Stormwater Retention and Reuse at the Residential Plot Level—Green Roof Experiment and Water Balance Computations for Long-Term Use in Cyprus

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Abstract: Green roofs can provide various benefits to urban areas, including stormwater retention. However, semi-arid regions are a challenging environment for green roofs as long dry weather periods are met with short but intense rainfall events. This requires green roofs to retain maximum volumes of stormwater, while being tolerant to minimal irrigation supplies. The objectives of this study are (i) to quantify the stormwater retention of two substrate mixtures with two plant species under natural rainfall; (ii) to assess the performance of two plant species under two levels of deficit irrigation; and (iii) to compute stormwater runoff reduction and reuse by green roofs and rooftop water harvesting systems for three standard residential plot types in urban Nicosia, Cyprus. A rooftop experiment was carried out between February 2016 and April 2017 and results were used to compute long-term performance. Average stormwater retention of the 16 test beds was 77% of the 371-mm rainfall. A survival rate of 88% was recorded for *Euphorbia veneris* and 20% for *Frankenia laevis*, for a 30% evapotranspiration irrigation treatment. A combination of a green roof, rainwater harvesting system and 20-m^3 tank for irrigation and indoor greywater use reduced stormwater runoff by 47–53%, for the 30-year water balance computations.

Keywords: green roof; stormwater retention; deficit irrigation; water balance; rainwater harvesting; greywater use

1. Introduction

Sustainable urban drainage systems are being strongly promoted for managing stormwater in cities, due to their reliance on natural catchment processes that reduce runoff and improve stormwater quality close to its source [1–3]. Green roofs are a sustainable urban drainage system that can offer additional benefits, such as energy savings, reduction of the urban heat island effect, improved air quality, increased biodiversity, as well as improved aesthetic value of urban environments [4–6].

Weather-related factors such as antecedent substrate moisture, rainfall depth and the intensity and duration of rainfall events affect green roof stormwater retention [1,7,8]. Green roof substrate composition and depth, the plants and roof slope also influence stormwater retention [9–11]. Various studies have examined the substrate composition to optimize stormwater management,

minimize weight and support adequate plant growth [8,12,13]. However, few studies have investigated stormwater retention performance of different substrate mixtures under natural rainfall.

For arid and semi-arid environments, green roof plants should use high amounts of water post rainfall to reduce soil moisture and thereby runoff of subsequent precipitation events, but also persist and survive extended drought periods [14]. Green roof plants should be selected by comparing the microclimate of the green roof with the climate of the native habitat of potential plant species [15]. The identification of plants that are able to survive and grow under severe stress determines the success of a green roof's establishment.

Various modelling studies have examined the irrigation of green roofs using stormwater harvesting and greywater reuse systems and investigated required storage volumes [16–20]. However, no studies have modelled the collection of stormwater at the residential plot scale and its reuse for greywater demand and green roof and garden irrigation.
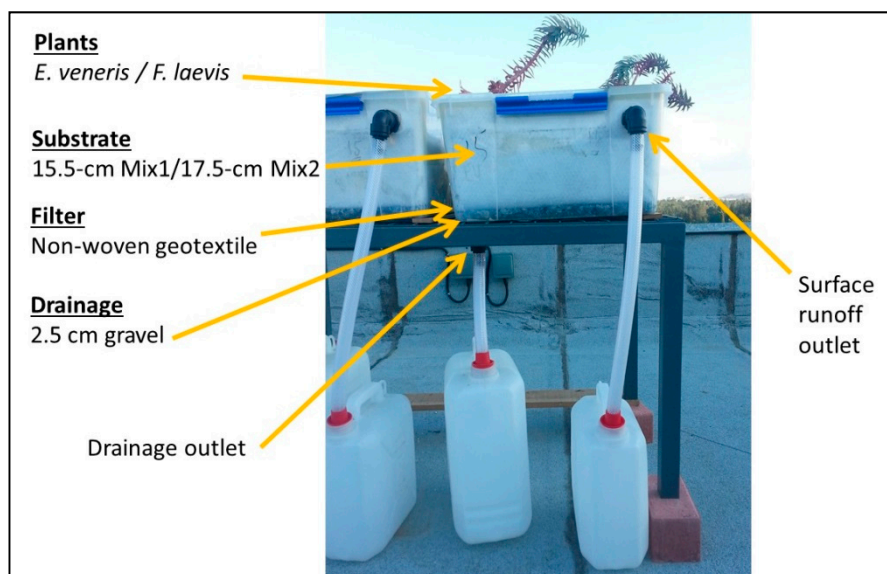
Few studies have investigated green roof water management in semi-arid environments. With an average annual rainfall of 315 mm, a daily maximum of 86 mm and a reference evapotranspiration (ET_o) of 1515 mm and daily maximum temperature averaging 37 °C in July (1980–2010), Nicosia, located in the center of Cyprus, is a challenging environment for green roof development. The specific objectives of this research are (i) to quantify the stormwater retention of two substrate mixtures with two plant species under natural rainfall; (ii) to assess the performance of the two plant species under two levels of deficit irrigation during the summer period; and (iii) to compute the reduction and reuse of stormwater runoff from green roofs and rooftop water harvesting systems for three standard residential plot types in urban Nicosia.

2. Materials and Methods

2.1. Green Roof Experimental Setup and Water Balance Monitoring

A green-roof experiment was established on the roof of the three-story Cyprus Institute's Guy Ourisson Building in Nicosia, Cyprus (latitude 35°08′26″, longitude 33°22′53″, elevation 180 m above sea level). The experimental design simulating a green roof comprised two substrate mixtures and two plant species (four replicates) and two irrigation treatments during the summer months. The experiment was carried out between February 2016 and April 2017.

Sixteen green roof test beds were setup in individual polypropylene plastic boxes (Figure 1). Each box consisted of a 2.5-cm drainage layer comprising gravel of 4 to 10 mm diameter, followed by a filter layer sheet of non-woven geotextile, which had a mass of 200 g/m^2, an 0.06-mm aperture opening size ($O_{90,w}$) and a cut through strength of 2.3 kN. This was overlaid by a substrate layer and plants. The test beds were individually given a 5% slope and each had an outlet at the bottom of the box for drainage, and a second outlet at the top of the substrate layer for surface runoff. Drainage and runoff were measured daily. A weather sensor (WS501; LUFFT, Fellbach, Germany) was installed next to the test beds and measurements were used to compute reference evapotranspiration (ET_o) using the methodology of the Food and Agricultural Organization, referred to as (FAO)-56 approach [21]. A tipping bucket rain gauge (16 mm diameter; 0.25 mm resolution; Davis, Hayward, CA, USA) and a manual rain gauge were placed next to the test beds. Thirteen 5TM capacitance soil moisture and temperature sensors (Decagon, Pullman, WA, USA) were installed in the test beds, seven in the Mix1 substrate and six in Mix2.

Figure 1. Setup of a green roof test bed (**top**), layout of the 16 green roof test beds (**bottom**).

Two substrate mixtures, referred to as Mix1 and Mix2, were developed from locally-available materials, based on the green roof specifications [22]. The main difference is the inclusion of the light-weight material perlite in Mix2, while keeping the load nearly the same. This allowed a depth of 17.5 cm for Mix2, compared to 15.5 cm for Mix1 (Table 1). The soil included in the substrate mixtures was 70% sand and 30% clay and silt (d < 0.063 mm). The compost components included 65.5% organic matter, 250 ppm Nitrogen-NO_3 and 315 ppm Phosphorus (Olsen), all on a dry basis. The substrate characteristics fall in line with other studies [8,12,13].

Table 1. Substrate component fractions by volume (v/v) for Mix1 and Mix2, depth of substrate, load, dry and saturated (Sat.) bulk density.

Substrate Mix	Substrate Components (v/v)						Depth	Load	Dry Bulk Density	Sat. Bulk Density
	Perlite	Pu1 [a]	Pu2 [b]	Zeo [c]	Soil	Com [d]	cm	kg/m^2	g/cm^3	g/cm^3
Mix1	0	0.3	0.25	0.15	0.15	0.15	15.5	121	0.79–0.84	1.01–1.18
Mix2	0.12	0.13	0.27	0.22	0.13	0.13	17.5	124	0.71–0.76	0.9–1.16

[a] Pumice1, with particle size range 5–8 mm; [b] Pumice2, with particle size range 0–8 mm, [c] Zeolite, with particle size range 0.8–2.5 mm; [d] Compost.

The plant species examined were *Euphorbia veneris* (Euphorbiaceae) and *Frankenia laevis* (Frankeniaceae). *Euphorbia veneris* (*E. veneris*) is a perennial with several simple stems up to 35-cm long arising from woody stock and is endemic to Cyprus [23]. *Frankenia laevis* (*F. laevis*), is a low prostrate shrub, minutely hairy, perennial with many branches, forming dense mats, with 2–5 mm long linear-lanceolate leaves [24]. Each test bed was planted with either six *E. veneris* plants or 12 *F. laevis* plugs.

2.2. Deficit Irrigation and Plant Performance

The test beds were rainfed between February and June 2016. On 1 June 2016, all test beds were irrigated until steady drainage was observed (approximately maximum water capacity), before commencing a deficit irrigation period during the summer period (2 June and 31 October 2016). Following studies carried out in similar environments [13], two levels of deficit-irrigation were applied, equal to 15% and 30% of ET_o, minus any rainfall, and were administered once every week. The low levels of irrigation were applied taking into account that the plants are adapted to the local environment and can survive without rain for long periods. Plant performance was assessed by measuring the number of surviving plants at the beginning and the end of the deficit irrigation period.

2.3. Stormwater Retention and Reuse for Residential Plots in Cyprus

2.3.1. Green Roof Water Balance Computations

A daily green roof water balance model was set up in Microsoft Excel, following the approach by [24]. The water balance equation was:

$$SM(t+1) = SM(t) + P(t) + IR(t) - Q(t) - ET_a(t) \tag{1}$$

where SM is the soil moisture (mm), P is the precipitation (mm), IR is the irrigation (mm), Q is the drainage and surface runoff (mm), ET_a is the actual evapotranspiration (mm), t is the current day and $t + 1$ the next day. The Q and ET_a components were computed as follows:

$$Q(t) = MAX((SM(t) + P(t) + IR(t) - FC), 0) \tag{2}$$

$$ET_a = K_s \times K_c \times ET_o \tag{3}$$

$$K_s = (SM - LL)/(UL - LL) \quad \text{for } LL < S < UL \tag{4}$$

$$K_s = 0 \qquad\qquad\qquad \text{for } SM < LL \tag{5}$$

$$K_s = 1 \qquad\qquad\qquad \text{for } SM < UL \tag{6}$$

where FC is the soil moisture at field capacity (mm), K_s is the water stress coefficient, K_c the crop coefficient, ET_o is the reference evapotranspiration (mm), LL (lower limit) is the substrate's soil moisture level below which no evaporation occurs (mm) and UL (upper limit) is the soil moisture level below which ET_o becomes constrained by available moisture (mm). Because of the shallow depths of the substrate, soil evaporation cannot be separated from plant transpiration. Therefore, no wilting point was established. The K_c parameter combines soil evaporation and plant transpiration and expresses the ratio between ET_o and the evapotranspiration of a green roof without soil moisture stress, while K_s describes the effect of water stress on evapotranspiration.

The collected experimental data were used to derive the values of FC, LL, UL and K_c. The parameters were fitted by minimizing the mean absolute error and bias between the observed (average of 13 sensors) and computed daily soil moisture, for the November 2016 to April 2017 period.

2.3.2. Plot-Level Stormwater Retention and Reuse Computations

The stormwater runoff for three types of residential plots was computed considering the inclusion of green roofs, roof-top rainwater harvesting, use of the harvested stormwater for garden and green roof irrigation, as well as for non-potable indoor water (greywater) use. Three typical urban plot types, with a standard Cypriot plot size of 520 m^2, are used for the analysis [25]. PlotType1 represents a residential plot with a single house and a large garden (340 m^2), PlotType2 represents a semi-detached two-unit family complex with a small garden (140 m^2) and PlotType3 represents a small-scale multi-storey residential complex with a 50-m^2 garden.

For Cyprus, household water consumption is approximately 150 L/d per person, for an average household of four people. Excluding garden irrigation, average non-potable water demand per household member has been estimated to be 56 L/d, consisting of 28% for toilet flushing, 2% for car washing and 7% for other uses [26]. Two tank sizes are considered for stormwater storage, a 10 or 20-m^3 tank, based on the availability of tank sizes in the market.

Daily runoff and greywater use is computed using the daily rainfall and climate data from the Nicosia meteorological station, for the 31-year period 1 January 1980 to 31 December 2010. Daily runoff for roof and paved areas was computed using the Curve Number equation [27]. A curve number of 98 was selected based on the value for impervious areas by the TR-55 manual on urban hydrology for small watersheds [27]. The daily soil water balance model (Equation (1)) was used for computing total stormwater runoff (Q) from the green roof and gardens. Irrigation was applied based on soil moisture levels, preventing the too high levels of plant stress observed in the experiment. For green roofs, irrigation was applied when the stress level reached 30% of the total available water capacity (*TAW* = UL − LL). For the gardens, irrigation was applied when soil moisture reached 50% of *TAW*. During the wet winter months (November to February) 10-mm of irrigation was applied, while during the other months 80% of the available soil moisture storage (UL − SM) was filled up, as to leave some storage for rainfall.

Runoff from garden areas was assumed to occur when the soil moisture exceeds the *TAW*. The *TAW* for garden soils in Nicosia was assumed to be 100 mm, which represents a medium coarse or fine texture soil with 70-cm depth [28]. Considering the highly variable conditions and management of residential gardens, the above equations and assumptions aim to give a general representation of the hydrology of private gardens.

3. Results and Discussion

3.1. Observed Stormwater Retention under Natural Rainfall

Total rainfall during the 15-month study period was 371 mm and ET$_o$ was 1704 mm. Rain and ET$_o$ for the 12-month period (May 2016–April 2017) were 316 mm and 1390 mm, respectively. The absolute maximum temperature was 41.7 °C (23 June 2016) and absolute daily minimum −0.4 °C (31 January 2017). The weather data fell in line with the long-term data from the nearby Athalassa station of the Cyprus Meteorological Service, which had an annual ET$_o$ ranging between 1405 and 1607 mm, for the 1980–2010 period.

Table 2 presents the combined drainage and surface runoff per treatment and the average retention, for all rainfall events that generated runoff. Total stormwater retention for the 15-month study period ranged between 74% and 79% of the rainfall for the four substrate and plant combinations. A 2-way analysis of variance showed that there were no statistically significant effects of the substrate ($p = 0.639$) and the plant species ($p = 0.864$) on stormwater retention. Surface runoff was observed for nine of the nineteen recorded drainage events. For seven of the nine events, surface runoff was less than 6% of the combined drainage and surface runoff of each event. For the other two events (17 December 2016 and 9 February 2017), the combined drainage and surface runoff was low but surface runoff was 0.01 mm (39%) and 0.11 mm (86%), respectively.

No clear patterns could be established between retention and rainfall intensity, rainfall depth or the substrate's antecedent moisture. However, for all events with high antecedent soil moisture, retention was low. Antecedent soil moisture did influence retention during events with high intensity. In the case of the 36.7-mm rainfall event with a high maximum 15-minute intensity (25.6 mm/h) and high antecedent soil moisture (19%) on 24 December 2017, low retention (32%) was observed. On the contrary, the 63.5-mm event with high maximum 15-minute intensity (34.4 mm/h) but very low antecedent soil moisture (3%) led to high retention (80%) on 14 April 2017. The high rainfall intensity of both events also led to the generation of surface runoff, irrelevant of the antecedent soil moisture.

Table 2. Rain; maximum 15-minute rainfall intensity (Max int.); combined drainage and surface runoff (average of four replicates) for four green roof treatments, consisting of two substrate mixtures (Mix1, Mix2) and two plant species (EU = *E. veneris*, FR = *F. Laevis*); and average retention (Ret.) of the 16 test beds, for all rainfall events with drainage between 1 February 2016 and 30 April 2017 (total rain 371 mm).

Date	Rain	Max int.	Combined Drainage and Surface Runoff				Ret.
			Mix1-EU	Mix1-FR	Mix2-EU	Mix2-FR	
	mm	mm/h	mm	mm	mm	mm	%
30/11, 1–2/12/16 [a]	41.3	7.4	6.7	14.6	3.6	6.4	81
12–13/12/2016 [a]	9.6	3	0.1	0	0.1	0	99
17/12/2016 [a]	7.6	1.4	0.1	0	0	0	99.5
21/12/2016 [a]	25.4	3.6	15.6	15.2	12.8	11.6	46
22/12/2016	8.6	2.4	4.4	3.5	5.1	3.5	52
23/12/2016	1.3	0.7	0.8	1	0.8	0.9	33
24/12/2016 [a]	36.7	25.6	21.5	21	31.4	25.4	32
25–26/12/2016	8.1	1.7	0.6	0.8	0.8	0.8	91
28/12/2016 [a]	13.6	5.8	7.8	10.4	9.5	7.5	35
29/12/2016	3.5	1.7	2.4	2.3	2.8	2.8	26
30/12/2016	3.5	1	1.9	2.5	2.3	2.7	33
02/01/2017	4	0.7	0.6	1.3	1.1	1.3	73
03/01/2017	2.1	0.3	1.2	1.5	1.4	1.4	35
05/01/2017	0.3	0.3	0	0	0	0	91
7–8/01/2017	3	1	0	0	0	0	100
10/01/2017 [a]	7.3	3	2.1	4	3.9	4.9	49
09/02/2017 [a]	10.3	3.4	0.2	0.1	0.1	0.1	99
10–12/03/2017	20	11.6	0.51 [b]	0.6	N/A	0.72 [c]	98
14–17/04/2017 [a]	63.5	34.4	13.9	16.6	10.3	9.4	80
Total	270		81	96	86	79	66

[a] surface runoff observed, [b] average of 3 replicates, [c] average of 2 replicates.

Figure 2 presents the soil moisture and water balance components between 26 November 2016 and 30 April 2017. The increase in soil moisture at the end of April was due to a 9-mm irrigation application. The average soil moisture observed by the seven sensors in Mix1 and the six sensors in Mix2 reached a maximum of 24% and 27%, respectively, both observed on 24 December 2016 at 23:00, after 113 mm rain during the previous 25 days. The soil moisture of the individual sensors at this time ranged between 13.4% and 43.5%. The absolute maximum soil moisture recorded by the 10-minute readings during the study period for the 13 sensors ranged between 15.3% and 43.6%. The large range could be due to preferential flow paths in the substrate. Soil moisture after drainage (field capacity) during the December and January rainfall events was around 20 to 22%. Total retention for the 16 test beds ranged between 71% and 87% of the 371 mm rainfall for the 15-month period.

There was no clear relation between the observed drainage and the average soil moisture of the test beds during the November 2016 to April 2017 period. In a similar study, a maximum water capacity of 63% was observed on samples from a field-installed green roof substrate, using tension plates, after rainfall exceeded laboratory-derived water storage potential [8]. The relatively low maximum water capacity values observed in the current study can be attributed to the test beds starting to drain before a homogeneous soil moisture level is obtained, due to preferential flow paths. Thus, this indicates that green roofs may not reach the maximum water capacity observed on samples tested in the laboratory, after 24 h submergence, as defined by green roof guidelines [22]. The reduction of substrate water storage capacity has also been suggested to be due to plant roots. For larger events (>25 mm), it has been shown that some plant species (*S. glauca*) had (36%) lower retention than unplanted modules or low-water using succulent species (*S. pachyphyllum*), even though these species would have higher ET rates [29]. The root structure of these plants potentially results in a greater number of macropores and sub-surface channels causing uneven and rapid water movement through unsaturated parts of the substrate.
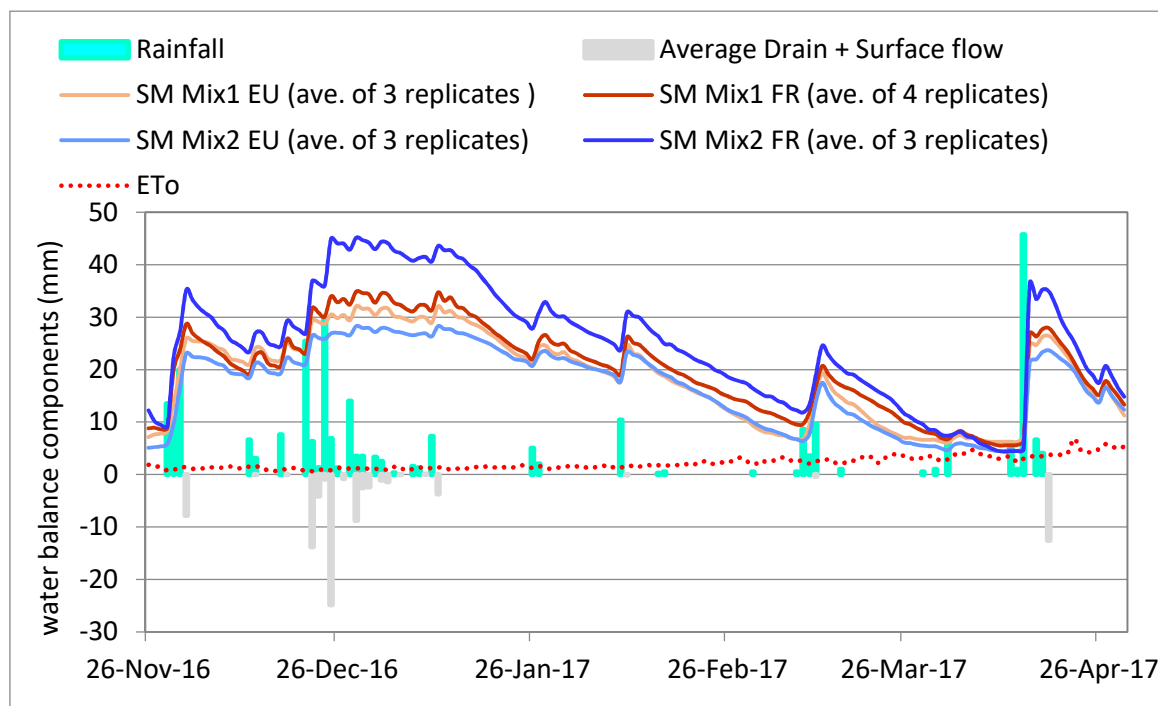
Figure 2. Water balance components and soil moisture (SM) for four green roof treatments, consisting of two substrate mixtures (Mix1, Mix2) and two plant species (EU = *E. veneris*, FR = *F. Laevis*) from 26 November 2016 to April 2017.

3.2. Deficit Irrigation and Plant Performance

After a five-day heatwave from 19 to 23 June 2016 (daily maximum temperatures between 40 and 42 °C) 74% of the *F. laevis* plants appeared severely stressed. Therefore, only the 30%-ET_o irrigation treatment was applied thereafter to all *F. laevis* test beds. The survival rate for the 30%-ET_o irrigation treatment was 20%. The survival rate for the *E. veneris* plant species was 88% for the 30%-ET_o treatment and 38% for the 15%-ET_o treatment. Thus, it is evident that a 15%-ET_o irrigation treatment is insufficient for either species. These results fall in line with a similar study [30], where a 30% survival rate was reported for *F. laevis* in a rainfed green roof treatment, under 640 mm rain and 925 mm ET_o in Barcelona, Spain, while a 100% survival rate was noted for a 20% and 40%-ET_o irrigation treatment.

The soil moisture sensors showed that 15%-ET_o irrigation did not substantially increase soil moisture, especially for Mix2 and towards the end of the deficit irrigation period. The soil evidently became so dry that water did not reach the sensor at 9-cm depth. This supports the finding that weekly irrigation applications at 15%-ET_o may not be sufficient to sustain green roof plants in this environment.

3.3. Stormwater Retention and Reuse for Residential Plots in Cyprus

Considering that the difference in the observed stormwater drainage of the two substrates was not statistically significant and their properties were nearly the same, the experimental results were averaged to determine the parameter values of the green roof water balance model. The fitted soil physical characteristics were 4% (7 mm) for LL, 16% (27 mm) for UL, and 22% (36 mm) for FC, with a K_c value of 1.0. The absolute mean error between the observed and modelled daily soil moisture was 3.2 mm and the bias was 0.02 mm.

Table 3 presents the average annual runoff from the three plot types with and without the inclusion of a green roof and a greywater reuse system for the 30-year computation period. For the cases without greywater use and without tank, a green roof reduces average annual stormwater runoff by 15–17%. These reductions become smaller with the addition of a 10- or 20-m³ tank. For the cases with greywater use, the effect of a green roof on runoff reduction is negligible. This is because the daily greywater use

leaves sufficient space in the tank to store the runoff from the roof that would otherwise be captured by the green roof. Average yearly stormwater runoff from paved areas was 5.1, 25.6 and 41 m^3/yr for PlotType1, 2 and 3, respectively. For garden areas this was 23.1, 9.5 and 3.4 m^3/yr for PlotType1, 2 and 3.

Table 3. Average stormwater runoff from the three residential plot types with and without green roof, indoor greywater (GW) use and storage tank for 1980–2010; Dif. is the percentage difference between the case with and without green roof.

Tank Size	Runoff No Green Roof No GW Use	Runoff Green Roof No GW Use	Dif.	Runoff No Green Roof GW Use	Runoff Green Roof GW Use	Dif.
	m^3/yr	m^3/yr	%	m^3/yr	m^3/yr	%
		PlotType1 [a]				
no tank	53.8	45.4	15.6			
10 m^3 tank	35.6	33.5	6.1	29.2	29.2	0.1
20 m^3 tank	30.2	29.7	1.8	28.2	28.2	0.0
		PlotType2 [b]				
no tank	74.4	61.5	17.4			
10 m^3 tank	53.3	47.2	11.4	38.5	38.4	0.2
20 m^3 tank	44.2	40.7	7.8	35.2	35.3	−0.2
		PlotType3 [c]				
no tank	83.5	70.7	15.4			
10 m^3 tank	65.5	56.7	13.4	46.3	46.0	0.7
20 m^3 tank	56.2	50.1	10.9	44.4	44.4	0.0

[a] 150 m^2 roof, 30 m^2 paved area, 340 m^2 garden, 4 residents; [b] 230 m^2 roof, 150 m^2 paved area, 140 m^2 garden, 8 residents; [c] 230 m^2 roof, 240 m^2 paved area, 50 m^2 garden, 20 residents.

Table 4 shows the water requirements for each case and the savings that can be achieved with a 10 or 20-m^3 tank. The requirement for greywater use is equivalent to the number of residents for each plot type and is 81, 164 and 409 m^3/yr for PlotType1, 2 and 3, respectively. Green roof irrigation water requirements are slightly less for PlotType1 (104 m^3/yr) than for PlotType2 and 3 (159 m^3/yr) as the roof area is smaller. Water requirements for garden irrigation decreased from 390 m^3/yr for PlotType1 to 161 and 57 m^3/yr for PlotType2 and 3, respectively. For PlotType3, savings of up to 48% can be achieved with the installation of a 20-m^3 tank for the case without greywater use and without a green roof, as the collected stormwater will be used for the small garden area. However, for all other cases the inclusion of collected stormwater will allow for limited savings in residential plots (2–19%).

Table 4. Average annual water requirements for irrigation and greywater (GW) use and savings that can be achieved with the installation of a 10 and 20-m^3 tank, for 1980–2010.

Water Requirements and Savings	No Green Roof No GW Use	Green Roof No GW Use	No Green Roof GW Use	Green Roof GW Use
	m^3/yr	m^3/yr	m^3/yr	m^3/yr
		PlotType1		
Water requirements	389.9	493.5	471.7	575.4
Savings—10 m^3 tank	18.1	11.9	24.6	16.3
Savings—20 m^3 tank	23.5	15.7	25.6	17.2
		PlotType2		
Water requirements	160.5	319.4	324.2	483.1
Savings—10 m^3 tank	21.0	14.2	35.9	23.1
Savings—20 m^3 tank	30.1	20.7	39.1	26.2
		PlotType3		
Water requirements	57.3	216.2	466.4	625.3
Savings—10 m^3 tank	18.0	14.0	37.3	24.7
Savings—20 m^3 tank	27.3	20.6	39.3	26.4

The best case for reduction of average annual stormwater runoff, for all plot types, is the inclusion of a 20-m^3 tank and greywater use. The inclusion of a green roof did not influence the reduction in stormwater runoff in this case. However, the inclusion of a green roof made a difference in the average annual stormwater runoff when no greywater use was included. It also made a difference for the cases with a 10-m^3 tank and greywater use, reducing runoff from 28.2 to 25.7 m^3/day for PlotType1, 27.4 to 24.8 m^3/day for PlotType2 and 30 to 27.6 m^3/day for PlotType3.

For a 1963-m^2 building in Athens, Greece, a combination of a green roof, rain water harvesting (200-m^3 tank) and greywater use was found to be the most preferable flood reduction option (average annual runoff 369 m^3/yr), compared to combinations of a green roof with greywater use (600 m^3/yr) and rainwater harvesting with greywater use (874 m^3/yr) [19]. In the current Nicosia study for the inclusion of a green roof only the case without a water-harvesting tank or without greywater use provides a significant difference (15–17%) in the retention of annual rain.

The use of a daily time step in calculations for the performance of rainwater tanks has been found to underestimate roof runoff yields compared to a 6-min time step [31]. Moreover, the water quality of the collected runoff may reduce the volume that can be used for indoor greywater use. Thus, further research can optimize the availability of collected runoff for greywater use and irrigation.

4. Conclusions

- A 15.5-cm deep green roof substrate made up of pumice, zeolite, soil and compost and a 17.5-cm deep substrate, which contained lightweight perlite aggregates in addition to the above, achieved an average retention of 77% of the 371 mm rainfall for a 15-month study period in Nicosia, Cyprus.

- A 30%-ET$_o$ irrigation treatment during the dry June to October summer months gave an 88% survival rate for the stalky, endemic succulent *E. veneris* and a 20% survival rate for the groundcover species *F. laevis.* Thus, a higher irrigation rate should be tested, while the combination of the two species could improve the water use efficiency and greenness of the roof.

- The substrate type and plant species had no statistically significant effect on stormwater retention. The observed variabilities in soil moisture and drainage showed that the substrates start draining before they reach a homogeneous field capacity soil moisture level, indicating the importance of in situ testing of green roof performance.

- The water balance computations showed that the combination of a green roof with a rainwater harvesting system, a 20-m^3 tank, and use of the collected water for outdoor irrigation and indoor greywater use reduced long-term average annual stormwater runoff up to 47–53%, for three types of standard 520-m^2 residential plots in Nicosia. For the cases where collected runoff was used for indoor greywater demand, the inclusion of a green roof did not affect the reduction of stormwater runoff. The use of a 20-m^3 tank for storage of stormwater runoff, for green roof, garden irrigation and indoor greywater use, provides an average annual water saving of 3–5% for urban plots in Nicosia.

- Green roofs can reduce stormwater runoff but are not as effective as rainwater harvesting systems with large storage tanks. However, the environmental benefits of green roofs, aside from stormwater management, support the importance of implementing them. Further research could examine the environmental trade-offs between green roofs with various irrigation levels and plant species and the heating and cooling requirements of buildings.

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