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Are Biocrusts and Xerophytic Vegetation a Viable Green Roof Typology in a Mediterranean Climate? A Comparison between Differently Vegetated Green Roofs in Water Runoff and Water Quality

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Abstract: Green roofs can be an innovative and effective way of mitigating the environmental impact of urbanization by providing several important ecosystem services. However, it is known that the performance of green roofs varies depending on the type of vegetation and, in drier climates, without resorting to irrigation, these are limited to xerophytic plant species and biocrusts. The aim of this research was therefore to compare differently vegetated green roofs planted with this type of vegetation. A particular focus was their ability to hold water during intense stormwater events and also the quality of the harvested rainwater. Six test beds with different vegetation compositions were used on the roof of a building in Lisbon. Regarding stormwater retention, the results varied depending on the composition of the vegetation and the season. As for water quality, almost all the parameters tested were higher than the Drinking Water Directive from the European Union (EU) and Word Health Organization (WHO) guidelines for drinking-water quality standards for potable water. Based on our results, biocrusts and xerophytic vegetation are a viable green roof typology for slowing runoff during stormwater events.

Keywords: nature-based solutions; ecosystem services; sustainability; stormwater retention; water reuse; Mediterranean climate; biocrust roofs; xerophytic vegetation

1. Introduction

Many urban areas have been steadily increasing both in size and density as more people migrate from rural areas [1]. Increasing population densities in urban environments can lead to an intensification of the urban heat island effect [2] and higher vulnerability to flooding, as settlements on floodplains, deforestation, land conversion and an increase in impervious surfaces areas can increase the number of flood events and their associated risks [3–5]. In fact, the Mediterranean basin experiences several flood episodes every year, mainly during the autumn and winter months [6,7], namely in southeast Spain, southern

France, Italy, Greece and Israel [6–8]. With climate change set to intensify this trend in the future, not only will such episodes become more frequent, but also more people will be vulnerable to them, increasing the risk of health hazards [5,9–14] and significant economic losses [9,12]. The reduction in biodiversity due to habitat fragmentation and/or degradation [15–18] and the increase in pollution levels [19–21] are two other major threats that can arise or be aggravated by higher population densities in urban environments. One of the solutions to counter these threats is to create more and improve existing, green spaces. These not only cool the atmosphere due to the evapotranspiration process [22–24] but also can be used both to regulate the urban water cycle by reducing the amount of stormwater runoff and to improve water quality by removing pollutants from runoff. Vegetated streetscapes designed to absorb water, such as bioswales and rain gardens, have been shown to be particularly effective, and while street trees intercept rainfall in their canopies and store water on their leaves and stems until it is subsequently evaporated, those planted in tree pits considerably increase the infiltration rate and thereby reduce surface water runoff [25]. However, the rise in the demand for more housing and industry in urban areas tends to prevent the expansion and preservation of green areas.

A possible solution to compensate for these issues is the use of green roofs, which are classified as intensive, semi-intensive or extensive, depending on the depth of the substrate. An extensive green roof type has a shallow substrate, small plants, and low maintenance requirements, usually without irrigation, which makes it more suitable for implementation at a large scale. In contrast, an intensive green roof is characterized by a deeper substrate, taller vegetation varieties, and therefore higher maintenance and usually more advanced irrigation systems. Green roofs have the potential to offer a wide range of benefits [26–28], such as: (i) stormwater management [29], since they absorb and hold rainfall, thereby preventing or at least mitigating flooding episodes, with the possibility of reusing the water retained for irrigation [30]; (ii) increase building insulation, keeping it warmer in the winter and cooler during summer, thereby reducing energy consumption [26,31]; (iii) mitigating the urban heat island effect [32,33]; (iv) sequestering air pollutants such as CO_2 [34]; and (v) creating habitats for flora and fauna, mainly insects and birds [35–37]. They may also be partially noise absorptive. Extensive research has been undertaken on these benefits in comparison to more traditional roof materials. Several studies have already assessed how green roofs perform concerning stormwater retention [38–43], not only when compared to traditional roofs but also comparing different types of green roof vegetation. Green roofs may delay the timing of peak runoff, thereby alleviating stress on storm-sewer systems, by storing water in the growing medium and to a lesser extent in the vegetation canopy. The ability of a roof to retain stormwater depends on factors such as the intensity and duration of the rain event, the drainage element of the roof, as well as substrate depth and composition, substrate moisture content at the start of the rain event, and the type, health, and density of the vegetation [25].

In a Mediterranean climate, extensive green roof vegetation is limited to species able to endure a dry and hot environment, high solar exposure, and wind. One way to extend the range of plants would be to use irrigation systems, a solution already used on most green roofs, particularly during the summer season. However, this solution is neither feasible on a large scale, as it would be very costly, nor is it sustainable. Therefore, innovative ideas need to be explored to enable more widespread use of green roofs in southern Europe. The NativeScapeGR project [44–46], conducted in the city of Lisbon, tested the idea of using various native vascular plants and mosses, which are well adapted to the Mediterranean climate (http://www.isa.utl.pt/proj/NativeScapeGR/). The results showed that different species were able to survive summer harsh conditions by only using small irrigation volumes [46]. Nevertheless, it is important to note that this innovative typology for green roofs for hot, dry climates may not be as efficient as other types of plants in terms of the ecosystem services they provide. Therefore, a study was carried out to assess how differently vegetated green roofs perform concerning episodes of intense stormwater runoff, by simulating intense rainfall events. Additionally, tests were conducted on the concentration of several key parameters of the runoff water to ascertain whether it meets European and international potable water standards.

2. Materials and Methods

2.1. Study Area

The fieldwork was conducted from February to October 2019 on the roof of the Herbarium building (38.707992, −9.184544) at the *Instituto Superior de Agronomia* (ISA) (Figure 1) on the outskirts of the city of Lisbon, Portugal. The surrounding landscape consists of farmland and urban areas composed of housing and roads.

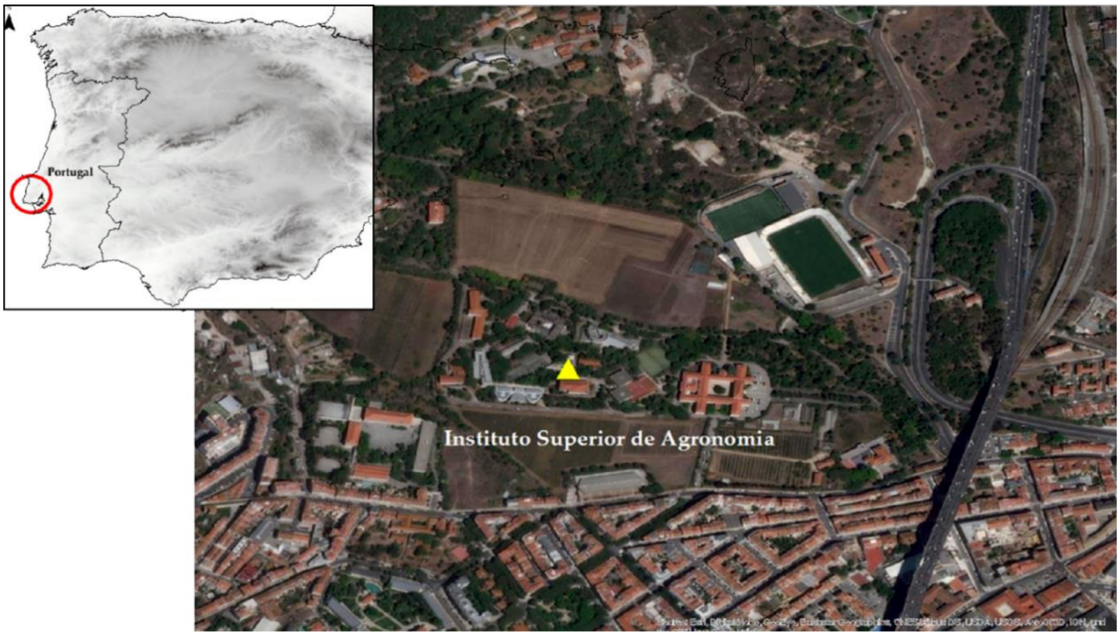

Figure 1. Location of the Instituto Superior de Agronomia, Lisbon, Portugal. Test beds were installed on the roof of a building in the Instituto complex. The yellow triangle marks the precise location of the test beds.

For this study, six of the twelve metal test beds that had been constructed for the 2014 NativeScapeGR project [44] were used (Figure 2). The test beds (2.5 × 1 × 0.2 m) are elevated 1 m above the roof surface and have a slight slope of 2.5% to facilitate rainwater drainage towards a small drainage hole in the top right corner of the test bed. The test beds were designed to mimic an extensive green roof. They consist of a bottom layer of geotextile, followed by a 25 mm polyethylene drainage layer with cavities for water storage with an effective storage depth of 3 L/m^2 or 3 mm and a filter. The upper layer consists of a commercial green roof substrate, with 71% organic matter content (texture not classified due to high organic matter content) mixed with a medium to coarse texture LECA (Lightweight Expanded Clay Aggregate) with a 2 to 4 mm thickness, corresponding to approximately 30% of the composition of the substrate layer.

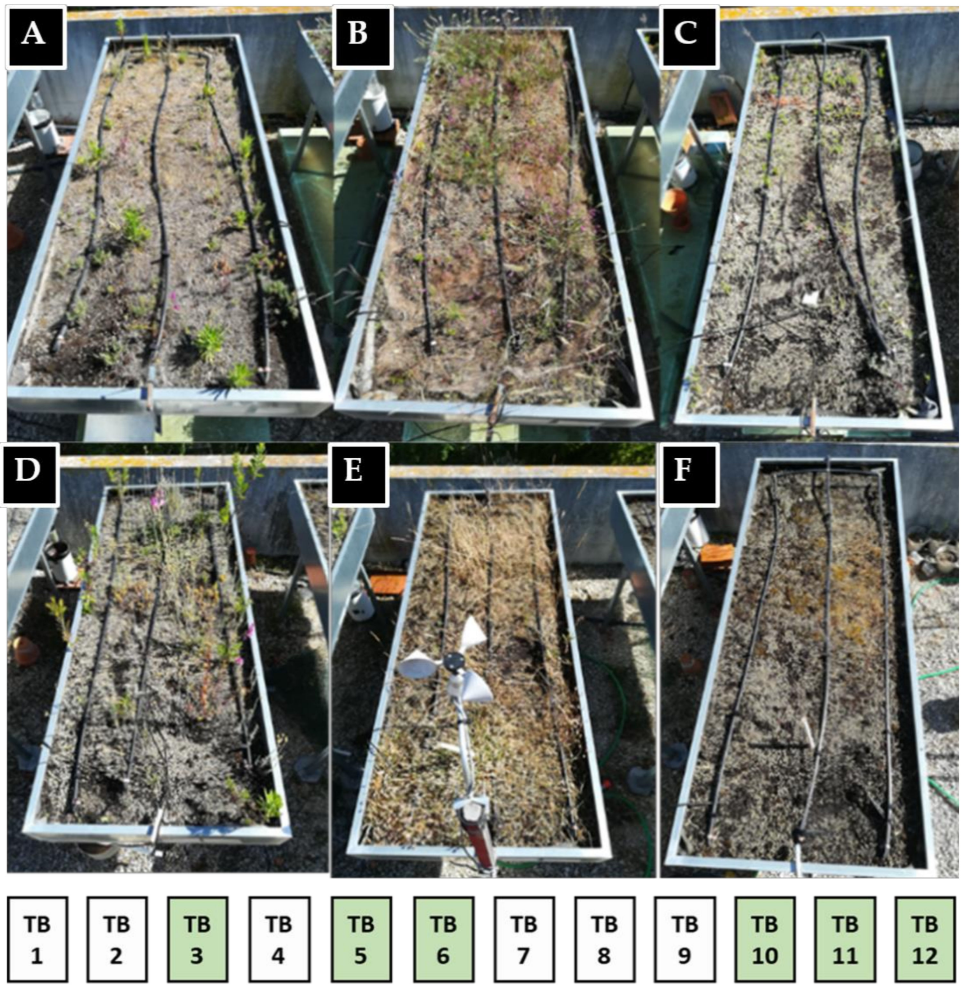

Figure 2. Metal test beds (2.5 × 1 × 0.2 m). The test beds used in this study are marked in green. From (**A**–**F**): (**A**) test bed #3; (**B**) test bed #5; (**C**) test bed #6, (**D**) test bed #10, (**E**) test bed #11 and (**F**) test bed #12 (photographs taken on the 20 May 2019).

2.2. Vegetation Composition, Functional Traits and Cover

Although the test beds had already been used in previous studies [44–46] and therefore undergone different substrate and vegetation compositions, since the end of 2018 they had all been filled with a commercial green roof substrate, with 71% organic matter content. Since the end of 2018 [44,45], the vegetation composition within each test bed has been a combination of four species that were planted during a previous project (2014–2017) [44]—*Dittrichia viscosa* (L.) Greuter, *Lavandula stoechas* subsp. *luisieri* (Rozeira) Rozeira, *Pleurochaete squarrosa* (Brid.) Lindb. and *Sedum sediforme* (Jacq.) Pau—and nine species that naturally colonized the test beds—*Briza maxima* L., *Conyza* sp., *Digitaria sanguinalis* (L.) Scop., *Filago pyramidata* L., *Gomphocarpus fruticosus* (L.) W.T.Aiton, *Illecebrum verticillatum* L., *Teucrium scorodonia* L., *Trifolium angustifolium* L. and *Vulpia geniculata* (L.) Link. Species composition is shown in Table 1 and their functional attributes in Table 2. Test bed #3 had the highest species richness with a total of eight species, followed by test bed #5 with seven species, test bed #6 with six species, test bed #10 with four species and lastly test beds #11 and #12 with, respectively, three and one species. *Filago pyramidata* and *Sedum sediforme* were the most common species, being present in four of the six test beds. In contrast, *Digitaria sanguinalis*, *Gomphocarpus fruticosus*, *Illecebrum verticillatum* and *Lavandula stoechas* var. *luisieri* were present in only one of the test beds (Table 1).

Table 1. Plant composition, taxonomic diversity and functional diversity regarding plant life form and root type.

Species	Test Bed #3	Test Bed #5	Test Bed #6	Test Bed #10	Test Bed #11	Test Bed #12
Briza maxima		•			•	
Conyza sp.	•	•	•			
Digitaria sanguinalis	•					
Dittrichia viscosa	•			•		
Filago pyramidata	•	•	•	•		
Gomphocarpus fruticosus				•		
Illecebrum verticillatum	•					
Lavandula stoechas subsp. *luisieri*	•					
Pleurochaete squarrosa	•				•	•
Sedum sediforme	•	•	•	•		
Teucrium scorodonia		•	•			
Trifolium angustifolium		•	•			
Vulpia geniculata		•	•		•	
Total number of species	8	7	6	4	3	1
Functional diversity	19	18	17	16	10	4
Life form diversity	5	3	3	4	2	1

Functional diversity (Table 1), considering all traits seen in Table 2, was higher in test bed #3, #5, #6 and #10, and lower in test bed #11 and #12. Life form diversity (Table 1) was also higher in test bed #3, which had at least one specimen of each life form functional group, except for tall shrubs, followed by test bed #10, test bed #5 and #6, and lower in test bed #12, with only a moss species present.

The amount of vegetation cover also varied among the test beds (Figure 2). Vegetation cover was determined based on vertical photographs taken of each test bed and refers to the area of the test bed surface covered by vegetation. Test beds #5 and #11 had the highest amount of vegetation cover, both with approximately 80% cover. They were followed by test bed #10, with approximately 40%. Test bed #3 and #6 had a similar amount of cover, with approximately 25%. Test bed #12 had the lowest amount, with approximately 15%.

2.3. Methodologies Used to Assess Ecosystem Services

2.3.1. Stormwater Management

Tests on the duration and volume of stormwater runoff were conducted on three different occasions in 2019, one before summer (21 of May) and two after (4 and 24 of October). All six test beds were irrigated with 40 L of water from the municipal drinking water system during 135 s to simulate a very extreme episode of flash flooding, as this corresponds to approximately 427 mm/h. It is important to note that this value was chosen as the substrate in all test beds was very dry by the time of the tests. For that reason, a very high irrigation volume was used to ensure that significant runoff differences between test beds would be produced and avoid the majority of the irrigated water being absorbed and not runoff. Irrigation was conducted by placing a hose vertically above the test bed and using a flow control water meter (NATRAIN NWC) to keep track of the volume of water. A vertical irrigation process was established to mimic, to the best extent possible, a normal rainwater pattern, which mainly falls vertically or slightly tilted. To ensure that the test beds surface was evenly irrigated, the hose was placed approximately 1.70 m above the test beds surface. Irrigation was immediately stopped after reaching the desired irrigation volume (40 L). Runoff time was measured using a chronometer that initiated counting when irrigation started and stopped when the water started to pour out of the drainage hole. Runoff volume was measured using several 5 L plastic buckets. No surface runoff occurred as the height of the metal frame of the test bed was always, at least, 10 cm higher than the substrate level.

Table 2. List of species present in the test beds and their respective functional characterization. Stem height classes: small (0 to <20 cm), medium (20 to 100 cm) and tall (>100 cm). Stem height for each species is given in centimeters (cm) and refers to the average height found in the literature. All functional information was gathered from extensive online research.

Species	Average Stem Height	Canopy Density	Life Form	N Fixation	Hydric Regulation	Life Cycle	Root Type	Photosynthetic Pathway	Exotic/Native
Briza maxima	Medium (80 cm)	Low	Grass	No	Homoiohydric	Annual	Fibrous root	C3	Native
Conyza sp.	Tall (120 cm)	Medium	Forb	No	Homoiohydric	Annual	Taproot	C3	Exotic
Digitaria sanguinalis	Medium (60 cm)	Low	Grass	No	Homoiohydric	Annual	Fibrous root	C4	Exotic
Ditrichia viscosa	Tall (130 cm)	Medium	Shrub	No	Homoiohydric	Perennial	Taproot	C3	Native
Filago pyramidata	Medium (35 cm)	Low	Forb	No	Homoiohydric	Annual	Taproot	C3	Native
Gomphocarpus fruticosus	Tall (200 cm)	High	Tall shrub	No	Homoiohydric	Perennial	Taproot	C3	Exotic
Illecebrum verticillatum	Small (2 cm)	Mat-forming	Forb	No	Homoiohydric	Annual	Taproot	C3	Native
Lavandula stoechas var. *luisieri*	Medium (60 cm)	Medium	Shrub	No	Homoiohydric	Perennial	Fibrous root	C3	Native
Pleurochaete squarrosa	Small (2 cm)	Mat-forming	Moss	No	Poikilohydric	-	-	C3	Native
Sedum sediforme	Medium (60 cm)	Mat-forming	Succulent	No	Homoiohydric	Perennial	Taproot	CAM	Native
Teucrium scorodonia	Medium (50 cm)	Medium	Forb	No	Homoiohydric	Annual	Fibrous root	C3	Native
Trifolium angustifolium	Medium (50 cm)	Low	Forb	Yes	Homoiohydric	Annual	Taproot	C3	Native
Vulpia geniculata	Medium (60 cm)	low	Grass	No	Homoiohydric	Annual	Fibrous root	C3	Native

2.3.2. Runoff Quality

Runoff water for the quality tests was collected on the 21 May 2019. A volume of 40 mL of runoff water was collected in plastic sample collection containers (50 mL), labelled, and taken to the laboratory. During the test, water pooled on the surface of the test beds. Water that infiltrated faster was potentially less contaminated that the one who pooled, as the later had more time to absorb contaminants, present in the substrate surface, before infiltrating to deeper layers of the test bed. For that reason, only the initial runoff was collected, which corresponds to the water that infiltrates immediately instead of pooling. We also collected water from the municipal drinking water system and used it as a control. In the laboratory, each of the seven water samples, one for each test bed plus the control, was tested for ammonia and ammonium (NH_3; NH_4^+), nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations using an Aquaculture Photometer HI8339 (Hanna Instruments, UK) and following the procedures recommended in its instructions.

2.4. Statistical Analysis

All runoff times and volume values, as well as the water parameter concentration values, were stored in a database using Microsoft Excel, version 2010 [47]. Averages runoff time and volume were calculated for each of the six test beds and each of the three runoff tests. Runoff coefficient, per test bed, was calculated by dividing the average volume of water runoff (mean of the three tests) by the irrigation volume (40 L). Plant functional diversity (Table 1) was calculated based on the number of functional groups from all traits (Table 2) present in each test bed and was included as a variable and related to the runoff performance of the test beds. Plant life form diversity derives from the total functional diversity. For each response variable considered in this study, differences between the test beds were evaluated with a one-way ANOVA with Tukey's multiple comparisons test, using GraphPad Prism 6.03 for Windows (GraphPad Software, San Diego, CA, USA) [48].

3. Results

3.1. Stormwater Management

Runoff time and volume varied both among test beds and across the three different tests (Tables 3 and 4; Figures 3–7). The average of the three runoff tests showed that higher runoff volumes were accompanied by lower runoff times (Figure 3).

Table 3. Measurements of all test bed runoff times, in seconds, for test 1, 2 and 3. The bottom line represents the average runoff time measured across all test beds, for each test. The last column represents the average time average runoff time measured across all tests, for each test bed.

Runoff Time (s)	Test nr. 1 (21 May)	Test nr. 2 (4 October)	Test nr. 3 (24 October)	Test Bed Average
Test bed #3	110	64	136	103
Test bed #5	118	101	137	119
Test bed #6	125	116	119	120
Test bed #10	134	116	150	134
Test bed #11	140	64	123	109
Test bed #12	107	57	127	97
Test Average	122.3	86.3	132.0	

Table 4. Measurements of all test bed runoff volumes, in liters for the three distinct test periods (Test nr. 1, 2 and 3). The bottom line represents the average runoff volume measured across all test beds, for each test. The antepenultimate column represents the average runoff volume measured across all tests, for each test bed. The last column represents the runoff coefficient, calculated for each test bed, based on their test bed averages.

Runoff Volume (L)	Test nr. 1 (21 May)	Test nr. 2 (4 October)	Test nr. 3 (24 October)	Test Bed Average	Runoff Coefficient
Test bed #3	9.65	15	13.75	12.80	0.32
Test bed #5	9.75	11.7	14	11.82	0.30
Test bed #6	6.5	13.5	15.5	11.83	0.30
Test bed #10	5.9	10	15	10.3	0.26
Test bed #11	7.6	21.5	20	16.37	0.41
Test bed #12	10.6	22.5	18	17.03	0.43
Test Average	8.3	15.7	16.0		

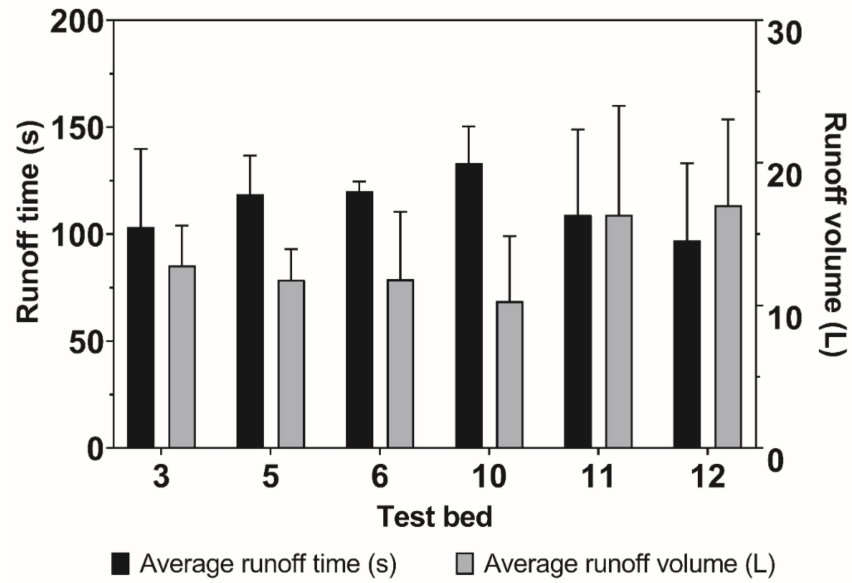

Figure 3. Average runoff time and volume values registered during the three distinct test periods across all test beds. Whiskers represent the standard deviation. Runoff volume is expressed in liters (L). Runoff time is expressed in seconds (s).

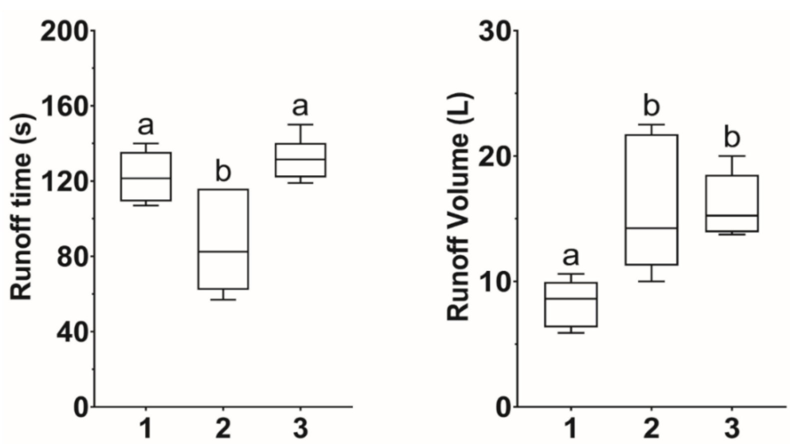

Figure 4. Average runoff time and volume values registered during the three test periods. Letters (a) and (b) represent statistical differences between variables (tests). Whiskers represent the minimum and maximum values. Runoff volume is expressed in liters (L). Runoff time is expressed in seconds (s).

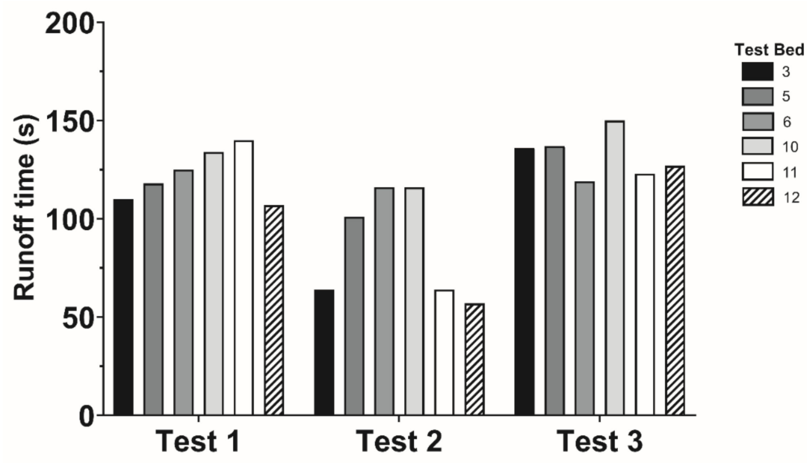

Figure 5. Runoff time values registered in the three distinct test periods across all test beds. Runoff time values expressed in seconds (s).

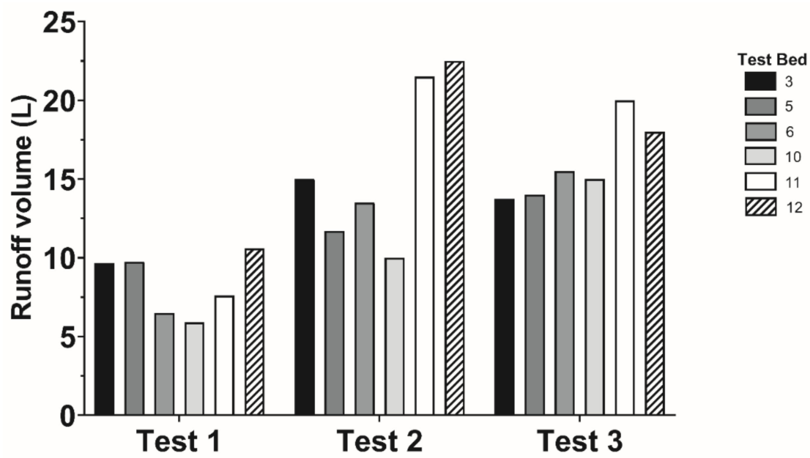

Figure 6. Runoff volume in the three distinct test periods across all test beds. Runoff volume values expressed in liters (L).

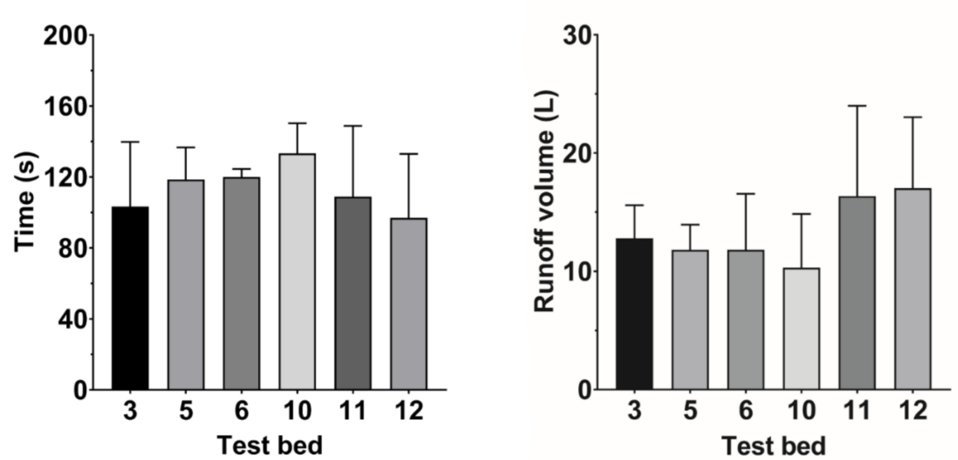

Figure 7. Average runoff time in each of the six test beds (on the left). Average runoff volume values registered in each of the six test beds (on the right). Whiskers represent the standard deviation. Runoff time values expressed in seconds (s), runoff volume values expressed in liters (L).

The one-way ANOVA test allowed for comparison to be made between the average values registered across the three test periods (Figure 4). Regarding the runoff time, test 1 and 3 are statistically similar (a) while test 2 is statistically different (b), while for the runoff volume, test 1 is statistically different (a) from test 2 and 3 (b). Average runoff time in the three test periods showed that lower values were recorded during test number 2 (Table 3; Figure 4). Thus, average runoff volume in the three test periods showed that there was a higher runoff volume registered during the second and third test, both performed after the summer season when compared to the first test, which was performed during late spring (Table 3; Figure 4). This tendency was not observed in the runoff time (Figure 4). Comparison of the average runoff time between the three tests (Table 3) showed that the third test recorded the highest average runoff time value and was closely followed by the first test. Test number two registered the lowest value in all the test beds on every test occasion. Comparison of the average runoff volume between the three tests (Table 4) showed that the third test recorded the highest average runoff volume, followed by the second test, while test number one registered the lowest value in all test beds.

As shown in Table 3 and Figure 5, runoff time (measured in seconds) varied not only across tests but also across test beds. Test bed #6 recorded the highest runoff time average and test bed #12 the lowest. All test beds recorded the lowest runoff times during test number 2, which was conducted during late spring, and the majority of the test beds recorded higher runoff times during test number 3, conducted during the autumn season.

As seen in Table 4 and Figure 6, runoff volume (measured in liters) also varied across tests and test beds. The highest average runoff volume was recorded in test bed #12, which was similar to test bed #11. In contrast, test bed #10 had the lowest average runoff volume from all test beds. All test beds had the lowest runoff volumes during the first test, conducted during late spring. Runoff coefficients, relating the amount of runoff to the amount of irrigation received (40 L), ranged from 0.26 in test bed #10 to 0.43 in test bed #12.

There was no statistical difference between test beds concerning the average runoff time and runoff volume, across the three tests (Figure 7).

Runoff volumes showed a tendency to decrease with increasing overall functional diversity and with life form diversity alone, as seen in Figure 8. When reaching higher functional and life form diversity, average runoff volume values stabilized. Test bed #3 had five life forms: forbs, grasses, mosses, shrubs and succulents. It was also the test bed with the highest overall functional diversity. Test bed #5 and #6 had three life forms—forbs, grasses and succulents—and scored, respectively, the second and third highest overall functional diversity. Test bed #10 had four life forms—forbs, shrubs, succulents, and tall shrubs—and had the fourth overall functional diversity. Test bed #11 had two life forms—grasses and mosses—and finally, test bed #12 had only a moss species. These last two test beds also had the lowest overall functional diversity.

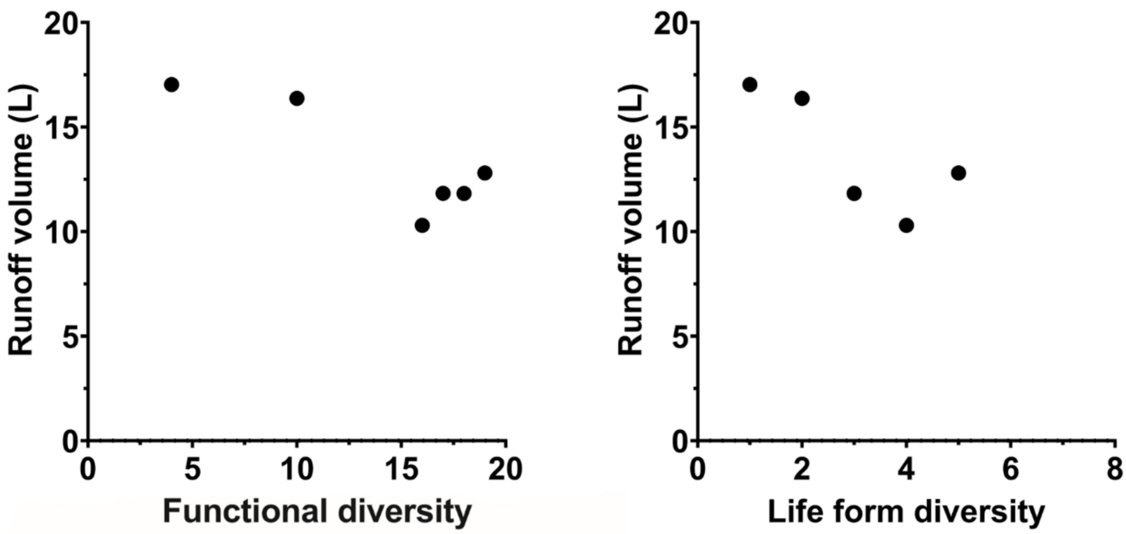

Figure 8. Runoff volume average values concerning functional diversity and life form diversity (Table 1) in each test bed. Functional diversity comprises all functional groups from all traits in Table 2. Life form diversity comprises the following functional groups: grasses, forbs, mosses, shrubs, succulents and tall shrubs. Runoff volume values expressed in liters (L).

3.2. Runoff Quality

Runoff quality tests conducted on water collected during the first test (Table 5; Figure 9) revealed significant differences between ammonia and phosphate concentration values in all test beds and the concentrations in the control. Nitrate concentrations in all test beds and in the control registered values below the test accuracy (<0.05 mg/L).

Table 5. Concentration measurements of four water quality parameters (Ammonia—NH_3, Ammonium—NH_4^+, Nitrate—NO_3^- and Phosphate—PO_4^{3-}) across all test beds as well as in the control. Runoff quality test was performed during the first water runoff test. All values are expressed in mg L^{-1}.

Concentrations Measurements	Test Bed #3	Test Bed #5	Test Bed #6	Test Bed #10	Test Bed #11	Test Bed #12	Control
Ammonia (NH_3)	1.30	4.22	2.89	2.83	2.66	2.64	0.02
Ammonium (NH_4^+)	1.38	4.47	3.06	3.00	2.81	2.79	0.02
Nitrate (NO_3^-)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Phosphate (PO_4^{3-})	1.97	2.04	0.65	1.54	2.44	1.72	0.58

When compared with the control sample (Table 5), the runoff from test bed #3 registered higher values in every parameter apart from nitrate (NO_3^-). The nitrate concentration in all of the test bed water samples was lower than 0.05 mg L^{-1}, which is below the accuracy of the sensor (±0.05 mg L^{-1}) for this parameter test. Ammonia (NH_3) and ammonium (NH_4^+) concentrations in the runoff from test bed #3 were 1.30 mg L^{-1} and 1.38 mg L^{-1}, respectively, and much higher than in the control, but the lowest recorded in the six test beds. Phosphate (PO_4^{3-}) concentration values were also higher than in the control. Test bed #5 recorded the highest concentration values of ammonia and ammonium, and also much higher than the control. Phosphate values were also high in this test bed and again higher than in the control. Test beds #6, #10, #11 and #12 recorded a similar concentration of ammonia and ammonium. Phosphate concentration values in the runoff from test bed #6 were lower than in the other test beds and closer to the control for this parameter. In contrast, test bed #11 recorded the highest phosphate values of all the test beds, more than four times the control. Lastly, test beds #10 and #12 both recorded similar phosphate concentration values.

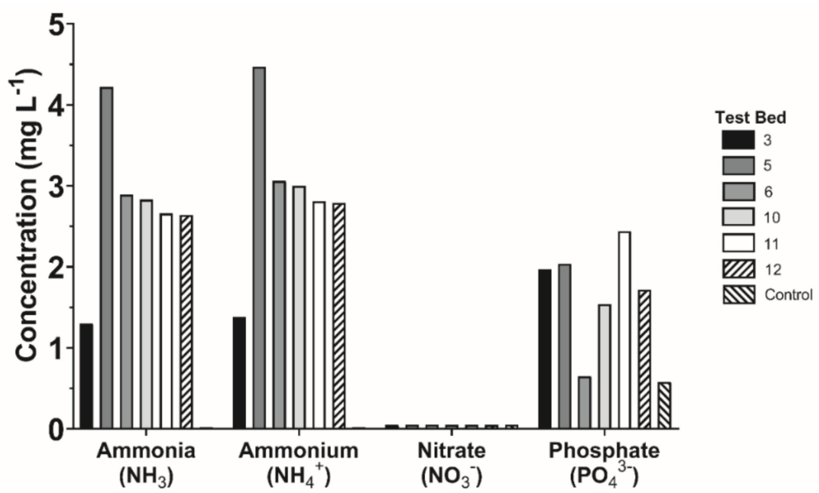

Figure 9. Concentration values of four water quality parameters (Ammonia—NH_3, Ammonium—NH_4^+, Nitrate—NO_3^- and Phosphate—PO_4^{3-}) across all test beds as well as in the control. The runoff quality test was performed on water collected during the first test. Concentration values expressed in mg L^{-1}.

4. Discussion

One of the potential ecosystem services provided by green roofs is their ability to retain rainwater [29,49–51]. In flash flood events, urban drainage systems are often overwhelmed due to the combination of fast, intense precipitation together with debris accumulation. During such events, green roofs can retain substantial amounts of water, potentially slowing down the pace at which stormwater reaches the ground and thus acting like a buffer that may help decrease the pressure on the drainage system, thereby preventing flooding [52,53].

In our study, runoff time and volume had a clear negative relationship (Figure 3). The tests beds where it took less time between the start of the simulated rainfall event and the first water runoff were also the ones where final runoff reached higher volumes, and vice versa. This is because runoff time is directly related to the ability of the test bed to absorb as much water as possible before saturating, and thus surplus water starts to runoff. Thus, the faster saturation point is reached, the faster water starts to runoff (runoff time), therefore reaching higher runoff water volume values.

During rainwater and stormwater episodes, water retention by green roofs is influenced by three different components. One component is the substrate, namely its depth and physical properties [53,54], which translates into different field capacities [55,56]. The second is the vegetation composition [40], above-ground biomass and cover, and the third is the interaction between the vegetation and the substrate, such as the vegetation root system [41,57], which is known to alter the physical condition of the substrate [58,59], namely soil bulk density [60,61] and porosity [39]. Therefore, it is important to discuss the runoff performance of the test beds concerning these three components.

All the test beds had the same depth and type of substrate. Therefore, analyzing the variation in runoff time and volume across test beds with the physical characteristics of the substrate in term of its nature and quantity would be meaningless. However, soil moisture also plays a key role in water runoff, as the higher it is, the faster it reaches its saturation point and starts leaching during rainwater/stormwater episodes. The results from the three runoff tests performed (Figure 4), one in late spring (21 May) and two in the middle of autumn (4 and 24 of October) suggest exactly this. As seen in Table 4, the first test recorded the lowest average runoff volume (8.3 L) across all test beds while the second and third tests not only showed almost double the average volume but also registered almost identical average runoff volumes (respectively, 15.7 L and 16 L). This is probably due to the weather conditions typical of both seasons in Portugal and goes in accordance with [39,49,53,62] which also observed higher runoff volumes in winter months compared to summer months. Values registered at the meteorological station of *Tapada da Ajuda* [63], distanced approximately 200 m from our study area (38.7095611, −9.18282500), showed that in May 2019, before the first test, rain had fallen on only three days (between the 7th and 9th) (Table S1). Thus, at the time of the test, the substrate in the test beds was very dry, increasing the volume of water retained before saturation point was reached and therefore decreasing the amount of runoff volume registered. In fact, during the beginning of the simulated rainfall of the first test, we observed that a significant volume of water pooled on the surface of the test beds instead of infiltrating the substrate. This is an indication of a hydrophobic soil which repels water rather than absorbing it [64]. This phenomenon further increases runoff time and decreases runoff volume during drier months [65]. Unfortunately, due to unknown issues with the weather station, data were not available for October. However, historical data (1971–2000) from the Instituto Português do Mar e da Atmosfera [66] show that October has almost double mean precipitation accumulated values compared with May. We can, therefore, to some degree, assume that the precipitation values in October 2019 were higher than in May of the same year. Thus, at the time of the second and third test, the soil in the test beds was closer to saturation point than in May, consequently increasing the amount of runoff volume compared to the first tests. Water pooling during the simulation was not observed during the second and third test, contrary to what occurred during the first test. Furthermore, weather data accessed from [67] revealed that the days before tests 2 and 3 were mainly cloudy with some precipitation episodes. Average runoff time recorded across the three test events did not show the same pattern, thus indicating that, in contrast to the runoff volume, soil moisture is not an influencing factor.

Since vegetation cover and composition (Tables 1 and 2) also varied between the test beds, so did interactions between the vegetation and the physical characteristics of the substrate [58,59]. As water precipitates on a green roof, vegetation intercepts some of the rainwater which then evaporates [38]. As the water reaches the substrate, it starts to infiltrate at a rate which is dependent on the soil porosity, which is in turn affected by the density of the plant roots [39]. At the same time, water is absorbed and incorporated in the plant tissues and returns to the atmosphere through evapotranspiration [38].

In test bed #12 only a moss species, *Pleurochaete squarrosa*, was present, and only on a small central area of the test bed (Figure 1 and Table 1). This test bed was therefore the one with the smallest vegetation cover and taxonomic and functional diversity. *Pleurochaete squarrosa* is a poikilohydric (meaning that it cannot regulate/maintain its water content) moss found in Mediterranean biocrusts [68]. This could potentially mean that during precipitation events, this moss would absorb water until it is in equilibrium with the surrounding moisture levels. In [69], *Pleurochaete squarrosa* scored the third longest water retention time in a drying event experiment. Furthermore, an additional study [70] revealed that the moss is tolerant of substantial periods of desiccation, but has a relatively slow recovery after re-wetting. However, due to the very low cover in this test bed (approximately 15%), this effect is weakened, which is in agreement with [71] who link increased vegetation density with higher water retention. Moreover, this species is a low-growing, mat-forming moss and therefore intercepts less water than other, more erect life forms [42,72,73]. All these factors translate into test bed #12 having the quickest average runoff time across the three simulated rainfall events (97 s) and the highest average runoff volume (17.03 L) (Tables 3 and 4). Due to the much-reduced vegetation cover, these values are presumably attributed almost exclusively to the natural water retention capacity of the substrate and the infiltration rate. This means that differences in runoff time and volume, between this test bed and the others, are the result of the direct and indirect effects that vegetation cover and diversity have on the water retention capacity and soil infiltration rates.

Test bed #11, which contained two species of grasses (*Briza maxima* and *Vulpia geniculata*) and the *Pleurochaete squarrosa* moss (Figure 1 and Table 1), scored the second highest average runoff volume of all the test beds (16.37 L) (Table 4) which is inconsistent with the results of previous studies [39,42,74] where green roofs with grasses were found to have the highest water capture. The type and physical properties of the substrate used in the test beds may be one of the reasons for this inconsistency. In fact, [39] saw that highly dense fibrous roots could disrupt the natural physical properties of soil, by reducing its porosity and thus its ability to retain water, leading to more runoff. In our case, both species of grasses have a dense fibrous root type which may help explain our results. An additional explanation is that all the previously mentioned studies were conducted in colder, humid areas, where grasses can naturally uptake more water for quick growth. In a much drier environment like the Mediterranean, some grasses may have evolved into being more water-efficient. Nevertheless, further research is necessary to better understand these differences.

Test beds #3 and #11 had similar average runoff times (103 s and 109 s, respectively) (Table 3) although they had different runoff volumes, as well as different vegetation cover and diversity (Tables 1 and 2). This means that although the water infiltration rates were similar, the soil water retention capacity differed, with test bed #11 having a higher runoff volume. When looking more closely at the species composition of these test beds (Figure 1, Tables 1 and 2), test bed #3 has greater taxonomic, functional (n = 19) and life form diversity (n = 5) compared to test bed #11 (n = 10 and n = 2, respectively), despite having significantly less vegetation cover (25% and 80% respectively). One potential explanation for this discrepancy may relate to the stem height of the grasses in test bed #11. As mentioned by [42,72,73], taller plants intercept water before it even reaches the soil surface due to their greater surface area. This could explain the slower than expected infiltration rate based on the runoff volume, as the interception of water by the plants slows runoff time. Test bed #3 registered an intermediate runoff volume (Table 4) and was similar to test beds #5 and #6. Vegetation cover and height were low, and the majority of the species present were forbs. According to [42,74], forbs scored average performances in water capture tests, being lower than grasses but higher than succulents. The majority of the species had a taproot, which according to [39] does not impact soil porosity as much as dense fibrous roots do. This might explain the intermediate runoff volume values.

The runoff time and volume measurements in test beds #5 and #6 were very similar (Tables 3 and 4). This was initially expected, as both test beds had very similar taxonomic and functional diversity. Nevertheless, test bed #5 had much greater vegetation cover (80%) and stem height (Figure 1 and Table 1), mainly due to the high abundance of the species *Trifolium angustifolium*, a forb with a taproot. In comparison, test bed #6 had lower vegetation cover (25%), mainly comprised of *Sedum sediforme*, a succulent taproot plant, and *Conyza sp.*, a forb taproot plant. Following the discoveries of [72,73] who correlated higher runoff values with lower above-ground biomass and cover, as well as the discoveries of [42,74] where *Sedum* green roofs had the highest runoff values, we would expect test bed #5 to have a much lower runoff time and volume than test bed #6. However, that is not the case. This suggests that further studies focusing on water retention should pay attention to other potential factors, beyond vegetation composition, that influence runoff. Test bed #10 had the highest average runoff time (134 s) and lowest volume (10.3 L) (Tables 3 and 4), while having intermediate taxonomic and functional diversity (n = 16), vegetation cover (40%) and high stem height which, according to [72,73], enables greater water interception and delayed evaporation after precipitation episodes. Furthermore, the majority of the plants in this test bed were forbs, alongside one specimen of *Gomphocarpus fruticosus*, a tall, woody taproot shrub. All these factors combined not only to allow for better water retention at the soil level but also for delayed infiltration due to water interception.

Runoff coefficients across the test beds ranged from 0.26 in the test bed with lower average runoff across the three tests to 0.43 in the one with the highest average runoff. Although these values are higher than expected for vegetated areas, according to [75] they are still significantly lower than the runoff coefficient of a tiled or concrete roof (0.75–0.95) [76].

Lastly, there was a potential link between functional and life form diversity and runoff volume, as seen in Figure 8. Test beds with lower functional and life form diversity (test bed #11 and #12) also had the highest runoff volumes among all test beds. In contrast, test beds with higher life form and overall functional diversity had the lowest runoff volumes. This is in accordance with [74] who also found that green roof modules with multiple life forms performed better than treatments with monocultures concerning water retention. Furthermore, the results in this study seem to show that runoff volumes stabilize at four life forms per test bed.

Another potential ecosystem service provided by green roofs is rainwater harvesting [30], thereby reducing the use of municipal water. However, this needs to be approached carefully, as different roof materials and different commercial growing media used for green roofs can alter specific water parameters [77]. In general, the concentrations of the parameters measured were higher in the test beds than in the control water sample (Table 5; Figure 9). The exception was the nitrate concentration, where all the measured values were too low for the accuracy of the machine ($\pm$0.05 mg L^{-1}) and therefore close to the control concentration values. This would indicate that both the vegetation and the associated microbial communities are using all the available nitrate, thereby causing it not to leach during runoff. This would probably also indicate that all the test beds are nitrogen starved. However, by looking at the ammonia and ammonium concentrations across all test beds (Table 5; Figure 9), we can see that nitrate did leach, therefore implying that there is, in fact, available nitrogen in the soil. This suggests that the lack of nitrate leaching results from a lack of activity by the nitrifying bacteria, most likely due to the low soil moisture in the test beds that limits microbial activity [78].

We were unable to identify any significant link between test bed parameter concentrations and vegetation cover, which points to the possibility that the commercial soil properties, rather than the vegetation, are the main driver for the observed parameter values. Ammonia and ammonium are major sources of nitrogen for vegetation, one of the most important elements in plants, contributing to chlorophyll production [79,80], proteins [81,82] and others like DNA and ATP molecules [83]. Ammonia can occur naturally in the environment due to nitrifying bacteria [84] and animal waste [85], although it is also widely used in fertilizers. Ammonia in the soil rapidly converts to ammonium by reacting with soil water, which explains the higher ammonium concentration values in all test beds when compared to the ammonia values. Ammonium is then either used by nitrifying bacteria which converts it to nitrate, or it is absorbed directly by plants. Soil bond ammonium leaches during precipitation events. High values of ammonia and ammonium and low values of nitrate in our test beds water samples indicate that vegetation uptake and nitrifying bacteria activity are low across all test beds.

Phosphate compounds are minerals found in rocks and contain phosphorus, an important element for plant growth [86,87]. Inorganic phosphate needs to be dissolved in water before uptake by plants. Phosphate concentration values were high in all of the test beds (Table 5; Figure 9), possibly due to the LECA on top of the soil surface. Additionally, this can also be a result of the low soil water content in all the test beds, due to a combination of the lack of recent irrigation and the dry, hot Mediterranean climate.

Regarding water quality, the concentrations of all the tested parameters in the test beds were compared with WHO (World Health Organization) potable water standards [88] and the EU potable water standards. Ammonia parametric values are not established by either organization, with the WHO, however, stating that values under 0.2 mg L^{-1} are normally found in freshwater/surface water/groundwater, which is the case of our control value. Therefore, the ammonia concentration in all of the test beds measured above the level recommended by WHO. Both organizations set the ammonium parametric values under 0.5 mg L^{-1}, again above the control value but significantly below the test bed measurements. Regarding the recommended nitrate concentration, both organizations establish it under 50 mg L^{-1}, which is above the concentrations measured in the control and all test beds. Finally, none of the previously mentioned organizations establishes a phosphate limit, and therefore no discussion can be made around this parameter. It is, however, important to point out that its concentration was significantly higher than in the control in all test beds except for test bed #7. Our results unequivocally show that runoff water from the test beds do not conform with the minimum potable water quality standards defined by the WHO and the EU, and should not, therefore, be used for that purpose. We do, however, suggest that it still can be used in other applications, such as flushing toilets and irrigation of non-edible plants.

5. Conclusions

Green roofs are gaining increasing attention in urban areas due to the ecosystem services they can provide. This study assessed some of those services related to the water cycle, by using small test beds to mimic green roofs with different vegetation composition and mainly using native species which are well suited to the hot and dry Mediterranean summers. Runoff volume and time, as well as water quality, were found to be greatly affected by the substrate characteristics. Soil moisture and water retention capability previous to the three test events was the main factor affecting runoff volume. Root system type played a major role in the runoff across the six test beds as they are known to alter soil physical properties. Although vegetation cover was low in the majority of the test beds, which is a consequence of the lack of irrigation combined with the historic climatic conditions, the results showed that they were able to act as a buffer against stormwater episodes, by storing water in the vegetation and substrate. Furthermore, the differences noted between the test beds demonstrate that species selection, in terms of functional and life form diversity, can further enhance this ecosystem service, since a combination of different vegetation functional characteristics leads to increased water retention. Runoff water quality also varied across the test beds, but the results did not show a link between parameter concentrations and vegetation composition and cover, which suggests that the substrate composition has the greatest impact on green roof performance regarding rainwater quality. Overall, we showed that biocrusts and xerophytic vegetation species composition, when chosen carefully, are suitable for green roofs in Mediterranean areas, as they can delay runoff during intense rainfall events.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4441/13/1/94/s1, Table S1: Weather data from the meteorological station of *Tapada da Ajuda*, distanced approximately 200 m from our study area (38.7095611, −9.18282500) for April and May 2019. Mean T, Max T and Min T represent the daily mean, maximum and minimum temperature recorded at 1.5 m above ground. Values expressed in tenths of °C. Grass T represent the daily minimum temperature recorded at 1.5 cm above the ground. Values expressed in tenths of °C. Soil mean T, Soil max T and Soil min T represent the daily mean, maximum and minimum temperature recorded at 10 cm below ground. Values expressed in tenths of °C. Mean H, Max H and Min H represent the daily mean, maximum and minimum air relative humidity at 1.5 m above ground. Values expressed in %. Precipitation represents total daily precipitation. Values expressed in tenths of mm.

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