSE) and correlation coefficient (R^2) are used to evaluate the simulated runoff time series. The quantile–quantile plot (Q. Q. plot) is used to compare the observed and simulated runoff distributions. Moreover, we compare the characteristics of the urban and rural sub-flows from the model output and the observed runoff data collected from the urban and rural sub-catchments (Sui, 2019).

For the parameter calibration, the initial range of each parameter is given roughly based on the experiences and local conditions according to the physical meaning of these parameters (Breuer et al., 2003; Gharari et al., 2014). Then, random parameter sets are sampled between the maximum and minimum limitations with the Monte Carlo method. More complex models with more parameters are tested with larger numbers of parameter sample sets to ensure that the calibration scale is as "fair" as possible. The final selection of the semi-distributed model is a six-bucket model. The schematic figure of the model structure, mathematical expressions of water processes, and the parameter calibration results are shown in Fig. 2a and Table 2.

3.2.2. The expression of urban development in the model

In the semi-distributed model, three urbanization scenarios are expressed with two parameters, 1) the proportion of urban areas in the whole catchment and 2) the proportion of urban grey areas in urban areas. The degree of urban construction (including water drainage systems) and population density are assumed to be homogeneous in urban areas. The numerical expressions of three urbanization scenarios are shown in Table S1 in the supplementary material.

3.2.3. The expression of LID practices in the model

The expression of LID in the semi-distributed model follows two procedures. First, the hydrological processes of LID practices are designed and fit in the urban module of the calibrated semi-distributed model. Then, reasonable values are assumed for the LID parameters based on literature, field test results, and local government documents (Carter and Jackson, 2007; Carter and Rasmussen, 2016; Collins et al., 2008; Hunt et al., 2008; Li et al., 2009; San Antonio River Authority, 2015; San Antonio Water System, 2020; Van Seters et al., 2006). The specific assumptions for LID parameters include the construction and drainage areas, maximum interception depth, soil depth and porosity, and the lag time for peak flows (Sui, 2019). The schematic model structures of four LID practices fitting in the urban module are shown in Fig. 2b. The mathematical expressions of hydrological routes and parameters are in Table 3 and Table 4.

The parameters, D_{LID}^{a} and A_{R}^{b}, are dependent on the specific LID implementation scenarios.

4. Results

The observed and simulated rainfall-runoff relationships under the current condition are shown in Fig. 3. The semi-distributed model has good performance with high NSE and R^2 of 0.68 and 0.90 during the calibration period and 0.69 and 0.84 during the verification period. The observed and simulated total basin runoff is 166 and 160 mm in 600 research days. According to the model result, urban areas (27 % of the basin) produce 63 % of the total runoff volume, and rural areas (73 % of the basin) generate only 37 %. Urban areas generate peak runoff frequently, no matter in dry or rainy seasons, while in rural areas, the peak runoffs appear less often with lower peaks (Fig. 3a).

4.1. Urbanization influences on basin runoff

Fig. 4 compares the simulated total basin runoffs for three urbanization scenarios and the current condition. The simulated total runoff volumes and maximum peak values in 600 research days are shown in Table 5. We found that all three urbanization scenarios generate larger numbers of total basin runoff volumes compared to the current condition. Scenario C, with the highest level of urban sprawl development (50 % of new residents following the infill development) without the compaction of per capita living space, produces an additional 14.3 % of total basin runoff. For scenarios B and A (70 % and 100 % of new residents following the infill development) with the compact factors 0.9 and 0.85, the growth rates of basin runoff volume are 8.7 % and 2.7 %, respectively. As for peak flows, all three urbanization scenarios bring obvious increases in most peak runoffs (Fig. 4a). Similar to the total basin runoff volumes, scenario C always brings the largest peak runoffs, followed by scenarios B and A consecutively. Even though urbanization may inevitably bring the growth of basin runoff, the infill urban development strategy is more helpful in basin runoff control for both total volumes and peak values than the sprawl urban development strategy in our case study.

Compared to the current condition, the maximum peak runoff in 600 research days is increased by 16 % and 7.5 % in scenarios C and B (Table 5). However, in scenario A, as a fully-infill urbanization plan without any urban expansion, the maximum peak runoff unexpectedly declines by 4.3 % compared to the current condition. Fig. 4b shows the maximum peak runoff and its two successive peak runoffs during flood season. We found that urbanization scenario A not only reduces the

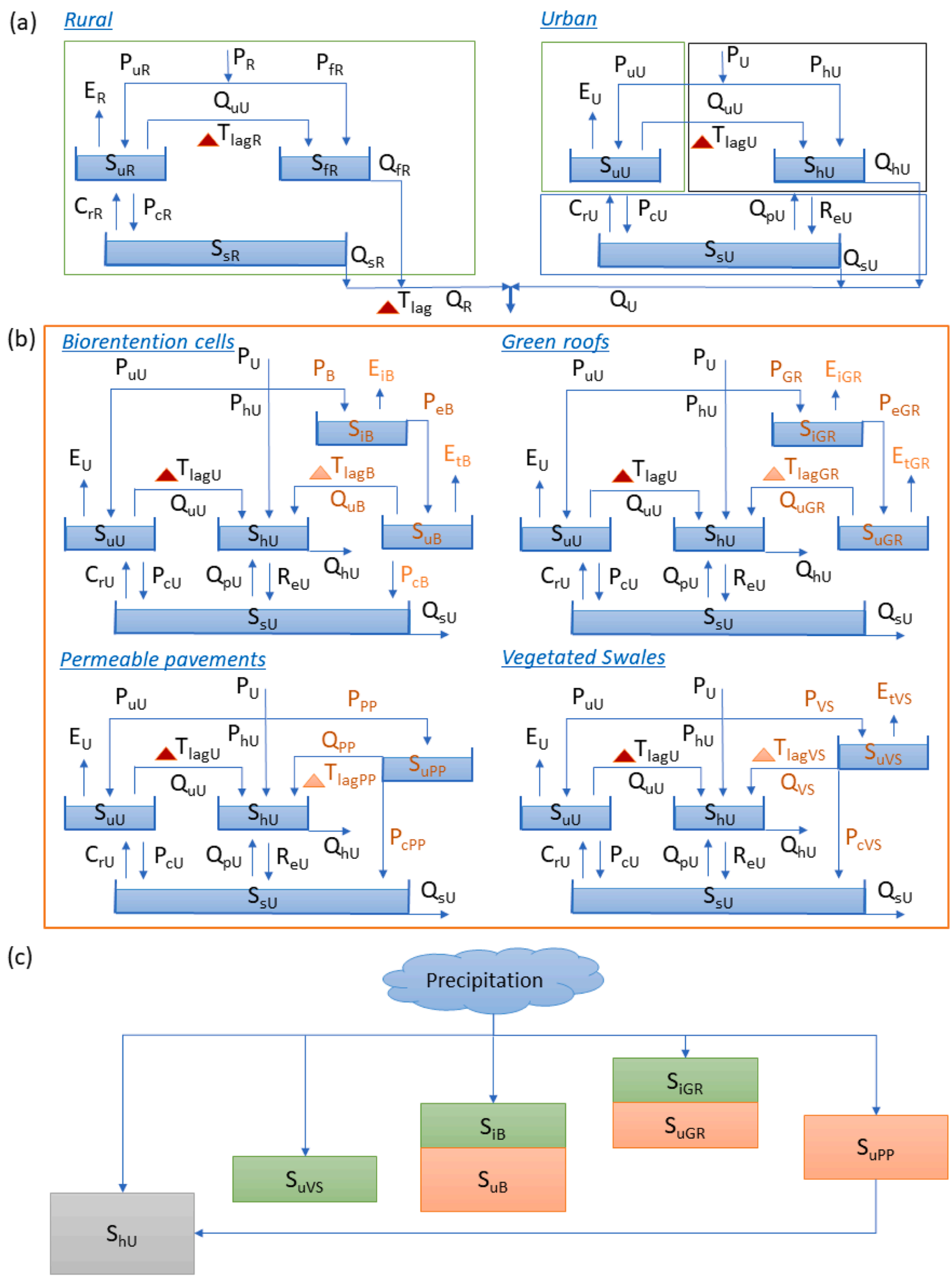

Fig. 2. Schematic figures of model structures. (a) The semi-distributed model simulates the rainfall-runoff relationship of the study catchment without LID implementation. The rural module includes three reservoirs, unsaturated reservoir (S_{uR}), fast reacting reservoir (S_{fR}), and slow reacting groundwater reservoir (S_{sR}). The urban module consists of three parts, urban green surface, urban grey surface, and underground parts, corresponding to three reservoirs, unsaturated reservoir (S_{uU}), human impact reservoir (S_{hU}), and slow reacting reservoir (S_{sU}). The hydrological processes and their mathematical expressions are shown in Table 2. (b) The urban module coupling with four LID modules for four single LID scenarios. Bioretention cells module contains one interception reservoir (S_{iB}) and one unsaturated reservoir (S_{uB}). Permeable pavements module and vegetated swales module include one permeable pavement reservoir (S_{uPP}) and one vegetated Swales reservoir (S_{uVS}), respectively. Green roofs module contains one interception reservoir (S_{iGR}) and one unsaturated reservoir (S_{uGR}). The hydrological processes within LID modules and their mathematical expressions are indicated in Table 3. (c) The hydrological processes for the cascade connection among four LID practices in the mixed LID scenario.

maximum peak runoff but also reduces the runoff value of its next two peaks. This phenomenon is because intensive rainfall events have filled up the water retention capacity in rural areas during the flood season. Under this circumstance, the basin peaks are contributed by the urban and rural sub-flows together (Fig. 4c). Without any urban expansion, urbanization scenario A shares the same rural sub-flow as the current condition. However, the urban sub-flow in urbanization scenario A is increased and comes faster compared to it under the current condition.

Table 2
Mathematical expression of water processes, parameters, and their calibration results in the semi-distributed model for the current condition.

Description of water process	Mathematical expression	Parameter	Description of parameter	Rural	Urban
Precipitation on Su (mm d^{-1})	$P_u = D \times P$	D [–]	Precipitation distribution factor for Su	0.98	0.83
Precipitation on Sf or Sh (mm d^{-1})	P_f or $P_h = (1 - D) \times P$	Ce [–]	Evaporation correction coefficient	2.7	1.1
Evaporation (mm d^{-1})	$E = C_e E_{ref}$	Sumax [mm]	Maximum unsaturated storage	186	51
Overflow from Su (mm d^{-1})	$Q_u = P_u \left(\frac{S_u}{S_{umax}}\right)^{\beta}$	β [–]	Discharge exponent	6.5	1.6
Percolation (mm d^{-1})	$P_c = P_{cmax} \frac{S_u}{S_{umax}}$	Pcmax [mm d^{-1}]	Maximum percolation velocity	4.9	4.8
Capillary rise (mm d^{-1})	$C_r = C_{max}\left(1 - \frac{S_u}{S_{umax}}\right)$	Cmax [mm d^{-1}]	Maximum capillary rise velocity	0.7	1.0
Groundwater recharge (mm d^{-1})	$R_e = R_c S_h$	Rc [1 d^{-1}]	Recharge coefficient	–	1.5
Groundwater pumping (mm d^{-1})	$Q_p = A \times \sin\left(\frac{2\pi}{T} t + \varphi\right) + A$	Kh or Kf [1 d^{-1}]	Human impact or fast reservoir coefficient	0.88	0.51
Discharge from Ss (mm d^{-1})	$Q_s = K_s S_s$	A [mm d^{-1}]	Amplitude of water pumping rate	–	0.65
Discharge from Sf or Sh (mm d^{-1})	$Q_f = K_f {S_f}^{\alpha} Q_h = K_h {S_h}^{\alpha}$	φ[–]	Phase of water pumping rate in a day	–	2.2
Lag time function	$f = \begin{cases} \frac{4t}{(T_{lag})^2}, 0 < t < \frac{T_{lag}}{2} \\ \frac{4(T_{lag} - t)}{(T_{lag})^2}, \frac{T_{lag}}{2} < t < T_{lag} \\ 0, t > T_{lag} \end{cases}$	Ks [1 d^{-1}]	Slow reservoir coefficient	0.004	0.002
		α [–]	Discharge exponent	8.0	1.5
		Tlag,u [d]	Lag time coefficient for overflow from Su	1.75	1.75
		Tlag [d]	Lag time coefficient for rural sub-flow	0.83	–

Table 3
Hydrological routes and parameters used in the LID module.

Description of water process	Mathematical expression	Parameter	Description of parameter
Precipitation on LID practices	$P_{LID} = D_{\mathrm{LID}} \times P$	D_{LID}^{a} [–]	Precipitation distribution factor for LID practices
Evaporation (Interception)	$E_{iLID} = C_e E_r \frac{D_{\mathrm{LID}}}{A_{R,\mathrm{LID}}}$	A_R^{b} [–]	The ratio of the construction area to the drainage area
Effective precipitation after the interception	$P_{eLID} = S_{iLID} - I_{max,\mathrm{LID}} \frac{D_{\mathrm{LID}}}{A_{R,\mathrm{LID}}}$	C_e [mm]	Evaporation coefficient
Transpiration from LID practices	$E_{tLID} = (C_e E_r - E_u - E_{iLID}) \frac{D_{\mathrm{LID}}}{A_{R,\mathrm{LID}}} \frac{S_u}{S_{umax}}$	E_r [mm d^{-1}]	Reference Evaporation
Discharge from vegetated swales	$Q_{VS} = K_{VS} S_{VS}$	$I_{max,LID}$ [mm]	Maximum interception depth on LID practices
Overflow from bioretention cells	$Q_{uB} = P_{eB} \left(\frac{S_{uB}}{S_{umax,B} \frac{D_{\mathrm{LID}}}{A_{R,\mathrm{LID}}}}\right)^{\beta_U}$	$S_{umax,LID}$ [mm]	Maximum water storage depth in subsoil layer of LID practices
Overflow from green roofs	$Q_{GR} = P_{eGR} \left(\frac{S_{uGR}}{S_{umax,GR}}\right)^{\beta_U}$	P_{cmax} [mm d^{-1}]	Maximum percolation velocity
Overflow from permeable pavements	$Q_{PP} = S_{uPP} - (I_{max,PP} + S_{umax,PP})$	S_{iLID} [mm]	The depth of water storage in I.R.
Percolation from bioretention cells to groundwater	$P_{cB} = P_{cmax} \frac{D_{\mathrm{LID}}}{A_R} \frac{S_{uB}}{S_{umax,B}}$	S_{uLID} [mm]	The depth of water storage in U.R.
Percolation from vegetated swales to groundwater	$P_{cVS} = P_{cU} \frac{D_{\mathrm{LID}}}{A_R}$	T_{lagLID} [–]	Lag time coefficient of LID practices
Percolation from permeable pavements to groundwater	$P_{cPP} = \begin{cases} P_{cmax} D_{\mathrm{LID}} \frac{S_{PP}}{S_{umax,PP}}, S_{PP} < S_{umax,PP} \\ P_{cmax} D_{\mathrm{LID}}, S_{PP} > S_{umax,PP} \end{cases}$	K_{VS} [mm]	Discharge coefficient of vegetated swales
Lag time of overflow from LID practices	$f = \begin{cases} \frac{4t}{(T_{lagLID})^2}, 0 < t < \frac{T_{lagLID}}{2} \\ \frac{4(T_{lagLID} - t)}{(T_{lagLID})^2}, \frac{T_{lagLID}}{2} < t < T_{lagLID} \\ 0, t > T_{lagLID} \end{cases}$	S_{VS} [mm]	Water storage depth in vegetated swales
		P_{cU} [mm d^{-1}]	Percolation velocity of urban green areas

Table 4
The parameter values of four LID practices based on literature, field test results, and local government documents.

	D_{LID}^{a} [–]	A_R^{b} [-]	$I_{max,LID}$ [mm]	$S_{umax,LID}$ [mm]	T_{lagLID} [–]	K_{VS} [–]
Bioretention cells	D_B	$A_{R,B} \geq 1$	3.5	300	13	–
Vegetated swales	D_{VS}	$A_{R,VS} \geq 1$	–	–	11	0.34
Green roofs	D_{GR}	1	3.1	42	3	–
Permeable Pavements	D_{PP}	1	4.0	120	11	–

As Fig. 4c shows, the urban sub-flow moves slightly far from slow rural peaks and decreases the basin peak compared to the current condition. Hence it is undoubted that urbanization would increase the runoff from urban surfaces. However, considering the accumulation of rural sub-flow, urbanization does not always bring higher basin peaks in a half-urbanized catchment, as the faster urban runoff can help to spread the peak over a longer period of time.

4.2. LID performance in the non-flood season

Fig. 5 shows the comparisons of the runoff time series between the five LID scenarios and the conventional urban development scenario (urbanization scenario C). Compared to conventional urban development, all five LID scenarios significantly reduce most peaks in the non-

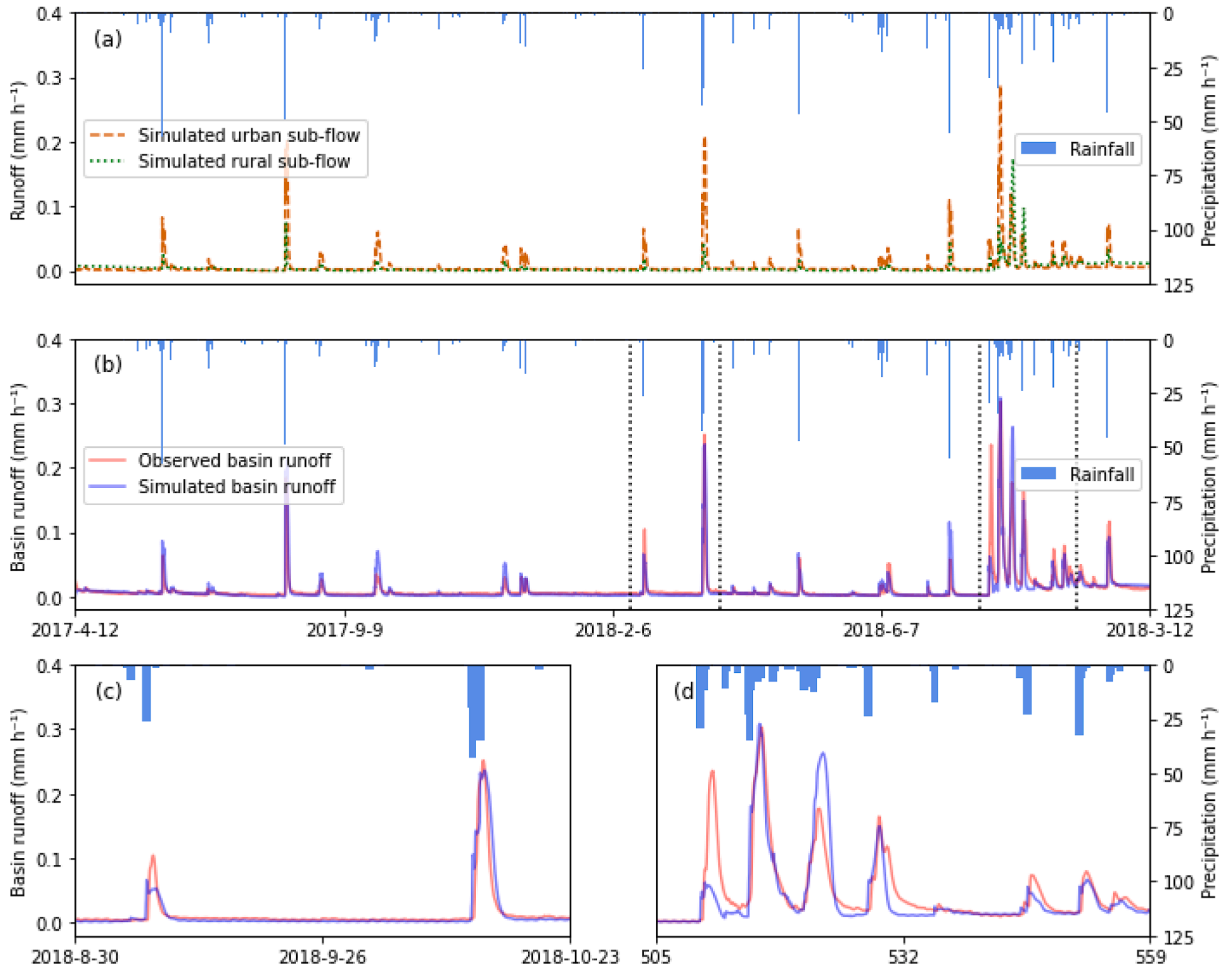

Fig. 3. The observed and simulated rainfall-runoff relationships for the current condition. The first 365 days are the calibration period, and the last 235 days are the verification period. (a) The time series of simulated rural and urban sub-flows. (b) The comparison of observed and simulated total basin runoff. (c) and (d) magnify several peak events in non-flood and flood seasons, respectively.

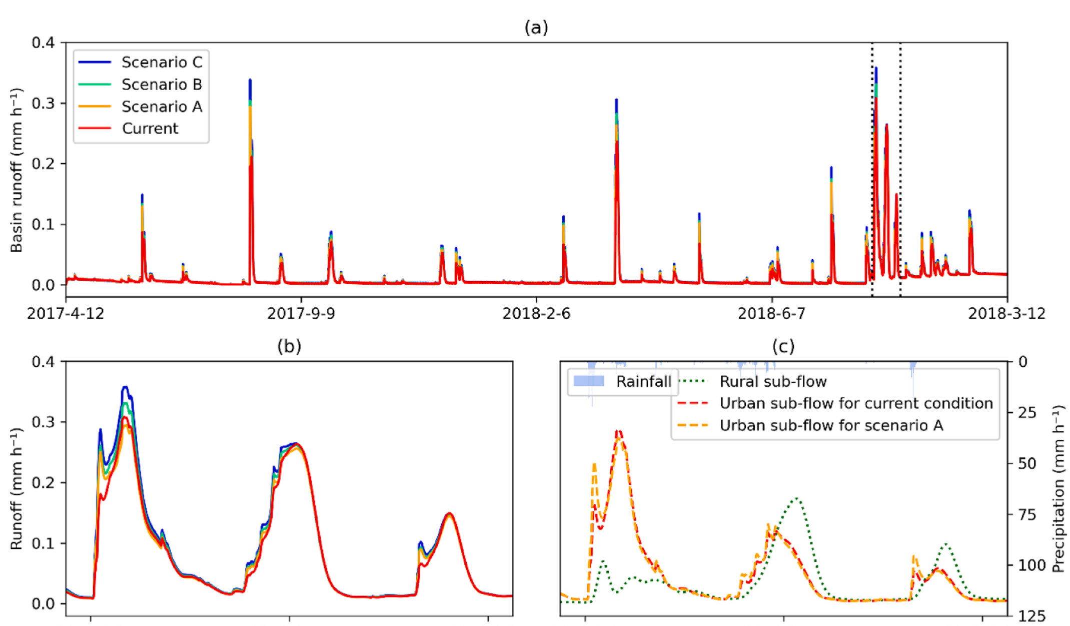

Fig. 4. (a) The simulated total basin runoffs for three urbanization scenarios and the current condition. (b) The maximum basin peak runoff and its two successive basin peaks during flood season. (c) Their urban and rural sub-flows for urbanization scenario A and current condition. The total runoff volumes and the maximum peak runoff values during 600 research days are shown in Table 5.

Table 5
The simulated basin runoff volumes and the maximum peak runoff values in 600 research days for three urbanization scenarios and the current condition.

Urbanization scenario	Current	A	B	C
Total runoff volume in the research period [mm]	160	164	174	183
The increasing proportion of the total runoff [–]	–	2.7 %	8.7 %	14.3 %
The maximum peak runoff [mm h^{-1}]	0.308	0.295	0.331	0.358
The increasing proportion of the maximum peak runoff [–]	–	*−4.3* %	7.5 %	16.1 %

flood season.

The third maximum peak runoff in 600 research days happening in the non-flood season (March 29, 2018), is analyzed to further reveal the LID performance on peak value reduction (Fig. 6a). Two peaks (I and II) appear in succession after one precipitation event. The LID practices always reduce the first peak more significantly than the second one. This is because peak I is mainly generated by urban grey areas with the rapid hydrological response, which is the domain of LID practices. Peak II is contributed by urban green surfaces with a slow hydrological response, and therefore the LID practices have limited influence on peak II.

The specific runoff reduction amounts consumed by each water process in four single LID scenarios are listed in Table 7.

4.2.1. Bioretention cells scenario

Bioretention cells significantly reduce both the total runoff volume and the peak runoff value, second only to permeable pavements. The total basin runoff is reduced by 2.4 % from 182.5 mm to 178.1 mm in 600 research days. As for peak values, bioretention cells considerably reduced the peak I on March 29, 2018, by 8.8 % from 0.306 to 0.279 mm h^{-1}. The robustness of bioretention cells is also satisfactory after the continuous water consumption resulting in a 1.4 % reduction for the next peak II.

The strong ability of runoff consumption can ascribe to the massive water percolation through soil granules and large amounts of water transpiration by dense vegetation for bioretention cells. As shown in Table 7, bioretention cells only generate 16.0 % of the precipitation as outflow. 54.5 % of the precipitation percolates underground, and 21.5 % and 8.1 % evaporate and are retained. This result is consistent with the previous research. According to the studies of Chapman and Horner (2010) and DeBusk and Wynn (2011), bioretention cells can reduce runoff volume from 48 % to 97 %.

4.2.2. Permeable pavements scenario

Permeable pavements demonstrate the best ability for runoff reduction among four test LID practices. The total basin runoff volume is declined by 2.5 % in the permeable pavements scenario from 182.5 to 177.9 mm (Table 6). Two basin peak values in the non-flood season are reduced by 9.5 % and 2.2 %, respectively. Even though sharing a similar total runoff volume reduction with bioretention cells, permeable pavements are better at reducing peak runoff values.

In 600 research days, permeable pavements generated the least overflow as 8.6 % of the precipitation amount (Table 7). 87.7 % of the rainwater is consumed by percolation because of the abundant stormwater retention space in the subbase or base and between the permeable pavers. The result is consistent with previous studies, in which permeable pavements consume 50 % to 93 % of runoff (Rushton, 2001; Hunt et al., 2002; Dreelin et al., 2006). With large water retention capacity and forceful peak runoff reduction ability, permeable pavements and bioretention cells can be considered the two most effective LID practices to control urban floods and release the pressure on urban drainage systems.

4.2.3. Vegetated swales scenario

The peak runoff reduction ratio of vegetated swales is similar to bioretention cells and permeable pavements. As shown in Table 6, vegetated swales decrease 7.6 % of the peak I in the non-flood season. But the sustainability of this peak runoff reduction ability is weak.

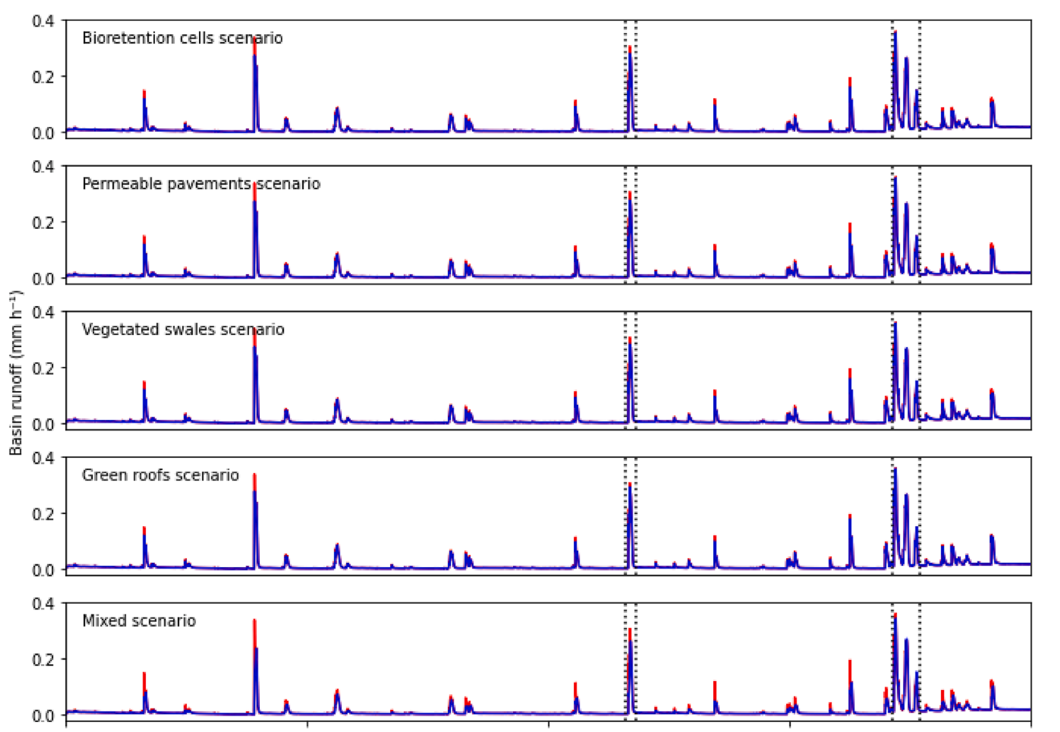

Fig. 5. The comparison of the basin runoffs for five LID implementation scenarios (blue lines) and the conventional urban development scenario (red line) during 600 research days. Fig. 6 shows a zoom-in on five peak events in non-flood and flood seasons. The total runoff volumes and five peak values are demonstrated in Table 6.

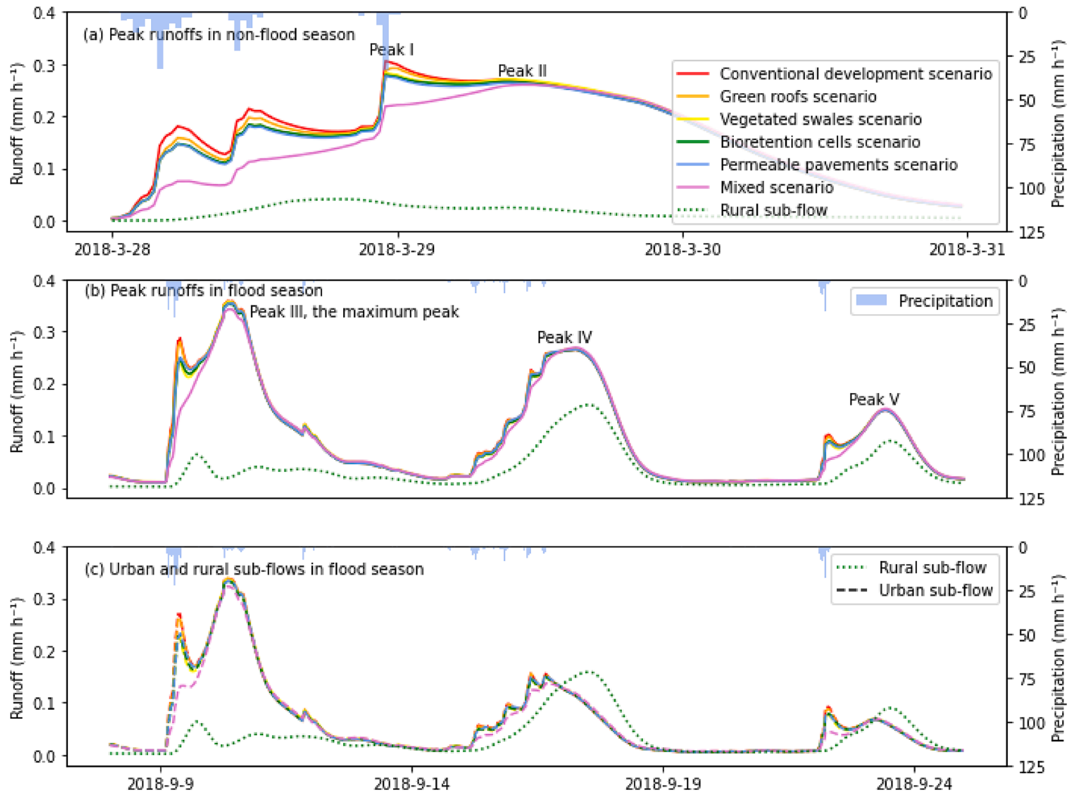

Fig. 6. The comparison of five peak runoff events under the LID implementation and the conventional urban development scenarios. The specific peak values are shown in Table 6. (a) Two basin peak runoffs and their rural sub-flows happening in non-flood season. (b) Three successive basin peaks in flood season and (c) their rural and urban sub-flows.

Table 6
The simulated result of total basin runoff volumes in 600 research days and five peak runoff values in non-flood and flood seasons for five LID implementations and one conventional urban development scenarios.

Scenarios	Conventional development	Bioretention cells	Permeable pavements	Vegetated swales	Green roofs	Mixed LID
Total basin runoff volume [mm]	182.5	178.1	177.9	180.5	178.2	168.0
Decrease proportion of the basin runoff [–]	–	2.4 %	2.5 %	1.1 %	2.3 %	7.9 %
Two peak runoffs in the non-flood season						
Peak I on March 29, 2018 [mm h^{-1}]	0.306	0.279	0.277	0.283	0.292	0.220
The decreasing proportion of the peak value I [–]	–	8.8 %	9.5 %	7.6 %	4.4 %	27.9 %
Peak II on March 29, 2018 [mm h^{-1}]	0.270	0.266	0.264	0.271	0.269	0.260
The decreasing proportion of the peak II [–]	–	1.4 %	2.2 %	−0.2 %	0.2 %	3.6 %
Three peak runoffs in flood season						
Peak III on September 10, 2018 (the maximum peak) [mm h^{-1}]	0.358	0.353	0.355	0.356	0.358	0.342
The decreasing proportion of the peak value [–]	–	1.6 %	1.0 %	0.5 %	0.1 %	4.4 %
Peak IV on September 17, 2018 [mm h^{-1}]	0.265	0.265	0.265	0.267	0.265	0.269
The decreasing proportion of the peak value [–]	–	*−0.1 %*	*−0.1 %*	*−1.0 %*	*−0.1 %*	*−1.7 %*
Peak V on September 23, 2018 [mm h^{-1}]	0.149	0.149	0.148	0.150	0.149	0.152
The decreasing proportion of the peak value [–]	–	*−0.3 %*	0.1 %	*−1.1 %*	*−0.4 %*	*−2.0 %*

Rather than exhaustively consuming, vegetated swales delay the runoff of peak I till peak II, which causes a larger peak II.

The performance of vegetated swales is not outstanding in retaining total runoff volume in the long term. For the 1335 mm stormwater conveyed by vegetated swales during 600 research days, 68.3 % of the rainwater was discharged to the urban drainage system. Only 24.1 % and 7.7 % of the total rainfall was absorbed and consumed by the soil and vegetation. Previous studies reported that the performance of vegetated swales is significantly different between facing small rainfalls and large storms. For small rainfall, 85 % of the runoff volume can be retained; however, for large storms, this proportion ranges from 35 % to 66 % (Hunt et al., 2010). It can be explained by the fast water transportation mechanism of vegetated swales. Without sufficient water retention capacity, vegetated swales do not support stable and continuous percolation during large storms. Therefore, the total runoff reduction volume of vegetated swales is distinctly smaller than the other three test LID practices.

4.2.4. *Extensive green roofs scenario*

The extensive green roofs reduce the least peak runoff among four

Table 7
Specific water balance components for four single LID practice scenarios in research days.

		Precipitation	Evaporation	Percolation	Overflow	Storage
Bioretention cells	Amount (mm)	1335	287	727	213	107
	Ratio	100 %	21.5 %	54.5 %	16.0 %	8.1 %
Permeable pavements	Amount (mm)	1335	–	1170	115	49
	Ratio	100 %	–	87.7 %	8.6 %	3.7 %
Vegetated swales	Amount (mm)	1335	102	322	911	0
	Ratio	100 %	7.7 %	24.1 %	68.3 %	0 %
Green roofs	Amount (mm)	1335	574	–	491	270
	Ratio	100 %	43.0 %	–	36.8 %	20.2 %

test LID practices. Two peak values in the non-flood season are reduced by 4.4 % and 0.2 %, which are far less than in other scenarios. However, the green roofs scenario reduces 2.3 % of the total runoff volume, which is close to the performance of permeable pavements (2.5 %) and bioretention cells (2.4 %) scenarios. By the end of 600 research days, 43.0 % of precipitation was evaporated, and 20.2 % was stored in the green roof buckets. 36.8 % of the rainwater overflowed. In literature, the runoff reduction capacity of green roofs varies largely between 23 % and 100 % (Vanwoert et al., 2005; Hathaway et al., 2008; Carpenter and Kaluvakolanu, 2011).

We found a significant difference between runoff volume and peak value reductions of green roofs. It can be ascribed to the small water retention capacity. Although green roofs share a similar model structure to bioretention cells with one interception and one unsaturated bucket, the soil thickness of extensive green roofs is much smaller, and there is no continuous percolation available from rooftops to the groundwater. The small water retention capacity of green roofs leads to a sensitive hydrological performance to the predecessor rains: If there are no or fewer predecessor rain, the green roof can still play a role in peak runoff reduction; however, when it comes to rainy seasons, the green roof will be easily filled up by the frequent storm events and lose its peak runoff reduction function.

4.2.5. Mixed LID scenario

The mixed LID scenario is the most forceful LID scenario to reduce both the peak runoff and the total runoff volume. The peak runoff values decrease considerably in the mixed LID scenario by 28 % for peak I and 3.5 % for peak II. As for the total runoff volume, the mixed LID scenario reduces the total basin runoff volume from 182.5 to 168.0 mm with a 7.9 % reduction ratio in 600 research days. Except for the large contribution area of LID practices, another advantage of the mixed LID scenario attributes to the cascade connection among LID practices, which adjusts the unbalanced water capture capacities of different LID practices and reinforces the robustness of the whole LID system.

Table 8 shows the specific water retention amounts of 4 LID practices in the mixed LID scenario. The evaporation of green roofs and bioretention cells and the percolation of bioretention cells and permeable pavements consume a large amount of rainwater. Comparing the hydrological performances of bioretention cells in the single bioretention cells scenario and the mixed LID scenario, the water retention ability of bioretention cells is better developed (especially the evaporation) under the condition of more water input and less construction area.

Precipitation[a] and Inflow[b] indicate the stormwater collected directly by the LID practices and the recharge from other LID practices.

4.3. LID performance in the flood season

Fig. 6b and 6c show three basin peaks in the flood season and their rural and urban sub-flows, respectively. It can be found that all five LID scenarios lost the peak reduction ability for the last two peaks dominated by rural runoffs. Table 6 records the specific basin peak values in five LID scenarios and one conventional scenario. It is noticed that five LID scenarios could bring larger values of peak IV and V compared to them in the conventional urban development scenario. Further, the mixed LID scenario, which is supposed to be the most powerful runoff reduction plan, led to peak *increases* of 1.7 % from 2.65 to 2.67 mm h^{-1} and 2.0 % from 1.49 to 1.52 mm h^{-1}.

This anomalous phenomenon heavily depends on the study catchment's specific hydrological condition. As a half-urbanized catchment, the peak runoffs are generated from urban and rural areas together during flood season. Normally, urban peaks come earlier than rural peaks because of a faster runoff response time. However, the urban runoffs are slowed after the implementation of LID practices (Fig. 6c). It causes a larger stacking of urban and rural peaks and in consequence, increases the total basin peak runoff.

To further confirm this argument, ten precipitation events with different rain intensities and durations are selected from the 600 days of precipitation observation. These rain events are tested in the mixed LID scenario in the flood season (from September 15, 2018 to September 21, 2018). Among ten test precipitation events, eight basin peaks increase from 0.7 % to 2.84 % after the LID implementation (Figure S1), considering the overlapping of urban and rural sub-flows. Even though the increase ratios are small, it is to be concluded that, in basins with combined urban and rural land use like our case study, the basin peak flow reduction of LID measures is negligible during extremely wet conditions, if not negative.

5. Discussion

5.1. Transferability of research results

Given the specific condition of our case study, the research results should be interpreted consciously, in particular, the growing total basin peaks after LID implementation. The transferability of this result needs

Table 8
Specific water balance components of 4 LID practices in the mixed LID scenario in 600 research days.

		Precipitation[a]	Inflow[b]	Evaporation	Percolation	Storage	Overflow
Green roofs	Amount (mm)	1335	–	775	–	8	552
	Ratio	–	–	58.0 %	–	0.6 %	41.4 %
Bioretention cells	Amount (mm)	1335	184	780	410	77	252
	Ratio	87.9 %	12.1 %	51.4 %	27.0 %	5.1 %	16.6 %
Vegetated swales	Amount (mm)	1335	252	355	112	0	1119
	Ratio	84.1 %	15.9 %	22.4 %	7.1 %	0 %	70.5 %
Permeable pavements	Amount (mm)	1335	–	–	1170	49	115
	Ratio	–	–	–	87.7 %	3.7 %	8.6 %

to consider the following characteristics: The basin should have a substantial portion of urban areas to generate a significant urban runoff that makes the effects relevant for downstream areas. Besides, the rural and urban sub-flows are generated and contribute to the basin runoff together after several continuous storm events in the flood season. Moreover, before the LID implementation, there should be a time difference between urban and rural peaks as the urban surfaces have a faster hydrological response time, and the urban peak would come faster. Finally, the extent of LID implementation will quantitatively influence the basin peaks, as a higher degree of LID implementation may slow down the urban sub-flow and bring a larger stack of urban and rural sub-flows.

5.2. Limitations

To decrease the model uncertainty caused by over-complex models and to determine a suitable level of model complexity (Savenije, 2001; Hrachowitz et al., 2014), this research used a relatively simple semi-distributed model to simulate the rainfall-runoff relationship on the catchment scale. Our semi-distributed model does not represent heterogeneity within the rural and urban areas.

Then, important assumptions are made in the urban development and LID implementation scenarios. First, 2.4 million residents are supposed to live in San Antonio City with three compact factors (0.85, 0.9, and 1) for living space in 2040 in three urbanization scenarios. Uncertainty in these projections is high. Next, the extent of urban construction and LID implementation is assumed to be consistent throughout urban areas. However, the construction density of urban core areas might be larger than the new-developed suburban areas. Five LID implementation scenarios presume optimistic LID implementation conditions by using favorable LID parameters, hence overlooking practical implementation, operation, and maintenance problems such as the damage to LID practices and the blockage in soil media. Such forecasting limitations lead to the discrepancy between the scenario and reality. The results, however, show that the answer to our research question, "*what is*" the influence of LID implementation on the basin runoffs at a catchment scale, remains valid for different urban development and LID implementation scenarios.

5.3. Comparative analysis

The research results about LID performances are supported by former studies. The permeable pavements are concluded as the most effective LID practices for runoff reduction among the four test LID practices. A similar conclusion was drawn by Ahiablame et al. (2012). In addition, the ineffective runoff reduction of vegetated swales is ascribed to its fast rainwater transportation and short residence time in this research. Huang et al. (2018) used the same reason to explain the less effective performance of infiltration trenches and vegetated swales compared with bioretention cells, porous pavements, green roofs and etc. Then, the mix of various LID practices should be adopted since its high robustness. A similar argument was also mentioned by Qin et al. (2013), Askarizadeh et al. (2015), Fang et al. (2017), and Huang et al. (2018).

5.4. Recommendations

Although urbanization may inevitably result in a rising in total runoff volume, infill urban development is recommended for peak flood control rather than sprawl development. Additionally, the stacking of peak flows from rural, urban green, and urban grey parts of a basin should be avoided by making use of their different runoff response times. Future research can investigate the hydrological response times of areas with different landscapes, soil types, topographic conditions, urbanization extents, and the distance to the catchment outlet. Besides, this research assumes homogeneous rural and urban landscapes and hydrological performances. Future research could further analyze the impact of LID implementation on the basin runoff by considering heterogeneity problems, such as partial urban development and uneven LID implementation plan spatially, using distributed models with more sufficient data.

6. Conclusions

This research conducts a case study for the catchment of San Antonio, Texas, to investigate the influence of LID implementation on the basin runoff. Scenario analyses for both urban development and LID implementation are adopted to give a reliable answer to the research question. A SUPERFLEX conceptual model is adapted as a semi-distributed model to simulate the rainfall-runoff relationships and study the catchment's hydrological behavior under different scenarios. We found that:

1. The urban areas, taking 27 % of the study catchment, generate 63 % of total basin runoff, while the last 73 % of rural areas only produce 37 % of total runoff. Urban surfaces yield more frequent peak runoffs with less water retention capacity than rural surfaces.
2. In a case study at hand, the infill urban development benefits more from runoff control than the sprawl urban development. All three urban development scenarios bring the growth of total runoff volume with increase ratios as high as 14.3 % for scenario C (half-infill and half-expansion urban development plan), 8.7 % for scenario B (70 %-infill and 30 %-expansion), 2.7 % for scenarios A (fully infill development). Fortunately, however, by converting the urban development strategy from urban expansion to infill development, the extreme peak runoff can be reduced from 0.358 (scenario C) to 0.331 (scenario B) and 0.295 mm h^{-1} (scenario A).
3. All five LID implementation scenarios perform powerful runoff reduction ability in non-flood seasons. Bioretention cells and permeable pavements significantly decrease total basin runoff volume by 2.4 % and 2.5 %, and one typical peak value by 8.8 % and 9.5 %. With more water input and less construction area, the water retention ability of bioretention cells, in particular the evaporation function, can be better developed. Vegetated swales achieve a lower runoff volume (1.1 %) than the other three LID practices without substantial water retention capacity but have satisfactory peak runoff reducing ability (7.6 %). On the contrary, green roofs are good at runoff volume reduction (2.3 %) and only remove 4.4 % of the peak runoff.
4. However, all five LID scenarios have a weaker peak reduction ability and may even bring larger total basin peak runoffs when it comes to the flood season. This is because these basin peaks are generated by the rural and urban sub-flows together. The LID implementation delays the urban peaks, which causes a larger stack of urban and rural sub-flows and thus increases the total basin peak.

7. Data availability

Precipitation, evaporation, and runoff data are available on the USGS website (https://www.usgs.gov/). The impervious surface data is from NASA Socioeconomic Data and Applications Center (SEDAC, https://sedac.ciesin.columbia.edu/).

8. Code availability

Please contact the first author regarding code scripts.

CRediT authorship contribution statement

Xinxin Sui: Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft. **Frans van de Ven:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The hydrological data we used can be download from the USGS website (https://www.usgs.gov/).

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Appendix A. Supplementary data

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