

Evaluating Retention Capacity of Infiltration Rain Gardens and Their Potential Effect on Urban Stormwater Management in the Sub-Humid Loess Region of China

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Abstract Recognized as an effective low impact development (LID) practice, rain gardens have been widely advocated to be built with urban landscaping for stormwater runoff reduction through the retention and infiltration processes; but the field performance and regional effect of rain gardens have not been thoroughly investigated. In this paper, we presented a four-year monitoring study on the performance of a rain garden on stormwater retention; hydrological models were proposed to predict the potential effect of rain gardens on runoff reduction under different storms and the future urban development scenarios. The experimental rain garden was constructed in a sub-humid loess region in Xi'an, China; it has a contributing area ratio of 20:1 and depth of 15 cm. During the study period, we observed 28 large storm events, but only 5 of them caused overflow from the rain garden. The flow reduction rate for the overflow events ranged from 77 to 94 %. The runoff coefficient from the contributing area (*RC*) was reduced to less than 0.02 on annual basis, and 0.008 over the four years average. Field observations also showed that infiltration rate remained stable during the operation period. The predictions based on the future landuse and storm variability of the study area showed that by converting a small fraction of the city land area into rain gardens, the negative hydrological effect from expansion of impervious area can be reduced significantly. The challenge, however, lies in how to plan and build rain gardens as an integral part of the urban landscape.

Keywords Rain garden · Storm runoff · Design storm · Infiltration · Overflow · LID

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1 Introduction

The negative impact of urban sprawl on regional hydrological cycle has become a worldwide concern (Tsihrintzis and Hamid 1997; He et al. 2009). and searching for practical stormwater management measures to meet the Low Impact Development (LID) requirement is urgently needed for urban water resources management (Dietz 2007; Davis et al. 2011; Ravagnani et al. 2009). Localized bioretention facilities, including rain gardens that receive stormwater runoff from surrounding areas have been found effective in treating stormwater runoff in urban areas (Davis et al. 2009; Roy-Poirier et al. 2010; Trowsdale and Simcock 2011). These facilities can be easily constructed with the city landscape to make them an integral part of the city drainage system, and the growing plants provide aesthetic attractions besides their functions in absorbing some pollutants and modifying the soil hydrology.

Various studies have shown that rain gardens are effective in flow retention and pollutants removal (Dietz and Clausen 2005; Hunt et al. 2006; Davis 2008; Zhang and Guo 2014). The reported flow reduction with rain gardens ranged from 46 % to 100 % as affected by seasonal difference and storm characteristics (Hunt et al. 2006). The observed peak flow reductions were between 49 and 80 % from different rain gardens (Hatt et al. 2009). Brown and Hunt (2011) studied stormwater retention from two bioretention cells of different media depth, they found that larger depth resulted in greater flow volume reduction. DeBusk and Wynn (2011) studied a retrofit bioretention cell treating a parking lot runoff, they found that the cumulative volume reduction reach 97 % for the 28 observed storm events. Davis (2008) reported a monitoring study on flow reduction through two bioretention cells; for the recorded 49 runoff events in nearly 2 years, the observed flow peak reductions ranged from 44 % to 63 %, satisfying the LID goals for storm water management.

As the retention capacity of a rain garden partially depends on infiltration capacity of its soil media, it is important to sustain infiltration rate of a functional rain garden. But frequent inflows of stormwater runoff pose a potential threat to soil clogging from deposition of fine particles. Some laboratory scale studies have shown that clogging of the filter media by fine particles will occur with time as result of the stormwater characteristics and consequently reduce infiltration rate of the filter (Siriwardene et al. 2007; Kandra et al. 2014, 2015). A few field studies, however, indicate that accumulation of fine particles may not necessarily result in decrease of infiltration rates of rain gardens, thanks to the development of plant roots and macro pores in the soil medium (Jenkins et al. 2010; Le Coustumer et al. 2012).

Current studies on rain garden mostly focused on the performance of individual facilities, which achieve hydrological benefits through storage and infiltration of storm runoff; the regional effect of rain gardens in retaining storm runoff and their long-term use have not been paid enough attention. Research by Endreny and Collins (2009) showed that the regional effect of rain gardens is closely associated with the distribution of such facilities.

Existing field studies on the hydrological effects of rain gardens were mostly conducted over a short time period. Considering the climate variability and the soil and vegetation changes, long term monitoring of the rain garden flow processes is important for proper evaluation of the system performance, and validating hydrological models, which can be subsequently used for predicting hydrological impact of rain garden constructions on urban stormwater runoff reduction.

In this paper, we present a research on the effects of rain garden constructions on stormwater control from both local and regional scales based on a four year field experiment

of infiltrating stormwater runoff with a rain garden in Xi'an, China (E107.40 ~ 109.49 °, N 33.42 ~ 34.45°) (Fig. 1). The objectives of this research were to:

- 1) Assess the effectiveness of an infiltration rain garden in runoff retention from intensive storms in different years,
- 2) Estimate the effect of rain garden installation on reducing *RC* of the contributing area under both individual storm events and long term records, and
- 3) Predict the effect of different rain garden installations on reducing regional *RC* under future projections of the city development and storm variability.

2 Materials and Methods

2.1 Site Description and Data Collection

As shown in Fig. 1, the experimental rain garden was built on campus of Xi'an University of Technology in Xi'an, China in spring 2011. Xi'an is located at the southern edge of the vast Loess Plateau of the Northwestern China; it has a temperate continental climate with annual mean temperature of 13.3 °C (degree centigrade). The mean annual precipitation in recent 60 years was 554 mm, ranging from 312 mm in 1995 to 903 mm in 1983. Normally, 60 % of rainfall occurs between July and September. Summer rainfall events typically exhibit short duration and high intensity. Table 1 lists rainfall intensity values for storms of different durations and recurrence intervals that are normally used for the city storm drainage design in Xi'an (Lu et al. 2010). The natural rainfall pattern in Xi'an generally coincides with the plant evapotranspiration process, making the city an attractive place for early settlers; but the rapid urban sprawl in recent decades has prevented natural rainfall from recharging the soil reservoir, groundwater table in the city range has fallen to an average depth of 10 m, water shortage and land subsidence have become serious problems in the area.

As shown in Fig. 1, the rain garden was built next to an old house with a gable roof, and runoff from one side of the roof was diverted to the garden through a cement gutter on the ground. The garden has a retention depth of 15 cm and surface area of 30.2 m². The runoff contributing roof area was 604.7 m², making the flow contributing area to the rain garden surface area ratio as 20:1 (or the rain garden size factor as 0.05). Two V-notch weirs, one 45-degree and another 30-degree, were installed at the inlet and outlet of the rain garden for inflow and outflow measurement; hydraulic heads over the weir crest were measured by pressure transducers. A staff gauge was installed in the garden to measure water level change with time. Rainfall was recorded by a weather station about 100 m from the site. Between 2011 and 2014, we monitored 29 storm events, and measured the infiltration process 8 times.

2.2 Flow Retention by the Rain Garden for Individual Storm Events

As an engineering structure, a rain garden is designed to retain runoff from the contributing area of a design storm, and allow excessive runoff from more intense storms to bypass the rain

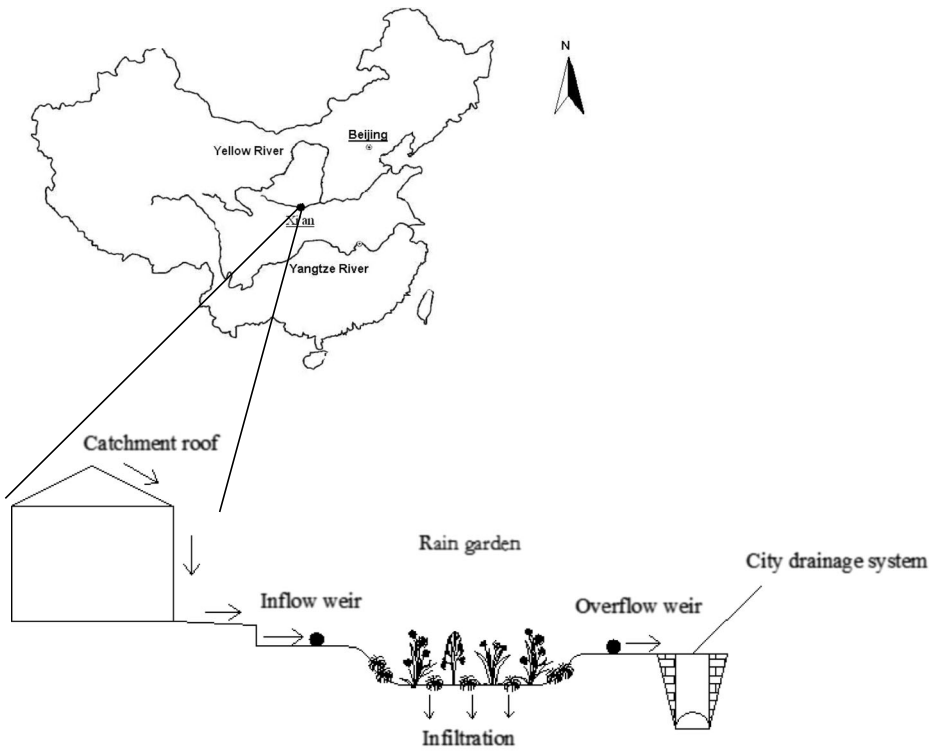


Fig. 1 The general location of study area and the experimental setup in Xi'an, China; the photo at bottom shows the rain garden after vegetation establishment (E107.40 ~ 109.49 °, N 33.42 ~ 34.45°)

garden as outflow. The effect of flow retention by a rain garden from an individual storm event can be evaluated by a flow reduction rate (ξ_{rg}) as:

$$\xi_{rg} = 1 - w_{out} / w_{in} \tag{1}$$

Where w_{in} is the inflow and w_{out} is the overflow of the rain garden.

Table 1 Rainfall intensity for different recurrence intervals and durations in Xi'an, China (mm/min)

Recurrence interval (yr)	Rainfall duration (min)				
	5	20	30	60	120
20	2.403	1.492	1.179	0.741	0.411
10	2.069	1.281	1.013	0.638	0.358
5	1.736	1.070	0.848	0.536	0.304
3	1.491	0.914	0.726	0.460	0.265
2	1.296	0.791	0.630	0.400	0.234
1	0.963	0.580	0.464	0.298	0.181
0.5	0.629	0.369	0.299	0.195	0.128

The rain garden inflow (w_{in}) can be estimated as:

$$w_{in} = W_t \psi \tag{2}$$

Where W_t is the total storm depth and ψ is the runoff coefficient (RC) of the flow contributing area.

A rain garden serves as a hydrological sink for its contributing area, so the RC of the area can be seen as being reduced to a new value (ψ_{rg}) as:

$$\psi_{rg} = \xi_{rg} \psi \tag{3}$$

Municipal storm drainage facilities are normally sized by design storms that are defined by the intensity (i), duration (T) and frequency (f) relationship, or IDF curves. The intensity is often taken as the average value over the entire storm duration. By such concept, we derived a simple model to represent the relationship between flow retention and rain garden design parameters under different storms. Assuming that flow concentration time is negligible, the rain garden inflow rate (I_{in}), expressed as depth of water over the rain garden surface area can be calculated as:

$$I_{in} = i \psi s \tag{4}$$

Where s is the ratio of the flow contributing area over the rain garden surface area.

Assuming that the rain garden has a constant infiltration rate (K), and including the rainfall over the rain garden surface, we define an excess inflow rate (I') as:

$$I' = I_{in} + i - K \tag{5}$$

The excess flow will build up in the rain garden, and the ponding depth (H') before overflowing is simply the product of I' and the storm lapsing time (t):

$$H = I' t \tag{6}$$

The design storm is defined as a storm that just fills up the rain garden without any overflow. Denote T^* as the design storm duration, the retention depth (H^*) of a rain garden besides infiltration can be calculated as:

$$H^* = I' T^* \tag{7}$$

Under the larger than the design storm events, the rain garden overflow starting time (t') and lasting time (t) can be calculated with the following equations:

$$t' = H^* / I' \tag{8}$$

$$t = T - t' \tag{9}$$

The overflow depth over rain garden surface area can be calculated as:

$$I_{out} = I' (T - t') \tag{10}$$

Substituting the above relationships into Eq. 3, the reduced RC (ψ_{rg}) of the controlling area can be further written as:

$$\psi_{rg} = (I' T - H^*) / siT$$

or

$$\psi_{rg} = [(i(1+\psi_s) - K)T - H^*] / siT \tag{11}$$

Note that the above derivation is for individual storm event only. For storms that are less intensive than the design storm, the rain garden will be partially empty, or has no ponding water at all. One of the key parameters, the infiltration rate can be determined either with an infiltrometer or through field measurements of water balance in the rain garden. As introduced earlier, the study area has a very deep water table (>3 m), which allows free infiltration in the rain garden. So by assuming a unit hydraulic gradient, the general water balance for a rain garden as shown in Fig. 1 in a time period Δt can be written as:

$$w_{in} = \Delta H \cdot A_{rg} + K \cdot A_{rg} \cdot \Delta t + w_{out} \tag{12}$$

Where A_{rg} is the rain garden surface area, ΔH is the change in ponding depth.

The average infiltration rate during Δt can be calculated as:

$$K = \frac{w_{in} - \Delta H \cdot A_{rg} - w_{out}}{A_{rg} \cdot \Delta t} \tag{13}$$

The above analytical models/equations were built on several simplifications, such as the IDF assumption for a storm process, constant infiltration, and negligible influence of antecedent soil moisture and flow concentration time in the rain garden. To examine the validity of the model, we compared the model predictions with observed overflow events in terms of the number of overflow events, overflow volumes and timings.

2.3 The Long-Term Effect of the Flow Retention by Rain Gardens

Initially the flow monitoring in the rain garden targeted the medium to large storm events referring to the weather forecast, the small storms that caused little ponding in the rain garden were skipped. During the experiment, the overflowing events were found rare for the rain

garden configuration. To overcome the shortcoming of using the flow reduction rate as defined in Eq. 2, we proposed an average reduced runoff coefficient ($\overline{\psi_{rg}}$) for the contributing area to estimate the long-term flow retention effect of rain gardens. Assuming there are totally n rainfall events, among which m events caused rain garden overflow, thus the $\overline{\psi_{rg}}$ with rain garden installations can be calculated as:

$$\overline{\psi_{rg}} = \frac{\sum_{i=1}^m w_{out,i}}{\sum_{j=1}^n W_{t,j}} \tag{14}$$

Where $\sum_{i=1}^m w_{out,i}$ is the total overflow volume from the rain garden, and $\sum_{j=1}^n W_{t,j}$ is the total storm volume from the contributing area. Because n is expected to be much larger than m , lower values of $\overline{\psi_{rg}}$ can be expected comparing with the event-based ψ_{rg} (Sect. 2.2) owing to full retention of smaller storms.

For urbanized areas, rain gardens distributed over the largely impervious land surfaces act like many small hydrologic sinks that effectively reduce stormwater runoff from the contributing areas. Assume that the urban land areas can be simply classified as pervious and impervious types, or mathematically written as:

$$A_t = A_p + A_{imp} \tag{15}$$

Where A_t is the total urban area, A_p is the pervious land area, and A_{imp} is the impervious land area. Recognizing the fact that rain garden installations in some urban areas may be constrained by land availability, economics or other factors, the impervious area (A_{imp}) can be further partitioned into with and without rain gardens, or:

$$A_{imp} = A_{imp-no} + A_{imp-rg} \tag{16}$$

Where A_{imp-rg} is the area with rain gardens and A_{imp-no} is the area without rain garden installation. Thus the overall runoff coefficient (ψ_t) can be computed as an area-weighted average as:

$$\overline{\psi_t} = (\psi_p A_p + \overline{\psi_{rg}} A_{imp-rg} + \psi A_{imp-no}) / A_t \tag{17}$$

Where, ψ_p is the RC of the pervious surface areas. The RC for the impervious area uncontrolled by rain gardens remains to be ψ .

2.3.1 Current and the Projected Landuses of the Study Area

Based on the observed inflow and outflow processes of the experimental rain garden, we estimated the hydrological effects from different rain garden installations in the study area considering the long-term projections of urban landuse and storm intensity change. According to local statistics, the landuse in Xi'an has changed dramatically in the last three decades; the impervious surfaces increased rapidly due to housing development and road construction. Table 2 lists the landuse data for the metropolitan area derived from several sources (Li 2006; Guo and Ren 2009; XALR 2013). The residential area was separated from the total impervious area, and the green space from the total pervious area. We assume that the residential area is the most suitable place for rain garden installation in the impervious urban area, and stormwater

Table 2 Historical record and projected future land cover types in Xi'an, China

	Impervious surface (%)			Pervious surface (%)		
	Residential	Others ^a	Subtotal	Green space ^b	Others ^c	Subtotal
1996†	17.40	18.80	36.20	14.10	49.70	63.80
1999†	19.80	18.70	38.60	18.90	42.60	61.40
2001†	22.00	19.00	41.00	21.00	38.10	59.00
2004†	25.90	19.60	45.50	22.30	32.20	54.50
2007†	28.70	19.50	48.20	23.70	28.10	51.80
2013 ^d	29.30	25.10	54.30	24.20	21.50	45.70
2023 ^e	32.00	27.40	59.40	26.40	14.20	40.60

† The data from 1996 to 2007 were based on previous studies (Guo and Ren 2009; Li 2006, XALR 2013),

^a Mainly consists of traffic roads,

^b Including green space in residential area,

^c Mainly agricultural field (orchards), undeveloped area and woodland,

^d Projection based on the rate from 2007 to 2013,

^e Projected

runoff can be collected for groundwater recharge through rain garden infiltration. The 'other pervious' area listed in Table 2 refers to the agricultural lands (including orchards) and some unused land. Guo and Ren (2009) reported that nearly 50 % of the metropolitan area was either agricultural or unused land in 1988; the recent expansion of impervious and green space came mostly from converting these areas.

The residential area change over years can be calculated with a simple exponential model as below:

$$A(t) = A_0 r^t \quad (18)$$

Where A_0 is the initial residential area, $A(t)$ is the residential area in year t , and r is the annual growth rate of residential area.

Based on the available data as listed in Table 2, the average annual growth rate of the residential areas was 1.021 between 1996 and 1999, 1.031 between 1999 and 2001, 1.035 between 2001 and 2007, and 1.020 between 2007 and 2013. From 1996 to 2013, the impervious surface increased from 36 to 54 % of the whole area. The urban sprawl across China reached the maximum speed in late 2000, and then slowed down due to the environmental concerns in many large cities. Assume that the urban expansion will end in 10 years from 2013, and with a gradually slowing growth rate, we calculated the projected land cover areas for Xi'an as listed in Table 2.

2.3.2 Current and the Projected Storm Intensity Variations

The storm intensity may negatively affect flow retention in rain gardens as indicated by Eq. 13. Since the long-term data on storms of shorter durations are not available, we used annual maximal 24-h storm intensities to estimate the effect of potential storm intensity changes in the future on rain garden performance. Figure 2a presents the maximum 24-h storm intensities from 1951 to 2006 in Xi'an, China; these data showed fluctuations over short

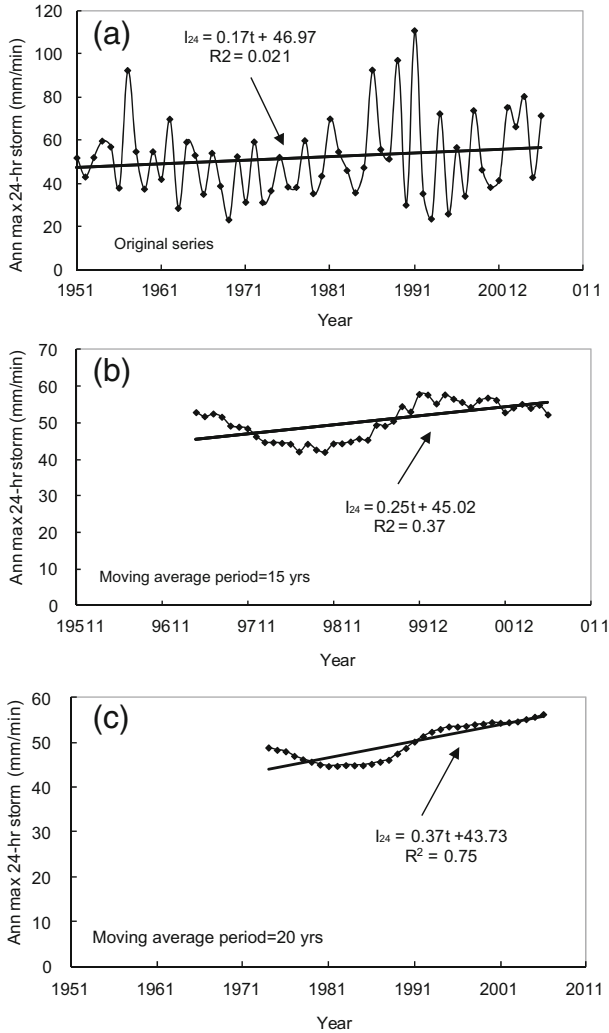


Fig. 2 Regressions for observed maximal 24-h storms (a) and two moving average periods (15 and 20 yrs) (b and c)

term and long-term period. Linear regression for the entire data series as shown in Fig. 2a yielded the following equation:

$$I_{24} = 0.17t + 46.97, R^2 = 0.021 \tag{19}$$

Where I_{24} is the annual maximal 24-h intensity in mm/min, and t is the number of years from 1951.

Equation 19 predicted a 3 % increase in storm intensity over 10 years. However, the low value of R^2 (0.021) indicates that the correlation relationship was very poor due to short-term fluctuation. So we employed the moving average method to filter out the short-term interferences. After a few trials with different time periods, averages over periods of 15 yrs. and

20 yrs. resulted in better regression relationships as shown in Fig. 2b and c. The regression equations for processed data of 15- and 20-yr. moving average periods are:

$$\text{Period} = 15\text{yrs} : I_{24} = 0.25t + 46.19; R^2 = 0.36 \tag{20a}$$

$$\text{Period} = 20\text{yrs} : I_{24} = 0.37t + 73.73; R^2 = 0.75 \tag{20b}$$

With Eq. 20, the predicted storm intensity in 10 years increased by 4–6 % over the current level; so we used a 5 % increase over 10 yrs. in the study.

2.3.3 Scenarios for Future Prediction

Based on the current situations and future projections on land use and storm variability in the study area, we predicted the effect of rain garden installations on regional stormwater reduction for different scenarios as listed below:

- I) The impervious surface area remains unchanged at the present level as in 2013, or 54.3 % of the total city area;
- II) The impervious area will increase by 5 %, from present 54.3 % to 59.4 % of the total city area by 2023 as listed in Table 2;
- III) The future storm intensity will increase such that the retention capacity of rain gardens will be reduced by 5 % as predicted by Eq. 13;
- IV) The projected 5 % increase in storm intensity will result in certain increase in RC of the rain garden controlled area as predicted by Eq. 11,

3 Results and Discussion

3.1 Experimental Results

3.1.1 Observed Storms, Overflow and Runoff Retention

In nearly 4 years’ operation of the experimental rain garden, we observed the inflow and outflow processes of 28 storms. As presented in Fig. 3, among the observed storms, 5 of them

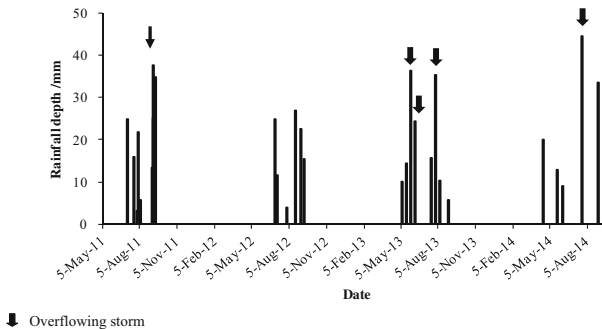


Fig. 3 Measured storm events from 2011 to 2014

caused overflow from the rain garden, including one in 2011 (Sept. 28), 3 in 2013 (May 28, June 8, July 28) and 1 in 2014 (July 22). We missed measuring overflow volume for the event on Sept. 28, 2011, so we estimated the volume by comparing it with a similar storm on May 28, 2013. Figure 4 present the four measured overflow processes along with the inflows. The percentages of flow retention during the four storms were 94, 78, 78, and 77 %, respectively. The RC from the contributing area was between 0.53 and 0.68 during the 4 storm events; with the rain garden, however, the reduced RCs (ψ_{rg}) were found to be between 0.04 and 0.15.

There was no overflow occurred in 2012, indicating that RC from the rain garden controlled area was essentially zero. Table 3 lists the reduced RC (ψ_{rg}) for each year from 2011 to 2014, the average value was only 0.009, which is much smaller than RC (ψ_{rg}) for the individual overflow storms. Among the 4 year monitoring period, 2011 (656 mm) and 2014 (698 mm) had higher than average (596 mm) rainfall, while 2012 (383 mm) and 2013 (455 mm) had lower than average rainfall. Though the year 2012 was relatively dry, it had three large storms that generated overflow from the rain garden, and the annual RC (ψ_{rg}) was 0.022, the highest in the 4 years.

Figure 5 shows that the storms that caused rain garden overflow were generally intense rainfall over short time period. The rainfall record shows that these intense rainfall periods rarely lasted longer than 60 min, so we computed the rainfall intensity of 60 min duration for all observed events based on the storm record as shown in Fig. 4. As expected, for the rain garden overflow events, the storms had the highest intensities of the 60 min duration. Although a wet year is more likely to have large storms, our observations showed that the high intensity storms occurred over a short time period are more likely to cause rain garden overflow. For the five overflow events, the recorded daily rainfall depth was only 24.2 mm, 25.2 mm, 35.2 mm, 36.4 mm and 44.6 mm, respectively, ranking 17, 19, 23, 24 and 26th among the 29 observed storms. Conversely, two recorded storm events with daily rainfall depth of 51.8 mm and 53.2 mm did not cause any overflow from the rain garden due to their long durations. The recorded maximum daily (24-h) rainfall was 53.2 mm on Sep. 11, 2011. This storm event, however, did not result in any overflow in the rain garden due to its long duration. The average intensity of this storm was only 53.2 mm/d, which is equivalent to a total inflow of 1064 mm/d over the rain garden area considering the flow contributing area ratio. This inflow rate is much smaller than the measured infiltration capacity (2500 mm/d) of the rain garden. The deep water table in the study area also provided ample storage space for stormwater infiltration in the soil profile.

The generally available rainfall data are the daily record values, and the 24-h storms are normally used for rain garden design. Our field observations indicate that using 24-h storms is sufficient for evaluating hydrological processes of rain gardens, the potential rain garden overflow events may not be predicted correctly.

The total retention volume of a rain garden for a storm of duration T is essentially $(H^* + KT)A_{rg}$, including the infiltration and the storage in the rain garden. It is a constant for storms of the same duration, but less retention for more intensive storms. Based on the storm characteristics in the study area as listed in Table 1, we computed the rain garden overflow volume and flow reduction rate as the percentage of the total inflow, and examined the effect of infiltration process on overflow processes in the following text.

Comparing with the undeveloped, bare surface land area, the advantage of rain gardens constructions is the storage capacity for concentrated stormwater runoff, although rain garden depths are normally around 20–30 cm (and 15 cm in our case study). Referring to the storms of

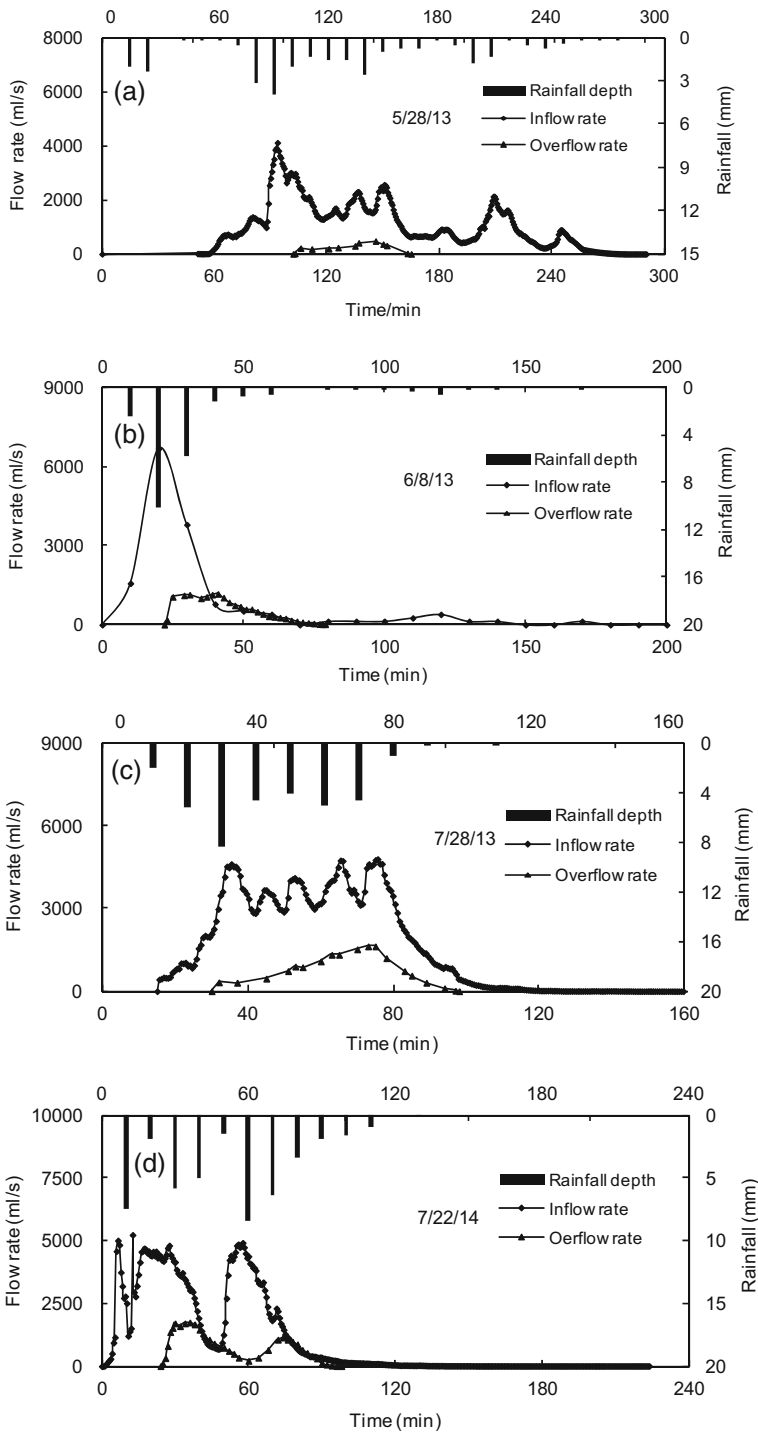


Fig. 4 Measured four rain garden overflow storm events, during which flow reductions were: **a** 93.8 %, **b** 77.6 %, **c** 77.8 %, and **d** 76.6 %, respectively

Table 3 Annual runoff coefficient of the contributing area with rain garden installation

Year	Rainfall depth (mm) ^a	Overflow depth (mm) ^a	Annual flow reduction with RG (%) ^b	Contribut. area RC (RC_{rg}) ^c
2011	656	3.21	99.5	0.005
2012	383	0.00	100.0	0.000
2013	455	10.54	97.9	0.021
2014	698	5.26	99.2	0.008
Avg	548	4.50	99.2	0.008

^a Over the contributing area

^b The overflow over the inflow for the rain garden

^c For the contributing area, and the original RC was 0.68

different intensities and durations in the study area as listed in Table 1, for the experimental rain garden with storage depth of 15 cm and infiltration capacity of 2.53 m/d, the total water retention depth in 60 min was 36.1 cm (i.e., $15 + 253/12$), which is equivalent to fully retaining a storm depth of 18 mm considering the contributing area ratio of 20: 1. According to the storm characteristic data listed in Table 1, the experimental rain garden can retain storms of 0.5 yr. recurrence interval of all three durations; or storms of 1 yr. recurrence interval of the 45 min and the 60 min durations. For the storm of 1 yr. recurrence interval and 90 min duration, there would be 0.2 cm overflow from the rain garden, accounting for 10 % of the total storm. For storms of 2-yr. recurrence interval, the potential rain garden overflow for storm durations of 30, 60 and 90 min would be 0.4 cm, 0.6 cm and 0.8 cm, respectively, accounting for 18 %, 25 %, and 31 % of the total storm depths.

The above calculations somehow underestimated the holding capacity of the rain garden, because the calculations assumed steady state infiltration and ignored the rapid infiltration at the initial stage. Even so, the results showed that the rain garden reduced the stormwater runoff significantly. Note that the above analyses were conducted for the intense storms, which are considered ‘rare’ in the study area. In the four year monitoring period, only four overflow events was observed in the experimental rain garden, showing the effectiveness of adopting such simple bioretention devices in stormwater management.

The calculated high ratio of flow retention and the sustained retention effect of the rain garden during the monitoring period were based on two conditions, i.e., 1) the groundwater table is deep enough to provide adequate storage space for stormwater infiltration; and 2) the

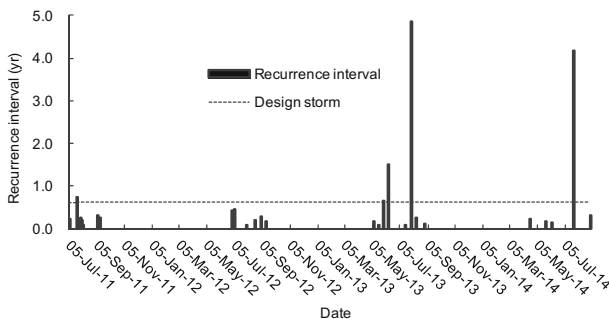


Fig. 5 The storm recurrence intervals for 60 min duration for the observed intense storms

ponded water can infiltrate in a reasonably short time to empty the rain garden for next storm. The rain garden infiltration will be discussed later in more detail.

3.1.2 Sustainability of the Rain Garden Infiltration Capacity

The sustainability of the rain garden infiltration capacity was assessed by measuring the stabilized infiltration rates to detect potential declining factors. Also, surface soil sampling was conducted to examine whether fine particles were deposited to reduce soil infiltration over time. Between 2011 and 2014, the infiltration rates in the rain garden was measured 9 times in different seasons, the infiltration capacity, or the steady infiltration rate ranges from 2.12 to 2.78 m/d; the average infiltration capacity was 2.37 m/d with a small variation of 0.2 m/d. Apparently, the infiltration capacity of the rain garden remained relatively stable in the 4 year operation period. The rain garden was planted with several perennials, including the Black Eyed Susan (*Rudbeckia laciniata*) and the Chinese Rose (*Rosa Chinensis*), the growth of these deep rooted plants may have contributed to macropore development in the soil and sustained the infiltration capacity of the rain garden. Similar findings were reported by Jenkins et al. (2010).

3.2 Validation of the Flow Retention Model

The analytical model for rain garden flow retention was based on several assumptions as mentioned in Section 2. To validate the model, we firstly examined the agreement of the predicted overflow occurrence with the real condition, and then compared the predicted overflow volumes and timings with the observed values. Because the experimental rain garden was built on an available space without a pre-determined design storm, its design storm can only be backtracked. The measured infiltration rate in the rain garden was 2.4 m/d, and the runoff coefficient of the contributing area was 0.69. The ‘design storm’ intensities for durations of 60 min was calculated with Eq. 5, and the corresponding recurrence intervals was estimated by interpolating from the regional storm characteristic data as listed in Table 1. Thus we obtained the design storm for the experimental rain garden as 0.62 yr. recurrence interval for 60 min duration.

If the proposed model was accurate, it would predict overflow from the rain garden during events that are larger than the design storm. Figure 5 presents frequencies of the observed storms. Comparing with the design storm, the rain garden would produce overflow during four storm events (one in 2011 and three in 2013) in 60 min duration as presented in Fig. 5. The field observations on overflow events agreed well with the model predictions, indicating good accuracy of the proposed model in predicting overflow events for real storm processes.

Table 4 lists 4 large storm events, which overflow was observed in the experimental rain garden. The results showed that the predicted overflow volume was generally in good agreement with the field measurement. For the storm event on May 28, 2013, the predicted overflow at 60 min was zero, while the measured volume was merely 25.2 L; for the other three events that exceeded the design storm duration of 60 min, the relative errors between the predicted and the measured overflow volume was -16.1% , -15.0% , and -13.3% , respectively. The overflow starting time was predicted less accurate due to the variable rainfall pattern; the absolute difference between the predicted and observed time was between 7.7 and 19.0 min, while the relative error ranges from -30.8% to -111.8% , indicating that the proposed model generally predicted earlier occurrence of rain garden overflow volume.

Table 4 Measured and calculated overflow starting time and volume in 60 min duration of the four intense storms

Date	Average rainfall intensity (mm/min)	Return period (yr)	Overflow starting time (min)			Overflow volume (L)		
			Measured	Calculated	Mean error	Measured	Calculated	Mean error
2013.05.28	0.230	0.67	44.0	69.0	-56.8 %	25.2	0.0	100.0 %
2013.06.08	0.350	1.51	17.0	36.0	-111.8 %	3556.1	2982.5	16.1 %
2013.07.28	0.530	4.84	23.0	24.0	-4.3 %	5964.8	6862.3	-15.0 %
2014.07.22	0.505	4.18	25.0	32.7	-30.8 %	3344.7	3791.1	-13.3 %

Although the initial infiltration rate is usually higher before soil gets saturated, the analytical model assumed constant infiltration rate in the rain garden, considering the high inflow rate to rain gardens often saturates the soil in very short time. The close agreement between the predicted results with the field observations as presented above indicates that the error from using constant infiltration rate was not significant. Table 5 lists the relative error in cumulative infiltration depth between the calculated and the measured values. These errors ranged from -35 % in 28 min and -2 % in 12 min observation period. The weighted average error over all time periods was only -6.9 %. The largest error was -35 % for the event on July 28, 2013. This was the result of using constant infiltration rate in the prediction model; there were 6 dry days before the storm event, and the air temperature was the highest of the year; the dry soil surface led to the higher infiltration rate initially, then stabilized gradually with time. During the other six events, the infiltration rate reached a stable value within 20 min, resulting in relative small errors between predictions and observations.

3.3 Predicted Regional Impact of Rain Garden Installations

Figure 6 presents the regional impact of different rain garden installations for the four scenarios listed in Sect. 2.3. The average runoff coefficient was assumed 0.25 for the natural land surface and 0.85 for the paved impervious surfaces. In the above analyses, we have shown that increasing storm intensity by 5 % will result in ψ_{rg} of the contributing area increasing slightly from current 0.008 to 0.009. Figure 6 shows that the two lines representing the present and the future contributing area runoff coefficients (ψ_{rg}) are almost indifferent; indicating that the

Table 5 Relative error of cumulative infiltration calculated with the steady state infiltration rate

No.	Date measured	Measured, V_m (m ³)	Estimated by steady infil. Rate, V_e (m ³)	Relative error, $(V_e - V_m)/V_m$
1	2012/6	8.5	9.5	12 %
2	2013/5	2.0	2.0	-2 %
3	2013/5	7.8	6.4	-17 %
4	2013/6	13.8	11.4	-18 %
5	2013/7	7.1	4.6	-35 %
6	2013/10	5.2	4.8	-8 %
7	2014/7	9.9	10.5	6 %
Average				-6.9 %

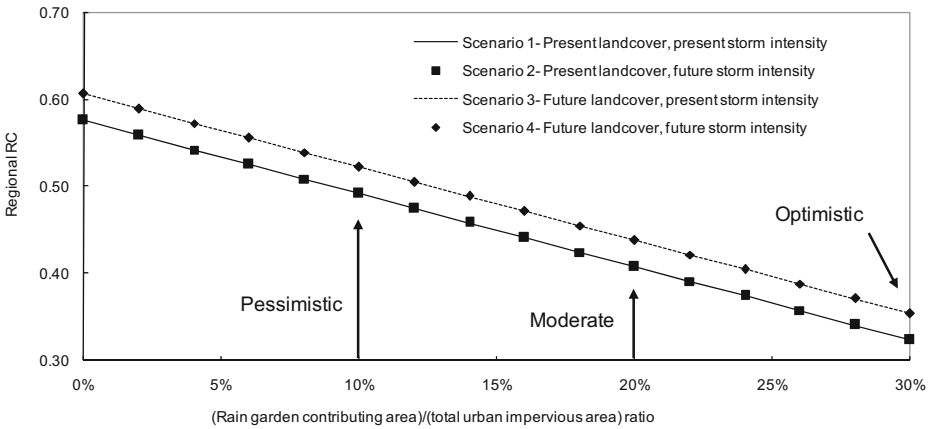


Fig. 6 Regional runoff coefficient under different landuse and storm intensity scenarios

effect of storm intensity change can be ignored for regional hydrologic evaluation. Without taking any storm retention measures, the increase in impervious surface area will cause the overall ψ_t to increase from 0.58 to 0.61. Such effect can be offset by converting merely 3 % of the impervious surface to rain gardens. This is equivalent to 132 ha rain garden construction area in the study area, i.e., the city Xi'an, which has a metropolitan area of 881 km².

From Eq. 16, the change in the runoff coefficient of the contributing area in relation to the change in contributing area can be expressed as:

$$d\psi_t/dA_{imp-RG} = (\psi_{imp} - \psi_{rg})/A_t \tag{21}$$

For the current pervious to impervious surface area ratio in Xi'an, 1 % increase in rain garden controlled area will reduce the regional runoff coefficient by 0.0077. This indicates that the change in the overall runoff coefficient (ψ_t) is linear to the rain garden controlled impervious surface. For the three different scenarios listed in Section 2.3.3, we predicted the hydrological impacts of rain garden (with contributing areal ratio of 20:1) installations as bellow:

- 1) Pessimistic goal: to drain storm runoff from 10 % of the total urban area into rain gardens. For the current landuse, the impervious surface covers about 54.3 % of the total urban area, reducing the regional runoff coefficient (ψ_t) from current 0.58 to 0.49 will require constructing rain gardens area of 441 ha, accounting for 0.5 % of the total urban area;

For the future landuse pattern, the impervious surface covers 59.3 % of the total urban area; the same rain garden construction will reduce the regional runoff coefficient (ψ_t) to 0.52;

- 2) Moderate goal: to drain storm runoff from 20 % of the total urban area into rain gardens.

For the current landuse pattern, this will reduce the regional runoff coefficient (ψ_t) from current 0.58 to 0.41, requiring a rain garden area of 881 ha, accounting for 1.0 % of the total urban area. For the future landuse pattern, this will reduce the regional runoff coefficient (ψ_t) to 0.44;

- 3) Optimistic goal: to drain storm runoff from 30 % of total urban area into rain gardens.

For the current landuse, this will reduce the regional runoff coefficient (ψ_r) from current 0.58 to 0.35, requiring a rain garden area of 13.22 ha, accounting for 1.5 % of the total urban area. For the future landuse pattern, this will reduce the regional runoff coefficient (ψ_r) to 0.35.

Note that, even for the optimistic goal, the percentage of total rain garden drained impervious area (30 %) is lower than the future residential area ratio, which is 32 % in 2023 (Table 2). The moderate goal scenario requires less than 2/3 of the total residential area, and the pessimistic goal requires 1/3 of the total residential area to be facilitated with rain gardens.

Above analysis showed that rain gardens can be extremely effective in reducing stormwater runoff in the study area; they can significantly mitigate the negative effect of urbanization on regional hydrology. Like most rain garden studies, we focused more on large storm events. For smaller storms, rain gardens are usually more effective in flow retention and infiltration. The temporary storage of rain gardens is very important for intense storm events; even with a medium retention depth of less than 20 cm, rain garden constructions can produce significant impact on the regional hydrology.

4 Conclusions

Based on a 4-yr. experimental study of retaining stormwater runoff with a rain garden in a sub-humid loess region in China, this paper presents a comprehensive analysis on the effects of runoff retention with rain gardens on single storm events and long term average weather condition. Out of the 28 storms observed during the four year study, the rain garden overflowed only in five events. The runoff retention rates for these overflow events ranged from 0.80 to 0.94. The contributions to flow retention from rain garden storage and infiltration differed with storms of different intensity, and infiltration played more important role during small storms. Because most storms in a year were fully retained, the flow retention rate on the annual basis was much higher, and the overall *RC* for the contributing area was reduced to minimum. The infiltration capacity of the experimental rain garden was not affected by soil clogging in the study years.

With a simple regional development model, our analyses based on the current and the future landuse pattern and storm changes showed that, rain gardens may act as effective hydrological sinks for storm runoff from the contributing area. To achieve the predicted effect, the rain gardens have to be placed appropriately to collect the designated storm runoff by rational planning. The installation of rain gardens on regional hydrology is often limited by many factors, such as available sites and spaces, the connection to city drainage systems, and most importantly, the ability for the available space to collect runoff from the impervious spaces. The regional impact of focused recharge with rain gardens on the groundwater will be studied in the future research.

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