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Determining the Effectiveness of Street Cleaning with the Use of Decision Analysis and Research on the Reduction in Chloride in Waste

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Abstract: Waste from street cleaning is usually of a fine fraction below 10 mm and varies greatly in both quantity and composition. It may be composed of chlorides, especially for that resulting during winter due to the use of street de-icing agents. Chlorides can cause the salinization of surface water and groundwater, and the salinization of soils, which in turn lead to the deterioration of water purity and a decrease in biodiversity of aquatic organisms, changes in microbiological structure, and increases in toxicity of metals. Therefore, it is very important to determine the level of salinity in stored waste and its impact on the environment. The present study was conducted in a city of about 55,000 inhabitants. The highest chloride concentrations were observed after winter in waste from street and sidewalk cleaning around the sewer gullies, amounting to 1468 mg/dm^3. The lowest chloride concentration in this waste occurred in summer and amounted to 35 mg/dm^3. The multi-criteria analysis indicated that the most beneficial form of street cleaning and, thus, of reductions in chloride concentration in the waste from street cleaning, would be sweeping and daily washing. The objective of this research was to determine the amount of chlorides in sweepings on an annual basis in order to determine the potential risks associated with their impact on select aspects of the environment and to evaluate the frequency of necessary cleaning for city streets, considering the effects. The methodology used was a multi-criteria evaluation, which as a decision analysis, allowed us to determine the frequency of cleaning and washing of streets, in such a way that an ecological effect is achieved with simultaneous economic efficiency.

Keywords: street pollution; street cleaning; waste; chloride content; decision analysis; multi-criteria analysis

1. Introduction

According to the World Bank's report on the future of solid waste management, the world generates about 2.01 billion tons of solid waste annually and 33% (663 million tons) is not managed in an environmentally safe manner. According to research by the International Solid Waste Association (ISWA), 70% of municipal waste worldwide becomes landfill without treatment. By 2050, the amount of waste in the world will increase by 70%, reaching 3.40 billion tons of solid waste generated annually.

Waste management should be carried out according to the following hierarchy: prevention at the source, preparation for reuse, recycling and reuse of usable materials, other recovery methods including incineration, and final disposal of treatment residues. There is a wide variety of waste streams in large metropolitan areas, and this diversity creates the need for mass reduction and the need to dispose of all streams, regardless of their nature. Building and managing comprehensive systems would allow for a solution for waste management to be found, and by managing them, emissions to the environment can be reduced while recovering the raw material fraction and following the "polluter pays" principle. The basis for the creation of an objective function in the research on the optimization of regional waste management is the economic efficiency index for a complex system, which is extremely important because of the necessity to establish fees for waste management in accordance with the "polluter pays" principle. It is also important to reconcile the ecological and economic balance in such a way that the activities carried out balance both issues.

2. Chlorides and Their Impact on the Environment

One of the municipal waste streams is street sweepings generated during street cleaning and washing processes. What is interesting is both their quantity as well as their composition and variability in characteristics over the course of the year, which have a significant impact on the quality of the natural environment as they may affect the quality of the soil, water, and municipal infrastructure (roads, sidewalks, sewers, cars, etc.). According to the European Waste Catalogue [1], street cleaning waste, classified as "20 03 03–street-cleaning residues", is treated as one of the municipal waste streams that should be collected and disposed of in a comprehensive system. This waste may constitute 10–15% of the mass of municipal waste. However, the amount of suspended solids washed out during street cleaning and washing processes, which also has a significant impact on the quantity and quality of waste, has not been taken into account in previous studies. According to research [2,3], the amount of suspended solids represents 7–75% of the solid waste in relation to the amount of sweepings collected on particular days, only during sweeping. In general, the most commonly studied phenomenon reported in the literature is the impact of street cleaning on air quality and secondary emissions. They do not present conclusive results. Some studies conducted in this regard have registered an increase in PM10 (Particulate matter) levels [4,5] and an increase in the proportion of mineral components in particulate matter especially in the PM10 fraction [6]. On the other hand, it has been proven that only street sweeping may have periodical adverse effects on the removal of pollutants from the air; Vaze and Chiew [7] found that there were more fine dust particles in the air after street sweeping compared with before sweeping. In addition to studying street cleaning by sweeping alone, street washing and its effects on ambient air quality have also been studied. Some studies have shown that the effectiveness of street washing (without sweeping) is more related to the wetting effect than to the effective removal of particulate matter. On paved roads, the effect of street washing on air quality has been studied in Germany and Scandinavian countries [4,5,7]. The results showed that the effectiveness depends strongly on the local situation (location, meteorology, and road quality). Results presenting the effectiveness of street sweeping and washing are also presented in Reference [8], where the concentration of suspended particulate matter was controlled. References [9,10] describe the evaluation of the effectiveness of mechanical sweeping and street washing with water to reduce PM10 concentrations in ambient air. A significant number of publications describe the negative effects of the composition of sweepings deposited on city streets and in urban areas on the environment of these areas. Reference [11] analyzed dust collected from streets and soil from cities with high, medium, and low population densities and in a non-urbanized area. That study concluded that high population density increases the salinity of sweepings and soil but has no effect on the concentration of metals in soil. Reference [12] presented the results of a study on the identification of contaminants found in street dust from London (UK), New York (USA), Halifax (Canada), Christchurch (New Zealand), and Kingston (Jamaica). The pollutants identified were divided into two groups: of soil origin and from other sources, including tire wear, car emissions, and salt use. That study showed that the concentrations of most elements increase with a decrease in dust particle size. The salinity of the sweepings consequently increases the salinity of wastewater, either from street cleaning or runoff during precipitation, and the increased chloride content interferes with the dephosphatation and deflocculation process [13]. Due to a lack of management technology, this waste is deposited in landfills [14–17], consequently causing salinization of the landfill leachate [18,19]. De-icing agents are common road-safety maintenance materials during winter. According to the Polish law [20], the following can be used to maintain roads in winter: NaCl, $CaCl_2$, and $MgCl_2$. In addition, sand is used for road maintenance during winter in Poland to improve grip. On average, more than 500 thousand tons of sodium chloride is applied to roads in Poland [21]. For comparison, a country such as Sweden, where snowfalls are significantly higher, does not exceed the consumption of road salt above the level of 300 thousand tons per year. In the United States, on the other hand, 20 million tons of road salt is used annually. As the snow and ice melt, the salt is washed away and, together with precipitation or street cleaning water, it ends up in the ground, groundwater and surface water, polluting them. The greatest chloride leaching occurs during storms and downpours. It affects entire ecosystems. A heavy influx of chloride ions disrupts the ability of freshwater organisms to regulate fluid flow [22]. Changes in the salinity of a pond or lake can also affect the way water mixes with the change of seasons, leading to the formation of salt pockets near the bottom and biological dead zones. Increased salinity in water bodies can lead to decreased biodiversity of aquatic organisms, changes in microbial structure, and increased metal toxicity [23]. Increased chloride concentrations also contribute to groundwater salinity [24]. According to the Polish law, concentrations in groundwater for quality class I waters must not exceed 60 mg/dm^3, those for class II must not exceed 150 mg/dm^3, and those for class III must not exceed 250 mg/dm^3 [25]. For surface water, the chlorides concentration for class I must not exceed 5 mg/dm^3, while those for class II must not exceed 8.2 mg/dm^3, and there are no standards for other classes [26]. When road salt runs off the road, it can destroy soil, trees, and vegetation or limit their growth [27] up to 100 m from where the salt is spread. In addition, it corrodes sewage infrastructure and erodes road surfaces [28]. Roadside roads can also turn into artificial licks, attractive to animals such as deer and elk, increasing the risk of accidents [29–31].

In this article, an assessment of the chloride removal strategy from the environment in washing and cleaning processes is made based on a decision analysis (multi-criteria). Multi-criteria decision models have been used since the 1980s as an environmental impact assessment tool in environmental engineering [32–46]. The objective of the research presented was to determine the amount of chlorides in the sweepings on an annual basis in order to determine the potential risks associated with their impact on select aspects of the environment and to evaluate the frequency of cleaning urban streets, taking into account environmental and economic effects.

The methodology used is a multi-criteria evaluation, which as a decision analysis, allows use to determine the frequency of cleaning and washing of streets, in such a way as that an ecological effect is achieved with simultaneous economic efficiency.

3. Proposed Research Methodology

The scientific objective of the proposed methodology was to use a multi-criteria assessment to assess the degree of street pollution and to determine the optimal solution from the perspective of economic and ecological aspects.

The utilitarian/practical goal was to create a decision-making tool for waste management processes, taking into account environmental issues.

In the proposed research approach, a research methodology that allows us to determine the amount of chlorides in street cleaning waste and to determine the potential environmental risks associated with their presence is presented. In terms of the works undertaken, we propose the following:

- a selection of test times and places, and a selection of sampling locations;

- laboratory testing of the samples, processing of the test results, and conclusions from the analytical tests; and
- a decision analysis and a selection of the system of treatments and removal of chlorides from the environment according to the following scheme: development of treatment options taking into account environmental quality studies with costs, proposal of conditions and limitations to the decision analysis, and identification of the most beneficial scenario taking into account environmental and economic factors.

The necessary condition for finding the solution is a set of well-designed criteria that can be used for the evaluation of different options. The criteria taken into account should represent diverse goals that sometimes are even contradictory, e.g., a solution that is the cheapest and, at the same time, the most reliable. Thus, the options analyzed should be defined in detail, and the final selection is always a compromise based on the relative weights assigned to individual criteria. For the multi-criteria analysis, the compromise programming method was used, using the concept of organizing individual variants of technology modernization according to their distance from an established ideal point $X'(x_1{}', x_2{}', \ldots, x_m{}')$, all $x_m{}'$ coordinates of which are equal to the maximum value of the adopted normalization scale. The utility of s_n strategy with regard to all criteria can be expressed as follows:

$$U(s_n) = \sum_{m=1}^{M} w_m \cdot (r\prime_{nm} - x*_m); m = 1, \ldots, M \quad (1)$$

where

$U(s_n)$—s_n strategy utility function;
n—number of strategies;
m—number of criteria;
W_m—the weight of each criterion, assumed by the decision-maker;
r'_{nm}—standardized evaluation criterion; and
x^*_m—mth nadir coordinate, which is the most unfavorable strategy.

The search for the most favorable strategy is carried out according to the following rule:

$$s_j \Leftrightarrow U(s_j) = \max U(s_n); n = 1, \ldots, N \quad (2)$$

where

s_j—the most advantageous technological variant sought.

The applied method leads to a complete ordering of the elements of the decision area and finding the most environmentally beneficial solution.

4. Description and Results of Analytical Research

The research was conducted in a medium-sized city with a population of about 55,000 inhabitants. The area from which street cleaning waste was removed is about 140 km^2, while the area of the sidewalks is about 450 thousand m^2. The amount of sweepings collected annually ranges from 300 to 1200 tons per year, depending on the severity of winter in a given year. The ratio in which sand is mixed with NaCl during winter is 50:50; at temperatures below 20 °C, $CaCl_2$ is also used at a ratio of 50:50 with sand. Sidewalks are only gritted with sand, without salt. After collection, this waste is deposited in a landfill for non-inert and hazardous waste. The fee for depositing this waste is EUR 65 per ton.

Samples for the research were taken during two periods of increased street and sidewalk cleaning, that is, the end of summer—August/September—and the end of winter—March. Sampling for laboratory tests (solid waste and street washing wastewater samples) were taken directly from the waste container of the street and sidewalk cleaning truck according to the standards [47,48].

The maximum amount of street cleaning waste collected was 270 kg/km, while the minimum was 200 kg/km. The content of organic parts was 9% and the content of mineral parts was 91%, which are shown in Figure 1.

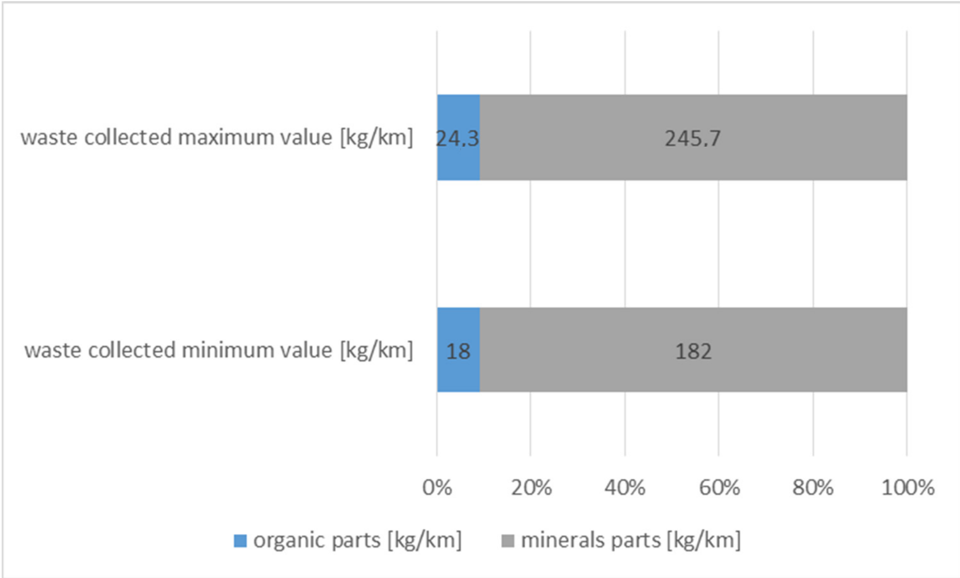

Figure 1. Maximum and minimum amounts of street cleaning waste collected, divided into organic and mineral components.

The maximum collected suspended solids from street cleaning was 26 mg/dm^3, while the minimum was 12 mg/dm^3. The organic content of the suspended solids was 17% and the mineral content was 83%, which are shown in Figure 2.

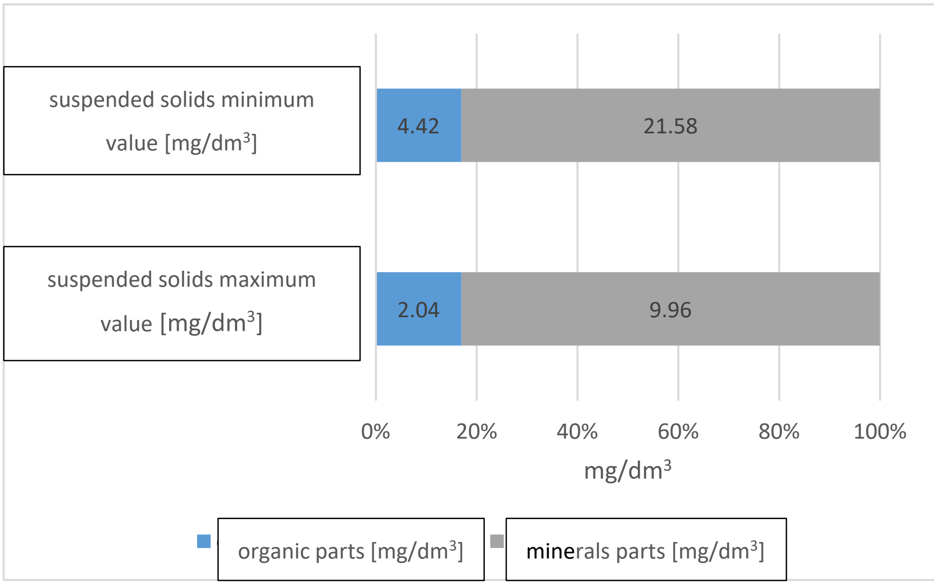

Figure 2. Maximum and minimum amounts of collected suspended solids, divided into organic and mineral components.

Due to the possibility of salt accumulation in different areas of roads, we proposed to take samples not only from streets but also from wastewater and gullies. The samples labeled Street 1 and Sidewalk are solid samples. Samples for the research were taken from this waste by dissolving about 200 g of waste in distilled water and then filtering it, and a representative sample was obtained for testing. On the other hand, samples from Street 2 from around the gullies and samples from Street 3 (streets washing) were taken in semi-liquid form and filtered, and a representative sample was obtained for testing. For each sampling location—Street 1, Street 2, Street 3, and Sidewalk—30 representative samples were obtained and analyzed for chloride content. The chloride contents of wastewater and street sweepings were determined using the standard: PN-ISO 9297:1994 [49]. The results for the chloride content in 30 samples for each site are presented in Table 1 and Figure 3.

Table 1. Chloride content in individual street and sidewalk cleaning samples after summer and winter.

Site	Chloride Content in Street Cleaning Wastewater (mg/dm^3) after Summer		Chloride Content in Street Cleaning Wastewater (mg/dm^3) after Winter	
	Minimum Value	Maximum Value	Minimum Value	Maximum Value
Street 1	29.3	41.4	321.6	399.8
Street 2 (gullies)	45.6	71.9	1201.4	1732.8
Street 3 (washing)	38.3	49.3	436.3	468.5
Sidewalk	25.8	46.2	45.9	59.2

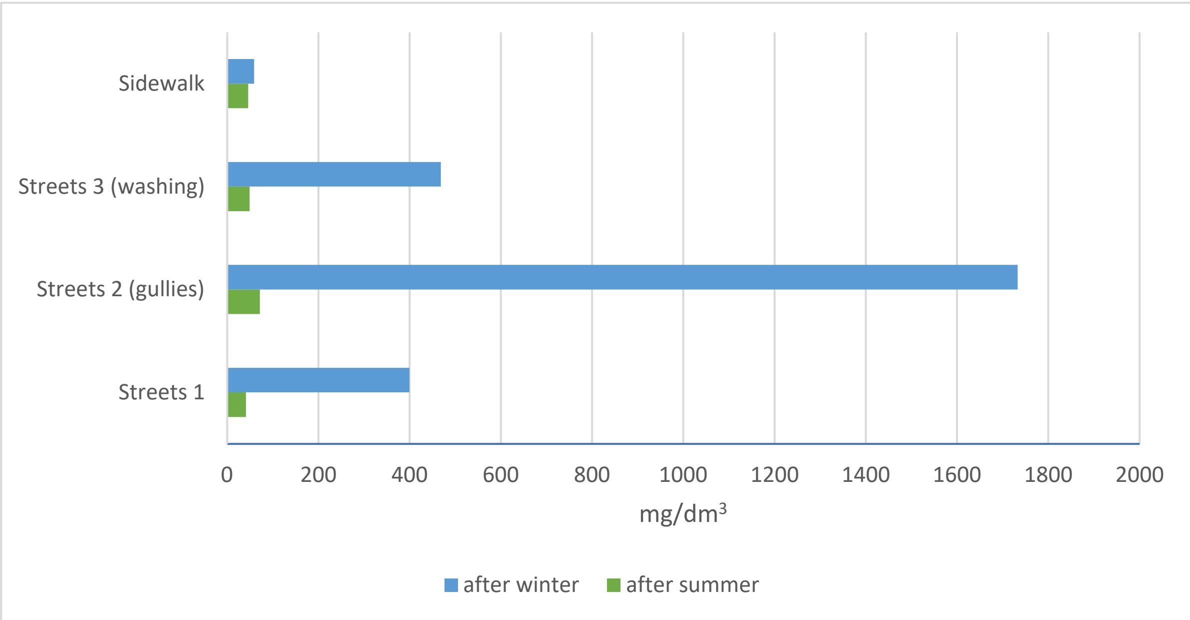

Figure 3. Comparison of chloride content (mg/dm^3) on select streets in cleaning sweepings collected after summer and winter (average values).

The study showed significant differences in the amount of chloride in the "after winter" and "after summer" periods. This is understandable given the nature of the periods in which the study was conducted. In the samples collected for testing in the "after summer" period, the highest average chloride concentration of about 60 mg/dm^3 was obtained in the Street 2 samples collected from the vicinity of sewer gullies. This was followed by an average concentration of about 44 mg/dm^3 obtained in the Street 3 samples collected from street washing. Similar average concentrations were obtained in the Street 1 samples, approximately 35 mg/dm^3, and in the Sidewalk samples, approximately 36 mg/dm^3.

During the post-winter season, the average chloride concentrations peaked at approximately 1468 mg/dm^3 in the Street 2 samples collected from around sewer gullies. In the Street 3 samples (street washing), the average chloride concentration was approximately 422 mg/dm^3. In the Street 1 samples, the average chloride concentration was approximately 362 mg/dm^3. The lowest chloride concentration from this period was obtained in the Sidewalk samples, about 53 mg/dm^3 on average.

From the results obtained in these two seasons, a correlation in the concentration levels is observed at the respective sampling sites. The highest chloride concentrations are found in samples collected near gullies and the lowest chloride concentrations are found in samples collected from sidewalks.

The low chloride concentrations on the sidewalks are due to a ban on salt gritting the sidewalks. The high concentration of chlorides at sewer gullies is due to runoff into the sewer system and the accumulation of street runoff along with sweepings near the gullies. This high average concentration of chlorides present in street cleaning residues is due to the long, snowy, and cold winter, during which roads were abundantly gritted with sand and salt.

5. Results of Decision Analysis Using Multi-Criteria Analysis

The decision problem was formulated when the evaluation criteria were established and their values were expressed in the form of a finite set of numbers (measurable values), which are the result of evaluating the different variants of the proposed chloride removal system from an urbanized area, against the selected criteria. The presented strategies described by measurable criteria constitute a decision matrix (Table 2).The values of emissions to the environment as a result of the maintenance process in the study area are presented in the columns of Table 2. Among the studied strategies, the following were proposed:

Table 2. Decision matrix for evaluating the adopted scenarios for the system of chloride removal from the environment.

Criteria	Unit	Sweeping	Sweeping + Washing 1 Day	Sweeping + Washing 2 Days	Sweeping + Washing 5 Days
		Scen1	Scen2	Scen3	Scen4
waste amount	kg/km	200	200	250	270
amount of wastewater from street cleaning	l/km	0	25	50	75
reduction in suspended solids on subsequent cleaning days		0	30	45	67
costs	euro/km	3	5	7.5	10
chloride content reduction		0	56	78	90

Scen1—proposing street cleaning only by sweeping followed by 1 week off;

Scen2—proposing street cleaning by sweeping and washing on 1 day followed by 1 week off;

Scen3—proposing street cleaning by sweeping and washing on the following 2 days, followed by 1 week off; and

Scen4—proposing street cleaning by sweeping and washing on the following 5 days, followed by 1 week off.

Among the criteria for evaluating the presented scenarios, the following were suggested:

1. Amount of waste collected cumulatively in consecutive days of cleaning measured in kg/technological km;
2. Amount of wastewater from street cleaning, cumulatively over successive days of street cleaning, measured in l/technological km;
3. Reduction in suspended solids calculated as the result of the difference between the first (on the first day) and the last street washing (on the last day);
4. Costs of each consecutive street cleaning activity, including equipment maintenance costs, water and fuel consumption, employee costs, and environmental emissions fees, that were estimated on the basis of actual measurements; and
5. Reduction in chloride content calculated as the difference in chloride content between the first and last days of cleaning and washing.

The matrix defined in this way became the formulated decision problem to be solved, in which the compromise programming method expressed by formulas (1) and (2) was used. The results and final ordering of the individual maintenance strategies, with a particular emphasis on chloride removal, are presented in Table 3, ranking them from most to least favorable. The ranking depends additionally on the adopted weights of each group of criteria or individual criteria. In Table 3, the first column presents the weights of the criteria proposed by the authors of this research. In most cases, these weights were given to individual criteria described in Table 3. Thus, in the first row of Table 3, all criteria were given a weight of 1, while in the second row, the first criterion was given a weight of 2, while the remaining criteria were given weights of 1. In the last two rows of Table 3, only the criterion assessing the costs of individual solutions received a lower weight than the remaining ones.

Table 3. Multi-criteria analysis results ranking maintenance and chloride removal scenarios.

Validity of the Criteria	Ranking of Scenarios		
	$\alpha = 1$	$\alpha = 2$	$\alpha = \infty$
1:1:1:1:1	Scen2→Scen3→Scen4→Scen1	Scen2→Scen3→Scen4→Scen1	Scen2↔Scen3→Scen1↔Scen4
2:1:1:1:1	Scen3→Scen2→Scen4→Scen1	Scen2→Scen3→Scen4→Scen1	Scen2↔Scen3→Scen1↔Scen4
10:1:1:1:1	Scen4→Scen3→Scen2→Scen1	Scen3→Scen4→Scen2→Scen1	Scen2↔Scen3→Scen1↔Scen4
1:2:1:1:1	Scen2→Scen1→Scen3→Scen4	Scen2→Scen1→Scen3→Scen4	Scen2↔Scen3→Scen1
1:10:1:1:1	Scen1→Scen2→Scen3→Scen4	Scen1→Scen2→Scen3→Scen4	Scen2↔Scen3→Scen1
1:1:2:1:1	Scen4→Scen3→Scen2→Scen1	Scen3→Scen2→Scen4→Scen1	Scen2↔Scen3→Scen4
1:1:10:1:1	Scen4→Scen3→Scen2→Scen1	Scen4→Scen3→Scen2→Scen1	Scen2↔Scen3→Scen4
1:1:1:2:1	Scen2→Scen1→Scen3→Scen4	Scen2→Scen1→Scen3→Scen4	Scen2↔Scen3→Scen1
1:1:1:10:1	Scen1→Scen2→Scen3→Scen4	Scen1→Scen2→Scen3→Scen4	Scen2↔Scen3→Scen1
1:1:1:1:2	Scen3→Scen4→Scen2→Scen1	Scen3→Scen2→Scen4→Scen1	Scen2↔Scen3→Scen4
1:1:1:1:10	Scen4→Scen3→Scen2→Scen1	Scen4→Scen3→Scen2→Scen1	Scen2↔Scen3→Scen4
2:2:2:1:2	Scen4→Scen3→Scen2→Scen1	Scen2→Scen3→Scen4→Scen1	Scen2↔Scen3
10:10:10:1:10	Scen4→Scen3→Scen2→Scen1	Scen3→Scen2→Scen4→Scen1	Scen2↔Scen3

Summarizing the results of the analysis, the following should be noted:

- It is possible to select a cleaning scenario for a selected area using a decision analysis, proposing environmental and economic criteria for evaluation.
- According to the results of the calculations presented in Table 3, it can be seen that the most frequently selected scenario is Scen2 with sweeping and one-day street washing.
- Scen4, sweeping and washing the street in a 5-day system, is selected as the most advantageous eight times (including two times while the weight of the cost criterion was reduced in relation to environmental criteria), which allows us to conclude that costs should be taken into account and calculated in the selection and analysis of cleaning strategies each time.
- Scen1 (sweeping only) and Scen4 (where the cleaning and washing process is the longest 5-day process) are selected as the least favorable in a significant number of cases; therefore, it can be said that, by balancing the economic and ecological effects, a scenario that allows for an observance of the principles of sustainable development is selected.
- This method gives the possibility of additional weighting of the criteria by using the α exponent in formula (2). This exponent allows for additional weighting of each deviation from the ideal point in proportion to their value. The larger the value of α is, the greater the importance of large deviations of the strategy from the ideal point. For $\alpha = \infty$, scenario 2 is always selected as the most favorable.

6. Conclusions

1. The results of this research carried out in a medium city show how much chloride is present in sweepings. The diversification of sampling locations allowed us to determine where pollutants accumulate. These differences are very significant and amount to almost 1050 mg/dm^3 in the period after winter between the place of sampling near the sewage gully and the roadway. Such a high concentration of chlorides in the sweepings deposited in the landfill in large quantities can cause an increase in the salinity of the landfill leachate, which in turn affects the prolonged decomposition of matter, the formation of biogas, and the possibility of salinization of groundwater and impede biological processes in sewage-treatment plants.
2. The selection of a cleaning strategy with a particular emphasis on chloride reduction in this region is a difficult decision task that must take into account various, often conflicting goals and objectives, and socioeconomic interests. The measuring criteria defined allowed us to establish a quantitative and objectified evaluation of the performance of such a system. The proposed methodology provides the possibility of a quantitative; multifaceted; and at the same time, objectified evaluation of scenario solutions, replacing intuitive evaluations or those requiring expert opinions used so far. In the proposed example, Scen2, which includes sweeping and one-time street cleaning in a 1-day system, was selected as the most beneficial.
3. The proposed methodology allows us to evaluate the system on an ongoing basis in accordance with the requirements of environmental management even if the objective or conditions in the region change.

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