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Effect of Seawater Irrigation on *Arthrocnemum macrostachyum* Growing in Extensive Green Roof Systems under Semi-Arid Mediterranean Climatic Conditions

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Abstract: The effects of climate change in coastal semi-arid and arid Mediterranean areas are intense. Green roofs planted with native plant species that are able to withstand saline conditions can contribute to supporting climate-change adaptation and species preservation in wetlands, enhancing the character of local landscapes and reducing disaster risk. Considering the limited availability of water resources, there is increasing interest in the use of seawater for irrigation, particularly near coastal areas. The growth of a native Mediterranean halophyte, *Arthrocnemum macrostachyum*, on a simulated extensive green roof system with six different irrigation treatments with or without seawater for 97 days is presented. The irrigation treatments included tap water every 4 or 8 days, seawater every 4 or 8 days, and seawater alternated with tap water every 4 or 8 days. The plants' growth indices, heights, ground-cover surface areas, and relative shoot water content, as well as the electrical conductivity of the green roof's substrate leachates (EC_L), were measured at regular intervals. Overall, the plants irrigated with tap water every 4 days and the plants irrigated with seawater alternated with tap water every 4 days showed the greatest growth amongst the different irrigation treatments, while the plants irrigated with seawater or seawater alternated with tap water every 8 days showed the least growth. Furthermore, the plants irrigated with tap water every 8 days or seawater every 4 days showed intermediate growth. To conserve water, irrigation with seawater alternated with tap water every 4 days is proposed. To further conserve water, irrigation every 4 days with seawater only is also proposed.

Keywords: halophyte; salt-tolerant; plant ground cover; salinity; growth index; urban horticulture

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1. Introduction

The effects of climate change are more intensely apparent in dense urban areas, compared to rural areas, due to the high building density and amount of impervious surfaces that characterize most urban areas. In coastal areas, particularly low-lying areas, the effects of climate change are exacerbated by the increase in sea levels and heavy precipitation, making them vulnerable to floods [1]. Approximately half of the EU's population lives less than 50 km away from the sea, with the majority concentrated in urban areas along the coast [2]. Coastal areas also constitute Europe's most popular holiday destinations [2]. Meeting the needs of the increasing population densities along coasts has led to the degradation of both marine and coastal ecosystems. Biodiversity loss reduces ecosystem resilience and increases vulnerability to pressures. The progress in the protection of coastal habitats and species has been slow and difficult [2]. In and around coastal urban areas, the use of green infrastructure, such as wetlands, dunes, and forest restoration, is explored for climate-change adaptation and reducing disaster risk [3]. Hybrid infrastructures (or hybrid, green–gray approaches), in which engineering and ecosystem functions are used together, are important complementary infrastructures when space is limited, particularly when the use of purely green infrastructures may be insufficient to combat the adverse effects of climate change [3].

The use of green roofs constitutes a hybrid approach to climate-change adaptation and reducing disaster risk [4]. In addition to promoting biodiversity, green roofs contribute to carbon storage and stormwater retention and constitute a nature-based solution (NBS). Nature-based solutions are defined as "actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions, for example, mimicking how non-human organisms and communities cope with environmental extremes. Nature-based solutions use the features and complex system processes of nature, such as its ability to store carbon and regulate water flows, to achieve desired outcomes, such as reduced disaster risk and an environment that improves human well-being and socially inclusive green growth" [5,6]. However, the limiting factor when establishing a green roof on an existing buildings is the building's load-bearing capacity. The building developments in many coastal areas worldwide, including Greece, were constructed before national policies and regulations for the development of green roofs [7–9], are several decades old, and feature limited load-bearing capacity, as they were not originally designed for the development of green roofs. As the load-bearing capacity of older buildings is limited, of the various types of green roofs that are available, extensive green roofs have the greatest potential for implementation [10,11].

As with all green roofs, extensive green roofs are exposed to wind and solar radiation. Additionally, extensive green roofs are characterized by lightweight and shallow substrates, leading to wide temperature and moisture fluctuations [12,13]. In coastal semi-arid and arid Mediterranean areas, drought, water scarcity, and exposure to sea spray (salt-spray) [14] play a definitive role in the selection of appropriate plant species for green roofs, particularly extensive green roofs [15]. Research on the suitability of native saline wetland plant species for use in green roofs is limited [16]. Halophytes often dominate saline wetlands, such as inland and coastal salt marches and coastal fringe forests [17]. Native plant species that can withstand both drought and saline conditions, such as halophytes, could be used to plant extensive green roof systems in coastal areas, enhance the character of natural landscapes, and contribute to the preservation of species in local salt marshes [18].

The availability of natural water resources for potable water worldwide is decreasing. The water-table level of groundwater gradually decreases due to human over-exploitation, causing increases in dissolved solids in the water due to the leaching of minerals from the deeper earth strata, or other geological factors [19,20]. Surface runoff from agricultural land also increases the amount of solids dissolved in water due to human activity [20]. In coastal areas, the encroachment of seawater causes groundwater levels to increase while increasing salinization [21]. With decreasing natural water resources, researchers' interest in seawater use for irrigation has increased [22]. To address salinity stress, plant species have developed tolerance mechanisms that either limit the entry of salt into the plant by the roots or control the concentration and distribution of salt within the plant [23]. Halophytes are typically found growing in soils with elevated NaCl levels and, thus, with low water potential [24]. Salt tolerance can vary at different stages of a plant's life cycle; generally, for a given species, the seed-germination stage is considered more sensitive to salinity stress than the mature plant-growth stage [25]. Therefore, several halophytes, such as *Arthrocnemum*, *Batis*, *Halocnemum*, *Halostachys*, *Salicornia*, *Sesuvium*, *Suaeda*, etc., can complete their life cycle while exposed to seawater [25–27]. On the other hand, halophytes may also grow better with half the salt concentration of seawater [27].

Arthrocnemum macrostachyum (Moric.) K. Koch, syn. *Arthrocnemum fruticosum* var. *glaucum* Moq., *Arthrocnemum fruticosum* var. *macrostachyum* (Moric.) Moq., *Arthrocnemum glaucum* (Moq.) Ung.-Sternb., *Arthrocnemum indicum* subsp. *glaucum* (Moq.) Maire & Weiller, *Salicornia glauca* Delile, *Salicornia macrostachya* Moric., and *Arthrocaulon macrostachyum* (Moric.) Piirainen & G. Kadereit (family Amaranthaceae) [28,29], is a stem-succulent perennial halophytic shrub typical of Mediterranean salt marshes found on the coasts of southern Europe [30–32]. It is native to Greece and is often found in coastal areas, forming evergreen low-growing ground cover, with foliage that changes color throughout the year, ranging from various shades of green through yellowish-green to red [33].

The current study investigates the effect of seawater irrigation on the growth of the halophyte plant species *A. macrostachyum* in an extensive green roof system for use as a NBS. As a NBS, *A. macrostachyum* has the potential to offer multiple benefits, such as the mitigation of the negative effects of climate change, the preservation of wetlands in coastal areas, and the enhancement of the character of local natural landscapes in coastal areas.

2. Materials and Methods

2.1. Experimental Site and Setup

Thirty *A. macrostachyum* plants grown in 489-mL square pots (dimensions: 9 cm top width, 6.5 cm bottom width, and 9.5 cm height) were supplied by a local nursery in Marathonas, Greece. On 21 April 2021, uniform-sized plants were individually transplanted into the center of rectangular-shaped plastic containers (Holiday Land S.A., Piraeus, Greece) with internal top dimensions of 49 × 34 cm, bottom dimensions of 51 × 37 cm, and 16 cm in height, providing a net planting surface of approximately 0.19 m^2. These constituted the experimental plots (Figure 1). Before transplanting, a 15-mm-diameter drainage hole was opened in the center on one end of the bottom of each container and connected to a flexible plastic pipe that was attached to a sealed 5-L-volume plastic container located immediately beneath. Next, within the containers, a simulated extensive green roof system was developed (Figure 1). More specifically, a 4-mm-thick protection mat was placed in the bottom of each of the containers. The mats were made of non-rotting synthetic fibers, with a dry weight of 0.50 kg m^{-2}, and water permeability of 50 mm s^{-1}, which enabled it to retain 3.6 L m^{-2} of water, according to the manufacturer's claims (VLS-500, DIADEM, Landco Ltd., Athens, Greece). Above the protection mat, a 25-mm-tall drainage layer was placed, with a weight of 1.35 kg m^{-2} (DiaDrain-25H, DIADEM, Landco Ltd., Athens, Greece). The drainage layer, made of recycled high-impact polystyrene, was composed of "waffle-like" sheets with recessed water-retaining areas and ascending holes for facilitating sub-surface aeration, and had a water-holding capacity of 11.8 L m^{-2}. The drainage layer was covered with a non-woven geotextile (VLF-150, DIADEM, Landco Ltd., Athens, Greece) made of reinforced polypropylene, with a thickness of 1.2 mm, weight of 150 g m^{-2}, and water permeability of 105 mm s^{-1}. The geotextile was used to prevent fine-particle migration from the substrate into the drainage layer, thus ensuring free drainage and preventing potential waterlogging. Above the geotextile, a substrate designed for extensive green roof construction that complied with the FLL guidelines [34] was added (SEM, Prasini Stegi, Landco Ltd., Athens, Greece) to a depth of 10 cm. The physical and chemical properties of the substrate are presented in Table 1. Light compression and leveling were applied to the substrate immediately after filling the containers. Finally, all containers were positioned on metal benches with a 1% gradient lengthwise, and plants were transplanted. After transplanting, plants were irrigated every other day with tap water to allow them to establish until the seawater-irrigation treatments started (30 June 2021). Fertilization was not applied to the plants throughout the study period. The study took place 40 days after transplanting, from 30 June 2021 until 4 October 2021 (totaling 97 days), and was located in the experimental field of the Laboratory of Floriculture and Landscape Architecture, of the Agricultural University of Athens, Athens, Greece (37°59′ N and 23°42′ E, 35 m asl) (Figure 2). The experiment terminated a few days before the first forecasted autumn rainfall (8 October 2021).

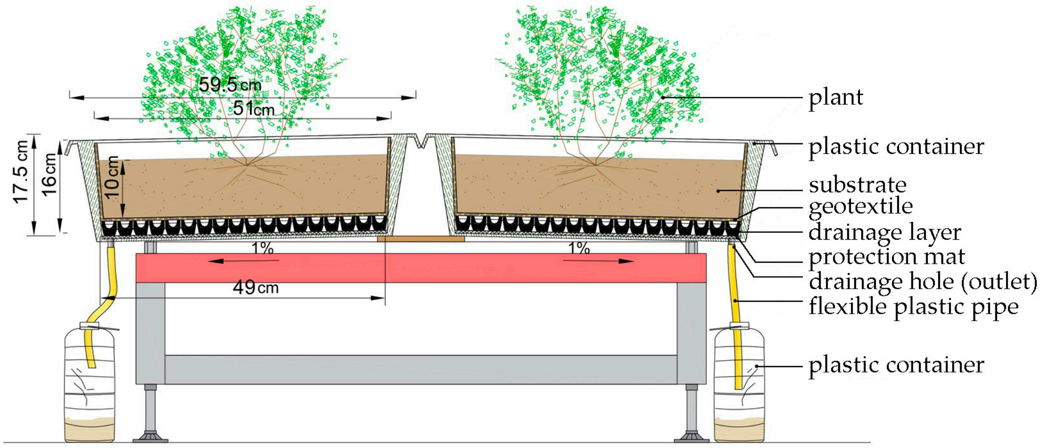

Figure 1. Construction details of the simulated extensive green roof-system experimental plots.

Table 1. Physical and chemical properties of the substrate used in the study (SEM, Prasini Stegi, Landco Ltd., Athens, Greece).

Parameter	Units Measured	Value
pH ($CaCl_2$)		7.3
Electrical conductivity (water, 1:10, m:v),	dS m^{-1}	0.19
Dry bulk density	kg L^{-1}	0.98
Bulk density at maximum water-holding capacity	kg L^{-1}	1.36
Total pore volume	%	56.7
Maximum water-holding capacity	% (*v*/*v*)	40.7
Air-filled porosity	% (*v*/*v*)	16.0
Water permeability	cm·s^{-1}	0.007
Organic matter content	% (*w*/*w*)	7.5
Phosphorus, P_2O_5 (CAL)	mg L^{-1}	167.4
Potassium, K_2O (CAL)	mg L^{-1}	663.8
Magnesium, Mg ($CaCl_2$)	mg L^{-1}	165.7
Nitrate + Ammonium ($CaCl_2$)	mg L^{-1}	1.5
Particle-size analysis:		
>12.5 mm	% (*w*/*w*)	0.3
12.5–9.5 mm	% (*w*/*w*)	5.9
9.5–6.3 mm	% (*w*/*w*)	8.4
6.3–3.2 mm	% (*w*/*w*)	18.7
3.2–2.0 mm	% (*w*/*w*)	24.7
2.0–1.0 mm	% (*w*/*w*)	19.5
1.0–0.25 mm	% (*w*/*w*)	12.1
0.25–0.05 mm	% (*w*/*w*)	4.3
0.05–0.002 mm	% (*w*/*w*)	4.7
<0.002 mm	% (*w*/*w*)	1.2

2.2. Irrigation Treatments

The effect of seawater irrigation on the growth of the halophyte plant species *A. macrostachyum* was studied. The irrigation treatments commenced on 30 June 2021 and ended on 4 October 2021, before the first autumn rainfall, lasting 97 d in total. At the beginning of the experiment, all plants were irrigated with tap water (EC of 0.3 dS m^{-1}) at saturation of the substrate to generate uniform substrate-moisture conditions. Thereafter, irrigation was applied either every 4 or 8 days, depending on the treatment, at an amount equal to 60% of the cumulative reference evapotranspiration (ET_o); this amount of water irrigation was sufficient for the substrate to reach its water-holding capacity and to collect sufficient leachate for the simulated green roof substrate's electrical conductivity to be calculated (EC_L, see below). The ET_o was calculated daily with a Class A Evaporation Pan, positioned adjacent to the experimental plots, and by applying a pan coefficient (K_p) value of 0.65, as defined in Table 5 of FAO's Irrigation and Drainage paper 56 [35] (Figure 3).

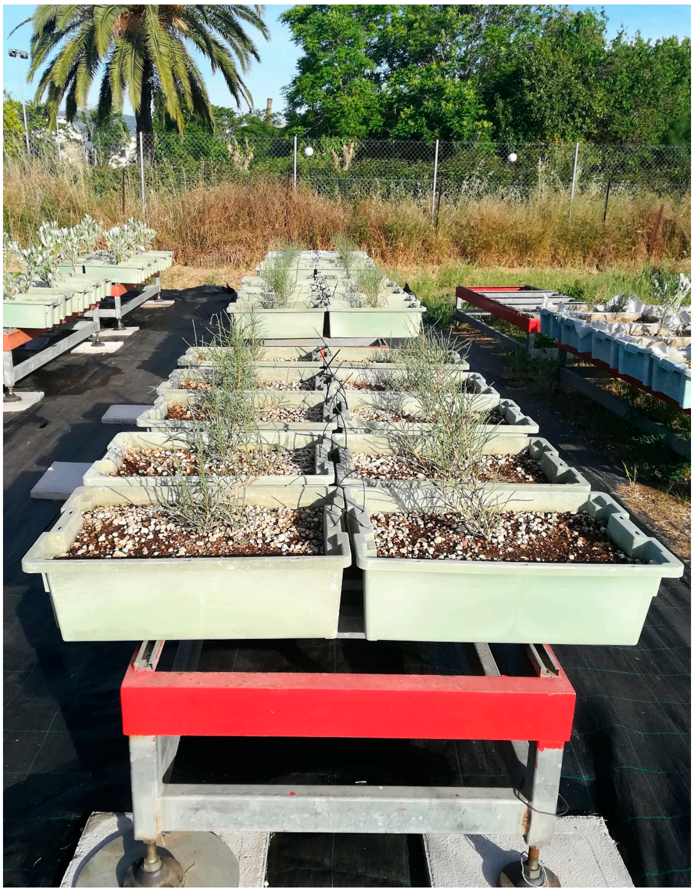

Figure 2. Simulated extensive green roof-system experimental plots planted with *Arthrocnemum macrostachyum* and located in the experimental field of the Laboratory of Floriculture and Landscape Architecture, of the Agricultural University of Athens, Athens, Greece.

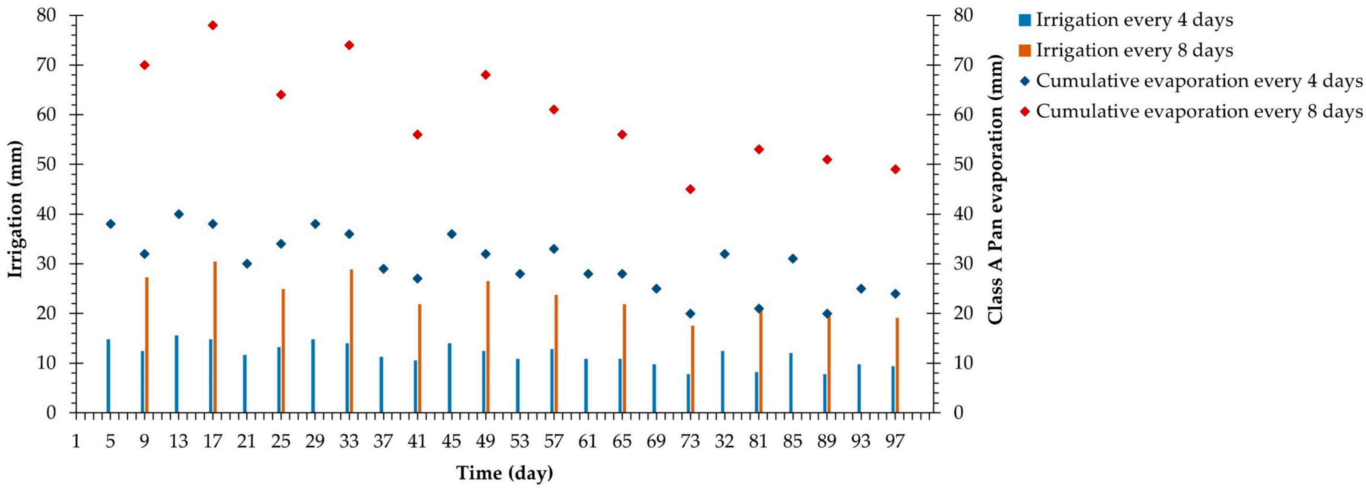

Figure 3. The Class A pan evaporation, measured every 4 and 8 days, and the corresponding amount of irrigation applied at 60% of the reference evapotranspiration (ET_0) throughout the duration of the experiment (30 June–4 October 2021). Note the surface area of each experimental plot is 0.19 m^2.

Chemical analysis of the seawater showed, as expected, greater pH and electrical conductivity values compared to those of the tap water (Table 2). The total hardness of the tap water was 137 mg L^{-1}, as $CaCO_3$, and was classed as moderately hard (75–150 mg $CaCO_3$ L^{-1}), while the total hardness of the seawater was 6615 mg L^{-1}, as $CaCO_3$, and was classed as very hard (>300 mg $CaCO_3$ L^{-1}) [36]. Moreover, the levels of nutrients in the seawater, i.e., K, Ca, Mg, and Fe, exceeded the usual levels found in irrigation water [37]. Seawater showed a high content of Na, which, although not an essential element for most plant species, can be an essential element for some halophytes [38].

Table 2. Chemical analysis of seawater and tap water used in the study.

Parameter	Units Measured	Tap Water	Seawater
pH		7.8	8.2
Electrical conductivity (25 °C)	dS m^{-1}	0.3	57.6
Total hardness ($CaCO_3$)	mg L^{-1}	137	6615
Carbonate (CO_3^{2-})	mg L^{-1}	0	32.4
Bicarbonate (HCO_3^-)	mg L^{-1}	134.2	136
Sulphate (SO_4^{2-})	mg L^{-1}	24	2350
Chloride (Cl^-)	mg L^{-1}	9.2	22,100
Calcium (Ca^{2+})	mg L^{-1}	46	415
Magnesium (Mg^{2+})	mg L^{-1}	5.6	1284
Potassium (K^+)	mg L^{-1}	1.0	399
Sodium (Na^+)	mg L^{-1}	6.6	10,900
Iron (Fe)	μg L^{-1}	12.8	304

Accordingly, in the current study, six different irrigation treatments were applied: (i) tap water every 4 d, (ii) tap water every 8 d, (iii) seawater every 4 d, (iv) seawater every 8 d, (v) seawater alternated with tap water every 4 d, (vi) seawater alternated with tap water every 8 d. The seawater used in the study was collected on a single day from Drapetsona, Attica, Greece (lat. 37°57′ N and long. 23°37′ E) and was transported and stored in a plastic tank located within a shed. The amount of seawater collected sufficed for the entire study period. On the other hand, the tap water used had an electrical conductivity of 0.3 dS m^{-1}. Experimental plots were manually irrigated using a watering can with an attached rose head to ensure homogenous irrigation.

2.3. Meteorological Conditions

The daily ambient maximum, minimum, and average temperatures, relative humidity, and precipitation were obtained by the National Observatory of Athens (lat. 37°58′ N, long. 23°43′ E, 107 m asl), which is a nearby meteorological station located at Thision, 1.8 km from the experimental site (Figure 4) [39]. Generally, throughout the experiment (30 June–4 October 2021) warm thermal conditions prevailed. More specifically, the mean daily ambient temperature ranged between 18.6 °C, on 23 September, and 36.5 °C, on 3 August. Moreover, the absolute maximum and minimum daily ambient-temperature values of 43.9 °C and 15.0 °C were recorded on 3 August and 24 September respectively. The daily ambient-temperature variation (T_{max}–T_{min}) ranged between 4.7 and 13.5 °C, with a mean value of 9.1 °C. Precipitation occurred only on one day (9 September 2021), and it was minimal (0.2 mm). Climatic conditions during the experiment (30 June–4 October 2021) were appropriate for evaluating *A. macrostachyum* response under seawater irrigation, since no rainfall events occurred during that time (Figure 4). During the experiment, the average air temperature was 27.6 °C (±3.8 °C), while the class-A pan evaporation totaled 725 mm, resulting in an average daily evaporation rate of 7.6 mm d^{-1} (Figure 3).

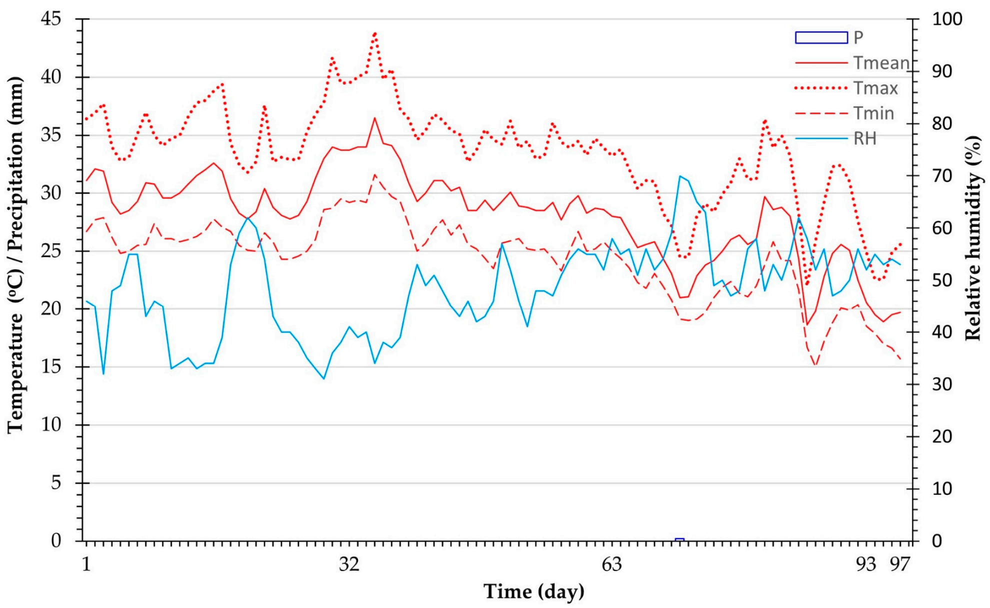

Figure 4. The daily maximum, minimum, and mean ambient temperatures, precipitation, and relative humidity present during the simulated extensive green roof experiment undertaken from 30 June (day 1) to 4 October (day 97) 2021. Data were acquired from the meteorological station of the National Observatory of Athens at Thision (lat. 37°58′ N, long. 23°43′ E, 107 m asl) [39]. P: precipitation (mm); Tmean, Tmax, and Tmin: mean, maximum, and minimum temperature (°C), respectively; RH: relative humidity (%).

2.4. Measurements

Throughout the study, the salinity of the substrate's leachate (EC_L) was determined every 4 d, soon after irrigation, from the leachate collected in the plastic containers positioned beneath the simulated green roof through a flexible plastic pipe (see above). For EC_L measurements, a handheld conductivity meter (Hanna HI98192, Hanna Instruments Inc., Woonsocket, RI, USA) was used, which automatically corrected EC to 25 °C.

The plant-height and -growth indices (GI) [(height + widest width + perpendicular width)/3] were determined every 8 days. To assess the progressive development of the plants' ground cover during the experimental period, every 8 days, RGB images were taken using a Canon IXUS 100 IS (Canon Europe Ltd., Uxbridge, UK) from a constant distance (70 cm) above each experimental plot. The images were taken between 12:00 and 16:00 h, while full sunlight was available, thereby avoiding the formation of shadows over the experimental plots. Each image was cropped using photo-editing software GIMP 2.8.20 (GNU Image Manipulation Program, Boston, Massachusetts, U.S.A.) to remove unwanted portions of images. The surface area of plant ground cover (cm^2) was determined using the image-processing software ImageJ ver. 1.54d [40].

Shoots' relative water content (RWC) was calculated following the method described by González and González-Vilar [41]. Three 0.5-cm^2 shoot sections were collected from each experimental plot every 8 days, before irrigation, between 12:00 and 14:00 h. The shoot sections were weighed to determine the fresh weight and then immersed into deionized water for 4 h in a fridge to prevent growth but allow hydration; after gently drying, the turgid weight of each shoot section was determined. Next, the shoots were oven-dried for 48 h at 70 °C, and their dry weights were determined. Hence, RWC was calculated based on the following formula:

$$RWC = \frac{(FW - DW)}{(TW - DW)} 100 \quad (1)$$

where FW = fresh weight, DW = dry weight, and TW = turgid weight of the shoot tissue.

2.5. Experimental Design and Statistical Analysis

The experimental plot arrangement followed a completely randomized design and each treatment was replicated five times, resulting in 30 experimental plots (i.e., six irrigation treatments × five replications = 30 experimental plots). One-way analysis of variance (ANOVA) was performed on the collected data employing the statistical analysis software Statgraphics Centurion, version 15.2.11 (Statpoint Technologies Inc., Warrenton, VI, USA). A similar statistical analysis was conducted on pooled data (EC_L, plant height, growth index, ground cover, and shoot RWC), to examine the overall effects of the different irrigation treatments on the growth of *A. macrostachyum.* Significant differences between the treatment means within each separate sampling date for all the measurements taken were determined using Fisher's least significant difference (LSD) at $p < 0.05$.

3. Results and Discussion

3.1. Leachates' Electrical Conductivity

Statistical differences between the different irrigation treatments were observed from day 5 onwards (4 July 2021). Throughout the experiment, from the second recorded measurement onwards (day 9), the irrigation with seawater every 4 days exhibited higher EC_L values than the other irrigation treatments (Figure 5).

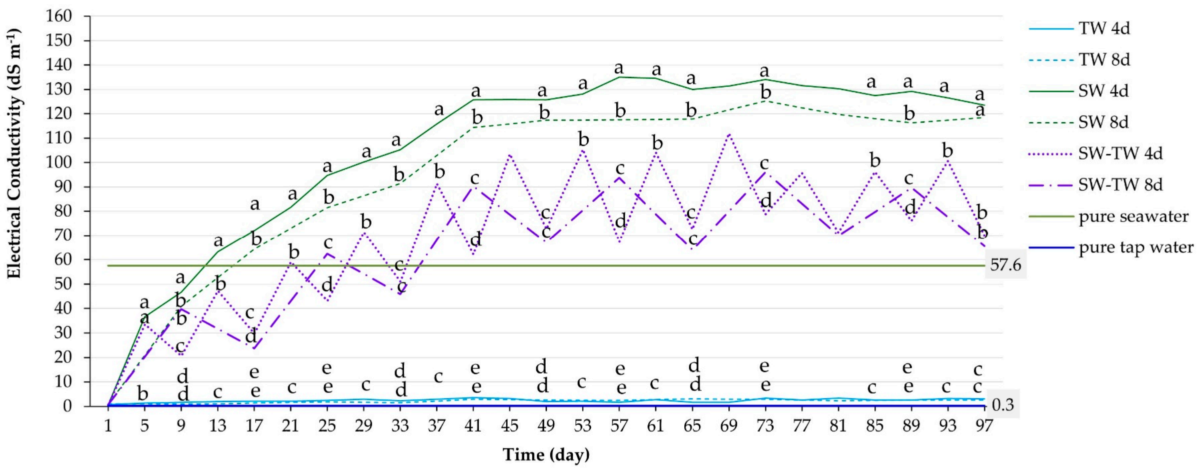

Figure 5. The effects of irrigation treatments (tap water every 4 days, tap water every 8 days, seawater every 4 days, seawater every 8 days, seawater alternated with tap water every 4 days, and seawater alternated with tap water every 8 days), on the electrical conductivity (dS m^{-1}) of the substrate's leachates collected from the corresponding simulated extensive green roof system experimental plots planted with *Arthrocnemum macrostachyum* during the period of 30 June (day 1)–4 October (day 97) 2021. The electrical conductivity (dS m^{-1}) values of the applied seawater (57.6 dS m^{-1}) and tap water (0.3 dS m^{-1}) are depicted. Values are the means of five replicates. Differences between means on a given day according to Fisher's least significant difference (LSD) at $p < 0.\ 05$ are shown with different letters. TW 4d: tap water every 4 days; TW 8d: tap water every 8 days; SW 4d: seawater every 4 days; SW 8d: seawater every 8 days; SW-TW 4d: seawater alternated with tap water every 4 days; and SW-TW 8d: seawater alternated with tap water every 8 days.

Amongst the various seawater-irrigation treatments, the EC_L level of the "seawater every 4 days" was the first to exceed the seawater's electrical conductivity value (57.6 dS m^{-1}), 12 days after the start of the irrigation treatment (day 13), followed by the "seawater every 8 days" (day 17), the "seawater alternated with tap water every 4 days" (day 25), and the "seawater alternated with tap water every 8 days" (day 29) irrigation treatments. The repeated irrigation with additional amounts of seawater caused the EC_L to increase. More specifically, from the day on which the irrigation treatments began (30 June 2021, day 1), the electrical conductivity of the leachates (EC_L) from the simulated green roof experimental plots planted with *A. macrystachyum* and watered with seawater (either exclusively or in alternation with tap water) increased gradually over time, reaching a plateau 41 days later (mid-August 2021) (Figure 5). From this point (day 41) until the end of the experiment (day 97/4 October 2021), the EC_L values remained relatively stable. The mean EC_L values were as follows: 129.3 dS m^{-1} for the "seawater every 4 days" treatment, 118.5 dS m^{-1} for the "seawater every 8 days" treatment, 85.9 dS m^{-1} for the "seawater alternated with tap water every 4 days" treatment, and 79.9 dS m^{-1} for the "seawater alternated with tap water every 8 days" treatment. Note that these levels were much higher than the EC level of the seawater (57.6 dS m^{-1}) used in the study. Ntoulas and Varsamos [42] evaluated the potential of using seawater for irrigating two varieties of seashore paspalum (*Paspalum vaginatum* Sw.), "Marina" and "Platinum TE", growing in shallow green roof substrates and reported a similar steady-state condition after successive seawater-irrigation events. Although, from day 37 onwards until the end of the experiment, the EC_L values from both the "seawater every 4 days" and "the seawater every 8 days" treatments remained relatively constant above the seawater's EC value (57.6 dS m^{-1}), the EC_L values from the treatments involving seawater alternated with tap water every 4 or 8 days fluctuated above the seawater's EC value. The fluctuation in the EC_L values was due to the tap water washing away the substrate's accumulated salts, keeping them between the EC_L values of the seawater-irrigation treatments and the seawater EC value (57.6 dS m^{-1}).

In contrast, the EC_L values of the experimental plots irrigated exclusively with tap water either every 4 or every 8 days were similar ($p < 0.05$) and remained relatively constant throughout the study, at relatively low levels (<3.5 dS m^{-1}), but above the tap water's EC value (0.3 dS m^{-1}). The mean EC_L values were 2.4 dS m^{-1} and 2.2 dS m^{-1}, respectively. Apart from the tap-water-irrigation treatments, the EC_L levels of all the seawater treatments exceeded by far the maximum allowable EC_L levels for growing media for plant species, depending on their sensitivity (the maximum allowable EC_L values that do not affect the plant growth of very sensitive and very tolerant species are 1 dS m^{-1} and 8 dS m^{-1}, respectively) [43]. Halophytes such as *A. macrostacyum* are capable of surviving and growing under extreme saline conditions; unlike glycophytes, they have developed ion homeostasis through various mechanisms, such as ion extrusion and compartmentalization, osmotic adjustments, and antioxidant production [44,45].

3.2. Plant Height

The height of the *A. macrostachyum* plants were affected significantly ($p < 0.05$) on only two days (days 49 and 65) (Figure 6). On day 49, the heights of the plants irrigated with either tap water every 4 days, seawater alternated with tap water every 8 days, or seawater every 4 days were significantly greater than the corresponding heights of plants irrigated with seawater every 8 days. On day 65, the heights of the *A. macrostachyum* plants irrigated with tap water every 4 days were significantly greater than the corresponding heights of the plants irrigated with seawater every 8 days, which demonstrated the lowest height values ($p < 0.05$). Despite the very high levels of the EC_L of the experimental plots irrigated with the seawater treatments, with the exception of two days in mid-August 2021 (day 49) and at the start of September 2021 (day 65), the heights of the *A. macrostachyum* were not affected.

Moreover, *Arthrocnemum macrostachyum* is a stem-succulent perennial halophytic shrub forming evergreen low-growing ground cover. In its natural habitat, *A. macrostachyum* develops upright-branched, distinctly segmented shoots and, as it grows, it forms a clump of shoots that accumulates wind-borne sand, forming a hummock [46]. Therefore, it is likely that after reaching specific heights, the *A. macrostachyum* plants began to form clumps and grew sideways rather than upwards; this assumption agrees with the significant difference ($p < 0.05$) found in the corresponding plant ground-cover surface areas across the various irrigation treatments applied (see below).

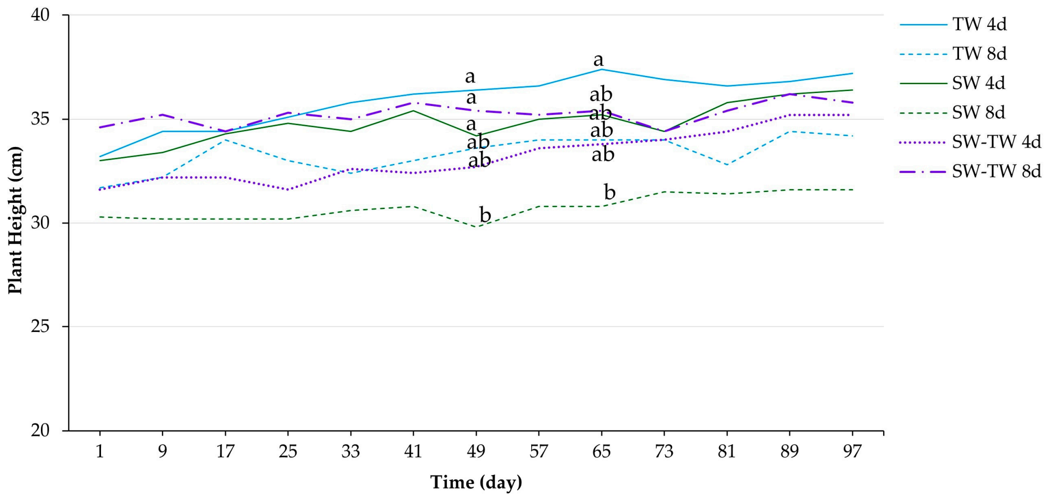

Figure 6. The effects of irrigation treatments (tap water every 4 days, tap water every 8 days, seawater every 4 days, seawater every 8 days, seawater alternated with tap water every 4 days, and seawater alternated with tap water every 8 days), on the heights (cm) of *Arthrocnemum macrostachyum* plants established in simulated extensive green roof-system experimental plots during the period of 30 June (day 1)–4 October (day 97) 2021. Values are the means of five replicates. Differences between means on a given day according to Fisher's least significant difference (LSD) at $p < 0.05$ are shown with different letters. TW 4d: tap water every 4 days; TW 8d: tap water every 8 days; SW 4d: seawater every 4 days; SW 8d: seawater every 8 days; SW-TW 4d: seawater alternated with tap water every 4 days; and SW-TW 8d: seawater alternated with tap water every 8 days.

3.3. Plants' Ground Cover

The surface area of the *A. macrostachyum* plants' ground cover showed relatively sharp increases during the first week after the start of the experiment in response to all the irrigation treatments studied (Figure 7). The NaCl of the seawater as well as the tap water at low concentrations may have stimulated the halophyte plants' growth. The substrate EC_L levels of the plants irrigated with seawater were relatively low during the first week of the study. Similar results were shown in another study, which reported stimulated height growth at low NaCl concentrations (0.2, 0.7, 4, 8, and 13 dS m^{-1}) in the halophyte species, *Juncus maritimus* [47]. Most research concentrates on the inhibition of plant growth by high salinity levels rather than the effects of low levels of salt on plant growth [24,48]. Even in highly tolerant halophytes, salts are not compulsory for the development of many halophytic species, such as *A. macrostachyum* [24,48]. The growth and development of the latter halophytes in natural saline habitats do not seem particularly dependent on soil salinity per se; rather, they are probably due to competition with other species [48]. It has been reported that dicotyledonous halophytes generally show optimal growth at 50–250 mM NaCl [49,50]; note that electrical conductivity of 7.8 dS m^{-1} is equivalent to approximately 80 mM NaCl [51]. In another experiment, greenhouse-grown *A. macrostachyum* plants potted in perlite showed optimum stimulated relative growth rates over a broad range of NaCl concentrations (171–510 mm NaCl) [32]. The fresh mass of *A. macrostachyum* shoots, grown in sand in pots, was increased at 200–400 mM NaCl [52]. Furthermore, moderate concentrations of NaCl have been found to stimulate the growth of halophytes, such as *Atriplex halimus* (irrigated with 150 mM NaCl) [53], *Batis maritima*, *Halimione portulacoides*, and *Salsola longifolia*, (irrigated with 25–50% seawater) [54].

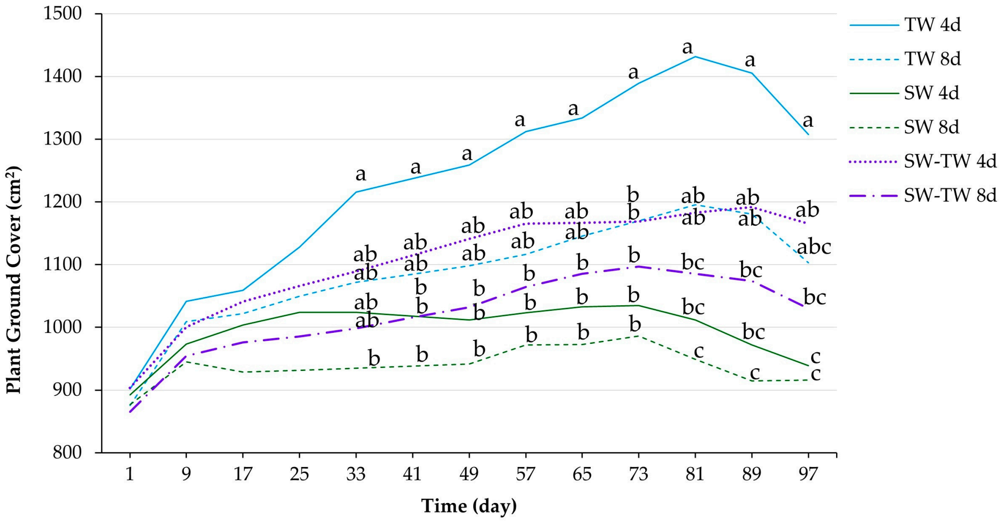

Figure 7. The effects of irrigation treatments (tap water every 4 days, tap water every 8 days, seawater every 4 days, seawater every 8 days, seawater alternated with tap water every 4 days, and seawater alternated with tap water every 8 days) on the ground cover of *Arthrocnemum macrostachyum* established in simulated extensive green roof-system experimental plots during the period of 30 June (day 1)–4 October (day 97) 2021. Values are the means of five replicates. Differences between means on a given day according to Fisher's least significant difference (LSD) at $p < 0.05$ are shown with different letters. TW 4d: tap water every 4 days; TW 8d: tap water every 8 days; SW 4d: seawater every 4 days; SW 8d: seawater every 8 days; SW-TW 4d: seawater alternated with tap water every 4 days; and SW-TW 8d: seawater alternated with tap water every 8 days.

More specifically, in the current study, the ground cover of *A. macrostachyum* plants was affected significantly ($p < 0.05$) by the different irrigation treatments from the start of August onwards (day 33) (Figure 7). From day 33, the ground cover of the plants irrigated with tap water every 4 days was significantly greater than the corresponding ground cover of the plants irrigated with seawater every 8 days. Furthermore, from day 41, the ground cover of the plants irrigated with tap water every 4 days was significantly greater than the corresponding ground cover of the plants irrigated with either seawater every 4 days or with seawater alternated with tap water every 8 days. Although the ground cover of the plants irrigated with tap water every 4 days was greater than the corresponding ground cover of the plants irrigated with either tap water every 8 days and that of the seawater alternated with tap water every 4 days, this difference was not significant. Thus, of the various seawater-irrigation treatments, *A. macrostachyum* showed the best plant ground cover when irrigated with seawater alternated with tap water every 4 days. The least ground cover from the development of *A. macrostachyum* was observed in the plants irrigated with seawater every 8 days, which did not differ significantly from the corresponding ground cover of the plants irrigated either with seawater every 4 days or with seawater alternated with tap water every 8 days. In the current study, although the ground cover of the *A. macrostachyum* plants irrigated with seawater every 4 or 8 days or seawater alternated with tap water every 8 days was significantly less than that of the plants irrigated with tap water every 4 days, all the plants appeared healthy, without visual signs of chlorosis or necrosis, suggesting tolerance of increased saline conditions (the measured seawater EC was 57.6 dS m^{-1}).

The decline in the plant-ground-cover surface area after day 81 (mid-September) suggests that further studies are necessary to determine the effect of seawater irrigation over longer periods; on the other hand, this decline was also evident in the plants irrigated with tap water. Therefore, in relation to the seasonal gradual decline in ambient temperature, as the stems gradually matured and took on a light brown color, they became difficult to distinguish from the substrate during the image processing, which can probably explain the reduced surface area of the plant ground cover from day 81 onwards. Furthermore, should the experiment have continued, it is expected that the need for irrigation would have stopped, as the seasonal drop in ambient temperature and increase in relative humidity would have reduced the loss from evapotranspiration and the seasonal rainfall would have met the plants' water needs until the following spring, when the gradual rise in ambient temperature would have necessitated the irrigation of the plants. Further research is necessary to determine the substrate's EC during this time and to determine the effect of irrigation with seawater over consecutive years. However, the results seem promising for the continued irrigation of *A. macrostachyum* with seawater over consecutive years. In a field experiment over a period of two years, seven species of *Atriplex* (*A. atacamensis*, *A. barclayana*, *A. cinerea*, *A. lentiformis*, *A. linearis*, *A. undulata*, and *A. nunnularia*) irrigated with undiluted seawater were able to survive [55].

3.4. Plant-Growth Index

Overall, from the start of the experiment, the growth index showed a relatively steady increase. Specifically, the growth index of *A. macrostachyum* was affected significantly ($p < 0.05$) by the different irrigation treatments from mid-August onwards (day 49) (Figure 8). From day 49, the growth index of the plants irrigated with tap water every 4 days was significantly greater than the corresponding growth index of the plants irrigated with seawater every 8 days. Although these were not measured in the current study, other authors found similar results for the dry weights of halophytes irrigated with undiluted seawater; the halophytes *Batis maritima*, *Halimione portulacoides*, *Salsola longifolia*, *Tamarix aphylla*, and *Tamarix gallica* showed lower dry weights when irrigated with undiluted seawater compared to tap water [54]. On the other hand, the growth index of the plants irrigated with tap water every 4 days was not significantly different from the corresponding growth index of the plants irrigated with either tap water every 8 days, seawater every 4 days, seawater alternated with tap water every 8 days (with the exception of the growth indices recorded on day 65 and 73), or seawater alternated with tap water every 4 days. Furthermore, the growth index of the plants irrigated with seawater every 8 days did not differ significantly from the corresponding growth index of the plants irrigated with seawater alternated with tap water every 8 days (with the exception of the growth index recorded on day 65).

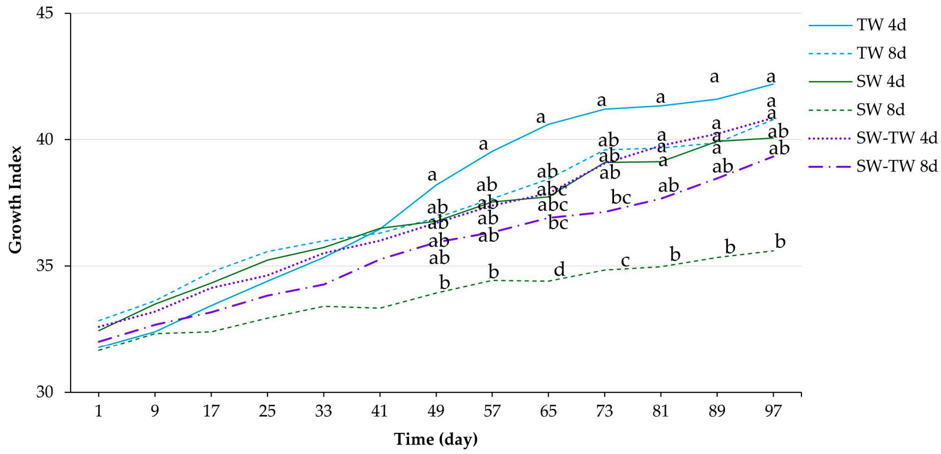

Figure 8. The effects of irrigation treatments (tap water every 4 days, tap water every 8 days, seawater every 4 days, seawater every 8 days, seawater alternated with tap water every 4 days, and seawater alternated with tap water every 8 days) on the growth indices of *Arthrocnemum macrostachyum* established in simulated extensive green roof-system experimental plots during the period of 30 June (day 1)–4 October (day 97) 2021. Values are the means of five replicates. Differences between means on a given day according to Fisher's least significant difference (LSD) at $p < 0.\ 05$ are shown with different letters. TW 4d: tap water every 4 days; TW 8d: tap water every 8 days; SW 4d: seawater every 4 days; SW 8d: seawater every 8 days; SW-TW 4d: seawater alternated with tap water every 4 days; and SW-TW 8d: seawater alternated with tap water every 8 days.

The latter results were unexpected, as *A. macrostachyum* is considered an extreme halophyte [56]. Furthermore, since seawater contains some nutrients, it was anticipated to affect the plants' growth positively (see Table 2). In another study, researchers [57] found that the total yield of two ecotypes of both *Salicornia persica* and *Sarcocornia fruticosa* species decreased with increasing percentages of seawater above 50% in the irrigation water, and that while the shoots' sodium and chloride contents increased significantly, only the potassium contents of the shoots slightly increased, while the shoot contents of both calcium and magnesium were similar. Although the assessment of yield and nutrient uptake was beyond the scope of the current study, it seems that even for extreme halophytes with the ability to grow successfully in NaCl concentrations equivalent to or greater than seawater concentrations, the optimum concentration for plant growth is less than the seawater's salt concentration [57].

Accordingly, the results in this study suggest that *A. macrostachyum* is tolerant of salinity and, in particular, irrigation with seawater every 4 days or seawater alternated with tap water every 4 or 8 days. However, in response to the various seawater-irrigation treatments, the *A. macrostachyum* showed better overall growth when irrigated with seawater every 4 days and seawater alternated with tap water every 4 days. Halophytes are adapted to saline environments and naturally survive and reproduce at soil-salinity values of 100 mM NaCl (approx. EC 10 dS m^{-1}) or more [58], and some are even able to grow at soil-salinity values of 500 mM–1 M NaCl [24,52,58,59]. Indeed, the salinity of seawater varies; however, on average, it is 598.9 mM NaCl [60] (approx. EC 50-8 dS m^{-1}) [51], while glycophytes complete their life cycles at soil salinities < 100 mM NaCl, and many sensitive plant species complete their life cycles below 50 mM NaCl.

3.5. Shoots' Relative Water Content

The relative water content (RWC) is used to measure plant hydration, represents the capacity for osmotic adjustment [61], and is used as an indicator of plants' responses to salinity [62]. A decrease in RWC is indicative of reduced shoot water hydration, an increase indicates the accumulation of osmolytes, while a steady state is indicative of stable shoot hydration [62]. The results showed that the shoot RWC of the *A. macrostachyum* plants was affected significantly ($p < 0.05$) by the different irrigation treatments from the start of August (day 33) until mid-September (day 73) (Figure 9). From day 33, the shoot RWC of the plants irrigated with tap water every 4 days was significantly greater than that of the plants irrigated with the other treatments, with the exception of the plants irrigated with seawater alternated with tap water every 4 days on days 65 and 73. In another study, similarly, although not significantly ($p < 0.05$), the shoot RWC of pot-grown *A. macrostachyum* plants under greenhouse conditions decreased with increasing NaCl concentrations of irrigation (96% at 0 mM NaCl to 94% at 340 mM NaCl). In the current study, during this time period (days 33–73), the summer temperatures increased (with a maximum ambient temperature of 43.9 °C on day 35), stimulating evapotranspiration and increasing water loss, which lasted until a few days after the relative humidity increased (to 70%, on day 72). However, the RWC values of all the studied seawater-irrigation treatments exceeded the typical RWC (60–70%) for the initial wilting (with exceptions) of the crop species, indicating *A. macrostacyum*'s tolerance of salinity, particularly under ambient temperatures above optimal temperatures for photosynthesis (35 °C) [63]. Osmotic adjustment is an effective adaptive trait for dehydration avoidance [59,64], and salt tolerance has been found to be related to the accumulation of osmolytes [65]. Sisay et al. [62] also suggest that *A. macrostachyum* is tolerant of salinity through the accumulation of osmolytes. The current study suggests that *A. macrostachyum* is tolerant of high levels of salinity and, in particular, of seawater irrigation.

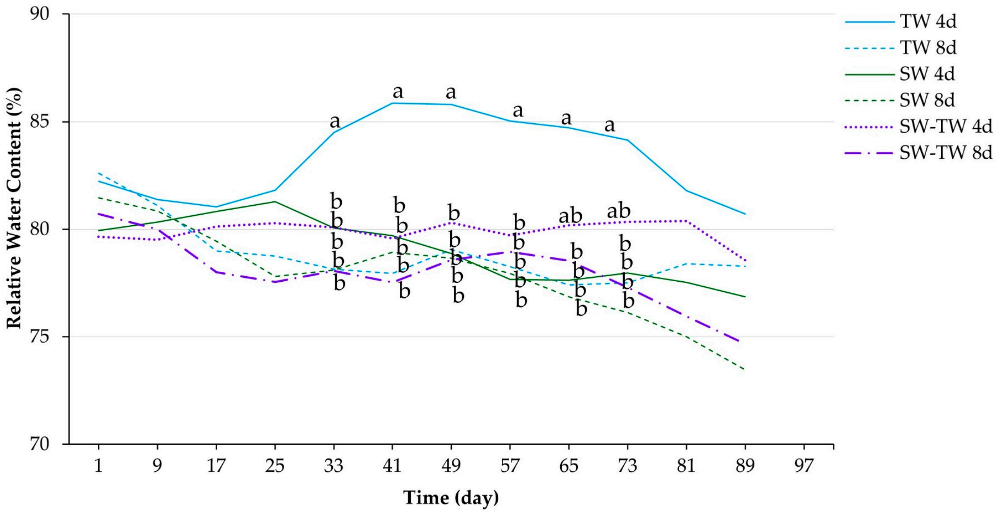

Figure 9. The effects of irrigation treatments (tap water every 4 days, tap water every 8 days, seawater every 4 days, seawater every 8 days, seawater alternated with tap water every 4 days, and seawater alternated with tap water every 8 days), on the shoot relative water content (%) of *Arthrocnemum macrostachyum* established in simulated extensive green roof system experimental plots during the period of 30 June (day 1)–4 October (day 97) 2021. Values are the means of five replicates. Differences between means on a given day according to Fisher's least significant difference (LSD) at $p < 0.05$ are shown with different letters. TW 4d: tap water every 4 days; TW 8d: tap water every 8 days; SW 4d: seawater every 4 days; SW 8d: seawater every 8 days; SW-TW 4d: seawater alternated with tap water every 4 days; and SW-TW 8d: seawater alternated with tap water every 8 days.

3.6. Overall Effects of Irrigation Treatments (Pooled Data)

Of the six different irrigation treatments applied, the pooled electrical conductivity of the leachates (EC_L) was greatest for the *A. macrostachyum* plants irrigated with seawater every 4 days, followed, in descending order, by the plants irrigated with seawater every 8 days and by seawater alternated with tap water every 4 or 8 days (Table 3), all of which exceeded the electrical conductivity of the applied to the irrigation treatments seawater (57.6 dS m^{-1}). In comparison to the seawater's EC, the increase in the pooled EC_L was twofold for the plants irrigated with seawater every 4 days, and approximately one and a half times greater for the plants irrigated with seawater every 8 days. On the other hand, the EC_L of the plants irrigated with seawater alternated with tap water every 4 or 8 days was greater than the seawater's EC. Furthermore, the EC_L of the plants irrigated with tap water was low (EC_L < 3 dS m^{-1}), albeit higher than the tap water's EC value (0.3 dS m^{-1}). Halophytes have been found to grow at soil-salinity values of 500 mM–1 M NaCl [24,52,58,59]. In the current study, the *A. macrostachyum* plants were able to survive and grow under extreme saline conditions, without developing signs of chlorosis or necrosis. Furthermore, in another study, seven species of the halophyte *Atriplex* irrigated with undiluted seawater were able to survive and grow for two years [55].

Table 3. The effects of various irrigation treatments on the electrical conductivity of the substrate leachates (EC_L), heights (H), ground cover (GC), growth indices (GIs), and shoot relative water content (RWC) of *Arthrocnemum macrostachyum* plants established in simulated extensive green roof-system experimental plots during the period of 30 June (day 1)–4 October (day 97) 2021. The mean values represent pooled data. Means in columns followed by the same letter are not significantly different, based on Fisher's least significant difference (LSD), at $p < 0.05$.

Irrigation Treatments	EC_L [1] (dS m^{-1})	H (cm)	GC (cm^2)	GI (cm)	RWC (%)
tap water every 4 d	2.41 d	35.92 a	1232.34 a	37.58 a	83.25 a
tap water every 8 d	2.14 d	33.33 a	1086.16 b	37.08 a	78.87 ab
seawater every 4 d	106.23 a	34.81 a	996.84 cd	36.77 ab	79.05 ab
seawater every 8 d	94.30 b	30.76 a	938.96 d	33.81 c	77.89 c
seawater alternated with tap water every 4 days	69.44 c	33.19 a	1107.37 b	36.77 ab	79.89 b
seawater alternated with tap water every 8 days	62.22 c	35.24 a	1020.21 c	35.61 b	77.98 c
significance	***	ns	***	***	***

[1] note that the electrical conductivity of the irrigation treatments applying tap water was 0.3 dS m^{-1}, and that the value of the treatments using seawater was 57.6 dS m^{-1}. ns: non-significant at $p < 0.05$; *** significant at $p < 0.001$.

With regard to the *A. macrostachyum* plants' growth, the pooled plant heights were not significantly affected by the different irrigation treatments ($p < 0.05$) while the corresponding pooled GI, plant ground cover (%), and shoot relative water content were ($p < 0.001$). As mentioned above, *A. macrostachyum* is a stem-succulent perennial halophytic shrub that forms evergreen low-growing ground cover. Hence, it is likely that after reaching a particular height, the plants began to grow sideways rather than upwards. The former was reflected in the corresponding plant groundcover depicting differences ($p < 0.05$) amongst the various irrigation treatments applied. Therefore, the plants irrigated with tap water every 4 days showed the greatest ground cover ($p < 0.001$), followed by plants irrigated with tap water every 8 days and the plants irrigated with seawater alternated with tap water every 4 days; these were followed by the plants irrigated with seawater every 4 days and those irrigated with seawater alternated with tap water every 8 days, while the plants irrigated with seawater every 8 days showed the least ground cover. These results agreed with the results recorded throughout the duration of the experiment for the ground cover of the *A. macrostachyum* plants, described above, according to which the plants irrigated with seawater alternated with tap water every 4 days showed the greatest ground cover of the various seawater-irrigation treatments studied. Note that although the EC_L values of the plants irrigated with seawater alternated with tap water every 4 or 8 days were not significantly different, the plants irrigated with tap water every 8 days and the plants irrigated with seawater alternated with tap water every 8 days showed significantly less ground cover ($p < 0.05$) than the plants irrigated with tap water every 4 days and the plants irrigated with seawater alternated with tap water every 4 days, respectively. These results suggest that the longer irrigation intervals and, hence, the longer duration of the "drier" conditions between irrigations, affected the plants' ground cover. In fact, the total amounts of irrigation water in the 4- and 8-day-irrigation treatments were similar (i.e., the amount of irrigation water for the 8-day-irrigation treatments was equal to the cumulative irrigation water amount of the preceding and the current measured 4-day irrigation treatments; see Figure 3). It is possible that, in addition to the saline conditions, the plants also experienced drought conditions when irrigated every 8 days. Papafotiou et al. [66] found that 5-day-interval irrigation negatively affected the dry weights of the shoots of several Mediterranean species, such as *Artemisia absinthium* and *Helichrysum orientale*, as well as the heights of *H. orientale* growing in a simulated green roof system with a 15-cm-deep compost-amended substrate. Accordingly, the substrate's hydraulic properties are important when conducting irrigation management on extensive green roof systems [67]. More detailed studies are necessary to determine the substrate's water-retention curve and, hence, the effect of the substrates' tension and relative water content on the plant-ground-cover surface area, as well other growth parameters of *A. macrostachyum*. Nevertheless, in all the irrigation treatments studied, the *A. macrostachyum* plants appeared healthy and showed no apparent signs of chlorosis or necrosis.

The plants irrigated with tap water every 4 or 8 days showed the greatest GI, which was not significantly different from the GI of the plants irrigated with seawater every 4 days or with seawater alternated with tap water every 4 days ($p < 0.001$). Similar to the results already shown throughout the duration of the experiment, of the various seawater irrigation treatments, the *A. macrostachyum* plants showed the best GI when they were irrigated with seawater every 4 days, and with seawater alternated with tap water every 4 days.

The relative water content of the shoots was greatest for the plants irrigated with tap water every 4 or 8 days or with seawater every 4 days, followed by the plants irrigated with seawater alternated with tap water every 4 days and with the least ground cover, the plants irrigated with seawater every 8 days, and those with seawater alternated with tap water every 8 days ($p < 0.05$). These results agree with the results of Amor et al. [65], who showed that although the RWC of pot-grown *Crithmum maritimum* under greenhouse conditions and irrigated with different concentrations of saline water (0, 100, 200, and 400 mM NaCl) was unaffected at moderate concentrations of NaCl (100 mN NaCl) in relation to the control (0 mM NaCl), the RWC decreased with increasing concentrations of NaCl (200, and 400 mM NaCl).

4. Conclusions

In the current study, the halophyte *A. macrostachyum* demonstrated healthy growth on simulated extensive green roofs with a 10-cm-deep substrate under all the studied seawater-irrigation treatments. The EC_L values of all the seawater irrigation treatments exceeded the maximum allowable EC_L levels for growing media for very tolerant plant species (8 dS m^{-1}), as well as the EC of the applied seawater (57.6 dS m^{-1}), suggesting that *A. macrostachyum* can tolerate extreme saline conditions. This study showed that both the partial and the exclusive use of seawater for irrigation are feasible. In particular, the growth of the *A. macrostachyum* plants was not affected when they were irrigated over short periods (4 days) with seawater alternated with tap water. Nevertheless, irrigation with seawater only decreased the plants' growth; furthermore, this decrease in plant growth was greater when irrigation was applied every 8 days than when it was applied every 4 days.

In conclusion, *Arthrocnemum macrostachyum* is a promising candidate for introduction into Mediterranean green roof systems using seawater irrigation. Irrigation with seawater alternated with tap water every 4 days is proposed to conserve water resources. For the further conservation of water, irrigation every 4 days with seawater only is also proposed.

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