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Are Rain Gardens Resistant to Salinization Stresses? The Consequences of De-Icing Chemicals' Implementation for Soil Health, Plant Condition, and Groundwater Quality

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Abstract: Rain gardens are efficient nature-based solutions (NBSs) for the sustainable management of surface run-off in urban areas. The functionality of a rain garden in an urban environment depends on the resistance of plant and soil components to anthropogenic stressors. In temperate climates, the negative effects of de-icing chemicals applied in wintertime are one of the major anthropogenic stressors for the rain gardens' ecosystem. The research aimed to study the effect of a NaCl-based de-icer in the mesocosm experiment, where materials of soil mixtures (seven parts by volume of quartz or carbonate sand and three parts by volume of loam or peat), plants (*Hemerocallis hybrida*), de-icer dose (529 mg L⁻¹ for Cl⁻ and 472 mg L⁻¹ for Na⁺ concentrations), and irrigation period simulated typical conditions for the Moscow city—the largest world megapolis with permanent snow cover during the wintertime. For all soil mixtures, a short-term negative impact of salinization on soil health included a decrease in microbial biomass (4–7-times) and basal respiration (2–3.6-times). After six months, soil health indicators recovered by 80–90% in the peat and carbonate sand mixture, whereas the negative effects on the quartz sand and loam mixtures remained irreversible (1.3 and 3 times lower than the control, respectively). The chlorophyll content of the plants on all soil mixtures was reduced compared to the control plants (37.1 ± 4.1 vs. 39.9 ± 1.2 SPAD units). The worst plat condition was observed for soil mixtures based on quartz sand. In this variant, the negative effect of salinization coincided with low nutrient content. In our results, the ash content was up to three times less compared to the initial state, as well as to the other materials. Plants grown in mixtures based on loam were more resistant to salinization due to higher nutrient content than peat. Overall, based on soil Na uptake, plant biomass, and recovery of soil microbiota, soil mixtures based on peat, loam, and carbonate sand will be the most resistant to NaCl-based de-icers and could be recommended for the creation of rain gardens in cities with permanent snow cover in winter.

Keywords: salinization; de-icing agents; NaCl; soil construction; rain garden; *Hemerocallis hybrida*



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1. Introduction

Urbanization presents significant challenges. While it offers economic, social, and cultural benefits, it also leads to the depletion of natural resources, biodiversity loss, and the degradation of ecosystem services (ESs), adversely impacting human health and well-being [1,2]. Cities, as major contributors to climate change, are increasingly vulnerable to its effects, such as heat waves, droughts, and flooding [3,4]. Addressing these challenges requires enhancing urban resilience, improving resource efficiency, promoting social inclusiveness, and mitigating ecological impacts [5]. Nature-based solutions (NBSs) have been adopted as a central concept in the principal policies on sustainable development, such as the European Union's Nature Restoration Law and Green Deal [6–8]. NBSs are natural-anthropogenic systems that use the natural processes of ecosystems to solve environmental, social, and economic problems in cities, including those caused by the consequences of climate change. Based on the worldwide expert survey by Castellar et al. (2021) [9], NBS categories include NBS units defined as 'green technologies and green urban spaces, either autonomous or integrated into a larger assemble forming complex living systems' and NBS interventions defined as 'acts of intervening in specific ecosystems to support natural processes and biodiversity' [9]. NBSs are considered an efficient tool to enhance ecosystem services (ESs), e.g., noise reduction [10], air quality improvement [11–13], carbon sequestration [14], maintaining the microclimate of urban spaces [15,16] and biodiversity [17], flood control [18], improving the condition of water bodies [19,20], etc. NBS integration and development have shown a positive impact on citizens' longevity, health, and psycho-emotional state [21–23]. Under ongoing climate change, flood mitigation and surface runoff management are widely considered among the most important ESs provided by NBS in cities. The rain garden is recognized as a ready-to-use NBS for surface water uptake and flood mitigation [24,25]. The efficiency of these NBS units strongly depends on the state and functionality of the main ecosystem components: plants and soil constructions. In urban environments, plants and soils are exposed to multiple anthropogenic stressors, such as over-compaction, contamination, and anthropogenic salinization [26–28].

The main sources of anthropogenic soil salinization are chloride-based de-icing agents. These de-icers are applied to roads and walking paths in cold-climate regions, such as Canada, the USA, China, Russia, Japan, and many European countries, to lower the freezing point and prevent traffic accidents and injuries during wintertime [29–32]. The negative effects of chloride-based de-icers on plant condition and soil health include osmotic stresses and ion toxicity for plants, alteration of soil structure, mineralization, and suppression of soil microbial activity [33–37]. For example, a comparative toxicological study of NaCl, NaCl + CaCl₂, and MgCl₂ showed that the implementation of Na-based de-icers inhibited plant biomass and root growth of non-halophytic turf grasses from 30 to 100%, depending on the dose [38]. However, tolerance to different chlorine salts varies from species to species as it depends on plant adaptation mechanisms [39,40]. The effects of salinization on soil's physical properties include structural disruption and changes in soil texture. In results, the fine fraction poses risks of soil erosion and denudation, followed by an increased particulate matter content in air with a potential health hazard to humans [41,42].

Studies focused on salinization consequences for soil microbiomes report a decrease in microbial diversity under salt exposure, along with a marked increase in halotolerant and halophilic Bacteria and Archaea in soils adjacent to treated roads, with salt-impacted soils harboring up to 10 times more halophiles than unaffected areas [36,43]. Nevertheless, research on the physiological responses of microorganisms to salinization stress remains limited and often contradictory [44,45], although soil physiological functions appear to be more susceptible to salt levels than the structural diversity of microbial communities [46].

The dose-effect study of sodium chloride (NaCl)-based de-icers showed inhibition of microbial biomass and respiration at the electrical conductivity (EC) of 11 mS cm^{-1} , with severe suppression occurring at 31 mS cm^{-1} [47]. A complex effect of several salts can either increase or decrease microbial activity depending on the soil type, salt composition, and doses. For example, in floodplain soils, a 3.6-fold reduction in microbial biomass and a 2.5-fold decrease in basal respiration were observed in a $\text{NaCl} + \text{MgCl}_2 + \text{CaCl}_2$ treatment with an electrical conductivity of just 2.66 mS cm^{-1} [48]. In contrast, in sodosols and solonetz soils, microbial biomass increased by up to 3.5 times under high-salinity treatment ($30 \text{ mS cm}^{-1} \text{ NaCl} + \text{CaCl}_2$), while cumulative respiration decreased up to fivefold under mid-salinity conditions (10 mS cm^{-1}) [49]. Research on the long-term effects of salt exposure on the soil microbiome physiological functions—particularly in relation to the resilience of different soil textures used in urban greening—remains scarce [37].

Despite well-documented adverse effects, sodium chloride (NaCl) remains the most widely used road de-icer because of its low cost and effectiveness at temperatures below -10°C [34,50]. However, its toxicity to soil and plants is also concentration dependent [38]. In urban areas where sodium chloride is widely used, soil conductivity ranges from 0.15 to 0.6 mS cm^{-1} in the topsoil near pedestrian areas, with increasing concentration towards roads [32,51,52]. Near motorways, EC can reach 20 mS cm^{-1} , which indicates a very high salt concentration. Given that rain gardens are usually located near motorways and pedestrian roads, a negative effect of NaCl on soils and vegetation is usually reported [33,53]. NaCl is a rapidly soluble compound, and previous studies have shown that up to 60% of the application dose can leach into groundwater, especially in soils with coarse texture and high infiltration [51,54]. Rain gardens' soils are dominated by coarse materials [55,56], and an active vertical migration of soluble salts during snowmelt can result in groundwater pollution and secondary salinization. However, in contrast to agricultural areas [57,58], vertical migration of soluble salts in rain gardens remains overlooked. We are not aware of any field or mesocosm experiments that quantify the processes and mechanisms of soluble salts transport in rain garden soil constructions exposed to NaCl-based de-icers. There is a lack of information on the parameters of water retention curves, Peclet numbers, hydrodynamic dispersion, and sorption constants needed to support process-based modeling of water and salt transport in layered soil constructions of rain gardens. The experimental determination of these parameters could complement the wide range of laboratory and field studies on the salinity tolerance and biofiltration capacity of herbaceous plants [59–61] to select the most sustainable NBS units in temperate cities.

The research aimed to study the effect of NaCl application on the plant and soil health, and the groundwater quality of a model rain garden. The short-term (hours and days) and long-term (half a year) consequences for the plant condition, soil health, and groundwater quality were studied for the case of Moscow (Russia)—the largest city with permanent snow cover in wintertime. Model rain gardens with different materials used for soil construction (mixtures of sand, loam, and peat) were compared to promote the most tolerant soil construction for further implementation in rain gardens exposed to salinization in urban areas.

2. Materials and Methods

2.1. Selecting Materials for Soil Construction

A typical soil constructed for a rain garden includes a fertile organo-mineral topsoil layer underlain by one or several drainage layers. Prior to the experimental set-up, soil substrates and materials recommended for rain garden construction were analyzed based on existing standards and best practices (Table 1).

Table 1. Mixture standards for the top organomineral horizon of a rain garden.

Standard	Soil Mixtures	Recommended Infiltration, mm h ^{−1}
LID [55]	50%—sand, 30%—organic compost, and 20%—excavated soil	>6
G1760 [56]	30%—sand, 30–40%—loamy topsoil, and 30%—organic material from waste compost	>6
RGA [62]	70%—sand, 30%—compost mix	>6
SuDS [63]	A wide range of sand-based mixes with local soil and/or compost to satisfy the requirements of the infiltration rate.	100–300
Nordic climate [64]	Recommendations for the depth profile of the rain garden. Soil–sand mixes are recommended with low clay content	50–300
Guild LAEN [65]	90–40%—sand, 10–60%—sphagnum peat or compost mix	50–300
Pat. 2540620 [66]	50–70%—sand, 10%—sphagnum peat, 20–40%—zeolite	<300

For the experiment, seven types of mixtures were selected and adapted to the landscaping practices of the Moscow metropolis (with compost replaced by peat). These mixtures were created by combining locally available substrates (components): medium loam (L), sphagnum peat (P), and two types of fine sand (S) with predominant fractions of 1–2 mm—carbonate sand (Sc), which is widely used in landscape design, and quartz sand (Sq), which was used as a reference. All seven types of mixtures were prepared using carbonate and quartz sand in the following substrate ratios by volume: S9L1, S7L3 (LID), S7P3 (LID), S7L1P2 (LID), S7L2P1 (LID), S5L2P3 (G1760), and S3L4P3 (RGA).

2.2. Hydrophysical Properties of Soil Substrates and Mixtures

Filtration and accumulation of surface water run-off is the primary function of the soil construction of rain gardens. Therefore, testing the hydrophysical properties of the selected soil substrates and mixtures was the first research step. Soil texture was determined by standard sieve, pipette, and areometric methods [67]. The Soil–Water Retention Curves (SWRCs) of the substrates and mixtures were assessed using the equilibrium centrifugation method [68], and an approximation of the experimental outcomes was performed with the van Genuchten model [69]. The infiltration coefficient (K_f) was measured in vitro for individual substrates (components) and mixture variants (Table 1). The analysis was conducted using the pressure-absorption method, which calculates the volume of filtrate per unit of time based on the capacity of the column filled with a mixture and the height of the water column [70] based on Formula (1):

$$K_f = V \times L / (S \times t \times (L + h)), \quad (1)$$

K_f —is infiltration coefficient, cm s^{−1} (mm h^{−1} units used in results);

V —is volume of filtered water, mL;

t —is time, s;

L —is the soil column height in the experiment, cm;

Q —is volume of filtered water per unit time, mL s^{−1};

S —is cross-sectional area, cm²;

h —is water head, cm;

The K_f (infiltration coefficient) values were then converted to standard values at 10 °C using Hazen's formula that accounts for the filtration rate as a function of water viscosity at different temperatures (Formula (2)) [70]:

$$K_{10} = K_f / (0.7 + 0.03 T), \quad (2)$$

K_{10} —infiltration coefficient at 10 °C, cm s^{-1} (mm h^{-1} units used in results),
 T —temperature, °C.

The resulting filtration properties (K_{10}) of the soil mixtures were compared with the LID and SuDS recommendation range. The SuDS requirements of 100 to 300 mm filtration were used as the main criteria, as they standardize the upper limit of filtration, which is also the basis for recommendations from Northern European countries and Russian recommendations. The mixtures with K_f within the recommended range were used to create soil construction for the mesocosm experiment.

Substrate volumes and weights, including the top and sub layers of the monoliths, were calculated to model pore filling in the columns. The bulk density of the monolith layers was determined by ring sampling and the gravimetric method as a result of drying in a muffle furnace (105 °C), the solid phase density was determined by a pycnometer (OAO 'KHIMLABORPRIBOR', Klin, Russia), and the total porosity and porosity coefficients had already been calculated on the basis of the values of these indices [71]. For the sub layers, these characteristics were determined after removing the top layers from columns.

2.3. Chemical Properties of Soil Substrates, Mixtures, and Filtrate

The following chemical properties were measured in soil substrates and mixtures: (1) pH in water and salt extracts by potentiometric method is the soil-to-water ratio 1:5 for soil and 1:10 for peat [72,73]; (2) available phosphorus content by spectrophotometer DR3900 (HACH LANGE GMBH, Düsseldorf, Germany) (depending on pH, GOST 26205-91, GOST 26204-91, or GOST R 54650-2011 methods were used) [74–76]; (3) potassium and sodium content by atomic emission spectroscopy [74–77]; (4) total nitrogen by Kjeldahl method, which includes sequential ignition, distillation, and determination of the titration endpoint (EP) [78]; (5) total carbon (TC) content using the nondispersive infrared method with an Elementar vario TOC select (Elementar Analysensysteme GmbH, Langenselbold, Germany) analyzer at a combustion temperature of 900 °C; and (6) total content (bulk content) of heavy metals by express pXRF method [79].

During the salinization experiment, the electrical conductivity of the substrates and filtrates was measured using an Ohaus Starter ST3100C conductometer (OHAUS Instruments (Shanghai) Co., Ltd., Shanghai, China) [72]. Chloride ions in water extracts and filtrates were measured using the direct ionometry method [80]. Potassium and sodium were determined by atomic emission spectroscopy [74–77,81], while calcium and magnesium were determined using the complexometric method [82]. The content of total, organic, and inorganic carbon in liquid samples was analyzed with the Elementar vario TOC select analyzer at a combustion temperature of 850 °C.

2.4. Microbial Properties of Soil Substrates and Mixtures

For assessing soil health, microbial community characteristics, such as microbial biomass, basal respiration, and the metabolic quotient ($q\text{CO}_2$) (the ratio of basal respiration to microbial biomass), were chosen as the most sensitive and effective indicators due to their responsiveness to biotic and abiotic factors [83]. The carbon content of microbial biomass (C_{mic}) was assessed using the substrate-induced respiration (SIR) method, measuring the maximum concentrations of CO_2 from the soil after adding a readily available substrate, glucose, and incubating the samples for 3.5–5 h at 22 °C, then measuring them using

a gas chromatograph Chromatec-Crystall-2000M (Chromatec instruments, Yoshkar-Ola, Russia) [84,85]. The C_{mic} value was calculated using the Formula (3):

$$C_{mic} (\mu\text{gC g}^{-1}) = \text{SIR} (\mu\text{l CO}_2 \text{ g}^{-1} \text{ h}^{-1}) \times 40.04 + 0.37, \quad (3)$$

The rate of basal (microbial) respiration (BR) of soil samples was assessed based on CO_2 production in the unamended sample after incubation at 22 °C for 24 h. The concentration of CO_2 was measured using gas chromatograph. The specific respiration of microbial biomass or the microbial metabolic coefficient ($q\text{CO}_2$) was calculated as the ratio of BR to C_{mic} .

2.5. Set-Up of the Mesocosm Experiment

To simulate the effect of NaCl on rain gardens in Moscow conditions, a mesocosm experiment was set up. Rain gardens were simulated by PVC columns (100 cm height, 15 cm inner diameter, PVC external sewer pipe SN4, ООО «POLITECH-SPB», Saint Petersburg, Russia) filled with a three-layer soil construction and vegetated with *Hemerocallis hybrida*. The following layers were used (from bottom to top): (1) a 10 cm drainage layer consisting of crushed gravel with a fraction size of 5–20 cm; (2) a 30 cm mineral layer consisting of quartz or carbonate sand; (3) a 30 cm organo-mineral topsoil layer composed from the mixtures, selected based on the hydrophysical properties (see Section 2.2). For each column, one specimen of the hybrid daylily (*Hemerocallis hybrida*) was planted in the topsoil layer. All plants were pre-grown in a plant growth chamber under controlled conditions before being planted into columns.

To model the input of NaCl, the period of active spring snowmelt was considered. Water volumes were calculated based on the average snowdrift height in Moscow over the past five years (a period of snowy winters), estimated at approximately 1 m with a snow cover density of 380 kg m^{-3} . Based on these calculations, 6.7 L of water was expected to flow into a pipe with an internal cross-section of 15 cm (excluding horizontal runoff). The amount of de-icing reagent KP-2 (LLC Construction Company “RAMON”, Moscow, Russia) was determined using an application rate of 20 g m^{-2} for roads and walking paths, with an increased dose of up to 150 g m^{-2} during extreme weather events [86]. The number of applications was estimated from the averaged data over the past five years (November to March) and included transitions through 0 °C ($n = 34$), precipitation above 5 mm ($n = 19$), and freezing rains ($n = 2$) [87]. It was further assumed that approximately 30% of the applied reagents used for road and path maintenance reached the green areas. The studied de-icing reagent consisted of 50% of the mass being a sand and gravel mix, and the other 50% being a soluble portion based on NaCl, with up to 10% sodium formate also present in the composition. Based on this assumption, the soil monolith columns were treated with a solution of 3.95 g de-icing reagent per 1 L of water at a rate of 1.675 L per day for four days. Following this, the columns were spiked daily with 1000 mL of pure water until the EC values of blank solutions were reached. In parallel, blank columns ($n = 2$ for each) were irrigated with identical volumes to serve as a reference for comparison.

During the experiment, the filtration rate and EC were measured directly in each 200 mL of filtrate. Soil moisture was determined with a Delta-T HH150 portable moisture meter (Delta-T Devices, Cambridge, United Kingdom (UK)), filtrate EC was measured with a Hanna HI98130 analyzer (Hanna Instruments Deutschland GmbH, Vöhringen, Germany), and the substrate EC was assessed with a Hanna HI98331 analyzer (Hanna Instruments Deutschland GmbH, Vöhringen, Germany). Substrate conductivity was measured at the surface and along the profile through pre-prepared holes in the columns, both before spillage and after the runoff of gravity water. At the end of each day, final filtrates were collected for laboratory analysis of pH, chloride ion content, sulfate, and water-soluble

forms of potassium, sodium, calcium, and magnesium. After the salinization and washing phases, soil samples were collected to analyze chemical and microbiological properties in comparison to the initial and blank substrates. Additionally, after six months of the experiment, soil samples were collected and analyzed to assess the recovery of the soil microbiome. The experimental design and observations are summarized in Figure 1.

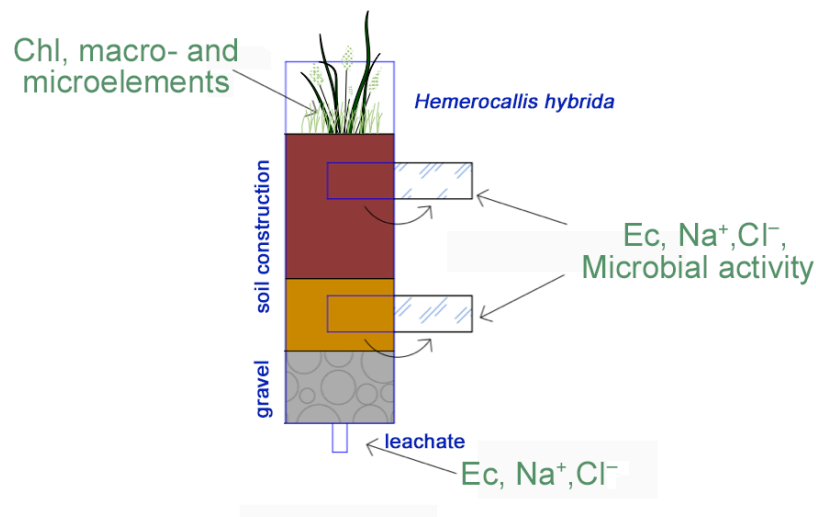


Figure 1. Salinization experiment: set-up and observed indicators.

2.6. Plant Properties and Condition

The physiological properties and conditions of *Hemerocallis hybrida* plants were observed before and after salinization. The following indicators were observed: (1) plant morphology (number, length, and raw weight of leaves; length and raw weight of roots; and plant condition by visual assessment); (2) chlorophyll levels detected by measuring leaf optical density using a SPAD-502 Plus chlorophyll meter (Konica Minolta Inc, Langenhagen, Germany); (3) elemental composition of plants. To measure the elemental composition, plant samples were prepared by drying them at 105 °C to a constant weight, followed by combustion in a muffle furnace EKPS 10 mod.4005 (OAO 'Smolensk SKTB SPU', Smolensk, Russia) at 525 °C with gradual heating. Humidity and dry matter fraction were determined by the gravimetric method, while ash content was calculated as the percentage of ash mass relative to the dry plant mass [88]. Extraction of elements from the ashes was performed using a solution of nitric acid (1:1 with water), heated to boiling [89]. The bulk contents of Pb, Zn, Cu, Ni, Mn, Fe, P, K, Na, and Mo were determined by atomic emission spectrometry (ICP-OES) [90].

2.7. Data Analysis and Modeling

Significant differences were assessed using a one-way ANOVA followed by Tukey's Honestly Significant Difference (HSD) test for pairwise comparisons. Results are presented as means $\pm$ standard deviations. Data visualization was performed in RStudio (version 2024.12.0 + 467) using the ggplot2 package (version 3.5.2), with bar and stacked bar plots illustrating soils, filtrates, and plants properties across treatments.

The hydrodynamic dispersion parameter (mixing step) was estimated as the height of substrates in the monolith divided by the Peclet number (Pe), which was calculated in the STANMOD for Windows (Version: 2.xx, December 2003) program based on real geometric and physical parameters of column monoliths.

3. Results

3.1. Hydrophysical Properties of Soil Substrates and Mixtures Used in Rain Gardens

Carbonate sand was dominated by medium (0.25–0.5 mm, 32.7%) and coarse (0.5–1.0 mm, 37.9%) fractions, whereas the medium fraction had 64.4% in the quartz sand. Loam was dominated by the clay fraction (81.6%). Peat material is usually not analyzed following the standard soil texture protocols. To obtain an idea about the particle size, we analyzed the fraction of particles between 0.25 and 2 mm (an optimal fraction based on LID and SUDS standards) based on the sieve residue and obtained 56%. Based on the SWRc, soil hydrological constants (wilting point (WP), field capacity (FC), and water holding capacity (WHC)). The highest water holding capacity was obtained for peat, whereas loam and sand had values similar to natural Retisols dominating in the Moscow region [71,91]. Soil mixtures S3L4P3 and S5L2P3 had water holding capacity comparable to loam, whereas the water holding capacity of the mixtures with a sand fraction of 70% was about 6% higher compared to sand substrate. The lowest water holding capacity was obtained for the mixture S9L1, whose volumetric fraction of sand was 90% (Table 2).

Table 2. Hydrologic constants of the soil substrates and mixtures based on the SWSc.

Soil Substrates	WP	FC	WHC
Carbonate sand	1.1	2.6	22.8
Quartz sand	0.4	2.9	22.7
Loam	11.0	27.4	42.4
Peat	151.9	167.6	455.1
S3L4P3	6.9	17.2	39.9
S5L2P3	5.4	11.2	36.3
S7L1P2	2.8	6.8	26.3
S7L2P1	2.8	5.8	26.1
S7L3	3.0	7.8	28.6
S7P3	3.3	5.4	29.5
S9L1	2.0	4.4	23.2

Where hydrologic constants are abbreviated: WP—Wilting point, FC—Field capacity, WHC—Water holding capacity. Soil mixture abbreviations: S—sand, L—loam, P—peat.

The average infiltration rate (K_{10}) was measured in six subsequent trials to confirm the linearity of the flux (R^2 of the linear model considered for K_{10} estimation was 0.97–0.99). Among the substrates, the highest K_{10} was obtained for carbonate and quartz sand, whereas the values for loam were the lowest. For peat, a huge difference was shown between air-dry (5 mm h^{-1}) and moisture-saturated (above 1100 mm h^{-1}) conditions. Among the mixtures, the highest K_{10} values were obtained for S7L2P1 and S5L2P3, where sand volumetric fractions were 70 and 50%, respectively. The loam fraction also had an impact on K_{10} of the mixture. For the mixture with the same sand fraction, an increase in the loam fraction decreased K_{10} . For example, K_{10} of the S7L3 mixture was only half of the S7L1P2 mixture. S7L2P1 and S3L4P3 were at the upper and lower limits of the SuDS recommendations. Of all the mixtures, only S7L3 and S7P3 were within the SuDS recommendations (Figure 2).

Mixing carbonate sand with peat or loam resulted in alkaline soil mixtures, whereas the mixture of quartz sand and peat was acidic. A neutral reaction was obtained only for the S7L3 mixture. Total C content in soil mixtures ranged between 1 and 3%. TC is below the optimum level in all mixtures when assessed against the Moscow soil standard for greening and landscaping [92]. With regard to the nitrogen content, the majority of the mixtures even exceeded the values recommended by the standard for Moscow soils. The highest potassium and phosphorus were obtained for the mixtures, where peat, sand, and loam components were balanced or predominantly loam over peat. The S7P3 mixture,

composed of peat and quartz sand, had P and K content indicating a substantial nutrient deficit (Table 3).

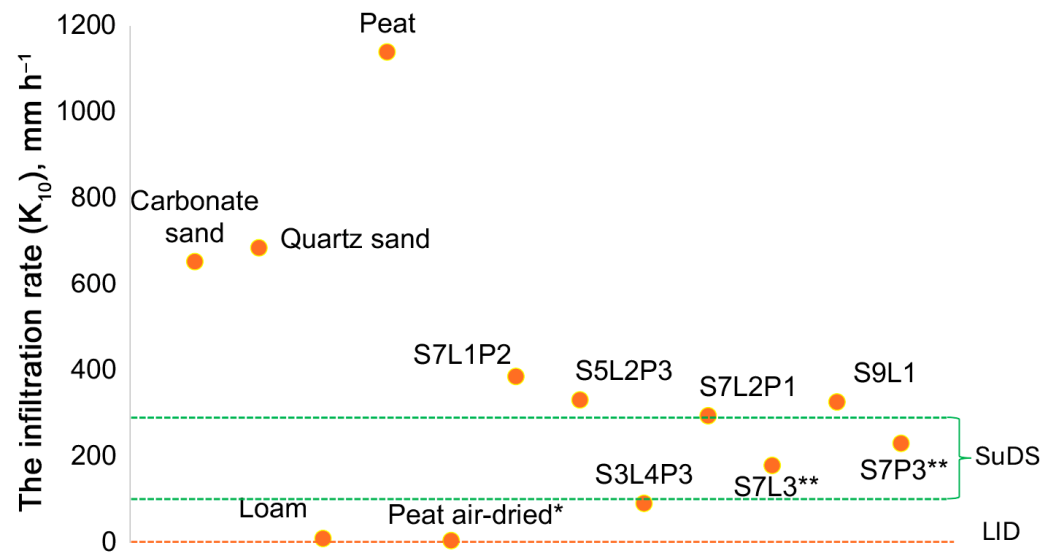


Figure 2. K_{10} of soil substrates and mixtures determined under laboratory conditions using the pressure absorption method. * For peat, values are provided for both the air-dry state and after full saturation. ** Substrates S7L3 and S7P3 exhibit infiltration coefficient values recommended by SuDS.

Table 3. Agrochemical properties of substrates and soil mixtures for rain gardens in comparison with the standard of Moscow soils for greening and landscaping.

Substrates and Soil Mixtures	TC, %	N _{tot} , %	pH _{H₂O}	EC, mS cm ⁻¹	P, mg kg ⁻¹	K, mg kg ⁻¹
L (Loam)	1.14	0.150	6.60	0.088	134	122
Scarb (Carbonate sand)	1.09	0.006	9.46	0.046	1	18
S (Quartz sand)	0.04	0.003	7.48	0.058	9	7
P (Peat)	18.08	1.055	3.98	0.046	42	141
S7P3carb	3.61	0.078	8.14	0.196	26	42
S7P3	1.51	0.040	5.67	0.037	8	11
S7L3carb	1.20	0.034	8.46	0.171	48	81
S7L3	0.43	0.098	7.02	0.058	45	37
S7L2P1carb	1.30	0.019	8.85	0.087	53	80
S7L1P2carb	2.21	0.020	8.83	0.083	28	48
S5L2P3carb	3.15	0.089	7.79	0.090	30	30
S5L2P3	1.54	0.084	5.49	0.028	40	34
S3L4P3carb	3.65	0.135	7.62	0.097	60	79
S3L4P3	1.90	0.142	5.61	0.065	82	79
Standard for Moscow soils [92]	4–15	0.005–0.02	5.5–7.0	<3.000	44–88	83–166

Mixtures with the sand volumetric fractions below 50% had better agrochemical properties (higher soil fertility) compared to sand-dominated mixtures, however these mixtures did not meet the filtration requirements described above. Therefore, the mesocosm experiments were based on the mixtures with 70% sand content (S7P3 on carbonate and quartz sand and S7L3 on carbonate sand), even though the nutrient content in these mixtures was limited.

3.2. The Effects of Salinization on a Raingarden Ecosystem in the Mesocosm Experiment

A mesocosm experiment was carried out for soil columns composed of S7L3 or S7P3 (organo-mineral topsoil layer) underlain by carbonate or quartz sand (mineral subsoil layer) and a drainage layer. For S7P3, both subsoil materials were studied, whereas only carbonate sand was studied as a subsoil layer for S7L3. The drainage horizon was the same

for all variants. For each of the three variants of soil constructions, the effect of salinization on groundwater quality, soil health, and plant condition was studied by comparing the affected (salinized) construction to a non-affected (blank) construction.

3.2.1. The Effect of Salinization on Groundwater Quality

To explore the transport of NaCl solution in porous soil systems, we estimated the basic hydrophysical parameters of topsoil and subsoil layers in soil columns. Subsoil bulk density was on average 0.6 g cm^{-3} higher, and total porosity on average 20% lower compared to topsoil layers. The Peclet number indicated the domination of advective solute transport over dispersive transport in all constructions, with the highest value obtained for S7P3 underlain by quartz sand (Table 4). At first, soil constructions were irrigated by pure water (in total 3 L) until a stable linear flux was achieved. The EC of the filtrate was 0.6 mS cm^{-1} in S7L3carb, S7P3, and S7P3carb, respectively. Then, the soil constructions were irrigated with NaCl solution, and changes in EC of the filtrate were observed. After 5.2 L of NaCl solution was added, the EC of the filtrates for all constructions stabilized at values close to 3.65 mS cm^{-1} —the EC of the solution. Based on the estimated porosity and the irrigation volume, the entire pore space of the soil constructions was filled in by the time the EC equilibrium was achieved (Figure 3).

Table 4. Hydrophysical properties and modeling parameters of the soil construction.

Column Design	Weight, g	The Bulk Density, g cm^{-3}	The Density of Solid Soil, g cm^{-3}	Total Porosity, %	Porosity Coefficient	Pe Value
top: S7L3carb	6222	1.3 ± 0.1	2.6 ± 0.1	48.5 ± 2.3	0.9 ± 0.1	4.8
sub: carbonate sand	9856	1.8 ± 0.0	2.8 ± 0.0	35.7 ± 0.3	0.6 ± 0.0	
top: S7P3	5993	1.3 ± 0.2	2.4 ± 0.2	46.1 ± 1.2	0.9 ± 0.1	10.1
sub: quartz sand	9308	1.7 ± 0.1	2.8 ± 0.1	39.3 ± 1.2	0.6 ± 0.1	
top: S7P3carb	5956	1.2 ± 0.1	2.5 ± 0.1	52.0 ± 6.2	1.1 ± 0.3	5.7
sub: carbonate sand	9856	1.8 ± 0.0	2.8 ± 0.0	35.7 ± 0.3	0.6 ± 0.0	

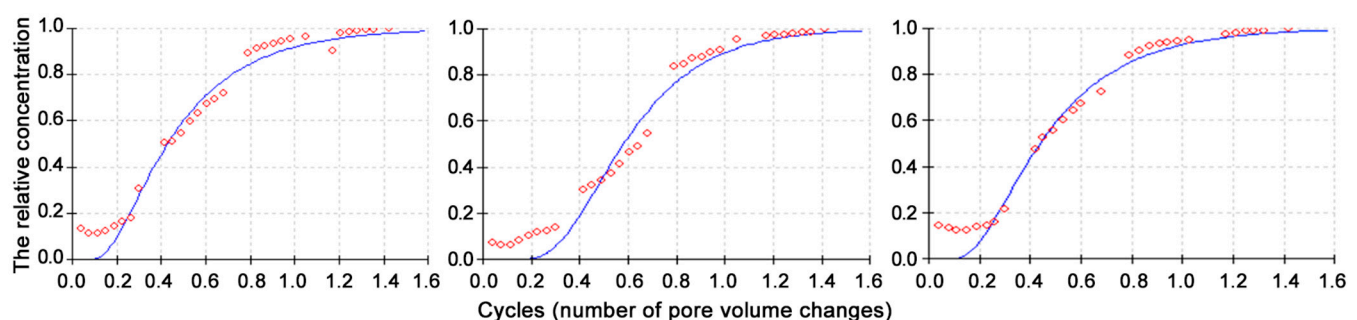


Figure 3. The ratio of cycles of pore volume changes for monoliths from left to right S7L3carb, S7P3, S7P3carb, to the relative concentration (the ratio of the electrical conductivity of the solution to the maximum electrical conductivity). Points are experimental data; curved lines are convective diffusion model from STANMOD for Windows (Version: 2.xx, December 2003).

The average concentrations of sodium and chlorine in the solution for all irrigation days were 604 mg L^{-1} and 562 mg L^{-1} , respectively, giving, in total, 175.7 mmol of sodium and 99.4 mmol of chlorine in the irrigation water. The maximum concentrations of chlorine ions in the filtrates of all columns were already observed at the end of the third day of continuous irrigation with a mean value of 529 mg L^{-1} , while the sodium concentrations on the fourth day averaged 472 mg kg^{-1} for all columns. Moreover, after the second day of irrigation, the chloride (234 mg L^{-1}) and sodium (112 mg L^{-1}) concentrations in the filtrate of the S7P3 column on quartz sand were lower compared to S7P3carb (288 mg L^{-1} and

141 mg L⁻¹, respectively) and the S7L3carb mixture (332 mg L⁻¹ and 192 mg L⁻¹, respectively). On the fourth day, the highest concentrations in the leachate were also recorded for chloride for the S7L3carb mixture –537 mg L⁻¹ and sodium for the S7P3 mixture with peat on quartz sand –493 mg L⁻¹. The total irrigation water simulated an intensive snow melting with a fast solute transport down the soil profile. Therefore, the results show the amount of substance that can leach out of the different soil constructions. For example, the amount of chlorine leached from the filtrate after complete solution run-off (before washing) from the S7L3carb column was higher (63.0 mmol) than for the substrates on peat-sand mixtures (55.4 mmol for S7P3 and 56.6 mmol for S7P3carb). For sodium, the values in the filtrate were distributed in ascending order as follows: 70.5 mmol—S7L3carb, 67.0 mmol—S7P3, and 64.1 mmol—S7P3carb.

After reaching the maximum ion concentration in the filtrate, the columns were washed with distilled water at 1000 mL per day, simulating the second stage of spring snowmelt and the arrival of ‘clean’ runoff. Washing on day 8 (7.5 L of distilled water) resulted in EC values similar to baseline; however, some sodium and chlorine ions remained in the substrates. The amount of chlorine in the substrate after washing decreased from 27.7 to 10.5 mmol for S7L3carb, from 31.2 to 7.7 mmol for S7P3carb, and from 36.8 to 7.7 mmol for S7P3. The amount of sodium in the total substrate mass after washing decreased from 33.9 to 11.0 mmol for S7L3carb, from 31.8 to 14.2 mmol for S7P3carb, and from 37.5 to 6.3 mmol for S7P3. Meanwhile, measurements of chlorine and sodium ions six months after salinization and irrigation by pure water showed that sodium and chlorine continued to leach slowly, with the chlorine concentration decreasing by almost a further half to average values of 5.2 mmol and background sample averages of 5.0 mmol. The amount of sodium decreased over the six-month period to average values of 1.1 mmol with background averages of 0.7 mmol (Figure 4).

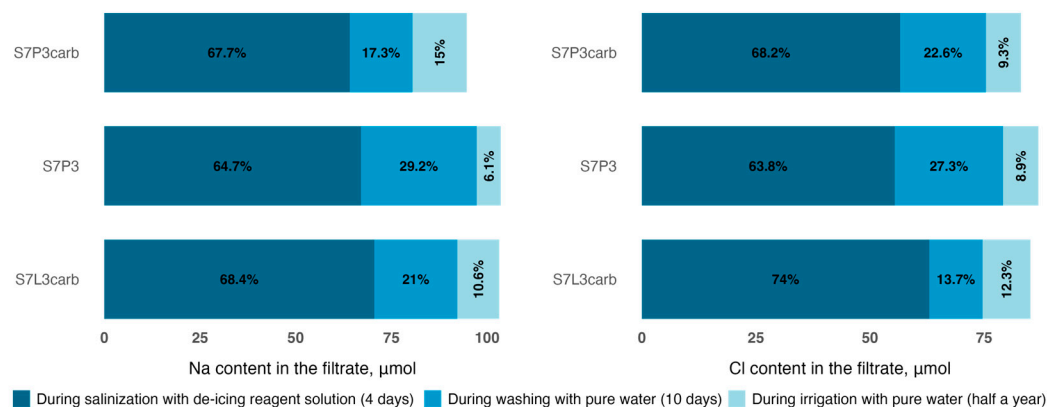


Figure 4. Dynamics of sodium and chlorine ions yield from the filtrate during salinization and irrigation with clean water.

3.2.2. The Effect of Salinization on Soil Health

Before salinization, microbial biomass in the topsoil layer ranged from 130 to 145 μg C g⁻¹, and basal respiration ranged from 0.25 to 0.50 C-CO₂ g h⁻¹, which is comparable to the values reported for constructed Technosols in Moscow [93,94]. After salinization, microbial biomass significantly decreased in all variants of soil constructions from a minimum of 4.3 times in the S7L3carb mixture to 7 times in the S7P3carb mixture. Similarly, basal respiration after salinization decreased from 2 to 3.6 times for the S7P3quartz and S7L3carb mixtures, respectively. The microbial metabolic coefficient of the soil mixtures prior to salinization ranged from a minimum of 1.9 to a maximum of 5.6 CO₂-C mg⁻¹ Cmic h⁻¹ for the S7P3quartz and S7L3carb mixtures, respectively. Even though these values are already high and indicate stressful conditions for the soil micro-

biome, after salinization, the qCO_2 of S7P3carb and S7P3quartz mixtures increased by 2 to 2.5 times, respectively. Six months after, microbial biomass carbon and basal respiration in all constructions significantly increased in comparison to the values measured directly after salinization. The best recovery rate was obtained for the S7P3carb mixture, where microbial biomass and basal respiration reached 80–90% of the pre-salinization values, and qCO_2 decreased almost twofold. Moreover, these values were not significantly different from the blank S7P3carb mixture not exposed to salinization. In contrast, in the salinized S7P3quartz and S7L3carb, microbial biomass and basal respiration were 1.3 and 3 times lower compared to the corresponding salt-free variants. Apparently, the salinization effect on the soil microbiome of these mixtures was irreversible, or at least half a year was not enough for recovery (Figure 5).

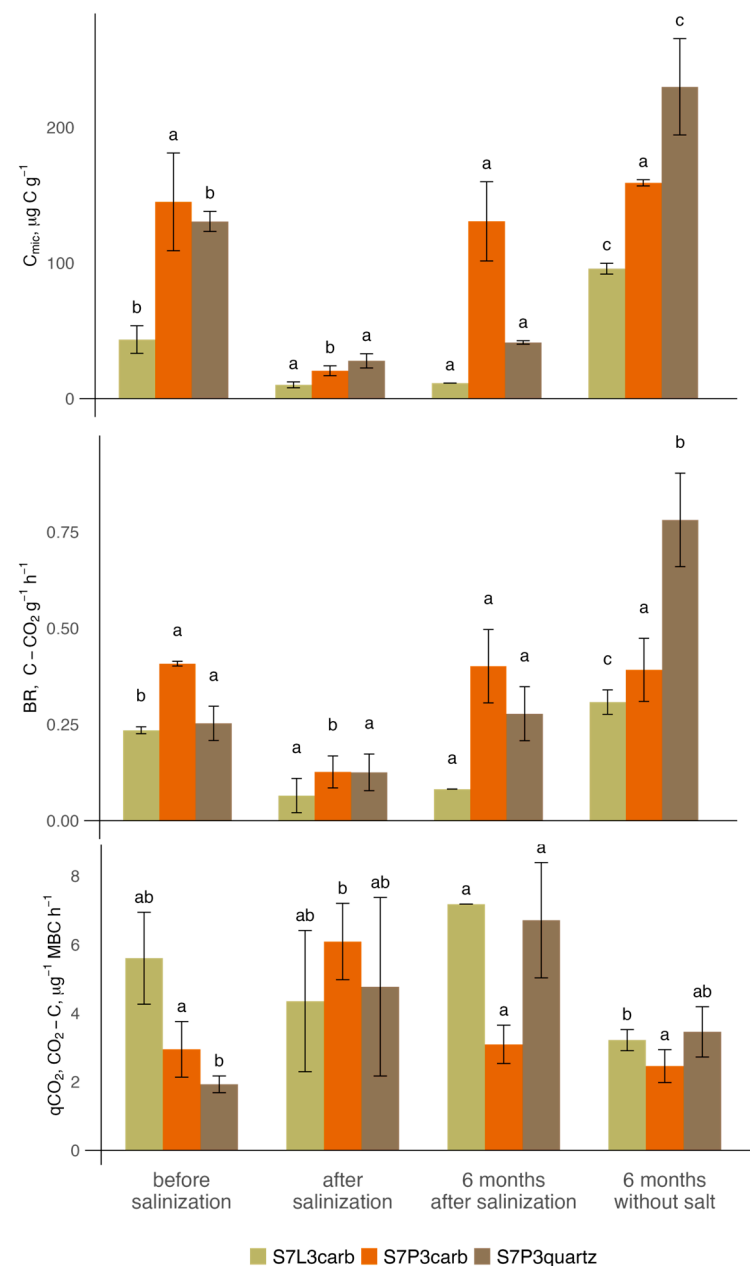


Figure 5. The values (mean $\pm$ sd) of microbial biomass C_{mic} , basal respiration BR, and microbial metabolic coefficient qCO_2 for soil mixtures in different experimental variants. Values with different letters ($p < 0.05$; ANOVA, Tukey test) indicate significant differences between time points across each treatment (salinization and no salinization).

3.2.3. The Effect of Salinization on Plant Condition

Salinization had a clear effect on *Hemerocallis hybrida* plant morphology, biomass, chemical composition, and physiology. Based on the visual assessment six months after salinization, plants in all mixtures were oppressed. The worst plant condition was observed for S7P3, where almost all leaves were dry except for one young leaf, for which further measurements were made, and the root biomass was less than in the other variants. The negative changes in plant conditions were less severe for the other two constructions. Although edge burn and chlorosis on individual leaves were observed, leaf length and number of live leaves were considerably higher. The root biomass and maximum root length were higher for the plants on the peat-sand mixture (Table 5, Figure 6).

Table 5. Morphometric characteristics of plants are exposed to the salinity of de-icing salt.

Type of Top Substrate	Maximum Leaf Length, cm	Mature Living Leaves	Middle Living Leaves	Young Living Leaves	Chl Values by SPAD	Raw Weight of Leaves, g	Visual Evaluation of Leaves	Maximum Length of Roots, cm	Average Length of Roots, cm	Raw Weight of Roots, g	Visual Evaluation of Roots
S7L3carb	52	4	4	2	39.1	6.57	Edge burn, chlorosis	50	30–45	54.66	There are small roots in the drainage
S7P3	11	0	0	1	15.1 *	0.27	Almost all the leaves are dry	60	20–30	41.11	The main root of the drainage
S7P3carb	47	4	0	2	36.6	6.71	Edge burn, chlorosis, and many dried leaves	61	45–55	78.94	There are small roots in the drainage

Note: Value marked with * refers to measurements taken from a single leaf.

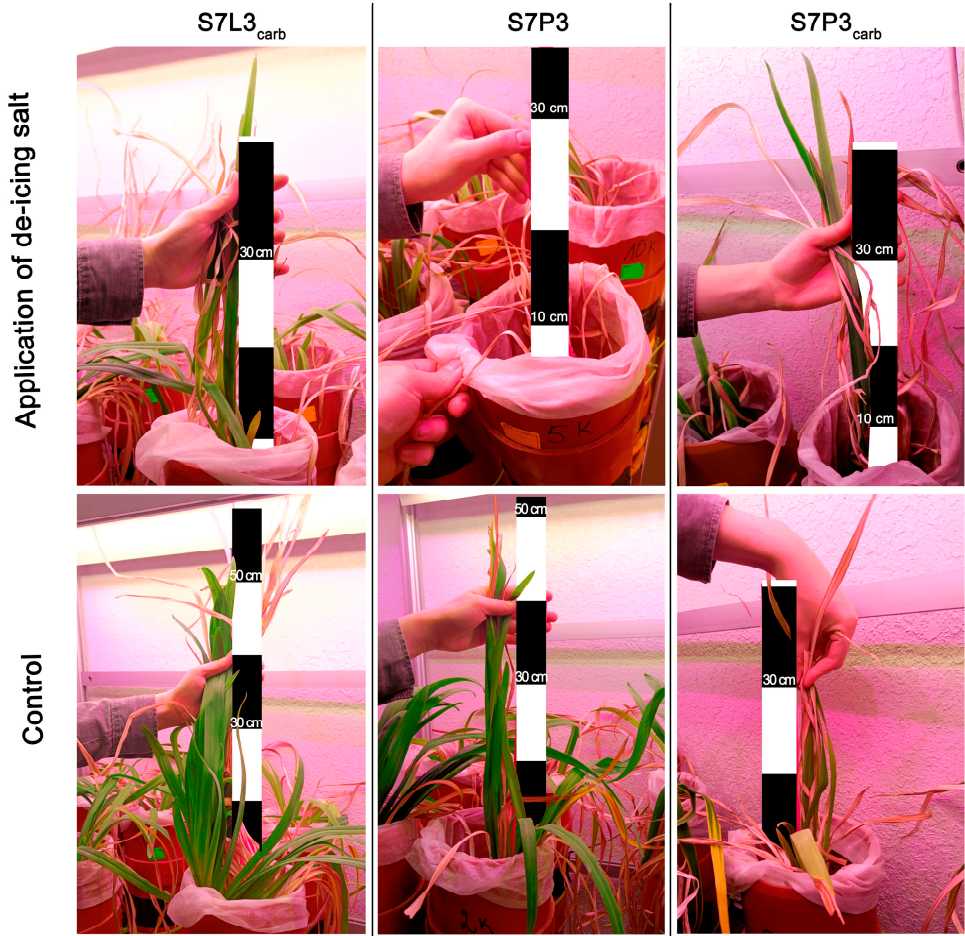


Figure 6. Visual comparison of daylily (*Hemerocallis hybrida*) exposed to de-icing salinity and control samples.

The effect of salinization on plant physiology was studied based on the chlorophyll content in plant leaves. No significant ($p > 0.05$) differences were found between plants on the three types of mixtures and control plants on the zero point and after 2 months of observation, but after two months of the experiment, the chlorophyll content was significantly ($p < 0.05$) lower than at the zero moment, for both salinized and control plants. The relative decrease was higher for the plants affected by salinization (37.1 ± 4.1 SPAD units) than for control plants (39.9 ± 1.2 SPAD units) (Figure 7).

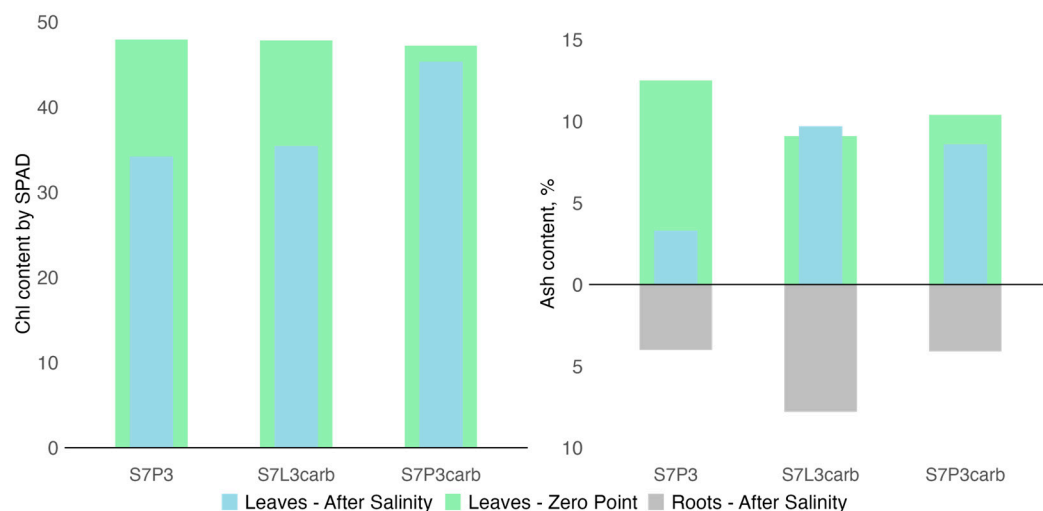


Figure 7. Chlorophyll content in leaves of hybrid daylilies (*Heimerocallis hybrida*) at the zero moment and 2 months after salinization (on the left side) and ash content in leaves and roots of hybrid daylilies (*Heimerocallis hybrida*) at the zero moment and 6 months after salinization (on the right side).

The chemical composition of plant biomass was studied based on the ash content and composition. Six months after salinization, the ash content decreased from 17% for S7P3carb to 3.8 times for S7P3 compared to the values obtained prior to salinization. Among the salinized variants, the lowest ash content in roots and leaves was observed in the plant growing on peat-sand quartz mixture (Figure 7). For this mixture, sodium, manganese, and zinc accumulation in roots and leaves was also shown, whereas potassium contents were the lowest compared to other mixtures (Figure 8). A depletion in potassium, copper, and plant biomass as a result of salinization was shown for all variants of soil constructions. However, plants on the S7L3carb mixture were more resistant to salinization compared to the other variants, which can be illustrated by visual assessment, higher content of P, K, and total ash content.



Figure 8. Changes in elemental composition (P, K, Na, Cu, Pb, Mn, Zn, and Mo) in leaves and roots of hybrid daylilies (*Hemerocallis hybrida*) 6 months after salinization.

4. Discussion

4.1. The Effect of De-Icing Reagent on Water Quality

The use of NaCl-based de-icers results in increased concentrations of chlorides, sodium, and other mineral components of de-icing agents in groundwater and surface water. For example, a long-term study of groundwater in Minnesota, USA [95] shows increases in chloride concentrations in groundwater, as well as intra-annual fluctuations in groundwater chloride concentrations reaching 40% during snowmelt periods. Similar changes in groundwater salt concentrations are noted in other studies [96,97]. An increase in chlorides and sodium ions' concentration in groundwater has a negative impact on freshwater ecosystems, limits the possibility of using water for domestic and technological needs, and increases the corrosion of buildings basements and engineering infrastructure [98–100], however the threshold concentrations depend on the national/state regulations and water use category (e.g., sewage water, irrigation water, water for fishery, etc.). Alternative de-icers derived from agricultural by-products (acetates, formates, glycols, and succinates) are less toxic and less aggressive to infrastructure. However, their use increases the biological oxygen demand (BOD) of water systems, which can lead to the depletion of dissolved oxygen and the death of aquatic organisms [101].

In our study, the maximal concentrations of chlorine and sodium ions in filtrates were observed after 3–4 days of irrigation and exceeded 500 mg L^{-1} . These concentrations are considerably higher than Russian and international thresholds for discharge into the freshwater bodies (Table 5). The results indicate that during the snow melting period, the filtrate shall be isolated from the groundwater and needs special treatment. The observed maximal concentrations were also 5–7 times higher than FAO recommendations for the irrigation water, therefore filtrate cannot be used for this purpose either. At the same time, the observed concentrations are below 1000 mg L^{-1} , which is the threshold for entering the stormwater system in Russia (Table 6). Further irrigation with pure water, simulating the volume of spring rainfall during an approximately one-month period, decreased NaCl concentrations to the baseline values. It can be concluded that the snow melting period, which in Moscow usually occurs for 10–14 days in March–April, is the most risky for the groundwater quality. For this period, the rain garden drainage system shall be disconnected from the groundwater and shall not be accumulated in irrigation tanks, unless further water treatment is planned. Approximately one month after the period of active snow melting, the negative effect of de-icers on groundwater is negligible, and free drainage as well as collecting filtrate for irrigation is possible.

Table 6. Limit values in mg L^{-1} of permissible concentrations for different types of water use.

Document		Chloride	Sodium
MARE, 2016 [102]	Discharge into freshwater bodies	300	120
US EPA, 1988 [103]		230 (860) *	-
CEQG, 2011 [104]		120 (640) *	-
MEEC, 1996 [105]		300	-
RG RF, 2013 [106]	Discharge into the wastewater system	1000	-
FAO, 1994 [107]	Sprinkler irrigation	106	69

* Chronic (long-term) exposure (acute (short-term) exposure).

Comparison of the total amount of NaCl leached through different soil constructions and dynamics showed that S7P3carb was the most efficient barrier to protect groundwater from the de-icing reagents. The total amount of NaCl leached through this construction was 10% less compared to others, and the maximal concentrations in the leachate were reached several days later, which indicates a slower solute transport through the soil construction

and, therefore, a lower contamination over a given time period. Likely, this outcome can be explained by a higher sorption of chlorine ions on peat particles and chemical reaction with carbonates in sandy subsoil. On the other hand, a higher sorption in topsoil can increase the negative effect of de-icers on soil health and plant condition.

4.2. The Effect of De-Icing Salts on Soil Health and Plant Condition

Salinization had a significant negative effect on microbial biomass and respiratory activity across all types of mixtures, by causing osmotic stress and ion toxicity, which impair water uptake, disrupt cellular functions, and reduce energy available for growth and metabolism [14,37,44,108]. After salinization, the lowest microbial biomass was observed in the S7L3carb mixture; however, compared to its initial values, the reduction in biomass in this mixture was minimal. While this mixture experienced the least short-term effect, salinization significantly impacted the long-term recovery of the microbiome, as no significant changes in biomass were detected after six months compared to the initial values. Soils amended with loam exhibit good aeration, water retention capacity, and nutrient availability, which provide favorable conditions for microbial communities. However, under salinization, the high-water retention capacity may exacerbate osmotic stress, reduce microbial biomass and respiratory activity, and hinder further recovery of microbial activity. These results are consistent with earlier findings highlighting that fine-textured soils exacerbate the effects of salinization by limiting water movement and retaining ions [44].

Soils amended with peat and different types of sand demonstrated lower short-term resilience to salinization but better long-term recovery, which can be explained by their lower water retention capacity and better aeration. These properties facilitate salt leaching and reduce osmotic stress. The chemical inertness of quartz sand and its high drainage capacity are believed to support more effective microbial community recovery after salinization [109]. However, this was not confirmed in the current experiment, as soils with carbonate sand showed more effective recovery. It is likely that the carbonates neutralized the acidity resulting from the biochemical activity in saline soils, stabilized pH, and restored favorable conditions for microbial communities.

As noted by Wichern et al. (2006) [108], prolonged salinization causes microbial communities to use substrates less efficiently, as indicated by the high metabolic coefficient observed six months later in the S7L3carb and S7P3quartz mixtures. This reflects the higher energy expenditure of microorganisms to adapt to salinity stress.

On the other hand, salinization also negatively affects the productivity of plants that act as remediate in rain gardens. In comparison to our case, studies on the salinity tolerance of different daylily species have yielded inconclusive results. For example, the resistance of daylily plants when irrigated under controlled conditions with water containing three times less sodium and 1.5 times less chloride showed average resistance, with less than 10% of the leaves showing signs of salinity-induced stress [110]. The work of Kratsch et al. 2008 [111] indicates that daylilies are resistant under $EC < 4 \text{ mS cm}^{-1}$ conditions, which is the same as our results [111]. Work on the effects of complex salt solutions and carbonate compounds, but at lower concentrations, gives a moderate tolerance rating for the genus *Hemerocallis* [112,113].

As for the morphological evaluation of *Hemerocallis hybrida*, none of the plants showed any yellowing of the leaves during 4 days of salinization, a single chlorosis appeared during washing and intensified during half a year, in contrast to studies on other cultivars (with almost twice as high of a NaCl concentration), where signs of chlorosis were already observed on the second day [114]. The ash content of the plants corresponded to that of lily of the valley under urban conditions, except for lily of the valley on the S7P3 mixture [115].

In comparison with samples of *Hemerocallis hybrida* lily of the valley growing under urban conditions in the continental climate zone, the content of Pb, Zn, Cu, K, and Mo in roots corresponded to samples from the city, while Mn was 2–3 times lower. In leaves, before salinization, Pb and Mn corresponded to the samples from the city; after salinization, they became 2–3 times higher, and Zn, Cu, K, and Mo decreased, but within the range of values typical for the city [116,117]. Phosphorus and potassium are primarily responsible for plant responses to stress conditions, and their deficiency in the soil of the S7P3 mixture could be reflected in the form of plant desiccation 6 months after salinization [118,119]. Zinc, which is responsible for proline synthesis and salinity tolerance, increased in the plant with worse conditions on the S7P3 substrate [120,121]. However, this may be due to the fact that zinc is more easily assimilated in acidic and slightly acidic soils [122].

4.3. Recommendations for Raingardens Soil Guidelines

Based on the results of our work, we offer the following recommendations for rain gardens in temperate regions:

1. The design of rain gardens in temperate regions should consider not only hydrophysical recommendations, but also the agrochemical properties of the soil mixtures in the context of the plant substrate to perform bioremediation functions and tolerance. It is fair to say that in some cases, there are agrochemical recommendations, e.g., the LID Guideline regulates not only mechanical composition but also phosphorus and acidity. The guideline compares well with the demonstrably poor condition of the plant in the S7P3 mixture, where the phosphorus content was below 10 mg kg^{-1} . Agrochemical indicators are also used in SuDS to assess the immobilization capacity of soils. According to these criteria, the mixtures presented fall into the medium-risk category for carbon (1–15%) and acidity (pH 5–8). Mixtures with a carbonate sand volume fraction of 70% have a pH above eight and are therefore in the low-risk category. An alkaline environment favors the immobilization of most heavy metals, e.g., Ni, Zn, Pb, Cu, but values above eight are detrimental to plant growth and development and inhibit microbiological activity [123]. Therefore, rain garden substrates cannot be considered solely in terms of their function as a geochemical barrier.
2. Consider snow management when siting rain gardens to reduce plant stress. Rain gardens in temperate climates should be located at least 1.5–2 m from the edge of the road, as this area is used for snow storage and is most susceptible to contamination by reagents. In addition, studies of plant conditions under real-life conditions in temperate regions have noted the resistance of daylilies, with uncertain salt tolerance depending on the distance from the road and necrotic leaf lesions observed, which was also illustrated in our experiments [124].
3. Separate areas into ‘conditionally clean’ and ‘contaminated’ runoff from winter de-icing salts when planning the location of rain gardens or ‘gray’ stormwater systems. SuDS and LID are recommended for all land uses, including green strips along roads and streets, car parks, and pavements. In terms of modeling concentrations, our study has generally shown that soil mixes have a rather limited capacity to intercept chlorine and sodium when applied for a short period of time. In real-world conditions, NaCl and other highly soluble salts can exceed our study’s calculations by a factor of 10 during the city’s snow management regime [86]. In such cases, the use of rain gardens to intercept runoff in front of water bodies or to treat irrigation water should be partially or fully combined with a gray stormwater system, and full substitution with rain gardens for these functions is possible on sites without inputs of runoff contaminated with highly soluble salts according to FAO recommendations (Table 5, [107]).

4. Monitoring rain garden components in an area with ‘contaminated’ runoff from de-icing salts to adjust maintenance regimes. It will be difficult to assess the impact of salts on the condition of broadleaved plants in early spring using simple visual and instrumental methods, but the presence of dangerous salt concentrations can be assessed by direct measurements of soil substrates and leachates, the simplest of which are conductivity values. High concentrations allow maintenance and flushing of rain gardens to be adjusted in the event of insufficient rainfall before active plant growth begins. Some studies show that at NaCl concentrations up to 150 mM, the application of low concentrations of zinc has a positive effect on plant resistance [121]. More comprehensive monitoring systems, including indicators of the soil microbiome and nutrient elements, should be targeted at fertilizer application, especially in the case of substrates designed for high leachate.

Following these recommendations will allow the development of sustainable rain garden systems even in cities with permanent snow cover in wintertime, like Moscow.

5. Conclusions

The mesocosm experiment clearly showed the negative impact of NaCl-based de-icers on the rain garden ecosystems. The negative effects on plants resulted in an oppressed condition, a decrease in stem height of 2–4 times, and changes in chemical composition with low nutrient content in ash. Consequences for soil health included a decrease in microbial biomass of 2 to 7 times, followed by an increase in the metabolic quotient of 2–2.5 times, which indicates stressful conditions for the soil microbiome. Although the negative effects were observed for all variants of soil constructions, the variant based on peat and carbonate sand was more resistant compared to the others. For this variant, plant oppression was lower than for the others, and microbial biomass and activity have almost recovered six months after salinization stopped. This outcome allows drawing a more general conclusion on the relevance of revising existing standards and guides for rain garden construction, which are mainly based on hydrologic properties and give less attention to soil health indicators. We recommend considering agrochemical and microbial indicators of soil health as sensitive predictors of the resilience of raingarden ecosystems to salinization stress. This can be achieved by using multicomponent mixtures composed of peat, loam, and carbonate sand. Finally, water management, drainage, and recycling systems in rain gardens shall be tuned to avoid water quality violations. During the 10–12 days of the snow melting period, the filtrate shall be drained to the sewage water system or treated locally, whereas the remaining part of the city water reused for irrigation is possible and recommended.

The research conclusions are based on the mesocosms experiment, which was limited in the number of investigated factors. The mechanisms of ion sorption by different natural and artificial materials used for soil construction (e.g., peat, biochar, vermiculite, or hydrogels), and the effects of different de-icers composition and doses were out of the experimental scope. Standard laboratory conditions of the mesocosm experiment limit extrapolation of the experimental outcomes to the larger areas and real-life conditions, where the effects of de-icers on plants and soil health will also depend on the seasonal dynamics of microclimatic conditions and complex anthropogenic pressures (e.g., physical disturbance or pollution by heavy metals and oil products). These limitations shall be addressed by further research, including multi-factorial laboratory and field experiments, real-time monitoring in Living Labs, and process-based modeling. This approach will further improve our understanding of the functionality of rain gardens’ ecosystems under the stressful conditions of an urban environment

Author Contributions: Conceptualization, O.R.; methodology, O.R.; software, A.S.; validation, O.R., V.V. and I.S.; formal analysis, E.K., A.L. and A.S.; investigation, A.L.; resources, O.R.; data curation, E.K.; writing—original draft preparation, O.R.; writing—review and editing, V.V., E.K., I.S. and A.S.; visualization, O.R. and E.K.; supervision, A.S. and V.V.; project administration, O.R.; funding acquisition, O.R. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in the study are available upon request from the corresponding authors.

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Conflicts of Interest: The authors declare no conflicts of interest.

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