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Hydrological Regulation Performances of LID Practices Based on Different Rainfall Reappearance Periods

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Abstract: Urbanization caused hydrological change and increased stormwater runoff volumes, which led to flooding, erosion and the degradation of instream ecosystem health. Low impact development (LID) options had been proposed as an alternative approach to mimic the natural flow regime by using decentralized designs to control stormwater runoff at the source, rather than at a centralized location in the watershed. Hydrological regulation performances of these LID practices can be influenced by rainfall characteristics, such as rainfall intensity and duration. To evaluate the impacts of different rainfall reappearance periods, rainfall analysis was conducted to determine the rainfall characteristics and SCS II type was selected for the analysis. A modeling approach based on SWMM was described to incorporate these LID practices into an existing hydrological model to estimate the impacts of LID practices on the surface runoff. Results demonstrated that the LID practices led to significant stormwater control for different rainfall reappearance periods. Hydrological regulation performances of the LID practices were varied with rainfall reappearance periods. For LID practices with the same surface area, the detention pond performed the best in reducing peak flow rate, which was followed by infiltration trench, bioretention cell and porous pavement. Detention pond was capable to reduce the peak flow rate of 100-year storm to the value of 10-year storm, indicating significant performances. Differences in peak flow reduction were due to structure differences in the LID practices. For the infiltration regulation performances, infiltration trench had the highest recharge ratio for all the rainfall reappearance periods, followed by bioretention cell and porous pavement. Porous pavement, though made of 100% pervious material, infiltrated small runoff which was limited by the native soil infiltration rate when the rainfall volume exceeded the storage capacity. Deep analysis was conducted to determine the reasons that the LID practices performed differently when they had the same surface area. Results showed that the "effective storage", which was the water volume that a facility can contain, was the crucial factor. When rainfall intensity was larger than native soil infiltration rate, the excessive water was stored in the facility, and then it was released or infiltrated to the groundwater, depending on the facility structure. Consequently, the water exceeded the "effective storage" was flowed over the LID practices and made contribution to the surface runoff directly. Calculation results showed that the "effective storage" for the detention pond was 1 861.20 m^3, which was the largest among the four LID practices, and it explained the reason that detention pond worked the best in peak flow reduction. The "effective storage" for the infiltration trench, porous pavement and bioretention cell were 744.48 m^3, 80.37 m^3 and 565.14 m^3, respectively.

Key words: low impact development; runoff; SWMM; return period

0 Introduction

The process of urbanization transforms natural landscape into impervious land cover, affecting the ecosystem health of receiving water bodies and downstream communities by changing the timing and volumes of the natural flow regime[1-5]. Urban flooding is one of those typical problems caused by urbanization[6]. In order to minimize the negative effects caused by urbanization and to meet the new stormwater rules, strategies, such as low impact development (LID), put forward by Prince George's County in 1980s, that employ infiltration are increasingly adapted. The goal of LID is to plan and construct a site so that the hydrology and water quality mimic that of the initial undeveloped site[7-11].

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Currently, the main LID practices include bioretention facilities, green roof and porous pavement, which have been studied from different scales, say, lab, residential site or parking lot. The hydrological performances, design methods of these LID practices have been the learned from both the modeling approach and based on the field observation data[10-15]. However, hydrological performances researches of LID practices mainly focus on a specific rainfall events, few analyzed impacts of rainfall characteristics and rainfall magnitude on the hydrological performances of LID practices[16-21]. The goal of this research was to discuss the hydrological performances of LID practices under different rainfall events and tried to analyze how they varied by the rainfall magnitude. The results may help to know the hydrological performances of LID practices and enlighten the urban drainage system design.

Taking a parking lot in Lenexa City, Kansas as the study area andusing different modules of EPA SWMM, this paper presented hydrological simulation approaches of typical LID practices and evaluated their hydrological performances using the SWMM models developed. A series of hydrological indicators attempting to represent the entire spectrum of rainfall events were used to evaluate impacts of LID practices of detention pond, infiltration trench, bioretention cell and porous pavement.

1 Case study area

The study area is located within Little Mill Creek watershed in Lenexa, Kansas, USA. The Kansas City region is generally characterized by Soil Conservation Service (SCS) Type II storm distribution. The study area here is located to the north of W87th street of Lenexa City and is composed of a parking lot and buildings, shown in Fig. 1. The study area is 0.017 km^2, moderately sloped at a three percent grade with a high imperviousness of 86%. Soils are characterized as hydrologic soil groups of C with low infiltration rate. By analyzing the soil condition and appropriate building condition of LID practices, the open green space in the lower part of the study area was selected as the proposed LID area, which will receive the runoff from all over the study area. The proposed LID area is 846 m^2. Typical LID practices of detention pond, infiltration trench, bioretention cell and porous pavement were chosen and drained out to the drainage system.

Fig. 1 Location of study area

Hydrologic modelof study area has been developed and implemented using U. S. Environmental Protection Agency (US EPA) Stormwater Management Model (SWMM) for hydrologic simulation. Use of this site as the case study area can save the effort to build and calibrate the initial SWMM models.

2 Methodology

2.1 Introduction to SWMM

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall – runoff simulation model used for single event or long – term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. SWMM was first developed in 1971 and has undergone several major upgrades since then. Infiltration of rainfall from the pervious area of a subcatchment into the unsaturated upper soil zone can be described using three different models: Horton infiltration, Green – Ampt infiltration and Curve number infiltration. Based on the flow continuity and Manning's equation, each subcatchment surface is treated as a nonlinear reservoir to calculate the surface runoff. Three methods of steady flow routing, kinematic wave routing and dynamic wave routing can be used to solve the equations of flow routing[22].

Since its inception, SWMM has been used in thousands of sewer and stormwater studies throughout the world, especially in design and sizing of drainage system components for flood control anddesigning control strategies for the stromwater management practices.

2.2 Rainfall events and evaporation

To study the impact[23-24] of rainfall events with different return periods, a series of designed rainfall events with the return periods of 2 years, 5 years, 10 years, 20 years and 100 years were selected. Hourly rainfall data extending from August, 1948 to February, 2010 for the Kansas City downtown (KCD) Airport (gage number 234359) is available on National Climatic Data Center (NCDC), USA. By analyzing the frequency, duration and intensity of the rainfall events, a SCSII distribution was selected. The rainfall were 9.1 cm, 12.5 cm, 13.7 cm, 15.6 cm, 17.4 cm and 19.7 cm respectively. Since the single rainfall events was studied, an average evaporation rate of 5.1 mm/d was used, recorded by U. S. National Oceanic and Administration Association (NOAA).

2.3 Parameters of SWMM subcatchment

Based on the calibrated SWMM model, main parameters of the subcatchment without LID were listed in Tab. 1. When LID practice applied, the subcatchment area needed to deduct the LID practice area and the area was 0.016 km^2.

Tab. 1 Main input parameters of SWMM

Parameters		Value
Area/km^2		0.016
Imperviousness/%		86
Subcatchment width/m		120
Slope/%		1
Depression depth on impervious area/cm		0.15
Depression depth on pervious area/cm		1.27
Horton infiltration	Maximum infiltration rate/($cm \cdot h^{-1}$)	11.43
	Minimum infiltration rate/($cm \cdot h^{-1}$)	0.76
	Decay constant	4.14

2.4 Modeled scenarios

Hydrological performances analysis of LID practices needs an comparison between the runoff control values with and without LID practices controlled. Five scenarios of "undeveloped", "detention pond", "infiltration trench", "porous pavement" and "bioretention cell" were modeled. SWMM models were developed for each scenario and a duration of 24 hours with time step of minute for all the rainfall events with different return periods were simulated. The peak flow, flow duration curve were summarized based on the simulation results. The modeled scenarios are discussed as follows:

(1) Developed uncontrolled. The study area was modeled as a high-density commercial development with eighty-seven percent direct connection impervious area (DCIA). No stormwater management practices were applied to the study area in this scenario.

(2) Detention pond. In the detention Pond scenario, runoff from the high-densitycommercial development described above was routed through a detention pond in the BMPS/LID area. Detention pond is a typical storage structure to store water temporarily and then release it according to the design criteria. In this study, detention pond is simulated to release a 100-year storm within 48 h. The largest surface area of the detention pond is 846 m^2 with the maximum depth of 2.20 m. The simulation of detention pond scenario in SWMM was illustrated in Fig. 2a.

(3) Infiltration trench. Runoff from the high-density commercial development described above was routed through an infiltration trench in the BMPS/LID area. Infiltration trenches are excavations backfilled with stone aggregate used to capture runoff and infiltrate it to the ground. It can be simulated as a rectangular, fully pervious subcatchment whose depression storage depth equals the equivalent depth of the pore space available within the trench. In this study, the infiltration trench was simulated as a 100% pervious rectangular area of 846 m^2. For comparison purpose, the infiltration trench depth is set as same as the depth of detention pond of 2.2 m which generated a valid depression depth of 0.88 m with the porosity is 0.40. Schematic representation of an infiltration trench in SWMM is shown in Fig. 2b.

(4) Porous pavement. According to the suitable area, the parking lot can be replaces by porous pavement, which is different from the other three scenarios. To analyze the hydrologcial differences of LID practices while they have the same surface area, the porous pavement was simulated in the LID area, with a depth of 15.8 cm. The runoff flows into the porous pavement eventually. The porosity of the porous pavement is 0.6, which makes the actual depression depth of 9.5 cm. Porous pavement was simulated by 100% pervious subcatchment, illustrated in Fig. 2c.

(5) Bioretention cell. In the Bioretention cell scenario, runoff from the high-density commercial development area described above was routed through a

bioretention cell in the LID area. Due to the complicated process of water movement in bioretention, simulation of bioretention in SWMM is limited. As a consequent, we used an external model of RECARGA to simulate the water movement of the bioretention and then the results are incorporated into SWMM using an outlet structure with obtained time-flow series. Tab. 2 listed the design elements of bioretention.

Tab. 2 Design parameters of bioretention cell

Parameters	Value
Bioretention surface area/m^2	846
Ponding depth/cm	15
Saturated infiltration rate of planting soil/($cm \cdot h^{-1}$)	6.12
Depth of planting soil/cm	122
Saturated infiltration rate of planting soil/($cm \cdot h^{-1}$)	15.0
Depth of gravel layer/cm	30
Saturated infiltration rate of native soil/($cm \cdot h^{-1}$)	21.01

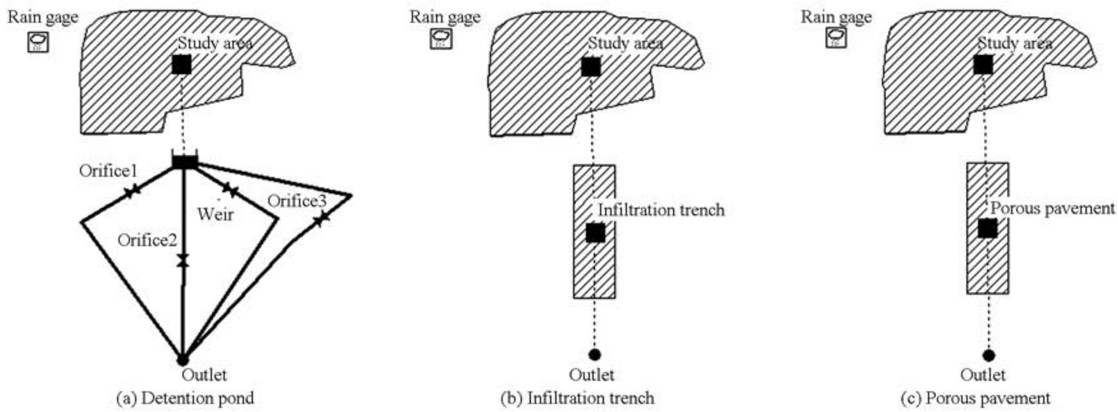

Fig. 2 Modeling of each regulation practices in SWMM

3 Hydrological performances analysis

Single rainfall events with the return periods of 2, 5, 10, 20, 50 and 100 years were used to test their impact on LID practices. The hydrological performances indicator included hydrograph shapes, peak flow reduction and recharge ratio. Peak flow reduction was the ratio of peak flow reduced by the LID practice to the peak runoff under the "developed uncontrolled scenario", and recharge ratio referred to the ratio of the infiltrated runoff to the total surface runoff under each scenario.

3.1 Detention pond

Tab. 3 listed the peak flow reduction results for the detention pond under different rainfall events. It showed that for the two-year rainfall event, the peak flow reduction was 68.11%, reduced by 0.174 m^3/s. When it came to the 100-year rainfall event, the peak flow reduction was 39.41%, reduced by 0.235 m^3/s. The tendency showed that with increase of return periods, peak flow reduction decreased, which can be explained because the larger return period always brings the larger peak flow at the same time. However, it was noted that reduced peak flow increased at the same time, indicting a better hydrological performances. Taking 100-year rainfall event as the example, the peak flow was close to the value of 10-year rainfall event, which implied that detention pond reduced the peak flow under 100-year rainfall event to the level of 10-year return period, even when the detention pond area was only 5% of the impervious area. However, the detention pond can not infiltrate runoff, consequently, detention pond can not decrease the surface runoff.

Tab. 3 Peak flow reduction of detention pond at different reapperance periods

Return periods/year	Developed uncontrolled peak flow/($m^3 \cdot s^{-1}$)	Detention pond controlled peak flow/($m^3 \cdot s^{-1}$)	Peak flow reduction/%
2	0.255	0.081	68.11
5	0.387	0.182	52.97
10	0.433	0.214	50.52
20	0.524	0.288	45.04
50	0.609	0.351	42.36
100	0.725	0.439	39.41

Fig. 3 displayed the hydrographs under the scenarios of "developed uncontrolled" and "detention pond controlled". It can be seen from Fig. 3 that the detention pond controlled hydrograph was smooth with obvious peak flow delay for the 2-year rainfall event. With the increase of return periods, the hydrographs were similar to the 2-year rainfall events, but the increase and decrease slopes were gradually steeper.

For all the rainfall events, a small flow after detention pond controlled remained a long time when the flow under the "developed uncontrolled" scenario reached zero.

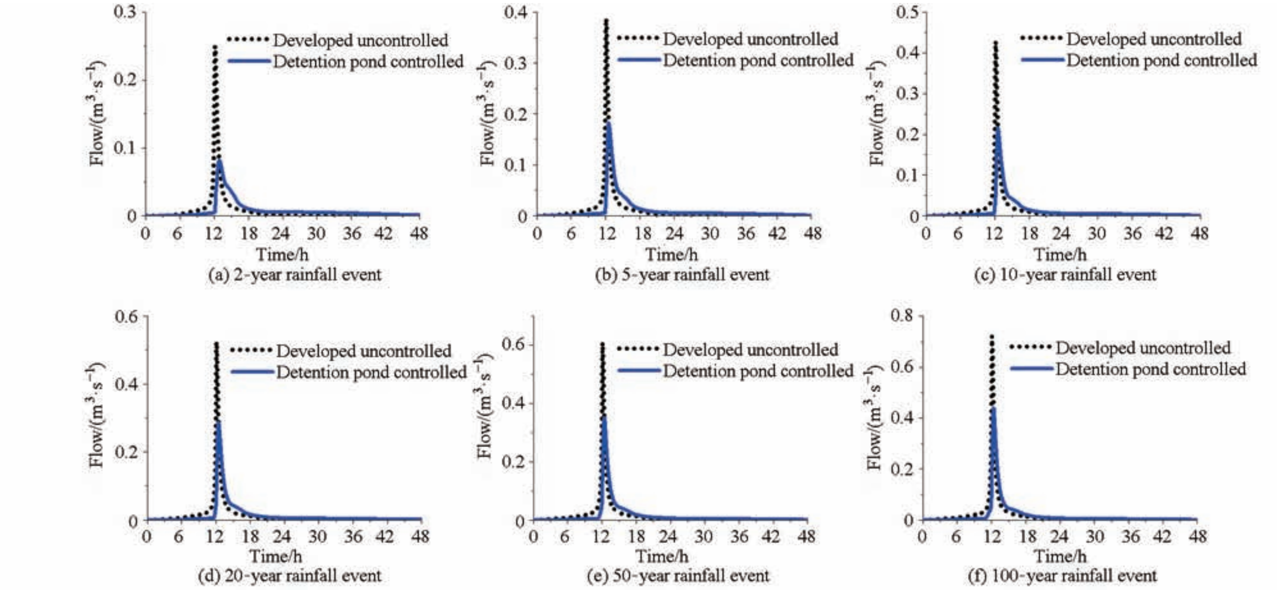

Fig. 3 Uncontrolled and detention pond controlled hydrographs at different reappearance periods

3.2 Infiltration trench

Tab. 4 listed the peak flow reduction results for the infiltration trench under different rainfall events. It showed that for the 2-year rainfall event, the peak flow reduction was 73.67%, reduced by 0.188 m^3/s, higher than the detention pond. However, with the increase of return periods, and for the 5-year rainfall event, the peak flow reduction was smaller than the detention pond controlled value. The reason was that infiltration trench decreased the peak flow by storing runoff temporarily and infiltrated it to the native soil. Consequently, when the rainfall intensity was small enough and close to the native soil infiltration rate, the peak flow reduction was high. When the rainfall intensity exceeded the native soil infiltration rate and the infiltration trench could not store any more water, the peak flow flow reduction decreased and consequently the infiltrated water decreased. The recharge ratio decreased with the increase of return periods and the infiltrated water did not show an obvious change for all the rainfall events. The possible reason was that the runoff generated by a 2-year rainfall event had exceeded the storage capacity the infiltration trench can store. When the native soil infiltration rate was low, infiltration trench had a smaller peak flow reduction compared with detention pond for the large rainfall events. However, most of the rainfall events belong to the small ones and infiltration trench is still a very good stormwater practice for the area with groundwater recharge demand.

Tab. 4 Hydrological regulation performances of infiltration trench at different reappearance periods

Return periods/year	Developed uncontrolled peak flow/($m^3 \cdot s^{-1}$)	Infiltration trench controlled peak flow/($m^3 \cdot s^{-1}$)	Peak flow reduction/%	Recharge ratio/%
2	0.255	0.067	73.67	63.42
5	0.387	0.214	44.70	43.92
10	0.433	0.267	38.30	41.66
20	0.524	0.383	26.91	33.96
50	0.609	0.500	17.90	29.71
100	0.725	0.632	12.84	27.31

Fig. 4 displayed the "uncontrolled developed" and "infiltration trench controlled" hydrographs under different rainfall events. Infiltration trench worked differently from detention pond, and thus generated a different hydrograph. As seen from Fig. 4, controlled by infiltration trench, the flow was 0 until it reached a moment when the flow increased sharply and afterwards, the hydrograph was similar to the "developed uncontrolled" scenario. The reason this phenomenon appeared was that infiltration trench was simulated by a 100% pervious subcatchment. Before the depression depth of the pervious area was filled, all the generated runoff was used to fill the pore area in the infiltration trench without generating surface runoff. As soon as the depression area was filled, the infiltration rate was the saturated native soil infiltration rate and the runoff generation mechanism was the same to the "developed uncontrolled" scenario. This explained why the "infiltration trench controlled" hydrograph was similar to the "developed uncontrolled" for the late period of a rainfall event.

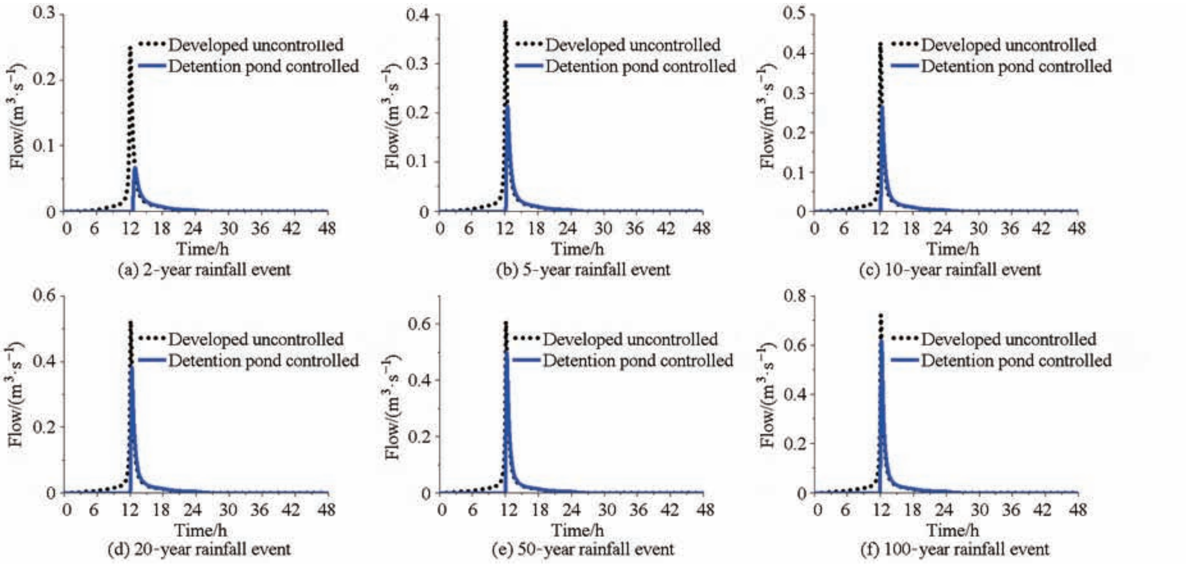

Fig. 4 Uncontrolled and infiltration trench controlled hydrographs at different reappearance periods

3.3 Porous pavement

Porous pavement is a design strategy converting impervious into pervious area and increases the depression depth on pervious area. The parking lot in the study area is the best place to be simulated as porous pavement, and the imperviousness will be reduced to 38.5% from 86%, which confirmed that porous pavement was a typical LID practice by reducing the area imperviousness. Additionally, the depression depth increased on the pervious area and the stored water will infiltrated into groundwater instead of becoming surface runoff. By increasing depression depth, porous pavement can control the surface runoff more efficiently. To compare the hydrological performances of porous pavement with other LID practices, the simulated porous pavement was located in the LID area, and the porous pavement surface area was only 5% impervious area and the depression depth was only 9.5 cm, much smaller than the depression depth of infiltration trench.

As a result, when simulated with the same surface area, the hydrological performance of porous pavement controlled was not significant for all the rainfall events. It can be seen from Tab. 5 that, the peak flow reduction was 9.73%, reduced by 0.025 m^3/s. With the increase of return periods, the reduced peak flow increased to 0.079 m^3/s, which was small compared to the value under "developed uncontrolled" scenario. Overall, peak flow reduction was 10% and varied by return periods, without a certain increasing or decreasing tendency. As far as the infiltrated runoff was concerned, the infiltrated runoff were 13.36 cm and 15.29 cm respectively for the 2-year and 100-year rainfall event and little difference was observed. The reason was that the surface area and depth of porous pavement was small and had a limited control capacity.

Tab. 5 Hydrological regulation performances of porous pavement at different reappearance periods

Return periods/year	Developed uncontrolled peak flow/($m^3 \cdot s^{-1}$)	Porous Pavement controlled peak flow/($m^3 \cdot s^{-1}$)	Peak flow reduction/%	Recharge ratio/%
2	0.255	0.230	9.73	21.59
5	0.387	0.353	8.66	15.98
10	0.433	0.388	10.41	14.91
20	0.524	0.467	10.96	12.93
50	0.609	0.543	10.92	11.61
100	0.725	0.646	10.90	10.24

Fig. 5 displayed the hydrographs of scenarios of and "developed uncontrolled" and "porous pavement controlled". Fig. 5 reflected the hydrological performances of porous pavement like Tab. 5. But it is noted that, the pervious concrete material is expensive, which costs more than detention pond, infiltration trench and biortention cell. Additionally, the retrofit area is generally the whole parking lot and the high cost has limited the development of porous pavement. It has been an important research topic to develop the porous concrete material with reasonable price.

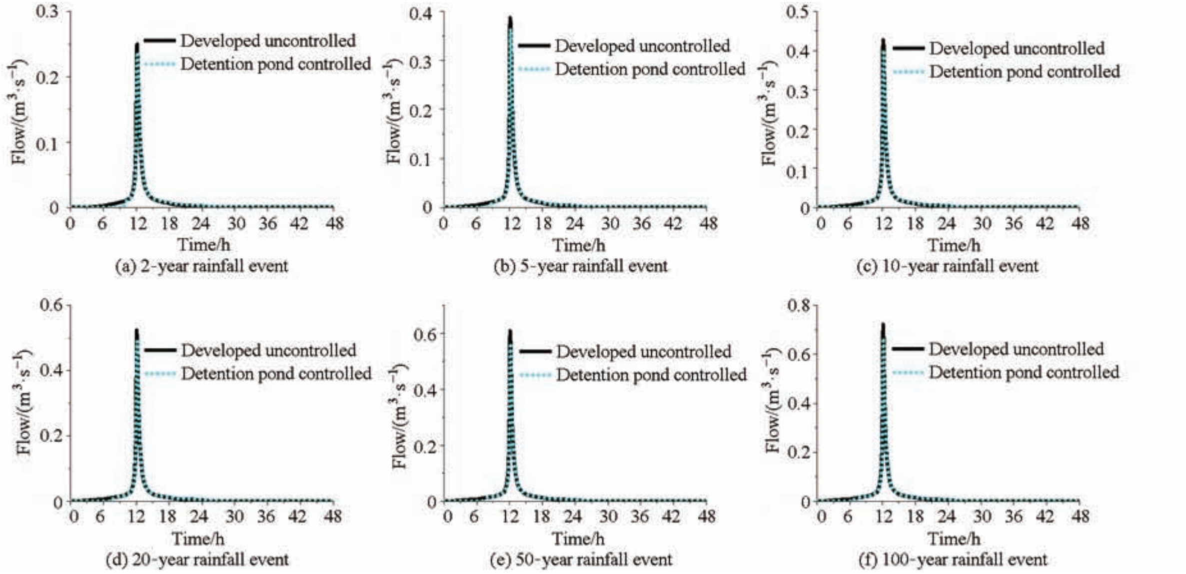

Fig. 5 Uncontrolled and porous pavement controlled hydrographs at different reappearance periods

3.4 Bioretention cell

Same as infiltration trench, bioretention cell controlled the runoff by infiltration. However, different from infiltration trench, the structure of bioretention cell was more complicated and root soil storage and plant evapotranspiration were also included. RECARGA, a model designed to simulate the water movement of bioretention facilities was used to simulate the hydrological performances of bioretention cell. Peak flow reduction and recharge ratio for all the rainfall events were summarized in Tab. 6. The results showed that the peak flow reduction was 58.04%, reduced by 0.148 m^3/s for the 2-year rainfall event. For the 100-year rainfall event, peak flow reduction barely changed but the reduced peak flow was 0.389 m^3/s. Meanwhile, recharge ratio decreased with the increase of return periods. For the 2-year and 10-year rainfall event, the infiltrated runoff was 10.86 cm and 10.63 cm respectively and no obvious change was observed.

Peak flow reduction increased with the increase of return period, however, no obvious change in recharge ratio was noticed. The reason was that an underdrain was set to guarantee the water stored in the bioretention cell drain out within 48 hours for the 10-year rainfall event. A large ratio of water will drain out through the underdrain facility and can not infiltrate to the groundwater, which will reduce the peak flow reduction but not promote the infiltration.

Tab. 6 Hydrological regulation performances of bioretention at different reappearance periods

Return periods/year	Developed uncontrolled peak flow/($m^3 \cdot s^{-1}$)	Bioretention cell controlled peak flow/($m^3 \cdot s^{-1}$)	Peak flow reduction/%	Recharge ratio/%
2	0.255	0.107	58.04	17.54
5	0.387	0.169	56.33	14.36
10	0.433	0.193	55.43	11.78
20	0.524	0.237	54.77	10.01
50	0.609	0.279	54.19	8.79
100	0.725	0.336	53.66	7.12

Fig. 6 displayed the hydrographs for the scenarios of "developed unctrolled" and "bioretention cell controlled". It can be seen from Fig. 6 that the hydrographs displayed here were similar to the hydrographs under the scenario of "detention pond controlled". The difference was that the hydrograph controlled by bioretention cell was smoother due to the fact that the outflow consisted underdrain flow and surface overflow. The underdrain flow works the same way as the orifice of detention pond, which determined that part of the hydrograph was similar to the detention pond. Surface overflow appeared when the runoff flowing into the bioretention cell exceeded the ponding depth. The hydrograph caused by surface flow was smooth and accounted for most part of the outflow, which made the hydrograph smooth. Compared with other LID practices, bioretention cell also has environment aesthetic function and significant pollutant

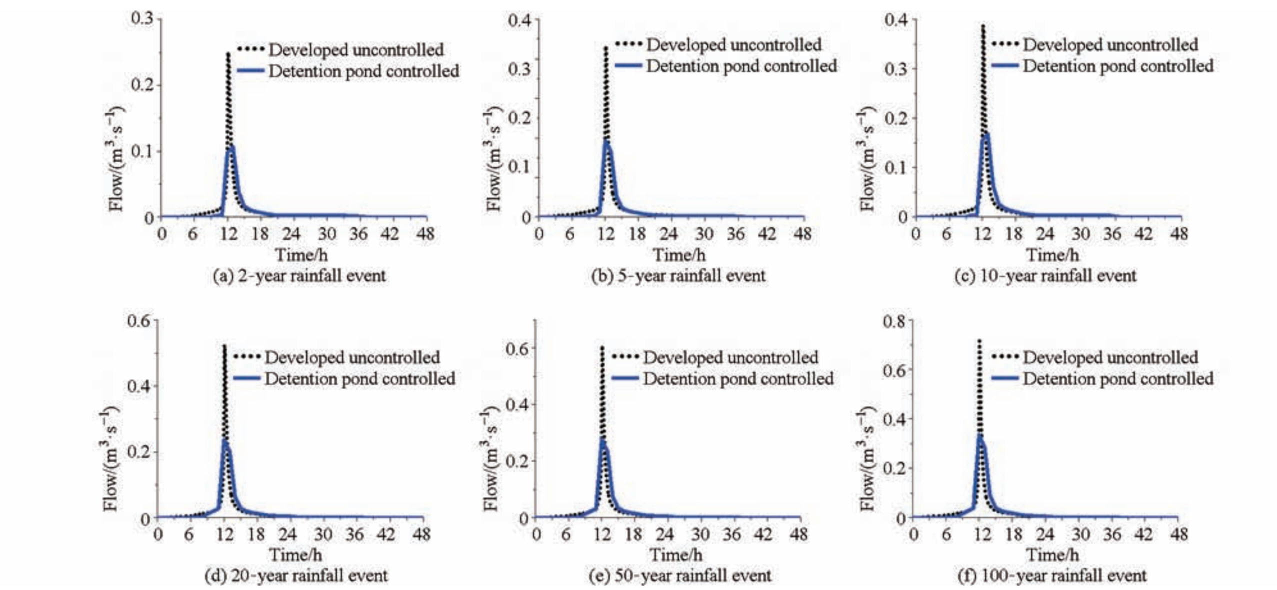

Fig. 6 Uncontrolled and bioretention cell controlled hydrographs at different appearance periods

removal function. It is also cheap compared with the porous pavement. For the 2-year rainfall event, the recharge ratio was only 17.54%, but it was still widely used because most of the rainfall events are small ones.

4 Diccussion

Further analysis about the impact of design elements on the hydrological performances of LID practices showed that, the efficient storage, which is the maximum water the practice could store is the dominant factor influencing the hydrological performances. When the rainfall intensity exceeds the native soil infiltration rate, the excessive rainfall will store in the facility and then flows out or infiltrates into groundwater no matter what specific design of LID practices are. As soon as the efficient storage is filled, the rainfall will become surface runoff. Results from this study showed that the efficient storage for the infiltration trench, porous pavement and bioretention cell were 744.48 m^3, 80.37 m^3 and 565.14 m^3 respectively, and consequently, infiltration trench, with the largest efficient storage had the highest peak flow reduction and recharge ratio, followed by bioretention cell and porous pavement. The findings here is important in guiding the construction of LID practices.

Hydrological performances of LID practices also relied on the area land cover, imperviousness, native soil infiltration and duration, intensity of rainfall events. In this study, only one rainfall type of SCS Ⅱ with different magnitudes were discussed, how LID practices perform under other factors needs further research.

5 Conclusion

(1) Designed with the same surface area, detention pond performed best in peak flow reduction and reduced peak flow decreased with increase of return periods, followed by infiltration trench, bioretention cell and porous pavement.

(2) Designed with the same surface area, infiltration trench performed best in infiltration and the recharge ratio decreased with the increase of return periods while the infiltrated runoff remained the same, followed by bioretention cell and porous pavement.

(3) The efficient storage, which is the maximum water the practice could store is the dominant factor influencing the hydrological performances.

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基于不同重现期降水的LID措施水文调控性能研究

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摘要:作为最典型的土地利用变化过程之一,城市化进程通过改变该地区的下垫面条件,改变了天然状态下的水文机制,并进而产生一系列水环境问题。低影响开发(LID)的雨洪调控措施通过在源头上消纳径流,被视为解决城市雨洪问题的新方法。通过SWMM(Storm water management model)软件建立模型,对不同重现期降水的典型LID措施截流池、入渗带、透水性路面和生物滞留池进行了模拟。模拟结果表明,各LID措施的调控性能随着降水重现期的不同而产生明显的变化;随着降水量的增大,各措施的洪峰流量消减率及入渗补给率(截流池除外)均有不同程度的下降,但洪峰流量消减量随着降水量的增大而增大,入渗量基本保持不变(截流池除外);当采用相同的表面面积设计时,滞留池的洪峰流量消减性能最好,入渗带的入渗补给性能最好;决定其调控性能最主要的因素本质上为其“有效容积”,即各措施所能容纳的水量。

关键词:低影响开发;径流;SWMM;重现期

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Hydrological Regulation Performances of LID Practices Based on Different Rainfall Reappearance Periods

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Abstract: Urbanization caused hydrological change and increased stormwater runoff volumes, which led to flooding, erosion and the degradation of instream ecosystem health. Low impact development (LID) options had been proposed as an alternative approach to mimic the natural flow regime by using decentralized designs to control stormwater runoff at the source, rather than at a centralized location in the watershed. Hydrological regulation performances of these LID practices can be influenced by rainfall characteristics, such as rainfall intensity and duration. To evaluate the impacts of different rainfall reappearance periods, rainfall analysis was conducted to determine the rainfall characteristics and SCS II type was selected for the analysis. A modeling approach based on SWMM was described to incorporate these LID practices into an existing hydrological model to estimate the impacts of LID practices on the surface runoff. Results demonstrated that the LID practices led to significant stormwater control for different rainfall reappearance periods. Hydrological regulation performances of the LID practices were varied with rainfall reappearance periods. For LID practices with the same surface area, the detention pond performed the best in reducing peak flow rate, which was followed by infiltration trench, bioretention cell and porous pavement. Detention pond was capable to reduce the peak flow rate of 100-year storm to the value of 10-year storm, indicating significant performances. Differences in peak flow reduction were due to structure differences in the LID practices. For the infiltration regulation performances, infiltration trench had the highest recharge ratio for all the rainfall reappearance periods,

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followed by bioretention cell and porous pavement. Porous pavement, though made of 100% pervious material, infiltrated small runoff which was limited by the native soil infiltration rate when the rainfall volume exceeded the storage capacity. Deep analysis was conducted to determine the reasons that the LID practices performed differently when they had the same surface area. Results showed that the "effective storage", which was the water volume that a facility can contain, was the crucial factor. When rainfall intensity was larger than native soil infiltration rate, the excessive water was stored in the facility, and then it was released or infiltrated to the groundwater, depending on the facility structure. Consequently, the water exceeded the "effective storage" was flowed over the LID practices and made contribution to the surface runoff directly. Calculation results showed that the "effective storage" for the detention pond was 1 861.20 m^3, which was the largest among the four LID practices, and it explained the reason that detention pond worked the best in peak flow reduction. The "effective storage" for the infiltration trench, porous pavement and bioretention cell were 744.48 m^3, 80.37 m^3 and 565.14 m^3, respectively.

Key words: low impact development; runoff; SWMM; return period

引言

城镇化建设中,土地利用形式的不同使得流域下垫面发生了急剧的变化,透水性的农田及森林转化为不透水性的路面,对水系及其所在流域的自然水文循环造成严重的干扰、破坏,并由此引发了一系列问题[1-5],其中以洪涝灾害为典型代表的水资源问题愈来愈突出[6]。基于此,美国马里兰州的普润丝·乔治县于 20 世纪 90 年代提出了低影响开发(Low impact development, LID)的设计策略,通过一系列分布式的雨洪调控措施创造与天然状态下功能相当的水文和土地景观,从而实现雨洪调控和生态环境保护的双重功能[7-11]。目前,国内外 LID 措施的研究主要为生物滞留池、绿色屋顶和透水性路面,并基于实验室尺度、住宅社区或者停车场为主的小尺度以及模型模拟方法对其水文调控性能、设计方法进行了实测及模拟研究[10-15]。虽然 LID 措施的研究已经相对深入,但目前国内外还是主要对 LID 措施在特定降水条件下的水文调控性能进行分析,缺乏对降水特征以及降水量的分析[16-21]。因此,从不同重现期降水的角度出发,分析探讨各 LID 措施的雨洪调控性能随降水量的变化情况,可深入认识其水文调控性能,并能启发城市排涝防洪系统的设计。

本文以位于美国堪萨斯州 Lenexa 市的一个停车场为例,通过设置不同的 LID 措施,采用具有不同重现期的单个降水事件,利用能够反映不同土地利用情景的 SWMM 软件,针对 LID 典型措施中的截流池、入渗带、生物滞留池和透水性路面建立模型,从流量过程线的形状、入渗以及洪峰流量等方面来揭示不同 LID 措施对不同重现期降水的水文响应。

1　研究区概况

研究区位于美国堪萨斯州 Lenexa 市 Gillette 街道和 W87th 街道附近,是一个主要由停车场和建筑物构成的不透水性面积比例极高的区域,如图 1 所示。研究区面积为 0.017 km^2,不透水性面积比例为 86%,区域坡度为 1%,土壤主要为透水性系数比较低的粘土。目前,该研究区已建有一个截流池,根据 Lenexa 市的要求,该截流池将在原有的基础上进行扩建改造,使其在能够容纳水质控制体积(Water quality capture volume)的基础上,可以对更大的径流量进行调蓄处理。原有截流池面积为 218 m^2,拟扩建后的截流池面积为 846 m^2,几乎占据了研究区可利用的全部面积。在对研究区土壤情况和各调控措施的适宜修建条件进行分析的基础上,根据研究区域的坡度及径流走向,使各调控措施能充分接纳场地所产径流,并充分考虑用地情况,选定位于区域下方的开放性绿地作为各调控措施模拟的区域,并选定截流池、入渗带、生物滞留池和透水性路面作为拟模拟 LID 的调控措施,其径流出口与市政雨水管网系统相连。除此之外,研究区为 Lenexa 市《Lenexa 市截流池报告》中一个汇水子区域,且已经建立有 SWMM 模型并已根据实测数据进行了校核,因此,选取该区为研究区域,可以节约模型建立和校核的时间。

2　模型模拟

2.1　SWMM 模型简介

SWMM 首次被美国环保署(EPA)于 1971 年提出,是基于单个降水事件或者长期降水序列的降水-径流模拟软件,通过气象要素、地表要素、含水层要素和传输要素 4 个环境要素来实现对城市发展区域的水量或水质的动态模拟。在产汇流方面,SWMM

图1 研究区地理位置
Fig. 1 Location of study area

利用 Horton、Green - Ampt 和 Curve number 3 种入渗模型实现区域降水的入渗；并在水流连续性方程及曼宁公式的基础上，通过建立一个非线性水库来模拟径流的形成过程；利用稳定流法、动态波法和 Kinematic 法模拟汇流过程[22]。

由于其强大的功能，SWMM 目前已经在世界范围内城市排水系统设计以及雨洪调控措施的设计和计算方面得到了广泛的应用。

2.2 降水量及蒸发量

降水量及降水特征的不同对于产汇流的影响非常大[23-24]。为了体现不同重现期降水对各 LID 措施调控性能的影响，拟采用重现期为 2、5、10、20、50、100 a 的单个降水事件对各调控措施的性能进行分析比较。美国国家气象资料中心（National climatic data center，NCDC）记录了距研究区 19 km 处 Kansas 市国际机场自 1948 年 8 月—2014 年 12 月间隔为小时的降水数据，其监测站站号为 234 359。在对降水数据进行频率、历时、强度等降水特征分析的基础上，从对雨洪调控措施最不利的角度出发，确定研究区的降水类型主要为 SCS II 型分布，其中，重现期 2、5、10、20、50、100 a 的降水量分别为 9.1、12.5、13.7、15.6、17.4、19.7 cm。由于针对单个降水事件进行模拟，因此，蒸发量采用美国国家海洋及管理协会（National oceanic and administration association，NOAA）记录的全年蒸发量的平均值，为 5.1 mm/d。

2.3 SWMM 子区域的输入参数

依据已建且校核后的 SWMM 模型，未添加任何 LID 措施的子区域输入参数如表 1 所示。当采用 LID 措施进行模拟时，其区域面积为原来的面积减去调控措施的面积，为 0.016 km^2。

2.4 模拟情景

对各 LID 措施的调控性能进行分析需要将其与区域没有采取任何调控措施情景下的结果进行对比，因此，针对研究区拟模拟的雨洪调控措施，共设定 5 种情景，分别为：无调控措施、截流池调控、入渗

表1 SWMM模型主要输入参数
Tab. 1 Main input parameters of SWMM

参数		数值
面积/km^2		0.016
不透水性面积比例/%		86
区域宽度/m		120
平均坡度/%		1
不透水区域的积水深度/cm		0.15
透水区域的积水深度/cm		1.27
Horton 入渗参数	最大入渗速率/(cm·h^{-1})	11.43
	最小入渗速率/(cm·h^{-1})	0.76
	消减系数	4.14

带调控、透水性路面调控和生物滞留池调控。通过对各调控措施建立 SWMM 模型，模拟其不同降水重现期下历时 24 h、时间间隔为 1 min 的产汇流过程，并绘制其流量过程线，得到其洪峰流量及峰现时间。各模拟情景的具体描述如下：

（1）无调控措施：对现状不采取任何雨洪调控措施的研究区进行模拟。其中，研究区为高密度的商业区域，不透水性面积比例为 86%。

（2）截流池：在该种情景下，研究区的产流最后汇到位于 LID 措施模拟区的截流池中。截流池是一种典型的暂时存放雨水，再以一定流量排向排泄管道的蓄流装置。在本研究中，截流池采取其典型设计，即在 48 h 内能流出重现期 100 a 降水的产流。截流池的表面积为 846 m^2，最大深度为 2.2 m。其中，截流池在 SWMM 中的模拟如图 2a 所示。

（3）入渗带：在该种情境下，研究区的产流最后汇到位于 LID 措施模拟区的入渗带中。入渗带是一个由卵石填充的狭长区域，用来对径流实现储存和入渗。入渗带在 SWMM 中的模拟可以通过一个 100% 透水性区域得以实现。本研究中，入渗带被模拟为一个面积为 846 m^2 的 100% 透水性子区域，其厚度用可透水性区域的积水深度来表示。为了达到比较的目的，模拟入渗带的深度与截流池的深度相同，均为 2.20 m，入渗带的孔隙度为 0.40，则实际积水深度为 0.88 m。入渗带在 SWMM 中的模拟示意图如图 2b 所示。

（4）透水性路面：根据透水性路面的适宜安装区域，研究区中停车场可进行透水性铺装；该区域与其他 3 种措施所在区域不同。为了分析当不同措施具有相同设计表面面积时其水文调控性能的不同，从模型模拟及可比性的角度出发，在 LID 措施模拟区进行了透水性路面的模拟，其厚度为 15.8 cm。在该情景下，研究区产流最后汇到位于 LID 措施模拟区的透水性路面中。由于透水性路面的材料为大分子混凝土，其孔隙度为 0.60，则实际积水深度为

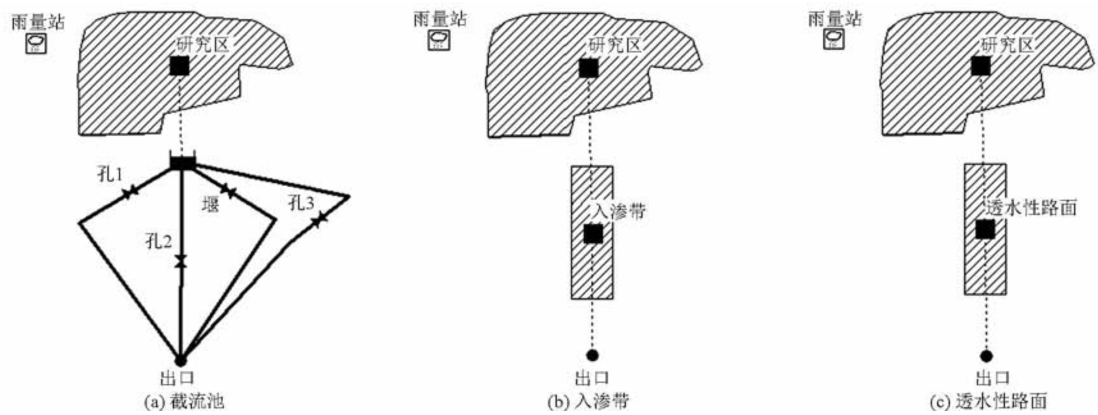

图 2　各调控措施在 SWMM 中的模拟

Fig. 2　Modeling of each regulation practices in SWMM

9.5 cm。透水性路面在 SWMM 中的模拟也通过一个透水性为 100% 的区域实现，如图 2c 所示。

(5) 生物滞留池：在该情景下，研究区的产流最后流入到位于 LID 措施模拟区的生物滞留池中。其中，生物滞留池的设计参数如表 2 所示。考虑到生物滞留池内水分运动的复杂性，首先利用 SWMM 生成进入生物滞留池的径流序列，之后在专门进行生物滞留池设计和模拟的软件 RECARGA 中对生物滞留池内的水分运动进行模拟，最后将其结果嵌入到 SWMM 中进行分析。

表 2　生物滞留池的设计参数

Tab. 2　Design parameters of bioretention cell

参数	数值
表面积/m^2	846
积水深度/cm	15
根系层饱和入渗率/($cm \cdot h^{-1}$)	6.12
根系层深度/cm	122
砂砾层饱和入渗率/($cm \cdot h^{-1}$)	15.0
砂砾层厚度/cm	30
天然土壤饱和入渗率/($cm \cdot h^{-1}$)	21.01

3　水文效应分析

选用重现期分别为 2、5、10、20、50、100 a 的单个降水事件对各 LID 措施调控下的水文效应分析，主要包括对流量过程线的形状、洪峰流量消减率以及入渗补给比例分析。其中，洪峰流量消减率为经各措施调控后的洪峰流量减小量占区域无调控措施下所产生的洪峰流量的比例；入渗补给比例为各措施入渗补给的水量占区域总地表径流量的比例。

3.1　截流池

表 3 为不同重现期降水下截流池洪峰流量消减率的模拟计算结果。表 3 表明，截流池具有较好的洪峰流量消减效果。当降水的重现期为 2 a 时，其洪峰流量消减率为 68.11%，消减量为 0.174 m^3/s；当降水的重现期为 100 a 时，洪峰流量消减率为 39.41%，消减量 0.235 m^3/s。随着降水重现期的增大，洪峰流量消减率逐渐减小，这是因为较大重现期降水所产生的洪峰流量也较大，但是，其洪峰流量的消减量也逐渐增大，说明其调控性能随着降水的增大而增大。同样以重现期 100 a 的降水为例，经截流池调控后，其洪峰流量接近重现期为 10 a 的降水无调控下的值。表明当采用约占区域不透水性面积比例 5% 的区域修建截流池时，在合适的设计下，截流池能将重现期为 100 a 降水的洪峰流量消减至重现期为 10 a 的洪峰流量。由于截流池本身不具备入渗补给功能，而是通过其出流设施对径流量进行调控，因此，截流池本身并不能减小地表径流总量。

表 3　不同重现期降水下截流池洪峰流量消减率

Tab. 3　Peak flow reduction of detention pond at different reappearance periods

重现期/a	无调控下洪峰流量/($m^3 \cdot s^{-1}$)	截流池调控后洪峰流量/($m^3 \cdot s^{-1}$)	洪峰流量消减率/%
2	0.255	0.081	68.11
5	0.387	0.182	52.97
10	0.433	0.214	50.52
20	0.524	0.288	45.04
50	0.609	0.351	42.36
100	0.725	0.439	39.41

图 3 为不同重现期降水下经截流池调控和无调控措施的流量过程曲线。图 3 表明，当降水的重现期为 2 a 时，经截流池调控后的流量过程线曲线比较平缓，且有一个明显的洪峰流量延时。随着降水重现期的增大，其流量过程曲线在形状上与无调控措施相似，上升与下降的坡度逐渐变陡。整体而言，对于各个重现期的降水而言，当无调控措施下径流流量为零时，截流池调控后的径流流量仍旧将以一个较小的值持续更长的时间。

3.2　入渗带

表 4 为不同重现期设计降水下，入渗带的洪峰

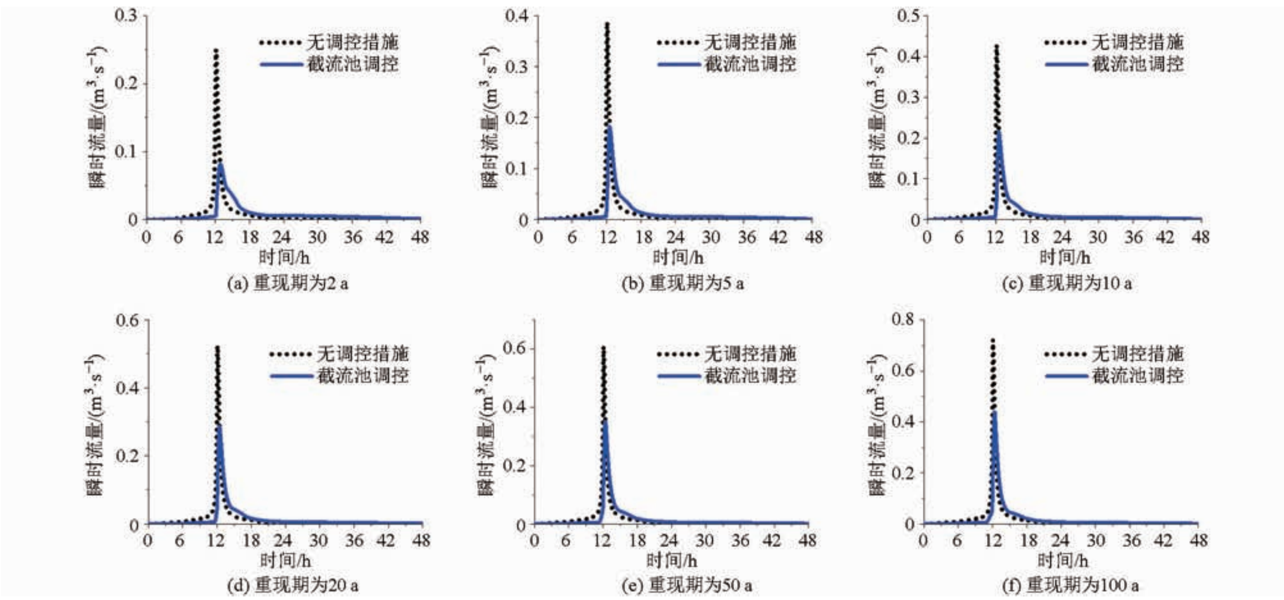

图3 不同重现期降水下截流池调控与无调控措施的流量过程曲线

Fig. 3 Uncontrolled and detention pond controlled hydrographs at different reappearance periods

流量消减率和入渗补给比例。由表4可知,当设计降水的重现期为2 a时,其洪峰流量消减率为73.67%,消减量为0.188 m^3/s;该值高于用截流池进行调控时的洪峰流量消减率及消减量。但是,随着降水量的增大,对于重现期5 a及其他重现期的降水而言,其洪峰流量消减率则低于截流池。究其原因在于入渗带主要通过暂时储存以及天然土壤的入渗来达到洪峰流量消减的目的,因此,当降水强度较小且与天然土壤入渗速率的差别较小时,其洪峰流量消减率较大;当降水强度较大且超出天然土壤的入渗速率时,入渗带无法容纳更多水量时,其洪峰流量的消减率变小,因此,入渗补给水量相应变小。入渗补给比例随着降水重现期的增大而减小,入渗水量基本保持不变。其原因在于对于重现期为2 a的降水,所产生的径流总量已经超出入渗带所能容纳的总水量。虽然当天然土壤入渗速率较小时,入渗带的洪峰流量消减率在对大的降水事件不如截流池,但是,入渗带可以促进入渗补给地下水,且降水

表4 不同重现期降水下入渗带调控性能

Tab. 4 Hydrological regulation performances of infiltration trench at different reappearance periods

重现期/a	无调控下洪峰流量/($m^3 \cdot s^{-1}$)	入渗带调控后洪峰流量/($m^3 \cdot s^{-1}$)	洪峰流量消减率/%	入渗补给比例/%
2	0.255	0.067	73.67	63.42
5	0.387	0.214	44.70	43.92
10	0.433	0.267	38.30	41.66
20	0.524	0.383	26.91	33.96
50	0.609	0.500	17.90	29.71
100	0.725	0.632	12.84	27.31

中的大部分事件为小降水事件,因此,在对地下水入渗有要求的区域,入渗带仍不失为一种良好的雨洪资源调控措施。

图4为不同重现期降水下经入渗带调控和无调控措施所产生的流量过程曲线。入渗带调控机理与截流池不同,因此,其流量过程曲线与截流池也有显著的不同。由图4可以看出,经入渗带调控后,其初始流量一直为零,直到达到某一时刻,其流量瞬间上升,此后,其流量过程曲线形状与无调控措施一致。其原因在于入渗带的模拟是通过一个100%透水性的区域来实现的,在透水性区域的可积水深度被填满之前,所有径流用以填充入渗带中卵石的空隙,而不产生地表径流;当区域的可积水深度被填满以后,其入渗速率为天然土壤饱和入渗速率,且产生径流的机制与无调控措施下产流的机制完全相同;除此之外,无调控措施下区域的入渗速率在此时也趋于其天然土壤饱和入渗速率,这是经入渗带调控后的流量过程曲线与区域无调控措施下的流量过程曲线在降水后半时段类似的原因。

3.3 透水性路面

透水性路面实际上是将不透水性区域转化为透水性区域的设计,同时提高了透水性区域的积水深度。若从实际情况出发,将该停车场修建为透水性路面,则其不透水性面积比例由原来的86%降低为38.5%,是典型的通过降低区域的不透水性面积比例减小径流量的调控方式。除此之外,由于该部分区域的可积水深度增加,其所容纳的水量将主要通过入渗的方式补给地下水,而不形成地表径流,这也是透水性路面对径流进行调控的另一个主要因素。

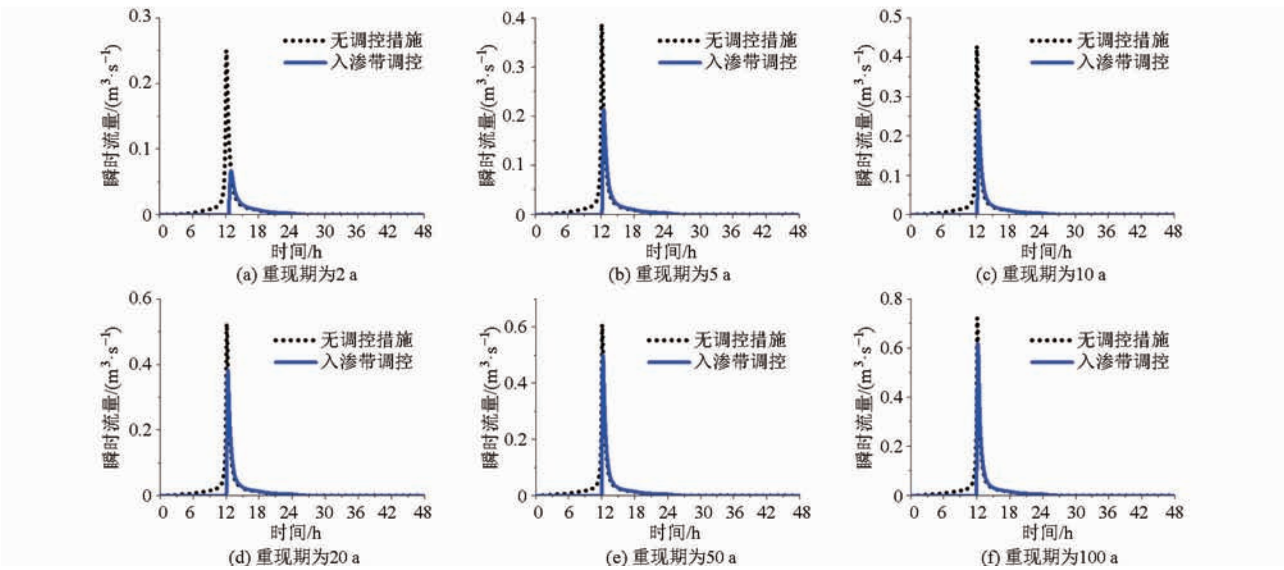

图 4　不同重现期降水下入渗带调控与无调控措施的流量过程曲线

Fig. 4　Uncontrolled and infiltration trench controlled hydrographs at different reappearance periods

为了与其他措施进行对比，本研究模拟的透水性路面面积仅为不透水性面积的 5%，且其可积水深度仅为 9.5 cm，远远小于入渗带的可积水深度，因此，当采用相同表面面积设计时，透水性路面的水文调控性能无论是针对较大降水事件还是较小降水均不显著。由表 5 可以看出，对于重现期为 2 a 的降水而言，其洪峰流量消减率为 9.73%，消减量为 0.025 m^3/s，随着降水重现期的增大，消减量由 0.025 m^3/s 增加至 0.079 m^3/s，虽然就其本身而言增加幅度较大，但与无调控措施下的洪峰流量相比仍然较小，因此，其洪峰流量消减率依不同重现期降水而有所不同，约为 10%，并未呈现确定的上升或者下降规律。同样，对于入渗水量而言，当重现期为 2 a 时，该值为 13.36 cm，重现期为 100 a 时，该值为 15.29 cm，变化幅度不大；其原因在于透水性路面的铺设面积和厚度较小，因此，所能调控的水量有限。

表 5　不同设计降水下透水性路面的调控性能

Tab. 5　Hydrological regulation performances of porous pavement at different reappearance periods

重现期/a	无调控下洪峰流量/($m^3 \cdot s^{-1}$)	透水性路面调控后洪峰流量/($m^3 \cdot s^{-1}$)	洪峰流量消减率/%	入渗补给比例/%
2	0.255	0.230	9.73	21.59
5	0.387	0.353	8.66	15.98
10	0.433	0.388	10.41	14.91
20	0.524	0.467	10.96	12.93
50	0.609	0.543	10.92	11.61
100	0.725	0.646	10.90	10.24

图 5 为不同设计降水下经透水性路面调控和无调控措施下的流量过程曲线。与表 5 所对应，其流

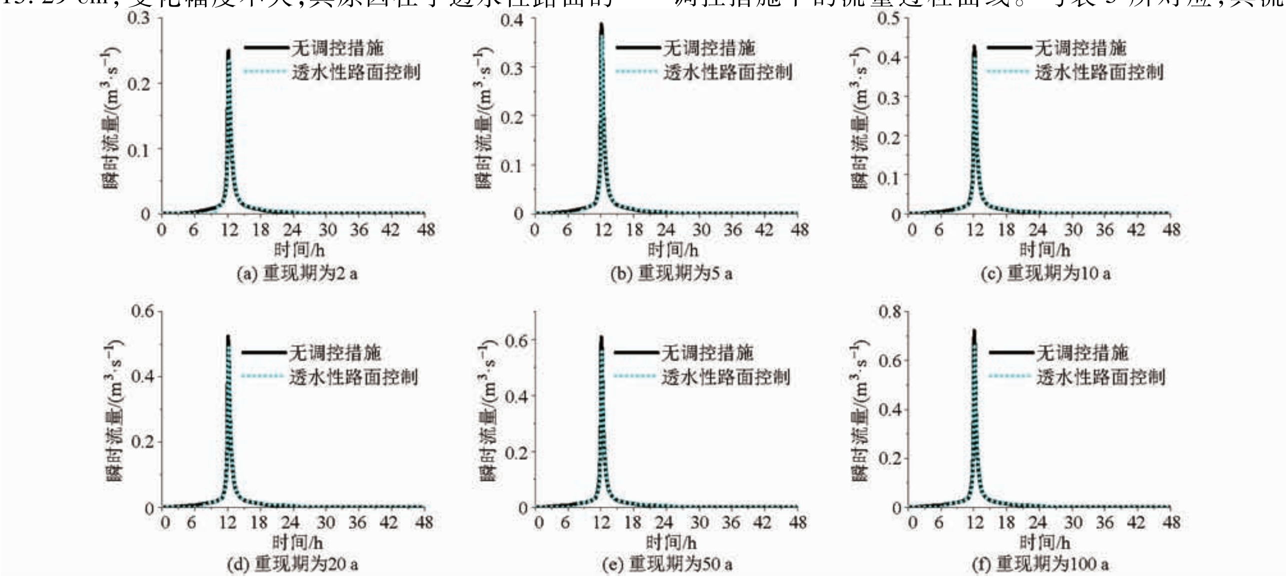

图 5　不同重现期降水下透水性路面调控与无调控措施的流量过程曲线

Fig. 5　Uncontrolled and porous pavement controlled hydrographs at different reappearance periods

量过程曲线同样反映了透水性路面的调控性能。但需说明的是，透水性路面所用的透水性混凝土材料比较昂贵，其造价远远高于截流池、入渗带以及生物滞留池，且其修建面积往往是整个停车场，因此，高修建成本很大程度地限制了透水性路面的发展，为此研究造价合理的透水性材料将成为透水性路面一个重要的研究方向。

3.4 生物滞留池

虽然生物滞留池与入渗带一样，主要通过入渗作用对径流进行调节，但是，与入渗带不同的是，生物滞留池的结构较为复杂，除入渗作用外，还包括作物根区土壤的储水作用以及植物的蒸发蒸腾作用。因此，采用 RECARGA 软件对生物滞留池的水分运动进行计算，各重现期降水下的洪峰流量消减率以及入渗补给比例模拟计算结果见表 6。由表 6 可知，对于重现期为 2 a 的降水而言，其洪峰流量消减率为 58.04%，消减量为 0.148 m^3/s，当降水重现期为 100 a 时，洪峰流量消减率变化不大，但消减量达到了 0.389 m^3/s。与此同时，入渗补给比例随着降水重现期的增大而减小；当降水重现期为 2 a 时，其入渗水量为 10.86 cm，当降水重现期为 100 a 时，其入渗水量为 10.63 cm，入渗水量并未发生大的变化。

生物滞留池的洪峰消减性能随着降水重现期的增大而增大，但是其入渗性能并未发生显著变化。其原因在于，在本研究所模拟的生物滞留池中，为了保证生物滞留池能对重现期为 10 a 的降水在 48 h 内排出，设置了排水孔，因此，当进入到生物滞留池的水量较大时，很大一部分水量会通过排水孔排出，这也是导致生物滞留池设置排水孔时能有效降低洪峰流量而不增加入渗水量的原因。

表 6 不同设计降水下生物滞留池的调控性能

Tab.6 Hydrological regulation performances of bioretention at different reappearance periods

重现期/a	无调控下洪峰流量/($m^3 \cdot s^{-1}$)	生物滞留池调控后洪峰流量/($m^3 \cdot s^{-1}$)	洪峰流量消减率/%	入渗补给比例/%
2	0.255	0.107	58.04	17.54
5	0.387	0.169	56.33	14.36
10	0.433	0.193	55.43	11.78
20	0.524	0.237	54.77	10.01
50	0.609	0.279	54.19	8.79
100	0.725	0.336	53.66	7.12

图 6 为经生物滞留池调控和无调控措施下的流量过程曲线。由图 6 可以看出，生物滞留池调控后的流量过程曲线在形状上与截流池比较接近，不同之处在于生物滞留池调控后的流量过程曲线形状相比截流池更为圆滑，其主要原因为经生物滞留池调控后的流量由两部分组成，一部分是经过排水孔流出的水量，另一部分为表面溢出水量。其中，经过排水孔流出的径流，其模拟原理与截流池中的孔是类似的，该部分决定了其流量过程线形状与截流池有相似的部分。表面溢出水量是当进入生物滞留池的径流超出其积水深度时由生物滞留池的表面直接流出的水量。该部分水量所形成的流量过程曲线相对比较平缓，且占据生物滞留池溢出水量的主要部分，因此决定了生物滞留池径流曲线总体比较平缓。相比较其他 LID 调控措施，生物滞留池同时还具有环境美化功能和显著的污染物移除功效，且相比较透水性路面而言，造价较低。虽然对重现期 2 a 降水，其入渗补给比例仅为 17.54%，但是，由于降水事件的大部分均为降水量较小的事件，因此，生物滞留池

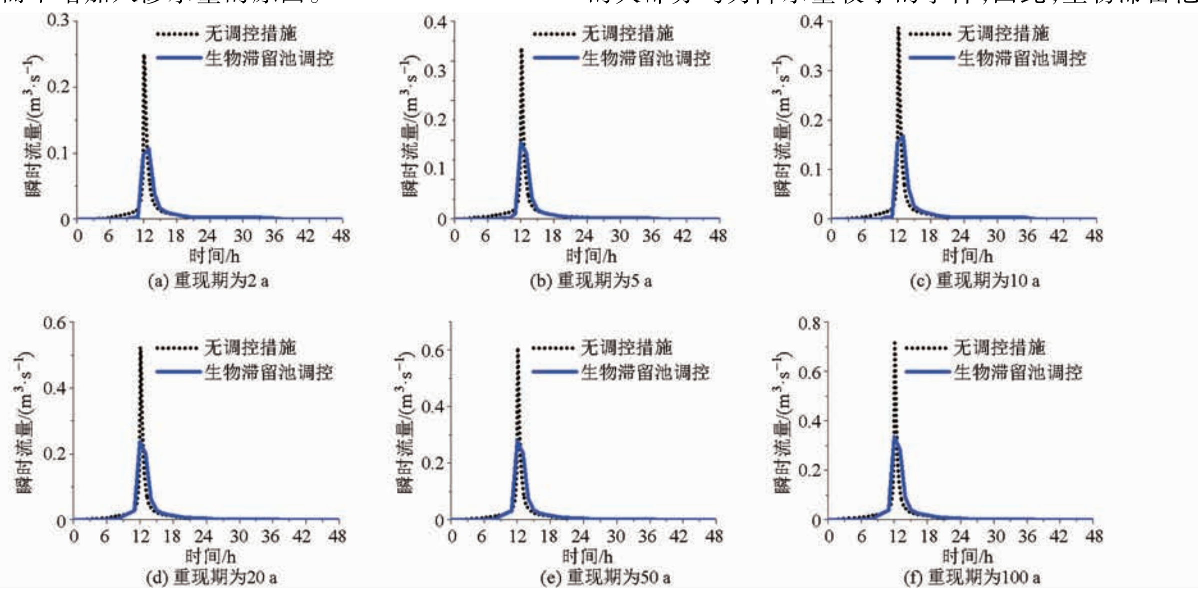

图 6 不同重现期降水下生物滞留池调控与无调控措施的流量过程曲线

Fig.6 Uncontrolled and bioretention cell controlled hydrographs at different reappearance periods

目前仍然是应用最为广泛的 LID 调控措施。

4　讨论

对各调控措施的调控性能及设计要素进行深入分析可知，决定其调控性能最主要的因素本质上为其“有效容积”，即各措施所能容纳的水量。当降水强度超出研究区的天然土壤入渗速率时，不管各措施的具体构造如何，多余的水量必然会储存在措施内部，这一部分水会依据构造的不同进行入渗或排出；超出其“有效容积”所容纳的水量将会直接形成地表径流。本研究结果表明，截流池的“有效容积”为 1 861.20 m^3，是 4 种措施中最大的，因此，其洪峰流量消减性能最好。入渗带、透水性路面和生物滞留池的“有效容积”分别为 744.48 m^3、80.37 m^3、565.14 m^3，因此，与其相对应，在这 3 种措施中，洪峰流量和入渗性能最好的为入渗带，其次为生物滞留池和透水性路面。在 LID 各措施适宜的前提条件下，本结论对于基于水文调控性能的 LID 措施修建具有指导意义。

LID 措施的水文调控性能除了与其本身设计有关外，还与区域下垫面因素、不透水性面积比例、区域天然土壤的饱和入渗速率、以及降水的历时、强度等特征密切相关；本研究分析了在 SCS II 型分布下，LID 措施随降水量的变化情况，但各 LID 措施针对不同降水特征、在不同下垫面条件下的调控性能仍需进一步深入的研究。

5　结论

（1）当设计表面面积相同时，截流池的洪峰流量消减性能最为显著，洪峰消减量随着降水重现期的增大而增大；其次为入渗带、生物滞留池和透水性路面。

（2）当设计表面面积相同时，入渗带的入渗性能最好，入渗比例随降水重现期的增大而减小，入渗水量基本保持不变；其次为生物滞留池和透水性路面。

（3）决定各措施调控性能最主要的因素本质上为其“有效容积”，即各措施所能容纳的水量。

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