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The impact of physical-geographical conditions on the sizing of rain gardens: A spatial case of Poland

Anita Białek[1*], Grzegorz Łagód[2]

[1] Faculty of Environmental Engineering, Geomatics and Renewable Energy, Kielce University of Technology, 25-314 Kielce, Poland
[2] Faculty of Environmental Engineering, Faculty of Environmental Engineering, Lublin University of Technology, 20-618 Lublin, Poland
* Corresponding author's e-mail: anita_bialek@interia.eu

ABSTRACT

Rain gardens are playing an increasingly significant role in the adaptation of urban areas to climate change, particularly in light of the growing frequency and intensity of rainfall events. The objective of this study was to assess the influence of physical and geographical conditions on the design, sizing, and effectiveness of rain gardens in Poland, with a particular focus on runoff control and regulation in the context of climate change adaptation. A computational tool was developed, integrating the kinematic wave equation with dynamic flow control algorithms, to support the modelling and optimization of infiltration systems. Analysis of meteorological data from 29 stations (covering 37 to 44 years of observations), along with soil infiltration characteristics, revealed a strong correlation between catchment imperviousness and the required infiltration trench capacity as well as the volume of controlled runoff. The highest storage capacity requirements were observed in Mikołajki (52.6–352.8 m^3), while the lowest were observed in Elbląg (28.7–187.1 m^3). The maximum controlled runoff volumes occurred in Katowice (91.4–213.7 m^3) and Mikołajki (56.2–260.8 m^3), while the lowest were recorded in Świnoujście (18.4–126.2 m^3), Leszno (19.6–87.9 m^3), and Poznań (32.7–84.9 m^3). The developed tool offers substantial support for enhancing the resilience of urban retention systems, highlights the importance of implementing advanced stormwater management strategies under changing climatic conditions.

Keywords: water retention, urban catchments, computational tool, rain gardens, runoff control.

INTRODUCTION

Ongoing urbanization of catchments and climate change are leading to increased rainfall intensity, resulting in greater runoff volumes, more frequent overflow events, and elevated flood risks. These changes directly impact urban quality of life in urban areas by increasing the likelihood of flooding and overloading existing sewer infrastructure (Shuster et al., 2022; Sakib et al., 2023; Bibi et al., 2023).

Literature data (Li and Babcock, 2020; Zhang et al., 2018) indicate that Nature-Based Solutions (NBS), such as retention basins, infiltration trenches, and rain gardens, effectively reduce and delay stormwater runoff, thereby improving the urban water balance (Bowler et al., 2010; Ferreira et al., 2021). The implementation of these technologies reduces flood risk in urban areas (Rogger et al., 2017), enhances stormwater quality, and supports infiltration processes by removing pollutants such as heavy metals, organic compounds, and suspended solids (Sharma and Malaviya, 2021; Ferreira et al., 2021). Cities like Singapore and Lisbon demonstrate the effectiveness of integrating NBS with traditional water infrastructure (Ramísio et al., 2022; Hasan et al., 2024).

Research shows that infiltration trenches with regulated runoff can reduce peak flow rates by up to 40% in urbanized areas and help limit erosion (Zhang et al., 2018; Dai et al., 2023), while green roofs can retain 50–80% of annual rainfall, depending on climate and system design (Li and Babcock, 2020).

For NBS facilities to effectively reduce pollution and delay stormwater runoff, appropriate modelling is essential. The storm water management model (SWMM) is one of the most commonly used tools for analyzing the hydrological performance of such solutions. However, its implementation requires detailed input data, which in practice can result in data gaps or inaccuracies, potentially affecting the quality of design. In response to these challenges, simplified models have been developed, based on available data, enabling quick estimations of solution effectiveness. Studies (Pons et al., 2023) show that simplified models are particularly effective for smaller catchments.

Rain gardens, as an example of NBS, are gaining increasing recognition in cities worldwide due to their efficiency in stormwater management and their support for sustainable development and climate change adaptation (Li and Babcock, 2020; Shuster et al., 2022). A key aspect of designing such solutions is calculating water runoff to ensure adequate soil moisture for plant growth and effective water retention (Meerow et al., 2017; Zhang et al., 2018). The performance of NBS installations depends on the appropriate selection of vegetation capable of withstanding variable hydrological conditions, particularly during heavy rainfall and prolonged droughts (Palermo et al., 2023; Zhao et al., 2024).

In Poland, despite the growing popularity of rain gardens, there is a lack of systematic analyses incorporating long-term rainfall data and climate change projections. Examples from cities such as Gdańsk, Poznań, Warsaw, and Łódź highlight increasing investments in sustainable infrastructure, yet integration with long-term runoff modelling is often missing (Kucharczyk & Piłat, 2019; Szulczewska et al., 2016). Gdańsk has implemented the SWMM model for flow analysis but did not consider comprehensive long-term rainfall analysis, which could improve project effectiveness over time (Kasprzyk et al., 2022). In Warsaw and Kraków, studies that account for long-term rainfall variability and climate change are still lacking (Jakubowska, 2020; Wolski et al., 2021).

To provide a clearer overview of the advantages and limitations of GI (Green Infrastructure) and modelling tools, particularly in the context of runoff management, a summary of their benefits and challenges is presented in Table 1.

In Poland, there is still a lack of advanced tools for modelling and designing GI systems that would account for long-term rainfall data and regional variability in climatic conditions. Previous studies on the design of retention systems, such as rain gardens or infiltration trenches, often overlook the integration of hydrological and climatic variables, which limits the effectiveness of these solutions. Sustainable stormwater management requires a synergy between NBS technologies and dynamic hydrological models, tailored to the specific environmental conditions of a given area.

In response to this issue, the aim of this study was to analyze the impact of rainfall conditions and physical characteristics of urban catchments on the hydraulic parameters of rain gardens, including both the volume of the infiltration trench and the dynamics of runoff during inter-event periods across Poland. The study was based on meteorological data from 29 rainfall stations, covering a period of 37 to 44 years. The analysis included 26 939 rainfall events, which served as the basis for calculations related to the effectiveness of infiltration systems, enabling a comprehensive assessment of the impact of meteorological variables on the functioning of rain gardens across the country in the context of specific urban catchment characteristics.

METHODOLOGY

Urban development simulations were conducted (Figure 1 a-c), covering the impact of increased impervious surface area on the effectiveness of rain gardens in stormwater retention and infiltration, as well as providing guidelines for optimizing their design and implementation in urban catchments across Poland.

The analysis was conducted using a custom computational application, which enabled: (a) modelling runoff from the catchment based on rainfall data using the kinematic wave equation, (b) calculating the runoff hydrograph, (c) designing the volume of the infiltration trench for the rain garden, and (d) forecasting the required runoff control between rainfall events to maintain the minimum water level in the trench essential for plant growth. Figure 2 presents the dialog window displaying the available functions of the tool.

The tool was developed in C^{++} and implemented in the Qt Creator environment. The application allows for the modelling of retention tanks, infiltration trenches, and infiltration basins, with runoff directed either to the ground

Table 1. Advantages and disadvantages of GI elements and modelling tools in stormwater management

Aspect	Advantages	Disadvantages	Studies
Green infrastructure elements	– Increased retention and infiltration of stormwater. – Support for biodiversity (e.g., green corridors, pollinator habitats). – Reduced flood risk and less load on drainage systems. – Mitigation of urban heat island effect and improved urban aesthetics.	– Require large areas, which can be limiting in densely built-up zones. – High initial construction and maintenance costs. – Dependence on local conditions, which may require adjustments. – Requires major investments in urban spaces, often in existing infrastructure.	Li & Babcock (2014) showed that green roofs can retain 50–80% of annual rainfall depending on climate and design. Example from London and Copenhagen (Van Mechelen et al., 2015) – green roofs supporting bee and butterfly populations. Zhang et al. (2018) – controlled-runoff infiltration trenches reduce peak flow intensity by 40%. Bowler et al. (2010) showed that urban greenery lowers air temperature by 1–3 °C, improving thermal comfort.
Modelling tools	– Accurate analysis of retention, runoff, and water quality (e.g., SWMM, HEC-RAS, InfoWorks ICM). – Optimizes design and forecasts GI system performance under changing conditions.	– Limited data availability; require precise local input data. – Requires complex model calibration, which may be time-consuming.	SWMM model (EPA, 2015) – used for analyzing stormwater drainage systems, including GI. HEC-RAS (Brunner, 2010) – used for flow analysis in sewers and ditches, including GI context.
Need for modeling	– Accurate prediction of GI performance during extreme rainfall events. – Supports investment decisions and local adaptation of systems.	– Expensive implementation; requires access to detailed datasets. – Requires specialist knowledge and modelling expertise.	Hydrus (Šimůnek et al., 2005) – tool for analyzing water and pollutant transport in soils within GI systems. InfoWorks ICM – used to model complex urban water systems.
Runoff control approach	– Better runoff control, flood prevention, and climate change adaptation. – Reduces peak runoff, improving system performance.	– Requires complex flow regulation; expensive and time-intensive to implement. – Risk of malfunction in case of system failure or poor regulation.	Zhang et al. (2018) – controlled-runoff trenches reduce peak flow by 40%. Li & Babcock (2014) – regulated runoff in green roof systems enhances stormwater management.
Inter-event water retention	– Enhances long-term water retention, especially during dry periods. – Increases absorption capacity for later events.	– Excess water retention may cause drainage issues during future events. – Requires continuous monitoring and adaptation to changing hydrological conditions.	Yang et al. (2016) – residual water in infiltration systems improves water availability during dry periods. Caparrós-Martínez et al. (2020) – studied residual water in GI systems and its impact on retention under varying conditions.
Regionalized analyses	– Allows for inclusion of local hydrological and climatic differences. – Supports the development of locally adapted standards.	– Requires extensive data and model calibration; time-consuming and costly. – Difficulties in obtaining accurate regional data may limit result precision.	Zhang et al. (2018) – regional analysis of GI impact on flow in various climates and hydrological conditions. Li & Babcock (2014) – use of regional meteorological data in modelling green roof performance.

or directly to the sewer system. Additionally, a runoff regulation function was incorporated, which is crucial for designing infiltration trenches integrated with vegetation and supporting sustainable stormwater management. The tool facilitated the simulation of long-term rainfall sequences, allowing water systems to adapt to changing climatic conditions and varying rainfall intensities. The algorithm's implementation in the software enabled rapid and accurate hydrological analyses.

Various hydrological modelling tools are widely used to evaluate the performance of rain gardens and green infrastructure in urban environments. Among the most frequently cited are SWMM, MIKE URBAN, HYDRUS-1D, and MUSIC (Shen et al., 2021; Li et al., 2020; Zhang et al., 2022; Šimůnek et al., 2005; Wang et al.,

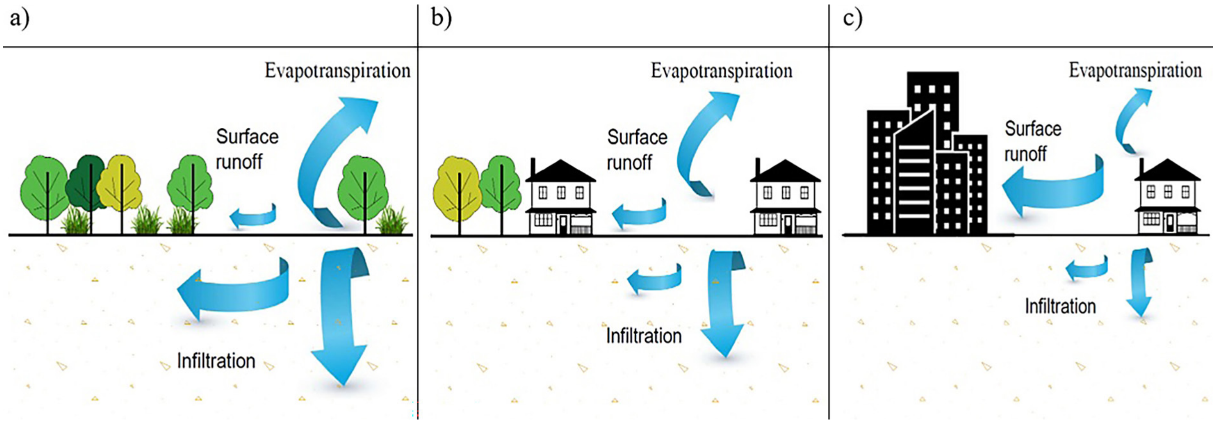

Figure 1. Catchment urbanization scenarios considering three levels of imperviousness: (a) low, (b) medium, and (c) high

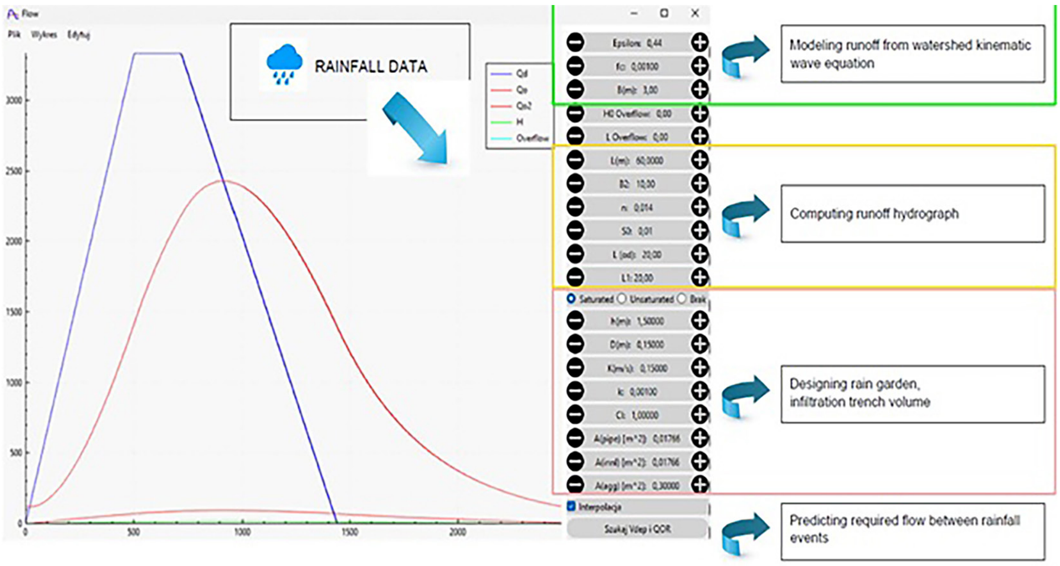

Figure 2. The dialog window displaying the available functions of the tool

2018). These models typically address catchment areas ranging from 0.1 to 2.0 hectares and incorporate parameters such as rainfall intensity, soil permeability, and retention depth. Their complexity spans from advanced simulations integrated with sewer networks and GIS systems (e.g., SWMM) to simplified frameworks designed for conceptual and spatial analysis (e.g., MUSIC). While advanced models demand extensive data inputs and calibration, simplified tools enable quicker assessments with lower data requirements, making them particularly valuable during early planning stages. A summary of the key features of these models is presented in Table 2, providing guidance for practitioners and researchers in selecting the most suitable tool for specific urban hydrology applications.

Rainfall data

The rainfall analysis was based on data from 29 IMGW-PIB stations (Institute of Meteorology and Water Management – National Research Institute) located in various parts of Poland, ensuring their spatial representativeness. The distribution of the stations is shown in Figure 3.

Poland, located in the zone of a temperate warm climate, is characterized by high rainfall variability due to the influence of both maritime and continental climates (Niedźwiedź et al., 2009; Szeląg et al., 2022). The average annual rainfall totals around 600 mm, but these values vary regionally – from 520 mm in the central part of the country to over 1000 mm in the mountains (Szeląg et al. 2024; Bogdanowicz and Stachý,

Table 2. Comparison of selected rain garden models

Model / Tool	Catchment area [ha]	Depth [m]	Key parameters	Advantages	Limitations
SWMM	0.3–2.0	0.6–1.0	Rainfall (IDF), CN, LID, soil permeability, time of concentration	Integration with sewer network, high accuracy	High data requirements, complex calibration
MIKE URBAN	0.5–2.0	0.6–1.2	Rainfall, retention, slope, land use, runoff	GIS integration, high spatial resolution	High complexity, topographic data required
HYDRUS-1D	0.1–0.8	0.5–1.0	Porosity, conductivity, layer structure, physicochemical properties	Accurate representation of infiltration and storage	1D model, no surface runoff or sewer representation
MUSIC	0.1–1.0	0.3–0.9	Delay time, runoff, retention volume, rainfall type, layer configuration	Intuitive GUI, fast scenario analysis	Simplified infiltration scheme, no system dynamics
Proprietary model	approx. 1.0	0.5–0.8	Rainfall, infiltration, geometric dimensions, Q_{max}, V_{max}, Q_{OR}	Few input variables, fast analysis	Simplified hydraulics, no sewer network simulation

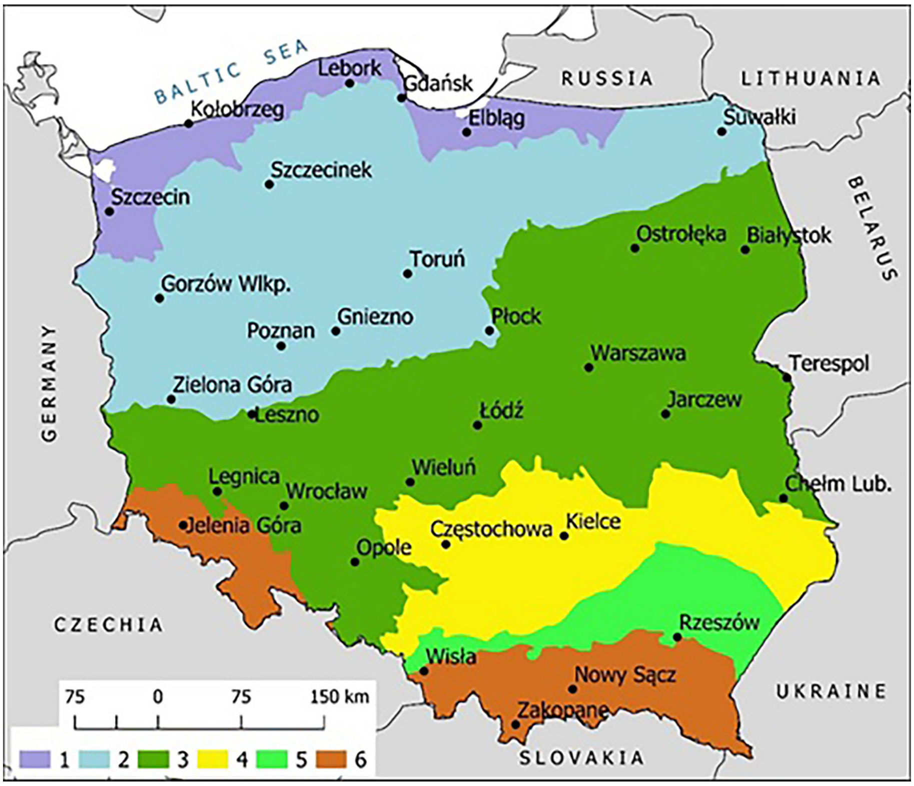

Figure 3. Location of rain gauges against the background of the main physical-geographical regions of Poland (1 – Baltic coastal lowlands, 2 – lakelands, 3 – central lowlands, 4 – uplands, 5 – sub-mountain basins, 6 – mountains); Source: Białek and Musz-Pomorska (2025)

1998). In cities with high urbanization, rainfall is more frequent and intense, mainly due to atmospheric convection, which increases flood risk and requires appropriate drainage system design (Kupczyk and Suligowski, 1997; Łupikasza, 2016). Particularly in mountainous and coastal areas, the highest intensity rainfall is recorded (Szeląg et al., 2022).

The identification of independent rainfall events was carried out according to the DWA – A 118 methodology, based on the analysis of three basic criteria: minimum inter-event time (MIT), minimum rainfall volume, and minimum intensity. According to this method, rainfall events with intensities below 0.5 mm were excluded from the analysis, allowing for more accurate results in the context of hydrological process modelling and runoff assessment in urban catchments. The study included rainfall data from 1961–2005, providing a long-term picture of rainfall variability. The detailed methodology is discussed by Szeląg et al. (2023a). It is also worth noting that, on average, dry periods in Poland last from 5 to 9 days, which is an important factor in assessing rainfall variability in different cities. Furthermore, the average annual rainfall exceeding 5 mm in intensity ranges from 11 to 15 mm, depending on the region, which also affects the hydrological characteristics of individual cities. Detailed results and rainfall data sets used in the calculations are presented in Table S1 (supplementary materials).

Sizing of rain gardens

The application for modelling runoff in infiltration systems supports the design of rain gardens by combining mathematical calculations with hydrological processes (Białek and Musz-Pomorska, 2025). Using Darcy's equation, it analyzes water infiltration into the soil, taking into account soil permeability and moisture content, while surface runoff is modeled using the kinematic wave equation, considering rainfall intensity and terrain shape. The tool allows for the design of rain gardens that effectively manage stormwater in various atmospheric conditions, including during intense rainfall or prolonged droughts.

Modelling runoff using the kinematic wave equation method

The kinematic wave equation, used in modelling surface runoff in infiltration systems, analyzes water flow by accounting for changes in water levels, soil infiltration capacity, and the impact of dry periods on runoff, thereby supporting the assessment of water retention efficiency by vegetation and soil. The kinematic wave Equation 1 can be expressed as follows:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = i - f \tag{1}$$

where: $\frac{\partial q}{\partial x}$ – flow gradient in the spatial direction, $\frac{\partial y}{\partial t}$ – change in water depth over time, i – rate of rainfall, (expressed in mm/hr), f – rate of losses from rainfall.

The surface runoff model for flat-bottom systems is based on the kinematic wave equation, the Darcy–Weisbach equation, and Manning's formula.

A simplified water balance for rain gardens is commonly used to evaluate the performance of green infrastructure (European Commission, 2015; Beven et al., 2012). Bhaskar et al. (2016) also applied this approach in green infrastructure flow analysis to support stormwater system modelling. The water balance equation (2) is expressed as:

$$dV = Q_{outS}(t)dt - Q_{out}(t)dt - \\ - Q_{inf}(t)dt - ET(t)dt \tag{2}$$

where: the input data include: $Q_{outS}(t)$ – inflow of water to the green infrastructure object at time t, (m^3/s), $Q_{out}(t)$ – runoff from the substrate at time t, including the flow to the ground, with overflow occurring if the allowable hydraulic capacity is exceeded, (m^3/s), $Q_{inf}(t)$ – volume of water flowing to the ground per unit time t, (m^3/s), $ET(t)$ – evapotranspiration from the surface layer, (m^3/s).

The computational scheme of the infiltration system is shown in the figure (Figure 4).

The initial form of Equation 2 for the soil, presented as Equation 3:

$$Q_{inf} = f_c \times \left(B \times L + h\,(B + L)\right) \tag{3}$$

$$Q_{outS}(t) - Q_{out}(t) = \varepsilon \cdot B \cdot L \cdot \frac{dh}{dt} \tag{4}$$

The solution of the balance equation for green infrastructure facilities (2) was used for the calculations of the infiltration trench, with appropriate transformations of relationships (5) and (6):

$$Qdmax \times \frac{t}{tp} - f_c \times \left(B \times L + h(B + L)\right) \\ = \varepsilon \times B \times L \times \frac{dh}{dt} \tag{5}$$

$$Qdmax \left(1 + \frac{1}{\lambda} - \frac{t}{\lambda \times tp}\right) - \\ - f_c \times (B \times L + h(B + L)) = \varepsilon \times B \times L \times \frac{dh}{dt} \tag{6}$$

where: Q_{inf} – stormwater infiltration flux into the soil, varying over time t, (m^3/s), f_c – infiltration rate, (mm/hr), B – width of the infiltration trench, (m), L – length of the infiltration trench, (m), h – water depth in the soil, (m), Q_{outS} – inflow rate of stormwater to the trench, variable over time t, (m^3/s), Q_{out} – runoff rate of sewer system, variable over time t, (m^3/s), Q_{dmax} – rainwater infiltration flow into the ground, variable over time t, (m^3/s), ε – porosity coefficient, (-), t – duration of rainfall, (min); t_p – time to reach maximum flow, (min), λ – linear resistance coefficient, (-), dh/dt – change in water depth in the soil over time.

For the saturation zone, the runoff through the drainage pipe is described by the following relationships (7) and (8):

$$Q_{out} = \frac{-\left(\frac{h+D}{L\cdot B\cdot K}\right)+\sqrt{\left(\frac{h+D}{L\cdot W\cdot K}\right)^2+4\cdot N\cdot H}}{2\cdot N} \tag{7}$$

for:

$$N = \frac{f\cdot L}{2\cdot g\cdot A_{pipe}^2\cdot D} + \frac{1}{2\cdot g\cdot A_{pipe}^2} + \frac{C_L}{2\cdot g\cdot A_{pipe}^2\cdot \Theta_{agg}^2} \tag{8}$$

where: H – thickness of the water table in the soil, (m), h – thickness of the soil above the top of the pipe, (m), D – inner diameter of the pipe, (m), L – length of the infiltration trench, (m), K – hydraulic conductivity of soil, (m/s), B – width of the infiltration trench, (m), A_{pipe} – cross-sectional area of the pipe, (m^2), Θ_{agg} – porosity of the soil, (-), C_L – coefficient of local resistances, (-), g – gravitational acceleration, (m/s^2), λ – linear resistance coefficient, (-), calculated using the formula (9):

$$\lambda = \frac{1}{\left(-2\cdot log\left(\frac{k}{3.71\cdot D}\right)\right)^2} \tag{9}$$

where: k – roughness of the conduit, (m), D – inner diameter of the pipe, (m).

Rain garden sizing assumptions

This study utilised independent rainfall events and delineated dry periods to determine:

- Infiltration trench volume (V),
- Runoff from the infiltration trench (Q_{OR}).

The optimal ratio of infiltration trench volume to catchment area is crucial for effective water retention, and its regulation through runoff control plays a key role in this process. An insufficient volume can result in excessive runoff, as noted by Fletcher and Shuster (2013). The analysis also took into account dry periods, which can affect the

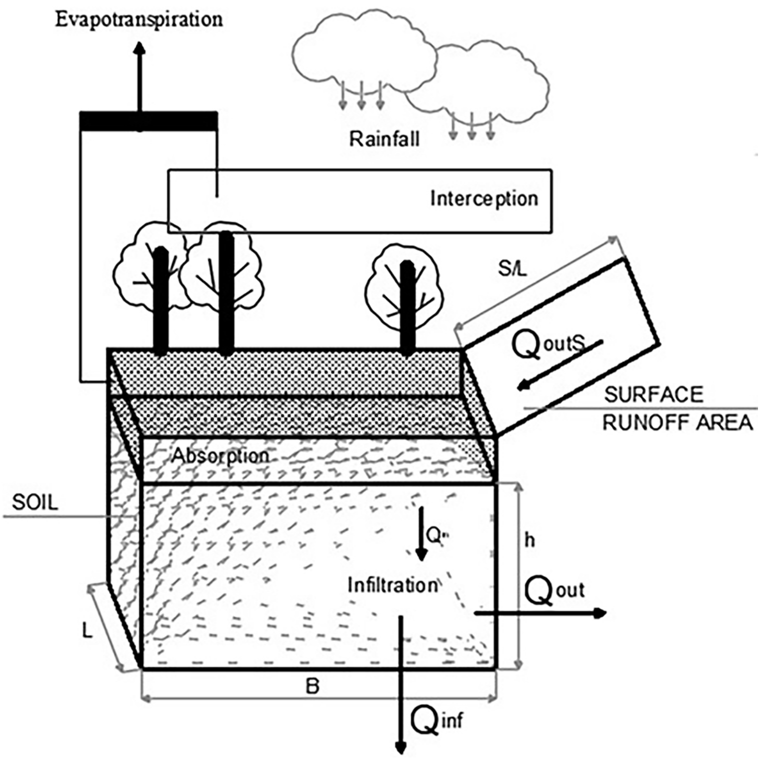

Figure 4. Schematic representation of the infiltration system

efficiency of infiltration systems. Prolonged dry periods may reduce soil infiltration capacity, impacting the ability to maintain adequate moisture levels in rain gardens, especially in the context of changing climatic conditions (Liu and Tan, 2014).

A system depth of 1.5 m and a minimum water level of 0.30 m in the infiltration trench were assumed to ensure constant retention and protect plants from desiccation (Li and Davis, 2009). Calculations encompassed three scenarios with increasing impervious surface areas in the catchment, reflecting urbanisation processes.

Designated rainfall events (Table S1- supplementary materials) were analysed, and the infiltration trench volume was calculated using Equation 11:

$$V = \varepsilon \cdot B \cdot L \cdot h_{max} \tag{10}$$

The application employs a proprietary method that models not only individual values for infiltration trenches concerning independent rainfall events but also accounts for dry periods. Regulated runoff, dependent on the dry period, can be modeled using Equation 12:

$$Q_{OR} = \varepsilon \cdot B \cdot L \cdot h_{max} \cdot t_{bd} \tag{11}$$

where: V – volume of the infiltration trench, (m³); ε – porosity coefficient, (-); B – width of the trench, (m), assumed B = 3 m; L – length of the trench, (m); h_{max} – maximum depth of the trench, (m), assumed h_{max} = 1.5 m; Q_{OR} – runoff from the infiltration trench, (m³/s); t_{bd} – dry period (s), derived from IMGW rainfall data for the period 1961–2005 for various Polish cities (Table S1 – supplementary materials).

Assumptions for calculations

The following input data were used in the application, as shown in Table 3.

RESULTS

Infiltration trenches are increasingly recognized as vital components in modern stormwater management strategies, facilitating the retention and gradual percolation of rainwater into the soil. Their effectiveness is influenced by factors such as soil permeability, rainfall intensity, and the available infiltration area. Proper design of infiltration systems, like rain gardens, is essential for mitigating flood risks and enhancing the hydrological balance in urbanized areas.

Table 3. Assumed input data used for the infiltration trench, catchment, and runoff (Akan and Houghtalen, 2003)

Name	Index	Unit	Value
Infiltration trench			
Rainfall duration	t_d	min	step 5 min
Porosity coefficient	ε	-	0.44
Infiltration rate	fc	m/s	0.001
Width	B	m	3
Length	L	m	to 200
Catchment			
Width of flow path	B	m	10, 40, 100
Length of flow path	L	m	20
Manning's roughness coefficient	n	$m^{-1/3} \cdot s$	0.0015
Hydraulic gradient	S_0	-	0.001
Runoff			
Maximum water depth in the soil	h	m	1.5
Diameter of drainage pipes	D	m	0.15
Hydraulic conductivity of soil	K	m/s	0.15
Cross-sectional area of the pipe	A_{pipe}	m²	0.01766
Porosity of the soil	Θ_{agg}	-	0.3
Coefficient of local resistances	CL	-	1
Roughness of the conduit	k	m	0.001

To investigate potential spatial differentiation in infiltration efficiency, the data were analyzed using k-means clustering – a widely used unsupervised machine learning method that partitions observations into k distinct clusters based on their similarity. The algorithm minimizes variance within clusters while maximizing differences between them, ensuring that data points within a cluster are more similar to each other than to those in other clusters.

In this analysis, the number of clusters (k) was set to two, based on a preliminary spatial assessment. The aim was to distinguish general areas with differing geographic and climatic characteristics that may affect the performance of nature-based stormwater management solutions.

As a result of the analysis, two distinct clusters – CL1 and CL2 – were identified, reflecting key spatial and rainfall-related differences within the study area. Table 4 presents the average values of key variables (latitude, longitude, and annual rainfall) for each cluster, along with variability indicators such as variances and quantiles at three thresholds (10, 40, and 100), illustrating the internal diversity of each group.

The analysis revealed that Cluster CL1, located in the southeastern region (Lat = 51.92; Long = 20.29), experiences higher mean annual rainfall (592.09 mm) compared to Cluster CL2 (Lat = 52.14; Long = 17.08; Rainfall = 585.00 mm). Furthermore, CL1 consistently shows higher values of both variances and quantiles, suggesting greater internal variability within this group. In contrast, CL2 exhibits lower variability and a more homogeneous distribution of parameters.

This pattern of regional differentiation aligns with the approach described by Szeląg et al. (2023b), which underscores the value of identifying spatial and statistical variability as a foundation for further modelling and classification. Although the inter-cluster differences are moderate, they are systematic and substantiate the presence of meaningful regionalization. To further validate the segmentation, advanced cluster quality assessments such as silhouette analysis or ANOVA (Analysis of Variance) are recommended, in line with established practices in environmental data analysis and spatial hydrological modelling.

Complementing the clustering results, a correlation analysis was conducted to assess the relationships between geographic variables and hydraulic performance metrics. The outcomes, summarized in Figure 5, confirm statistically significant correlations – particularly between longitude and key hydraulic indicators.

For example, longitude demonstrated a strong positive correlation with retention volume V(40) ($r = 0.524$) and outflow Q(40) ($r = 0.599$). Very high correlations were also observed between retention volumes under different rainfall scenarios, such as V(40) and V(100) ($r = 0.961$), as well as between Q(40) and Q(100) ($r = 0.928$). These findings underscore the potential to estimate infiltration trench dimensions using geographic location and rainfall data, without the need for complex hydraulic modelling.

The use of a standardized 1-hectare catchment area – selected based on the literature (De Paola and De Martino, 2013; De Paola and Ranucci, 2012; Aldrees and Dan'azumi, 2023) as representative of urban micro-catchments in Poland – strengthens the practical relevance of the results for planning green infrastructure in urban environments.

Analysis of infiltration trench volume

The conducted analysis of infiltration trench volumes under various urban catchment sealing scenarios (Figures 6a–c) provides valuable insights into the potential of infiltration systems, including rain gardens, for stormwater management in urbanized areas of Poland.

The results indicate a significant increase in the required volume of infiltration trenches across all six mesoregions, which is a key element in assessing the changing structure of rainfall infiltration on a national scale, considering the ongoing urbanization of urban catchments and the resulting increase in land sealing. In the first sealing scenario (Figure 6a), the volumes of the infiltration trench predominantly ranged from below 36 m³ to

Table 4. Mean parameter values in clusters CL1 and CL2

Parameter	Lat	Long	Rainfall	V(10)	V(40)	V(100)	Q(10)	Q(40)	Q(100)
CL1	51.92121	20.28939	592.0909	10.92833	19.08945	44.46508	2.209315	3.387168	7.621287
CL2	52.13519	17.07593	585.0000	10.34620	17.80728	41.39799	1.876057	2.979982	6.666438

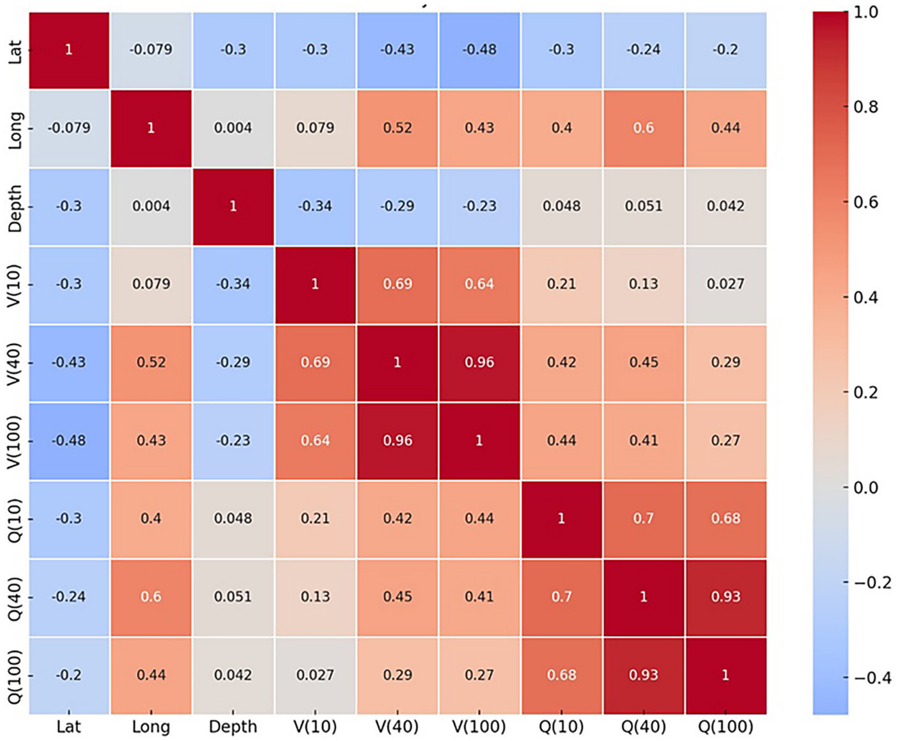

Figure 5. Pearson correlation matrix between geographical, physical, and hydraulic parameters

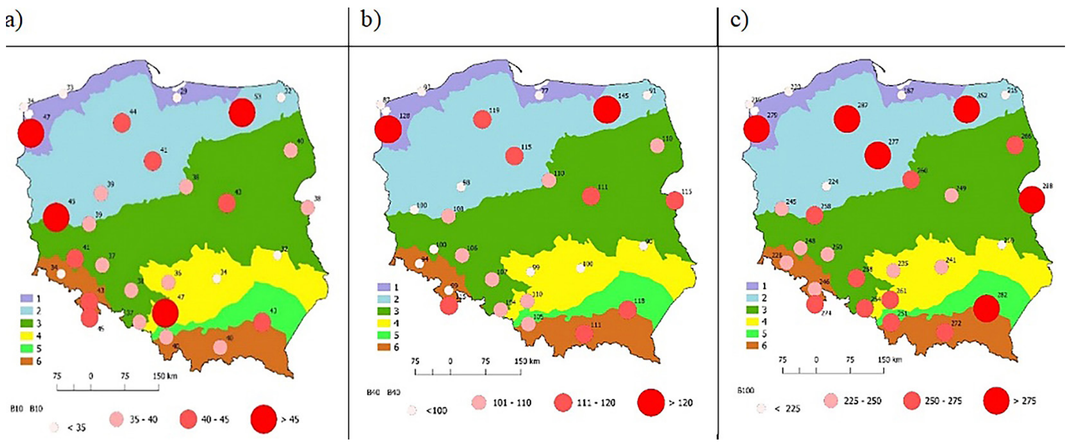

Figure 6. The volume of the infiltration trench, considering varying degrees of urban catchment sealing: (a) low, (b) medium, and (c) high

about 40 m³; in the second scenario (Figure 6b), they oscillated between 101 and 110 m³, while in the third scenario (Figure 6c), the volumes ranged from 250 m³ to approximately 275 m³. The largest trench volumes, regardless of the sealing degree, were recorded in Mikołajki (Mesoregion 2), where the values were 52.6 m³, 145.4 m³, and 352.8 m³, while the smallest volumes occurred in Elbląg (Mesoregion 1), with values of 28.7 m³, 77.4 m³, and 187.1 m³. In the first sealing scenario (Figure 6a), the highest trench volumes were recorded in lowland, lakeland, and upland areas: Mikołajki (52.6 m³), Szczecin (47.2 m³), Katowice (46.9 m³), and Zielona Góra (45.1 m³), while values below 35 m³ were observed in lowland, lakeland, upland, and mountain basin areas – in Elbląg (28.7 m³), Kołobrzeg (33.3 m³), Suwałki (32.0 m³), Lublin (32.3 m³), Kielce (34.3 m³), and Jelenia Góra (33.9 m³).

The analysis of the percentage increase in trench volume in relation to urbanization changes revealed that the highest increase was recorded in Terespol (7.7%), while the lowest was in Zielona Góra (5.4%). In cities with the highest trench volume values, the increases were as follows: Mikołajki (6.7%), Szczecin (5.9%), Katowice (5.6%), and Zielona Góra (5.4%). In cities with lower trench volumes, similar growth rates were observed: Elbląg (6.5%), Kołobrzeg (6.6%), Suwałki (6.7%), Lublin (6.5%), Kielce (7.0%), and Jelenia Góra (6.7%).

The research conducted in the six mesoregions of Poland revealed significant variation in infiltration trench volumes depending on the degree of surface sealing. The largest trench volumes were recorded in Mikołajki (Mesoregion 2), where the values in the three sealing scenarios were 52.6 m^3, 145.4 m^3, and 352.8 m^3, which is consistent with the characteristics of lakeland regions where the presence of numerous water bodies and highly permeable soils promotes infiltration. The smallest volumes occurred in Elbląg (Mesoregion 1) – 28.7 m^3, 77.4 m^3, and 187.1 m^3 – which is related to denser development and poorer conditions for infiltration. In lowland and upland mesoregions such as Szczecin, Katowice, and Zielona Góra, trench volumes were varied and dependent on local topographical conditions and soil types.

In the highest sealing scenario (Figure 6c), trench volumes were characterized by a wider range, with volumes exceeding 275 m^3 in Mesoregions 1, 2, 3, and 5, while in other mesoregions, they oscillated between 225 m^3 and 275 m^3. The division into mesoregions enables a more accurate assessment of the infiltration capacity of individual areas and their demand for infiltration trenches. The results of the analyses suggest that cities with a high degree of sealing require larger trench volumes, while lakeland regions benefit from better natural water retention conditions.

The obtained results confirmed the need to adjust stormwater management strategies in different mesoregions to increase their resilience to extreme weather events in the face of climate change. Similar challenges related to surface sealing are occurring worldwide. For example, in Singapore, as part of the "ABC Waters Programme" (Lim et al., 2016; Yau et al., 2017), green spaces were increased and rain gardens were implemented, enabling effective stormwater management. In New York, the "Green Infrastructure Plan" successfully reduced surface runoff by 1.2 million m^3 per year (Rosenzweig and Fekete, 2018).

The analysis of infiltration trench volumes in different mesoregions of Poland revealed distinct differences in the structure of rainfall infiltration, closely linked to the degree of watershed sealing. In cities with a higher degree of sealing, such as Szczecin, the highest retention capacities were observed, with trench volumes exceeding 45 m^3, 120 m^3, and 275 m^3 in three different sealing scenarios. Climate change may affect the water retention capacity in different mesoregions, with lowland and lakeland areas potentially experiencing periodic flooding due to increased rainfall intensity, while upland and mountain regions may face sudden surface runoff leading to erosion.

Analysis of runoff volume from the infiltration trench in an urban catchment

Changes in land use structure, particularly in urbanized areas, have a key impact on the water balance. Surface sealing, such as covering it with concrete, asphalt, or building roofs, limits the infiltration of rainfall, leading to an increase in surface runoff (Arnold and Gibbons, 1996; Fletcher et al., 2013). This phenomenon is commonly observed worldwide, especially in cities with a high degree of urbanization, such as New York, Tokyo, or Paris.

This study analyzes the impact of surface sealing on surface runoff in Poland, taking into account the diverse physical and geographical conditions of individual mesoregions (Figure 7a-c). The analysis considers three surface sealing scenarios: low, medium, and high.

The results of the analysis indicate significant variability in the size of runoff depending on the degree of sealing and specific geographic conditions. In the first scenario (Figure 7a), characterized by a low degree of sealing, cities with runoff values in the range of 30–40 m^3/d dominate. In the second scenario (Figure 7b), with medium sealing, runoff ranges from 55 to 70 m^3/d, while in the third scenario (Figure 7c), with the highest sealing, runoff values increase to the range of 130–160 m^3/d. Observations show that as the surface sealing increases, the number of cities with higher surface runoff also increases.

The highest runoff values are found in mountainous (Mesoregion 6), upland (Mesoregion 4), and lake regions (Mesoregion 2), where terrain morphology and lithological properties promote intensification of surface runoff. In the analysis of the impact of urban catchment sealing on runoff, cities with the highest runoff values (> 50 m^3/d) at a low degree of sealing (Figure 7a) include

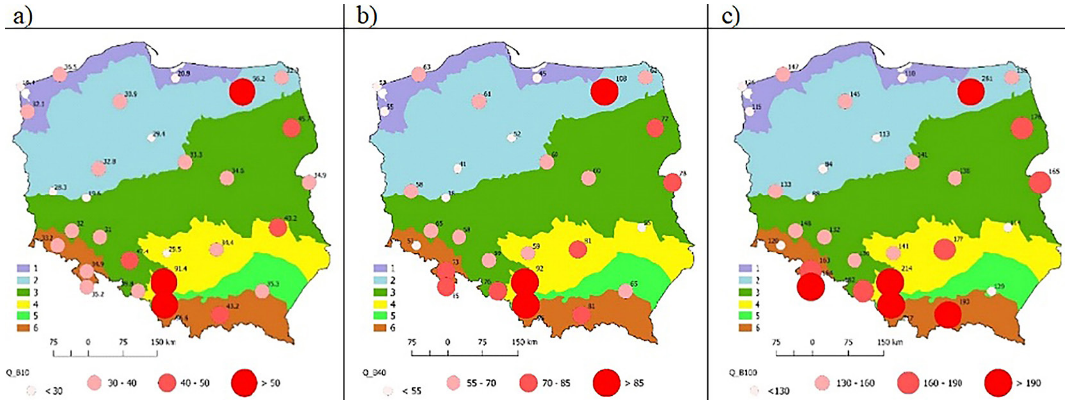

Figure 7. The size of the regulated runoff from the infiltration trench considering the sealing of the urban catchment: a) small, b) medium, c) high

Katowice (Mesoregion 4), Mikołajki (Mesoregion 2), and Bielsko-Biała (Mesoregion 6). In conditions of increased sealing (> 100 m³/d, Figure 7c), this trend remains particularly noticeable in mountainous areas, especially in Bielsko-Biała and Nowy Sącz (Mesoregion 6).

A specific case is Mikołajki (Mesoregion 2), where runoff values remained high regardless of the degree of catchment sealing (Figure 7a – 56.2 m³/d; Figure 7b – 107.5 m³/d; Figure 7c – 260.8 m³/d).

The results of the analysis confirmed the significant variability of runoff depending on the degree of sealing and specific geographic conditions, which is supported by numerous studies conducted worldwide. Research by Booth et al. (2002) in the United States indicates that in cities like New York, Los Angeles, and Chicago, intense surface sealing leads to a significant increase in runoff, resulting in overloaded sewer systems and increased flood risk. In Chicago, the rapid discharge of water into the sewer system limits infiltration, leading to soil moisture deficits and affecting the microclimate (Shuster et al., 2005). In Europe, studies conducted by Salvadore et al. (2015) in London and Paris showed that surface sealing in these cities led to a more than 70% increase in surface runoff compared to natural areas (Zhou et al., 2017; Fletcher et al., 2013). Similar observations were made in Asian cities such as Beijing and Tokyo. As studies by Li et al. (2020) and Endo et al. (2021) indicated, the increase in sealed surfaces in these metropolises leads to a reduction in the concentration time of runoff and an increase in its peak values, which burdens drainage systems and increases the risk of local flooding.

In Poland, particularly in cities such as Warsaw and Kraków, hydrological studies conducted by Szulc and Zelewski (2021) and Banasik et al. (2014) indicate a significant increase in surface runoff, which now exceeds 60% compared to earlier years, mainly due to intensive urbanization and infrastructure development. These changes lead to overloaded sewer systems and an increased flood risk, particularly in areas with higher levels of sealing.

At the international level, solutions based on green infrastructure, such as rain gardens, infiltration systems, and green roofs, show positive effects in reducing surface runoff. Research by van de Meene et al. (2011) in the Netherlands shows that the implementation of such solutions allowed a 30% reduction in runoff, effectively reducing flood risk in cities with high levels of urbanization.

Dependence between catchment sealing, infiltration trench volume, and runoff from the infiltration trench

To investigate the relationship between the degree of catchment sealing and the volume of the infiltration trench (Figure 8a) as well as runoff from the infiltration trench (Fig. 8b) in cities in Poland, the data presented in Figure 8 were analyzed.

The data presented in Figure 8a show clear differences in the impact of surface sealing on the volume of the infiltration trench across various mesoregions of Poland. Particularly in the mesoregion 3 (Terespol) and the mesoregion 4 (Kielce), where sealing has the greatest effect, noticeable changes in the water balance are observed, and an increase in sealing leads to a reduction in the land's ability to infiltrate rainfall.

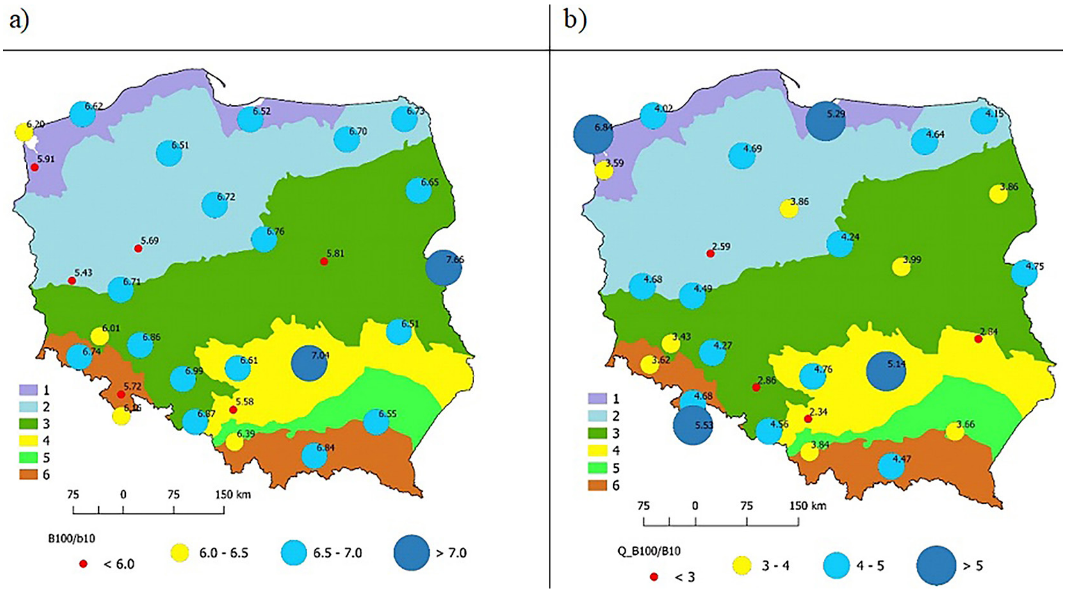

Figure 8. The relationship between catchment sealing and: a) the volume of the infiltration trench; b) runoff from the infiltration trench in cities in Poland

On the other hand, in Poznań (Mesoregion 2) and Katowice (Mesoregion 4), where the impact of sealing on the volume of the infiltration trench is smaller, this may be due to other geographical or hydrological factors, such as soil type, terrain structure, or the presence of retention infrastructure.

The data in Figure 8b show a clear variation in the relationship between catchment sealing and runoff from the infiltration trench in Poland. The greatest impact of sealing on runoff was recorded in the 1st mesoregion, with values of 6.84 in Świnoujście and 5.29 in Elbląg. In lowland regions, sealing significantly contributes to an increase in runoff, due to smaller terrain slopes and more intensive development. In contrast, in Katowice (Mesoregion 4) and Poznań (Mesoregion 2), where runoff relationships are smaller (2.34 and 2.59, respectively), the impact of sealing on surface runoff is less pronounced.

According to global studies, the relationship between catchment sealing and runoff depends on local geographical conditions. In lowland regions, such as Sydney (Australia) or Świnoujście and Elbląg (Poland), surface sealing leads to a significant increase in runoff due to limited infiltration. Increased urbanization in lowland areas leads to a significant rise in stormwater runoff, which is consistent with research in the Netherlands (de Lange et al., 2019), where runoff increased by over 70% due to intensive urbanization. In these regions, other factors, such as terrain structure, the presence of green infrastructure (e.g., rain gardens), or natural water retention, can reduce the impact of sealing on runoff, as confirmed by the findings of Barton et al. (2021) regarding ecological solutions in water management. Studies by Jafari et al. (2020) indicate that in lowland regions of Australia, such as around Sydney, surface sealing leads to a significant increase in runoff, while in more mountainous regions, such as the United States (Leopold et al., 2018), sealing has a lesser impact on runoff due to favorable terrain morphology and natural water retention.

In mountainous areas, such as Nowy Sącz or Bielsko-Biała (Mesoregion 6), the ratio of sealing to the volume of the infiltration trench remains high, exceeding a value of 6 (Figure 8a). In this region, due to the varied terrain morphology, water tends to naturally infiltrate, which means that despite high levels of sealing, runoff does not increase as drastically as in lowland areas. For example, in Bielsko-Biała, the runoff ratio with medium sealing is 3.84, and in Nowy Sącz, it is 4.47 (Figure 8b). Furthermore, the presence of green infrastructure, such as stormwater retention systems, may also contribute to limiting the intensity of runoff in these areas.

These results highlight the importance of considering specific geographical, urban, and climatic conditions in hydrological analyses and stormwater management in different regions.

CONCLUSIONS

This study investigated the impact of changing rainfall patterns and the characteristics of urban catchments on the effectiveness of rain gardens in six mesoregions of Poland. The analysis was based on meteorological data from 29 stations covering a period of 37 to 44 years, as well as a custom-built simulation tool that accounted for three levels of land sealing. The research showed an increase in the required volume of the infiltration trench across all regions in response to increased sealing. In the first scenario, the volumes of the trench ranged from 28.7 m^3 (Elbląg) to 52.6 m^3 (Mikołajki), in the second scenario from 77.4 m^3 to 145.4 m^3, and in the third scenario from 187.1 m^3 to 352.8 m^3. The largest infiltration capacities were recorded in Mikołajki, Szczecin, and Katowice, while the smallest were in Elbląg, Kołobrzeg, and Suwałki. The highest relative increase in trench volume occurred in Terespol (7.7%), while the lowest was in Zielona Góra (5.4%). In lake regions such as Mikołajki, natural soil conditions favored more efficient infiltration.

Surface runoff analysis revealed higher runoff volumes in cities with a high degree of sealing, particularly in mountainous, upland, and lake regions. In the case of high sealing, runoff reached values from 130 m^3/d to 160 m^3/d, while with low sealing, it was limited to 30–40 m^3/d. The highest runoff was observed in Katowice and Mikołajki, despite differences in the level of urbanization. The correlation between catchment sealing and increases in the volume of the infiltration trench and runoff was particularly pronounced in lowland regions, while in mountainous regions (e.g., Bielsko-Biała, Nowy Sącz), the increase in runoff was moderate.

The developed application enables the design of infiltration systems tailored to changing urban and climatic conditions. The results underscore the importance to consider local physical-geographical variability in the process of planning sustainable stormwater management. Strategies based on the development of rain gardens can significantly enhance the resilience of cities to the impacts of climate change, while simultaneously improving the quality of life for residents and the quality of the urban environment.

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