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THE CONCEPTION OF RAINWATER HARVESTING FOR WAREHOUSE HALL

Abstract:

Due to the decreasing resources of non-renewable fresh water and climate changes leading to more frequent intense rainfalls, designed solutions are desired to manage rainwater in accordance with the principles of blue-green infrastructure. This paper discusses four concepts of rainwater management for a warehouse hall using solutions such as drainage boxes and bio-retention basins with hydrophytic vegetation. The designed rainwater drainage system also includes a rainwater pre-treatment system, including a sedimentation tank and a petroleum derivatives separator and, depending on the concept's requirements, a rainwater pumping station. Some amount of rainwater will be reused for building maintenance needs (e.g. toilet flushing, cleaning) and for irrigating green areas. The aim is to maximize the use of rainwater within area where it occurs and to show the hybrid solutions of rainwater management.

Keywords: blue-green infrastructure, climate change, rainwater harvesting

ОСМИШЉАВАЊЕ И РАЗРАДА КОНЦЕПТА ПРИКУПЉАЊА КИШНИЦЕ ЗА СКЛАДИШНУ ХАЛУ

Сажетак:

Усљед смањења расположивих ресурса необновљиве слатке воде и климатских промјена, које доводе до све учесталијих интензивних падавина, јавља се потреба за пројектованим рјешењима управљања кишницом у складу са принципима плаво-зелене инфраструктуре. У овом раду разматрају се четири концепта управљања кишницом за складишну халу, примјеном рјешења као што су кутије за дренажу и биоретензије са хидрофитском вегетацијом. Пројектовани систем за дренажу такође обухвата систем претходног пречишћавања кишнице, који укључује таложник и сепаратор нафтних деривата, и у зависности од захтјева концепта, пумпну станицу. Одређена количина кишнице биће поново искоришћена за потребе одржавања објекта (нпр. испирање тоалета, чишћење) и наводњавање зелених површина. Циљ истраживања је максимизација искоришћења кишнице у зони њеног настанка, као и приказ хибридних рјешења управљања атмосферским водама.

Кључне ријечи: плаво-зелена инфраструктура, климатске промјене, прикупљање кишнице

1. INTRODUCTION

Due to climate change and the increasingly rapid development of urban areas, the difficulties regarding the management of rainwater occur. Rainfalls have become less frequent, but more intense, which causes, e.g. flash floods in cities. The solution to this problem is to retain as much water as possible in the place where it falls, which allows to reduce the overloading of the storm sewerage system.
Rainwater used to be treated as a problem – it was captured in sewage systems and discharged outside urban areas to avoid local flooding. Nowadays, however, it is used as a valuable resource that helps minimize the impact of human activities on water management. A properly designed rainwater sewerage network allows for the retention of collected water and its consumption, e.g. during droughts.
Poland's water resources are getting poorer, which may result in a water deficit. The amount of renewable freshwater resources is below the value of the water security level defined by the United Nations and amounts to 1.6 thousand m^3 per capita [1]. A comparison of this value is shown in Figure 1.

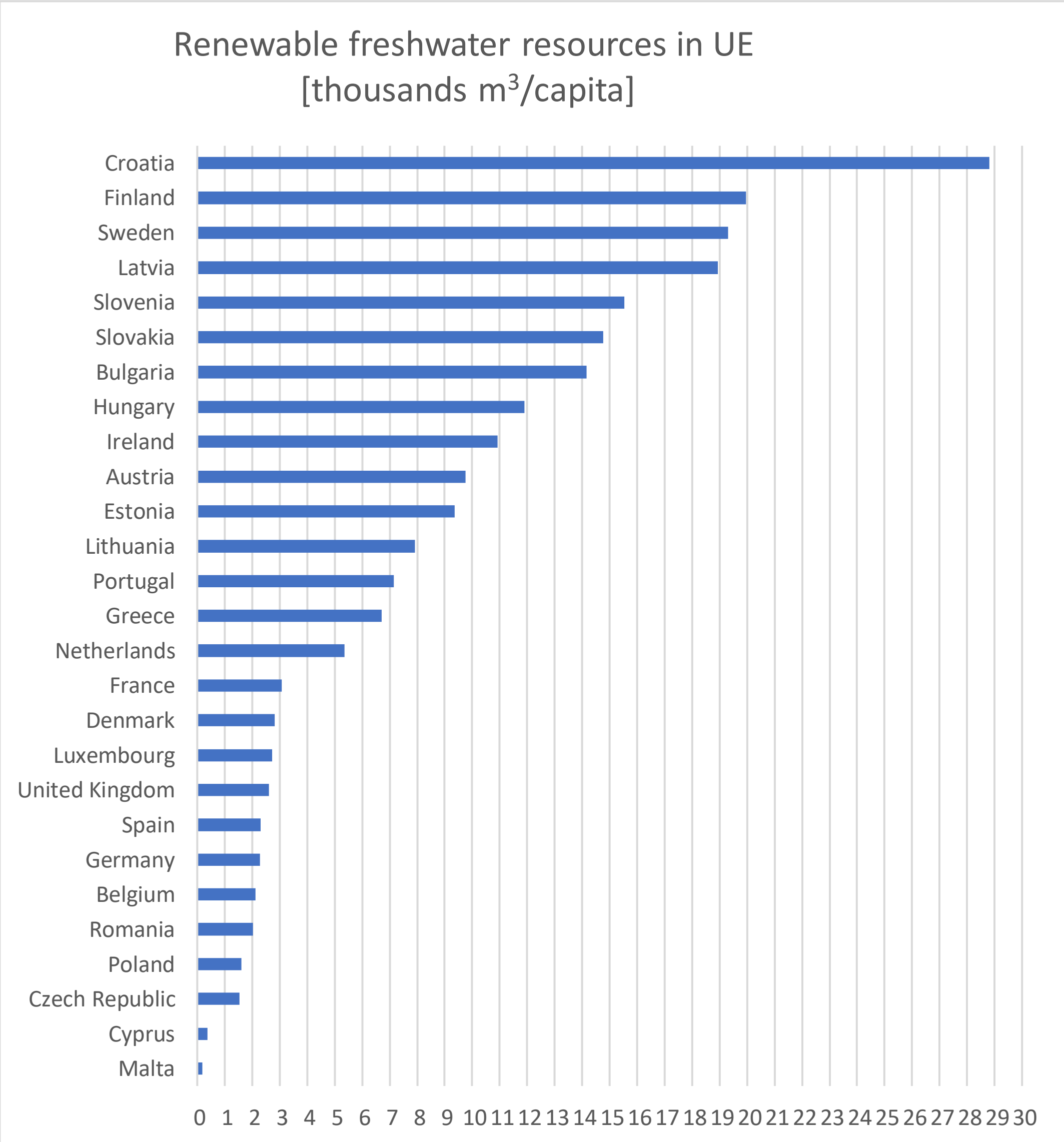

Figure 1. Comparison of renewable freshwater resources in EU (prepared by the authors based on [1]).

The most significant and noticeable effects of increased surface runoff in urban areas include:

- property damage, such as flooding of buildings and assets,
- damage to transport and utility infrastructure,
- threats to the health and safety of humans and animals.

Additionally, increased surface runoff results in higher peak discharge rates and a reduction in catchment concentration time. Consequently, small receiving water bodies are often degraded, as they become components of urban drainage systems during intense rainfall events [2], [3]. Reuse of rainwater not only prevents floods, but also protects stormwater and combined sewer systems from deterioration of pipes, and helps to avoid the discharge of pollutants into receiving waters [4].

Rainfall also plays an important environmental and social role in urban areas. It can mitigate the urban heat island effect, increase air humidity, and reduce excessive dust formation. Furthermore, open water bodies serve as spaces for recreation and relaxation.

Despite the evident risks associated with heavy rainfall—such as floods, economic losses, and threats to human life and health—rainwater contributes to improving living conditions in highly urbanized areas with a large proportion of impervious surfaces. Therefore, appropriate stormwater management is essential to minimize its adverse impacts while maximizing its potential benefits [5], [6].

The literature [3], [7], [8], [9], [10], [11] reports numerous implementations of rainwater management systems in various urban areas. These solutions typically involve retention tanks that collect rainwater from building rooftops, which is subsequently reused for non-potable purposes such as cleaning, landscape irrigation, and toilet flushing. The design of rainwater management systems depends on multiple factors, including climate conditions, the quantity and quality of rainfall, soil and groundwater conditions, space availability, site characteristics, and the technical and operational conditions of the existing sewer system. Consequently, each rainwater management system is site-specific and characterized by its own capabilities and limitations.

The main aim of the paper is to present various concepts of the rainwater management for the designed warehouse hall located in northern Poland in the city of Chojnice. The conducted calculations focus on the use of rainwater collected from the roof of the building and on minimizing the runoff of rainwater from the investment site to the municipal rainwater sewer system.

As part of the research, calculations of reused rainwater and runoff were made; several concepts for rainwater management were prepared, a rainwater management project was prepared along with the necessary hydraulic calculations and sewer profile; appropriate devices and hydrophytic vegetation were selected.

2. METHODOLOGY AND DATA

2.1. AMOUNT OF RAINWATER

The volume of rainwater is primarily determined by two factors: the depth of precipitation and its intensity [12]. Poland, due to its diverse geographical conditions, is characterized by an average annual precipitation of 500-600 mm in the central part and 450-550 mm in the lowlands. The highest values were recorded in mountainous regions with the amount to 800-1500 mm [13], as shown in Figure 2. For Chojnice city the value of average annual precipitation is 650 mm.

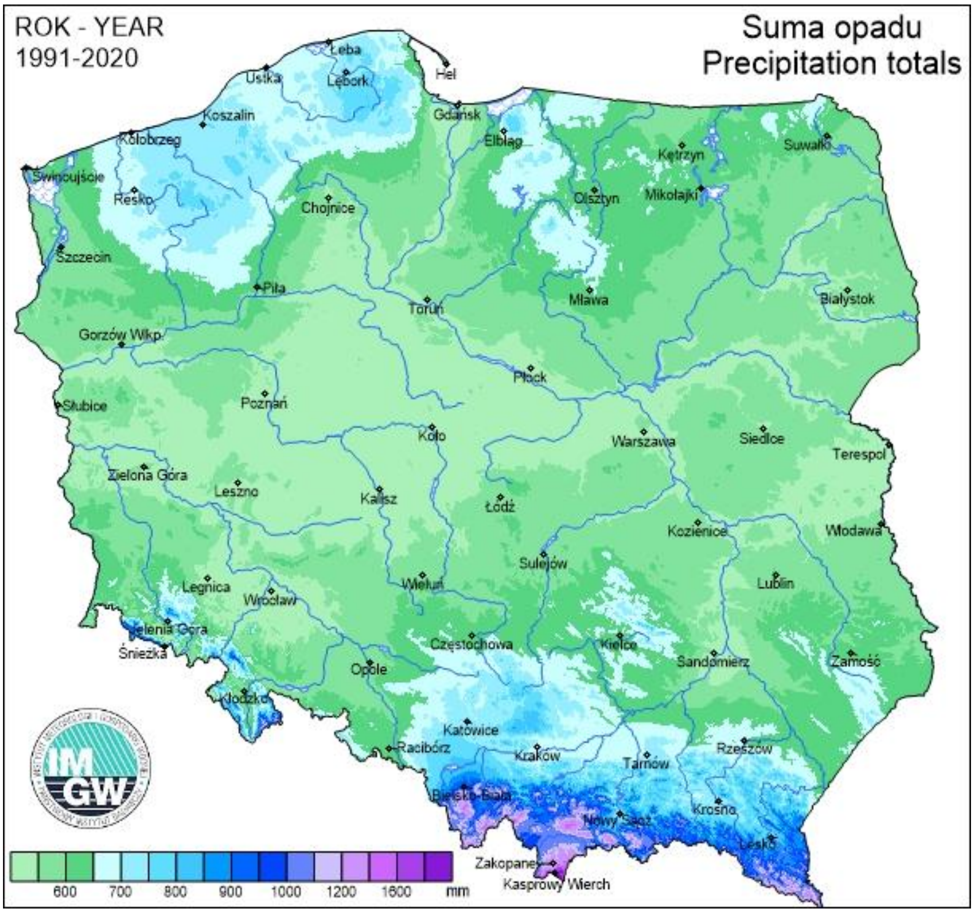

Figure 2. The average rainfall depth in Poland [14].

2.2. QUALITY OF RAINWATER

The quality of rainwater is influenced by chemical compounds found in the atmospheric air and pollutants with which the water comes into contact during the surface runoff phase. Depending on the degree of industrialization of a given region, the composition of rainwater will differ from each other.

The main pollutants that rainwater absorbs from the atmosphere are: significant amounts of dissolved gases, e.g. carbon dioxide, oxygen, nitrogen and residues of insecticides, herbicides or fungicides. The composition of rainwater, and thus the degree of pollution, is influenced by factors such as traffic intensity and distance from green areas [15].

The contaminants that enter rainwater from the surface on which it falls depend on the type and intended use of that surface. The most common dangers are those resulting from the abrasion of tires and the upper layer of the road. Equally dangerous are the pollutants that remain on the surface as a result of car accidents or poorly transported materials. Rainwater from parking lots and communication routes is particularly contaminated with the presence of petroleum substances, heavy metals, etc. A serious danger appears after a period of drought, when pollution accumulates on the roads and then ends up in sewage systems with rain. It should be noted that in winter there is an increase in contaminant concentrations resulting from de-icing agents entering the drainage system [16].

Runoff from smooth roof surfaces (i.e., those covered with ceramic tiles, metal roofing, glass, synthetic materials, etc.) is not contaminated with petroleum-derived substances or heavy metals. It can therefore be reused, provided that this water is collected before coming into contact with other catchment areas where the above-mentioned contaminants are present [15].

2.3. METHODS OF RAINWATER HARVESTING

In order to minimize the outflow in the stormwater sewer systems in urban areas, the rainwater should be harvested within the catchment. This can be achieved by using devices such as, e.g.: retention basins; retention reservoirs, retention and infiltration reservoirs; green and gravel roofs [16].

These devices retain rainwater during the highest rainfall intensity and allow water to be retained or gradually drained, while reducing the risk of overloading sewers [17]. In addition, they help in the fight against water deficit. Some of the above-mentioned devices allow for water retention and use during drought, while others support water infiltration.

2.3.1. Drainage boxes

Drainage boxes, which are a type of retention tank, are gaining more and more popularity among designers. Ease of operation and the ability to be installed in a limited space further support the selection of this device. Drainage boxes do not have a significant impact on the development of adjacent areas [18].

2.3.2. Retention basins

A solution eagerly used in green urban areas is the retention basin planted with hydrophytic vegetation (Fig. 3). It supports water infiltration, which can contribute to the protection of non-renewable water resources. In addition to the benefits of water management, it also has a positive effect on the aesthetic values of the landscape and the microclimate, as during the period of increased temperatures they cause a decrease in air temperature and better thermal comfort. These basins create ideal conditions for lush vegetation or for various species of animals to live in [18].

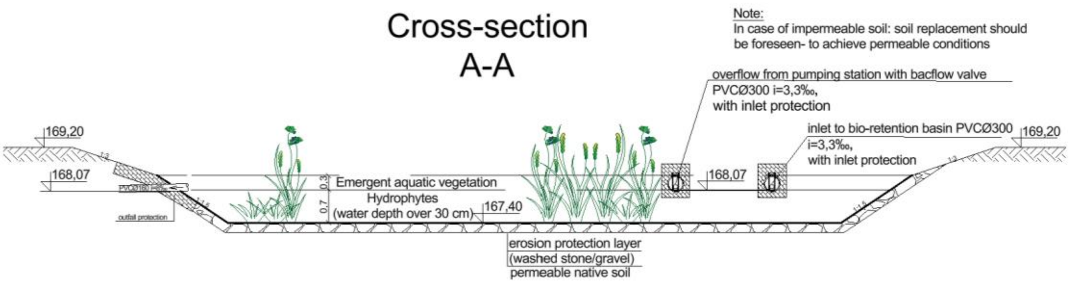

Figure 3. Scheme of bio-retention basin with hydrophytes (prepared by the authors based on [19]).

2.3.3. Retention reservoirs

Retention reservoirs are widely used in stormwater sewer systems in order to enable the management of excess runoff and minimize the overloading of sewers [2]. Retain rainwater can be reused for purposes that do not require drinking water quality. The quality of water retained in the reservoir may prove problematic, as it is variable and depends, among other things, on the type of the catchment, the water retention time in the reservoir and the temperature. The retention time depends on the length of the dry and rainy seasons [20].

2.4. DESCRIPTION OF EXISTING CONDITION

Designed warehouse hall is located in northern Poland in Chojnice city (Fig. 4)

Figure 4. Location of Chojnice city in Poland (own source).

The planned facility will be located within a catchment with a total area of 2.05 ha.
At present, the construction plot is undeveloped. Adjacent areas contain existing electricity, water supply, telecommunications, and gas networks, as well as planned sanitary and stormwater sewer systems [21].
The catchment is located in a lowland region. The average height of the area is 169.00 m above sea level. The city of Chojnice is located in the first zone of ground freezing, which means that the freezing depth is 0.8 m.
The catchment is located outside the flood risk area for a probability equal to 1% and 0.2% [21] and is not located within the boundaries of areas covered by nature protection. The nearest natural monument is located at a distance of about 1 km in a straight line and it is a common yew.

Table 1. List of surface areas

Surface type/Use	Area [m^2]
Warehouse hall	3160.00
Administrative and office areas	465.54
Parking lots and circulation areas	5373.56
Green areas	11178.9
Total area	20178.00

The designed facility will be a warehouse hall with an area of 3160 m^2 and an administrative and office part with an area of approx. 465.5 m^2. The areas adjacent to the building will be designated for parking lots and a communication route made of cobblestones. The remaining part of the plot will be adapted as green areas. A detailed list of surfaces can be found in Table 1.

3. CONCEPTS OF RAINWATER MANAGEMENT

Rainwater from the catchment area will be collected using two separate storm sewer systems. Regardless of the rainwater management concept, rainwater from the roofs will be collected using a vacuum roof drainage system and conveyed into a retention tank, from where it will be reused for the maintenance of the warehouse hall. Although vacuum roof drainage systems are typically designed for the rapid removal of large volumes of rainwater from extensive roof surfaces, their application in rainwater harvesting systems is less common. This is because such systems operate under pressurized flow conditions and are optimized for high-intensity rainfall events rather than controlled water retention.
In the present concept, however, the vacuum system is used to efficiently collect runoff from the large roof area of the hall and convey it to a retention tank, enabling effective utilization of the collected rainwater while maintaining high drainage performance during extreme events.

Rainwater collected from the remaining surfaces will be directed to the other stormwater sewer system using rainwater drains and linear drainage, and then it will be conveyed to a pre-treatment system consisting of a high-efficiency vortex sediment tank and a high-efficiency lamellar separator of petroleum derivatives. The further part of the storm sewer system is varied depending on the concept.
Concept I (Fig. 5) provides an underground retention tank for water collected from the hall roof, with an emergency overflow to a retention basin planted with hydrophytic vegetation, from which a further overflow leads to a stormwater sewer system collecting runoff from other surfaces. After the pre-treatment system, the collected water goes to the drainage boxes, from which the emergency overflow leads to the municipal stormwater sewer system.

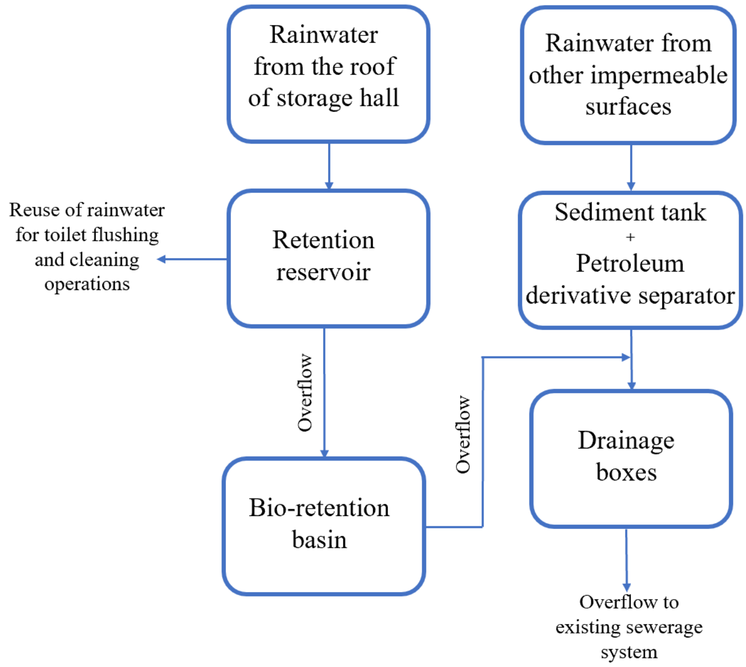

Figure 5. Scheme of concept I (own source).

Concept II (Fig. 6) assumes an emergency overflow from the retention tank for water collected from the roof of the hall to the drainage boxes, from which an emergency overflow will be made to the stormwater sewer system in the catchment area. Rainwater from the remaining areas will be directed to a bio-retention basin and then will be directed to the municipal stormwater sewer system through an emergency overflow.

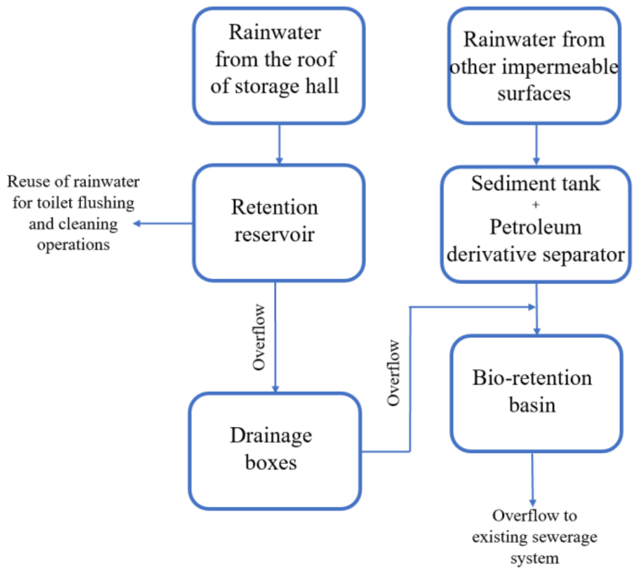

Figure 6. Scheme of concept II (own source).

Concept III (Fig.7) describes the management of rainwater collected from the roof of the hall in the same way as in concept I. Water collected from the remaining catchments will be directed to a separate bio-basin, which affects the aesthetic values of the area adjacent to the hall. Basin 1 (intended for water from the retention reservoir) will be located next to the administrative and office part. Basin 2 is being designed behind the warehouse building near the truck docks. After flowing through Basin 2, the water will be conveyed to the drainage boxes, from where it will be directed to the municipal stormwater sewer system by emergency overflow.

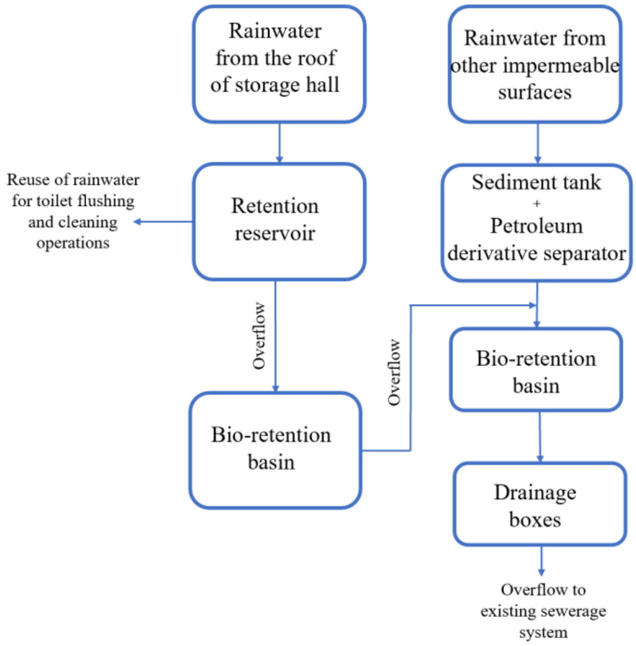

Figure 7. Scheme of concept III (own source).

In concept IV (Fig. 8), rainwater from the roof of the hall and pre-treated rainwater from other surfaces will be conducted to a bio-retention basin with hydrophytic vegetation, and then to drainage boxes. An emergency overflow to the municipal stormwater sewer system is designed.

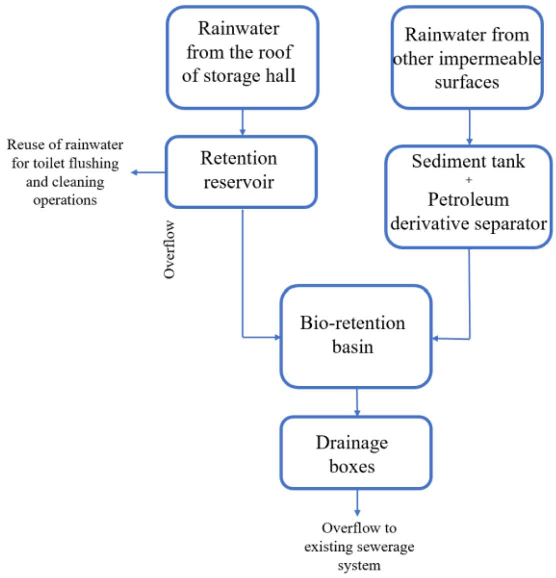

Figure 8. Scheme of concept IV (own source).

For each concept, hydraulic calculations were performed to avoid unnecessary oversizing of the sewers, and the slopes of sewers were designed to achieve at least the self-cleaning velocity. The construction of green roof was not taken into account due to large additional investment cost according to the strengthening of the building's construction.

All presented stormwater management concepts met the hydraulic loading requirements and allowed for the full retention of rainwater runoff under the assumed design conditions (e.g., frequency of occurrence c = 5 years and a rainfall duration of 15 minutes). For comparison purposes, only their impact on the surrounding environment was considered, while investment costs were not taken into account.

For detailed hydrological and hydraulic calculations, the investment area was divided into 12 sub-catchments (Fig. 9), thus determining the flow through a given cross-sections. A list of the areas of sub-catchments is presented in Table 2.

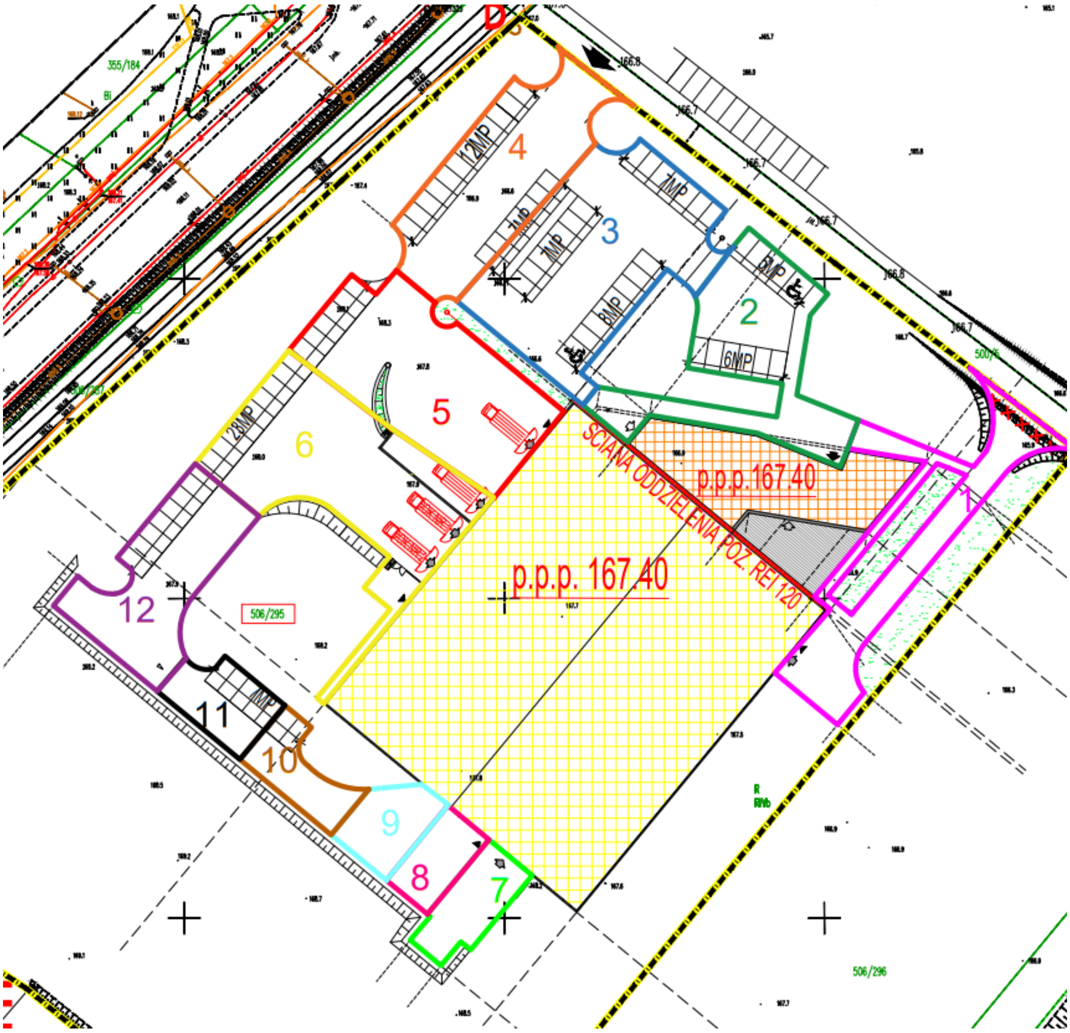

Figure 9. The investment area divided into sub-catchments for detailed hydrological and hydraulic calculations.

Table 2. Areas of sub-catchments

Sub-catchment	Area [m^2]	Area [ha]
1	478,13	0,048
2	553,98	0,055
3	858,13	0,086
4	608,74	0,061
5	719,9	0,072
6	810,32	0,081
7	162,36	0,016
8	126,1	0,013
9	151,83	0,015
10	147,71	0,015
11	165,93	0,017
12	449,82	0,045

4. ANALYSIS OF THE CONCEPTS

For all four conceptual variants, stormwater management devices were selected. Due to the lack of Polish procedures for the dimensioning of the selected devices, German standards were applied.

Retention tanks for the reuse of rainwater were designed in accordance with the German standard DIN 1989-1:2001-10 [22]. In this method the rainwater resources V_r *[dm³]* are calculated as:

$$V_r = \mathrm{A} \cdot \mathrm{c} \cdot h_{av} \quad [dm^3] \tag{1}$$

where:
A [m²] catchment area,
c [-] average runoff coefficient,
h_{av} [mm] average annual rainfall

Next step is calculating water demand V_{wd} *[dm³]* for building area (e.g. for toilet flushing, cleaning, laundry, irrigation of green area):

$$V_{wd} = L_p \cdot \mathrm{UADD} \cdot 365 + A_{green} \cdot q_{irrigation} \quad [dm^3] \tag{2}$$

where:
L_p [resident] number of residents/employees in the building,
UADD [dm³/(day·resident)] unit average daily demand,
A_{green} [m²] irrigated green area,
$q_{irrigation}$ [dm³/m²] water demand for irrigating the green area while the whole year

The value of V_r *[dm³]* is compared with the water demand V_{wd} *[dm³]* and the lower value is chosen for further calculations. This value then is multiplied by the coefficient equal to 0,06 to compute the volume of retention tank V_{rt} *[dm³]*. The coefficient 0,06 represents the retention storage time during the year- it is assumed that the storage time should be 3 weeks, which gives $\frac{21}{365} = 0{,}06$.
Water demand in the research was calculated for the following purposes:

- toilet flushing (UADD= 12 dm³/(day·employee)) , assuming 158 employees working in the warehouse hall and 20 employees working in the office area;
- cleaning of the warehouse hall area (UADD= 2 dm³/(day·employee));
- cleaning of office spaces (UADD= 3 dm³/(day·employee));
- irrigation of green areas, assuming manual watering ($q_{irrigation}$= 60 dm³/m²).

Drainage boxes and retention basins were designed in accordance with the German standards ATV-A 117 [23] and ATV-A 138 [24]. The length of drainage boxes *L [m]* was calculated by using formula [23]:

$$L = \frac{q \cdot A \cdot c \cdot T}{b \cdot h \cdot a + (b + \frac{h}{2}) \cdot \frac{k}{2} T} \quad [m] \tag{3}$$

where:
q [m/s] design rainfall–runoff flux (infiltration rate per unit area),
A [m²] catchment area,
T [s] rainfall duration,
b [m] width of drainage box,
h [m] height of drainage box,
a [-] storage coefficient for drainage box,
k [m/s] filtration coefficient

The calculations were performed for rainfall with the frequency of occurrence c= 5 years and rainfall durations from 5 min to 360 min. The soil was assumed to consist of medium-grained sand with a filtration coefficient of $k_f = 10^{-4}$ m/s, extending to a depth of approximately 3–4 m below ground level, depending on the location of the stormwater infiltration devices. Geotechnical investigations confirmed the absence of groundwater. For the calculations, drainage boxes with parameters specified in the manufacturer’s technical data sheet were adopted: width 0.6 m, height 0.6 m, and a storage coefficient of 0.95. The side slopes of the designed retention basins were set at a gradient of 1:1.5.
Stormwater pumping stations, a separator, and a sedimentation tank were designed in accordance with the latest technical knowledge. The separator and sedimentation tank were required according to Polish regulation [25] for the discharge of stormwater from parking lots, roads, and paved surfaces. The dimensioning of those devices was based on the maximum flow through them.
The volume of retention basins V_r *[m³]* were computed by using the following equation [24]:

$$V_r = (\mathrm{q} \cdot \mathrm{A} \cdot \mathrm{c} - V_{outflow} \cdot T) \cdot \frac{1}{1000} \quad [m^3] \tag{4}$$

where:
q [$dm^3/(s \cdot ha)$] design rainfall intensity,
$V_{outflow}$ [m^3] outflow volume,
$\frac{1}{1000}$ unit converter from [dm^3] into [m^3]
The basins will be planted with hydrophytic vegetation.

The adopted solutions were designed according to the principles of sustainable stormwater management, with a focus on retaining the maximum possible amount of rainfall within the catchment area. Rainwater collected from the roof of the warehouse hall will be reused to partially meet the water demand of the planned building, resulting in both economic benefits related to building operation and a reduction in potable water consumption.
The solutions applied for the management of stormwater collected from the remaining sub-catchments focus on increasing infiltration into the ground, thereby reducing hydraulic overload of the municipal stormwater sewer system during extreme rainfall events.
Concept I focuses on efficient water management using solutions optimized in terms of both investment and operational costs. The majority of collected stormwater is directed to an infiltration system made of drainage boxes. This concept not only minimizes the occupation of green areas but also eliminates the need for stormwater pumping, resulting in additional cost savings.
Concept II focuses on the separate management of stormwater collected from the hall roof and from parking lots and traffic routes. Rainwater not reused within the building is directed to the drainage boxes secured with an emergency overflow. The remaining stormwater is discharged to a bio-retention basin.
Concept III assumes two bio-retention basins planted with hydrophytic vegetation, located in different areas of the site. The smaller basin, intended for stormwater collected from the warehouse roof, is located near the administrative and office part of the building, allowing employees to use the green area during breaks, which may positively affect well-being and work efficiency. The second basin is located near the warehouse area. The planted retention basins will serve as a visual enhancement of the undeveloped part of the site. Stormwater not managed by these basins will be directed to the system of drainage boxes.
Concept IV is based on collecting stormwater not used to meet the building's water demand and combining it with runoff from the remaining surfaces into a single system. Stormwater is directed to a bio-retention basin located near the warehouse hall and subsequently to the drainage boxes.
The parameters of the selected devices for all concepts are presented in Table 3.

Table 3. Parameters of selected devices for all concepts

	Concept I	Concept II	Concept III	Concept IV
Retention reservoir	V_{rt}=128 m^3	V_{rt} =128 m^3	V_{rt} =128 m^3	V_{rt} =128 m^3
Drainage boxes	L= 253 m V= 95 m^3	L= 108 m V= 39 m^3	L= 43 m V= 15,6 m^3	L= 108 m V= 39 m^3
Bio-retention basin	V_r= 40 m^3	V_r = 81 m^3	V_{r1}= 39 m^3 V_{r2}= 65 m^3	V_r= 81 m^3
Sediment tank	Q=100 $\frac{dm^3}{s}$	Q=100 $\frac{dm^3}{s}$	Q=100 $\frac{dm^3}{s}$	Q=100 $\frac{dm^3}{s}$
Petroleum derivative separator	Q=100 $\frac{dm^3}{s}$	Q=100 $\frac{dm^3}{s}$	Q=100 $\frac{dm^3}{s}$	Q=100 $\frac{dm^3}{s}$

Each concept also differs from each other with the configuration of the devices and pipes according to the schemes on Fig.5-8. Concept III as an example is shown on Figure 10.

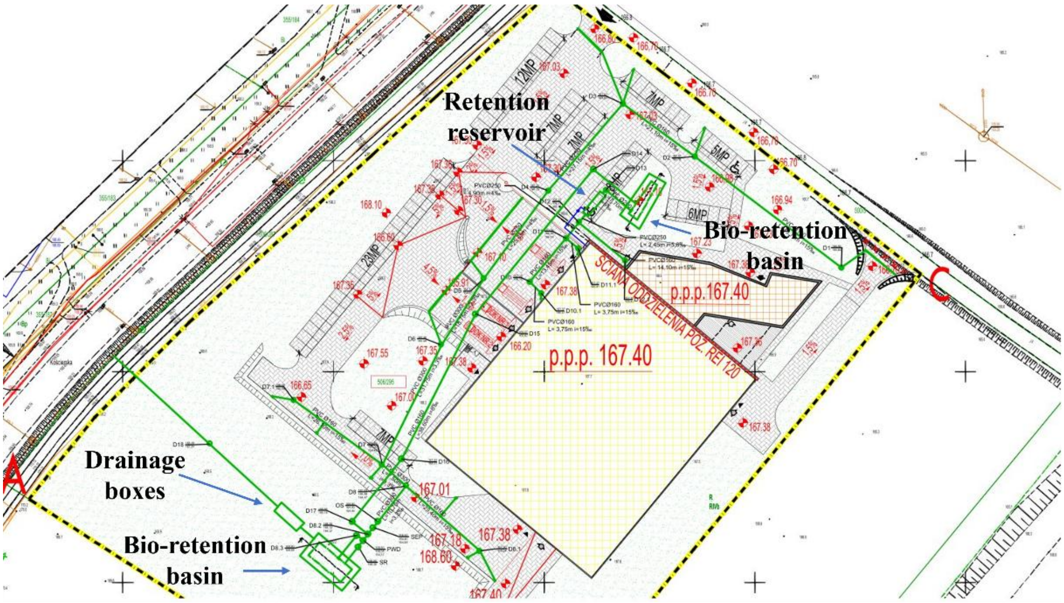

Figure 10. The investment area divided into sub-catchments for detailed hydrological and hydraulic calculations (sewers are green lines)

The use of rainwater reduces the amount of stormwater discharged into the sewer system and contributes to reducing the fees for the service of conducting rainwater into the sewer. At the same time, by reusing rainwater for specific purposes, water intake from local municipal water supply system is reduced, which is also associated with another reduction in fees. The rainwater which can be collected from impervious surfaces is equal to 2135 m^3 in one year (assuming average rainfall depth).

5. SUMMARY AND CONCLUSION

The increasing degree of urbanization is accompanied by an expansion of impervious areas. This has a direct impact on rainwater runoff: the reduction of permeable areas significantly increases the risk of floods during intense or prolonged rainfall events. Consequently, this not only results in material losses for residents but also leads to greater outflows within the sewer system and higher concentrations of pollutants in the wastewater reaching the treatment plant or other receiver.

The solutions presented in the paper are in line with the principles of sustainable rainwater management through the use of retention basins, retention tanks and drainage boxes. In order to protect non-renewable freshwater resources, rainwater reuse is designed to reduce the amount of water taken from the local municipal water supply system. These solutions will bring economic and ecological benefits to the investment.

The designed rainwater management will not cause overloading of the municipal stormwater sewer system to which the designed investment is connected. The research focuses on increasing rainwater infiltration, storage retention, a pre-treatment of rainwater in bio-retention reservoirs. It was also decided to reduce the expenses related to the operation of the warehouse hall by using a rainwater reuse system. A key element of this system is a retention tank, which allows water to be collected and reused for building maintenance.

It was decided to design bio-retention basins, which, in addition to having a positive impact on water management, improve the aesthetic values of the areas adjacent to the facility. They create a friendly environment where employees can relax during breaks at work and also improve the microclimate. Bio-retention basins contribute to reducing the urban heat island effect by providing cooling through evapotranspiration processes.

The above mentioned properties make bio-retention basins preferred solutions for rainwater management. They are also highly valued by the public, serving as spaces for relaxation, social interaction, and contact with nature. In addition, bio-retention systems contribute to lowering ambient temperatures, thereby improving thermal comfort in the closest surroundings. With the use of appropriate plantings, they can also provide preliminary treatment of rainwater and snowmelt runoff.

The four presented stormwater management concepts were not compared in terms of investment costs, which depend on numerous factors, including the selected materials, strength parameters, soil and groundwater conditions, and the depth of installed devices. Moreover, costs may vary depending on the contractor and require market research and comparison of at least several offers for each solution. Taking into account a hydraulic criteria, each of the proposed concepts is technically correct and allow to retain the total runoff caused by the design storm.

Considering environmental benefits and employees comfort, the recommended solution is concept 3, which incorporates two bio-retention basins.

The results of the paper shows the diversity of hybrid solutions for rainwater harvesting including:

- reuse of rainwater, what causes the decrease of tap water usage;
- infiltration, what helps to recharge the groundwater;
- bio-retention basins which improve thermal comfort during hot weather and have high aesthetic values.

Future research should consider advanced stormwater management systems incorporating real-time monitoring and control. Such systems are typically equipped with flow meters or sewer level sensors, water level sensors in retention tanks, rain gauges, and data loggers integrated with weather forecasting systems. This configuration enables predictive operation, allowing the system to respond to rainfall events. For instance, in the case of a forecasted intense rainfall, retention tanks can be emptied by using pumps to be enabled to capture the maximum part of surface runoff. The implementation of such intelligent systems may significantly improve the operational performance of rainwater infrastructure and contribute to more effective management of urban runoff under changing climatic conditions.

AKNOWLEDGMENT

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