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Technical solutions and benefits of introducing rain gardens – Gdańsk case study

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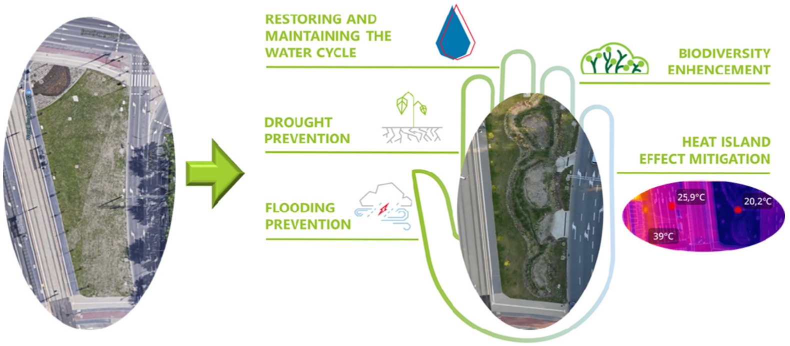
HIGHLIGHTS

- Rain gardens as a smart tool for climate city adaptation
- High variation in infiltration rate between monitored rain gardens
- Infiltration rate of emptying to contribute to less flooding and drought mitigation
- Variety of technical solutions tailored for a different types of urban runoff
- Rain gardens as a unit for building system recovery in an urban circular economy

GRAPHICAL ABSTRACT



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ABSTRACT

Nowadays, Nature-Based Solutions (NBSs) are developing as innovative multifunctional tools to maximize urban ecosystem services such as storm water preservation, reduction of runoff and flood protection, groundwater pollution prevention, biodiversity enhancement, and microclimate control. Gdańsk is one of the first Polish cities to widely introduce rain gardens (one example of an NBS) in different areas such as parks, city center, main crossroads, and car parks. They involve different technical innovations individually tailored to local architecture, including historic buildings and spaces. Gdańskie Wody, which is responsible for storm water management in the city, adopted a pioneering strategy and started the construction of the first rain garden in 2018. Currently, there are a dozen rain gardens in the city, and this organisation's policy stipulates the construction of NBSs in new housing estates without building rainwater drainage.

Various types of rain gardens can be created depending on location characteristics such as geo-hydrology, as well as local conditions and needs. Furthermore, each of them might be equipped with specific technical solutions to improve the rain garden's function – for example, an oil separator or setter can be included to absorb the initial, most polluted runoff. During winter, the large amount of sodium chloride usually used to grit the roads may pose the greatest threat

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to biodiversity and plants. These installations have been included in a large rain garden in Gdańsk, located in the central reservation of the main streets in the city center.

This work presents various technical considerations and their impact on ecosystem functions, and the urban circularity challenges provided by rain gardens operating in different technologies and surroundings. The precipitation quantity and the following infiltration rate were estimated by installing pressure transducers. Furthermore, mitigation of the urban heat island was analysed based on remote sensing images.

1. Introduction

According to the Baltic Marine Environment Protection Commission (HELCOM Recommendation 23/5-Rev.1, 2021) from June 2021, a reduction of discharges from urban areas by proper management of storm water systems must be ensured. Unsuitable sewerage systems can cause highly polluted runoff from urban areas which is eventually discharged into the receiver (e.g. The Baltic Sea).

The Helsinki Commission (HELCOM) recommendation stands for specific storm water planning, reduction of discharge from urban areas through proper storm water management, especially high-risk storm waters. These objectives should be supported by integrated storm water management, assessment of local storm water impact, green infrastructure planning, and green technologies.

Green technologies include Water Sensitive Urban Design (WSUD) developed in the 1990s in Australia. The objective of WSUD is to manage water balance, maintain or improve water quality, and preserve water-related ecosystem services. This particular approach to storm water management aims to address the entire urban water cycle at all scales and densities. Water Sensitive Urban Design is a part of a larger group of solutions based on nature (Abbott et al., 2013; Ballard et al., 2015; Dickie et al., 2010; Digman et al., 2012; Fletcher et al., 2015; Graham et al., 2012; HELCOM Recommendation 23/5-Rev.1, 2021).

Nowadays, increasing urbanization and the harmful effects of climate change have influenced the water balance, resulting in unfavourable events such as flooding, droughts, and heat stress (European Environment Agency, 2015; IPCC, 2014a, 2014b). Implementing Nature-based Solutions (NBS) can help, treat, and infiltrate storm water that runs off roofs and impermeable surfaces and potentially into the subsurface (Venvik and Boogaard, 2020). Green infrastructure, especially rain gardens and swales, creates permeable pavements to restore water balance by capturing, retaining, and improving the infiltration capacity in urban areas. Moreover, such systems can better treat storm water runoff, restore groundwater levels, increase soil moisture to alleviate drought impacts, and lower temperatures by evapotranspiration. Nevertheless, in practice, predicted infiltration capacities are usually not met, often for unknown reasons (Atanasova et al., 2021; Katsou et al., 2020; Oral et al., 2020; Veldkamp et al., 2021; Venvik and Boogaard, 2020).

In recent years, the use of rain gardens as an NBS to create blue-green infrastructure has received much more attention as a multifunction solution for storm water management to adapt existing urban spaces to climate changes through flash flood prevention, intensification of infiltration and evapotranspiration processes, heat island effect mitigation, and biodiversity enhancement (Atanasova et al., 2021; Kisser et al., 2020; Pearlmutter et al., 2020; Raymond et al., 2017; Skar et al., 2020).

Nevertheless, the environmental effect of the development of blue-green infrastructure in cities, especially in Polish circumstances, is still in the investigation phase. Rain gardens began to be created in Gdańsk in 2018 and such actions were an answer to flooding event in 2016 which cause significant damages in the city. Still blue-green investments are local initiatives and there is no legal requirements for stormwater management in Poland. Pomeranian city is known in Northern Europe as a forerunner in innovative storm water management and development of technical solution which could be easily replicable, transfer and applied in existing urban space in other countries.

A detailed analysis of the environmental impact of rain gardens in urban areas will be of great interest to contractors and maintenance entities. Specific verification can provide information on potential weaknesses of the system and help adjust the solution to a particular issue. The significance of such research is also of interest to the city's authorities and decision-makers. Furthermore, the planned investigation will be carried out on several working objects on a full scale (not on pilot objects), which presents tremendous added value in Polish circumstances.

This work presents various technical considerations and their impact on the effectiveness of rainwater treatment, and ecosystem functions offered by rain gardens operating in different technologies and surroundings, as well as urban circularity challenges. Precipitation quantity and the subsequent infiltration rate were estimated through the installation of pressure transducers. Furthermore, mitigation of the urban heat island was analysed based on remote sensing, and biodiversity enhancement was estimated as one of the functions of ecosystem services.

Due to the increasing number of rain gardens, many questions arise regarding their environmental impact, use, and maintenance. This paper is a summary of the experience of Gdańsk in sustainable storm water management and aims to answer the following:

- What type of technical solutions could be introduced in the rain garden system and what problems might they solve?
- What is the actual infiltration rate of the rain garden system?
- Do rain gardens mitigate the urban heat island effect?
- Are rain gardens a solution to biodiversity enhancement?
- What circular challenges can be achieved with rain gardens?
- What are the future challenges for developing and optimizing the design of the rain gardens as a multifunctional NBS?

2. Research objects and methods

2.1. Local conditions

The local conditions in Gdańsk are quite idiosyncratic: (i) there are 3 altitude zones: from depression to a plateau, (ii) which results in a steep slope and large and fast outflows to the lower terrace of the city, (iii) there is a dense network of erosion valleys of varying sizes, (iv) the influence of the sea condition on water receivers, and (v) numerous mountain streams encountering multiple roads and railway.

Fig. 1 presents a hypsometric map of Gdańsk, where the upper terrace causing large and fast runoff directed to the lower terrace.

2.2. Research objects

Over the last few years, the approach for storm water management in Gdańsk has changed, especially in regard to designing recommendations. The first precipitation (up to 30 mm) should be held by urban greenery. Precipitation above 30 mm is directed to the rainwater harvesting storage tanks. Finally, storm water is directed to the municipal storm water drainage system (Gdańskie Wody, 2020).

In the case of the existing urban space, technical solutions have been put in place for storm water from rooftops with relatively good storm water quality, from car parks with petroleum waste, and from streets featuring heavily polluted runoff, e.g. heavy metals.

NSB such as rain gardens may be introduced to existing urban spaces such as residential areas, main crossroads in the city center, and even old towns. Gdańsk is consequently developing a small urban retention system, which includes more than 50 retention reservoirs and over 30 rain gardens.

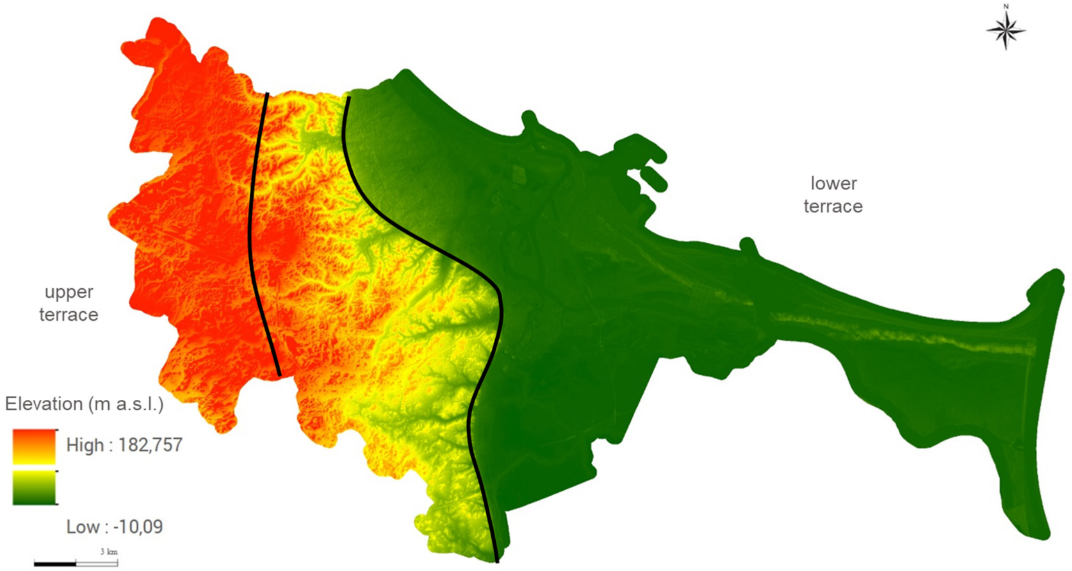

Fig. 1. Hypsometric map of Gdańsk (modified from Gdańskie Wody (2020)).

Fig. 2 shows the location of the existing rain gardens with analysed locations marked.

Table 1 presents the basic specifications of the analysed rain gardens.

2.2.1. *Rain garden no. 1–3 Maja St.*

This rain garden (54°20′55.3″N/18°38′31.2″E) was built in 2020 and consists of three basins connected in a cascade to manage (retain) excess storm water. In order to redirect the storm water from the traffic route to the green belt located in the road layout, three inlets were made along the length of the curb bordering the plot, separating the driving lanes of 3 Maja Street from the green area. The catchment area is around 2105 m^2.

2.2.2. *Rain garden no. 2 – Bishop O'Rourke Square*

The rain garden located in the Gdańsk Wrzeszcz (54°22′58.0″N/18°37′32.4″E) district was constructed in 2018. This small retention object is a system of retention basins connected by an overflow system and deals with the runoff from pavements, car parks, and drain inlets. It is equipped with an emergency overflow at the inlet of the rainwater drainage system. The catchment area (type of impermeable pavements and their area) is a street with an asphalt surface and surrounding concrete pavements with a total area of around 3145 m^2.

2.2.3. *Rain garden no. 3 – eMOCja Center*

Constructed in 2020, there are two rain gardens (54°21′46.8″N/18°42′19.6″E). The first is a multistep raised planter that deals with storm water from the roof area. The catchment area is around 75 m^2. The second is a typical ground rain garden to manage storm water from the rooftop and impermeable pavement near the building.

2.2.4. *Rain garden no. 4 – Lastadia st.*

In the area of the Lastadia buildings (54°20′44.0″N/18°39′06.5″E), surface management in the form of ‘dry’ rain gardens has been designed for storm water from impermeable surfaces in small urban retention systems. It was constructed in 2020. The road system has been designed in such a way as to enable a gravitational flow of water from sealed surfaces – i.e., carriageways, pavement surfaces, and car parks – and curbs have been cut to redirect storm water to green areas. Storm water is managed in the depressions to a maximum depth of about 30 cm and flows down

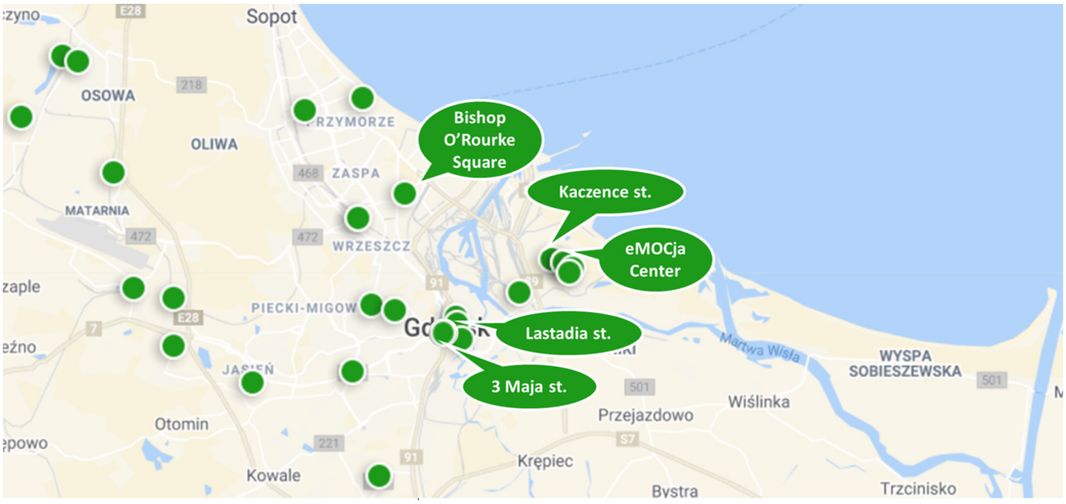

Fig. 2. Rain gardens in Gdańsk with analysed locations marked (modified from http://www.gdmel.pl/).

Table 1
Summary of the research locations.

No.	Object	District	Type	Area	Retention capacity	Purpose	Construction year
1	3 Maja St.	City center	Ground	758.7 m^2	98.2 m^3	Main streets crossroads	2020
2	Bishop O'Rourke Square	Wrzeszcz	Ground	200.86 m^2	56.3 m^3	Roof, street, pavements	2018
3a	eMOCja Center	Stogi	Ground	25.1 m^2	2.3 m^3	Roof, parking lot	2020
3b			Box	4.9 m^2	1.2 m^3	Roof	2020
4	Lastadia st.	City center	Ground	325 m^2	108 m^3	Parking lot	2020
5	Kaczeńce	Stogi	Ground	449 m^2	224.5 m^3	Warehouse roof	2018

to accumulate in the basins (surface retention), where it will be used by existing vegetation. An emergency outlet was also designed and excess storm water is directed to the storm water drainage system.

2.2.5. Rain garden no. 5 – Kaczeńce st.

This particular rain garden (54°21′51.6″N/18°41′57.6″E) was the first construction of a small urban retention system in Gdańsk and was developed on the premises of the flood control warehouse of the Gdańskie Wody water company as an example of good practice. It is a system of connected retention basins with designed emergency overflow and connected with the existing storm water drainage system. The total catchment area is around 2700 m^2 and includes a car park with a cobblestone surface, lattice paving blocks, and a warehouse roof area.

2.3. Monitoring of precipitation

Precipitation was measured through an advanced system of weather monitoring by the Gdańskie Wody water company. The Gdańsk agglomeration is equipped with 26 rain gauges spread across each district.

In Gdańsk, the basic assumptions of the rain gauge setting are: (i) appropriate quality of the acquired data, (ii) appropriate location(s), (iii) appropriate operation, (iv) calibration of the cyclic sensor and (v) how to deal with equipment failure.

Particular precipitation data were analysed from one monitoring station (Stogi/Kaczeńce), which is located the closest to two rain gardens (eMOCja Center and Kaczeńce), where pressure transducers were placed for 10 days. The analysis ran from 15 to 24 November 2021. The precipitation was monitored every 1 min. The total precipitation during that time was 7.62 mm.

2.4. Infiltration capacity determination

In the study, pressure transducers were used as the primary method of measuring and recording the reduction in water levels over time in various locations in the rain gardens. Eight wireless, self-logging pressure transducers (Micro diver DI 501) were installed at the lowest points (Schlumberger Water Service, 2014). In the eMOCja Center rain garden – 4 pressure transducer loggers in each box and 2 in the ground rain garden were placed. In the Kaczeńce st. rain garden - 2 pressure transducer loggers were placed.

The transducers continuously (frequency of 1 min) monitored the static water pressures at those locations and transmitted this information to a laptop computer. The static water pressure was then converted to an appropriate depth of water in the rain garden. This process produced accurate and reliable data throughout the tests. It also enabled a visual representation of the pavement infiltration process.

Three different measurement methods can be used in conjunction with the pressure transducers in order to calibrate and verify the transducer readings. These methods were: (i) hand measurements when reading out the equipment, (ii) calibrated underwater camera images and (iii) time-lapse photography. This method is used in many projects to evaluate the hydraulic performance of green and grey infrastructure (Boogaard et al., 2014; Boogaard and Lucke, 2019; Venvik and Boogaard, 2020).

Each pressure transducer location was monitored as described above (Section 2.3 Monitoring of precipitation). After the measurement period, the pressure transducer readings were plotted against time to create an accurate infiltration curve for each of the investigated sites. Simple linear regression analysis was used to develop a linear function with the highest determination coefficient R^2 for the data loggers readings from each site. An achieved linear regression line was then used to estimate an average infiltration rate (k_1) in mm/h and (k_2) in m/day for each location. The period from maximum level storm water height to total infiltration was recorded for both rain gardens. To define the infiltration rate a simple equation was used (Eq. (1)):

$$k = \frac{h}{t} \tag{1}$$

where k is the infiltration rate (mm/h), h – the height of the water (mm), and t – duration of infiltration (h) (Boogaard et al., 2014).

2.5. Remote sensing for thermal imaging measurements

A DIJ Mavic 2 Enterprise Dual commercial unmanned aerial vehicle (UAV) was used to record images. It is equipped with two sensors: a classic camera that records the visible range of light and a thermal imaging camera that records an electromagnetic wave in the range of 8–14 μm. Drone, which makes thermal imaging measurements, could be used for many tasks: e.g. microclimate analysis in cities (Smith et al., 2021), animal detection and monitoring (Aulia Rahman and Setiawan, 2020; Matias, 2020) as well as drought monitoring (Dwiyaniek et al., 2021). The main technical specifications of the camera are presented in Table 2.

Looking at the technical specifications, it can be concluded that the image resolution is not too high compared to standard RGB vision cameras. However, when thermal images are taken near the object (in the case of a low-altitude UAV flight), the indicated resolution is sufficient (Rahman et al., 2020). A simple calculation can be made. By taking into account the pixel size of the matrix, the angle of view of the lens, the matrix resolution, and the flight altitude, the field pixel resolution is obtained. Assuming a flight at a height of 5 m with a nadir sensor setting, the terrain resolution of a pixel will correspond to about 3.4 cm (real/not artificially processed). If the height is increased to 10 m, we obtain a resolution of 6.7 cm, while at a height of 50 m, the pixel resolution is 33.9 cm. By adjusting the flight altitude, the obtained terrain pixel resolution values allow us to distinguish the temperature between the various elements of the rain garden.

A helpful function in the analysis of the thermal image is FLIR MSX, which superimposes the image from the RGB sensor on the thermal image, allowing for better readability and interpretation of the results.

Table 2
The technical specifications of the DIJ Mavic 2 Enterprise Dual thermal camera. Data source: https://www.dji.com/pl/mavic-2-enterprise/specs (access data 5.01.2022).

Sensor	Uncooled VOx Microbolometer
Lens	HFOV: 57° Aperture: f/1.1
Sensor resolution	160 × 120
Pixel pitch	12 μm
Spectral band	8–14 μm
Accuracy	High gain: max ±5% (typical) Low gain: max ±10% (typical)
Scene range	High gain: −10° to +140 °C Low gain: −10° to +400 °C

Fig. 3. Representative HOTMETAL colour palette.

The UAV used is a low-cost drone that has some limited functions. Unfortunately, there is no simple/dedicated possibility of processing and analysing thermal imaging data. Temperature data are acquired in real-time while taking measurements. Spot measurements may be taken or an area of interest selected, in which case the maximum and minimum temperatures are displayed. Therefore, during the image recording of rain gardens, the operator recorded the image displayed on the smartphone display (mobile device mounted on the controller). This facilitated analyses, and the temperature data was applied to the image during post-processing. Additionally, it should be noted that the acquired thermal images were saved using the HOTMETAL colour palette (Fig. 3).

The lighter the colour, the higher the recorded temperature, and vice versa for the darker shades (shades of purple, navy blue, and black). It should be noted that, in the case of this UAV used, there is no direct possibility to assign the appropriate temperature to the specific colour or export with the recorded image. The marked temperature points were noted on the side during the measurements. Measurements can only be made in real mode using the UAV thermal imaging camera. During the spot measurements taken at the time of the acquisition, the image displayed on the mobile device was recorded. Thanks to this, it was possible to edit the image in external graphic software and save the registered temperature.

2.6. Flora biodiversity assessment

Some univariate measures of biodiversity were calculated for selected rain gardens in Gdańsk. The number of species and total number of individual plants at each level of retention basins is known. The Shannon evenness index was calculated to express which rain garden was the most balanced in terms of performance against different aspects such as urban challenges and ecosystem services. The evenness index was established using the equation as follows:

$$\mathrm{D}_i = \frac{H_i}{\ln S_i} \tag{2}$$

where *i* is a specific rain garden, *H* is calculated as a Shannon index and *S* is the number of species in which the rain garden has a score greater than 0 (Castellar et al., 2021).

Both the Shannon Diversity Index (*H*) and Shannon Evenness Index (D) are recommended indicators of biodiversity. The Shannon Diversity Index is commonly used to evaluate species diversity within a defined area and is described by:

$$\mathrm{H}_i = -\sum_{i=1}^{N} \frac{n_i}{N} \left(\ln \frac{n_i}{N} \right) \tag{3}$$

where n_i is a percentage cover of all species present, where N is the total number of plants. While the Shannon Diversity Index does not qualify whether the species present are native, non-native, or alien invasive, it accounts for the number of different species observed within a given space and their relative abundance. The Shannon Evenness Index provides information about the relative number of individuals of each species in a given area (European Commission, 2021a).

3. Results and discussion

3.1. General technical assumption

The definition of a rain garden is wide, although the literature most frequently describes it as (i) a shallow depression with free-draining soil, (ii) a planted depression designed to collect, store, infiltrate and filter stormwater runoff on a small-scale, especially in urban areas, or (iii) a vegetated area into which runoff is drained, attenuated and stored and water infiltrates into the ground or is taken up by plants (Castellar et al., 2021; Dickie et al., 2010; Graham et al., 2012). It combines layers of soil for infiltration and mulch to promote microbial activity. Native plants are recommended based upon their relationship with local climate, ground, and humidity conditions without the use of any fertilizers (Castellar et al., 2021). A rain garden, in particular, slows rainfall run-off, is drained and stored for a certain period, and then infiltrates into the ground soil and improves water quality by filtering out pollutants and recharging groundwater (Castellar et al., 2021; Dickie et al., 2010). Furthermore, it should be planted with species able to tolerate short periods of inundation (Graham et al., 2012).

Design requirements stated that rain gardens can be integrated with adjacent hard and permeable surfaces. Moreover, rain garden overflows ensure that excess water flows to an existing drain, an alternative drain, or even to another rain garden. The soil should be permeable, however, soils rich in clay can be mixed with other materials (sand, etc.) to improve permeability and infiltration rate. Large rain gardens are better than small ones although most sizes will provide opportunities for controlling runoff, wildlife habitat, and enjoyment (Graham et al., 2012).

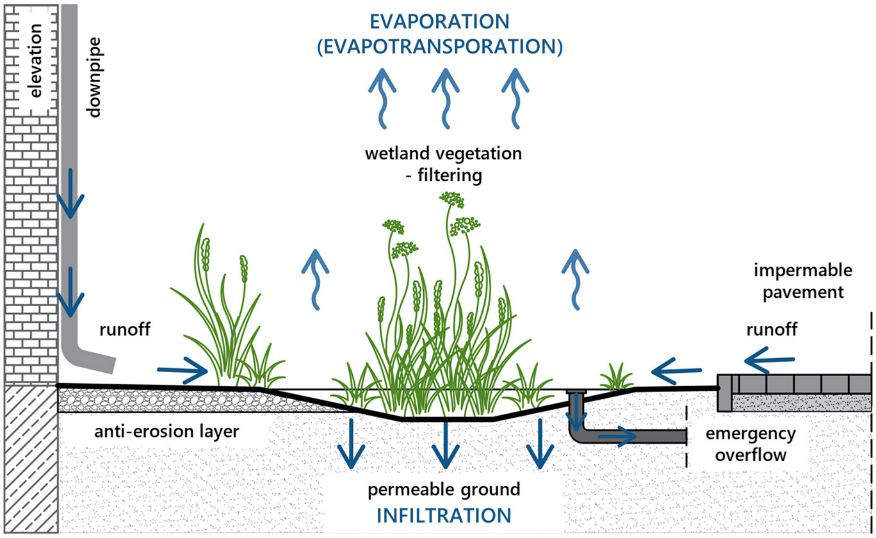

Fig. 4. The scheme of a rain garden (modified from Szpakowski et al. (2018)).

Fig. 5. Existing inlets examples from rain gardens in Gdańsk (photo M. Kasprzyk).

The general benefits from introducing rain gardens are reducing the amount of storm water that runoff and hence the flood risk, improving the quality of discharged rainwater, improving the quality of life and health of people, increasing biodiversity, affect the reduction of fees for water services (including watering the garden) and improve the aesthetics of the surroundings. An additional advantage of rain gardens is the possibility of combining them into an extended system – the Urban Small Retention System, allowing for gradual reduction of surface runoff of storm water and improving their quality (Szpakowski et al., 2018).

Using appropriate vegetation and filtering layers of substrate, the rain garden can pre-treat the water and allow access to deeper soil layers (Fig. 4). In this way, storm water is retained in the landscape. If the conditions on the ground are not conducive to water infiltration (e. g. there is clay soil), a rain garden can be arranged in a container or a sealed version in the ground. Excess water can be discharged into the storm water drainage system through an emergency overflow with a significant delay (Fig. 4). This solution reduces the negative effects of precipitation and improves the quality of discharged water (Okaikue-Woodi et al., 2020; Szpakowski et al., 2018; Wild, 2020).

Due to the uptake of water by plants through physiological processes and its transpiration (i. e. evaporation of water from above-ground plant parts), the final volume of water is significantly reduced. However, phytoremediation (the ability of plants to remove pollutants) improves the quality of the discharged water. A rain garden can be designed as both an infiltration solution for storm water, and a waterproof solution that mainly performs a retention function. In both cases, the total outflow is minimized by evapotranspiration (Boano et al., 2020; Graham et al., 2012; Schwarzer, 2020; Walsh et al., 2005).

The volume of an individual rain garden or small retention system should take into account the management of the so-called calculated precipitation, defined in local norms and standards. In order to discharge excess water from heavy rainfall the emergency overflow, from which water can be diverted, is used for e. g., to the nearest small retention system component, storm water drainage system, or absorption well (Ballard et al., 2015; Dickie et al., 2010).

3.1.1. Inlets

Storm water from all inlets is transported directly to the basins using hardened granite paving stones, which will prevent surface water runoff from degrading the top layer of the subsoil and underground installations occurring there.

Inlets were made by modifying the existing curb. Surface runoff of storm water is direct from the path into the basins. The inlet was made by breaking the continuity of the curb (Fig. 5). When the largest runoff is expected, the redirection of storm water is carried out by an inlet with the largest capacity and efficiency of water reception.

3.1.2. Settling tanks

Inlets are equipped with settling tanks (depth 25 cm) to separate solids from storm water runoff. Solid contaminants might cause a risk of silting the bottom of the basins (Fig. 6). Emergency overflows have been made in the settling tanks to allow storm water to drain directly into the storm water drainage system.

This solution is designed to limit the discharge of water that contains a high concentration of chlorides in winter into the greenery. During the summer, the emergency overflows in the settling basins are plugged.

3.1.3. Three levels of retention and tailored specific vegetation

The basins have been designed in an arrangement containing a cascade of three basins independently supplied with storm water. Each was separated by an embankment connecting the rain garden to the existing landscaped area.

The designed basins have a three-stage water damming and retention structure (Fig. 7):

Fig. 6. Examples of settling tank installations (photo M. Kasprzyk).

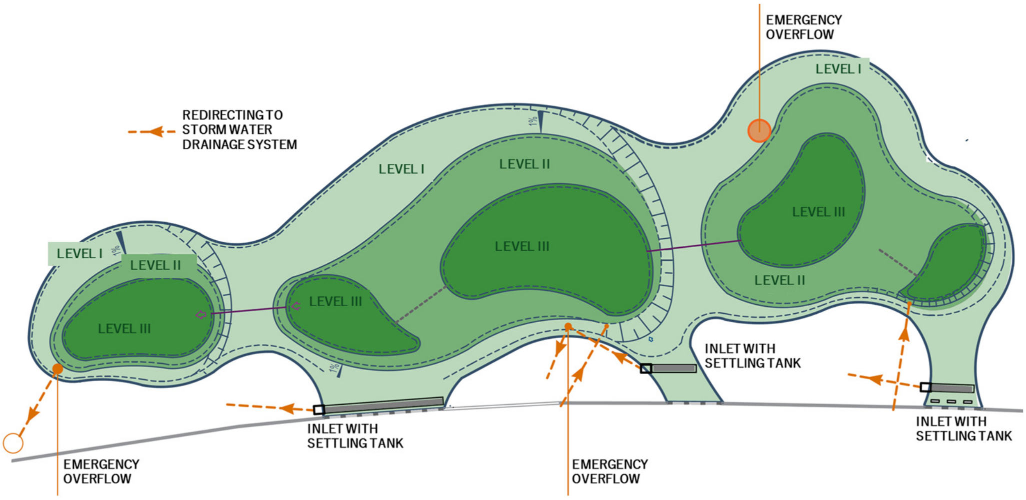

Fig. 7. The general concept of the triple-level storm water retention system.

i) the lowest basins designed to receive precipitation – LEVEL III; most humid area, where all basins have been landscaped with hydrophytic plants tolerating permanently stagnant water;
ii) designed to retain excess water during excessive precipitation – LEVEL II; most often this level will be free of damp; therefore, it has been designed with a grassy surface for recreational purposes (accessible greenery);
iii) a part of the terrain that regulates the water level of each basin – LEVEL I; these levels are connected with dikes dividing each basin and equipped with emergency overflows (with diameters of 450 mm to 600 mm), one for each basin.

According to our own experience based on the guidebook (Szpakowski et al., 2018) prepared by Gdańskie Wody, species selection is strictly dependent on the environmental conditions in each area, which are of key importance for the proper vegetation of plants. Access to light, temperature, type of soil should always be considered, and in particular access to water, which directly affects all physiological activities of plants (intake and transport of nutrients, gas exchange, structure of plant cells). Due to the specific water conditions in sustainable drainage systems, the wetland plants (hydrophilous plants) are used that can withstand periodic flooding with rainwater retained in ground depressions and are able to withstand a longer rainless period. Retention green areas are planted with vegetation characteristic of the following phytocoenosis:

i) the Reed Beds, characteristic of the *Phragmitetea* class of plant communities, occur in coastal zones of stagnant and flowing waters. Characteristic species include the *Glyceria maxima* (Reed Sweet Grass), *Typha Latifolia* (Great Reed Mace), *Acorus calamus* (Sweet Flag), *Butomus umbellatus* (Flowering Rush), *Phragmites australis* (Common Reed).
ii) communities of the *Salicetea purpureae* class of plant communities that occur naturally in river valleys, where there is periodic flooding. Such habitats are rich in nutrients due to the mud deposited by rivers (sand, gravel, dust, and clay parts in various proportions). Examples of plant species belonging to the class *Salicetea purpureae* are *Alnus glutinosa* (Common Alder), *Salix alba* (White Willow), many species of broad-leaved willow including i.e. *Salix aurita* (Eared Willow), *Salix cinerea* (Grey Willow), perennial plants i.e. *Symphytum officinale* (Comfrey), *Osmunda regalis* (Regal Fern), *Phalaris arundinacea* (Reed Canary Grass).
iii) meadows and pastures of the *Molinietalia* order, growing in damp or moderately damp habitats, substitute for the riparian communities of the *Salicetea purpureae* class of plant communities. Characteristic species of the *Molinietalia* order are *Filipendula ulmaria* (Meadowsweet), *Deschampsia cespitosa* (Tufted Hair Grass), *Trollius europaeus* (Globeflower), *Lysimachia vulgaris* (Yellow loosestrife), *Lythrum salicaria* (Purple loosestrife), *Iris sibirica* (Siberian Iris or Siberian Flag).

It is worth noting that when designing sustainable drainage systems in public places, special attention is paid to the decorative features of individual plant species and the selection of interesting varieties available on the market, e.g., a variety with striped and discoloured leaves, multi-coloured flowers, low height or slow growth, etc., which allow creating interesting plant composition that increase the social acceptance of such solutions.

3.1.4. Emergency overflow

The emergency overflow is placed at a height that allows the collection of excess water from the basin, approximately 15 cm below the surface of the adjacent pavement (Fig. 8).

The excess accumulated storm water will be discharged into the existing storm water drainage system.

Fig. 8. Emergency overflow directed to the storm water drainage system.

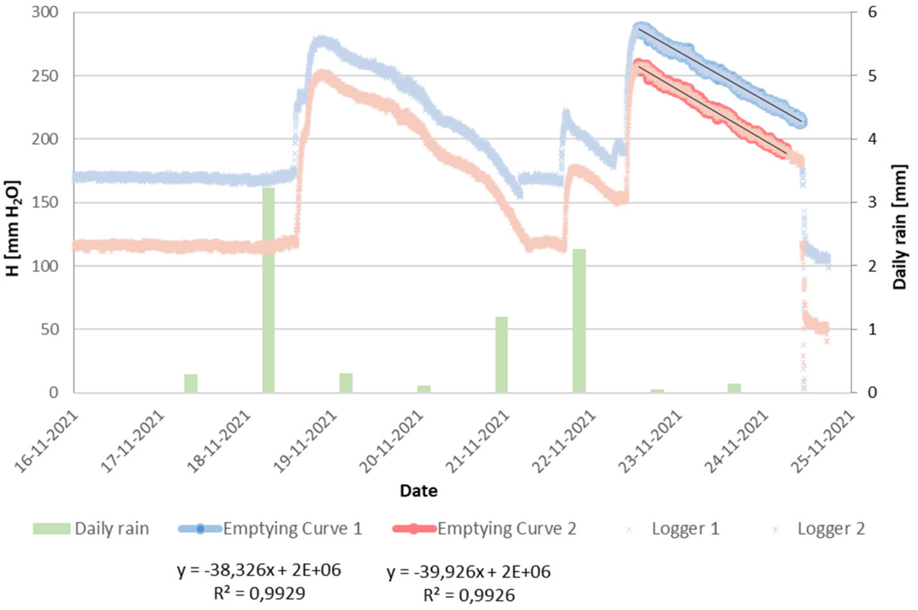

Fig. 9. Infiltration curve results for the Kaczeńce rain garden (two loggers).

3.2. Hydraulic efficiency of rain garden

Infiltration systems can provide a significant reduction in the volume of runoff by infiltrating over a certain period while restoring and maintaining the water cycle and supporting groundwater recharge processes. The rate of infiltration and hydraulic efficiency depends on the ground permeability of the surrounding soils. A suitable soil for infiltrating design is permeable and unsaturated (Ballard et al., 2015). Rain gardens in Europe have different requirement, for example Dutch raingardens (Netherlands) are required to have an infiltration capacity equal to 0.5 m/day (RIONED, 2006), which means that they should provide proper retention during 24-hour heavy rainfall events (Venvik and Boogaard, 2020). Full-scale infiltration tests are performed for many different green infrastructure such as permeable pavements, swales, and rain gardens to evaluate pavement infiltration rates (Boogaard, 2015).

Kaczeńce rain garden has been in operation over the longest period – almost 4 years – while the eMOCja Center rain garden has been operating for 2 years. The emptying curves for the analysed rain gardens (Fig. 9) are based on results obtained from the pressure transducers. The presented graph shows changes in hydraulic pressure during precipitation periods and how efficiently the collected runoff infiltrates the ground. It can be observed that after a certain duration of a particular rainfall event, the filling level of the rain garden basin increases significantly. There is a noticeable correlation between the sum of precipitation and water pressure at the lowest point of retention basins.

After calculations, the slope of the emptying curves, determination coefficient (R^2), and infiltration rate were determined (k_1, k_2) in different unit (Table 3). The eMOCja Center rain garden has a relatively higher infiltration rate, however, the determination coefficient was not high and did not exceed 0.8, which can indicate that provided linear function should be carefully used for infiltration rate assessment during another rainfall event. In the case of the Kaczeńce rain garden, the determination coefficient was equal to almost 1.0, which confirms the good approximation of the results presented with a linear function. Furthermore, in both cases, the achieved hydraulic performance is comparable to the values found in the infiltration capacity of rain gardens in New Zealand and Norway (Roelofs et al., 2017; Venvik and Boogaard, 2020). It is worth mentioning that investigated rain gardens were constructed using original soil, which contains clay amendment in Kaczence rain garden.

Table 3
Hydraulic performance of two rain gardens.

Rain garden	Logger	Slope	R^2	k_1 (mm/h)	k_2 (m/day)
eMOCja Center	1st box	− 38.809	0.763	24.4	0.586
	2nd box	− 28.433	0.715	22.2	0.534
	3rd box	− 28.595	0.724	23.7	0.569
	4th ground	− 42.621	0.723	29.5	0.707
	5th ground	− 36.600	0.682	17.5	0.420
Kaczeńce	1st ground	− 38.326	0.993	22.0	0.528
	2nd ground	− 39.926	0.993	17.7	0.426

Through achieved values of retained storm water level in the lowest points of rain garden basins and a sum of daily precipitation, it was possible to estimate an average volume of storm water runoff and compare the maximum achieved filling level with the calculated one (Table 4). Storm water runoff was calculated by multiplication of impermeable catchment area and a sum of precipitation period. While the average water level was determined by dividing storm water runoff by rain garden area, the slope of the retention basins was omitted.

It is obvious that storm water runoff is strictly related to the area of an impermeable catchment area, however, there is a noticeable connection with applied rain garden area. The estimated water level is close to achieved one only in the case of eMOCja Center box rain garden. In two other cases, the difference was significant, especially in the Kaczeńce rain garden where the obtained filling was 4 times higher than the calculated value. This observation may be correlated with rain garden size, where a larger area may cause irregular distribution of directed runoff, which can result in difficulties in the hydraulic modeling of storm water runoff.

3.3. Rain gardens for heat island effect mitigation

The recording took place during the 2021 summer season, which was characterized by low rainfall. According to Gdańskie Wody, June 2021 precipitation data was described as very dry (month sum of rain around 20 mm), July as dry, August as normal, and September as a dry month.

Unfortunately, in practice, the recoding was particularly difficult, in some cases even impossible, to acquire the image as originally planned. Namely, recording both during the dry season and after heavy rainfall when retained storm water may be observed in the reservoirs. Throughout the season, some of the rain garden locations could not be reached in weather conditions that allowed temperature measurements by drone – a

Table 4
Calculation of rain garden filling during precipitation period.

Rain garden	Impermeable catchment area	Rain garden area	The sum of precipitation period	Storm water runoff	Maximum filling (obtained)	Average filling (calculated)
	m^2	m^2	mm	m^3	mm H_2O	mm H_2O
eMOCja boxes (total)	75.0	4.9	3.52	0.264	56.00	53.88
eMOCja ground	140.0	25.1	3.52	0.493	11.08	19.63
Kaczeńce	2696.5	449.0	3.59	9.680	80.50	21.56

lack of precipitation and retaining storm water. Despite these limitations, the overall data collected were evaluated and conclusions drawn (Fig. 10).

The lighter the colour, the higher the recorded temperature, and vice versa for the darker shades (shades of purple, navy blue, and black). Nevertheless, it should be noted that each image should be treated separately. The same colours in two different images do not correspond to the same temperature level.

The temperature of the terrain basin is noticeably lower than the temperature of the other surrounding surfaces. A clear variation in temperatures on the ground surface can be observed depending on the type of pavement. Soil saturated with storm water along with specially selected hydrophyte plant species create a unique cooling effect right in the city center. This phenomenon contributes to the improvement of the ambient microclimate. Those observations were made even during cloudy weather, where the difference between the rain garden and playground area was 3.5 °C (O'Rourke rain garden), while in the car park the difference was more than 7 °C (Lastadia st. rain garden). In the case of O'Rourke Square, a smaller difference in ground temperature is most likely caused by the rain garden location at the existing park space, where high forms of greenery can fulfill an essential shading function, influence thermovision measurements and can be additional factor to microclimate regulation (Szopińska et al., 2019). At open space, without trees and other high forms of greenery, a temperature difference is more visible. The damp surface of the retention basin was cooler than ambient temperature. A significantly greater contrast

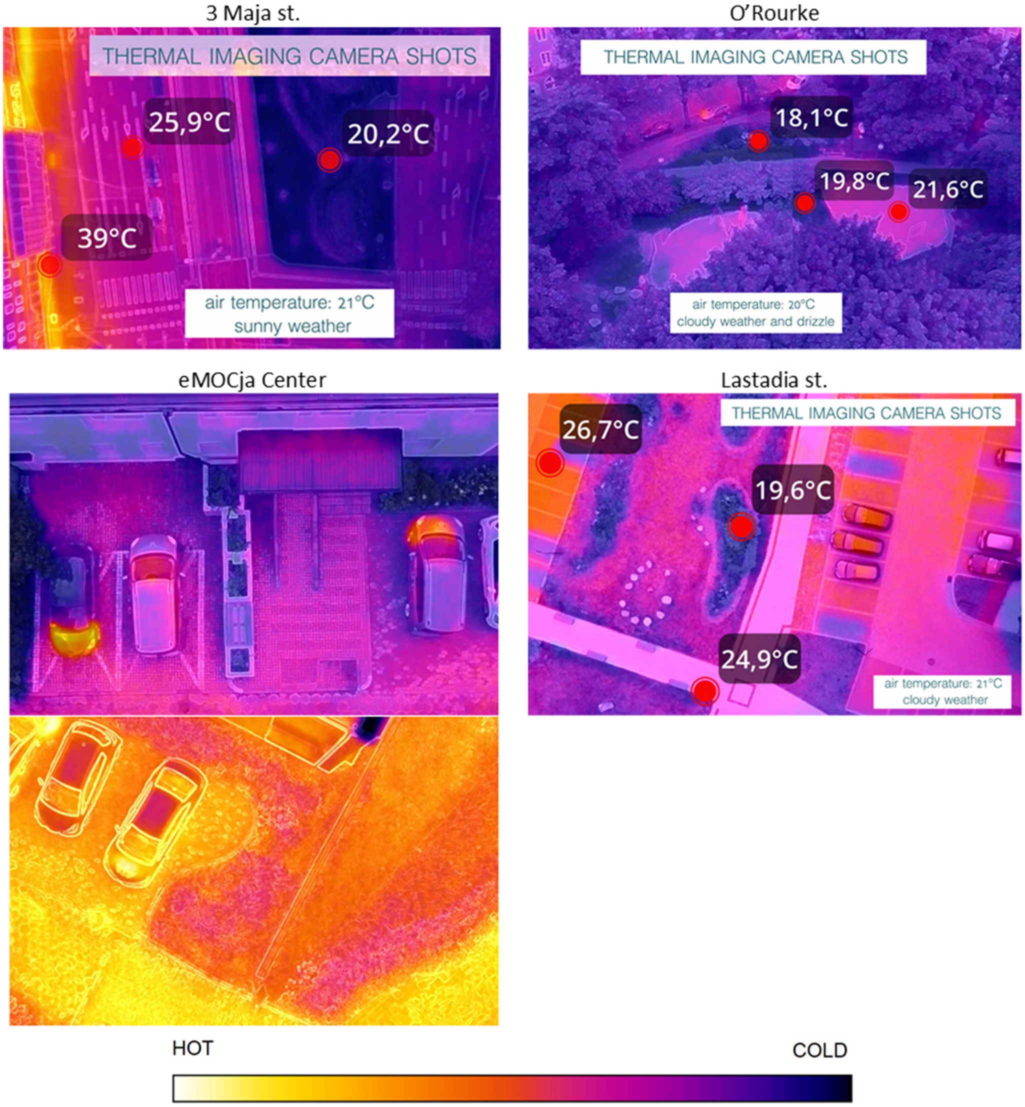

Fig. 10. Thermal imaging camera shots from rain gardens (photo K. Bobkowska).

in pavement temperature was experienced during sunny weather. The change in temperature almost amounted to 20 °C compared with the surface of the building wall (3 Maja St. rain garden).

Green infrastructure can contribute to cutting energy and resource demands as well as costs, while also cooling and reducing the urban heat island effect. Urban parks including rain gardens can reduce the ambient daytime temperature by an average of 0.94 °C; with an average nighttime reduction of 1.15 °C. In addition, those particular objects demonstrate the added value of NBSs for energy efficiency and climate change resilience in particular by reducing the urban heat island effect and by implementing blue and green solutions to create a resilient city (European Commission, 2015; Oral et al., 2020; Schwarzer, 2020).

Considering an analysis of ecosystem services, mitigation of the heat island effect corresponds to regulating services at human time scale, due to apparent microclimate regulation through moderation of ambient temperature (Pedersen Zari, 2015).

3.4. Rain gardens for flora biodiversity enhancement

According to The SuDS Manual (Ballard et al., 2015), biodiversity benefits might be offered by even very small, apart systems, but the greatest impact is delivered where such systems are planned as part of larger green landscapes to provide important habitat and wildlife connectivity. Due to their multifunctional character, NBSs are a powerful tool to increase different kind of investment (public or private) in biodiversity conservation efforts, especially in cases when biodiversity enhancement is viewed as a co-benefit of NBSs rather than the primary objective, which is the most common approach (Naumann and Davis, 2020). A Handbook prepared by European Commission (2021a) stated that NBS, including rain gardens, must benefit biodiversity and support the delivery of a range of ecosystem services.

Within the rain gardens, plants tolerating periodical flooding (hydrophytic plants) were planted (Table 5), while the exterior of the rain gardens were planted with ground cover and ornamental plants with lower water requirements.

In Table 5 a dominant plant species is noted. It also presents the number of plant species used in each rain garden (S) and the total number of planted plants (N). Those particular numbers were used for calculations of the Shannon Diversity Index (H) and Shannon Evenness Index (D) presented in Table 6.

Hydrophyte plants remove many pollutants from rainwater, e.g., biogenic substances (nitrogen and phosphorus compounds), heavy metals, oil derivatives. Many physical, chemical and biological processes occur in wetlands, which are characteristic of aquatic ecosystems, including aerobic and anaerobic decomposition of organic matter, for which microorganisms are responsible. The phytoremediation process, and more specifically phytofiltration – i.e., the removal of contaminants from surface water – is based on the ability of some plants to absorb harmful substances and decompose them (Mehmood et al., 2021; Obinnaa and Ebere, 2019). Through their roots and rhizomes, plants loosen the soil, take up biogenic compounds (nitrogen and phosphorus) and heavy metals, and provide the necessary nutrients, including oxygen for bacteria and fungi present in the root system, which supports the decomposition of harmful substances. It is worth mentioning that plants growing in wetland habitats have characteristic morphological features – i.e., the presence of *aerenchyma* (air crumb), whose function is to store a large amount of oxygen enabling the plant to float in water. Its transport to the root system, where nitrification (oxidation) occurs, ammonium ions are oxidized to nitrates, which are utilized by plants as an essential building element. Examples of species plants with the ability to purify water include *Alnus glutinosa* (Common Alder), *Salix cinrrea* (Grey Willow), *Phallaris arundinaceae* (Reed Canary Grass), *Deschampsia caespitose* (Tufted Hair Grass), or *Phragmites australis* (Common Reed), and many other vascular plants (plants that develop water-conducting vascular tissues), used in rain gardens (Mehmood et al., 2021; Sharma et al., 2021).

Table 6
Values of calculated biodiversity indexes for rain gardens in Gdańsk.

Rain garden	Shannon Evennes index (D)	Shannon Diversity index (H)
3 Maja St.	0.837	3.110
O'Rourke Square	0.909	3.205
eMOCja Center	0.963	3.100
Lastadia st.	0.943	3.631
Kaczeńce	0.929	3.275

With properly selected plants and layers, a rain garden can pre-treat storm water runoff from impermeable pavements. In this way, storm water is retained in the landscape through the processes of evapotranspiration (evaporation of water from plant cells and evaporation from the ground surface) and infiltration.

The evenness and diversity indexed for all analysed rain gardens are shown in Table 6. All rain gardens scored between 0.84 and 0.96. So, according (Castellar et al., 2021) they offer good overall performance addressing urban challenges and providing ecosystem services (Pedersen Zari, 2015). In comparison to the referred study, wherein a general rain garden as NBS achieved evenness score equal to 0.97, the gardens studied here obtained slightly lower scores, although across other different NBS, those scores are quite decent, e.g. a green walls system with an evenness of 0.91 and constructed wetlands with 0.925 (Castellar et al., 2021).

Clear relationships between biodiversity and ecosystem services contribution are highlighted in the scientific and policy literature, although the empirical evidence supporting these relationships (Schwarz et al., 2017) is limited. Biodiversity indexes can be supportive in terms of ecosystem evaluation; nevertheless, this is still an infrequent approach.

A research project presented by Connop et al. (2016) analysed a case study as an example of biodiversity-focused urban green infrastructure. This project discusses the relevance of habitats created within landscaping that has improved site biodiversity, recording 148 species of higher plants on just 0.5 ha of the urban landscape. The authors suggest that such a biodiverse green infrastructure can play a crucial role in urban conservation achievement if integrated on a landscape scale.

The basic aim was to ensure that urban green infrastructure design was multi-functional and self-sufficient, both in terms of being climate-resilient and relevant to biodiversity and conservation importance. To develop such objectives, the new development required a multidisciplinary, multi-stakeholder experimental approach to design and implementation into the strategic planning process, including design for amenity use, urban landscape design, and biodiversity (Connop et al., 2016).

Table 5
Dominant plant species used for rain gardens planting.

Rain garden	3 Maja St.	O'Rourke Square	eMOCja Center	Lastadia st.	Kaczeńce
Dominant plant species	• *Iris pseudacous* • *Glyceria maxima* • *Phalaris arundinacea* • *Acorus calamus* • *Phragmites australis*	• *Iris sibirica* • *Hemerocaliss* • *Anemone hybrid* • *Hosta sieboldiana* • *Darmera peltata*	• *Deschampsia caespitose* • *Lysimachia nummularia* • *Hemerocaliss* • *Myosotis scorpioides* • *Glyceria maxima*	• *Lysimachia nummularia* • *Iris sibirica* • *Deschampsia caespitose* • *Carex muskingumensis* • *Myosotis scorpioides*	• *Phragmites australis* • *Phragmites humilis* • *Rosa 'Rugby'* • *Glyceria maxima* • *Iris sibirica*
Total species number (S)	41	34	25	47	34
Total plant number (N)	4654	3913	783	4107	1248

3.5. Rain gardens for developing urban circularity challenges

According to many authors (Atanasova et al., 2021; Castellar et al., 2021; Langergraber et al., 2021; Oral et al., 2021), NBSs emerge as multifunctional and multiscale "green" technologies and solutions for reshaping the existing linear resource management as a circular one. Currently, the design and use of NBSs focus primarily on one specific urban challenge – for example, retaining storm water or mitigating the urban heat island effect, which was also confirmed in this paper. However, NBSs have the potential to address several urban challenges simultaneously, specifically concerning various Urban Circularity Challenges (UCCs). The following seven UCCs for shifting to circular management of resources with NBSs were identified by Atanasova et al. (2021): UCC1 "restoring and maintaining the water cycle", mainly through storm water management; UCC2 "water and waste treatment, recovery, and reuse"; UCC3 "nutrient recovery and reuse" with a focus on nitrogen, phosphorus, and potassium; UCC4 "material recovery and reuse", mainly as materials in a built-up environment; UCC5 "food and biomass production" in sustainable ways in cities; UCC6 "energy efficiency and recovery", including mitigation of the urban heat island effect, as well as heat and energy recovery from different waste streams; UCC7 "building system recovery" related to the topic of regeneration of a built-up environment.

The task of pre-existing rain gardens is to relieve the storm water drainage system in the city and to retain the storm water at the place where it is created in order to restore the natural water cycle. Thus, all rain gardens address urban circularity challenge 1 (UCC1) very well. By creating rain gardens throughout the city, it is possible to begin reestablishing a more natural water balance, reducing runoff peaks and volumes, and promoting infiltration, retention, and evapotranspiration. Groundwater recharge is an important factor in securing the drinking water supply of many cities (Foster, 2020).

In addition, rain gardens are designed to support biodiversity by planting various plant species depending on the water requirements (deep zones or shallow zones) in place of the monoculture grass currently present. Moreover, insect pots are planned for the rain gardens. Additionally, an objective of rain gardens is to treat storm water; therefore, different plants and depths of water are used to intensify unit treatment processes that address water and waste treatment, recovery, and reuse (UCC2). In the case of the rain gardens investigated, there has so far been no possibility of reusing water.

Urban circularity challenge 3 (UCC3) addresses the need for nutrient recovery and reuse. In the context of urban water, this is specifically related to the nutrients that are present in used water streams, and the different systems for recovering these nutrients. In the case of storm water the content of nutrients is limited (Nayeb Yazdi et al., 2021; Sharma et al., 2021) and so using rain gardens to address this challenge must be limited to exclusively local use of nutrients for the growth of rain gardens plants. According to data given by the operator of the rain gardens in Gdańsk, there has been no need to supplement rain gardens with artificial nutrients so far. Therefore, it seems that on this microscale of rain gardens, the nutrients from storm water could be sufficiently recovered by the plant at source to create a local habitat.

Circularity challenge 4 (CC4) concerns the materials pathways, and the possibilities for recovery and reuse within the urban environment. The main link that has been identified with the central water challenges is the connection between CC2 and CC4. Wastewater has attracted attention in recent years, not only as a source of nutrients but also raw materials for various other products. In this context, mature rain gardens could be a source of plants for planting newly built ones. The added value of this solution would be to reduce the adaptation time of plants. Local experience shows that plants purchased in gardening often adapt to the conditions of living in a highly urbanized area – e.g. in a lane of a busy road or a roundabout.

In the case of circularity challenge 5 (CC5), food and biomass production, can be linked to urban water in two directions, with both direct and indirect interdependencies. Rain gardens built in the city appear to address this change only indirectly by restoring and maintaining the water cycle, which will have a favourable impact on various aspects of food and biomass production: regular rainfall, increased humidity, moderate temperature peaks, and flood reduction. Moreover, enabling better growth of food, for example, in vertical farming or green roof or wall thus linking food and biomass production in the urban environment.

As mentioned above, rain gardens could also address urban circularity challenge 6 (UCC6) energy efficiency and recovery directly and indirectly. This aspect is often described as the water-energy nexus where water and energy are interlinked in terms of resource use (Carvalho et al., 2022; Scott et al., 2011). The water-energy nexus should be considered during the entire life cycle of resources and products. For instance, water is required for energy production and energy is essential for water abstraction, distribution, and treatment (Li et al., 2012; Zhang et al., 2018). Thus, rain gardens are constructed to retain the storm water before the pipe and thus unburden the grey infrastructure of Gdańsk city, including pumping stations; the more rainwater they retain, the less energy will be needed to pump the waste in the city.

Based on the above consideration made in the case study of rain gardens in Gdańsk, it could be concluded that this solution nicely meets urban circularity challenge 7 (UCC7). A rain garden could be an important item in the recovery of the building system, relates to urban water directly through UCC1 and UCC2, and indirectly through improvements in climate and resilience related to other implementations of NBSs from the urban water repository, the water-energy nexus (UCC3, UCC4, UCC5, UCC6).

3.6. Future challenges for rain gardens as a component of green infrastructure

Growing urbanization results in a considerable reduction in ecosystem services due to increasing impermeable pavement area, although ecosystem services are becoming ever more important because of climate change and growing urban population. Rain gardens as an NBS may be a crucial element for urban space to create cities resilient to climate change, increase biodiversity and protect landscape processes (Ishimatsu et al., 2017; Maes et al., 2015).

Currently, many European regulations have been directed at urban waste water quality and pollution reduction particularly in the terms of climate change, such as EU action plan: 'Towards zero pollution for air, water and soil' (European Commission, 2021b, 2019a, 2019b). A report on Water quality in Europe: effects of the Urban Wastewater Treatment Directive (Pistocchi et al., 2019) stated that 'in spite of the good progress made by most Member States, implementing wastewater treatment, (…) urban runoff (…) is not specifically addressed by the Directive, which contains only general principles regarding diffuse urban pollution and stormwater'. A representative example from Poland can be introduced, where according to Polish law regulation, it is possible to remove storm water runoff (including meltwater and snowmelt) without proper treatment from highly contaminated areas (i.e. industrial areas, main roads, airport areas, fuel storage, and distribution facilities) directly to the receiver (such as water, water devices, and ground) if a total suspended solid concentration of 100 mg/L and oil index (petroleum substances) of 15 mg/L are not exceeded. Furthermore, storm water runoff may also be discharged from unpolluted areas (like residence areas, impermeable pavements, roofs, etc.). However, under no circumstances can storm water be discharged into groundwater or water devices – if it contains substances that are considered to be particularly toxic to the aquatic environment (Journal of Laws of the Republic of Poland, 2019, 2017).

However, due to the urban characteristics of the catchment area, the storm water runoff can be affected by more than 700 different organic pollutants of anthropogenic origin, heavy metals, and trace inorganic compounds (Eriksson et al., 2007); therefore, contaminants such as persistent organic pollutants (POPs), including emerging pollutants and microplastics (Jakubowicz et al., 2022; Padervand et al., 2020; Werbowski et al., 2021) are expected to occur in urban runoff. Currently, these specific contaminants, because of their toxicity (carcinogenic and mutagenic effect) and their ability to bioaccumulate, pose a serious threat to living organisms and, as a result, to humans, by causing many diseases.

Among the basic specifications of storm water quality, the most significant is the amount of total suspended solids (TSS), particularly in urban runoff (Gavrić et al., 2019), because many pollutants are attached to particulate matter (Liu et al., 2019). Solids are considered as an important transport agent – e.g. metal contaminants (Bibby and Webster-Brown, 2005) – and in addition, the concentration of various pollutants can be strictly related to the number of suspended solids.

Microplastic contamination of different types of water is a relatively new addition to the scientific literature (Bigalke et al., 2021; Chia et al., 2021; Fu et al., 2021; Rakesh et al., 2021; Sucharitakul et al., 2021; Werbowski et al., 2021). However, the main source of microplastic pollution in receiving water is urban storm water runoff. In the long term, its toxicity can affect aquatic living organisms and the ecosystem. Moreover, the adsorption of persistent organic pollutants influences the human body through the bioaccumulation process (Godoy et al., 2021; Hossain et al., 2020). However, the presence of microplastics in the environment has not been adequately explored by the researchers, which is very sensitive and severe, as they become a part of the aquatic ecosystem by washing during rainfall, migrating in the vertical and horizontal direction to groundwater, impact soil properties, which influence the crop properties and transmit to plants, soil organisms and the human food-chain (Boots et al., 2019; O'Kelly et al., 2021).

A recent study conducted by Arslan and Gamal El-Din (2021), Garg et al. (2021), and Jakubowicz et al. (2022) showed that multistage treatment wetland as NBS, proved capable of removing microplastic and *per*- and poly-fluoroalkyl substances. For instance, the reduction efficiency ranged from 77.16 to 100% for microplastics (depending on the hydraulic load of the bed) and reached 100% for polycyclic aromatic hydrocarbons. However, further research is required on the processes of sorption and bioaccumulation of microplastic particles and how to remove and utilize them.

A specific contaminant that can also be expected in the urban catchment is caffeine as an anthropogenic marker of domestic waste (Kurissery et al., 2012); therefore, elevated levels of caffeine provide a strong indication of human faecal pollution (Panasiuk et al., 2015).

Other concerning contaminants are per- and poly-fluoroalkyl substances (PFAS). Their sources include aqueous film-forming foams derived from paper products, textile and leather coatings, cookware (non-stick coatings), waterproof fabrics, firefighting foams, industrial surfactants, and many others (Hossain et al., 2020). PFAS are characteristically persistent, mobile and bioaccumulative, repellent to water and oil, resistant to temperature, and non-degradable to the environment (Mueller and Yingling, 2017).

With increasing water pollution, monitoring and evaluating urban water quality are becoming more important. However, traditional evaluation methods are time-consuming, laborious, and vastly insufficient in terms of the continuity of spatiotemporal coverage. The remote sensing method has the advantages of a wide range, long time series, and cost-efficiency. Therefore, remote sensing has been applied to the assessment of urban water quality. Water quality specifications such as chlorophyll-a (Chla), total suspended solids, dissolved organic matter, and transparency have been retrieved from the remote sensing images of water areas significantly affected by urban activities, and the mapping results have been used for the evaluation of water quality (Cai et al., 2021).

The creation of one small-scale rain garden cannot guarantee provision of all benefits. The key factor in facing urban challenges and creating ecosystem services is to develop a network of green infrastructure in urban areas. Planning in the design process of rain gardens is crucial. It should consist of comprehensive site analysis including field inspection, geographic information system, analysis of planning documents, other city policies or flood hazard maps, and hydrological modeling of the catchment area with software such as flood screener, MIKE, or others. The second step should cover the identification of investment priorities and criteria such as range of influence point, neighbourhood, and frequency of nuisance occurrence.

Furthermore, developing a participation process and social acceptance during the introduction of the demonstrator site is a good practice, among others by inviting residents to plant rain gardens together, and promoting the demonstrator through the media to help introduce changes and counteract resistance from those who are unconvinced by an idea. Finally, the objectives of the new policy of smart and sustainable management of the storm water in existing urban spaces should be clearly defined.

4. Conclusions

The duration of the water level in NBSs such as rain gardens depends on many factors, including the retention area, the geological structure of the soil, the amount and type of vegetation used (transpiration area) and the degree of evapotranspiration, and usually lasts from several hours to several days. Additional infiltration processes allow for the maintenance of moisture in the top layer of the soil and the proper functioning of the root systems of plants, which, thanks to the water, take up the nutrients necessary for proper vegetation. The processes of photosynthesis in plants, which rely on the absorption of water and carbon dioxide (removing excess gas from the atmosphere) with the participation of light, produce oxygen necessary for life on Earth.

The performed investigation has shown strong variation in the infiltration rate between the monitored rain gardens. The measured infiltration rate ranged from 0.420 up to 0.707 m/day and is comparable to the international values of the infiltration capacity of rain gardens. This hydraulic performance of the natural substrate of Gdańsk rain gardens is sufficient to store 30 mm of precipitation in time to prevent flash flooding and drought mitigation.

All the processes mentioned above that take place in rain gardens systems contribute to the improvement of the local microclimate, e.g., increasing soil and air humidity (evapotranspiration), lowering the temperature, and thus minimizing the phenomenon of the so-called urban heat island. Even during cloudy weather, the surface temperature of the rain garden was up to 7 °C lower than the surrounding pavements or streets, while for sunny weather, this difference increased to 20 °C.

All the investigated rain gardens were characterized by a very high Shannon Evenness Index from 0.84 to 0.96 supporting biodiversity by creating comfortable living places for many species of plants and animals and by improving the quality of stormwater. In addition, rain gardens also perform an aesthetic and social function, thus supporting all ecosystem services. Furthermore, a properly designed network of rain gardens in the city could also meet all urban circularity challenges and support building system recovery related to the regeneration of a built-up environment.

In our work, we define the two most important challenges that rain gardens face: (i) the ability to remove new emerging pollutants such as microplastics and *per*- and polyfluoroalkyl substances and (ii) how to develop a network of green infrastructure with rain gardens in urban areas. Two challenges are equally relevant: planning in the design process with proper and tailored design, as well as developing the participation process and social acceptance of rain gardens.

CRediT authorship contribution statement

Magda Kasprzyk: Data curation; Methodology; Investigation; Visualization; Formal analysis; Writing - Original draft preparation; Writing - Reviewing and Editing.

Wojciech Szpakowski: Data curation.

Eliza Poznańska: Data curation; Writing - Original draft preparation.

Floris C. Boogaard: Data curation; Methodology; Investigation; Visualization; Writing - Original draft preparation.

Katarzyna Bobkowska: Data curation; Methodology; Investigation; Visualization; Writing - Original draft preparation.

Magdalena Gajewska: Conceptualization; Methodology; Validation; Supervision; Project administration; Writing - Original draft preparation; Writing - Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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