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DIAGNOSIS OF THE PROBLEM SITUATION RELATED TO THE RETENTION OF STORMWATER FROM ROAD SURFACES IN POLAND

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Abstract. This study examines the challenges and potential solutions associated with the retention of stormwater from road surfaces – a critical component of urban infrastructure in the face of climate change. The research highlights that intensified urbanisation and the increasing prevalence of extreme weather events have exacerbated issues related to rapid rainwater runoff, leading to urban flooding and infrastructural degradation. Employing quantitative empirical methods, a survey was conducted among 362 road infrastructure managers in Poland, assessing the technical condition of roads, drainage system performance, and the barriers to adopting modern retention and infiltration solutions. Findings reveal a mixed perception of current drainage performance, with many respondents reporting inadequate solutions that compromise both safety and sustainability. Key barriers include high implementation costs, technical and infrastructural challenges, resistance to change, and limited public awareness. The results underscore the necessity for modern, integrated stormwater management practices that not only protect infrastructure but also enhance urban water balance and sustainability.

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Introduction

The present study provides a detailed analysis of research findings on the retention of stormwater from road surfaces, a key element of urban infrastructure. In the era of climate change – characterised by an increase in the frequency and intensity of extreme weather events such as droughts, sudden downpours, and thaws – this issue assumes particular significance both theoretically and practically. Poland, classified as a water-scarce country, faces a serious challenge in effective water management. According to data from GUS (2023), Poland's average water resources amount to approximately 60 billion m^3, which can drop below 40 billion m^3 during periods of drought.

Thus, diagnosing the issues related to stormwater retention in urban centres is not only justified but essential for ensuring hydrological safety and sustainable water resource management (Barbosa et al., 2012; Webber et al., 2022). Stormwater retention from road surfaces plays a crucial role in preventing urban flooding – a phenomenon that is becoming increasingly common in urban areas. Intense rainfall that quickly flows over the impervious surfaces of roads and streets overloads sewer systems and results in the loss of water that could otherwise be stored and reused. Implementing retention systems on roads not only enables more efficient stormwater management but also contributes to the sustainable development of urban ecosystems (McFarland et al., 2019; Moretti & Loprencipe, 2018).

An important premise for this research is the issue of road traffic safety. Ineffective drainage of stormwater from roads and streets poses a key hazard for road users, including vulnerable groups. As a result, numerous defects may occur, the pavement layers may become less cohesive, and the structural load capacity of the pavement may be significantly reduced. On the one hand, an effective road drainage system is one of the key factors in maintaining pavement construction in good condition (Zofka et. al., 2014), while on the other hand, a malfunctioning drainage system can lead to a reduction in pavement structural health (Maliszewska & Maliszewski, 2024). This factor should also be considered important in any PMS systems (Świtała & Ledwolorz, 2023). Collectively, these factors not only diminish the safety of road and street users but also lead to increased expenses for the maintenance of transportation routes (Suchocka & Siedlecka, 2017). This phenomenon further contributes to road congestion, as exemplified by the recent flooding of the S8 route in Warsaw, which resulted in the paralysis of road traffic throughout the city.

The scientific objective of this study is exploratory in nature, aiming at a detailed examination of the research problem related to the drainage of stormwater from urbanised areas equipped with storm sewers, including roads, manoeuvring areas, parking lots, and pedestrian pathways. To determine the specific expectations and essential functional features of the solutions used thus far, direct surveys were conducted among local government units.

1. Theoretical framework

Intensive urbanisation significantly increases areas with impermeable surfaces such as roads, parking lots, and buildings, greatly limiting the natural infiltration of water into the ground and disrupting the local water balance (Hlushchenko et al., 2022). Impervious surfaces like classic asphalt pavements or cement concrete pavements generate a high level of surface runoff, which not only increases the risk of local flooding but also induces a heavy load on stormwater drainage systems, especially during intense rainfall (Zubala, 2024).

This problem is particularly evident in the centres of large Polish cities, where rainwater and meltwater often flow into combined sewer systems, turning into municipal wastewater. According to the Polish Water Law (Journal of Laws 2020, item 310, as amended), this wastewater should be treated before discharge, which entails the need to incur appropriate fees. However, the increasing imperviousness of urban surfaces and the intensification of climatic phenomena, such as heavy downpours, mean that the capacity of sewer systems is increasingly exceeded. Consequently, overflows, activation of storm overflows, and discharges of untreated water into receiving bodies occur, violating national legal regulations and increasing the risk of surface water contamination (NCBR, 2024). At the same time, the excess surface runoff and rapid drainage of rainwater prevent its infiltration, leading to a decrease in groundwater levels and the drying out of urban areas. This disrupts the natural balance of the water cycle in the environment, intensifying problems related to urbanisation and climate change (Siedlecka & Suchocka, 2017).

In the context of road infrastructure, according to the Polish Ministry of Infrastructure recommended guidelines WR-D-71-2 (Bała-Żółtowska et al., 2023), water running off from road surfaces and other parts of the road is collected using distributed infiltration devices or devices that collect water along the road, such as inlets, swales, or ditches. Solutions that support local retention and control of surface runoff are crucial, as they can minimise the negative effects of intensive urbanisation and climate change. Modern approaches in this field primarily include the use of permeable pavements, drainage systems, and retention infrastructure integrated with roads.

Numerous studies confirm that proper management of stormwater from road surfaces, utilising modern technologies, can significantly reduce both surface runoff and its negative impact on the environment (Li, 2015; McFarland et al., 2019; Hoang & Fenner, 2016).

Sartipi and Sartipi (2019) conducted research on the use of permeable concrete, demonstrating that it increased local retention, reduced surface runoff, and allowed for the integration of vegetation with road infrastructure. Similar findings were presented by Admute et al. (2017), who indicated the high efficiency of permeable pavements in reducing surface runoff and pollutants. According to the authors, these systems show potential for use on high-traffic roads due to their increased durability and retention capacity. On the other hand, the issue with permeable pavement maintenance arises in cold climate zones (Suchocka & Magdziak, 2018).

Bassani et al. (2017) analysed the effectiveness of biofilters and retention systems integrated with road surfaces, highlighting their ability to reduce pollutants and mitigate the urban heat island effect. Lin et al. (2021) further demonstrated that permeable pavements can retain up to 77.5% of rainwater, effectively reducing surface runoff.

In turn, Hale et al. (2015) examined the impact of stormwater infrastructure on controlling runoff and the export of dissolved materials from urban areas, pointing to the need for implementing retention systems on roads.

As Januchta-Szostak (2012) emphasises that urban flooding can be prevented through the retention and treatment of water in the landscape, the renaturation of watercourses, and the multifunctional management of stormwater. These actions not only improve the microclimate and the availability of water resources but also harness the cultural potential of water, enhancing residents' quality of life and the attractiveness of the urban landscape.

2. Research methodology

The research was based on quantitative empirical research, which enabled an in-depth analysis of the research issues with an applied focus. The study activities followed a predetermined sequence and were carried out using quantitative research methods and tools, including statistical data analysis techniques.

Primary research was conducted in the form of a survey using the Computer-Assisted Web Interviewing technique (CAWI) on a purposive sample of 362 road infrastructure managers located in Poland. The CAWI method was chosen because it enabled respondents from different regions to participate remotely, ensuring broader geographic coverage and reducing the costs and time associated with data collection. This approach also allowed respondents to complete the questionnaire at convenient time, which increased the likelihood of obtaining complete and reliable responses.

Two types of scales were used to measure respondents' opinions: binary nominal scales with "yes/no" responses and seven-point ordinal scales based on a single-choice response menu.

The research procedure consisted of the following steps: [1] preparation of the questionnaire and conducting a pilot study, [2] verification of the questionnaire based on the analysis of the pilot study results, [3] implementation of the main survey through the distribution of the questionnaire to the sample, [4] coding of respondents' answers to obtain data for statistical analysis, [5] statistical data analysis, and [6] development of the study results.

The study employed descriptive statistics, cross-tabulations, the Kruskal-Wallis test, and correlation analyses. Descriptive measures and cross-tabulations identified overall patterns and group differences, while the Kruskal-Wallis test assessed statistical significance for ordinal data. Correlation analyses were applied to examine the relationships between reported drainage problems and the perceived importance of specific barriers. This combination of methods ensured both a broad overview and a deeper understanding of interdependencies in the dataset.

3. Findings

3.1. Characteristics of the research sample

The research sample consisted of 362 representatives from various categories of road managers. Most respondents – over 60% – represented Municipal Road Managers. County Road Managers accounted for 16% of the participants, while Road Managers in cities with county rights comprised 6.7%. National Road Managers, including those responsible for high-speed roads (expressways and highways), were represented by 19 provincial road authorities, constituting slightly over 5% of the sample. Provincial Road Managers accounted for 3.4%, meaning that 12 respondents completed the questionnaire in that category. The study also included representatives of Internal Road Managers (0.6%) and Road Managers of Expressways and Highways operating on a concession basis (0.3%). In 24 cases, respondents preferred not to disclose their organisational affiliation, choosing the "other entity" option, which constituted 6.7% of the research sample.

The respondents were primarily senior and mid-level managers, including road inspectors and department heads, who comprised most of the sample. Other participants held positions such as road specialist, deputy inspector, chief, senior specialist, deputy head, director and mayor. It is worth noting that 22 respondents did not answer the question regarding the position of the person completing the questionnaire, representing slightly over 6% of all study participants.

In the analysis, respondents were classified into four occupational groups. Managerial and executive positions (32.0%) included directors, department heads, and other senior staff responsible for decision-making, supervision, and organisational leadership. Specialist positions (13.0%) comprised professionals with advanced expertise, providing technical knowledge, analyses, and expert opinions without direct managerial responsibilities. Control and operational positions (45.9%) encompassed inspectors, deputy inspectors, and administrative staff, whose primary tasks involved monitoring compliance, operational oversight, and day-to-day implementation of procedures. Auxiliary and junior positions (3.0%) included referents, junior clerks, and support staff performing preparatory, administrative, or assisting tasks under senior supervision. Participants with missing data on occupational position (6.1%) were considered in the overall results but not in the between-group analyses.

Table 1 presents the research findings on the length of the road network managed by the respondents. The data indicate that the participants manage a total network length of 86 465 km. According to GUS (2024) data on transportation, this length constitutes about 20% of the national road network, which in 2023 was 428 362.2 km. These results underscore the significant role the surveyed road managers play in maintaining the national road infrastructure, particularly regarding its importance for the economy and transportation mobility.

Table 1. Road network managed by the respondents

No.	Category	Mean, km	Standard Deviation, km	Median, km	Total, km
1.	County Road Manager	382.81	211.99	331.00	21 820
2.	Provincial Road Manager	1250.33	932.59	1224.00	15 004
3.	Road Manager in Cities with County Rights	460.04	650.50	254.00	11 041
4.	National Road Manager	446.43	416.57	210.00	6250
5.	Municipal Road Manager	136.06	148.85	101.00	28 708
6.	Internal Road Manager	140.50	43.13	140.50	281
7.	Road Manager of Expressways and Highways (concession)	200.00	–	200.00	200
8.	Other	166.37	291.91	80.00	3161
9.	Overall	254.31	375.37	149.00	86 465

Table 2 presents the research results regarding the assessment of the technical condition of road surfaces, taking into account the type of road manager as a grouping variable. The analysis was conducted in accordance with the guidelines of the pavement condition assessment system developed by GDDKiA and Statistics Poland, GUS (2024). Overall, the condition of the public road network showed considerable variability, with a predominance of ratings A and B, which indicated the desired level of technical condition. However, nearly 34% of the examined road network was classified as C or D, corresponding to warning and critical levels, respectively. This result indicates the need for urgent repair actions to ensure the safety of road users and improve the functionality of the roads.

Table 2. Assessment of the technical condition of the managed road network, %

Category		Class A (good condition)	Class B (satisfactory condition)	Class C (unsatisfactory condition)	Class D (poor condition)
County Road Manager	Mean	30.06	29.51	25.25	13.24
	SD	18.62	11.14	13.85	10.65
Provincial Road Manager	Mean	42.96	24.22	22.26	10.56
	SD	16.53	9.23	13,57	7.95
Road Manager in Cities with County Rights	Mean	30.12	28.64	21.51	16.26
	SD	17.06	12.99	9.96	10.84
National Road Manager	Mean	33.44	30.35	24.25	10.06
	SD	24.86	15.79	18.52	9.15
Municipal Road Manager	Mean	39.09	27.78	20.30	12.64
	SD	22.98	14.91	12.97	11.93
Overall	Mean	37.04	27.95	21.11	12.79
	SD	22.44	14.12	13.33	11.87

3.2. Stormwater and meltwater drainage from road surfaces

Figure 1 presents the research results determining whether there are issues with stormwater and meltwater drainage in the road network managed by the respondents, as well as their impact on road infrastructure. The data are presented as mean ratings with 95% confidence intervals. Respondents evaluated the issues using a 7-point scale, where a rating of 1 indicated a strongly negative response ("definitely not") and a rating of 7 indicated a strongly positive response ("definitely yes"). For the first question, the mean rating of 4.37 is above the midpoint of the scale (4), indicating that respondents generally tend to affirm that there are issues with stormwater and meltwater drainage in the road network they manage. The response distribution is as follows:

- 47.4% of respondents provided affirmative responses (ratings above 4), meaning that nearly half of the participants perceived such problems in their road network;
- 19.4% of respondents chose neutral responses (a rating of 4), which might indicate either a lack of a clear opinion on the subject or varied experiences depending on local conditions;
- 33.2% denied the existence of these problems (ratings below 4), suggesting that, for this segment of managers, the drainage systems functioned relatively well.

For the second question, the mean rating of 3.90 is slightly below the midpoint (4), suggesting that respondents more frequently gave neutral or negative responses. Compared to the first question, there is a more apparent tendency to indicate that issues with stormwater and meltwater drainage do not always lead to serious consequences such as flooding or submergence of road infrastructure. The response distribution for this question is as follows:

- 46.5% of respondents gave negative responses (ratings below 4), indicating a lack of serious consequences for the proper functioning of road infrastructure;
- 14.2% chose neutral responses (a rating of 4), which might reflect a lack of a clear opinion or a moderate impact of the issues;
- 39.2% confirmed that drainage problems led to flooding and submergence.

Overall, the findings highlight a mixed perception among respondents regarding the impact of drainage issues. A significant portion acknowledges the existence of problems, while others consider the consequences to be less severe.

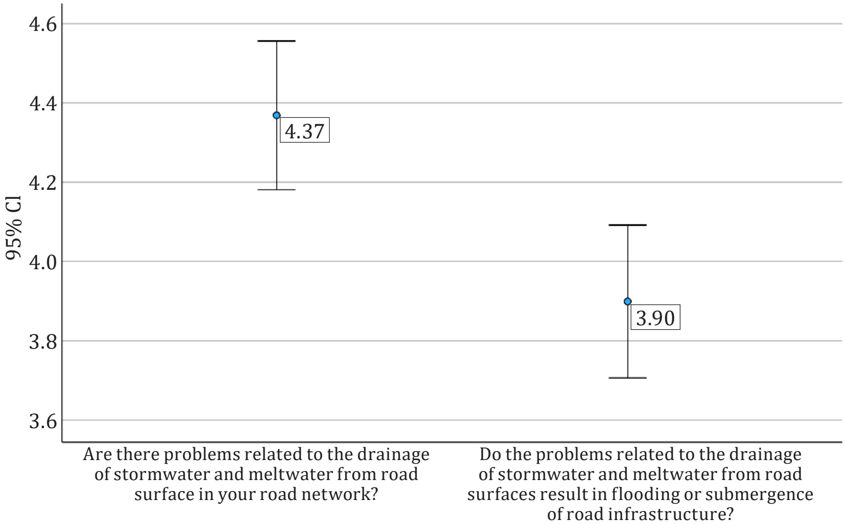

Figure 1. Respondents' opinions on stormwater drainage issues from road surfaces

Managers who most frequently reported flooding and submergence of road infrastructure were Municipal Road Managers (59.7%). The problem was reported to a lesser extent by County Road Managers (22.3%) and was least frequently reported by Provincial Road Managers (2.9%). These findings suggest that flooding and submergence are perceived as most acute at the municipal level, where drainage systems are often under greater pressure from local stormwater flows. At the same time, analyses based on the occupational typology revealed no statistically significant differences between groups ($p > 0.05$). However, certain tendencies could be observed: managerial respondents tended to be more critical, specialists were somewhat more favourable, and control/operational staff – more frequently neutral in their evaluations. Taken together, these results suggest that while concerns over drainage problems are broadly shared across occupational groups, they are voiced most strongly by managers responsible for road networks at the municipal level.

In the next part of the study, respondents were asked to indicate the frequency with which selected elements of road infrastructure become flooded or submerged. These results enabled the identification of the most vulnerable infrastructure elements and the determination of the scale of the problem depending on the type of object. Respondents rated the frequency of these events on a 7-point scale, where 1 meant "very rarely" and 7 meant "very frequently".

According to the data presented in Table 3, the mean ratings for most of the examined elements (i.e., underground passages, tunnels, bridges, viaducts, overpasses, and ramps) were between 1 and 2, indicating that flooding of these objects occurred very rarely or sporadically. Even for more vulnerable elements, such as intersections, roundabouts (mean 2.38), and parking lots (mean 2.25), the results indicate a relatively rare occurrence of the analysed problems.

The highest frequency of flooding was recorded for roads and sidewalks, where the mean rating was 3.24. This indicates a moderate frequency of the problem, though the result still falls closer to the lower end of the scale (1–3). This suggests that although flooding of roads and sidewalks is more noticeable than for other objects, the majority of respondents still perceive these events as relatively rare. The response distribution for roads and sidewalks is as follows: 60.1% of respondents indicated that flooding of these objects occurred rarely; 13.1% provided a neutral response; 26.6% rated that flooding of roads and sidewalks occurred frequently.

Table 3. Frequency of flooding of road infrastructure elements according to respondents' opinions

No.	Category	Mean	Standard Deviation
1.	Underground passages and tunnels	1.67	1.30
2.	Bridges and viaducts	1.65	1.23
3.	Roads and sidewalks	3.24	1.72
4.	Intersections and roundabouts	2.38	1.58
5.	Parking lots and parking areas	2.25	1.49
6.	Overpasses and ramps	1.26	0.80

Figure 2 illustrates the percentage distribution of respondents' answers regarding the level of exposure of the managed road infrastructure to flooding and submergence due to issues with stormwater and meltwater drainage. As can be observed, as the percentage of exposed infrastructure increases, the number of respondents indicating that level of risk decreases. The highest proportion of responses falls within the 1% to 5% category, indicating a relatively low risk of flooding for the majority of the managed infrastructure. As the percentage of exposed infrastructure increases (above 20%), the number of respondents drops significantly, suggesting that situations in which a larger portion of the infrastructure is exposed to flooding are less common.

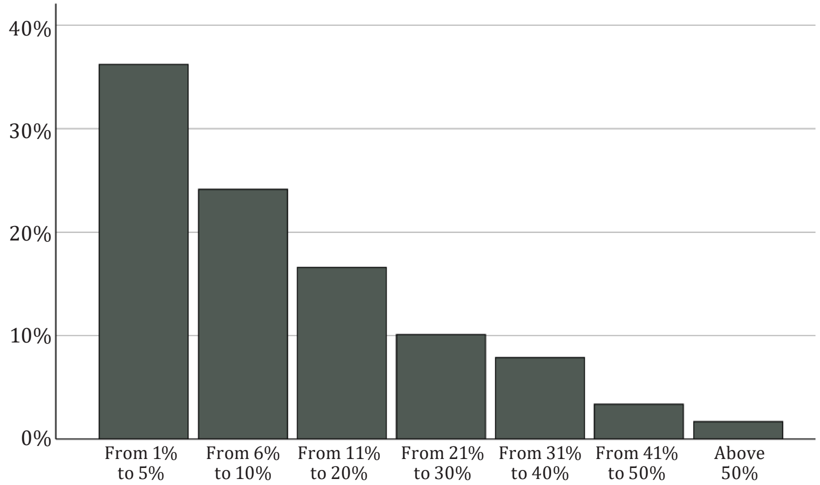

Figure 2. Percentage distribution of road infrastructure at risk of flooding and submergence according to respondents' assessments

It is important to note that even relatively short segments of flooded roads can significantly affect the functioning of the entire road network. Flooding can cause traffic delays, increase the risk of accidents, and generate additional costs related to infrastructure repair and the maintenance of road passability. In extreme cases, it may also lead to the temporary closure of strategic road segments, which is particularly disruptive in areas with limited alternative routes.

On the other hand, it is especially concerning when a large portion of the road network becomes flooded. Although respondents report these cases less frequently, they can lead to serious disruptions in transportation, including reduced road accessibility, delays in the transport of goods and passengers, and an increased risk of accidents. Moreover, widespread flooding can rapidly deteriorate the technical condition of road surfaces, resulting in high repair and maintenance costs.

Municipal Road Managers most frequently reported the occurrence of flooding and submergence affecting at least 30% of the road network (78.3%). This problem was less prevalent among County Road Managers (13%) and was reported least often by Provincial and National Road Managers (2.2%).

3.3. Assessment of the performance of the stormwater drainage system from road surfaces

Figure 3 illustrates respondents' evaluations of the performance of the stormwater drainage system in various aspects: overall performance, minimisation of flood risk, maximisation of water retention, and improvement of water quality.

The ratings are presented along with 95% confidence intervals. Respondents assessed the current performance of the system on a 7-point scale, where 1 meant "very poorly" and 7 meant "very well."

As can be observed, in every case, respondents more frequently gave negative or neutral ratings, which suggested a general dissatisfaction with the effectiveness of stormwater drainage systems. The most favourable ratings were given for the overall performance of the stormwater drainage system from road surfaces, with a mean rating hovering around the midpoint of the scale (4) and 29% of respondents expressing a positive opinion. A similar rating was observed for the system's performance in minimising flood risk, where the mean rating was 3.94 and over 30% of respondents rated this aspect positively.

In contrast, the performance ratings for maximisation of water retention and improvement of water quality were much lower. This may indicate that stormwater drainage systems are perceived as relatively ineffective in achieving these ecological objectives. Overall, the results suggest that while the general performance of the systems is evaluated as relatively neutral, their effectiveness in meeting ecological goals, such as water retention and improving water quality, remains a significant area in need of improvement.

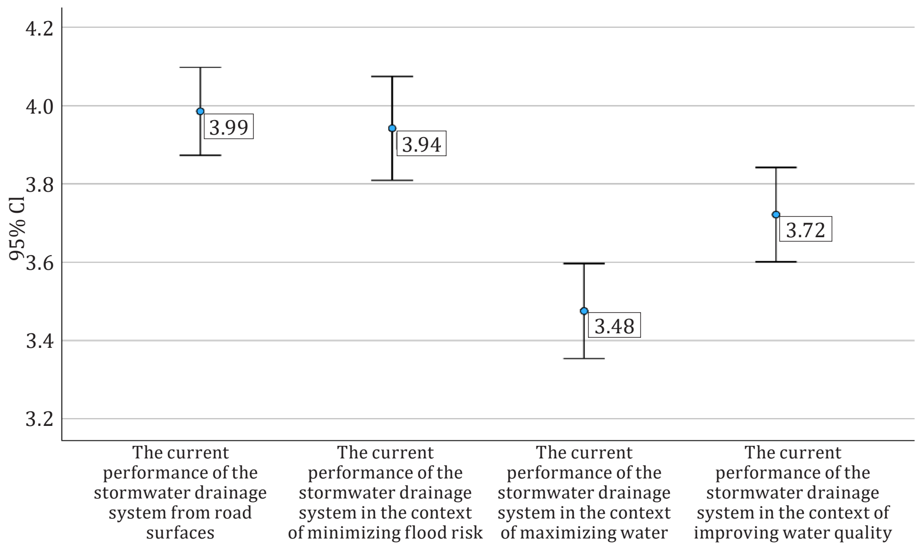

Figure 3. Current performance of the stormwater drainage system from road surfaces according to respondents' opinions

To examine potential differences across occupational groups, Kruskal-Wallis tests were conducted using the typology of respondents' positions as the grouping variable. The analyses revealed no statistically significant differences between groups in any evaluated aspects (all $p > 0.05$). The result closest to significance was observed for the assessment of water quality improvement ($H = 6.704$, $p = 0.082$), which may suggest a tendency toward divergent views among occupational categories. Cross-tabulations indicated that managerial respondents tended to be more critical, specialists somewhat more favourable, and control/operational staff more frequently neutral in their evaluations. Nevertheless, the overall pattern suggests that perceptions of stormwater drainage performance are largely consistent across respondent groups, with dissatisfaction most pronounced in relation to ecological objectives.

3.4. Overcoming barriers to changing the way stormwater and meltwater drainage from road surfaces

One of the key challenges in changing the philosophy of managing the drainage of stormwater and meltwater from road surfaces is shifting from the traditional "collect and drain" concept to a modern approach based on retention, infiltration, and in situ water management. The traditional model, which focuses on quickly channelling stormwater into sewer systems or natural receivers, primarily aims to minimise the risk of flooding and submergence – often at the expense of a valuable resource, water. Transitioning to retention and infiltration systems requires significant modifications to the existing infrastructure. It is necessary to design and construct new elements, such as retention basins, permeable pavements, infiltration swales, and other infiltration systems. This new approach also demands a redefinition of stormwater management goals, which should encompass not only protecting infrastructure from flooding but also sustainable water management, such as increasing water retention at the point of precipitation and improving the water balance in urban areas (NCBR, 2024).

In light of the above, this section of the paper presents the research results aimed at identifying the main barriers to changing the way stormwater and meltwater are managed from road surfaces (Table 4). Respondents evaluated seven barriers on a 7-point scale, where 1 indicated the least significant barrier, and 7 – the most significant. Overall, the ratings ranged from 3.92 to 5.78, indicating varied perceptions of the importance of the individual barriers. The results suggest that all the identified barriers play some role in limiting the transition to stormwater management solutions that promote on-site water management. However, some are being considered more significant than others. The standard deviation results indicate a moderate degree of polarisation in the responses.

The most significant deterrent was identified as the high costs of implementing new retention and infiltration solutions, which received an average rating of 5.78. This result is close to the upper end of the scale, reflecting the substantial impact of this factor in limiting the adoption of modern stormwater management systems based on retention and in situ infiltration. This finding applies both to the costs of designing, constructing, and servicing these solutions, which in practice require advanced technologies and specialised materials.

Table 4. Development barriers in managing the drainage of stormwater and meltwater from road surfaces

No.	Category	Mean	Standard Deviation
1.	Lack of knowledge and skills among designers regarding the calculation and design of facilities for stormwater retention and management	4.32	1.43
2.	High costs of implementing new retention and infiltration solutions	5.78	1.14
3.	Resistance to changing existing design methods and habits	4.12	1.51
4.	Insufficient quality of stormwater and meltwater discharged to receiving bodies	3.92	1.43
5.	Lack of appropriate regulations and legal guidelines supporting new approaches to stormwater management	4.60	1.35
6.	Limited public awareness of the benefits resulting from in situ stormwater retention and management	4.68	1.42
7.	Technical and infrastructural issues related to the implementation of new retention systems	5.12	1.24

The second most significant barrier turned out to be technical and infrastructural issues related to the implementation of new retention systems. The mean rating for this factor was 5.12, indicating its significant impact on the investment decisions made by respondents. This result is above the neutral midpoint of the scale, meaning that technical difficulties are perceived as a serious obstacle to the adoption of modern stormwater management solutions. In many cases, it is likely that existing stormwater drainage systems are not adapted to integrate modern retention solutions, and their modernisation would require considerable effort and expense. Moreover, modern retention systems may require more advanced management based on specialised expertise, as well as regular maintenance, which for many road infrastructure managers can be an additional challenge.

The next two factors were rated similarly, namely: limited public awareness of the ecological and economic benefits of in situ stormwater retention and management (4.68) and the lack of appropriate regulations and legal guidelines supporting new approaches to stormwater management (4.60). Both of these factors are well above the midpoint of the scale, indicating their significant, though not critical, inhibitory influence on the adoption of modern drainage practices. It seems that a lack of public knowledge about the benefits may lead to resistance to such changes, especially if their implementation involves temporary difficulties or additional costs. On the other hand, current regulations may be insufficient or imprecise, which could hinder investment decisions and discourage investors due to concerns about legal ambiguities or the absence of proper guidelines. This hypothesis, however, requires further empirical verification.

Slightly less, though still significantly, the change in the approach to managing stormwater and meltwater drainage from road surfaces is hampered by a lack of knowledge and skills among designers in calculating and designing facilities for stormwater retention and management. The mean rating for this barrier is 4.32, indicating a moderate but important role of this factor in hindering the implementation of modern solutions. More than 52% of respondents deemed this barrier significant, which underscored the widespread problem of insufficient competencies among professionals involved in water infrastructure design. This finding suggests that difficulties in designing retention facilities may considerably limit the efficiency of planned systems.

Closely related to this factor is another barrier concerning resistance to change from existing design methods and habits. The mean rating for this variable is 4.13, indicating a moderate significance of this barrier in the process of adopting modern solutions. This result suggests that although some designers and decision-makers are open to innovation, there remains a group that resists new methods. This may result from a preference for using traditional systems, which are well-known and proven, and in their view, minimise the risk of design errors.

The last barrier, with the weakest impact, is the insufficient quality of the stormwater and meltwater discharged to receiving bodies, which received a mean rating of 3.92, placing it below the midpoint of the scale. Although inadequate stormwater quality may contribute to environmental degradation, contamination of receiving bodies, or the need for more frequent cleaning, it is not considered a key factor hindering the adoption of modern stormwater management methods. Perhaps respondents believe that the quality of the discharged water does not pose a significant problem because they consider it sufficiently good in the context of current standards.

A non-parametric analysis of variance using the Kruskal-Wallis test did not reveal significant differences in the respondents' ratings based on the category of road manager. Only in the case of the lack of appropriate regulations and legal guidelines was a result obtained close to the level of statistical significance ($p = 0.081$), which might suggest that the perception of this barrier's importance differed among the various groups of managers. The least convinced regarding the significance of this factor were Municipal Road Managers (53.1%) and Road

Managers in cities with county rights (58.3%), whereas Provincial Road Managers (72.7%) and National Road Managers (82.4%) more frequently recognised its importance.

When the analysis was conducted according to occupational typology, no statistically significant differences were found. However, one barrier: technical and infrastructural issues related to the implementation of new retention systems approached significance (H = 7.646, p = 0.05). This result suggests that some occupational groups may perceive technical constraints differently. Cross-tabulation results support this tendency, showing that specialists most frequently rated these issues as highly significant, whereas control and operational staff more often provided neutral evaluations.

Taken together, these findings indicate that while the overall pattern of responses was broadly consistent across groups, differences tend to emerge both by managerial level and by occupational role, particularly in relation to regulatory and technical barriers.

The analysis indicates significant correlations between the barriers to modern management and the problems with stormwater and meltwater drainage (Table 5). The strongest correlations were observed for the high costs of implementing new retention solutions and for technical and infrastructural issues. This means that the more respondents perceived problems with drainage on their premises, the greater importance they attributed to barriers related to costs and technical difficulties. The research shows that the key obstacles to improving stormwater management are closely linked to the economic and technological aspects of implementing new systems.

Table 5. Correlation matrix between barriers to modern management and the occurrence of stormwater and meltwater drainage problems from road surfaces

No.	Category	Pearson Correlation	Two-tailed Significance
1.	Lack of knowledge and skills among designers regarding the calculation and design of facilities for stormwater retention and management	0.162*	0.03
2.	High costs of implementing new retention and infiltration solutions	0.266**	0.001
3.	Resistance to changing existing design methods and habits	0.108*	0.046
4.	Insufficient quality of stormwater and meltwater discharged to receiving bodies	0.138*	0.011
5.	Lack of appropriate regulations and legal guidelines supporting new approaches to stormwater management	0.151**	0.005
6.	Limited public awareness of the benefits resulting from in situ stormwater retention and management	0.174**	0.001
7.	Technical and infrastructural issues related to the implementation of new retention systems	0.260**	0.001

Conclusions

The research findings underscore the urgent need to monitor and improve stormwater and meltwater drainage systems to minimise their negative impact on road infrastructure. Despite the common occurrence of drainage problems, these issues do not always lead to severe consequences, likely due to regional differences in drainage system quality and management effectiveness. Nevertheless, even sporadic flooding events – particularly on roads and sidewalks – necessitate targeted improvements and the implementation of emergency protocols to mitigate risks.

While overall flooding of the road network appears relatively rare, cases where a significant portion of the network is affected highlight the need for prioritising high-risk areas. Investments in improved drainage infrastructure, enhanced water retention solutions, and the implementation of monitoring and rapid response systems are critical for ensuring transportation continuity and safety.

Moreover, the high costs associated with implementing modern retention and infiltration solutions represent a major barrier. To overcome this issue, it is essential to explore cost-reduction strategies or increased financial support through grants, tax incentives, or co-financing programs. Additionally, increasing designers' competencies in calculating and designing facilities for stormwater retention is crucial. Improved professional skills will not only facilitate the adoption of sustainable water management solutions but also contribute to the long-term efficiency of infrastructure and reduce risks associated with extreme weather events.

Comparative analyses did not reveal statistically significant differences, yet some patterns were visible across road manager categories and occupational groups. Municipal managers more often highlighted the practical consequences of flooding, specialists most frequently rated technical barriers as highly significant, while control and operational staff tended to give more neutral assessments. These observations indicate that both the level of road management and the type of occupational role can influence how challenges in stormwater drainage are viewed, and this should be considered in future studies and policy development.

Overall, the results point to a multifaceted approach, encompassing technological, financial, and educational strategies as key to advancing sustainable stormwater management in urban road networks. Such an integrated perspective ensures that infrastructure upgrades are supported by adequate funding mechanisms and complemented by improved professional expertise and public awareness, creating the conditions for long-term resilience and effectiveness.

The findings of this study are consistent with previous research highlighting the multidimensional barriers to implementing sustainable stormwater management. Similar to our results, international studies emphasise the dominance of economic constraints, with high costs frequently identified as the main obstacle (Landon et al., 2025). Technical and infrastructural challenges are also recognised, as the effectiveness of retention and infiltration systems often depends on local soil and catchment conditions (Hanley et al., 2024). Furthermore, insufficient regulations and limited public awareness have been shown to hinder the broader adoption of sustainable drainage solutions (Kwarciak-Kozłowska & Madełka, 2025). These parallels suggest that the barriers identified in Poland mirror international experience, reinforcing the need for integrated financial, technical, and institutional strategies.

Future research should investigate the long-term effectiveness of retention and infiltration systems, particularly their role in improving water quality, including pollutant removal, and climate change adaptation, as well as their potential for retrofitting existing infrastructure. Further work is also needed on the institutional, social, and economic dimensions, including public acceptance, regulatory frameworks, and cost-benefit analyses of financing models. In addition, studies should focus on developing new methods and tools for monitoring and assessing water management processes and strengthening integrated water resource management through water balance approaches and adaptive strategies. Pilot implementations of innovative retention and infiltration solutions under local conditions are also recommended to validate their practical applicability and provide evidence for scaling up. Finally, cross-country comparative research should be undertaken to capture regional variations in stormwater management practices and to support the transfer of best practices across different contexts.

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