Modeling stormwater management at the city district level in response to changes in land use and Low Impact Development

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Abstract

Mitigating the impact of increasing impervious surfaces on stormwater runoff by low impact development (LID) is currently being widely promoted at site and local scales. In turn, the series of distributed LID implementations may produce cumulative effects and benefit stormwater management at larger, regional scales. However, the potential of multiple LID implementations to mitigate the broad-scale impacts of urban stormwater is not yet fully understood, particularly among different design strategies to reduce directly connected impervious areas (DCIA). In this study, the hydrological responses of stormwater runoff characteristics to four different land use conversion scenarios at the city scale were explored using GIS-based Stormwater Management Model (SWMM). Model simulation results confirmed the effectiveness of LID controls; however, they also indicated that even with the most beneficial scenarios hydrological performance of developed areas was still not yet up to the pre-development level, especially, pronounced changes from pervious to impervious land.

Keywords: Stormwater management; LID; DCIA; Hydrological responses; SWMM; GIS

1. **Introduction**

The increase in the impervious surface areas as a result of urbanization has produced significant hydrological effects globally (Dietz, 2007; Choi & Deal, 2008; Ahiablame, 2012; Bell et al., 2016). It has been widely reported that such changes disrupt the natural water cycle, intensify the urban rain-island effect and the surface runoff, reduce water quality and diminish the groundwater supply (Pomeroy, 2007; Sheng & Wilson, 2009). Of these impacts, the most direct are significant increases in surface water runoff, flood peak frequency and volume, which intensify the risk, frequency, and extent of urban flood disasters (Pauleit et al., 2005) and threaten the safety and livelihoods of urban residents (Baxter et al., 2002; Dougherty et al., 2007). Recent increases in the intensity of precipitation events due to global climate change in various geographic locations further aggravate the impact of urbanization on the natural water system (Rosenberg et al., 2010; Hanak & Lund, 2012).

Traditional urban stormwater controls are mostly based on the grey infrastructure and involve measures such as increasing the drainage network and rainfall drainage pipe diameters to facilitate the rapid discharge of accumulated rainfall (USEPA, 2000; Cembrano et al., 2004). However, these measures directly affect generation of local water flow and associated conditions, increase the amount of stormwater, and complicate the task of urban flood prevention (Pomeroy, 2007), while also resulting in a substantial loss of urban water resources (Ahiablame et al., 2012). Therefore, it is important to develop new alternative urban stormwater management approaches globally.

Increasing infiltration has always been an important way to reduce stormwater runoff as well as to minimize its impacts (Huber & Cannon, 2004; Yao et al., 2016). Accordingly, a number of urban stormwater management strategies have been proposed and implemented in recent years, especially those controlling total impervious area (TIA) (Carter & Jackson, 2007; Roy & Shuster, 2009). Examples of these measures include water-sensitive urban design (WSUD) in Australia (Coffman, 2002; Zimmer et al., 2007), sustainable drainage systems (SuDS) in the UK (Scholz & Grabowiecki, 2007), and best management practices (BMPs) and Low Impact Development (LID) in the USA (USEPA, 2000; Ahiablame et al., 2012; Liu et al., 2016). Of these measures, LID is mentioned as an especially promising novel stormwater management strategy. It is mainly achieved by using green infrastructure, multilayer development and decentralized micro-scale control to create post-development hydrological conditions that mimic the pre-development natural hydrologic functions. LID has been widely applied for stormwater management in the USA, Australia, and several European countries (USEPA, 2000; Coffman, 2002; Adams, et al., 2010; Pyke et al., 2011; Ahiablame et al., 2012；Yazdi & Neyshabouri, 2014). Numerous research studies and practical applications have demonstrated that natural drainage systems that are based on an LID concept and incorporate urban green space can effectively reduce surface runoff, decrease peak flow volumes, reduce soil erosion, and promote water quality (Hunt et al. 2006; Dietz 2007; Gregoire & Clausen, 2011). In particular, the idea of LID-referenced "sponge" cities was developed in China, and a series of demonstration projections have been conducted in recent years (General Office of the State Council, 2015). However, most quantitative studies of LID scenarios to date have been limited to the lot or block scale. Currently, there are almost no comprehensive quantitative assessments of the hydrological effects of LID measures that go beyond this relatively small spatial scale. This limits the promotion and application of LID at the city or regional level (Dietz, 2007; Ahiablame et al., 2012).

Modeling LID impact at a larger scale of decision-making is necessary to generalize and provide guidance for stormwater management and LID practices (Lee et al., 2012). Hydrological models can be used to simulate the effects of LID application at various temporal-spatial scales in urban areas, thus enabling the potential multi-scale application of LID (Elliot et al., 2009; Ahiablame, 2012). Currently, various distributed hydrological models, including the SCS (Soil Conservation Service), SWAT (Soil-Water Assessment Tool), MOUSE (Model for Urban Sewers, Danish Hydraulic Institute, 1995), Hydro CAD, and the stormwater management model (SWMM) are available to manage urban runoff (Gironás et al., 2010; Mancipe-Munoz et al., 2014; Cunha et al., 2016). Bosely (2008) conducted a sensitivity analysis for the 19 most commonly used hydrological models or software programs by applying them to a representative area and found that SWMM was the most suitable hydrological model in the urban setting for various land-use scenarios and the application of LID simulation analysis.

SWMM developed in 1971 by the United States Environmental Protection Agency (USEPA, 2000) is a rainfall-runoff simulation model based on either a single rain event or a long-term rain series. This model can effectively simulate hydrology, hydraulics, and water quality using a series of sub-catchments that can accept rainfall as a source of runoff or as a pollutant (Hsu et al., 2000; Rossman, 2010; Cunhua et al., 2016). Currently, SWMM is widely used in simulation, analysis, and design in areas such as urban storm runoff, drainage piping systems, catchment planning and, specially, runoff mitigation with LIDs (Peterson & Wicks, 2006; Elliott & Trowsdale, 2007; Lee et al., 2013). However, compared to other hydrological models, the insufficiently large scale of application for SWMM remains a challenge. To address this issue, a number of researchers have used GIS or the catchment discretization method to apply SWMM to large urban catchments (Barco et al., 2008; Rosa et al., 2015; Dietrich, 2015).

Total impervious area (TIA) has often been used to represent the land surface modified by urbanization (Shuster et al., 2005; Mejía & Moglen, 2010.); however, recent studies have suggested that TIA is not sufficient to explain the impact of urbanization on the local hydrology, for it does not reflect the impervious land connectivity pattern (Roy and Shuster, 2009；Beck et al., 2016). Alternatively, the metric of directly connected impervious area (DCIA), or the effective impervious area (EIA), has been proposed, representing the subset of impervious surfaces that route stormwater runoff directly to streams via stormwater pipes (Roy and Shuster, 2009; Jarden et al., 2016). DCIA not only provides an indicator of the watershed ecological condition (Urrutiaguer et al., 2012), but also has been found to strongly affect the surface runoff changes (Yao et al., 2016; Ebrahimian et al., 2016; Sohn et al., 2017) and hydrological responses at the catchment outlet (Mejía and Moglen, 2010). DCIA can be calculated based on the empirical relationships with TIA (Jacobson, 2011; Shuster and Rhea, 2013; Ebrahimian et al., 2016). However, such efforts usually lack an explicit consideration of the spatial pattern of land use and specific methods of stormwater flow management (Lee and Heaney, 2003; Sohn et al., 2017). The use of LID controls, and especially the spatial pattern of their implementation, can play a significant role in reducing DCIA. However, until now, little research has been conducted to optimize the spatial pattern of LID controls in order to reduce the DCIA (Roy and Shuster, 2009; Jacobson, 2011; Ebrahimian et al., 2016).

In the present research, a framework was developed to simulate stormwater runoff at the city scale under different development scenarios, using the GIS-based SWMM5.0

model to bring together urban planning data, geospatial and hydrological information. Focusing on a case study area in a new developing region west of Bazhong, Sichuan Province, China, the stormwater runoff characteristics of the four urban land use conversion scenarios were simulated under the same heavy rainfall condition. The aim of this study was to investigate: (1) how the hydrological responses to changes in land use in the near future vary among different scenarios with rapid urbanization; (2) how a growing city can integrate the LID-based design into urban planning to decrease the DCIA and more effectively manage stormwater; and (3) what potential hydrological effects result from LID implementation, and whether such effects can be evaluated by the GIS-based SWMM at a large urban region scale. The study presents new LID-based urban stormwater management models in a rapidly urbanizing region, and the results will provide an important decision-making basis for the future urban and land-use planning of the study area.

2. Study area

Bazhong is a city located in the Qinba mountains, northeastern Sichuan Province, China (106°20'–107°49'E, 31°15'–32°45'N) (Fig. 1). The city has a subtropical monsoon climate with four distinct seasons. The average annual rainfall is 1,108.3 mm, approximately 80% of which falls from June to October. Excessive rainfall and rainstorms result in frequent flooding (Zhang, 2010). Bazhong is approximately 90% mountainous (Fig. 1b). Geological disasters, such as landslides and ground collapses, are common after the rainstorms.

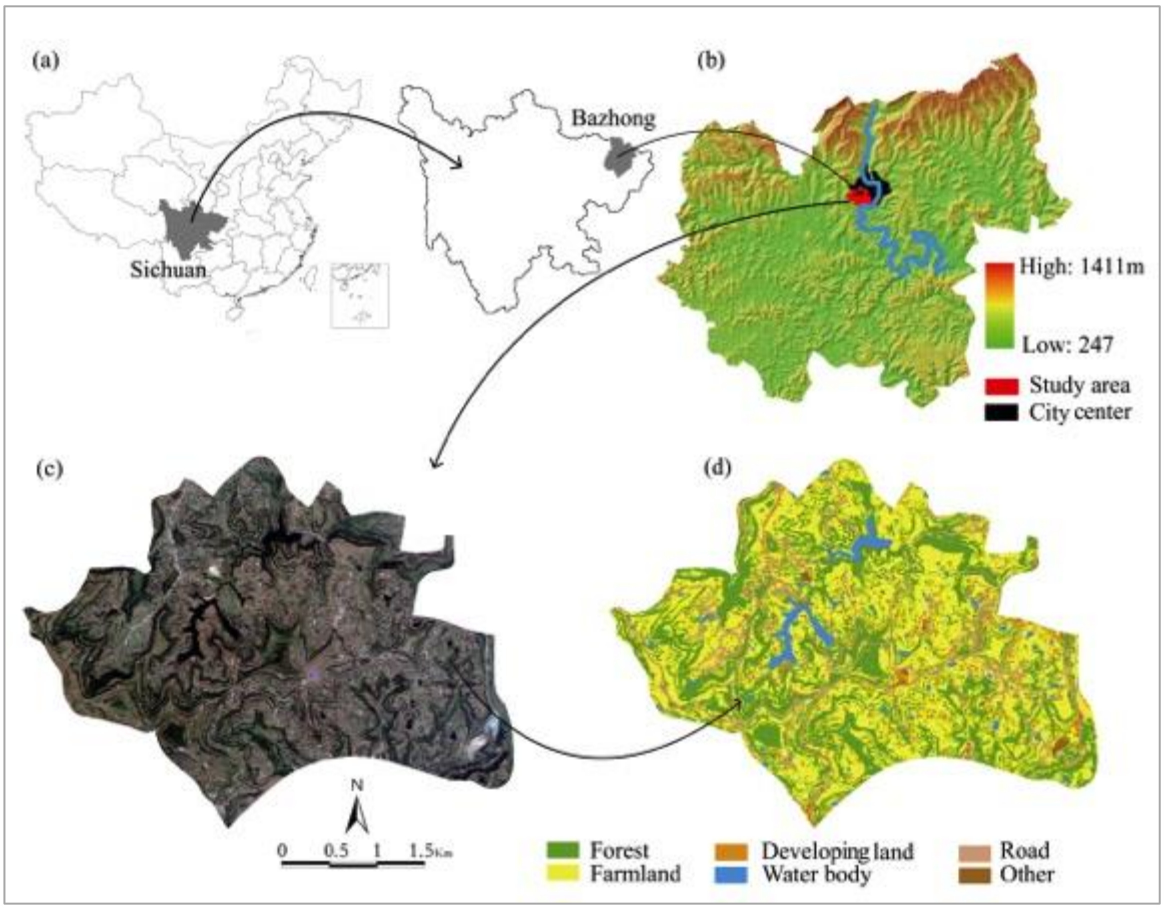

Fig. 1 Map of the study area: (a) location of Bazhong City in Sichuan Province; (b) the DEM (Digital Elevation Model) of Bazhong City; (c) aerial photograph and (d) land use map.

Our study area is located west of downtown Bazhong with a total area of about 838 ha (Fig. 1b). At the time of this research, this area was still a predominantly rural landscape covered by farmland (49.2%) and forest (42.0%) with the remaining 3% of land occupied by housing, roads, and water bodies. The TIA is about 5.8% of the total study area. During the rainy season, management of stormwater is mainly achieved by relying on the river networks in the study area (Fig. 1 b, c and d).

However, the 2013–2030 urban development plan for this study area indicates that the land use pattern will change significantly, and the region will likely become more intensively developed by 2030. Specifically, the impervious land is expected to increase greatly from the development of 331.85 ha (39.63%) as new residential, commercial, public service areas, and roadways (Fig. 2a). This plan also considers current natural drainage system by preserving the original ecological spillway channels and rivers. However, the land use change and the construction of the urban sewerage system will considerably alter this natural hydrological environment and runoff regulation (Fig. 2b), which creates the need to evaluate the opportunities for the green stormwater infrastructure as part of the current plan for the study area.

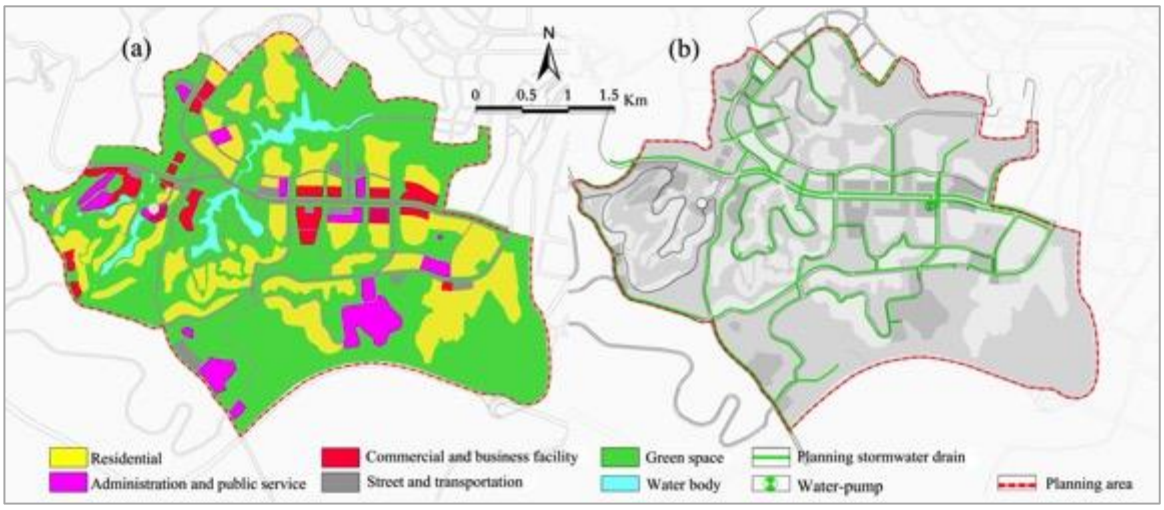

Fig. 2 Planned land use and drainage system of the study area: (a) the regulatory land use plan (2013–2030); (b) the planned stormwater drainage networks.

3. Data and methods

3.1 Data and data preprocessing

The following data were used for scenario modeling: a 2011 CAD topographic data; 2012 aerial photograph data (0.1m x 0.1m); the 2013–2030 regulatory planning data (CAD format) including a land-use layout map, a road planning map, and a rainwater conduit network map (supplied by Bazhong Landscape Bureau); and the daily rainfall and hourly rainfall distribution data for June 23–24, 2015, approximately corresponding to a 10-year return-period rainfall event in Bazhong City (obtained from Bazhong meteorological Bureau).

The CAD topographic data was first converted to a GIS shapefile dataset, and the projected coordinate system was set to a Universal Transverse Mercator (UTM)-projected Xi'an 80 geographical coordinate system. Then, the aerial photograph data were rectified and georeferenced to the UTM coordinate system using the reference topographic map (total root mean square (RMS) < 1 image pixel) in ArcGIS software (Version 10.2, ESRI, Redlands, CA 92373-8100, USA). A land use map was created through these aerial photograph data by manual delineation and interpretation of landscape polygons using eCognition (Trimble Inc.) software (version 8.7) (see Fig. 1d). Finally, the regulatory planning data were all converted to GIS shapefile datasets and then used to create the land use, road and rainwater pipe network maps for the planning scenario analysis.

3.2 Designs of urban development scenarios

Four land development scenarios were simulated in this research. The scenarios were:

S1, the pre-development scenario (current situation); S2, a traditional urban development scenario; S3, an urban development with hypothetical LID implementation; and S4, an urban development plan in which hypothetical LID controls were combined with the specific goal of reducing DCIA. These scenarios were designed according to the urban zoning and planning (regulatory planning), the current land use pattern and the planned stormwater management strategies.

1) Pre-development scenario (S1)

S1 represents the current, pre-development state. The hydrological environment in S1 was considered as the natural state in this research. The land cover in S1 consists of primarily forestland and farmland, and the TIA is about 5.8%.

2) Traditional urban development scenario (S2)

The traditional urban development scenario (S2) does not include the LID stormwater management. However, with rapid urbanization, the built-up land will significantly increase, replacing the farmland and forestlands. The TIA will rise to 40%.

3) Urban development with LID controls (S3)

This scenario includes a suite of potential LID implementations (Green-roof, Porous pavement, Vegetative swale and Rain garden) applied to the impervious areas that are not directly routing stormwater runoff to streams via stormwater pipes, that is, the non-directly connected impervious areas (NDCIA). After implementation of the LID controls, the percentage of pervious surface of S3 will be approximately 75.6%.

4) LID controls by considering overland flow routing and DCIA (S4)

This scenario has the same total area of LID and the drainage systems as S3, but two types of LID (Porous pavement and Green-roof) were specifically allocated within the DCIA regions, and a specific type of overall flow was designated for each sub-catchment. There are three routes for overland flow in the SWMM model: pervious, impervious, and outfall (Huber, 2001). This S4 scenario used the pervious route mode which implies that the stormwater runoff would be first routed to the LID sites, and accordingly the DCIA would be reduced.

3.3 SWMM model setup

3.3.1 Generation of sub-catchments, conduits, junctions, and outlets

The EPA (U.S. Environmental Protection Agency) Stormwater Management Model (SWMM, Version 5.0, EPA, Cincinnati, Ohio) was used to simulate the hydrological response to the land use changes and LID controls in the study area. In the SWMM model, a given watershed can be developed as a set of physical components, including sub-catchments, conduits, junctions, and outlets.

The sub-catchment is the fundamental unit of the hydrological model. To represent pre-development conditions, sub-catchments were first constructed based on the digital elevation model (DEM) (5m x 5 m resolution), using the ArcHydro extension in ArcMap (9.3 ESRI, Redlands, California) by creating a depressionless DEM (filling analysis), defining the flow direction, calculating the flow accumulation, and then creating the outlet of the river networks (Martz & Garbrecht 1992; Barco et al., 2008) (Fig. 3a and b).

As urbanization is expected to substantially alter the surface hydrological characteristics, the sub-catchments had to be further subdivided based on the surface types and land use types (Krebs et al., 2013). Incorporating the planned road network (e.g. the road width, slope, and cross-sectional shape) was especially important, as it affects the stormwater surface flow routing, and in the study area most of the planned stormwater drainage system will also be developed along the roads (Fig. 3c). Thus, the sub-catchments obtained using DEM were further discretized by overlaying the centerlines of the roads with the drainage pipes within their areas. The sub-catchment boundaries were further adjusted using DEM and in-situ observations to ensure their consistency in the surface runoff characteristics after the planned development (Ji and Qiuwen, 2015). These operations produced a set of 80 sub-catchments in the pre-development state (Fig. 3a), and 118 sub-catchments in the urban development scheme (Fig. 3d). Geometric properties of each sub-catchment, such as area, spatial coordinates, flow length and width, percentage of impervious surface cover, and slope were subsequently quantified and added to the attribute table of the spatial dataset.

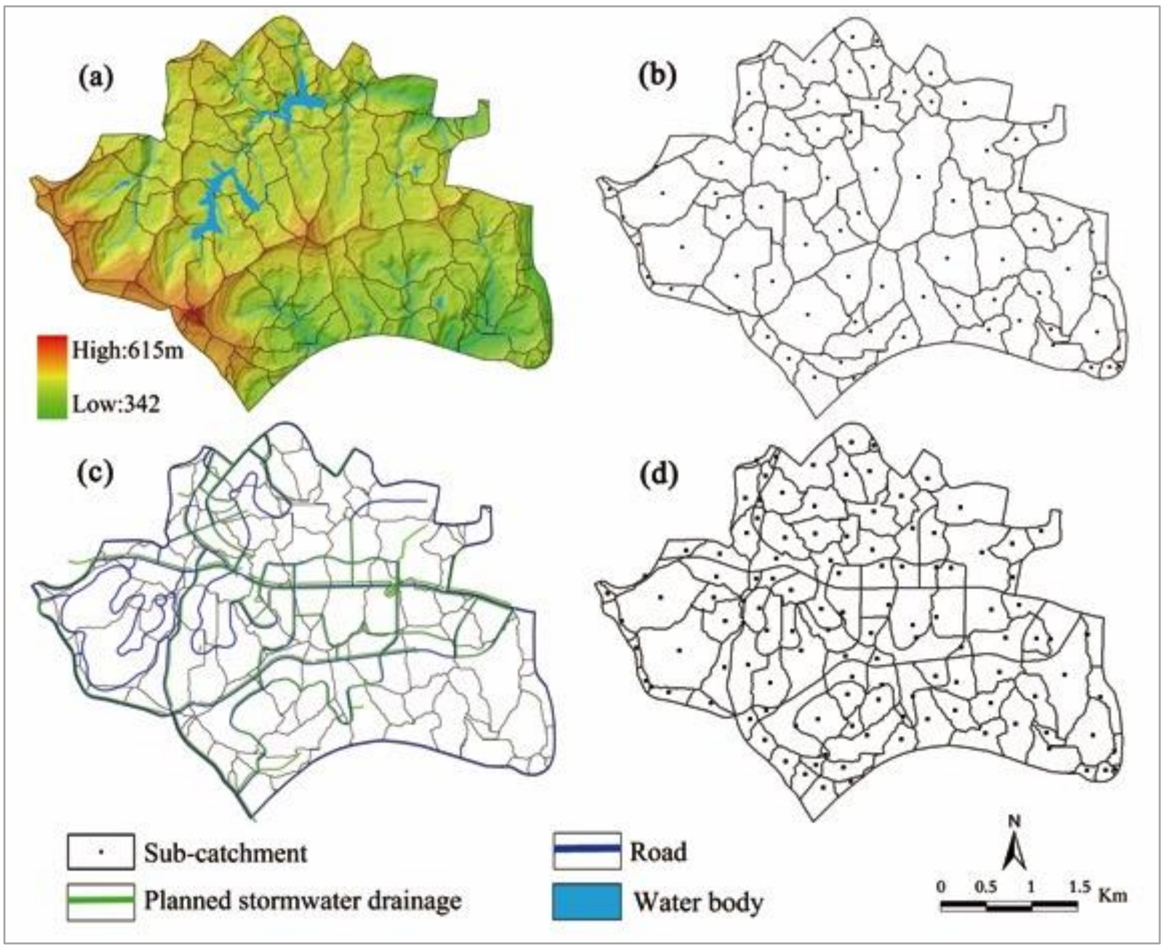

Fig. 3 Discretized sub-catchments in the planned study area: (a) digital elevation analysis; (b) current sub-catchment layout; (c) planned road and drainage networks; (d) discretized sub-catchments under the future planned land use

Next, the planned drainage network (Fig. 2b) together with flow directions within and between the sub-catchments and in-situ observations were used to generate detailed information on the rainwater conduit characteristics (i.e., spatial location, conduit diameter, conduit segment length, cross-sectional shape, and conduit slope), the conduit junctions (i.e., spatial location and depth), and the stormwater outlets (i.e., spatial location and depth). As a result, scenario S1 had 95 junctions, 95 conduit segments, 9 rainwater outlets in the study area (Fig. 4a), while scenarios S2 S3, S4 had 151 junctions, 150 conduit segments, and 10 rainwater outlets (Fig. 4b).

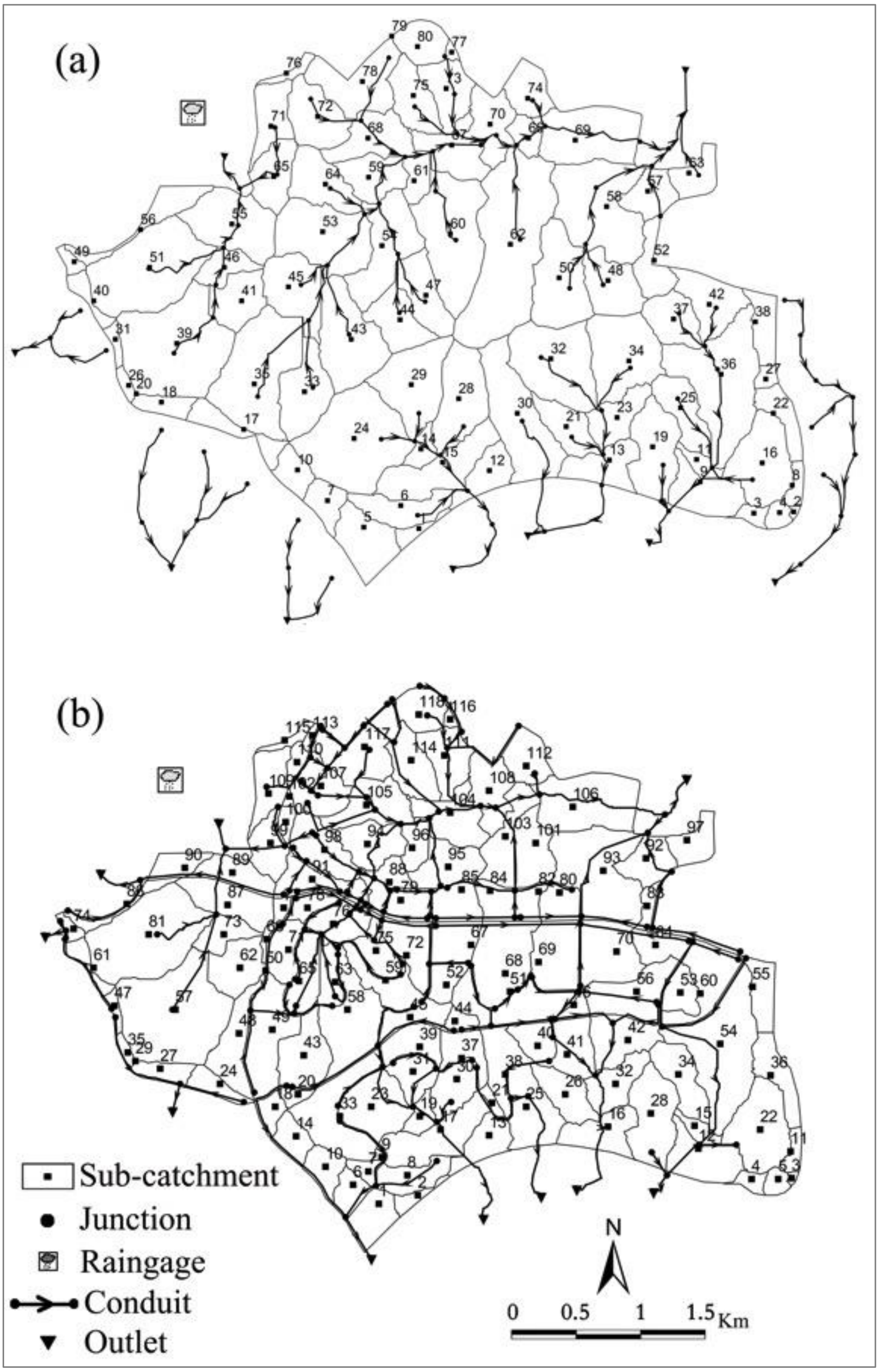

Fig. 4 The conceptualized stormwater drainage system: (a) the sub-catchments of study area (S1); (b) stormwater drainage system in the SWMM model (S2, S3 and S4)

3.3.2 Data conversion between GIS and SWMM

To enable the SWMM-based modeling at the city scale, all the relevant sub-catchment and rainwater conduit GIS vector datasets were converted to the *.inp* format of the SWMM. First, the sub-catchment polygon GIS vector shapefiles data were converted to point datasets, where all the vertices of the original polygons were preserved. Then, each relevant data layer required for the model was exported as a *.txt* file to satisfy the SWMM input data requirements (Rossman, 2010). Finally, the file extension of the TXT file (.txt) was changed to *.inp*, and the relevant SWMM inputs could now be used in the model. Thus, these steps coupled the SWMM with a Geographic Information System (GIS) to provide a database for the required model data. Such a GIS-based SWMM model can be used on a large scale, while the runoff and the flow routing modules in the SWMM can be used to simulate stormwater flow from the ground surface over the whole-city system (Krebs et al., 2013).

3.3.3 SWMM model parameters

Runoff simulations for pre- and post-development (or different land use scenarios) in SWMM required a substantial number of input parameters. The majority of the parameters used to define the ground surface and the stormwater drainage network characteristics were derived from the available GIS data and then coupled with the SWMM directly (Table 1).

Table 1. The SWMM parameters extracted from GIS datasets

Type	SWMM parameters	GIS datasets
Sub-catchment	Spatial location, Area	Land use data, 5m x5m resolution DEM
	Percentage of impervious land	Land use data
	Slope, outlet	5m x 5m resolution DEM Planned stormwater drainage
Conduit	Spatial location	Planned stormwater drainage
	Shape, diameter, length，depth of cross-section	Planned stormwater drainage Water bodies
Junction	Spatial location, depth	Planned stormwater drainage Land use data
Rainwater outlet	Spatial location, depth	Planned stormwater drainage and water bodies

The remaining parameters were determined by the land use type and the sub-catchment properties, which included: the depression storage for pervious (Per-DS) and impervious surfaces (Imp-DS); Manning's n value for overland flow for pervious (Per-n) and impervious (Imp-n) surfaces, and conduits (Conduit-n); the hydraulic conductivity of the impervious surface and the soil infiltration parameters (Rossman, 2010). The parameters values assigned to SWMM model based on the SWMM 5.0

manual (Rossman, 2010) and adjusted according to the characteristics of each sub-catchment were listed in Table 2. The soil infiltration in pervious areas was determined using the Horton method (Horton, 1933).

Table 2: Input Parameters for the SWMM model

Parameter	Type	Symbol	Value
Manning's n	Overland flow	Imp-n	0.010
		Per-n	0.100
	Conduit flow	Con-n	0.010
	Open channels		0.400
Depression storage	Per-DS		2.54–7.62 (mm)
	Imp-DS		1.27–2.54 (mm)
Soil infiltration	Horton infiltration parameters	Max. infil. rate	76.2 (mm/hr)
		Min. infil. rate	3.18 (mm/hr)
		Decay constant	3.12 hr
		Drying time	7d
		Max. infil. vol.	0

3.3.4 LID settings and estimation of DCIA

The number, types, and locations of LID elements are the most widely considered criteria in LID design (Martin-Mikle et al., 2015). In this study, the hypothetical LID control types were based mainly on the various land use characteristics of each sub-catchment, and LID design criteria were established according to the "Technical Guide for Sponge Cities-Construction of Low Impact Development" in China (MoHURD, 2014). In residential and commercial areas, LID controls were designed predominantly as green roofs; in the paved squares of residential and commercial districts, they were set mainly as the porous pavement; along the roads, LID were designed as grassed swales; and in the parks, the LIDs were designed as rain gardens (MoHURD, 2014). The numbers of LIDs were allocated based on the area of different land types in each sub-catchment, for example, the number (and area) of green roofs were determined by the residential area, building density (i.e., the area of the building ground floor footprints divided by the total site area, which can indicate the amount of open space left on the site; Ministry of construction, P.R. China, 1998; Yu et al., 2010) and potential greening rate of the roofs. The summary of how the LID controls were designed is shown in Table 3. The allocation of LID designs followed the rule that the runoff passes through a pervious area before entering the sewage system (inlet), which could reduce DCIA and facilitate stormwater management (Gironás et al., 2010). Accordingly, in the SWMM model, the pervious sub-area routing was set as the routing mode (Gironás et al., 2009 and 2010).

Table 3 LID control settings

Land type	LID controls	Set-up method
Residential land	Green roof	Area × Building density (35%)× Potential green roof rate (0.5)
Administrative land	Green roof	Area × Building density (50%)× Potential green roof rate (0.6)
Administrative land	Porous pavement	Area×[1-Greening rate (25%)-Building density (50%)] ×Potential porous pavement rate (0.3)
Commercial land	Green roof	Area × Building density (60%) × Potential green roof rate (0.8)
Commercial land	Porous pavement	Area×[1-Greening rate (25%)-Building density (60%)]× Potential porous pavement rate (0.5)
Transportation Land	Vegetative swale	Area × Potential vegetative swale rate (0.2)
Park	Rain garden	Area × Potential rain garden rate (0.1)
Plaza	Porous pavement	Area × Potential porous pavement rate (0.7)

Note: building densities of different land use types were taken as their upper limit according to building density requirement in the detailed planning regulations of China and Bazhong (Bazhong Planning Bureau, 2014); the green roof rate, porous pavement rate and potential rain gardens were set according to the Sponge city design technologies and practice manual 6 (MoHURD, 2016).

The type and numbers of the hypothetical LID controls were specified on a per-unit-area basis according to the land use type and the impervious surface coverage in each sub-catchment. Other parameters listed in Table 4 were set using recommended parameter thresholds in the SWMM manual and the relevant literature for the model (Rossman, 2010; Gomez-Ullate, 2011).

Table 4 Parameters used for LID controls in the SWMM model

Green roof	Surface	Berm height (mm)	Vegetation（%）	Manning's n	Surface slope (%)	
		75	100	0.1	0.3	
	Soil	Thickness (mm)	Porosity	Conductivity Slope	Conductivity (mm/hr)	Suction Head (mm)
		150	0.5	5	72	20
	Storage	Thickness (mm)	Void (%)	Conductivity (mm/hr)	Clogging factor	
		75	30	78	0	
Porous pavement	Surface	Berm height (mm)	Vegetation (%)	Manning's n	Surface slope (%)	
		5	0	0.05	2	
	Pavement	Thickness (mm)	Void (%)	Imp-n (%)	Conductivity (mm/hr)	Clogging factor
		150	40	30	72	100
	Storage	Thickness (mm)	Void (%)	Conductivity (mm/hr)	Clogging factor	
		150	50	78	100	
Vegetative swale	Surface	Berm height (mm)	Vegetation (%)	Manning's n	Surface slope (%)	Swale side slope (%)
		300	90	0.1	4	35
Rain garden	Surface	Berm height (mm)	Vegetation (%)	Manning's n	Surface slope (%)	
		350	100	0.1	8	
	Soil	Thickness (mm)	Porosity	Conductivity Slope	Conductivity (mm/hr)	Suction Head (mm)
		150	0.5	10	72	50

Finally, to understand the impacts of reducing DCIA on hydrological processes by improving the LID spatial locations, the DCIA was estimated for each scenario (Sohn et al., 2017). Generally, accurate and direct measurement of DCIA is complicated and usually requires high resolution land use data, but using GIS tools together with detailed CAD data and field verification could improve the accuracy of DCIA assessments (Lee and Heaney, 2003; Roy and Shuster, 2009). In the ArcGIS environment, all the merged impervious land areas (residential land, commercial land, administrative land and roads) were first overlaid with the sub-catchment data layer, and their attributes were assigned based on the attributes of each sub-catchment area. This step allowed the impervious land area to be intersected with the sub-catchment boundaries while preserving the attributes of the corresponding sub-catchments. Then, using the Location Selection tool in ArcGIS, all of the impervious land area was intersected with the drainage network system with different pipe widths (500 mm, 600 mm, 700 mm and 800 mm, 1000 mm and 1200 mm) (Roy and Shuster, 2009). Consequently, the resulting impervious area selected by the drainage networks represented DCIA with the attributes of each sub-catchment (Lee and Heaney, 2003). Finally, a general summary statistics for DCIA and other landscape characteristics were estimated for the four designed scenarios (Table 5).

Table 5 General characteristics and the LID controls of the four designed scenarios

General characteristics and the LID controls	S1	S2	S3	S4
Water (%)	3.0	1.5	1.5	1.5
TIA (%)	5.8	39.6	22.9	22.9
Pervious area (%)	91.2	58.9	75.6	75.6
Green roof (%)	——	——	10.3	10.3
Porous pavement (%)	——	——	5.4	5.4
Vegetative swale (%)	——	——	1.0	1.0
Rain garden (%)	——	——	2.2	2.2
DCIA (%)	0	24.0	18.5	13.3

3.3.5 Storm event

To evaluate the stormwater drainage systems, larger, less frequent storm events are often used to check whether such systems can meet flood control requirements (Rosa et al., 2015). In this research, a 10-year return period storm event in Bazhong city was used to examine the hydrological responses to the LID controls and different urban development scenarios.

According to the rain record of Bazhong Meteorological Bureau, the storm event occurred from 23–24 June, 2015 and produced a maximum precipitation of 191.7mm. The rainfall intensities were over 5 mm h^{-1} for the duration of the entire storm, with peak rain rates measured at over 29.4 mm h^{-1} (Fig. 5). Days of heavy rain caused mudslides and flooding. According to the historical statistics, 64.69 million people were affected by this storm, and the direct economic losses were 406 million Yuan (RMB).

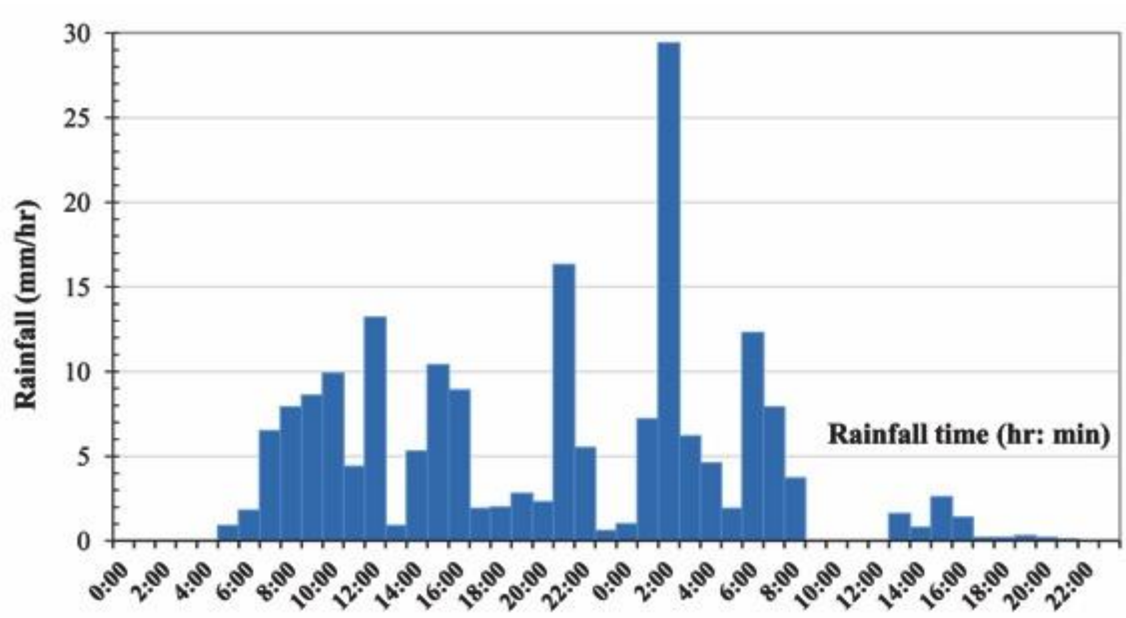

Fig. 5 Hyetograph from 00:00 on the 23th to 23:00 on the 24th, June, 2015

4. Results and discussion

4.1 Comparison of the surface hydrological characteristics under four scenarios

The SWMM-simulated results of the overland hydrological characteristics during the same storm event showed important differences among the four examined scenarios (Table 6). The traditional development scenario, S2 had the largest runoff volumes, runoff coefficients, peak flow and the lowest percentage of infiltration. This result implies that if the study area is developed in a traditional way, i.e. S2, then TIA would change from 5.8% in the pre-development scenario (S1) to 39.6% (Table 5). If there were no other changes in stormwater management, then the hydrological performance would be dramatically changed and the natural hydrological processes in S1 would be disrupted. Under scenario S1, the average runoff volume and runoff coefficient were 62.97 mm and 0.33 respectively, and the majority of the rainfall (67.2%) directly infiltrated to the ground. However, the runoff volumes and runoff coefficients of S2 were 121.44 mm and 0.63 respectively. The results showed that a 33.3% reduction in pervious area yielded up to 92.9% and 90.9% increase in runoff and runoff coefficients. At the same time, such reduction in pervious land of S2 will also result in a 31.7% increase in the peak flow and 35min earlier of peak runoff time compared with S1 (Table 6). Hence, traditional urban development would cause an increase in TIA and a sharp decline in surface permeability and water storage capacity, thereby dramatically increasing the surface runoff, the runoff coefficient and the peak flow rate (Fig. 6).

Compared with scenario S2, S3 improved the surface hydrological characteristics. Specifically, the runoff volumes and runoff coefficients of S3 decreased by 16.69% and 15.87%, respectively, while the peak runoff also decreased (Fig. 6). These changes in hydrological behavior can be attributed to the implementation of LID controls, which produce a 16.7% increase (Table 5) in pervious land in the study area in this scenario.

Even though S3 and S4 both implemented the LID controls and over the same total land area, S4 was obviously more effective in stormwater regulation by considering the overland flow routing and reducing impervious connectivity. Compared with S3, the runoff volumes and the runoff coefficients in scenario S4 decreased by 10.68% and 11.32%, respectively (Table 6). This indicates that measures such as designing the overland flow routing and blocking the impervious connectivity with an optimized LID spatial pattern may further decrease the risk of urban flooding. A spatially improved LID will disrupt the direct connectivity among urban impervious surfaces, which may reduce the DCIA and prevent the surface runoff from flowing directly into the conduits. With a decrease in DCIA from 18.5% to 13.3% (Table 5), the retention time and infiltration of the surface runoff will increase, the runoff volume and runoff coefficient will be accordingly reduced, and the peak runoff will also decrease (Table 6 and Fig. 6).

The lag time between rainfall and runoff generation in S1 was 10h 40 min (5:00-15:40 23rd June), which is clearly longer than in the other three scenarios. The rainfall peak time lasted around one hour from (02:00-02:55, 24th June). However, the surface peak runoff of S1 was at 03:00. This indicates that the undeveloped land surface obviously contributed to the rainfall infiltration and delay in the peak runoff generation. The surface peak runoff of S2 showed the smallest delay (2h00min *vs* 2h25min) compared to the rainfall peak (Table 6, Fig. 6). Such relatively small difference between the peaks of rainfall and runoff illustrates the short travel time for surface runoff after the area is urbanized as planned. Compared to S1, the surface peak runoffs of S3 and S4 showed around half-hour delay relative to the rain peak (02:30 and 02:35 *vs* 02:00); yet, the respective peak runoff times were S1 03:00, S3, 02:30 and S4 02:35 (Table 6, Fig. 6).

This evidence demonstrates that implementation of LID practices would impact the timing of runoff, but these effects are strongly dependent on land cover, and the increase in impervious area would still trigger an earlier runoff peak time. In general, compared with S2, the LID controls in S3 and S4 can greatly change and improve the overland hydrological characteristics under the traditional development model, even though LID controls cannot completely recreate hydrological functions equivalent to those of the pre-development state.

Table 6. Variation in surface hydrological characteristics under four scenarios

Hydrological characteristics Scenarios	Rainfall infiltration (mm)	Runoff volume (mm)	Runoff coefficient	Peak runoff rate (m3/s)	Peak runoff time (day, hr:min)
S1	128.73	62.97	0.33	48.54	24rd, 03:00
S2	70.26	121.44	0.63	63.93	24rd, 02:25
S3	90.56	101.14	0.53	52.12	24rd, 02:30
S4	101.37	90.33	0.47	48.69	24rd, 02:35

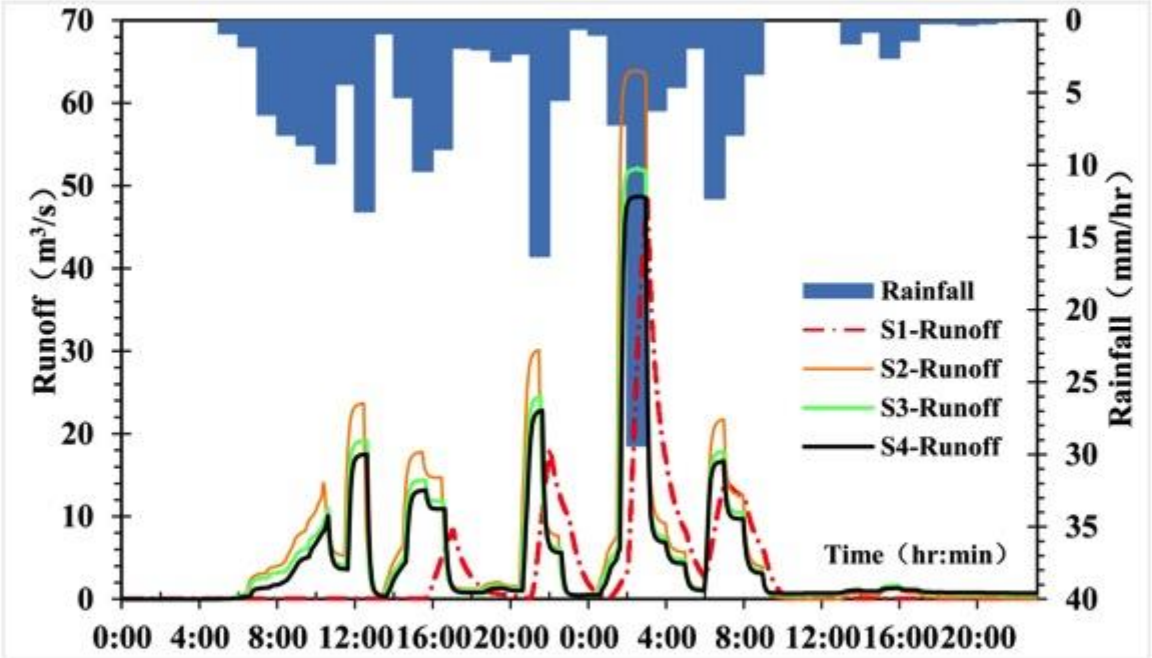

Fig. 6 Differences in the schedules of peak flow under four scenarios and the hyetograph for the selected rain event.

4.2 Comparison of the flow rate and flood peak time in conduits under four scenarios

The primary drainage conduits in scenario S1 are all natural rivers and canals without the urban drainage pipe networks, while scenarios S2, S3, and S4 have the same urban drainage pipe networks. Simulation results show that in scenario S1, the average peak flow in the rivers and canals was 1.24 m^3/s, and the flow rate was 0.19m/sec, the peak flow time was at 03:06 on the 24th (Tables 6, 7). However, compared with S1, the velocity of flow in the conduits in S2 was 1.06 m/sec, and the peak flow time occurred at 22:28 on the 23rd, indicating the 4.57 times increase in the flow rate and more than 4-hour advancement of the peak flow time. These results confirm that the loss of pervious land following urbanization will likely impact flow characteristics in conduits, thus increasing the risk of stormwater accumulation and urban flooding.

The effects of LID controls were clearly observed in the comparison of peak flows and peak flow times of S2 with S3 and S4. When the LID controls were considered, the peak flows in the conduits of scenarios S3 and S4 decreased substantially by 6.15% and 9.23% compared to S2, and the peak flow time was delayed by 1h 33 min, and 1h 37 min, respectively (Table 7). However, between scenarios S3 and S4, the flood flow rate in S4 decreased by 1.94%, and the peak flood time was delayed by only 4 min. Thus, simulation results indicate that LID controls will substantially improve hydrological performance of the developed areas; however, the decrease in DCIA via spatially improved LID controls may be less effective at reducing the flood rate and peak runoff time in the conduits, especially during large rainfall events.

Table 7. Variation in conduit peak flow, flow rate and peak runoff time for four scenarios

Scenario	Peak flow (m^3/s)	Flow rate (m/s)	Peak runoff time (day, hr:min)	Time-lag (compared with S2)
S1	1.24	0.19	24th, 03:06	4h38m
S2	0.65	1.06	23rd, 22:28	--
S3	0.61	1.03	24th, 00:01	1h33m
S4	0.59	1.01	24th, 00:05	1h37m

4.3 Comparison of flow rate and peak flow time at junctions under four scenarios

In the current pre-development state, scenario S1, the total inflow volume of the junctions was 2887.3×10^6 L, the average peak flow was 1.49 m^3/s, and peak flow time was at 03:08 on the 24th (Table 8). Compared with scenario S1, S2 had the total flow volume of 4117.4×10^6 L, which represented an increase of 42.6%. The corresponding peak flow time occurred 46 min earlier, and the average peak flow ($0.99 m^3/s$) decreased by 33.6%. These outcomes occurred because S1 did not include any drainage pipe networks besides the natural rivers and canals. These results confirm that if no measures are taken to compensate for the loss of pervious land, urbanization in the study area will substantially affect the junction flow characteristics and likely increase the risk of urban flooding.

Table 8. Variation in junction flow rate and peak flow time for four scenarios

Scenario	Peak flow time (day, hr:min)	Average peak flow (m^3/s)	Total flood volume (10^6L)
S1	24, 03:08	1.49	2887.3
S2	24, 02:22	0.99	4117.4
S3	24, 02:34	0.87	3671.2
S4	24, 02:40	0.83	3313.5

Compared to S2, the use of LID controls in S3 will decrease the average peak flow decrease by 12.1%, decrease the total inflow volume by 10.8%, and delay the peak flood time by 12 min, suggesting an improvement of the overall stormwater regulation following the application of LID, which indicates that the application of LID controls can mitigate the impacts that urbanization has on the stormwater conveying. Compared with S3, average peak flow and the total flow volume for scenario S4 decreased by 4.6%, and 9.7% respectively, and the peak flow time was delayed by 6 min. These results indicate that an appropriate spatial pattern of LID controls is also important for improving hydrological performance in the junctions (Table 8).

4.4 Comparison of outflows in the outlets under four scenarios

Differences in general outflow characteristics of the outlets could indicate the cumulative effects of the hypothetical LID applications (Gironás et al., 2009). The pre-development scenario S1 had the smallest total flow volume (464.7×10^6L), however, S2 had the largest total flow volume (733.8 ×10^6L). The results indicate that, compared to S1, the loss of pervious land (33.3%) will bring an increase of 57.9% flood volume. Furthermore, the largest average peak flow (5.1 m^3/s)and the earliest peak flow time (at 22:51 on the 23rd) of S2 show that urbanization will lead to a strong increase in peak discharge and a very early peak flow at the outlets. Compared with S2, the total flow volume for S3 and S4 decreased by 8.66%, 14.75% to 670.3 ×10^6 and 625.5×10^6L, respectively, and the average peak flow decreased by 8.59% and 14.14% to 4.7 m^3/s and 4.4 m^3/s respectively. The corresponding peak flow times were both delayed by 87 min. Thus, LID installations could reduce the average peak flow and total flow volume in S3 and S4. In comparison to S3, the average peak flow and the total flow volume of S4 decreased by 6.4% and 6.7%, respectively, despite the identical peak flow times of these scenarios. This result implies that reducing DCIA by changing the locations of hypothetical LID controls would contribute to reducing the outflow at the outlets. Thus it can be concluded that improving the LID spatial pattern and at the same time considering the overland flow routing by redirecting surface runoff to the LID units are both important for management of stormwater (Table 9).

Table 9. Comparison of the outflows in the outlets under the four scenarios

Scenario	Average peak flow (m^3/s)	Peak flow time (day, hr: min)	Total flow volume (10^6L)
S1	4.2	24rd, 03:47	464.7
S2	5.1	23rd, 22:51	733.8
S3	4.7	24rd, 00:18	670.3
S4	4.4	24rd, 00:18	625.5

5. Conclusion

Hydrological performances of the four urban development scenarios under the same single storm event were simulated using the GIS-based SWMM5.0 in a new urbanized area, west of Bazhong, China. Hydrological responses to the land use changes, as well as the effects of hypothetical LID practices were evaluated by comparisons with a traditional urban development scenario. This research integrated LID controls within urban planning to manage stormwater and provided an operable technical framework that demonstrated how SWMM, with the support of GIS, can be used at the city and district scale. The results of this study illustrate that urban development as described in regulatory planning (S2) would produce large increases in the impervious surface, and flood control will be a critical planning issue; however, traditional stormwater management strategies cannot cope with these problems well. Alternatively, urban development schemes integrating LID controls (S3) and designs to decrease DCIA (S4) can contribute to mitigating the impacts of urbanization by attenuating stormwater runoff, even though the study area could not be completely restored to the pre-development hydrological environment. Consistent with previous studies (Loperfid et al., 2014; Juan et al., 2016), results from this analysis also imply that following a massive increase in impervious land (from 5.8%-39.6 as in this study), the TIA might still be the main factor controlling stormwater hydrology behavior, especially under large rainfall events. Nevertheless, the results still corroborate the effectiveness of LID controls and design in providing some flood reduction benefits.

The research reported here presents a modeling study of the potential effects of the large-scale implementation of LID practices as an important step in guiding large-scale LID practices, planning and overall effort. Several limitations should be also acknowledged that present important directions for the future work. First, there are limitations to using the recommended model parameter values from the SWMM5.0 manual or relevant literature. Complex topography and large number of sub-catchments in urban areas ideally require that input parameters for the SWMM should be obtained through direct field survey and observations. Second, a better understanding of LID controls and their hydrological effects will require a finer level of sub-catchment discretization to properly account for their localized placement. Because this study was conducted at a district scale, the effects of factors such as the underground water level, evaporation and current water retention on the simulation results were not considered in the model simulation. In addition, a more informative comparison of development scenarios could be achieved with a continuous long-term simulation to evaluate the land use change and LID performance. Finally, in this research, the drainage pipe system of the three post-development scenarios are the same, and only one heavy rainfall condition was used to assess the impact of LID and DCIA decrease on stormwater runoff characteristics. The optimizing possibility of the grey stormwater drainage systems and the effect of LID controls and DCIA change on the sensitivity of stormwater runoff characteristics to different rainfall events were both not considered, which also represents an important future step to inform the improvement of urban planning and stormwater management strategies in growing cities such as our study region. Further research is needed to look into the integration of LID systems with grey stormwater drainage systems and fully understand the effects of LID controls and the DCIA under different rainfall conditions.

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