

Article

Energy Efficiency Assessment of the Electrodialysis Process in Desalinating Rest Area Water Runoff

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Abstract

The efficient use of energy is a sign of conscious environmental responsibility. Sustainable management also refers to water resources, where emphasis is placed on the possibility of retaining rainwater at the point of the precipitation occurrence. This article focused on the reuse of runoff from a rest area (RA) along the expressway, wherever drinking water quality is not required. The runoff from RAs can be significantly contaminated due to the traffic-related issues. The objective of this article was to evaluate the energy efficiency of preliminary treatment of raw meltwater from a selected rest area using electrodialysis for Cl^- and Na^+ removal. The treatment was carried out under various conditions, including different solution temperatures (20 °C and 30 °C) and electric voltages (10 V, 20 V, 30 V). The energy efficiency assessment was preceded by a characterization of runoff quality and the analysis of pollutant removal efficiency in the electrodialysis process. The most energy-efficient variant was characterized with the 0.097 Wh/(mg/L) energy expenditure ratio and 93% efficiency removal for Cl^- and 0.147 Wh/(mg/L) and 90% for Na^+ . In this variant, the permissible Cl^- and Na^+ concentrations limits were achieved after 27 min with an energy consumption of 57 Wh. In general, the observed highest energy efficiency occurred at the beginning of the electrodialysis process and decreased over time.

Keywords: energy efficiency; pretreatment; runoff quality; rest area; electrodialysis; EDR



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1. Introduction

Economical and efficient use of energy is currently being promoted worldwide as a model of conscious care for the environment. A responsible approach to this issue is reflected in government decisions and in actions at the national and international levels [1–4]. Energy saving involves not only the direct reduction of energy consumption by using low-energy products during operation, but also effective energy management, which can be assessed using the so-called carbon footprint. The standard [5] defines the carbon footprint of a product as the sum of greenhouse gas emissions and greenhouse

gas removals in a product system, expressed as CO₂ equivalents and based on a life cycle assessment using the single impact category of climate change. Some authors refer to carbon footprint exclusively as carbon dioxide emissions, e.g., [6–8], while others also take into account other greenhouse gases among those identified by the Kyoto Protocol [9–12].

The effects of climate change and progressing urbanization necessitate the rational management not only of energy, but also of water resources [13]. At the same time, the growing demand for water—combined with water shortages that are not regularly replenished by natural precipitation—forces increased energy consumption in water supply systems. Under water-scarce conditions, the availability of local water sources often significantly decreases or becomes depleted. This necessitates the extraction of water from deeper aquifers or distant intakes, which requires the use of higher-power pumps and longer transmission pipelines. Consequently, the energy consumption per unit of delivered water increases [14,15]. During drought periods, a decline in the quality of available water resources is frequently observed [16]. To meet water quality standards, more advanced or additional treatment processes must be employed, further increasing energy demands [17,18]. Therefore, the issues of sustainable energy management and sustainable water management are closely interconnected. In sustainable water management, particular attention is often paid to the possibility of retaining rainwater at its source. Local rainwater management has many advantages: it reduces the volume of water discharged into stormwater drainage systems, helps prevent urban flooding, supports the replenishment of groundwater levels, positively affects the microclimate by providing water to plants, and pre-treats rainwater [19,20].

In the literature, the issue of sustainable rainwater management is addressed from various perspectives—for example, in the context of urban flooding management, e.g., [21–23], or in the context of applying smart solutions, e.g., [24,25]. Another topic discussed in the literature is the collection of rainwater for reuse, taking into account the feasibility, limitations, and financial viability of such practices, e.g., [26–29]. Rainwater, after mechanical filtration, can be reused for purposes where drinking water quality is not required, e.g., toilet flushing, plant irrigation, or cleaning. Rainwater is a natural water resource, relatively easy to collect, and is characterized by a low content of calcium and magnesium ions, which results in low water hardness [29–32]. However, rainwater becomes contaminated already during precipitation due to contact with atmospheric air, which is polluted to varying degrees. During surface runoff, rainwater undergoes further contamination; the degree and type of pollution at this stage depend primarily on the type of surface the water falls onto and flows over [29,32,33].

Basing on numerous studies on water collection from the roofs of various buildings, e.g., [34–38], it can be said that the roof runoff water generally requires less treatment for utility purposes than the water running off from traffic areas [39–41]. The runoff from traffic areas (e.g., sidewalks, bridges, roads of various categories, highways, or parking lots) contains, among other things, petroleum-derived substances, heavy metals, salts, and suspended solids. The direct sources of these pollutants include exhaust gases, abrasive particles from tires and brake pads, residues from worn vehicle parts, de-icing agents, degraded road surfaces and construction materials, as well as contamination caused by collisions and uncontrolled spills of transported substances [39,42–44].

The quality of the runoff from transportation areas is highly variable and depends on many factors—not only on the type and nature of surface use, but also on the intensity of traffic, the characteristics of specific infrastructure elements (e.g., galvanized components on bridges, guardrails, road signs), climatic conditions, and the characteristics of the surrounding terrain [43,44]. Numerous publications can be found in the literature concerning runoff from various transportation-related areas, including parking lots, e.g., [45–51].

However, there are only a few studies presenting research results on runoff from Rest Areas (RAs) located along highways and expressways, where parking areas constitute a significant part. RAs may serve a basic function, meaning that in addition to parking spaces, they provide travelers with rest areas and sanitary facilities. They may also be more developed—equipped not only with basic infrastructure but also with fuel stations, electric vehicle charging stations, food services, hotel facilities, playgrounds, and more. It is reasonable to assume that the quality of runoff from RAs varies depending on the infrastructure and type of services offered.

Considering a rational approach to water and energy management, and taking into account the fact that a significant portion of rest areas (RAs) is often impermeable, it is worth exploring the potential for utilizing pretreated runoff from RAs. Theoretically, rainwater can be used within RAs wherever drinking water quality is not required—for example, for irrigating greenery during dry periods, washing vehicles, flushing toilets, and urinals. In practice, however, the reuse of rainwater runoff from RAs is considerably hindered due to the aforementioned contamination occurring in traffic areas. During the winter season, the problem becomes even more pronounced due to the accumulation of pollutants in snow. The use of anti- and de-icing agents for removing or preventing the formation of ice cause the runoff to become saline. Common de-icing agents include salts like sodium chloride, calcium chloride, and magnesium chloride, as well as glycols like ethylene glycol and propylene glycol [52–54].

One of the techniques used for water pretreatment and desalination is electrodialysis, which also demonstrates effectiveness in removing metals [55–57]. Electrodialysis is different from other membrane methods (reverse osmosis, nanofiltration, membrane distillation, forward osmosis). The essence of this process is the use of the phenomenon of electrochemical separation, in which ions are transferred through ion exchange membranes placed between two electrodes under the influence of an applied electrical potential difference. Electrodialysis is one of the processes used for water pretreatment. The salt solution flows between alternately arranged cation-exchange and anion-exchange membranes. When a direct current potential is applied to the electrodes, cations (e.g., Na^+) migrate through the cation-exchange membranes and are blocked by the anion-exchange membranes, while anions (e.g., Cl^-) migrate through the anion-exchange membranes and are blocked by the cation-exchange membranes. As a result of the process, the stream of salt solution is divided into a desalinated stream (diluate), in which the ion concentration decreases, and a concentrate, characterized by an increased ion concentration [58].

The main objective of this article was to evaluate the energy efficiency of meltwater pretreatment from a selected rest area (RA) equipped with basic infrastructure. Electrodialysis was chosen as the pretreatment method. The evaluation of energy efficiency of the process was preceded by a characterization of the quality of rain- and meltwater runoff from the selected RA and an analysis of the effectiveness of pollutant removal in the electrodialysis process.

2. Materials and Methods

2.1. Description of the Analysed Rest Area (RA)

The object selected for the study is an RA located next to an expressway in eastern Poland. A Google Maps view [59] of the analyzed RA is shown in Figure 1a. The analyzed RA serves a basic function, i.e., it includes a parking lot for passenger cars, buses, and trucks, small picnic shelters, a children's playground, and a building with toilets and showers. The average monthly consumption of drinking water in the RA facilities is 148.9 m^3 . The water is used for washing (11 sinks and 2 shower cabins), for flushing toilets (8 units) and urinals (2 units), as well as for cleaning purposes (2 tap valves). The surface of the RA, with a total

area of 3.34 ha, consists of an asphalt roadway and parking lot (1.0 ha), concrete pavements (0.44 ha), roofs (0.02 ha), and grassy areas (1.88 ha). The roof of the building with the sanitary facilities, as well as the roofs of the shelters, are covered with bituminous felt (Figure 1b). Surface runoff volumes were estimated as the product of rainfall height, land area, and runoff coefficients. Assuming the annual precipitation of 550 mm in accordance with the National Research Institute of Meteorology and Water Management [60], the total runoff from the RA area is equal to approx. 7266.5 m³/year, including the runoff from roof area equal to 95.4 m³/year. The elevation of the area within the RA ranges from 228 to 232 m above sea level. Stormwater and meltwater are drained from the RA area through a stormwater drainage system made of polypropylene pipes with diameters ranging from 0.2 to 0.6 m and a total length of over 700 m (Figure 1c). From there, the water flows into a roadside ditch running along the expressway, and subsequently into an infiltration basin located 790 m from the RA.

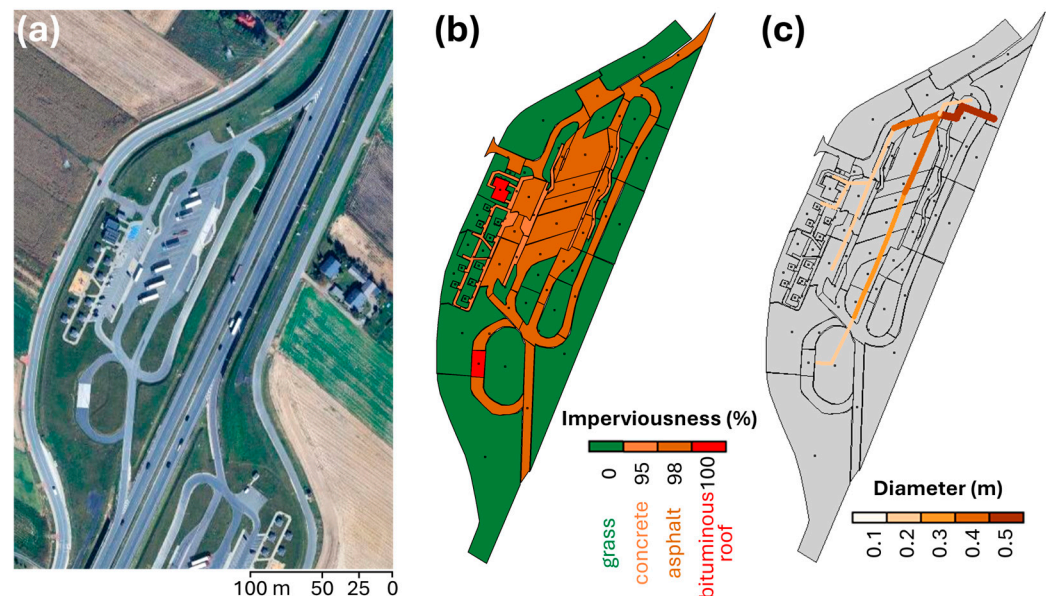


Figure 1. RA selected to investigate: (a) Google Maps view [59]; (b) site plan considering the permeability of the sub-catchment areas; (c) site plan considering storm system with pipe diameters.

2.2. Course of the Study

The assessment of the energy efficiency of the electrodialysis process in desalinating rainwater and meltwater from the selected RA was carried out according to the workflow scheme shown in Figure 2. Rainwater runoff samples were collected 6 times in the period from October 2023 to April 2024 at the outlet of the rainwater drainage system collecting rainwater from the entire RA area to the roadside ditch. The samples were collected manually into two 1.5 L bottles. The contents of metals (Na, Mg, Ca, V, Cr, Mn, Cu, Zn, Mo, Cd, and Pb) and total petroleum hydrocarbons (TPH) were determined in each sample. In addition to obtaining a comprehensive overview of the quality of runoff from the RA, the following parameters were analyzed: chemical oxygen demand (COD), total suspended solids (TSS), turbidity, electrical conductivity (EC), pH, sulfates N-NO_3^- , N-NH_4^+ , chlorides (Cl^-), total carbon (TC), inorganic carbon (IC), and dissolved organic carbon (DOC).

Meltwater runoff samples were collected from the RA surface in January 2024 into 1 L containers. Six locations on the RA surface were selected for sampling: the entrance to the RA, the exit from the RA, the passenger car parking lot, the truck parking lot, the storm drain grate in the central part of the RA, and the children's playground. One sample was obtained from each of the 6 locations. In the snow samples, basic physicochemical

indicators (total suspended solids, conductivity, pH) were analyzed, as well as the content of chlorides, metals (the same as those analyzed in water samples), and TPH. The methods used to determine the chemical and indicator parameters both in water and snow samples are listed in Table 1.

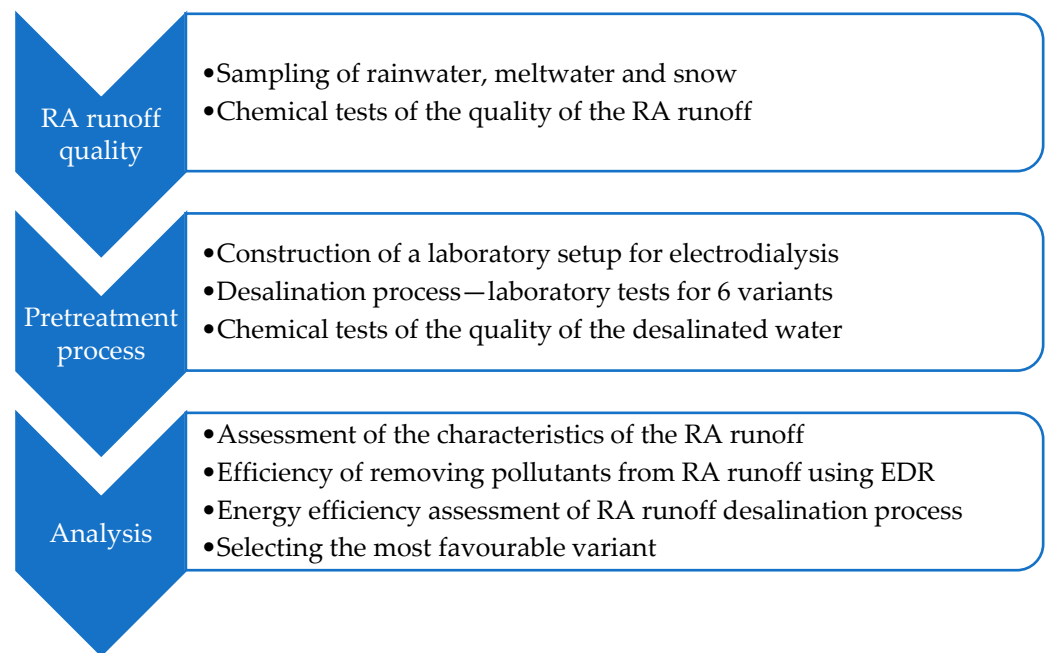


Figure 2. Workflow scheme of the study presenting 3 main research steps: rest area runoff quality tests, pretreatment with electrodialysis process, and results analysis.

Table 1. Methods used [61–71] in chemical tests.

Indicator or Chemical Parameter	Method	Standard/Justifying
COD	Spectrophotometric using the Hach Lange application (Method 8000), range 15–150 mg/L	ISO 15705 [61] www.hach.com [62]
TOC	Spectrometric with IR detection	USEPA 9060A [63]
TSS	Photometric using the Hach Lange application (Method 8006), range 5–750 mg/L	www.hach.com [62]
Turbidity	Nephelometric method	ISO 7027 [64]
EC	Conductometric method	ISO 7888 [65]
pH	Potentiometric method	ISO 10523 [66]
N-NO ₃	Spectrophotometric using the Hach Lange application (Method LCK 339), range 0.23–13.5 mg/L	ISO 23696-1:2023 [67] www.hach.com [62]
N-NH ₄	Spectrophotometric using the Hach Lange application (Method LCK 304), range 0.15–2.50 mg/L	ISO 7150-1 [68] www.hach.com [62]
Cl [−]	Titrimetric Mohr's method	ISO 9297 [69]
Metals *	ICP-MS technique	USEPA 6020B [70]
Sulfates	Spectrophotometric using the Hach Lange application (Method LCK 8051), range 2–70 mg/L	www.hach.com [62]
TPH	GC-MS technique	PN-C-04643: 1994 [71]

* Na, Mg, Ca, V, Cr, Mn, Cu, Zn, Mo, Cd, and Pb.

Validation of the metal analyses was ensured by the use of an inductively coupled plasma–tandem mass spectrometer (ICP-MS/MS), Agilent 8900 (Agilent Technologies, Inc., Santa Clara, CA, USA), which was calibrated using ICP-MS Standard Mix VIII (Supelco; Merck KGaA, Darmstadt, Germany) and an internal standard solution containing, among others, scandium (Sc) and lutetium (Lu) (ICP-MS Internal Std Mix—Agilent), as well as an additional IMS-115 standard (Agilent) containing yttrium (Y). The ICP-MS operated in “no-gas” mode for the determination of beryllium Be (not present in the samples), in helium collision mode for the determination of Na^+ , Mg^{2+} , Ca^{2+} , Cr^{T} , V^{3+} , Mn^{2+} , Cu^{2+} , Cd^{2+} , and Mo^{T} , which prevented molecular interferences. At least four-point calibration curves were used, providing correlation coefficients (R) of no less than 0.999. Instrumental limits of detection (IDLs) and background equivalent concentrations (BECs) are presented in Table 2. BEC represents the concentration of an analyte that would generate a signal equal to the background signal of the instrument.

Table 2. Instrumental limits of detection (IDLs) and background equivalent concentrations (BECs) for analytes.

Analyte	Internal Standard	IDL	BEC	R
Be^{2+}	Sc	0.004462 $\mu\text{g/L}$	0.01462 $\mu\text{g/L}$	0.9999
Na^+	Sc	0.01062 mg/L	0.1362 mg/L	0.9999
Mg^{2+}	Sc	0.00311 mg/L	0.0173 mg/L	0.9998
Ca^{2+}	Sc	0.02098 mg/L	0.1181 mg/L	0.9999
V^{3+}	Sc	0.005996 $\mu\text{g/L}$	0.004636 $\mu\text{g/L}$	0.9997
Cr^{T}	Sc	0.01423 $\mu\text{g/L}$	0.1061 $\mu\text{g/L}$	0.9997
Mn^{2+}	Sc	0.03119 $\mu\text{g/L}$	0.04061 $\mu\text{g/L}$	0.9998
Cu^{2+}	Sc	0.03279 $\mu\text{g/L}$	0.4696 $\mu\text{g/L}$	0.9997
Zn^{2+}	Y	3.919 $\mu\text{g/L}$	4.241 $\mu\text{g/L}$	1.0000
Mo^{T}	Y	0.0209 $\mu\text{g/L}$	0.1261 $\mu\text{g/L}$	0.9999
Cd^{2+}	Y	0.009593 $\mu\text{g/L}$	0.00777 $\mu\text{g/L}$	0.9998
Pb^{2+}	Lu	0.003996 $\mu\text{g/L}$	0.03893 $\mu\text{g/L}$	0.9997

The final metal concentration value consisted of 7 measurement results which were averaged and the relative standard deviation (RSD) for them was calculated. The TOC/TC/IC results represent the average of three to five measurements performed using a TOC-L analyzer (Shimadzu Corporation, Kyoto, Japan); five measurements were conducted when the RSD of the initial three exceeded 5%. Instrument calibration was carried out using potassium phthalate (for TOC) and sodium bicarbonate (for IC). The results of the remaining indicators or parameters were reported as the average of three independent determinations.

Due to the lack of specific requirements for the water intended for human use but not for drinking, the obtained results of the RA runoff quality were referred to the European requirements for drinking water [72], requirements for rain- or meltwater introduced into the soil [73], or literature data for RAs and parking lots.

In order to utilize the meltwater from RAs in winter, it is necessary to desalinate it. This study assessed the effectiveness of using reversible electrodialysis to desalinate the meltwater flowing from RA. As demonstrated by published research results [74,75], increasing the temperature of the treated solution, slowing the flow rate through the elec-

trodialyzer, or raising the voltage applied to the electrodes leads to enhanced purification efficiency of the solution in the electrodialysis process.

The pretreatment process was carried out on a laboratory setup, shown in Figure 3. The main components of the setup are a reversible electrodialyzer (EDR) EDR-Z/2x10-0.8 (MemBrain s.r.o., Stráž pod Ralskem, Czech Republic) and three circuits: diluate (D), concentrate (C), and electrolyte (E). Each of the three circuits consists of a 5 L PE tank, pipes with an inner diameter of 6 mm, a peristaltic pump BT300s (Lead Fluid (Baoding) Intelligent Equipment Manufacturing Co., Ltd., Baoding, China) with a head height of 1.5–2.0 m and a flow rate of 35–50 L/h, and a rotameter. EDR is a common component for all circuits; however, the circuits are not interconnected. The source of direct current enabling the electrodialysis process is a laboratory power supply (R&S®HMP4030; Rohde & Schwarz GmbH & Co. KG, Munich, Germany) with smooth adjustment of output voltage in the range of 0–32V. Additional equipment for the setup includes three 25-watt heaters (one for each circuit), pH meters, glass laboratory thermometers and plug-in energy meters for the power supply, each of the three pumps, and each heater. The tests were conducted using a synthetic solution, the chemical composition of which was determined based on the results of the carried-out meltwater tests. Synthetic meltwater was prepared using water from a Milli-Q system (Merck KGaA, Darmstadt, Germany) with the addition of 1.975 g NaCl/L and 1 mL of ICP-Standard VIII (Supelco) solution (Merck KGaA, Darmstadt, Germany) containing 100 mg/L of each of the following elements: Ca (calcium), Cd (cadmium), Cr (chromium), Cu (copper), Mg (magnesium), Mn (manganese), Pb (lead), and Zn (zinc). This resulted in final concentrations of 776 mg/L Na⁺, 1200 mg/L Cl[−], and 250 µg/L of each of the remaining elements. The concentrations of Na⁺ and Cl[−] reflected the levels measured in snowmelt water samples collected near one of the inlets located in the central part of the RA. The remaining elements were the same as those found in real meltwater, although their concentrations were determined by the fixed composition of the ICP-Standard VIII solution. Such artificially prepared snowmelt water ensured compositional stability essential for model-based experiments, eliminated the risk of sediments precipitation that could alter solution properties over time, and provided repeatable test conditions. This synthetic solution was used to fill circuits D and C, while a 4-molar Na₂SO₄ solution was introduced into circuit E, in accordance with the EDR manufacturer's recommendation.

Laboratory tests of the pretreatment process of the RA outflow were conducted for six variants, depending on the solution temperature and the applied voltage. The procedure for each variant was identical and followed the steps presented in Table 3.

Table 3. Variants and steps of the laboratory test of the RA runoff pretreatment procedure.

Variant	I	II	III	IV	V	VI
Temperature (°C)	20	20	20	30	30	30
voltage (V)	30	20	10	30	20	10
Preparatory activities	• Flushing and filling the setup with distilled water • Bleeding the setup • Heating the water (if necessary) • Preparing the solutions in circuits D, C, and E • Measuring pH and temperature, collecting initial samples • Starting the pumps and the power supply					
Pretreatment (activities performed every 3 min for 45 min test duration)	• Measuring the current supplied by the power supply • Measuring the electrical energy consumption • Measuring pH and temperature • Collecting samples from solutions D and C for chemical analysis					

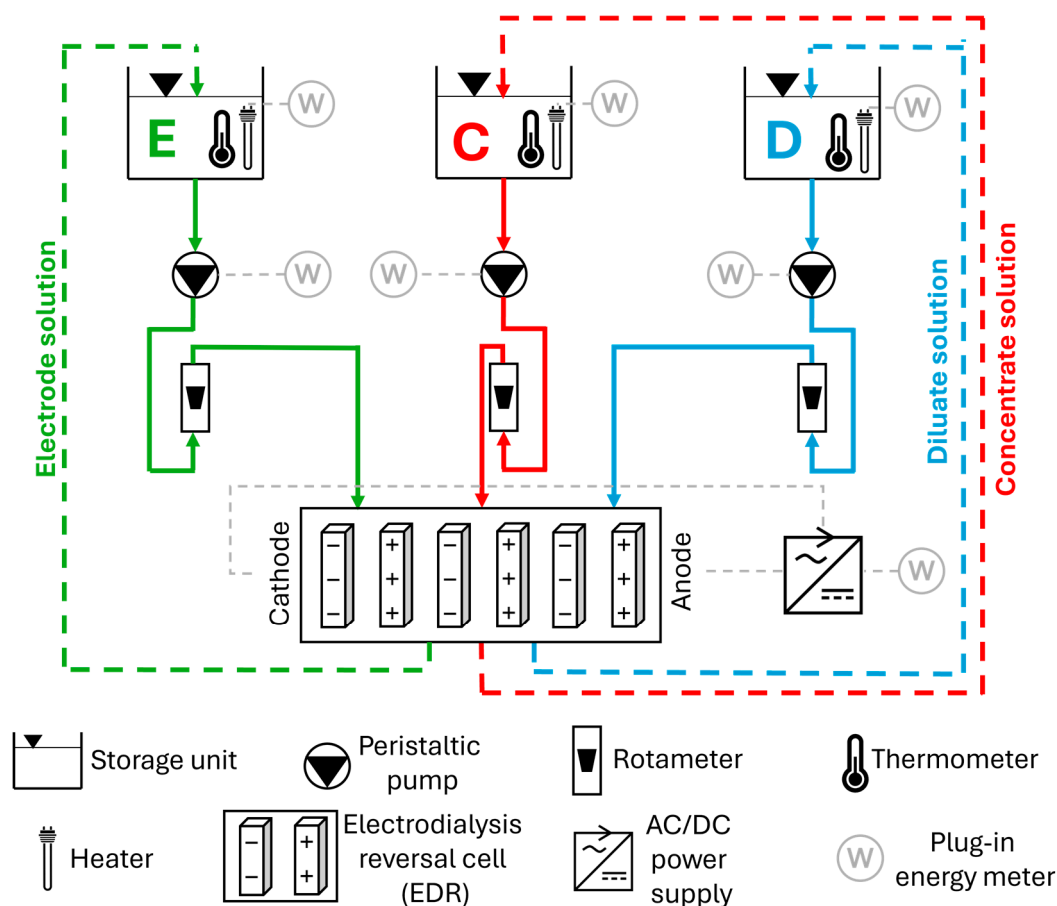


Figure 3. Laboratory setup scheme with reversible electrodyalyzer (EDR), three circuits: diluate (D), concentrate (C), and electrolyte (E), and necessary equipment.

To evaluate the impact of electrodesalination duration (number of complete cycles) on the effectiveness of pretreatment of RA runoff, samples of solutions D and C were collected every 3 min during the process for chemical analysis. In each sample, the concentration of chlorides (Cl^-) was determined, along with the concentrations of the metals that had been identified during the assessment of RA runoff quality (in the first stage of research). The chloride concentration was measured using the titrimetric Mohr's method according to ISO 9297 [69], while metal concentrations were determined using the ICP-MS technique (USEPA 6020B [70]). The effectiveness of the electrodesalination process was evaluated by comparing the concentrations of chlorides and sodium ions in the diluate solution after 3, 6, 9, ..., 45 min to their initial concentrations. It was also examined whether, and after what duration, the concentrations of chlorides and sodium decreased to the levels acceptable for drinking water [72]. The removal efficiency of the EDR was determined using Equation (1):

$$RE_t = \frac{C_0 - C_t}{C_0} \cdot 100\%, \quad (1)$$

where RE_t —removal efficiency (%) t minutes after starting electrodesalination, C_0 —initial concentration of chlorides or metals in the untreated solution (before the start of electrodesalination), C_t —concentration of chlorides or metals in the solution subjected to electrodesalination for t minutes.

The assessment of the energy efficiency of the electrodesalination process was based on the measurements of energy consumption by the powered devices (power supply, pumps, heaters). In evaluating energy efficiency, the effectiveness of chloride (Cl^-) and sodium (Na) removal was considered. The results obtained for the individual variants were compared,

taking into account the total energy consumption after a specified duration of the process, as well as the specific energy expenditure ratio (Wh/(mg/L)) (Formula (2)) relative to the removal efficiency of chloride and sodium.

$$EER = \frac{ENC}{C_0 - C_t} \quad (2)$$

where *EER*—energy expenditure ratio (Wh/(mg/L)) for chlorides and metals removal from diluate solution *t* minutes after starting electrodialysis, *ENC*—energy consumption (Wh).

3. Results and Discussion

3.1. RA Runoff Quality Analysis

Table 4 presents a comprehensive comparison of measured indicator parameters of rainwater and meltwater runoff against the literature data from selected international studies and law regulations. The rainwater runoff from the studied RA is characterized by moderate mineralization, as indicated by the measured values of electrical conductivity. The measured conductivity does not exceed the permissible limits for drinking water [72], is significantly lower than for the runoff from RA areas in Austria [76], but higher than values reported for RAs in California [77] and parking lots in South Carolina [78]. Meltwater exhibits significantly higher conductivity (with the maximum value exceeding the drinking water limit [72] by more than eight times), which suggests intense accumulation of pollutants during snow cover periods and their rapid transport during melting. For both rainwater and meltwater runoff, the pH is slightly alkaline and remains within the acceptable range for drinking water (6.5–9.5 according to [72]). An alkaline pH was also observed in runoff from the RA in Austria [76], while an acidic pH was reported for compared sites in the USA [77,78].

Table 4. Indicator parameters of the RA rainwater runoff.

Indicator	EC	pH	T *	TSS	Cl [−]	N− NH ₄ ⁺	N− NO ₃ [−]	Turbidity	COD	TC	IC	TOC	SO ₄ ^{2−}	TPH
Unit	μS/cm	pH	°C	mg/L	mg/L	mg/L	mg/L	NTU	mgO ₂ /L	mg/L	mg/L	mg/L	mg/L	μg/L
Measured data														
Rainwater runoff														
Min	826	6.58	14.2	6	92.3	0.00	35.2	2.95	67.4	16.11	5.22	7.80	49.0	0.136
Max	1095	7.64	19.2	106	177.5	19.64	115.1	31.1	167.0	74.28	52.55	23.04	54.0	18.650
Mean	980	7.12	16.50	31.17	114.78	3.55	78.48	12.35	134.07	33.71	18.23	15.48	50.75	4.19
Median	1019	7.07	16.15	13.00	104.73	0.41	81.65	8.08	152.50	25.60	12.48	13.97	50.00	0.92
Meltwater runoff														
Min	409	7.19		867.00	71.00									
Max	20,100	8.409		3074.00	7845.50									
Mean	7738	7.99		1604.17	2828.17									
Median	6650	8.087		1306.00	2325.25									
Literature data														
Road and campus parking lot (South Korea); 2010–2019 [49]														
Mean				143.3					155.2					
RA next to highway A21 (Austria); Dec 2005–May 2007 [76]														
Min	105	6.9		53	9.6	0.73						2.9		
Max	59,800	12.3		789	24,700	17						113		
Mean		9		267	5112	4.9						43.5		
Median		9		188	89.4									
RAs (California, USA); Jan 2000–Mar 2003 [77]														
Min	9	5.7		7		0.2						2.5		
Max	809	7.9		247		3.83						247		
Mean	78	6.9		63.3		0.96						22.2		
Median	52	6.8		44.2		0.69						15.0		

Table 4. Cont.

Indicator	EC	pH	T *	TSS	Cl [−]	N-NH ₄ ⁺	N-NO ₃ [−]	Turbidity	COD	TC	IC	TOC	SO ₄ ^{2−}	TPH
Unit	μS/cm	pH	°C	mg/L	mg/L	mg/L	mg/L	NTU	mgO ₂ /L	mg/L	mg/L	mg/L	mg/L	μg/L
Min	20	3.6		Two campus parking lots (South Carolina, USA); Oct 2006–Jul 2007 [78]										
Max	226	6.7		<0.1					<3					
				584.9					803					
Max	2500	9.5		Parametric values for drinking water [72]										
					250	0.50	50						250	
Max				Parametric values for rain- or meltwater introduced into the soil [73]										
				100.0										15,000

* Temperature of the RA runoff samples measured during chemical analysis.

Total suspended solids (TSS) varies widely, suggesting variable particulate wash-off depending on rainfall intensity and surface conditions. The maximum TSS values in the analyzed rainwater runoff samples are lower compared to all considered literature data [49,76–78], but slightly exceed the permissible limit in Poland for water entering the soil [73]. In the case of meltwater runoff, TSS is significantly higher than both the studied rainwater runoff and the values reported in the literature [49,76–78], with the maximum value exceeding the permissible limit for water entering the soil [73] by more than 30 times. Turbidity, which correlates with suspended solids, also varies considerably, indicating variable runoff intensity and sediment load.

Ammonium nitrogen (N-NH₄⁺) in rainwater runoff occurs across a wide range, with the maximum value being higher and the mean value lower compared to the literature data [76]. Both the maximum and mean values exceed the permissible limit for drinking water [72], which indicates the occurrence of biochemical decomposition of organic matter. The median is significantly lower than the mean and meets the drinking water standard. Nitrate nitrogen (N-NO₃[−]) reaches very high concentrations, significantly exceeding those reported in the literature [77], with only the minimum value falling below the drinking water limit [72]. This may indicate a substantial influence of traffic-related pollution and secondary runoff of fertilizers from nearby agricultural areas.

The amount of chlorides in rainwater runoff does not exceed the permissible value for drinking water [72], while the chlorides in meltwater runoff reach very high levels, although lower than the literature data [76]. Nevertheless, the results clearly reflect the impact of road salt application in winter conditions. The sulfate content in rainwater runoff remained stable during the analysis period, with the mean value close to the median and approximately five times lower than the maximum allowable value for drinking water [72]. The measured COD and TOC values indicate contamination of the runoff with organic substances; however, they are lower compared to the literature data [49,76–78], taking into account the maximum, mean, and median. The minimum values are lower for the literature data [76–78]. The TOC values indicate the presence of dissolved and partially particulate organic carbon, which may originate from engine oils, fuels, biological residues, road materials, and other components present on the RA surface. The obtained results of THT content in the runoff from the RA indicate a low level of hydrocarbon contamination, even in the case of the maximum value, which is significantly lower than the permissible value for water discharged into the soil [73].

Analysis of the data presented in Table 5 reveals significant differences in metal concentrations depending on the type of runoff. Snowmelt runoff is characterized by markedly higher concentrations of all analyzed elements compared to rainwater runoff. This result is consistent with the expectations due to the sampling locations—the rainwater runoff samples were collected from the outflow to a roadside ditch and were thus partially

pretreated in the drainage system, where the sedimentation of heavier particulate fractions could occur. Moreover, the results indicate intensive accumulation of pollutants during the winter period and their rapid release during snowmelt.

Table 5. Concentrations of metals in rainwater and snowmelt runoff from the RA compared with the literature data.

Metal	Na ⁺	Mg ²⁺	Ca ²⁺	V ³⁺	Cr ^T	Mn ²⁺	Cu ²⁺	Zn ²⁺	Mo ^T	Cd ²⁺	Pb ²⁺
Unit	mg/L	mg/L	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
Measured data											
Rainwater runoff											
Min	55.7	11.18	92.59	0.30	0.51	16	8.55	66.93	0.76	0.05	0.31
RSD	15.31%	1.54%	2.41%	2.48%	19.40%	2.08%	4.45%	3.28%	32.43%	11.81%	14.57%
Max	113.0	14.33	127.92	1.95	4.39	1391	40.00	340.00	1.97	0.19	4.29
RSD	2.68%	0.93%	0.38%	22.7%	24.94%	2.01%	3.46%	24.21%	64.7%	39.92%	23.47%
Mean	71.6	12.58	109.71	0.81	1.97	290	17.12	154.04	1.18	0.11	1.84
Median	64.4	12.25	109.14	0.49	1.56	49	11.55	110.27	0.90	0.11	1.62
Meltwater runoff											
Min	65.8	24.92	57.18	75.72	101.73	515	206.39	604.39	4.07	0.44	28.22
RSD	2.49%	0.34%	1.37%	2.71%	1.01%	1.65%	2.34%	3.12%	7.20%	28.85%	3.33%
Max	4655.6	194.87	657.41	402.93	624.10	3524	1299.43	4754.18	17.56	3.03	204.05
RSD	0.63%	5.32%	5.46%	6.21%	7.51%	5.98%	5.08%	2.76%	1.70%	7.70%	6.18%
Mean	1688.0	60.65	199.40	161.72	225.21	1279	575.72	2422.87	9.32	1.15	77.96
Median	1273.5	35.91	132.71	125.10	157.01	939	523.38	2551.52	7.45	0.81	59.95
Literature data											
Road and campus parking lot (South Korea); 2010–2019 [49]											
Mean					0.16		0.15	0.53		0.10	0.18
RA next to highway A21 (Austria); Dec 2005–May 2007 [76]											
Min							40	<10		<0.2	
Max							430	1000		<0.2	
Mean							205	360			
Median							182	294			
RAs (California, USA); Jan 2000–Mar 2003 [77]											
Min					1.0		4.6			0.2	1.1
Max					18.0		89.0			2.8	32.0
Mean					4.8		16.0			0.32	7.7
Median					3.8		13.1			0.17	5.1
2 campus parking lots (South Carolina, USA); Oct 2006–Jul 2007 [78]											
Min					<6	<2	<5	<2		<3	<59
Max					42.0	833	53.0	908		5	130
Parametric values for drinking water [72]											
Max	200				50	50	2			5	10

Compared to the literature data, the metal concentrations in snowmelt runoff are significantly higher than those reported in studies from South Korea, Austria, and the USA [49,76–78], which may be attributed to differences in climate, road conditions, traffic intensity, and the types of road maintenance and de-icing materials used. The mean sodium (Na⁺) concentration in snowmelt runoff exceeds 1600 mg/L, nearly 24 times higher than in rainwater runoff, pointing to the extensive use of road salt in winter. Exceptionally high values were observed for manganese (Mn²⁺), zinc (Zn²⁺), and copper (Cu²⁺) in snowmelt runoff—with mean concentrations of 1297 µg/L, 2423 µg/L, and 576 µg/L, respectively—greatly exceeding not only those found in rainwater runoff, but also values reported in the

literature. This may indicate the wash-off of accumulated pollutants from road surfaces and surrounding structures. Rainwater runoff results show lower, though still notable, contamination with metals, particularly Mn^{2+} . The maximum Mn^{2+} concentration was 1.6 times higher than the values from South Carolina [78]. Only the concentration of Cr in rainwater runoff was lower than the literature data [77,78], and it did not exceed the parametric value for drinking water quality [72].

Summarizing the quality of the runoff from the studied RA, the rainwater runoff is characterized by the levels of contamination comparable to those reported in the literature. In contrast, the meltwater runoff is significantly more polluted—the average indicator values and concentrations of elements are several to several dozen times higher than those observed in stormwater runoff. It is important to emphasize that this substantial difference in contamination levels is primarily due to the different sampling locations, as well as the accumulation of pollutants in snow and the use of de-icing agents during the winter.

3.2. Analysis of Pollutant Removal from RA Runoff in the Electrodialysis Process

To evaluate the effectiveness of pollutant removal from RA runoff in the electrodialysis process, a synthetically prepared solution was treated. The concentrations of chloride and metals in the untreated solution (C_0) and in the diluate after a 45 min electrodialysis process (C_{45}), as well as the removal efficiency of pollutants RE_{45} according to Equation (1) are presented in Table 6.

Chloride (Cl^-) and sodium (Na^+), representing the dominant ions from road salt contamination, were removed with very high efficiency across all variants—average RE_{45} values were 90% and 87%, respectively. These results are consistent with previously reported studies, e.g., [79]. Reduction in the concentrations of the remaining elements was lower—ranging on average from 49% for Zn^{2+} to 82% for Mg^{2+} . The highest reduction in the majority of elements was observed in variant IV. This was due to the most favorable conditions for electrodialysis efficiency among all tested variants, including the highest temperature and voltage values. Only Cr^{T} and Pb^{2+} were the most effectively removed in other variants—I and V, respectively. In variant IV, chlorides were completely removed, and most metals (Na^+ , Mg^{2+} , Ca^{2+} , Mn^{2+} , Cu^{2+} , Cd^{2+}) were reduced by more than 90%, with Cr^{T} and Pb^{2+} removed by 89% and 80%, respectively. Electrodialysis was the least effective in the case of Zn^{2+} ; however, even for this element, a 75% reduction in the diluate was achieved in variant IV. Therefore, it can be concluded that under the conditions of variant IV, electrodialysis may be an effective method for removing both salts and selected metals from the meltwater runoff originating from RAs. In contrast, for the least effective variant III—characterized by the lowest solution temperature and the lowest voltage applied to the electrodes—the 45 min process duration proved insufficient to achieve a satisfactory purification effect. The highest removal efficiency was observed for Mg^{2+} (80%), while the concentrations of Mn^{2+} and Zn^{2+} were reduced by only 10% and 29%, respectively. Chlorides and sodium were removed by 72% and 71%, respectively. In all other variants, similarly to variant III, the Cl^- removal efficiency was slightly higher than Na^+ .

As mentioned, increasing the voltage applied to the EDR electrodes enhanced the chloride removal efficiency (Table 6). This increase was more pronounced when the solution temperature was 20 °C (variants I–III) compared to 30 °C (variants IV–VI). Conversely, increasing the solution temperature to the permissible EDR maximum (30 °C) at a constant voltage influenced the process efficiency the most when the applied voltage was 10 V (variants III and VI). At higher voltages—20 V (variants II and V) and 30 V (variants I and IV)—the gains in efficiency were comparable to each other but clearly smaller than those observed at 10 V. The same trends were observed for the removal efficiency of Na^+ and Cu^{2+} . For the remaining elements, however, the patterns varied. For instance, in contrast

to Cl^- , increasing the voltage at 30 °C yielded higher removal efficiency for Mg^{2+} , Ca^{2+} , Cr^{T} , and Zn^{2+} . The effect of voltage increase was most pronounced for Mn^{2+} both for 20 °C and 30 °C: raising the voltage from 10 V to 30 V resulted in an increase in RE_{45} of as much as 77% (variants I and III) and 66% (variants IV and VI), respectively.

Table 6. Concentrations of chloride and metals in the solution before and after 45 min electrodialysis process.

Variant	Parameter	Cl^- mg/L	Na^+ mg/L	Mg^{2+} mg/L	Ca^{2+} mg/L	Cr^{T} μg/L	Mn^{2+} μg/L	Cu^{2+} μg/L	Zn^{2+} μg/L	Cd^{2+} μg/L	Pb^{2+} μg/L
I	C_0	923.0	668.95	0.88	1.71	17.34	16.35	350.15	416.00	14.91	36.01
	RSD for C_0	1.32%	1.15%	0.44%	1.30%	3.32%	1.37%	1.54%	1.19%	2.66%	0.75%
	C_{45}	35.5	58.62	0.15	0.56	1.74	2.15	61.83	249.00	2.01	12.64
	RSD for C_{45}	4.81%	0.58%	3.02%	4.92%	3.58%	2.58%	1.27%	1.64%	0.60%	2.24%
	RE_{45} , %	96	91	83	67	90	87	82	40	87	65
II	C_0	1029.5	700.45	0.45	0.95	3.16	6.61	414.71	756.00	6.99	33.41
	RSD for C_0	1.21%	0.69%	2.10%	2.13%	3.39%	1.14%	1.54%	0.26%	2.13%	0.78%
	C_{45}	71.0	69.61	0.09	0.56	0.70	2.33	95.00	321.00	1.97	13.04
	RSD for C_{45}	4.15%	1.37%	5.13%	1.21%	7.13%	2.95%	1.53%	1.36%	14.37%	1.84%
	RE_{45} , %	93	90	80	41	78	65	77	57	72	61
III	C_0	1029.5	663.59	1.03	1.28	8.80	16.09	348.21	535.00	10.82	41.95
	RSD for C_0	1.23%	3.29%	2.68%	2.44%	1.14%	1.07%	0.53%	3.16%	1.48%	0.20%
	C_{45}	284.0	191.41	0.21	0.76	2.38	14.53	124.00	381.00	3.67	12.60
	RSD for C_{45}	1.89%	1.45%	3.57%	1.57%	3.65%	1.95%	0.38%	1.62%	1.74%	2.00%
	RE_{45} , %	72	71	80	41	73	10	64	29	66	70
IV	C_0	994.0	663.65	0.51	1.18	5.51	10.38	519.65	839.00	7.73	43.30
	RSD for C_0	0.46%	1.11%	0.34%	1.85%	0.77%	2.63%	1.49%	0.74%	0.48%	0.55%
	C_{45}	0.0	29.49	0.03	0.07	0.58	0.74	44.49	209.00	0.69	8.60
	RSD for C_{45}	-	2.25%	11.27%	12.10%	5.10%	5.27%	0.27%	0.75%	7.67%	1.29%
	RE_{45} , %	100	96	94	94	89	93	91	75	91	80
V	C_0	1029.5	532.80	0.46	0.96	8.70	8.76	418.95	782.25	8.50	39.36
	RSD for C_0	0.32%	2.09%	1.71%	2.53%	0.98%	1.73%	2.07%	1.97%	6.78%	2.20%
	C_{45}	39.4	49.68	0.08	0.35	1.05	1.23	64.92	493.73	1.28	6.56
	RSD for C_{45}	6.34%	0.59%	0.74%	2.53%	2.87%	1.11%	1.30%	0.94%	6.17%	1.09%
	RE_{45} , %	96	91	83	64	88	86	85	37	85	83
VI	C_0	1065	739.22	0.33	0.75	3.69	6.27	492.96	597.70	7.38	40.34
	RSD for C_0	3.08%	0.48%	3.52%	4.02%	1.23%	2.43%	0.70%	0.98%	3.46%	0.77%
	C_{45}	177.5	128.38	0.09	0.37	2.10	4.60	99.99	259.59	1.61	7.21
	RSD for C_{45}	2.96%	1.25%	7.84%	1.70%	2.23%	1.91%	1.23%	1.58%	7.27%	0.61%
	RE_{45} , %	83	83	73	51	43	27	80	57	78	82
Mean RE_{45} for all variants, %		90	87	82	60	77	61	80	49	80	74

Figure 4 illustrates the change in chloride concentration in the diluate over time for each variant during electrodialysis. At an applied voltage of 10 V (variants III and VI), the decrease in Cl^- concentration progressed steadily, following a linear trend. In contrast, for the other variants, a more rapid decline in Cl^- content was observed up to approximately the 21st minute, followed by a slower reduction rate. This trend is most prominent in variant IV. In all variants except variant III, chloride concentration dropped below 250 mg/L—the maximum allowable concentration in drinking water [72]—within the 45-min electrodialysis period. In variant III, however, after 45 min, the Cl^- concentration still exceeded the 250 mg/L threshold by 13.6%.

A very similar pattern was observed for sodium concentrations, as shown in Figure 5. The key difference is that, during electrodialysis, Na^+ levels fell below the 200 mg/L limit for drinking water [72] in all variants. Additionally, in Figure 5, the plot for variant III stands out, showing slight increases in Na^+ concentration at 15, 24, and 36 min. Nonetheless, the overall trend remained downward.

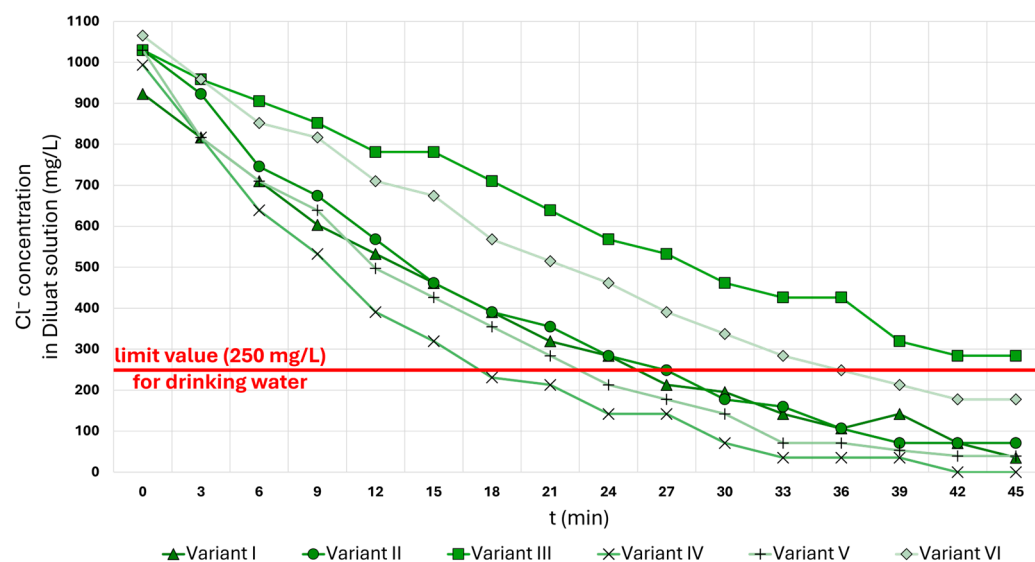


Figure 4. Dependence of Cl^- content (C) in the diluate on the duration (t) of electrodialysis.

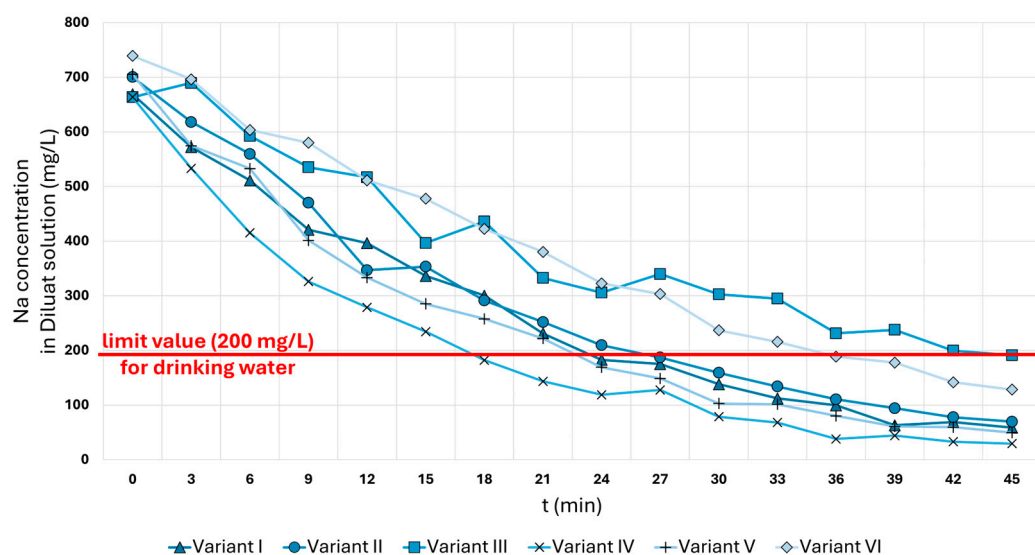


Figure 5. Dependence of Na^+ content (C) in the diluate on the duration (t) of electrodialysis.

Table 7 summarizes the time (in minutes) at which Cl^- and Na^+ concentrations in the diluate dropped below the drinking water limits, with the corresponding concentrations. The time values for Cl^- and Na^+ were the same in the vast majority of variants, and in variant I, they were similar.

Table 7. Time after which Cl^- and Na^+ content decreased below 250 and 200 mg/L, respectively.

		I	II	III	IV	V	VI
Cl^-	t, min	27	27	>45	18	24	36
	C, mg/L	213	248.5	-	231	213	248.5
Na^+	t, min	24	27	42	18	24	36
	C, mg/L	182.75	187.26	199.56	182.22	169.21	188.71

3.3. Energy Efficiency of the Electrodialysis Process

During the experimental studies, electrical energy was necessary in all variants to operate the power supply unit and the three pumps that ensured the circulation of the

diluate, concentrate, and electrolyte. Additionally, in variants IV–VI, electric heaters were used to maintain an elevated solution temperature throughout the entire electrodialysis process. The total energy consumption after 45 min of operation is shown in Figure 6. In all variants, the flow rate of the diluate, concentrate, and electrolyte was the same (0.8 L/min); therefore, the energy consumption by the pumps was identical across all variants. The heaters were set to maintain the same temperature (30 °C), so their energy consumption was very similar in variants IV–VI. The energy consumption by the power supply unit clearly depended on the set voltage level. Due to the elevated temperature and the highest voltage setting, the highest total energy consumption occurred in variant IV, while the lowest—due to opposite conditions—was observed in variant III.

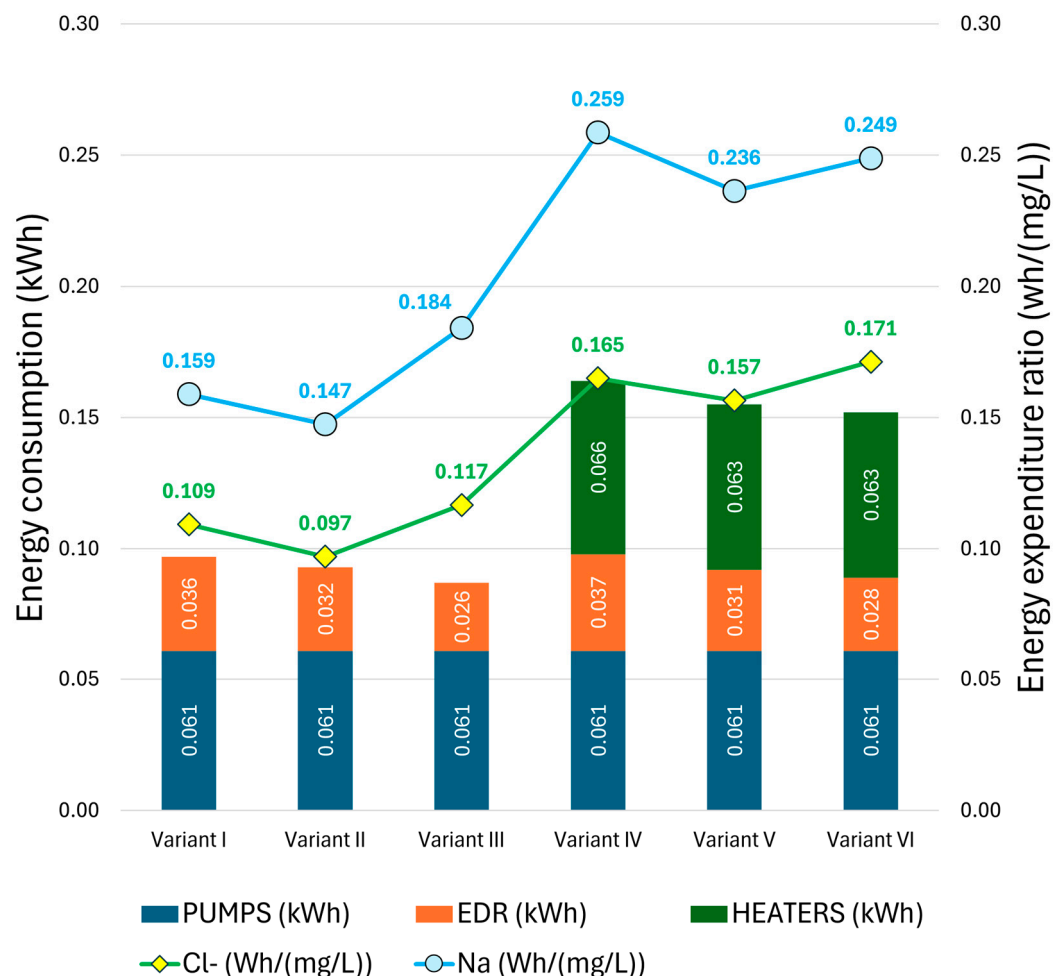


Figure 6. Electric energy consumption by laboratory equipment during 45 min of electrodialysis and energy expenditure ratio for Cl^- and Na^+ removal for variants I–VI.

In addition to the total energy consumption, the electrodialysis process in the individual variants was also characterized by the energy expenditure ratio (*EER*). This indicator informs about the amount of energy (Wh) required to remove 1 mg/L for chlorides and metals removal from diluate solution. The *EER* values for variants I–VI are presented in Figure 6. Among the analyzed cases, variant II turned out to be the most energy efficient, both in terms of Cl^- and Na^+ removal. In the case of Cl^- , the energy expenditure ratio was 0.097 Wh/(mg/L), while for Na^+ , it was 0.147 Wh/(mg/L). In turn, the case where the *EER* was the highest was variant VI for Cl^- (0.171 Wh/(mg/L)), and for Na^+ it was variant IV (0.259 Wh/(mg/L)). Due to the high percentage of pollutant removal (RE_{45}) and the lowest *EER* values, variant II can be described as being the most energy efficient.

The confirmation of the best energy efficiency for variant II is supported by the results of the energy consumption analysis from the start of electrodialysis until both Cl^- and Na^+ reach the permissible levels for drinking water, as specified in Table 7 (in the cases where Cl^- and Na^+ reached the limits at different times, the longer duration was considered). The results presented in Table 8 clearly indicate the lowest energy consumption for variant II and the highest—more than twice that of variant II—for variant VI. Although variants IV and V involve shorter operation times of electrical devices (due to faster achievement of drinking water limits for Cl^- and Na^+), they still exhibit higher energy consumption than variant II due to the use of electric heaters.

Table 8. Energy consumption during electrodialysis until Cl^- and Na^+ reach drinking water limits.

Variant	I	II	III	IV	V	VI
t (min)	27	27	>45	18	24	36
Energy consumption (Wh)						
Pumps	36	36	>61	24	33	49
Power supply	24	21	>26	18	19	23
Heaters	-	-	-	24	33	51
Total	60	57	>87	66	85	123

The course of Cl^- and Na^+ removal by electrodialysis for the most energy-efficient variant II is shown in Figure 7. Taking into account the general observed trends, the energy consumption increases steadily over time, while the removal rate of the elements (Cl^- or Na^+) is highest at the beginning of the process and decreases as time progresses. During the first 3 min, 106.5 mg/L of Cl^- and 82.5 mg/L of Na^+ was removed (respectively 10.3% and 11.8%), while in the last 3 min of electrodialysis, only 71 mg/L Cl^- and 96.6 mg/L of Na^+ was removed (respectively 6.9% and 9.9%). It can therefore be concluded that the energy efficiency of the electrodialysis process, relative to the intensity of purification, is greatest at the initial stage of the process.

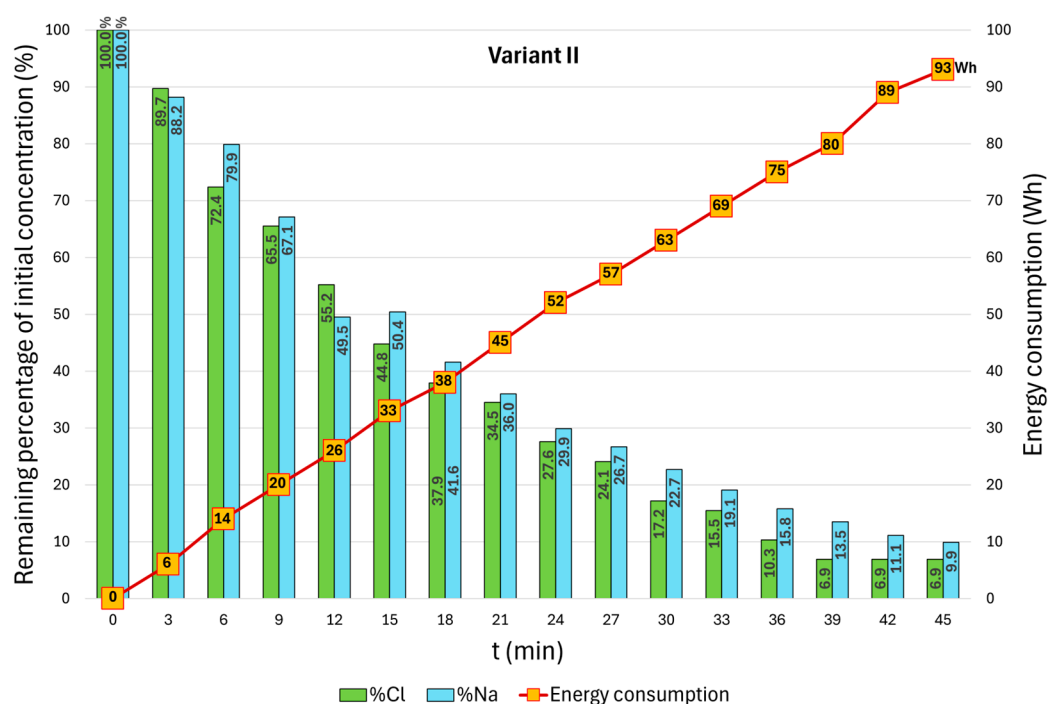


Figure 7. Remaining percentage of initial concentration of Cl^- and Na^+ together with energy consumption for 45 min of electrodialysis of variant II.

4. Conclusions

The rain- and meltwater runoff pretreatment processes are associated with energy consumption. The amount of energy consumption depends on the type of technology applied and the quantity and quality of the runoff. The conducted studies on the quality of runoff from the RA revealed significant seasonal variation—meltwater is much more polluted than rainwater. The chemical composition of the rainwater runoff from the analyzed RA is comparable to the literature data, whereas in the case of meltwater runoff, the values of the analyzed parameters are several times higher. The reuse of these waters within the RA, in line with current trends in sustainable water and energy management, requires additional treatment efforts and may be particularly challenging in winter.

In this article, electrodialysis was proposed as a method for the simultaneous removal of salts and selected metals from a contaminated solution. Considering energy consumption relative to pollutant removal efficiency, among the analyzed combinations of two temperatures (20 °C and 30 °C) and three voltages (10 V, 20 V, and 30 V), variant II (20 °C and 20 V) proved to be the most appropriate combination. In variant II, the energy expenditure ratio—indicating the amount of energy needed to remove 1 mg/L of contaminant—reached the lowest value of all variants after 45 min of electrodialysis: 0.097 Wh/(mg/L) for Cl^- and 0.147 Wh/(mg/L) for Na^+ . The permissible Cl^- and Na^+ concentrations for drinking water were achieved in this variant after 27 min with an energy consumption of 57 Wh. For comparison, in Variant IV, with the highest operational parameters (30 °C and 30 V) and the most effective pollutant removal, drinking water limits were reached after just 18 min, but using 16% more energy.

Therefore, electrodialysis appears to be a promising method for the treatment of meltwater runoff from RAs; however, further research is required, considering not only additional operational parameters (e.g., initial concentration of pollutants) and wider range of solution temperatures and voltages, but also testing real meltwater. In the longer term, the possibility of using renewable energy sources, such as solar energy, for the recovery of runoff from the research area (RA) may be considered. Nevertheless, the presented results provide a strong basis for continued investigation aimed at achieving the most efficient RA runoff purification with the lowest possible energy input.

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References

1. European Commission. Commission Notice—The ‘Blue Guide’ on the Implementation of EU Product Rules 2016. *Off. J. Eur. Union* **2016**, C272, 1–148.
2. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC. Available online: <http://data.europa.eu/eli/dir/2012/27/2023-05-04> (accessed on 13 May 2025).
3. Regulation (EU) 2017/1369 of the European Parliament and of the Council of 4 July 2017 Setting a Framework for Energy Labelling and Repealing Directive 2010/30/EU. Available online: <http://data.europa.eu/eli/reg/2017/1369/oj> (accessed on 13 May 2025).
4. United Nations. Goals of Sustainable Development of the 2030 Agenda for Sustainable Development. Available online: <https://sdgs.un.org/goals> (accessed on 13 May 2025).
5. ISO 14067:2018; Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification. International Organization for Standardization: Geneva, Switzerland, 2018.
6. Wiedmann, T.; Minx, J. A Definition of ‘Carbon Footprint’. In *Ecological Economics Research Trends, Chapter 1*; Pertsova, C.C., Ed.; Nova Science Publishers: Hauppauge, NY, USA, 2008; pp. 1–11.
7. Shang, W.L.; Chen, Y.; Yu, Q.; Song, X.; Chen, Y.; Ma, X.; Ochieng, W. Spatio-temporal Analysis of Carbon Footprints for Urban Public Transport Systems Based on Smart Card Data. *Appl. Energy* **2023**, *352*, 121859. [\[CrossRef\]](#)
8. Boulos, P.F.; Bros, C.M. Assessing the Carbon Footprint of Water Supply and Distribution Systems. *J. AWWA* **2010**, *102*, 47–54. [\[CrossRef\]](#)
9. Galli, A.; Wiedmann, T.; Ercin, E.; Knoblauch, D.; Ewing, B.; Giljum, S. Integrating Ecological, Carbon and Water Footprint into a “Footprint Family” of Indicators: Definition and Role in Tracking Human Pressure on the Planet. *Ecol. Indic.* **2012**, *16*, 100–112. [\[CrossRef\]](#)
10. Gómez-Llanos, E.; Matías-Sánchez, A.; Durán-Barroso, P. Wastewater Treatment Plant Assessment by Quantifying the Carbon and Water Footprint. *Water* **2020**, *12*, 3204. [\[CrossRef\]](#)
11. Zaborowska, E.; Czerwionka, K.; Małania, J. Integrated Plant-Wide Modelling for Evaluation of the Energy Balance and Greenhouse Gas Footprint in Large Wastewater Treatment Plants. *Appl. Energy* **2021**, *282*, 116126. [\[CrossRef\]](#)
12. Maktabifard, M.; Awaitey, A.; Merta, E.; Haimi, H.; Zaborowska, E.; Mikola, A.; Małania, J. Comprehensive Evaluation of the Carbon Footprint Components of Wastewater Treatment Plants Located in the Baltic Sea Region. *Sci. Total Environ.* **2022**, *806*, 150436. [\[CrossRef\]](#) [\[PubMed\]](#)
13. European Parliament; Council of the European Union. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy. *Off. J. Eur. Communities* **2000**, *327*, 1–73.
14. Plappally, A.K.; Lienhard, J.H. Energy Requirements for Water Production, Treatment, End Use, Reclamation, and Disposal. *Renew. Sustain. Energy Rev.* **2012**, *16*, 4818–4848. [\[CrossRef\]](#)
15. Flörke, M.; Schneider, C.; McDonald, R.I. Water Competition between Cities and Agriculture Driven by Climate Change and Urban Growth. *Nat. Sustain.* **2018**, *1*, 51–58. [\[CrossRef\]](#)
16. Ayele, G.T. Review of Climate Change Impacts on Water Quantity and Quality in the Murray–Darling Basin, Australia. *Water* **2024**, *16*, 3506. [\[CrossRef\]](#)
17. Yateh, M.; Li, F.; Tang, Y.; Li, C.; Xu, B. Energy Consumption and Carbon Emissions Management in Drinking Water Treatment Plants: A Systematic Review. *J. Clean. Prod.* **2024**, *437*, 140688. [\[CrossRef\]](#)
18. Grzegorzec, M.; Wartalska, K.; Kaźmierczak, B. Review of Water Treatment Methods with a Focus on Energy Consumption. *Int. Commun. Heat. Mass. Transf.* **2023**, *143*, 106674. [\[CrossRef\]](#)
19. Guptha, G.C.; Swain, S.; Al-Ansari, N.; Taloor, A.K.; Dayal, D. Assessing the Role of SuDS in Resilience Enhancement of Urban Drainage System: A Case Study of Gurugram City, India. *Urban Clim.* **2022**, *41*, 101075. [\[CrossRef\]](#)
20. Mosleh, L.; Negahban-Azar, M.; Pavao-Zuckerman, M. Stormwater Green Infrastructure Resilience Assessment: A Social-Ecological Framework for Urban Stormwater Management. *Water* **2023**, *15*, 1786. [\[CrossRef\]](#)
21. Karami, M.; Behzadian, K.; Ardeshtir, A.; Hosseinzadeh, A.; Kapelan, Z. A Multi-Criteria Risk-Based Approach for Optimal Planning of SuDS Solutions in Urban Flood Management. *Urban Water J.* **2022**, *19*, 1066–1079. [\[CrossRef\]](#)
22. Ferrans, P.; Reyes-Silva, J.D.; Krebs, P.; Temprano, J. Flood Management with SUDS: A Simulation–Optimization Framework. *Water* **2023**, *15*, 426. [\[CrossRef\]](#)
23. Mondal, A.; Garg, R.D. Assessing the Role of Sustainable Water Bodies in Urban Drainage Systems to Mitigate Urban Flooding: A Case Study of Gurgaon, Haryana, India. *Phys. Chem. Earth Parts A/B/C* **2025**, *137*, 103803. [\[CrossRef\]](#)
24. Webber, J.L.; Fletcher, T.; Farmani, R.; Butler, D.; Melville-Shreeve, P. Moving to a Future of Smart Stormwater Management: A Review and Framework for Terminology, Research, and Future Perspectives. *Water Res.* **2022**, *218*, 118409. [\[CrossRef\]](#)

25. Sweetapple, C.; Webber, J.; Hastings, A.; Melville-Shreeve, P. Realising Smarter Stormwater Management: A Review of the Barriers and a Roadmap for Real World Application. *Water Res.* **2023**, *244*, 120505. [\[CrossRef\]](#)
26. Islam, M.M.; Afrin, S.; Tarek, M.H.; Rahman, M.M. Reliability and Financial Feasibility Assessment of a Community Rainwater Harvesting System Considering Precipitation Variability Due to Climate Change. *J. Environ. Manag.* **2021**, *289*, 112507. [\[CrossRef\]](#)
27. de Sá Silva, A.C.R.; Bimbato, A.M.; Balestieri, J.A.P.; Vilanova, M.R.N. Exploring Environmental, Economic and Social Aspects of Rainwater Harvesting Systems: A Review. *Sustain. Cities Soc.* **2022**, *76*, 103475. [\[CrossRef\]](#)
28. Oladunjoye, O.; Proverbs, D.; Xiao, H. Retrofitting Sustainable Urban Drainage Systems (SuDS): A Cost-Benefit Analysis Appraisal. *Water* **2022**, *14*, 2521. [\[CrossRef\]](#)
29. Matta-Ortíz, A.F.; Güiza-Valdes, I.A.; Trujillo-González, J.M.; Rojas-Peña, J.I.; Torres-Mora, M.A.; García-Navarro, F.J.; Jiménez-Ballesta, R. Assessing Rainwater Quality and Harvesting Potential: A Spatial Analysis in a Medium-Sized City of Colombia. *Water* **2024**, *16*, 3411. [\[CrossRef\]](#)
30. Zdeb, M.; Papciak, D.; Zamorska, J. An Assessment of the Quality and Use of Rainwater as the Basis for Sustainable Water Management in Suburban Areas. *E3S Web Conf.* **2018**, *45*, 00111. [\[CrossRef\]](#)
31. Abdemanafi, D.; Meshkatee, A.; Hejam, S. The Study of pH, Total Dissolved Solids (TDS), Electrical Conductivity (EC), Total Alkalinity and Total Hardness of Rain Water over Tehran City. *J. Clim. Res.* **2021**, *1399*, 1–14.
32. Wartalska, K.; Grzegorzec, M.; Bełcik, M.; Wdowikowski, M.; Kolanek, A.; Niemierka, E.; Kaźmierczak, B. The Potential of RainWater Harvesting Systems in Europe—Current State of Art and Future Perspectives. *Water Resour. Manag.* **2024**, *38*, 4657–4683. [\[CrossRef\]](#)
33. Chughtai, M.; Mustafa, S.; Mumtaz, M. Study of Physicochemical Parameters of Rainwater: A Case Study of Karachi, Pakistan. *Am. J. Anal. Chem.* **2014**, *5*, 235–242. [\[CrossRef\]](#)
34. Słyś, D.; Stec, A. The Analysis of Variants of Water Supply Systems in Multi-Family Residential Building. *Ecol. Chem. Eng. S* **2014**, *21*, 623–635. [\[CrossRef\]](#)
35. Stec, A.; Zeleňáková, M. An Analysis of the Effectiveness of Two Rainwater Harvesting Systems Located in Central Eastern Europe. *Water* **2019**, *11*, 458. [\[CrossRef\]](#)
36. Mazurkiewicz, K.; Jeż-Walkowiak, J.; Michałkiewicz, M. Physicochemical and Microbiological Quality of Rainwater Harvested in Underground Retention Tanks. *Sci. Total Environ.* **2022**, *814*, 152701. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Gwoździej-Mazur, J.; Jadwiszczak, P.; Kaźmierczak, B.; Kózka, K.; Struk-Sokołowska, J.; Wartalska, K.; Wdowikowski, M. The Impact of Climate Change on Rainwater Harvesting in Households in Poland. *Appl. Water Sci.* **2022**, *12*, 15. [\[CrossRef\]](#)
38. Gupta, S.; Mishra, P.K.; Khare, D. Advancements and Challenges in Roof-Top Harvested Rainwater Filtration: A Review. *Environ. Process.* **2025**, *12*, 7. [\[CrossRef\]](#)
39. Müller, A.; Österlund, H.; Marsalek, J.; Viklander, M. The Pollution Conveyed by Urban Runoff: A Review of Sources. *Sci. Total Environ.* **2020**, *709*, 136125. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Zubala, T.; Patro, M. Time and Spatial Variability in Concentrations of Selected Pollutants in the New Bypass Rainwater Harvesting System. *Water Air Soil. Pollut.* **2021**, *232*, 211. [\[CrossRef\]](#)
41. Dia, M.; Peyneau, P.E.; Courtier-Murias, D.; Bechet, B. Detection and Quantification of Nanoparticles in Runoff from a Highly Trafficked Urban Motorway. *Environ. Sci. Nano* **2025**, *12*, 1993–2007. [\[CrossRef\]](#)
42. Opher, T.; Friedler, E. Factors Affecting Highway Runoff Quality. *Urban Water J.* **2010**, *7*, 155–172. [\[CrossRef\]](#)
43. Huber, M.; Helmreich, B. Stormwater Management: Calculation of Traffic Area Runoff Loads and Traffic Related Emissions. *Water* **2016**, *8*, 294. [\[CrossRef\]](#)
44. Huber, M.; Welker, A.; Helmreich, B. Critical Review of Heavy Metal Pollution of Traffic Area Runoff: Occurrence, Influencing Factors, and Partitioning. *Sci. Total Environ.* **2016**, *541*, 895–919. [\[CrossRef\]](#)
45. Revitt, D.M.; Lundy, L.; Coulon, F.; Fairley, M. The Sources, Impact and Management of Car Park Runoff Pollution: A Review. *J. Environ. Manag.* **2014**, *146*, 552–567. [\[CrossRef\]](#)
46. Schiff, K.C.; Tiefenthaler, L.L.; Bay, S.M.; Greenstein, D.J. Effects of Rainfall Intensity and Duration on the First Flush from Parking Lots. *Water* **2016**, *8*, 320. [\[CrossRef\]](#)
47. Suripin, S.; Sangkawati, S.S.; Pranoto, S.A.; Sutarto, E.; Hary, B.; Dwi, K. Reducing Stormwater Runoff from Parking Lot with Permeable Pavement. *E3S Web Conf.* **2018**, *73*, 05016. [\[CrossRef\]](#)
48. Charters, F.J.; Cochrane, T.A.; O’Sullivan, A.D. The Influence of Urban Surface Type and Characteristics on Runoff Water Quality. *Sci. Total Environ.* **2021**, *755*, 142470. [\[CrossRef\]](#)
49. Choi, H.; Geronimo, F.K.F.; Jeon, M.; Kim, L.H. Investigation of the Factors Affecting the Treatment Performance of a Stormwater Horizontal Subsurface Flow Constructed Wetland Treating Road and Parking Lot Runoff. *Water* **2021**, *13*, 1242. [\[CrossRef\]](#)
50. James, W.; Thompson, M.K. Contaminants from Four New Pervious and Impervious Pavements in a Parking-Lot. In *Advances in Modeling the Management of Stormwater Impacts*; CRC Press: Boca Raton, FL, USA, 2021; pp. 207–222.
51. Poudyal, S.; Cochrane, T.A.; Bello-Mendoza, R. Carpark Pollutant Yields from First Flush Stormwater Runoff. *Environ. Chall.* **2021**, *5*, 100301. [\[CrossRef\]](#)

52. Lembcke, D.; Thompson, B.; Read, K.; Betts, A.; Singaraja, D. Reducing Road Salt Application by Considering Winter Maintenance Needs in Parking Lot Design. *J. Green. Build.* **2017**, *12*, 1–12. [CrossRef]
53. Tirpak, A.; Winston, R.J.; Feliciano, M.; Dorsey, J.D. Stormwater Quality Performance of Permeable Interlocking Concrete Pavement Receiving Run-On from an Asphalt Traffic Lane in a Cold Climate. *Environ. Sci. Pollut. Res.* **2020**, *27*, 21716–21732. [CrossRef]
54. Mundahl, N.D.; Howard, J. Stormwater Management and Late-Winter Chloride Runoff into an Urban Lake in Minnesota, USA. *Hydrology* **2025**, *12*, 76. [CrossRef]
55. Juve, J.M.A.; Christensen, F.M.S.; Wang, Y.; Wei, Z. Electrodialysis for Metal Removal and Recovery: A Review. *Chem. Eng. J.* **2022**, *435*, 134857. [CrossRef]
56. Zhang, S.; Wang, J.; Shen, F.; Wang, D.; Zhang, S. Efficient Removal of Metal Ions from the Ionic Liquid Aqueous Solution by Selective Electrodialysis. *Sep. Purif. Technol.* **2022**, *295*, 121322. [CrossRef]
57. Cerrillo-Gonzalez, M.D.M.; Villen-Guzman, M.; Rodriguez-Maroto, J.M.; Paz-Garcia, J.M. Metal Recovery from Wastewater Using Electrodialysis Separation. *Metals* **2023**, *14*, 38. [CrossRef]
58. Valero, F.; Barceló, A.; Arbós, R. Electrodialysis Technology: Theory and Applications. In *Desalination, Trends and Technologies*; Schorr, M., Ed.; IntechOpen: London, UK, 2011; pp. 3–20. [CrossRef]
59. Google Maps. Available online: <https://www.google.pl/maps> (accessed on 13 May 2025).
60. IMGW-PIB. Charakterystyka Wybranych Elementów Klimatu w Polsce w 2024 Roku—Podsumowanie (Characteristics of Selected Climate Elements in Poland in 2024—Summary). Available online: <https://imgw.pl/charakterystyka-wybranych-elementow-klimatu-w-polsce-w-2024-roku-podsumowanie/> (accessed on 13 May 2025).
61. ISO 15705:2002; Water Quality—Determination of the Chemical Oxygen Demand Index (ST-COD)—Small-Scale Sealed-Tube Method. International Organization for Standardization: Geneva, Switzerland, 2002.
62. Hach. Water Analysis Methods and Procedures. Available online: https://www.hach.com/resources/water-analysis-handbook?srsId=AfmBOooOpfToSh_h1SlqESqfZAMj-Q0670EpFtFshoJOSOHHfaeexK02#T (accessed on 13 May 2025).
63. USEPA. Method 9060A (SW-846): Total Organic Carbon, Part of Test Methods for Evaluating Solid Waste, Physical/Chemical Methods; Revision 1; U.S. Environmental Protection Agency: Washington, DC, USA, 2004. Available online: <https://www.epa.gov/hw-sw846/sw-846-test-method-9060a-total-organic-carbon> (accessed on 13 May 2025).
64. ISO 7027-1:2016; Water Quality—Determination of Turbidity—Part 1: Quantitative Methods. International Organization for Standardization: Geneva, Switzerland, 2016.
65. ISO 7888:1985; Water Quality—Determination of Electrical Conductivity. International Organization for Standardization: Geneva, Switzerland, 1985.
66. ISO 10523:2008; Water Quality—Determination of pH. International Organization for Standardization: Geneva, Switzerland, 2008.
67. ISO 23696-1:2023; Water Quality—Determination of Nitrate in Water Using Small-Scale Sealed Tubes—Part 1: Dimethylphenol Colour Reaction. International Organization for Standardization: Geneva, Switzerland, 2023.
68. ISO 7150-1:1984; Water Quality—Determination of Ammonium—Part 1: Manual Spectrometric Method. International Organization for Standardization: Geneva, Switzerland, 1984.
69. ISO 9297:1989; Water Quality—Determination of Chloride—Silver Nitrate Titration with Chromate Indicator (Mohr’s Method). International Organization for Standardization: Geneva, Switzerland, 1989.
70. USEPA. Method 6020B (SW-846): Inductively Coupled Plasma-Mass Spectrometry; Revision 2; U.S. Environmental Protection Agency: Washington, DC, USA, 2014. Available online: <https://www.epa.gov/hw-sw846/sw-846-test-method-6020b-inductively-coupled-plasma-mass-spectrometry> (accessed on 13 May 2025).
71. PN-C-04643:1994; Water and Waste Water. Tests for Aliphatic Hydrocarbons Contents. Determination of Total of C7–C30 Hydrocarbons by Gas Chromatography. Polish Committee for Standardization: Warsaw, Poland, 1994. (In Polish)
72. The Council of The European Union. Council Directive 98/83/EC of 3 November 1998 on the Quality of Water Intended for Human Consumption. *Off. J. Eur. Communities* **1998**, *L 330*, 32–54. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31998L0083> (accessed on 13 May 2025).
73. Minister of Maritime Economy and Inland Navigation. Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 on Substances Particularly Harmful to the Aquatic Environment and the Conditions to Be Met When Discharging Wastewater into Water or Soil, as Well as When Discharging Stormwater or Meltwater into Water Bodies or Water Facilities. *Dziennik Ustaw* **2019**, 1311. Available online: <https://dziennikustaw.gov.pl/D2019000131101.pdf> (accessed on 13 May 2025). (In Polish)
74. Sadrzadeh, M.; Razmi, A.; Mohammadi, T. Separation of Different Ions from Wastewater at Various Operating Conditions Using Electrodialysis. *Sep. Purif. Technol.* **2007**, *54*, 147–156. [CrossRef]

75. Dévora-Isiordia, G.E.; Ayala-Espinoza, A.; Lares-Rangel, L.A.; Encinas-Guzmán, M.I.; Sánchez-Duarte, R.G.; Álvarez-Sánchez, J.; Martínez-Macías, M.D.R. Effect of Temperature on Diluate Water in Batch Electrodialysis Reversal. *Separations* **2021**, *8*, 229. [CrossRef]
76. Fuerhacker, M.; Haile, T.M.; Monai, B.; Mentler, A. Performance of a Filtration System Equipped with Filter Media for Parking Lot Runoff Treatment. *Desalination* **2011**, *275*, 118–125. [CrossRef]
77. California Department of Transportation (Caltrans). *Storm Water Monitoring & Data Management. Discharge Characterization Study Report*; CTSW-RT-03-065.51.42; Caltrans: Sacramento, CA, USA, 2003. Available online: <https://dot.ca.gov/-/media/dot-media/programs/environmental-analysis/documents/env/ctsw-rt-03-065-a11y.pdf> (accessed on 13 May 2025).
78. McQueen, A.D.; Johnson, B.M.; Rodgers, J.H., Jr.; English, W.R. Campus Parking Lot Stormwater Runoff: Physico-Chemical Analyses and Toxicity Tests Using *Ceriodaphnia dubia* and *Pimephales promelas*. *Chemosphere* **2010**, *79*, 561–569. [CrossRef]
79. Banasiak, L.J.; Kruttschnitt, T.W.; Schäfer, A.I. Desalination Using Electrodialysis as a Function of Voltage and Salt Concentration. *Desalination* **2007**, *205*, 38–46. [CrossRef]

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