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ASSESSING THE PERFORMANCE OF GREEN ROOFS FOR STORMWATER RUNOFF MITIGATION IN THE SOUTH AFRICAN URBAN ENVIRONMENT

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Abstract: Rapid urbanization has altered the hydrologic cycle, causing increased runoff rates and peak flows in the drainage system. Cities are now facing serious problems relating to stormwater management such as water scarcity, degraded waterways, and increased flooding. Under such circumstances, green roofs present numerous benefits including the retention of rainwater for a longer time and a delay in the peak discharge. Using data from various storm events, this study examined the performance of retrofitted green roofs for stormwater management in the eThekwini region of South Africa. The study also used the Personal Computer Storm Water Management Model (PCSWMM) to investigate the effect that the best performing green roof would have on stormwater flow rates and volumes for the region. The results concluded that the green roof systems proved to significantly reduce stormwater runoff flow rates and volumes, and retention largely depended on the intensity and duration of the rain events. The PCSWMM model further confirmed that when compared to the base model, peak flow rates from the green roof model decreased by over 40% for all storm intensities. It can therefore be concluded that the implementation of green roofs within the eThekwini Central Business District (CBD) will be highly effective in reducing peak stormwater flow rates.

Keywords: green roof, stormwater management, rainfall-runoff, storm events, peak flows, retention rates.

INTRODUCTION

Climate change is a global phenomenon posing serious threats to human life and the environment. According to the Intergovernmental Panel on Climate Change (IPCC), the past few decades have witnessed significant changes in the frequency and intensity of extreme weather events, exacerbating risks for natural and human systems (IPCC, 2014; Castro e*t al.,* 2019). Such risks include sea-level rise, floods, extreme rainfall, heat increase, drought, and water shortages, and it is anticipated that their impacts will be far more severe in urban areas. Due to factors such as population concentration and density, flood risks in cities is of particular concern (Jha *et al.,* 2012). According to the United Nations (2019), currently, almost half of the world's population lives in urban areas, with nearly 67% living in cities by 2050. Consequently, urban areas are now expanding considerably in terms of space and density which has given rise to buildings and new developments at the expense of urban green spaces (Berghage *et al.,* 2009; Palla *et al.,* 2010; M'Ikiugu *et al.,* 2014), which in turn has led to an increase in impervious surfaces (Oscampo, 2018; Zhou *et al.,* 2020).

The increase in impervious surfaces in urban areas has reduced the ability of natural soil areas to absorb rain, increasing the volume of water flowing into urban stormwater systems, causing frequent flooding (Oberndorfer *et al.,* 2007; Kundzewicz *et al.,* 2013; Papafotiou & Katsifarakis, 2015; Oscampo, 2018). These threats are estimated to intensify with climate change. Moreover, stormwater runoff is no longer able to infiltrate naturally into the soil, leading to changes in the ground-water balance. **Figure 1** illustrates the relationship between the type of cover and the surface runoff. During a rainfall event, part of the water is absorbed by the ground and the rest flows along the surface as runoff. In vegetated areas where the ground is porous, approximately half of the water from rainfall infiltrates into the ground where it recharges as groundwater. About 40% of this water returns into the atmosphere though evapotranspiration and the remaining 10% flows along the surface as runoff (Copeland, 2016). However, in urbanized areas, almost 40% of the land surface is impervious to rainfall which is unable to be absorbed by the ground and flows rapidly into sewers and then into rivers and streams. The US Environmental Protection Agency (EPA) (2003), estimates that, due to the impervious surface in urban areas, a city block will generate five times more runoff than a woodland area of the same size.

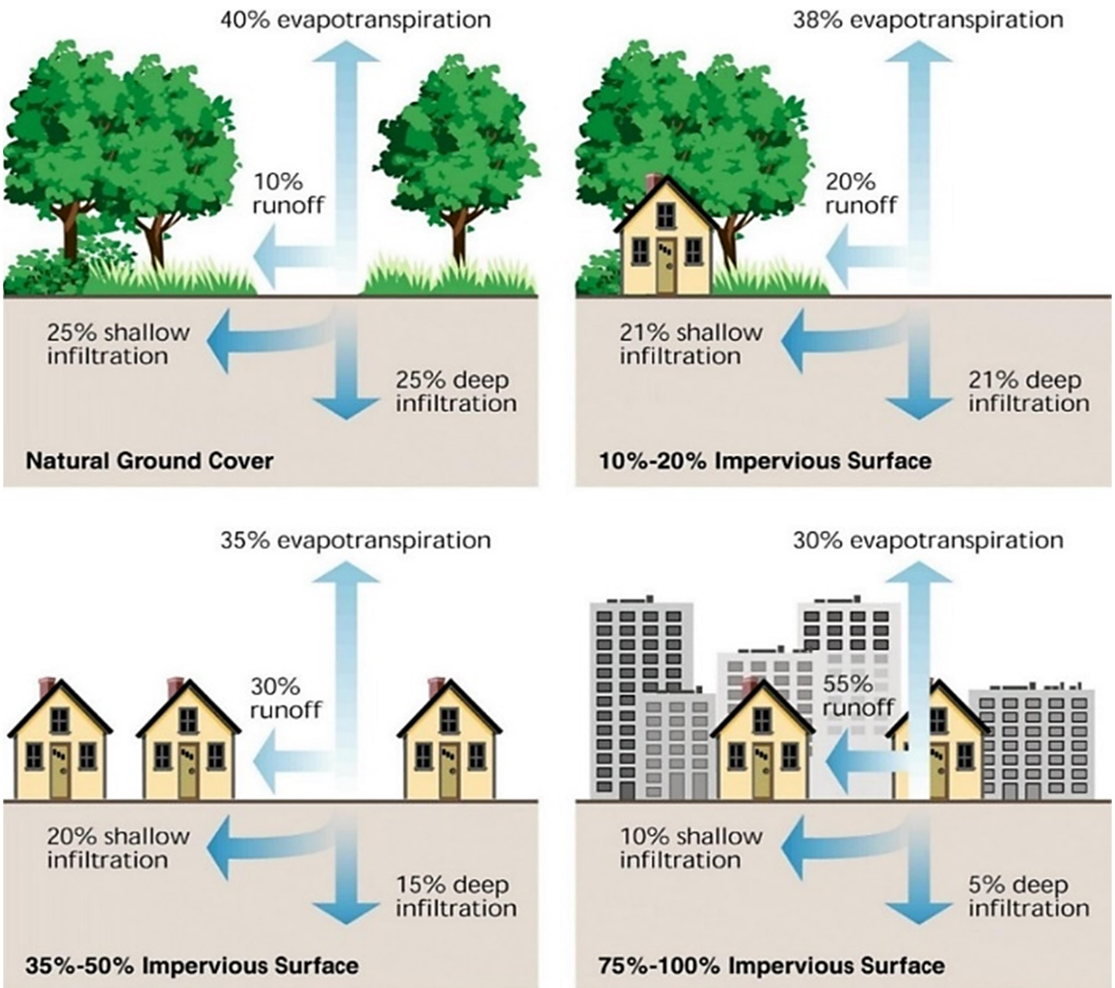

Fig. 1 Relationship between the impervious cover and surface runoff

Source: The Federal Interagency Stream Restoration Working Group (2001)

Urban environments are therefore challenged by extensive impervious surfaces and little room for green spaces or stormwater management facilities. The key environmental concern with urbanization is the ability of the urban hydrological system to cope with the fluctuation in surface runoff, as the urban water cycle has replaced the natural water cycle. Conventional approaches fail to address the increase in storm runoff volumes and peak flow rates caused by urban development (Oscampo, 2018). Thus, several sustainable urban drainage systems (SuDS) have been developed and implemented in numerous cities in the last three decades. SuDS mimic the hydrological process that would have taken place, had the site not been developed, by allowing stormwater to infiltrate, evaporate, runoff, and/or be used on-site (Liu *et al.,* 2014; Jusić, *et al.,* 2019). Examples of these SuDS include green roofs, rainwater harvesting, soakaways, permeable pavements, filter strips, swales, detention ponds, retention ponds, and constructed wetlands (Patel & Rangrej, 2021). Green roofs, in particular, are considered as favourable and sustainable tools to mitigate urban flood risk, water management and climate change adaptation due to their ability to retain stormwater (Samant, 2015; Berghage *et al.,* 2009; Shafique *et al.,* 2018; Baryla *et al.,* 2018; Jusić, *et al.,* 2019. Liu *et al.,* 2019; Chistiano *et al.,* 2020).

Green roofs and stormwater runoff

Green roofs have been suggested as a means to reduce stormwater impacts due to their ability to detain stormwater (Berghage *et al.,* 2009; Samant, 2015). They offer a practical alternative for new construction and for retrofitting existing structures. Green roofs can filter stormwater though their soil and vegetation layers and are based on the idea that the green space consumed by the footprint of the building should be replaced (Zhang *et al.,* 2015). Compared to conventional roofs, rainwater that lands on green roofs enter a 'complex hydrological system' whereby the roof system retains water in its vegetation and substrate, which provides a retention rate capacity for stormwater management (Zheng *et al.,* 2021:1). Essentially, green roofs alter stormwater runoff by reducing and delaying peak runoff (see **Fig. 2**), creating a time lag between peak flow from a hard roof and a green roof for the same rain event (Berndtsson, 2010; Samant, 2015; Liu *et al.,* 2019). The reduction in runoff peak consists of delaying the initial time of runoff due to the absorption of water in the green roof system; reducing the total runoff by retaining part of the rainfall; and distributing the runoff over a long time though a relatively slow release of the excess water that is temporarily stored in the pores of the substrate (Mentens *et al.,* 2006). Basically, "stormwater is retained by the roof membrane and taken up by plants

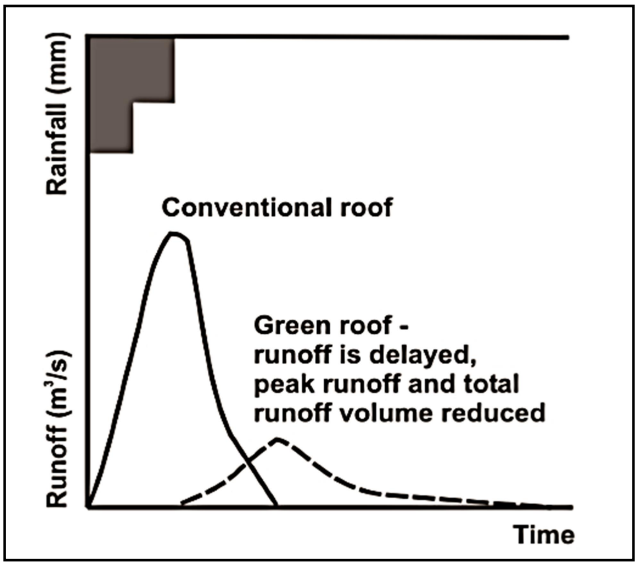

Fig. 2 Rainfall-runoff response. Source: Stovins *et al.* (2007)

and then gradually released though evapotranspiration back into the atmosphere, and water loads, which saturate the roof membrane beyond its holding capacity, escape the roof laterally via the drainage membrane and then out via drain" (Migall *et al.,* 2011: 25). Hence, green roofs result in the retention of a portion of the rainfall, and a delay and decrease in the peak rate of runoff from the site, leading to a reduction of flood risks (Berghage *et al.,* 2009; Ercolani *et al.,* 2018; Liu *et al.,* 2019; Zheng *et al.,* 2021).

Several studies confirm varying percentages of stormwater retention from green roofs ranging from 40-80% (Liu, 2003; Berghage *et al.,* 2009), to 34% (Stovins *et al.,* 2007), 63% (Van Seters *et al.,* 2009), 45-70% (Kolb, 2004), 62% (Zheng *et al.,* 2021); 44-88% (Simmons *et al.,* 2008), and 77% (Zhang *et al.,* 2015). However, some authors have argued that these claims depend on the amount of rain for every storm occurrence (Hilten *et al.,* 2008; Zheng *et al.,* 2021). For example, in a study of green roofs in China, Zhang *et al.* (2015) reported that retention varied with the rainfall intensity, showing retention of nearly 94% for small rainfall events (<10.0 mm), more than 72% for medium rainfall events (10.0–24.9 mm), more than 67% for large rainfall events (25.0-49.9 mm) and nearly 39% for storm events (>50 mm). In many cities, roofs comprise approximately 40-50% of the impermeable urban surface area and therefore reducing the rate and volume of roof runoff can lead to improved stormwater management (Stovins *et al.,* 2007). For instance, a monitoring project on green roof water quality and quantity of a 280m² green roof in Washington D.C. found that the roof retained approximately 75% of the total rainfall volume that fell over ten months. This equated to preventing 104 144 litres of water out of the city sewer system (Pevzner, 2013). Gutteridge (2003) also suggested that if 6% of the total roof area utilized green roof technology in Toronto, this would provide over 3.6 million cubic metres per year of stormwater retention capability. Green roofs are claimed to offer an array of advantages in terms of stormwater runoff, including their ability to temporarily and permanently store runoff (Oberndorfer *et al.,* 2007; Zhang *et al.,* 2015), and undeniably, green roofs can contribute to mitigating floods, by storing rainfall in the soil substrate and vegetation, and delaying the runoff peak (Stovin *et al.,* 2012; Viola *et al.,* 2017; Chistaino *et al.,* 2020).

Limited research has been conducted on retrofitted green roofs for stormwater management for South African cities. Green infrastructure within the South African context involves many green agendas but places more emphasis on the preservation of biodiversity within the country (Bobbins and Culwick, 2014). Implementing green roofs in South Africa has not been seen as a priority, with the only motivation for the implementation being the additional points allocated by the Green Building Council of South Africa (GBCSA) when a building is being assessed (Booysen, 2014). The poor integration of stormwater management with the rest of the urban water cycle results in South African municipalities not having a holistic approach to water services (Fisher-Jeffes and Armitage, 2012), and stormwater is often managed as a potential flood hazard and disposed of as rapidly as possible. It is against this background that the study seeks to analyze the potential of stormwater runoff from green roofs in improving stormwater attenuation. This study therefore examined the performance of retrofitted green roofs in stormwater retention, and the delay in the peak discharge for stormwater management in the highly urbanized area of eThekwini, South Africa. The study further investigated the effect of the best performing green roof on stormwater flow rates and volumes for the region, using the Personal Computer Storm Water Management Model (PCSWMM).

MATERIALS AND METHODS

Study Area

The eThekwini region, or Durban, is located on the south-eastern coast of South Africa, in the province of KwaZulu-Natal (KZN). The region covers approximately 98km of coastline, along with 18 river catchments, 16 estuaries, and over 4 000km of rivers. The eThekwini region has a population of 3.9 million people, accounting for 34.7% of the total population of the province, and this is estimated to grow at a steady rate over the next few decades with a projected population size of between 4.1 and 4.5 million by 2035 (eThekwini Municipality, 2014). The region receives an average of 828 mm of rainfall per year, or 69 mm per month. The eThekwini (Durban) Climate Change Strategy has identified an increase in rainfall until the year 2065, and a 500mm increase in rainfall between 2065 and 2100. This means that more intense and frequent storms are expected, and are evident in the weather patterns seen in eThekwini Municipality in the past decade (eThekwini Municipality, 2014).

The study experiment was conducted on the Green Roof Pilot Project under natural weather conditions. The Green Roof Pilot Project is part of the eThekwini Municipality's Municipal Climate Protection Programme and was launched on 22 May 2009. The project aimed to understand the city's resilience to climate change, based on projections of increased levels of surface run-off and flooding that result from the increase of non-permeable surfaces in the city, and to explore the extent to which green roof habitats can assist in reducing stormwater run-off, thereby enhancing the city's adaptive capacity (Environmental Planning and Climate Protection Department, 2014). The project site is the roof of a building within the eThekwini Municipality's Old Fort Complex (see **Fig. 3**).

Two adjoining flat-topped roofs at the eThekwini Engineering Services building have been planted with twelve different varieties of vegetation (see **Fig. 4A**). The roof was subdivided into three portions, namely an in-situ green roof system, a modular green roof system and the Control Roof (van Niekerk *et al.,* 2009; Greenstone, 2009). The total area allocated to the project is 550m², with each roof variation comprising approximately 50m^2. Each green roof system comprised different substrate compositions of varying depths (see **Table 1**), which allowed for a range of nutrient components, drainage properties, and loading capacities (Greenstone, 2009). The substrate media provided a suitable rooting zone for vegetation, which is a low-density aggregate with high-water holding capability, for effective drainage. The Green Roof Pilot Project substrates comprised different mixes as follows:

- Mixture A: 50% Light Expanded Clay Aggregate, 15% decomposed granite, 10% dark building sand, 10% fine decomposed compost, 10% vermiculite, and 5% perlite.

- Mixture B: 55% crushed brick, 23% decomposed granite, 11% fine decomposed compost, and 11% dark building sand.

Data collection

Primary data used in this study was based on rainfall depths and stormwater runoff rates from the Green Roof Pilot Project that was collected between March 2017 and September 2017. **Fig. 4A** illustrates the location of the various apparatus on the roof. The apparatus to measure rainfall depth and stormwater runoff flow rates included a system of electronic tipping rain gauges (see **Fig. 4B**), and flow meters and data loggers (see **Fig. 4C**).

Fig. 3 Location of the Green Roof Pilot Project in the eThekwini region

Table 1. Properties of the Green Roof Pilot Project roof systems

Roof area	Substrate type	Substrate depth (cm)	Area (m²)
Green Roof 1	Mixture B	3	46.8
Green Roof 2	Mixture A	10	43.6
Green Roof 3	Mixture A	10	47.2

Source: van Niekerk et al. (2009)

RESULTS AND DISCUSSION

Over the 7 months, a total of 20 rainfall events were monitored. Each event was analysed in terms of the retention rate, peak flow rate delay, and peak flow rate difference for the different roof systems. The data for this is presented in **Fig. 6** and **Table 2.**

Rainfall event: 9 March 2017

During this rainfall event, Green Roof 2 showed the highest retention rate of 100%, and Green Roof 3 was the lowest. Green Roof 2 and Green Roof 3 had the same substrate depth and substrate mix, but different plant types and densities. Green Roof 1 and Green Roof 3 experienced a 15-minute delay in their peak flow rates compared to the Control Roof. The peak flow rate recorded for Green Roof 1 was 0.012L/s, and 0.021L/s for Green Roof 2. The Control Roof measured a peak flow rate of 0.211L/s, indicating that the green roof systems were able to drastically reduce the peak flow rate for this particular rainfall event. No flow data was recorded for Green Roof 2. Retention during the second rainfall event on this day ranged from 7.82% for the Control Roof to 100% for Green Roof 2. The lowest retention of the green roofs occurred at Green Roof 3. The green roof with a thicker substrate layer and denser vegetation was able to retain more water. Using the peak flow rate of the Control Roof as a proxy, Green Roof 3 experienced a peak flow rate at the same time, which is possibly due to it being partially saturated from the previous rainfall event. Green Roof 1 delayed the peak flow rate by 15 minutes, and Green Roof 2 recorded no flow rate data for this rainfall event. A third rainfall event for this day recorded a peak intensity of 0.6mm/h.

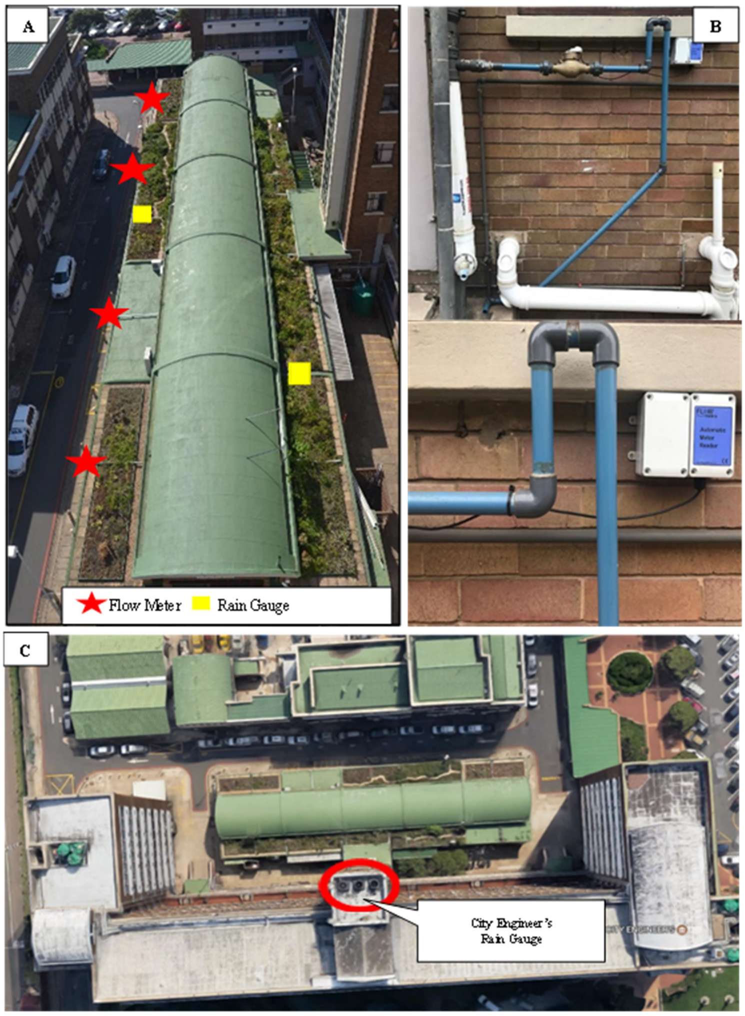

Fig 4. Location of various monitoring apparatus on the Green Roof Pilot Project

Fig. 5 Demarcated area for PCSWMM model

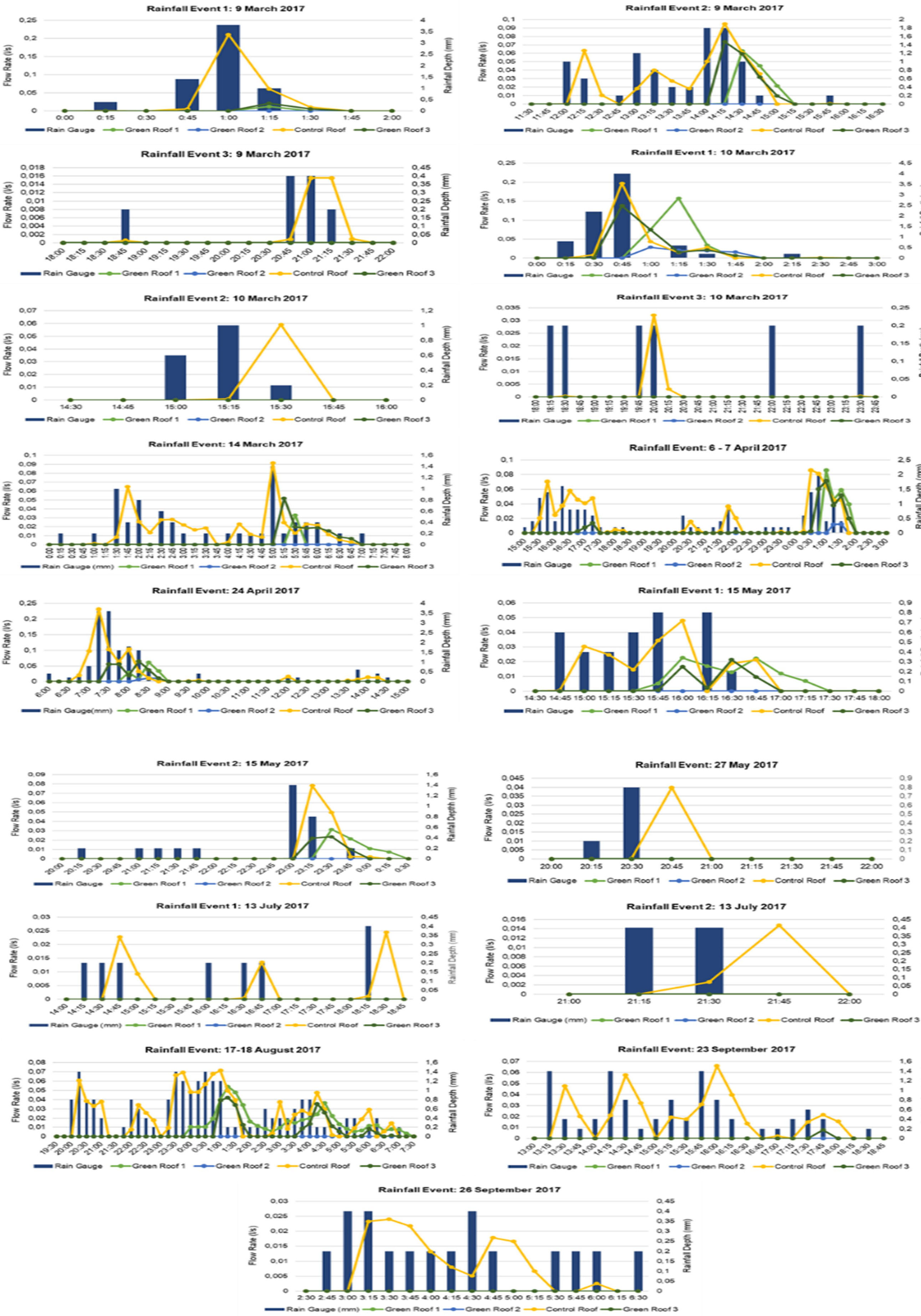

Fig 6 Stormwater retention behavior, delay in peak flow rate, and difference in peak flow rate

Table 2. Summary of rainfall and retention data

Rainfall event Date	Rainfall Intensity (mm/h)	Rainfall Depth (mm)	Rainfall Duration (h:min)	ADWP	Percentage Retention		
					Green Roof 1	Green Roof 2	Green Roof 3
Rainfall event 1: 9 March 2017	3.4	6.6	01:00	> 5 days	94.41	100	87.95
Rainfall event 2: 9 March 2017	1.8	9.6	03:45	10 hours	73.92	100	65.31
Rainfall event 3: 9 March 2017	0.6	1.2	02:45	2 hours	100	100	100
Rainfall event 1: 10 March 2017	3.8	8.4	04:30	3 hours	39.02	79.17	41.50
Rainfall event 2: 10 March 2017	0.8	1.8	00:30	2 hours	100	100	100
Rainfall event 3: 10 March 2017	0.4	1.2	05:05	3 hours	100	99.98	100
Rainfall event: 14 March 2017	1.2	8	09:00	3 days	91.94	100	66.83
Rainfall event: 15 March 2017	0.6	1	01:30	1.5 days	100	100	100
Rainfall event: 19 March 2017	0.8	1.6	01:15	3.5 days	100	100	100
Rainfall event: 24 March 2017	0.8	2.8	05:15	5.5 days	100	100	100
Rainfall event: 6-7 April 2017	1.6	18.2	10:30	12 days	75.70	97.30	71.81
Rainfall event: 24 April 2017	3.4	16.8	08:30	13 days	84.88	96.61	72.37
Rainfall event 1: 15 May 2017	0.8	3.8	01:45	4 hours	50.19	100	74.92
Rainfall event 2: 15 May 2017	1.4	3.4	03:30	4 hours	59.47	100	68.74
Rainfall event 3: 15 May 2017	0.6	1	00:15	9.5 days	100	100	100
Rainfall event 1: 13 July 2017	0.4	1.6	04:00	13 days	100	100	100
Rainfall event 2: 13 July 2017	0.8	0.8	00:15	13.5 days	100	100	100
Rainfall event: 17-18 August 2017	1.0	23	11:00	8 days	57.09	100	79.84
Rainfall event: 23 September 2017	1.2	11	05:15	5 days	100	100	98.64
Rainfall event: 26 September 2017	0.4	3.2	03:45	18 hours	100	100	100

Seemingly, the rain was too light to record any flow rate data from the 3 green roofs. The Control Roof had a retention of 41.52%, which may be due to ponding from the low-intensity rainfall.

Rainfall event: 10 March 2017

The first rainfall event on this day measured a peak intensity of 3.8mm/h, with a rainfall depth of 8.4mm. During this rainfall, the green roof systems did not work as well as previously, and this was because there were three rainfall events before the one under examination. The rainfall event also measured a higher peak intensity. These factors may have influenced the saturation of the green roof, and therefore its ability to retain water. The peak flow rate for Green Roof 3 occurred at the same time as the Control Roof, and Green Roof 3 did not delay the peak flow rate for this event. Using the Control Roof as a proxy, Green Roof 1 delayed the peak flow rate by 15 minutes, and Green Roof 2 by 30 minutes. The most notable difference in peak flow rates was observed between the Control Roof and Green Roof 2, where the Control Roof measured a peak flow rate of 0.197L/s and Green Roof 2 measured 0.029L/s. Green Roof 3 showed the highest peak flow rate amongst the green roof systems, at 0.138L/s. A lighter rainfall event occurred on the same day from 15:00 h to 15:30 h, with a peak rainfall intensity of 0.8mm/h and a rainfall depth of 1.8mm. The retention ranged from 30.19% from the Control Roof to 100% from all the green roof systems. The data confirms that the rainfall event was too light for any stormwater flow to leave the green roof systems. Another light rainfall event occurred on this day from 18:15 h to 23:30 h. The peak rainfall intensity was 0.4mm/h, and the rainfall depth was 1.2mm. Green Roof 1 and Green Roof 3 produced no flow for this rain event, whilst Green Roof 2 produced a 99.98% retention rate. The Control Roof showed a retention rate of 36.76%. The data verifies that none of the roofs discharged any stormwater after 20:30 h, except for the Control Roof (at 23:30 h) which was minimal, confirming that a very low rainfall does not produce runoff from a green roof system.

Rainfall event: 14 March 2017

This rain event measured a peak intensity of 1.2mm/h and a rainfall depth of 8mm. Green Roof 2 achieved a 100% retention rate, Green Roof 1 achieved a 91.94% rate and Green Roof 3 showed a 66.83% rate of retention. All three roofs performed significantly better than the Control Roof, which exhibited a 25.43% retention rate. When compared to the actual rainfall, Green Roof 3 delayed the peak flow rate by 15 minutes, and Green Roof 1 by 30 minutes. The greatest difference in peak flow rate when compared to the Control Roof came from Green Roof 2, as it measured no flow rate data for the rainfall event.

Rainfall event: 15 March 2017

This low-intensity rainfall event, which was 90 minutes in duration, measured 0.6mm/h, with a rainfall depth of 1mm. All the green roof systems did not produce any stormwater runoff, which infers that under low-intensity rainfall and short periods, green roofs can be highly effective in absorbing and retaining rainfall.

Rainfall event: 19 March 2017

This low-intensity rainfall event showed a depth of 1.6mm and a peak rainfall intensity of 0.8mm/h. As with the previous event, all three green roofs showed no record of stormwater runoff, whilst the Control Roof showed a retention rate of 42.54%.

Rainfall event: 24 March 2017

This rainfall event had a depth of 2.8mm, a peak rainfall intensity of 0.8mm/h, and a duration of 5 hours and 15 minutes. All green roofs demonstrated a 100% retention rate, whilst the Control Roof produced a retention rate of 9.58%.

Rainfall event: 6-7 April 2017

For this rainfall event, the retention rate amongst the green roof systems ranged from 71.81% for Green Roof 3 to 97.30% for Green Roof 2. Green Roof 2 recorded the lowest peak flow rate. Green Roof 2 also delayed the peak by the longest time, having reached its peak flow rate at 01:30 h. All three green roof systems delayed the peak flow rate in comparison to the Control Roof.

Rainfall event: 24 April 2017

This rainfall event had a peak intensity of 3.4mm/h and occurred over 8.5 hours. The maximum retention rate was 96.61% for Green Roof 2, and the lowest retention rate was 72.37% for Green Roof 3. The data reveals that the peak flow rate was delayed by one hour by Green Roof 3, and by one hour and 15 minutes by Green Roof 1 and Green Roof 2. The Control Roof achieved a peak of 0.231L/s, whilst Green Roof 2 achieved a peak of 0.011L/s. Overall, Green Roof 2 showed the greatest reduction in peak flow rate.

Rainfall event: 15 May 2017

This rainfall event occurred after an intense rainfall that lasted over two consecutive days (13 May-15 May 2017). Green Roof 2 retained 100% of the rainfall, Green Roof 2 attained a retention rate of 74.92%, and Green Roof 1 showed a 50.19% retention rate. The Control Roof yielded negative retention of -6.40%, due to the stormwater discharged being greater than the amount of rain that fell onto the roof. A possible reason for this occurrence is that the rainfall from the previous storm, ponded on the roof, and when this particular rainfall occurred, it washed out the previous runoff as well as the runoff from this storm. Using the Control Roof as a proxy, the peak flow rate for the Control Roof occurred at 16:00 h. The peak for Green Roof 1 also occurred at 16:00 h, demonstrating that it did not cause any delay. However, Green Roof 3 delayed the peak flow rate by 30 minutes. The most noticeable difference between peak flow rate measurements was between the Control Roof and Green Roof 2, where Green Roof 2 did not allow any stormwater to run off. Another rainfall event on the same day occurred over 3 hours and 30 minutes, which produced a peak intensity of 1.4mm/h. Once again, Green Roof 2 recorded no flow rate data denoting that it retained 100% of the rainfall. Green Roof 3 attained 68.74% retention and Green Roof 1 showed a 59.47% retention. Concerning the Control Roof, it is evident that the peak flow rate was achieved at 23:15 h, whilst Green Roof 1 and Green Roof 3 achieved their peak flow rate at 23:30 h. Although Green Roof 2 had no stormwater runoff, Green Roof 3 reduced the peak significantly, from 0.078L/s in the Control Roof to 0.023L/s. Green Roof 1 produced a higher peak than Green Roof 2, which is possibly due to Green Roof 1 reaching saturation before Green Roof 2.

Rainfall event: 27 May 2017

This rainfall measured a peak rainfall intensity of 0.6mm/h, and a total rainfall depth of 1mm. This was regarded as a low-intensity storm over a short time. None of the green roof systems discharged any stormwater during this rainfall event, whilst the Control Roof had a 16.25% retention rate.

Rainfall event: 13 July 2017

The first rainfall event on this day lasted for 4 hours and recorded a peak rainfall intensity of 0.4mm/h. All green roof systems had a 100% retention rate, whilst the Control Roof achieved a 5.87% retention rate. The second rainfall event attained a peak rainfall intensity of 0.8mm/h and the Control Roof retained 54.32% of rainfall.

Rainfall event: 17-18 August 2017

This rainfall event began on 17 August 2017 at 20:00 h and continued though to 18 August 2017 at 07:00 h. The data reveals that the retention rates from all the green roofs were higher than that from the Control Roof. Green Roof 2 achieved the highest retention rate of 100%, whilst Green Roof 3 showed a 79.84% retention rate and Green Roof 1 had a 57.09% retention rate. The peak flow rate for the Control Roof, Green Roof 1, and Green Roof 3 occurred at 01:00 h, 01:15 h, and 01:15 h, respectively. Green Roof 1 and Green Roof 3 were able to delay the peak flow rate by 15 minutes compared to the Control Roof. The greatest difference between peak flow rate measurements was found to be between the Control Roof and Green Roof 2, as this green roof system did not allow any stormwater runoff to be discharged. The Control Roof had a peak flow rate of 0.071L/s, Green Roof 1 0.050L/s, and Green Roof 3 0.042L/s.

Rainfall event: 23 September 2017

The rainfall event that occurred on 23 September 2017 experienced no prior rainfall in the previous 5 days. This rainfall had a peak intensity of 1.2mm/h and a duration of 5 hours and 15 minutes. Green Roof 1 and Green Roof 2 both achieved retention of 100%, whilst Green Roof 3 showed a 98.64% retention rate. A peak flow rate of 0.066L/s at 16:00 h was recorded for the Control Roof, and a peak flow rate of 0.008L/s at 17:45 h was recorded for Green Roof 3. This confirms that the green roof systems delayed, and reduced, the peak flow rate significantly for this rainfall event, compared to the Control Roof.

Rainfall event: 26 September 2017

A 0.4mm/h, high-intensity rainfall, lasting 3 hours and 45 minutes occurred on this day. All green roof systems achieved a 100% retention rate, whilst the Control Roof achieved a retention rate of 8.63%. The peak flow rate for the Control Roof was 0.024L/s.

DISCUSSION

The study found that for low-intensity rainfalls, average stormwater retention of 90.57% to 99.99% was achieved for the green roofs (see **Table 3**). Exceptions to this finding occurred during certain rainfall events and may be attributed to the prolonged duration of the storm. Also, on 15 May 2017, during the first rainfall event, Green Roof 1 and Green Roof 3 displayed a retention rate of 50.19% and 74.92%, respectively. This may have been a result of the rainfall event the day before which measured a peak intensity of 3.4mm/h and produced 148.6mm of rain. Rainfall event 2 on the same day saw the retention rate increase in Green Roof 1, but decrease in Green Roof 3. This event had a higher peak intensity, longer duration, but a slightly lower rainfall depth. A partial blockage to the outlet of the stormwater runoff system could be a reason for this anomaly. The event that took place over 17-18 August 2017, had an intensity of 1mm/h, lasted for 11 hours, and had a rainfall depth of 23mm. This longer rainfall duration and increased rainfall depth may have contributed to the reduced retention from Green Roof 1 and Green Roof 3.

For moderate-intensity rainfalls, the green roofs displayed an average retention rate of between 68.56% to 98.65% (see **Table 3**). Two events within this category were identified and occurred on 9 March 2017 during event 2, and over 6-7 April 2017. The properties of the former showed an intensity of 1.8mm/h lasting 3 hours and 45 minutes and resulting in 9.6mm of rain. During this event, retention was 73.92% for Green Roof 1, 100% for Green Roof 2 and 65.31% for Green Roof 3. The second moderate-intensity rainfall had an intensity of 1.6mm/h and lasted 10 hours and 30 minutes, with a rainfall depth of 18.2mm. During this event, retention was 75.70% for Green Roof 1, 97.30% for Green Roof 2 and 71.81% for Green Roof 3. Between event 1 and event 2, the retention in Green Roof 1 and Green Roof 3 increased, whilst the retention in Green Roof 2 decreased. The duration and rainfall depths were significantly different for the two events, whilst the rainfall intensity varied slightly. Results from Green Roof 1 and Green Roof 3 are consistent with research undertaken by Harper *et al.* (2015) and Shafique *et al.* (2018), which confirms that a storm of lower intensity will result in a higher retention rate.

The average retention rate for high-intensity rainfalls was between 67.27% and 91.93% (see **Table 3**). Green Roof 2 retained the most rainfall, and Green Roof 3 retained the least rainfall. Despite confirmation from previous studies which argued for a proportional relationship between substrate depth and retention capability (Mentens *et al*., 2006; Berndtsson, 2010; Zhang *et al*., 2015; Baryla *et al.,* 2018; Li *et al.,* 2018; Jusić *et al*., 2019), this study indicated that Green Roof 3, with the shallower substrate depth, had better retention rate than Green Roof 1, with a deeper substrate. This suggests that substrate mixture, vegetation type and vegetation density, affect the retention, and not just the thickness of the substrate layer. For Green Roof 2, 100% retention was achieved on 9 March 2017 during event 1, followed by 79.17% retention on 10 March 2017 during event 1, and 96.61% retention on 24 April 2017. The main differences between the three events were the rainfall duration and rainfall depth. There was also a slight difference in the rainfall intensity. Green Roof 2 did not follow the pattern in terms of rainfall depth and rainfall duration. Higher retention was produced during the shorter rainfall event with the lower rainfall depth. However, the second-highest retention did not occur during the second shortest rainfall event, as the pattern would suggest. The pattern did follow the rainfall intensity as there was higher retention achieved during the two 3.4mm/h rainfall events in comparison to the 3.8mm/h rainfall event. Green Roof 3 had the lowest retention in high-intensity rainfall events, the lowest of which occurred during the event with the second-longest duration and second-highest rainfall depth. The possible reason for this retention rate is the Antecedent Dry Weather Period (ADWP), as there was no rainfall before these events. It can therefore be concluded that during a high rainfall intensity, the retention capability of Green Roof 2 is largely controlled by the ADWP.

Substrate depth and mixture, as well as vegetation type and intensity, affect the retention capacity of green roofs. In this study, although Green Roof 2 and Green Roof 3 had the same substrate depth and mixture, they differed in terms of their plant type and plant density. The Green Roof 2 system has the densest vegetation from all the systems, and different plant types in comparison to the other two green roofs, and achieved the highest average retention rate in this study. These findings concur with observations made by other researchers that the type of vegetation planted on a green roof can affect the retention capability, with certain plant types contributing as much as 40% of the roof's retention capability (Berghahge *et al.,* 2007; Li *et al.,* 2018; Liu *et al.,* 2019; Zheng *et al.,* 2021).

The retention rate from Green Roof 1 and Green Roof 3 differ by more than 20%, which can be attributed to the varying substrate depths and mixtures. Several researchers argue that the substrate depth and mixtures are one of the major contributors to the retention capacity of a green roof system (Mentens *et al.,* 2006; Berndtsson, 2010; Zhang *et al.,* 2015; Baryla *et al.,* 2018; Shafique *et al.,* 2018). Green Roof 1 was constructed using a 3cm layer of a different substrate mixture, but similar vegetation to Green Roof 3. The difference in retention between Green Roof 3 and Green Roof 1 was 22.75%, with the former having the higher retention rate. The data, therefore, confirms that a deeper substrate layer leads to a higher retention rate during a rainfall event with similar properties, which corresponds with the findings of other similar studies (Mentens *et al.,* 2006; Berndtsson, 2010; Zhang *et al.,* 2015; Baryla *et al.,* 2018, Liu *et al.,* 2019; Zheng *et al.,* 2021). However, some inconsistencies were noted in this study, with particular rainfall events, where green roofs with a deeper substrate and denser volume of vegetation, resulted in a lower retention percentage than the green roof with a shallower substrate. A possible explanation for this is that the green roofs reached saturation and then mimicked the characteristics of the Control Roof, resulting in an excess amount of runoff. Overall, the findings of this study concur with that in previous studies which confirm a proportional relationship between retention capacity, and vegetation density and type (Berghage *et al*., 2009; Berndtsson, 2010; Berretta *et al.,* 2014; Harper *et al.,* 2015; Baryla *et al.,* 2018; Li *et al.,* 2018, Liu *et al.,* 2019).

Data from all storm events analyzed suggested that there was always a delay in the peak flow rate by a green roof system. Green Roof 2 had the greatest effect in delaying the peak flow rate, with an average retention of 98.6% over the six months. The main component of the growing medium in Green Roof 2 was LECA, which is known to have a high water-holding capacity (WHC). Vijayaraghavan & Joshi (2014), also confirmed a greater delay in runoff in substrates with a higher WHC. During certain events, some green roof systems recorded no flow data, which suggested that all the rainwater had been absorbed by the green roof. This may be attributed to a long period of dry days before the rainfall event. Past research also confirms that the ability of a green roof to retain water is improved with an increase in the number of dry days before the rainfall event (Stovin *et al.,* 2012; Lee *et al.,* 2015, Liu *et al.,* 2019), and is variable with storm intensity and duration (Ercolani *et al.,* 2018, Zheng *et al.,* 2021). By and large, the study confirmed that green roofs can delay the peak flow rate of stormwater runoff, which is consistent with the findings in other similar studies (Lee *et al.,* 2015; Stovin, 2010; Jusić *et al.,* 2019; Liu *et al.,* 2019).

PCSWMM model of the eThekwini CBD

The PCSWMM model investigated the effect of green roofs, similar to the composition of Green Roof 2, on stormwater peak and average flow rates and volumes within the eThekwini CBD. Green Roof 2 was the best performing green roof in terms of stormwater retention and was therefore believed to have the greatest impact in the modelling. A random block was selected within the CBD to implement the model (see **Figs. 5–7**). Two scenarios were compiled as follows: (a) a base model with the existing stormwater infrastructure (see **Fig. 7**), and (b) a model with green roofs installed on all the flat-roofed buildings within the block (see **Fig. 5**).

The results from the simulations of each of these models for different rainfall intensities were based on 1 in 2 years, 1 in 5 years, 1 in 10 years, 1 in 20 years, and 1 in 50 years' storms. The results of the base model were analysed based on peak flow. **Table 4** presents the peak flows at the outfall and inlet for different storm intensities, measured in m³/s. For all storm events, the values ranged from 0.308m³/s to 1.049 m³/s at the outfall, and 0.313m³/s to 1.063 m³/s at the inlet. The second model was of the

Table 4. Comparison of the peak flow rates (m³/s) from the base model and green roof model

	Outfall			Inlet		
	Base Model	Green Roof Model	Difference (%)	Base Model	Green Roof Model	Difference (%)
1 in 2 years	0.308	0.185	60.065	0.313	0.193	61.661
1 in 5 years	0.492	0.263	53.455	0.5	0.27	54.000
1 in 10 years	0.639	0.322	50.391	0.649	0.331	51.002
1 in 20 years	0.803	0.387	48.194	0.814	0.398	48.894
1 in 50 years	1.049	0.679	64.728	1.063	0.682	64.158

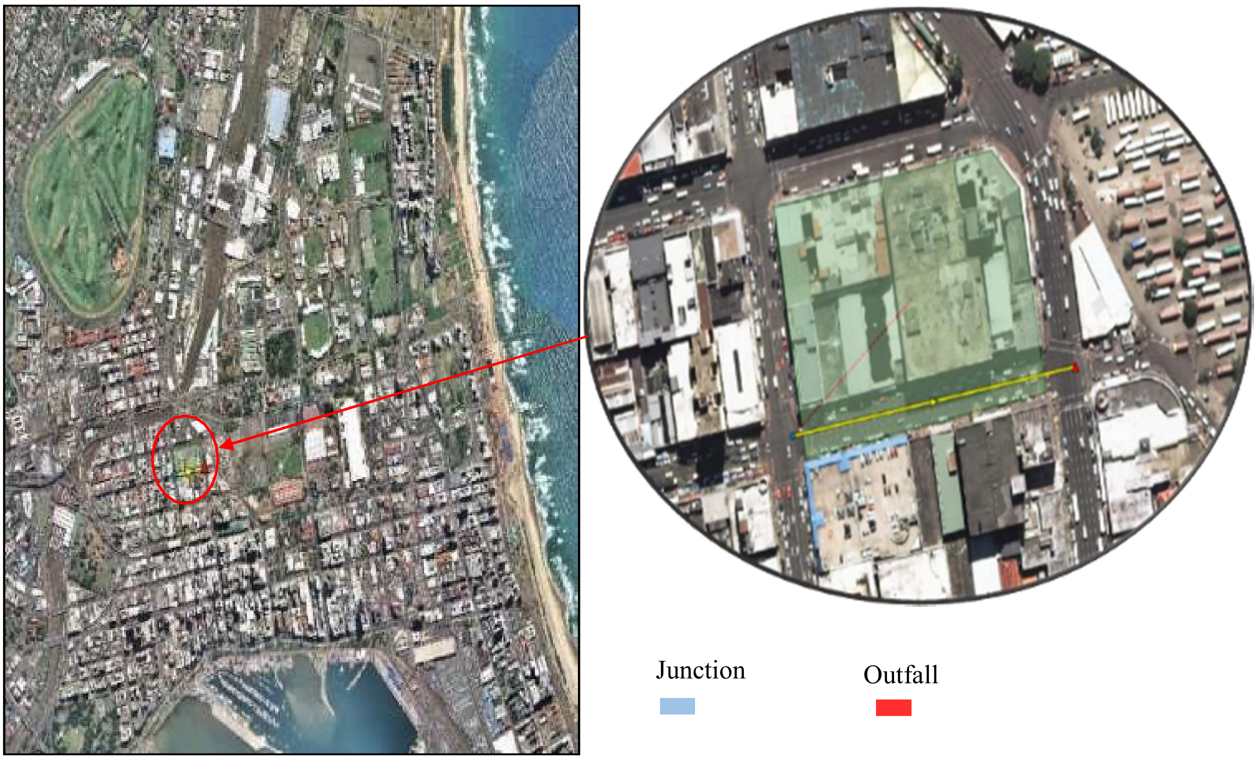

Fig. 7 Base model compiled in PCSWMM

eThekwini CBD block with green roofs, similar to Green Roof 2, installed on all the buildings. The adapted model was analysed based on peak flow rates, as shown in **Table 4**. For most of the storm events, the peak flow rate decreased when compared to the base model.

The PCSWMM model confirmed that when compared to the base model, peak flow rates from the green roof model decreased by over 40% for all storm intensities. For return periods 1 in 2 years, 1 in 5 years, 1 in 10 years, and 1 in 20 years, the percentage difference decreased with an increase in the return period. A break in the pattern occurred during the simulation of the 1 in 50 years return period, when the percentage difference increased and was the highest at both the outfall and the inlet. This indicates that green roofs performed the best in terms of stormwater management during the highest storm intensity. Assumptions made in the compilation of the PCSWMM model may be a reason for this discrepancy. The aforementioned assumptions include the absorption rate of the ground cover type and the dimensions of the inlet chamber to the stormwater system.

CONCLUSIONS

The data confirms that many factors affect the retention capacity of a green roof, such as substrate type, substrate depth, plant species, plant coverage, rainfall intensity, and the dry period length. The average retention percentage from green roofs with a thicker substrate was found to be higher than from green roofs with a thinner substrate layer. The results further indicate that two roofs with the same substrate mix and depth exhibited varying retentions, suggestive that the plant species and coverage impinge on the percentage of retention. The study further confirms that green roofs with a higher vegetation density showed a higher retention rate than green roofs with less dense vegetation cover. During longer dry period spells, the green roofs proved to perform better as opposed to during rainfall events with a shorter prior dry spell period, evocative that a green roof's ability to retain stormwater is very sensitive to the initial moisture conditions of the green roof system before a rainfall event. The outcome of the PCSWMM modelling showed that the implementation of the green roof system within the eThekwini CBD would reduce the peak flow rate of stormwater discharge by at least 40%.

Although green roofs have shown significant benefits in terms of reducing flow rates, and increasing retention capabilities, future research should target investigations into substrate mixes and plant types to understand and achieve the optimum retention abilities of a green roof system. The findings in this study and many others conclude that green roofs can and should be used as a means of reducing stormwater runoff rates and increasing stormwater retention, especially within urban environments. In this way, green roofs can be used as a means of flood mitigation. Results from the PCSWMM model suggest that implementing more green roofs within the eThekwini CBD could greatly reduce peak and average runoff flow rates, as well as reduce stormwater runoff volumes from the eThekwini CBD. This topic allows room for further research, education and implementation of green roofs in a South African urban context.

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