

Rainwater retention effect of extensive green roofs monitored under natural rainfall events – a case study in Beijing

Yongwei Gong, Dingkun Yin, Xing Fang, Dandan Zhai and Junqi Li

ABSTRACT

The rainwater retention and peak flow reduction effect of seven extensive green roof (EGR) modules were studied in Beijing under natural rainfall events from May to September 2015. Monitored EGR modules had a layer of vegetation widely planted in northern China and a substrate layer with a thickness of 20 or 50 or 100 mm. The EGRs effectively retained rainwater, and regression equations of the potential retention capacity as a function of rainfall depth were developed for five EGR modules, which show that generally the capacity decreased as rainfall depth increased. The EGR with Sedum lineare Thunb and 100 mm improved soil had relatively higher average retention capacity (61.8%) than others, but all EGR modules had similar retention for an extraordinary rainfall event of 114.4 mm. For rainfall events less than 15 mm, EGR modules had 100% rainfall retention most of the time. The reduction in peak runoff rate ranged from 30.8% to 85.4%. The EGRs with Sedum lineare Thunb using 20 mm improved soil and 50 mm either pastoral soil or ultra-low weight substrates have similar peak reduction (51.3–58.2%). The EGRs with Sedum lineare Thunb have better rainfall retention and peak reduction than EGRs with Angiospermae or Sedum aizoon L.

Key words | extensive green roof, green infrastructure, peak flow, rainwater, retention capacity, runoff

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INTRODUCTION

Over the past century, high-intensity human activities in many countries throughout the world have led to rapid urbanization. China, as a rapidly developing country, inevitably faces many challenging issues in the process of urbanization (Liu *et al.* 2016). One of the most serious impacts caused by urbanization is alteration of the urban water cycle (Lu *et al.* 2016), preventing the timely infiltration of stormwater and leading to frequent waterlogging problems in many cities (Jiao *et al.* 2017). China is proactively addressing these challenges, such as by vigorously promoting the construction of a 'sponge city' (Li *et al.* 2016; Shao *et al.* 2016; Jia *et al.* 2017). The construction of a sponge city promotes comprehensive urban stormwater

management through implementing low impact development facilities, middle-scale stormwater pipe and channel networks, and large-scale emergency flood control systems. A low impact development facility is a runoff source-control system designed mainly to reduce rainwater runoff through the construction of green rainwater infrastructure facilities (Jia *et al.* 2013). Various green infrastructures have diverse capacities for reducing rainwater runoff (Liu *et al.* 2014). Green roof (GR) is a typical form of green infrastructure, and has made contributions in reducing urban stormwater runoff (Chen 2013; Carpenter *et al.* 2016). Due to the limited amount of available urban land in China and many other countries, GRs have been gaining popularity as a sustainable

technology because these roofs do not require additional urban land.

Green roofs can be classified as intensive and extensive, also called garden-style and simple green roofs (Rowe 2011). Extensive green roofs (EGRs) are easy to install, manage, and maintain. Furthermore, they cost less than intensive green roofs and have substrate layers that are usually shallower than those of intensive green roofs, with vegetation often comprised simply of low-profile shrubs or grass. Both intensive and EGRs normally include a vegetation layer, substrate layer, drainage layer, and waterproof layer (Zhang *et al.* 2015). In contrast, most rainfall runoff flows away directly when it falls on the traditional or normal roof (NR) that consists only of an impervious surface. Although a small amount of rainfall is retained on an NR, most will flow off the roof to form surface runoff or directly into stormwater pipes. EGR has not only rainfall interception by the vegetation layer but also infiltration and storage of rainwater in the substrate before releasing the rainwater as surface runoff. Rainwater stored by EGR substrate is used by the EGR vegetation and is returned to the atmosphere through evaporation and evapotranspiration during dry periods.

Green roof has many environmental benefits (Ayata *et al.* 2011; Gagliano *et al.* 2015; Vijayaraghavan & Raja 2014). One of the most important benefits of EGRs is their capacity to reduce rainwater runoff. The effect of EGRs on rainwater runoff mainly includes total volume reduction, peak flow reduction, and a delay in the onset of runoff. Various studies have demonstrated the stormwater retention capacity of EGRs. Lee *et al.* (2015) suggested that a rainfall depth of less than 7.5 mm produced no runoff; furthermore, for rainfall between 16 and 115 mm, an EGR with a 200 mm soil depth reduced runoff by 42.8–60.8%, whereas an EGR with a 150 mm soil depth reduced runoff by 13.8–34.4%. Zhang *et al.* (2015) found that rainfall retention of EGRs (150 mm substrate depth) ranged from 35.5% to 100% based on different rainfall depths, with an average retention of 77.2%. Bengtsson (2005) showed that an EGR with a 30 mm soil layer retained 46% of annual rainfall. If EGRs (100 mm substrate depth) were installed on 10% of the total roof surface in Brussels, Belgium, and a runoff reduction of 54% for the individual buildings was achieved, the stormwater reduction for the whole city area could be 2.7% (Mentens *et al.* 2006). Monterusso *et al.* (2004)

showed that EGRs have a much higher retention capacity for low-intensity rainfall than high-intensity rainfall. However, EGRs are also very important in reducing peak flows. Soulis *et al.* (2017b) established a hydrological model and found that the observed peak flow reduction ranged between 8.7% and 100% with an average value of 70.2% when EGRs with 80–160 mm substrates were used.

Generally speaking, many factors affect an EGR's rainfall retention capacity, such as vegetation types, substrate type and thickness, antecedent dry period, and roof slope (Van Woert *et al.* 2005a). Diversification of EGR plants can create a healthy ecological system and rich landscape effects. Typically, EGRs are located in the center of a city, where the growth environment of plants is very poor (high wind speed, large temperature difference between morning and evening, poor nutrient status of substrate, and so on). These conditions affect the growth and survival of EGR plants. Therefore, evergreen plant species that can bear extreme weather conditions and have low nutritional requirements should be chosen as EGR plants. Sedums are the most commonly used plant species for EGRs because of their strong resistance to severe and harsh weather, high ornamental value and ease of maintenance. Sedums of different colors, flowering patterns and heights are usually used for EGRs in Lisbon, Portugal (Brandão *et al.* 2017). Many studies have shown that the type and thickness of substrates are the key factors influencing the EGR's retention capacity of stormwater runoff, while the effects of vegetation types are relatively weak. Monterusso *et al.* (2004) showed that differences in rainwater retention were likely attributed to substrate depth, rather than to the drainage system employed or vegetation type. But other studies hold the opposite view, namely, that in high temperatures and in the rainy season, the effect of the vegetation layer on EGR's rainfall retention capacity can be significant. Van Woert *et al.* (2005a) found that a typical EGR with vegetation can retain more stormwater than an EGR system without vegetation. Lundholm *et al.* (2012) stressed that use of a variety of EGR plants can reduce more rainwater runoff compared with a monoculture. Vanuytrecht *et al.* (2014) found that succulents and mosses were unaffected by drought stress in the winter since they grew well not only in summer but also in winter, and their rainwater retention capacity was nearly the same in both seasons. Nagase

& Dunnett (2012) showed that for EGRs with the same substrate layer and drainage layer, the runoff reduction by an EGR with sedum was 23–38% higher than the reduction achieved by an EGR with non-herbaceous plants.

The research conducted in the present study investigated how different types of EGR plants and substrates and thickness of substrate layer affect an EGR's rainfall retention capacity under different natural rainfall events in Beijing, China. Although various studies have been conducted to understand and determine rainfall retention capacity of green roofs, results of previous studies depend on many influencing factors including rainfall depth, antecedent dry period, substrate type (characteristics) and thickness and vegetation types among others (Carter & Rasmussen 2010; Nagase & Dunnett 2012), no unified results have yet been reached and additional studies on green roof performance are valuable for comprehensive urban stormwater management. This study provided scientific data for the optimization of the design parameters of green roofs to support the planning and design of the sponge city in China, and the green infrastructure development in many other countries. Results from the case study under the wide spectrum of natural rainfall events were analyzed in depth and compared with other studies.

MATERIALS AND METHODS

Site description

Seven EGR modules were installed in April 2015 on the roof of the laboratory in the Beijing University of Civil

Engineering and Architecture, which is located in Daxing, Beijing, China. The annual average air temperature of the study area is approximately 12 °C and the average annual rainfall is 626 mm, most of which falls from May to October (as is typical of a continental monsoon climate).

EGR plants and substrates

Three species of sedum widely cultivated in northern China were selected as experimental EGR plants for studying the effect of the vegetation layer on rainwater retention: *Sedum lineare* Thunb, *Angiospermae*, and *Sedum aizoon* L. (Figure 1). All the EGR modules had complete vegetation coverage throughout the monitoring period (Figures 1 and 2). The physical properties of the three sedums are summarized in Table 1.

The substrate used in the EGR modules included pastoral soil, ultra-low weight substrate and improved soil. No fertilizers were added to the substrate, thereby minimizing the leaching of phosphorus and nitrogen into runoff. The pastoral soil was obtained from farmland in Daxing, Beijing. Ultra-low weight substrate manufactured for use in green roofs was bought commercially. The improved soil consisted of a mixture of pastoral soil, peat, pine needles and perlite (1:1:1:1 weight ratio), and complied with the recommended technical specifications for planted roof substrate (Wang 2007). Table 2 summarizes the physical properties of three substrates. The porosity of the ultra-low weight substrate was very high (80%) leading to very high saturated infiltration rate (2.4 cm min^{-1}). Porosities for the other two substrates were similar, but the saturated infiltration rate for the pastoral soil was approximately four times lower



Figure 1 | Plants used for EGR modules: (a) *Sedum lineare* Thunb, (b) *Angiospermae*, and (c) *Sedum aizoon* L.



Figure 2 | An example experimental EGR module having Sedum linearis Thunb, drainage pipes and a rain gauge.

than that of improved soil (Table 2), which could affect the retention of rainfall.

Five EGR modules used Sedum linearis Thunb as the vegetation layer with three types of substrate and three thicknesses (Table 3), and, in the remaining two modules with 50 mm of improved soil as substrate, one used Angiospermae and the other used Sedum aizoon L. For ease of discussion and presentation of results in this paper, the EGR modules were designated using two letters and a number. The first letter represents vegetation type: A for Angiospermae, L for Sedum aizoon L., and T for Sedum linearis Thunb. The second letter represents substrate type: I for improved soil, P for pastoral soil, and U for ultra-low weight substrate. The number represents the substrate thickness in mm. Therefore, TP50 was the EGR module comprised of Sedum linearis Thunb with 50 mm pastoral soil substrate.

Table 1 | Physical properties of plants used for EGR modules

Species	Plant height			Leaf thickness		Leaf size		
	Low	Med.	High	Thin	Thick	Large	Med.	Small
Sedum Linearis Thunb	●				●		●	
Angiospermae		●		●				●
Sedum aizoon L.			●	●		●		
Species	Leaf color		Plant morphology		Plant root system			
	red/purple	green/yellow	creeping	erecting	coarse	medium	slender	
Sedum Linearis Thunb		●	●			●		
Angiospermae	●			●			●	
Sedum aizoon L.		●		●	●			

Table 2 | Physical properties of substrates used in EGR modules

Substrate type	Dry bulk density (g m ⁻³)	Total porosity (%)	Saturated infiltration coefficient (cm min ⁻¹)
Pastoral soil	1.331	49	0.067
Ultra-low weight substrate	0.234	80	2.366
Improved soil	0.671	57	0.257

Table 3 | Detailed information of seven EGR modules monitored in the study

Modules	Vegetation layer	Substrate type	Substrate thickness
TP50	Sedum linearis thunb	Pastoral soil	50 mm
TI50	Sedum linearis thunb	Improved soil	50 mm
TU50	Sedum linearis thunb	Ultra-low weight substrate	50 mm
TI20	Sedum linearis thunb	Improved soil	20 mm
TI100	Sedum linearis thunb	Improved soil	100 mm
AI50	Angiospermae	Improved soil	50 mm
LI50	Sedum aizoon L.	Improved soil	50 mm

EGR and NR modules

The EGR modules were each 0.5 m × 0.5 m (Figure 2) and had a substrate thickness of 20, 50 or 100 mm (Table 3). In addition, all modules had geotextile as a filter layer and a drainage board as a drainage layer and a slope of 1%, ensuring proper drainage of stormwater runoff. All of the hydrologic measurements were taken from individual

modules. The EGR modules were constructed of polyvinyl chloride and each module was fitted with two drainpipes (20 mm inner diameter) at the bottom and an overflow pipe (25 mm inner diameter) positioned 40 mm above the substrate layer (Figure 2).

A geotextile with a design pressure of approximately 250 g cm^{-2} was used as a filter to prevent small substrate particles from getting into the drainage layer. The drainage layer consisted of a 15 mm thick drainage board, which was made of polyethylene instead of traditional gravel layer due to lighter load and longer service life of polyethylene.

In addition, a NR module consisting of a typical roof surface (i.e., concrete) was installed beside the EGR modules to provide comparative performance data. This module was the same size and placed on the same slope as the EGR modules and was monitored in the same way as the EGR modules (except that there was no subsurface drainage).

Data collection and analysis

The rainfall data were collected using an HOBO U30 station (Onset, Bourne, MA, USA) installed on the roof of the laboratory. The runoff of EGR modules was monitored using either an HOBO data logging and tipping bucket rain gauge (detection limit 0.2 mm) (Onset RG3-M, Bourne, MA, USA) or a 50 mL tipping bucket flow meter (QT-SZZ40, Channel Technology, China). The runoff from an EGR was introduced into the rain gauge or flow meter through the drainage pipes (Figure 2). For both the rain gauges and flow meters, the tipping bucket flips when a fixed amount of water is collected and then the counting system records the number of flips for determining and monitoring runoff. Although this type of rain gauge is designed to monitor rainfall, it can also be used to monitor runoff. The rain gauges used to monitor the runoff were sealed so that no other rainfall but the runoff generated by EGRs entered the rain gauges. A rain event was defined as a period of precipitation followed by six consecutive hours of no precipitation. Any rainfall that resulted in more than one tip of the rain gauges (0.2 mm) was considered an event. This definition ensured that an observed event could not be the result of residual rainfall left stagnant in a

tipping bucket from previous events. Over the study period from 10 May to 29 September 2015, 36 rainfall events were recorded with depths ranging from 0.2 to 114.4 mm. According to the China Meteorological Administration, daily (24 h) rainfall less than 10 mm is classified as 'small'; likewise, 'moderate' rainfall includes 10.0 mm to 24.9 mm, 'heavy' rainfall includes 25.0 mm to 49.9 mm, and 'extraordinary' rainfall includes 50 mm to 200 mm. Characteristics of monitored rainfall events are presented in the *Results and Discussion* section below and Table 4.

The total depth of rainwater retained by an EGR module was computed as the difference between cumulative rainfall depth and drainage volume (in mm) during a given time period. Retention (R , %) is reported as the percentage of rainwater held by an EGR,

$$R = \frac{(P - Ro)}{P} \times 100\% \quad (1)$$

where P is total rainfall (mm) and Ro is total runoff (mm) drained from an EGR module for a rainfall event or over the continuous monitoring period.

The peak reduction is reported as the ratio of the peak flow reduction achieved by the EGR to the peak flow from a NR having the same slope as the EGR modules,

$$R_{\text{flow}} = \frac{(T_{\text{flow}} - G_{\text{flow}})}{T_{\text{flow}}} \times 100\% \quad (2)$$

where R_{flow} is the runoff peak reduction (%), T_{flow} is peak flow measured from a NR (L min^{-1}) and G_{flow} is the peak flow from an EGR module (L min^{-1}). Data for G_{flow} of the NR surface in response to the seven rainfall events (Table 4) are given in the Appendix.

RESULTS AND DISCUSSION

Characteristics of monitored rainfalls

The 36 rainfall events monitored covered the whole spectrum of rainfall events that are likely to occur in the Beijing area. The 33-year (1983–2015) record of daily rainfall data for Beijing was analyzed to develop a cumulative

Table 4 | Characteristics of seven monitored rainfall events

Event date	Rainfall duration (min)	Total rainfall (mm)	Average rainfall intensity (mm min^{-1})	Maximum rainfall intensity (mm min^{-1})	Antecedent dry period (days)
10 May 2015	561	20.6	0.04	0.2	–
26 June 2015	48	30.6	0.64	2.4	1
17 July 2015	245	114.4	0.47	1.6	21
18 July 2015	421	19.4	0.05	0.6	1
27 July 2015	152	45.0	0.30	1.8	4
1 August 2015	112	32.0	0.29	1.2	1
5 September 2015	1,367	36.6	0.03	0.4	3

distribution curve, which showed that 82.9% of daily rainfall greater than 0.2 mm is less than 15 mm. Thus, theoretically, 30 of the 36 events monitored ($36 \times 0.829 = 30$) could have been less than 15 mm. In fact, during the study period 29 rainfall events producing less than 15 mm were recorded and monitored. Only seven of the 36 rainfall events (ranging from 19.4 to 114.4 mm) produced relatively large runoff (Table 4). Twenty of the 29 events produced less than 7.5 mm rainfall, and 17 of these produced no runoff; the other three produced minor runoff (Zhai 2016). These observation results are the same or similar to the findings of Lee et al. (2015).

Of the nine events producing 7.5–15 mm rainfall, five events generated no runoff from the EGR modules. Thus, the rainfall retention and peak runoff reduction by the modules were both 100% for these events. For the remaining four events, although retention was less than 100% (due to either antecedent soil moisture or a dry period), no appreciable runoff was produced. Therefore, only seven rainfall events (Table 4 and Appendix) were chosen for analyzing the water retention performance of the seven EGR modules, and these included one extraordinary rainstorm event (17 July 2015), four heavy rainfall events (26 June, 27 July, 1 August, and 5 September), and two moderate rainfall events (May 10 and July 18, 2015).

Rainfall hyetograph and runoff discharge

The hyetograph (mm min^{-1}) of the rainfall event on 27 July 2015 is shown in Figure 3(a) and the corresponding runoff hydrographs and rainfall retention capacities for five of the EGR modules are shown in Figure 3(b) and 3(c),

respectively. All three 50 mm substrates (TP50, TI50, and TU50 in Figure 3(b)) affected runoff generation, delaying the onset of runoff by 1 min after rainfall intensity increased to 0.8 mm min^{-1} . Rainfall reached its peak intensity (1.6 mm min^{-1}) after 18 min, and the discharge from the subsurface drainpipes (Figure 2) increased rapidly. Due to its high porosity (and corresponding high infiltration rate), the discharges from the TU50 module (ultra-low weight substrate) in 18–30 minutes after the rainfall started were significantly higher than discharges from the other two EGR modules with different types of substrate but the same thickness (Figure 3(b)). From about 45 minutes after the rainfall started, the measured discharges from the three EGRs were not significantly different, and the retention curves for the three EGRs almost paralleled each other. These responses indicate that the substrates of EGR modules have more influence on discharge when cumulative rainfall is still small.

The cumulative retention capacity of all EGR modules started at 100% and decreased nonlinearly with time (Figure 3); the overall retention capacity R was calculated at the point when runoff stopped. The final retention capacities for TP50, TI50, and TU50 were 42.0%, 48.7%, and 36.4%, respectively (Figure 3(b)).

Figure 3(c) presents data for three modules with the same substrate and vegetation but different substrate thicknesses. Total runoff from TI20 was approximately 1.26 times that of TI50, and runoff from TI50 was approximately 1.27 times that of TI100. These results indicate that, for a given substrate, the thicker the substrate, the more rainwater can be retained by an EGR. The reduction in peak runoff by TI100 was almost 20% larger than that of TI20 according to

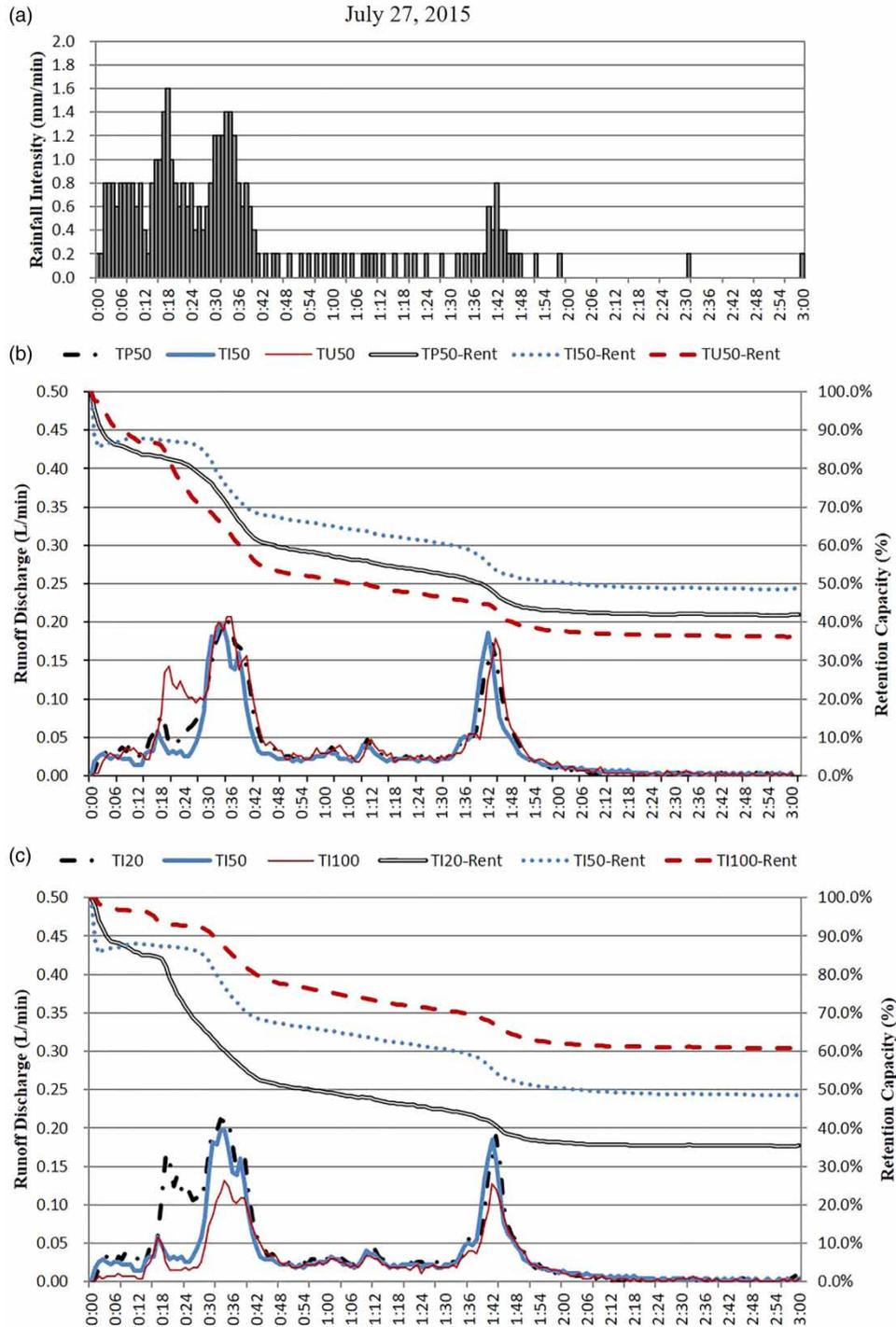


Figure 3 | (a) Observed rainfall hyetograph on July 27, 2015, corresponding runoff hydrographs and cumulative retention capacity (%) as a function of time for: (b) TP50, TI50 and TU50; and (c) TI20, TI50 and TI100.

the monitoring data in 2015. The rainfall event on 27 July 2015 had three peaks, and TI100 significantly reduced each peak. Although the reduction in peak runoff by TI50

was greater than that by TI20 in the first peak, neither TI20 nor TI50 achieved any significant reduction of the second and third peaks. Therefore, the substrates of TI20

and TI50 were saturated after the first peak. The final retention capacities for TI20, TI50 and TI100 were 35.5%, 48.7%, and 59.6%, respectively (Figure 3(c)).

Total rainfall (mm), overall retention capacities (%), retention volumes of rainwater (mm), reductions in peak runoff rates (%), and peak discharge (L min^{-1}) are summarized in the Appendix for all seven rainfall events and five EGR modules for which the vegetation layers are all *Sedum lineare Thunb.*, as well as the NR for comparison. Data for reductions in peak runoff for all seven modules on 17 July 2015 and for TI20 on 26 June 2015 are indicative only due to the very large rate of runoff that occurred on these dates. Because the HOBO rain gauges used to monitor the runoff could only record 60 flips of the bucket per minute (i.e., up to one flip per second) the maximum runoff rate that could be registered was $0.2184 \text{ L min}^{-1}$. When the rainfall was significant, the actual runoff exceeded $0.2184 \text{ L min}^{-1}$, and the runoff in excess of this maximum that occurred in the peak minute was attributed to the next minute.

Effect of vegetation layer on rainwater retention

The EGR modules AI50, LI50, and TI50 were designed and monitored for the impact of vegetal plant types on rainwater retention. These three EGR modules had the same type (improved soil) and thickness (50 mm) of substrate, such that the only difference among them was vegetation type (*Sedum lineare Thunb.*, Angiospermae, and *Sedum aizoon L.*). Compared to substrate layers, vegetation types of EGRs have little effect on retention capacity for individual rainfall events; therefore, cumulative retention effects of EGRs over a period of continuous monitoring were determined to explore the affect by vegetation layer.

Notably, continuous monitoring of AI50 and LI50 was accomplished only from 26 June to 1 August 2015 (12 events) due to equipment failure. Although TI50 was monitored much longer (from 10 May to 29 September), the total retention TR (mm) of TI50 shown in Figure 4 is for the same period as for AI50 and LI 50 (i.e., 26 June–1 August). The total precipitation from 26 June to 1 August 2015 was 258.4 mm for the continuous monitoring. For these 12 events, the average TR of the three modules was 122.1 mm with a standard deviation of 9.0 mm. By comparison, the

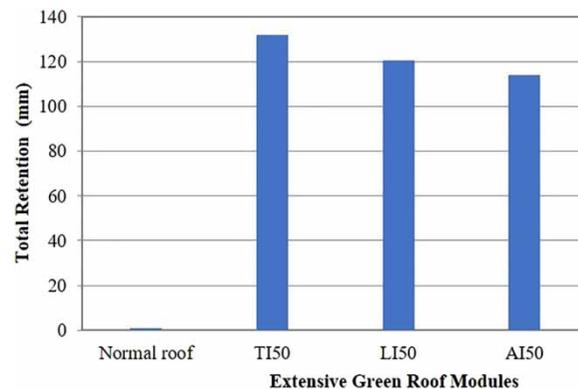


Figure 4 | Total retention (mm) of rainwater under the continuous monitoring period.

NR module retained only 0.8 mm of rainwater during the same monitoring period (Figure 4). The overall retention capacities of the three EGR modules were in the range of 44.1–51.0%, which are much larger than the NR's retention. The retention volumes and capacities of these three EGR modules were not significantly different, which might indicate that rainfall interception by different types of plants had an insignificant effect on rainwater retention by the EGRs. In the TI50 module (with *Sedum lineare Thunb.*) rainwater retention was relatively better than that of other modules with different plants. As the growth status of the three types of plants was basically the same, this result occurred because, compared with the other two plants, *Sedum lineare Thunb.* (Figures 1 and 2) has a relatively denser leaf canopy, which can intercept more rainwater. This result is somewhat different from what Nagase & Dunnett (2012) indicated: shorter plants with smaller diameter shed the greatest amount of runoff, while taller plants with bigger diameter intercepted more rainfall and retained the greatest amount of runoff by EGRs. Nagase & Dunnett (2012) studied/compared 12 species as vegetation layer (selected from the three major taxonomies: forbs, sedum and grasses), but in this study, we only examined three species of sedum.

During the continuous monitoring period, AI50 reduced peak runoff rate the least and its peak runoff rate was the highest of all three modules (Zhai 2016). This result was attributed to the comparatively smaller leaves, less dense canopy, and better-developed root system of Angiospermae (Table 1), which could loosen the substrate. Therefore, Angiospermae not only intercepts less rainfall in the leaf

canopy, but also reduces the capacity of the substrate to retain rainwater. This result corroborates previous research showing that the root structure of EGR vegetation can affect an EGR's rainwater retention capacity (Macivor & Lundholm 2011) because the more developed the root structure of a plant, the weaker its soil water-holding capacity. This reduction occurs mainly because the root structure of a plant changes the pore structure and, therefore, the water-holding capacity of the soil is reduced.

Effect of substrate layer on rainwater retention

In an EGR, substrate is the main component for retaining rainwater. The substrate not only allows roof plants to attach and grow on an EGR but also provides nutrition (Lata *et al.* 2017; Noya *et al.* 2017). The thickness of the substrate layer can affect the growth of roof plants as well as the rainwater retention capacity of the EGR (Soulis *et al.* 2017a). The composition and relative proportions of components in a substrate layer greatly affect the retention and the degree of purification of rainwater. The soil moisture in the substrate layer also influences the EGR's ability to reduce and delay the peak runoff (Berretta *et al.* 2014). Therefore, the substrate layer plays an important role in the hydrology performance of an EGR.

Effect of substrate thickness – individual rainfall events

Three EGR modules (TI20, TI50 and TI100) were designed and monitored to evaluate the impact of substrate thickness on rainwater retention. These modules had the same vegetation layer and the same type of substrate but different thicknesses of substrate (20, 50 and 100 mm, respectively). The values (open circles) for each rainfall event and statistical summary of R and R_{flow} for three EGR modules are presented in Figure 5 in comparison to the retention performance of a normal roof in response to the seven natural rainfall events (Table 4).

The maximum, minimum, and average values of R and R_{flow} increased as substrate thickness increased (Figure 5). However, the retention capacity did not linearly increase with substrate thickness. Rather, the first 30 mm increase of substrate thickness (i.e., the difference between TI20 and TI50) resulted in an average 14.7% retention capacity

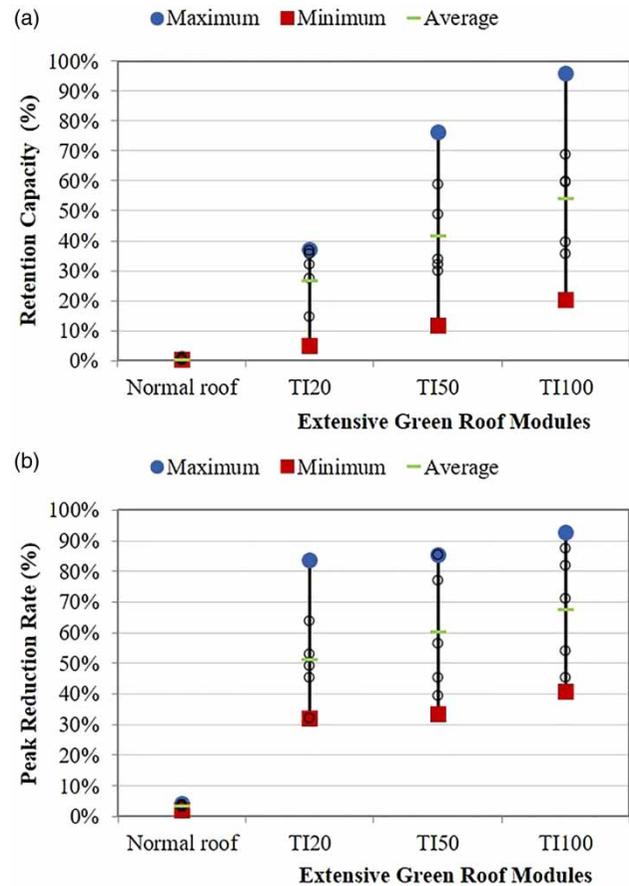


Figure 5 | Statistical summary (maximum, minimum, and average) and event values (open circles) of R and R_{flow} of three GR modules with different substrate thicknesses and normal roof under seven rainfall events (Table 4).

increase, whereas the next 50 mm increase in substrate thickness (from TI50 to TI100) resulted in an average 12.6% retention capacity increase. Overall, the thicker the EGR substrate, the greater the retention of rainwater (Figure 5(a)). The effect of substrate thickness on R for each rainfall event was further explored by plotting R as a function of the rainfall depth (Figure 6(a)). Four rainfall events (filled symbols in Figure 6(a)) that occurred on 10 May (moderate rainfall of 20.6 mm), 26 June (heavy rainfall of 30.6 mm), 27 July (heavy rainfall of 45.0 mm) and 17 July (extraordinary storm of 114.4 mm) were used to develop the regressions (dashed lines) of R (%) versus rainfall P for each of the three EGR modules (TI20 as squares, TI50 as diamonds, and TI100 as circles, as shown in Figure 6(a)). The best-fit regression equations (Table 5 including p -value) yield potential retention capacities R_p at different rainfalls,

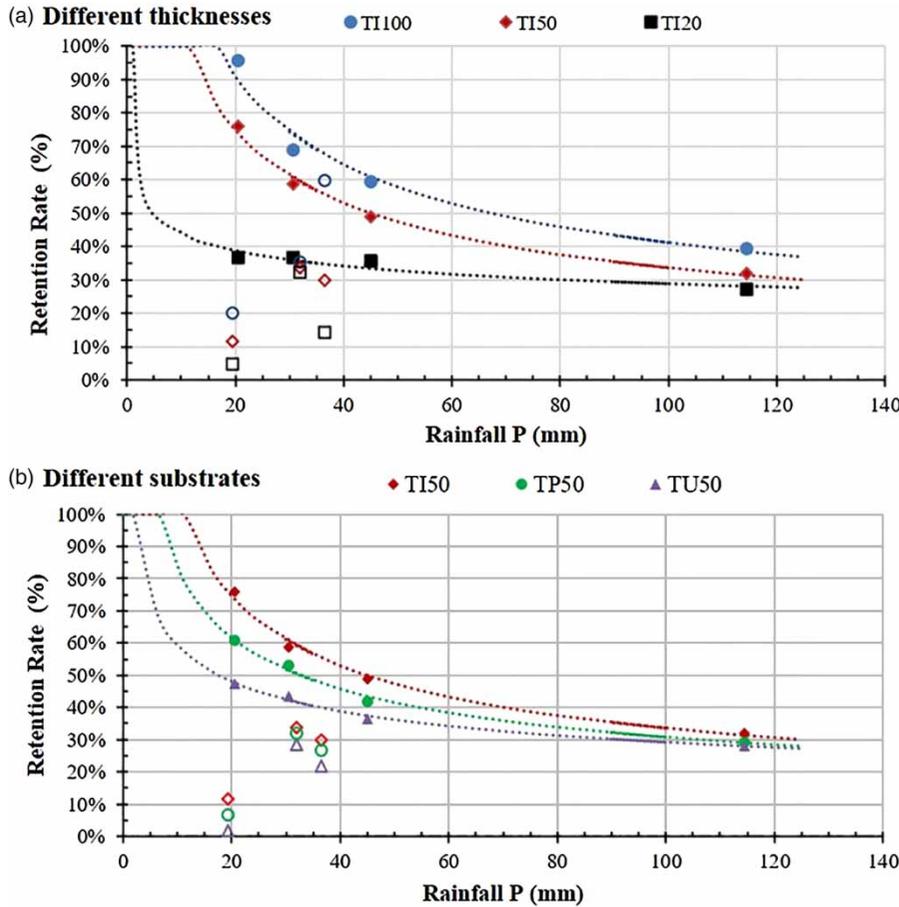


Figure 6 | Retention capacities (%) as a function of rainfall depth for (a) TI100, TI50 and TI20; and (b) TI50, TP50 and TU50.

and their determination coefficients (R^2 , representing the goodness of fit) exceeded 0.97 for TI50 and TI100 and 0.87 for TI20. The regression lines in Figure 6 clearly show that the potential retention capacity of an EGR decreased as rainfall depth increased and as substrate thickness decreased. When regression equations in Table 5 are applied to small rainfall depths, the equations result in R_p greater

than 1, and R_p should be reset to 1.0 or 100% for those cases.

Even though regression equations in Table 5 were developed from very limited data, rainfall retention capacities determined in this study as a function of rainfall depth are similar to other reported studies (Carter & Rasmussen 2010; Zhang et al. 2015). Carter & Rasmussen (2010) studied the rainfall retention of a green roof with 76 mm of light-weight roof garden mix under 32 natural rainfall events in Athens, Georgia, USA. Observed rainfalls ranged from 28 to 84 mm and corresponding rainfall retention ranged from 39.2% to 100.0%. Using their reported data, the fitted regression equation was developed: $R = 1.3418 P^{-0.221}$ ($R^2 = 0.71$). The root-mean-square error (RMSE) of retention capacities for seven rainfall events (Table 4) estimated from Carter and Rasmussen’s regression equation and from TI50 and TI100 equations (Table 5) are 7.3% and

Table 5 | The fitted regression equations of potential retention capacity R_p versus rainfall P (mm) for TI100, TI50, TI20, TP50 and TU50

GR modules	Fitted equation	R^2	p -value
TI100	$R_p = 3.9799 \times P^{-0.493}$ ($P \geq 16.5$ mm)	0.97	0.01
TI50	$R_p = 3.3244 \times P^{-0.498}$ ($P \geq 11.2$ mm)	0.99	0.003
TI20	$R_p = 0.6729 \times P^{-0.184}$ ($P \geq 0.1$ mm)	0.88	0.06
TP50	$R_p = 2.2600 \times P^{-0.433}$ ($P \geq 6.6$ mm)	0.99	0.004
TU50	$R_p = 1.2184 \times P^{-0.309}$ ($P \geq 1.9$ mm)	0.99	0.007

11.6%, respectively, since 76 mm substrate is between 50 mm and 100 mm substrates. Zhang *et al.* (2015) reported retention capacities of green roof experimental plots (1 × 1 m) with 15 mm of growing substrate (a mixture of light-weight materials) and Sedum linear Thunb under 19 rainfall events (2.5–84.8 mm) in Chongqing, China. Their reported regression equation is $R (\%) = -0.7815P + 92.655$ ($R^2 = 0.56$). The RMSE of retention capacities for seven rainfall events (Table 4) estimated from Zhang *et al.*'s regression equation and from TI50 equation (Table 5) is 12.4%. The maximum difference of retention capacity is 28.1% for 114.4 mm extraordinary storm, which were not observed in other two studies. Zhang *et al.* (2015) also grouped and reported their results by rainfall levels: their green roofs had nearly 94% rainfall retention from small rainfall events (<10.0 mm), >72% from moderate rainfall events (10–24.9 mm), >67% from heavy rainfall events (25.0–49.9 mm), and nearly 39% from rainfall events >50 mm, which are similar to results for TI50 and TI100 but much larger than results for TI20 in Figure 6.

Soulis *et al.* (2017a) studied EGRs with three vegetation covers: succulent plants (*Sedum sediforme*), xerophytic plants, and turf grasses; and two substrate depths (80 or 160 mm). They first reported and plotted the runoff reduction (6.6–100%) versus soil moisture (3–60%) and rainfall depth (0.6–45.4 mm). They used all and scattered data to develop regression equations: the runoff reduction as a function of either initial moisture (%) or rainfall depth (mm), with R^2 of 0.41 and 0.32 for linear fits and 0.53 and 0.32 for quadratic fits, respectively. Eventually they developed a quadratic regression equation of the runoff reduction as a function of both initial moisture and rainfall depth with R^2 of 0.7 (RMSE of 16%). With limited data in this study, we developed regression equations of potential retention capacity R_p as a function of rainfall depth, which give the potentially largest retention capacities at different rainfall depths (Figure 6) with much higher R^2 (Table 5) in comparison to regression equations from Soulis *et al.* (2017a).

On 17 July 2015, severe rainfall of 114.4 mm occurred over approximately 4 h, and all three modules had similar retention capacities ranging from 27.3% (TI20) to 39.5% (TI100), producing runoff volumes ranging from 36.4 to 32.3 mm. This performance was in line with the results of many studies (Van Woert *et al.* 2005a; Sandoval *et al.* 2015;

Soulis *et al.* 2017a) that have shown substrate thickness to be the main factor affecting rainwater retention, but that any extraordinary rainfall reduces the overall retention capacity. In response to the moderate rainfall (20.6 mm) on 10 May 2015, three EGR modules with substrate thickness from 20 to 100 mm had very different retention capacities (Figure 6(a)) that ranged from 36.8% (TI20) to 95.8% (TI100) and produced runoff volumes ranging from 19.4 mm to only 0.9 mm (see Appendix in supplementary information).

Three rainfall events (hollow symbols in Figure 6, on 18 July, 1 August and 5 September) were not used to develop the regressions. The moderate rainfall event (19.4 mm) on 18 July occurred after extraordinary rainfall on 17 July 2015; thus, most likely the EGR substrates were still saturated on July 18 and the retention capacities for EGR modules (ranging from only 4.9% to 20.1%; Figure 6) were much lower than R_p computed from the corresponding regression equations in Table 5. Furthermore, the retention effect of the three EGR modules on 1 August 2015 (32 mm heavy rainfall with one antecedent dry day) did not exhibit an obvious step-increase as a function of substrate thickness; instead the modules had similar retention capacities (32.1%, 33.7%, and 35.5%), and those of TI50 and TI100 were much lower than the R_p values predicted from the corresponding regression equations (Table 5). The rainfall on 5 September 2015 was heavy (36.6 mm) and lasted for approximately 22 h (at an average rainfall intensity of 0.03 mm min⁻¹ and a maximum intensity of 0.4 mm min⁻¹). The event on 5 September was preceded by three recent small rainfall events (each <10 mm) on 30 and 31 August and 1 September that did not produce any runoff. Thus, on 5 September the substrate moisture content of the EGRs was high, and although the rainfall retention capacity of TI100 was only slightly lower than the R_p computed from the corresponding regression equation, the capacities of TI50 and TI20 were much lower than R_p predicted (Figure 6). The retention effect of the three modules for the rainfall on 5 September did exhibit a step-increase as a function of substrate thickness, but the retention capacities were much lower than the R_p values predicted from the regression equations based on rainfall.

The regressions shown in Figure 6(a) indicate that rainfall less than 11 mm would produce no outflow from either

TI100 or TI50 (100% retention), but TI20 would retain only 43% of this rainfall. If rainfall exceeded 120 mm, TI20 and TI50 would have almost the same retention capacities while that of TI100 would be only slightly higher than the retention of TI50; furthermore, the retention capacities for all three EGR modules would tend to stabilize and become independent of rainfall depth. Out of the 36 natural rainfall events that were monitored, 29 had relatively low rainfall amounts and resulted in about 100% retention by the EGRs; therefore, these rainfall events are not listed in the Appendix.

Effect of substrate thickness – cumulative effect over all rainfall events monitored

Rainfall and runoff data for the three EGR modules (TI20, TI50 and TI100) were collected from 10 May to 29 September 2015 (36 rainfall events), and the total retention capacity for each EGR module was calculated using cumulative rainfall and runoff volumes over the entire monitoring period. Cumulative rainfall was 434 mm over the 36 events, and the total retention capacities of TI20, TI50 and TI100 were 39.2%, 56.5% and 61.8%, respectively (Figure 7); these long-term retention capacities were in the range of minimum and maximum retention capacities for individual events (Figure 5). These results indicate that the effect of substrate thickness on the reduction of rainwater runoff by EGRs is very significant, as is corroborated in many other studies, for example Van Woert et al. (2005b). Experiments in Germany showed that EGRs with a 100 mm soil layer reduced runoff by approximately 70% compared to a traditional roof (Shi et al. 2006). Figure 7 also shows that the total retention capacities of the modules were increased by 4–8% if the extraordinary rainfall event that occurred on 17 July 2015 was excluded. This difference also highlighted that heavy rain reduced the overall rainfall retention effect of green roofs.

Effect of substrate types

The EGR modules TP50, TI50 and TU50 were designed and monitored to evaluate the impact of substrate types on rainwater retention. The three modules had the same vegetation layer and the same substrate thickness (50 mm) but different

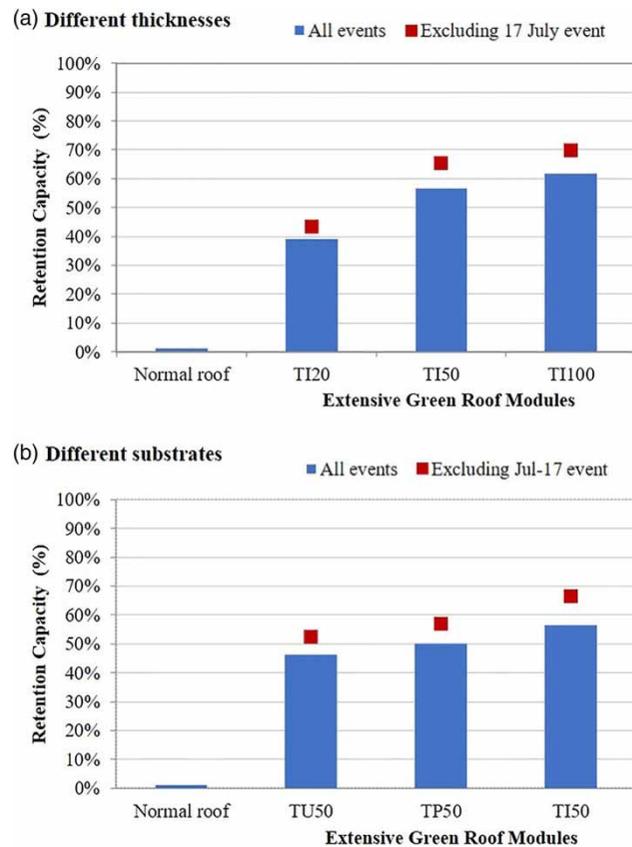


Figure 7 | Cumulative retention capacities (%) of (a) TI20, TI50 and TI100; (b) TI50, TP50 and TU50 over 36 rainfall events.

substrate types (i.e., pastoral soil, improved soil, and ultra-low-weight substrate, respectively). The statistical summary of R and R_{flow} for these three EGR modules is shown in Figure 8 and compared with the performance of a normal roof under the seven natural rainfall events (Table 4).

The maximum, minimum, and average values of R and R_{flow} under the seven rainfall events increased in the order of ultra-low weight substrate, pastoral soil and improved soil (Figure 8). The R of TI50 was in the range 11.7–76.0%, the mean of which was 11% higher than that of TU50 and 6% higher than that of TP50. This result is consistent with the study of Stovin et al. (2015) which shows that the EGRs with the most porous/permeable substrates showed the lowest levels of retention capacity, because higher porosity of substrates leads to faster moisture losses so that EGRs with ultra-low weight substrate produced more runoff in both individual rainfall event or cumulative monitoring (Berretta et al. 2014; Poë et al. 2015). Besides, the

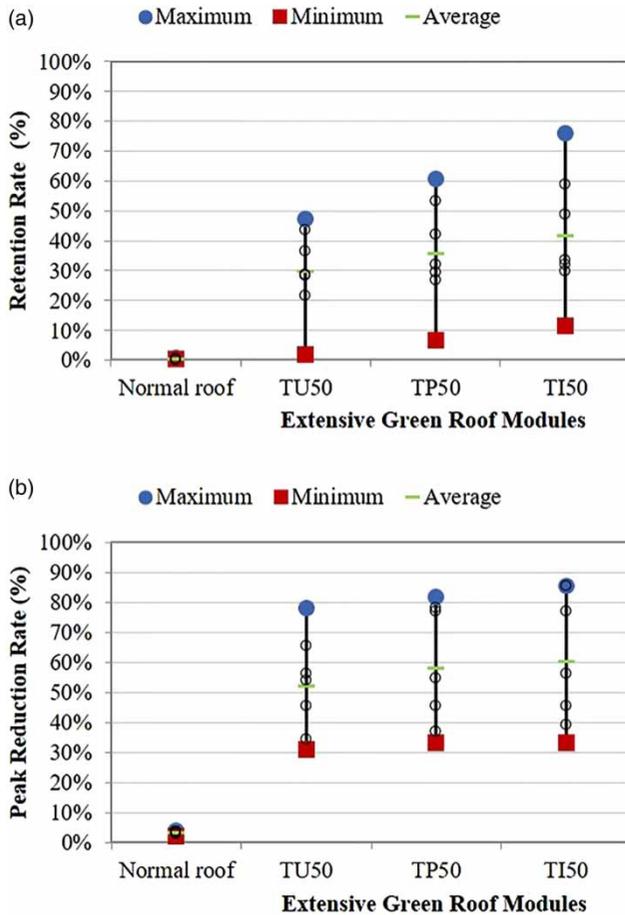


Figure 8 | Statistical summary of R and R_{flow} of three EGR modules with different substrate types and normal roof under seven rainfall events (Table 4).

reductions in the peak rate of runoff (Figure 8(b)) followed the same trend as R (Figure 8(a)) such that the improved soil substrate exhibited the best rainwater retention effect, and the ability of peak flow reduction of EGRs are much higher than NR in this study. Other studies also showed that EGRs have great peak flow reduction compared with traditional rooftops (Bliss *et al.* 2009; Soulis *et al.* 2017a).

In Figure 6(b) the retention rates as a function of rainfall depths are shown for TI50, TP50 and TU50, including regression lines developed using four events; the regression equations are given in Table 5 ($R^2 = 0.99$). The cumulative retention rates of the three modules over 36 rainfall events are shown in Figure 7(b). Results in Figures 6(b) and 7(b) as a function of substrate type were similar to those described for substrate thickness (Figures 6(a) and 7(a)). However, the effect of substrate on rainwater retention

was weaker than the effect of substrate thickness in the range 20–100 mm of rainfall.

CONCLUSIONS

A systematic study was conducted to investigate the influence of vegetation layer, substrate thickness and substrate types on EGR rainwater retention capacity and reduction in peak flow. EGR modules were monitored under 36 natural rainfall events from 10 May to 29 September 2015. Key conclusions of the study are given below.

Sedum lineare Thunb (TI50) was a relatively more effective plant vegetation layer for rainwater retention and peak flow reduction compared with Angiospermae (AI50) and Sedum aizoon L (LI50) during the monitoring period. The effectiveness was due to the plant's creeping stalk and dense leaf canopy. Nevertheless, the total runoff from each of these three EGR modules with a different vegetation layer differed by only 20 mm (Figure 4). Compared with the substrate layer, the vegetation layer has less effect on the rainwater retention capacity of EGRs.

For three EGRs that differed only in substrate thickness (TI20, TI50, and TI100), the thicker the substrate was, the better was the rainfall retention capacity (Figures 5 and 7). In general, EGR's retention capacity was closely and inversely correlated to rainfall depth when it exceeded 15 mm, with certain exceptional cases. Under an extraordinary rainfall on 17 July 2015, the retention capacities of EGR modules with different substrate thicknesses and substrate types were very similar. For the same EGR module, the difference in rainfall retention capacities for a moderate rainfall event and a heavy rainfall event can be more than 50%.

For three EGRs with different substrate types (TI50, TP50 and TU50), improved soil showed the greatest rainwater retention capacity (Figures 7 and 8). Improved soil had a lower dry bulk density compared to pastoral soil, and a lower porosity than that of the ultra-low weight substrate. The TI50 module retained 76% rainwater during moderate rainfall events, but only 31.8% in an extraordinary rainfall on 17 July 2015. The highest reduction of the peak flow of TI50 was 85.4% during moderate rainfall.

In this study, it is not clear if the size of the experimental EGR modules affected the amount of rainwater runoff, and more detailed studies are necessary using various plant combinations in individual modules. In future research, we will continue to study rainwater retention under short-term and long-term rainfall events and for several other substrates such as peat soil and pine needle mulch using substrate thicknesses that exceed 100 mm.

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