The Impact of Green Roofs on Runoff Quantity

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Green roofs are becoming popular in urban areas due to their potential benefits, including energy efficiency, urban heat island mitigation, and stormwater management. However, their water consumption can negatively impact water resources. Therefore, carefully managing the water consumption of green roofs is crucial to ensure they do not exacerbate existing water scarcity issues. Using integrated technologies and sensing systems can increase water management efficiency and sustainability.

green roofs runoff quantity runoff quality irrigation

1. Rainwater Retention

The capacity of a green roof to retain water influences its ability to reduce runoff and mitigate stormwater [1][2][3]. Most studies on the water retention of green roofs worldwide base their assessment on the percentage of rainfall harvested by a green roof over a specific period [4]. Generally, the average water retention capacity of a green roof ranges between 8% and 100% based on the climate and the green roof type and configuration [5][6][7][8][9][10][11][12], making it difficult to compare, as the numerical values vary across most studies [13]. For instance, Li and Yeung [14] reported that green roofs can retain water produced by any small rain event with a volume of less than 10 mm and can demonstrate a variety of runoff results, ranging from 26% to 88%. In contrast, Simmons and Gardiner [12] observed capacities ranging between 8% and 88% on different green roofs, and Burszta-Adamiak and Abdef [15] stated that the water retention rate for 153 rainfall events reached 82.5% and almost 100% in low-capacity events [15]. **Table 1** summarises the selected examinations of the water retention capacity of green roofs across different settings and climates to explain their influence on the hydrological performance of green roofs.

Table 1. Selected investigations on the rainwater retention of various green roof settings in different climates. RWR = rainwater retention.

Reference	Methods	Climate	Location	Green Roof Type	Green Roof Area (m^2)	Rainfall Depth (mm)	Rainfall Events	Substrate Depth (cm)	RWR Rate (%)
Li and Liu [16]	Experiment	humid subtropical	Chongqing, China	Test beds	1.44	2.26–71.20	99	20	40–83
Todorov, Driscoll [17]	Measurements	Cool, humid	Syracuse, NY, USA	Extensive	1190	6.93 ± 6.50 average	-	9.5	75–99.6

Reference	Methods	Climate	Location	Green Roof Type	Green Roof Area (m^2)	Rainfall Depth (mm)	Rainfall Events	Substrate Depth (cm)	RWR Rate (%)
Soulis, Ntoulas [9]	Experiment	Mediterranean	Athens, Greece	30 test beds	2	10.3 average	-	8 and 16	50.6–81.1
Brandao, Cameira [8]	Experiment	Mediterranean	Lisbon, Portugal	Test beds	2.5	13.05 average	184	15	71.1–82
Zhang, Miao [18]	Experiment	Subtropical, monsoon	Chongqing, China	Test bed	1	1116.5 total	19	15	35.5–100
Beecham and Razzaghmanesh [6]	Experiment	Hot, Mediterranean	Adelaide, Australia	16 test beds	0.15	24.12 average	5	10 and 30	52 and 95
Burszta-Adamiak [19]	Experiment	Temperate	Wroclaw, Poland	Five test plots	2.88	-	153	-	82.6–99.9
Simmons, Gardiner [12]	Experiment	Subhumid, subtropical	Austin, TX, USA	24 roof platforms	3.4	89.3 total	3	10	8–88
Stovin, Dunnett [7]	Experiment	Temperate	Sheffield, UK	Test bed	3	9.2 average	11	8	10–90
Carter and Rasmussen [20]	Experiment	Humid, subtropical	Athens, GA, USA	Test plot	42.64	1079 total	31	7.62	39–100
VanWoert, Rowe [3]	Experiment	Temperate	MI, USA	Vegetated roof	5.9536	-	-	2.5	60.6–96

Green roofs can experience runoff under certain conditions, such as during heavy rainfall or when the green roof substrate becomes saturated [21]. The rainwater retention feature of green roofs provides an opportunity to delay and reduce peak flows, specifically in frequent storms of smaller magnitudes [22]; this can help control the volume of stormwater. Many studies have reported delays in the runoff after rain events of a smaller intensity on green roofs [23][24]. However, their records contain vast differences due to the various green roof settings, environments, and investigated climates. For example, Getter and Rowe [25] studied 12 extensive green roof platforms with 4 different slopes (2%, 7%, 15%, and 25%) and observed marginal delays for all the studied platforms. By contrast, DeNardo and Jarrett [26] noticed delays in the start of the runoff on a green roof by an average of 5.7 h under an average rainfall intensity of 4.3 mm/hour. Therefore, rainfall characteristics and green roof settings significantly affect the delay time (peak to peak). However, it is challenging to draw a conclusion about the required green roof settings for the best performance from the reviewed articles, and a case-by-case assessment is needed, which will be presented in the discussion section. Lastly, the runoff delay increases with the increase in the rainwater retention ability of a green roof. **Table 2** summarises the selected investigations of the peak delay of the runoff of different green roof types and climates.

Table 2. Important papers on the peak delay of runoff waters in different green roof settings and climates.

Reference	Method	Climate	Location	Substrate Depth (cm)	Plants	Delay Runoff (h)
Wang, Garg	Experiment +	tropical	South	10, 19, 25	Grass	0.40–

Reference	Method	Climate	Location	Substrate Depth (cm)	Plants	Delay Runoff (h)
[27]	modelling		China			1.68
Santos, Silva [21]	Experiment	Mediterranean	Lisbon, Portugal	15	*Sedum album*, *Sedum sexangular*, *Sedum spurium*, *Sedum spurium tricolor*, *Sedum coral reef*, *Sedum oreganum*, *Sedum forsteriamum*, *Armeria Maritima* and *Thymus red creeping e Rosmarinus officinalis*.	0.03–0.30
Zhang, Lin [28]	Experiment	humid continental	Beijing, China	10, 15	*Sedum* spp.	1.05–2.18, 1.36–3.50
Brandao, Cameira [8]	Experiment	Mediterranean	Lisbon, Portugal	15	Mixed Shrubs, grass, and moss	0.49
					Grass (*Brachypodium phoenicoides*)	2.54
					Shrub (*Rosmarinus officinalis*)	1.26
					Bare soil	0.94
Burszta-Adamiak, Stańczyk [29]	Experiment	Temperate	Wroclaw, Poland	extensive green roof	*Sedum acre*, *Sempervivum*	1.5–1.7
Almaaitah and Joksimovic [30]	Experiment	continental climate	Toronto, ON, Canada	25–30	Planted with seeds of thirty different crops	7.70–8.00
Carter and Rasmussen [20]	Experiment	Humid, Subtropical	Athens, GA, USA	7.62	*Sedum* spp.	0.58
Nawaz, McDonald [31]	Measurements	Maritime, temperate	Leeds, UK	3	*Sedum* spp.	4.25–8.25

3. Influencing Factors

The water retention abilities of green roofs vary widely, and the current literature has conflicting results. This is mainly due to the various settings of green roofs and the climate in which they are situated and is an indication of the complexity of assessing their hydrological performance [5][6][7][8][9][10][11][12]. This section summarises the most important factors that influence the water balance in green roofs.

3.1. Climate Characteristics

Each climate has a different influence on the hydrological performance of a green roof, and its overall impact cannot be predicted or measured because each climate has different trends across different regions. In general, rainfall events, dry weather periods, and seasons were all found to be important factors in the assessment of rainwater retention in green roofs. Rainfall depth and intensity have a strong negative correlation with the water retention rate [2][32][33][34], and as they decrease, the retention rate increases [3][12][17][25][34][35]. Local weather patterns and seasonal conditions influence the soil moisture content [4][36][37]. For instance, a dry weather period is crucial for hosting rainwater, as it allows for evapotranspiration (ET) and vegetation water consumption to reduce the soil moisture content and increase the retention ability in the next rainfall [4][31][34][36][37]. Different climatic conditions cause variations in dry weather periods; therefore, their relationship with the green roof retention capacity must be characterised [2][10][11][38][39]. Different seasons also affect the capacity of a green roof to retain rainwater throughout the year and exhibit different retention rates [31][33][35]. Although the water retention percentage greatly depends on the rainfall input, it is not the only controlling factor [40]. The retention capacity of a green roof is finite and can be maximised only up to the maximum water-holding capacity of the green roof [2][17][26][38], which is dependent on the factors discussed in the following subsections.

3.2. Substrate Characteristics

The water storage capacity of the substrate mostly depends on the growing medium composition, depth, and maximum water-holding capacity [3][4][26][41][42][43]. An increase in substrate depth has been shown to improve water retention performance in green roofs [3][9][43][44]. The composition of the substrate is also an essential variable affecting its water-holding capacity [45]; for instance, coarser materials retain less rainwater [46]. Some papers have introduced new material compositions to increase the substrate's water-holding capacity. For instance, Vijayaraghavan and Raja [24] proposed a mixture of expanded perlite, coco peat, exfoliated vermiculite, crushed bricks, and sand with a particle size ranging between 0.25 mm and 4 mm, which showed a water-holding capacity of 39.4% [24]. Several researchers also suggested the addition of gritty loam soil, perlite-based substrates, foam sheets, fibreglass, and biological additives, such as seaweed and hydrophilic gels, for the same aim [47][48]. A few examples are summarised in **Table 3**.

Table 3. Selected articles on different substrate properties and their effects on runoff. WHC = water holding capacity, and RWR = rainwater retention.

Article	Substrate Depth	Max WHC%	Growing Media Composition	RWR Rate (%)
Beecham and Razzaghmanesh [6]	10	41	(A) Crushed red brick, scoria, coir fibre, and composted organics	70
	30			74
	10	44	(B) Comprised scoria, composted pine bark, and hydro-cell flakes	58
	30			60

Article	Substrate Depth	Max WHC%	Growing Media Composition	RWR Rate (%)
	10	48	(C) 50% of media type B with 50% organic compost	68
	30			70
Simmons, Gardiner [12]	10	34	(A) Expanded shale, sand, and organic matter	21.67
		37	(B) Expanded clay, expanded shale, sand, and organic matter	51.67
		43	(C) Expanded clay, sand, perlite, and organic matter	41.67
		46	(D) Decomposed granite, perlite, and organic matter	58.33
		38	(E) Expanded clay, expanded shale, sand, and organic matter	32
		32	(F) Expanded clay, expanded shale, sand, and organic matter	17
Baryla, Karczmarczyk [49]	8	20	Washed gravel	62.7
	8	20	Expanded clay aggregate	62.7
	17	55	Washed sand, chalcedony, clay, low peat, and compost	80
Soulis, Ntoulas [9]	8	54.2	Pumice (65%), attapulgite clay (15%), zeolite (5%), and grape marc (15%)	50.6
	16			54.8

Another important variable is the current moisture content of the substrate prior to a rain event [13][36]. Although some papers have suggested an uncertain correlation between the current moisture content of the substrate and rainwater retention [9][31][38], it strongly affects the substrate's retention capacity [2][10][11][34][37][38][39][50]. Dry substrate conditions before rainfall events will result in higher retention compared with initially wet conditions [31][36][37][41], as the runoff does not occur until the substrate is at field capacity [33][40]. **Figure 1** demonstrates the different factors that affect the moisture content of the green roof substrate.

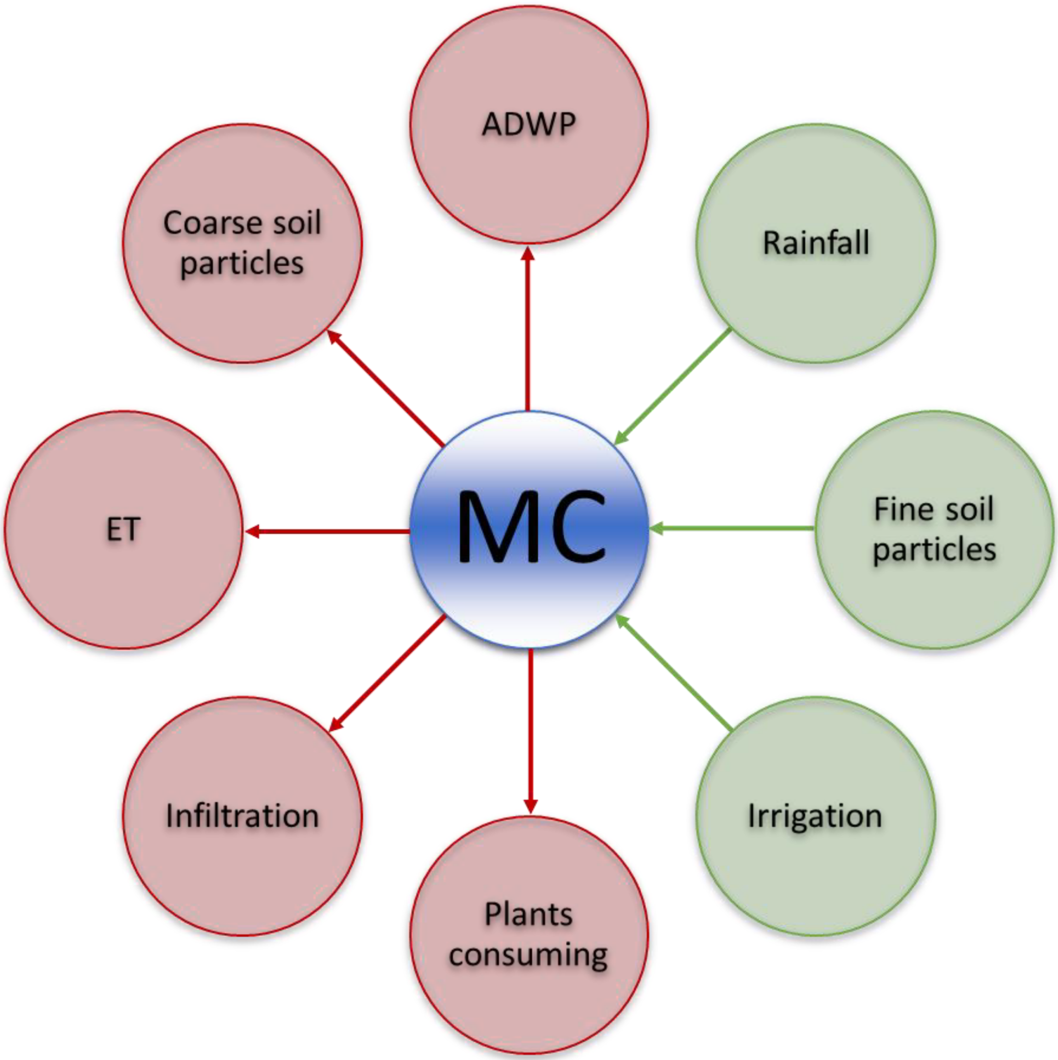

Figure 1. Effects of different factors on the substrate moisture content (MC) (red is negative, and green is positive). ADWP = anticipated dry weather period, and ET = evapotranspiration.

3.3. Vegetation

Vegetation is an important factor that substantially influences the moisture content of the substrate and the runoff rate of a green roof [6][51][52]. A reduction occurs through different processes, such as interception, transpiration, root uptake, retention, and water storage in plant tissue [38][41]. The water consumption of a plant determines its transpiration capacity, maturity, and root biomass and influences its water-storing capacity [32][39][41][53]. Increasing plant coverage on a green roof improves its ability to retain water [13], but species richness does not significantly affect the retention capacity unless different plants with higher water consumption rates are included [43][53]. **Table 4** provides two examples of the effects of vegetation species on green roof runoff rates.

Table 4. Selected studies on different plants and their effects on the rainwater retention of green roofs. RWR = rainwater retention.

Reference	Substrate Depth (cm)	Plants	RWR Rate (%)
Soulis, Ntoulas [9]	8	*O. onites*	63.6
	8	*S. sediforme*	50.8
	8	*F. arundinacea*	54.9
	8	-	50.6
	16	*O. onites*	81.1
	16	*S. sediforme*	60.3
	16	*F. arundinacea*	68.8
	16	-	54.8
Brandao, Cameira [8]	15	Mix of shrubs (*Rosmarinus officinalis*, *Lavandula stoechas subspecies Luisieri*), grass (*Brachypodium phoenicoides*), and moss (*Pleurochaete squarrosa*)	82
		Grass (*Brachypodium phoenicoides*)	73.2
		Shrub (*Rosmarinus officinalis*)	71.1
		-	64.2

Vegetation exhibits seasonal fluctuations in water consumption due to various factors, especially during growing seasons when ET increases significantly [4][17]. The effect of vegetation on the total hydrological performance of a green roof varies among studies. While some studies show significant effects of vegetation on moisture reduction [54], others report its influence only in specific seasons [42]. However, selecting vegetation for green roofs is crucial and should be based on plant characteristics and the local climate [55]. For example, plant height and stomata are positively correlated with green-roof water retention capacity, and the selection of suitable plants can conserve or promote the consumption of water more efficiently [56][57].

3.4. Drainage Layer

The drainage layer, also known as the drainage system, is an essential component of a green roof [3]. This layer can be made of different materials, but it is usually composed of granular-based materials, such as aggregate and geo-composites [3][58]. Different drainage layer types and the used materials alter the runoff performance of green roofs (**Table 5**). The drainage layer is crucial for proper plant growth and controlling water-related issues and can act as a water storage system to balance water surplus and deficit [3]. The layer can have an additional water retention layer made of such materials as mineral wool, polymeric fibres, or rubber sheets, which also store water and release it slowly [59][60]. The drainage and water retention layers can serve as an active water retention layer, thus acting as a potential water source for the green roof [3][61][62]. This setup is crucial for water sustainability practices on green roofs [63][64], as it decreases the need for irrigation or replaces it completely [65]. Several studies have also introduced new materials and approaches to improve the efficiency of the drainage layer [32][49].

Table 5. Two examples of the influence of the drainage layer's properties on the green roof's runoff rate. RWR = rainwater runoff.

Article	Drainage Layer	Substrate Depth (cm)	RWR Rate (%)
Burszta-Adamiak [19]	Plastic profiled drainage elements type FKD 12 (height: 1.2 cm)	-	82.5
	Gravel with 2–5 cm granulation	-	85.7
Baryla, Karczmarczyk [49]	Polypropylene mat (Terrafond Garden 20 L type with a thickness of 2 cm) and geotextile fabric on top of the drainage layer	17	80
	Washed gravel	8	62.7
	Expanded clay aggregate	8	62.7

3.5. Other Influencing Factors

Several other factors can also influence rainwater retention, such as the slope of the green roof, its age, and the irrigation system used. Although a few studies found no association between a green roof's slope and the volume of retained water [23][44], others observed a meaningful correlation between them [25][35][61][66]. **Table 6** presents three examples of studies that investigated the effects of different slopes on the runoff performance of green roofs.

Table 6. Selected studies on the effects of different slopes on green roof runoff rates. RWR = rainwater retention.

Article	Climate	Study Location	Green Roof Area	Substrate Depth (cm)	Slope	RWR Rate (%)
Getter and Rowe [25]	Temperate	USA	5.9536	6	2%	85.2
					7%	82.2
					15%	78
					25%	75.3
Villarreal and Bengtsson [35]	Oceanic	Sweden	1.544	4	2°	62
					8°	43
					14°	39

Article	Climate	Study Location	Green Roof Area	Substrate Depth (cm)	Slope	RWR Rate (%)
Chow and Abu Bakar [67]	Tropical	Malaysia	2	13	0°	56.9
					2°	56.4
					5°	55.9
					7°	52.3

roof and found that the maturity of a green roof can be considered an important factor [41][68]. Berndtsson [13] stated that over time, the root's development and loss of soil particles, such as the washout of some dissolvable materials and various organic content, can change the growing medium's porosity, which will influence its hydrological performance. For instance, Getter and Rowe [25] monitored soil properties on a vegetated roof for five years and tracked the organic matter content and other physical properties. They found that the pore space and organic matter content doubled within this period from 41% to 82% and 2% to 4%, respectively, increasing the water-holding capacity from 17% to 67% [25]. Lastly, although irrigation is needed to help vegetation survive when the substrate is dried out and to improve the thermal performance of a green roof [68][69][70], the use of irrigation prior to anticipated rainfall increases the soil's moisture, thus reducing retention and increasing runoff during the next rainfall event [71][72].

3.6. Summary

The above subsections provided various influencing factors for the hydrological performance of green roofs. To increase clarity, **Figure 2** summarises the hydrological performance of green roofs and the influencing factors.

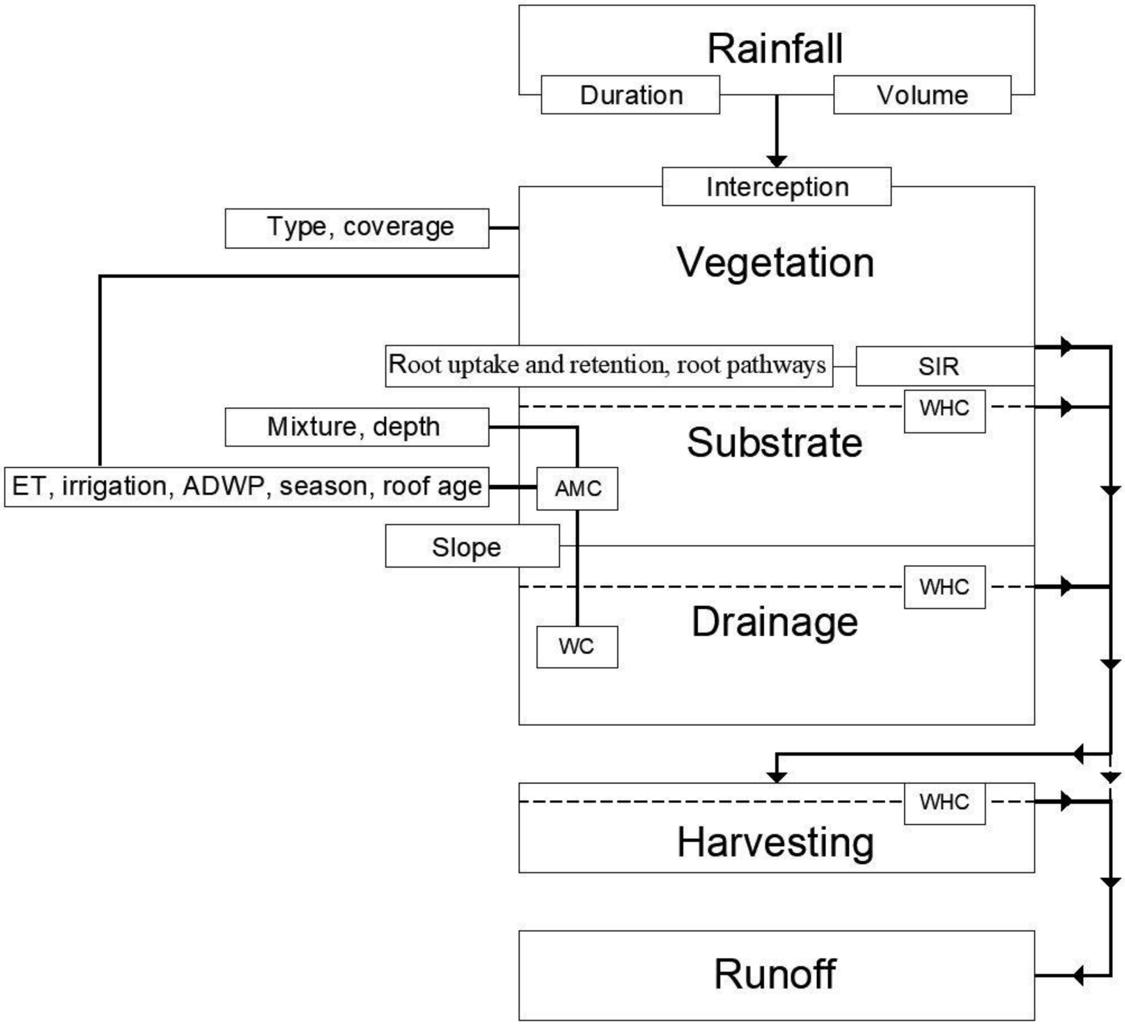

Figure 2. Hydrological performance of green roofs and the influencing factors. ET = evapotranspiration, ADWP = anticipated dry weather period, AMC = anticipated moisture content, WHC = water holding capacity, WC = water content, and SIR = substrate's infiltration rate.

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