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Assessment of blue and green infrastructure solutions used in housing estates – spatial and functional aspects

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ABSTRACT

The article presents the assessment of 14 solutions most often used for supporting water circulation in residential areas. They were valorized in relation to the spatial and functional aspects. The results were derived using the scoring method and allowed for the identification of the value of the studied solutions on three levels: high (rain gardens, street side bioretention basins), medium (green roofs, infiltration wells, infiltration trenches and grassed swales, grassed retention and infiltration basins, permeable pavements, and infiltration boxes), and low (wetland ponds, sealed surface and underground water reservoirs, and water squares). Sustainable water management in housing estates requires a conscious selection of blue and green infrastructure solutions based on their individual features. The implementation of solutions assessed as more valuable may increase the impact of these areas in mitigating the negative effects of climate change and support the aims of the European Green Deal strategy.

Keywords: Water retention; Rainwater management; Blue and green infrastructure; Sustainable development; Residential area; European Green Deal

1. Introduction

Water is a basic asset and an important element of the natural environment. Its value is fundamental to meeting the main aims of the initiatives of the European Green Deal launched by the European Commission to make European climate neutral in 2050 [1]. Sustainable development of contemporary cities should also achieve many of the United Nations Sustainable Development Goals, including Goal 6: which calls to ensure the sustainable management of water [2,3]. However, meeting them is difficult as many cities face serious problems in terms of water management. The urbanization processes of the last decades associated with increasing density of cities are conditioned by the intensification of buildings, domination by impermeable surfaces and reduction of biologically vital areas [4], which has a negative impact on water management [5]. Those changes have led to the disappearance of many natural water elements resulting in an increasing flooding risk and other various extreme hydrometeorological phenomena [6,7]. One of the serious problems of modern cities is also the unresourceful use of water. Regarding many problems, rainwater management is a great challenge to modern cities [8]. Commonly used methods of water discharge into stormwater drainage systems are ineffective in the event of torrential rains [5]. They are based on the use of sewage systems which do not cover the entire city, are subject to intense degradation and overloaded [9,10]. This approach disrupts the hydrological cycles including an increase in the water deficit within cities [11–13].

Modern, and therefore sustainable planning and design of housing estates should follow the contemporary trends related to the use of nature based solutions (NBS) [14,15] and concepts supporting water management such as sustainable urban drainage systems (SUDS), low impact development (LID), best management practices (BMPs),

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and water-sensitive urban design (WSUD) [16–18]. All of them focus on the achievement of a significant reduction of rainwater runoff (collecting water for utilization or storage), increased infiltration and evaporation by treating as close to the source as possible, as well as increased water quality and its reuse [19–22]. Their positive impact is also associated with supporting ecological processes within cities together with the development of greenery and biodiversity resulting in a better condition of the urban ecosystems [23], as well as the improvement of the quality of life and wellbeing of residents [24–26]. The most effective actions include the implementation of blue and green infrastructure solutions – diverse components introduced into architecture and space which combine water management and greenery to maintain natural water cycles [27–29] as part of a circular economy [3], thus enhancing the renewal of urban environment [30–32].

Housing estates form an integral part of cities. However, especially those built in the second half of the 20th century or earlier fall into degradation, and those processes apply to architecture, technical infrastructure, and open spaces in the functional, social and environmental contexts [33,34]. Many residential areas are not ready to deal with the threats resulting from climate change and extreme weather events [35], as well as insufficient rainwater management. At the same time, as places where most human activities occur, they are of particular interest to urban planners and designers [36,37]. Shaping a sustainable living environment through the implementation of blue and green infrastructure solutions become important for the comprehensive modernization and revitalization of old multi-family housing. It is also essential for the sustainable design of new housing estates, including both their buildings and open spaces [38,39]. Residential units need to be immediately transformed into more resilient areas [37], bringing benefits both to the urban environment and city residents [39,40].

Many technical and biophysical limitations have an impact on the available space of housing estates [13,41,42], especially those related to their morphology, for example, the number, size and arrangement of the basic components creating their urban structure [26,31] such as type and form of architecture, as well as development density (e.g., the more compact and intensive they are, the more constraints for the implementation of blue and green infrastructure solutions). One of the significant problems of housing estates is the limited open space – excessively built-up in old units and insufficient in those newly created [33,43]. At the same time, there is a growing demand for the introduction of hard impermeable pavements to support main function such as traffic (roads and parking lots, paths, squares). This results in surface sealing and reducing biologically vital areas, decreasing water infiltration, and at the same time increasing rainwater runoff. Many areas require also adaptation to recreational functions, thus can be only partially covered with greenery. Consequently, the space for the implementation of sustainable solutions is in many cases insufficient [31,44], reducing their environmental effectiveness and functioning. Spatial and functional problems are the key issues to overcome, as complex blue and green infrastructure solutions usually require more space than traditional drainage methods [45,46]. At the same time, the limited space available for natural elements significantly reduces the environmental functioning of housing estates. Therefore, it is crucial to combine rainwater management with the implementation of greenery. Blue and green infrastructure solutions introduced to residential units provide benefits related to the enhancement of ecosystem services [24]. They support also biodiversity by shaping more natural systems in local and supralocal scale in highly urbanized spaces [47]. These components may improve the adaptability and resistance of housing areas to both drought and flooding during heavy rainfall [42], resulting in modulation of the urban climate by mitigating negative changes such as reduction of the urban heat island (UHI) [48,49].

The individual characteristics of blue and green infrastructure solutions are also important, and can be considered in terms of their multiple features in the spatial and functional context of planning and design of housing estates. The categorization based on scale includes small elements such as rain gardens, or medium size elements such as street side bioretention basins, which can be easily adapted to different types of space. On the other hand, the implementation of large retention reservoirs is much more difficult and requires much interference with the ground. Spot solutions are more appropriate for limited areas, linear elements can be introduced in narrow and long spaces, and surface elements usually require much space and distance from buildings and other elements of technical infrastructure. Selected solutions are positioned above the ground (e.g., green roofs), on the ground (e.g., trenches, swales, different types of water reservoirs), or under the ground (e.g., water sealed reservoirs), which also has an impact on their implementation. Categorization by function [17] refers to the contribution of blue and green infrastructure solutions to the reduction of stormwater runoff by retaining and storing water during and after extreme rainfall, as well as contribution to other processes such as infiltration into the ground or water purification [27,28,50]. Many blue and green infrastructure solutions function together with vegetation and thus increase biodiversity. All of them may be introduced as individual elements or create well developed systems with others, thus providing many ecosystem services (environmental, social, etc.) [17,41,51]. The economic factor is also important, as higher costs of implementation and maintenance have an impact on the budget [29,32,52]. Regarding the above-mentioned limitations, the aim of the study is to recognize and assess which of popularly used blue and green infrastructure solutions are most valuable in implementation in housing estates in relation to both spatial and functional aspects.

2. Materials and methods

The subject of the presented pilot study are 14 blue and green infrastructure solutions – representatives of stormwater retention structures and systems commonly introduced in residential areas. The first stage of the study, based on literature review [27,28], concerned the selection of cases and they include: 11 solutions applied on the surface, 2 applied under the ground [27,28,53] and 1 applied above the surface [54–65]. The second stage focused on their assessment carried out in relation to spatial and functional aspects. Both aspects have been further developed to identify 5 key factors for each, as well as the main criteria used to define the limitations and possibilities related to the implementation of each solution in designing residential areas.

In the spatial aspect the main factors included:

- space needed for implementation where small size means an advantage;
- distance from the building where the need to lengthen means a disadvantage;
- size of the solution where large size means greater difficulties in implementation in the available space;
- shape of the solution with more possibilities of using spot than linear objects and surface solutions;
- interference with the ground which means a disadvantage.

In the functional aspect the main criteria included:

- retention capacity the increase of which means an advantage;
- contribution to other sustainable processes (rain water infiltration, treatment, etc.) the lack of which means a disadvantage;
- implementation as well as maintenance cost where high value means a limitation;
- functioning with plants which means an added value.

The presented studies are quantitative and use a scoring method assigning a specific number of points for each factor resulting from the characteristics of the relevant criteria. The points were assigned by adapting the methods used for valorization of urban landscape objects, linking subjective and objective approaches [66,67]. A 2-level rating scale has been developed as follows:

- The 0–1 scale refers to the presence of the factor where 0 means its absence, and 1 – its presence, for example, contribution to infiltration processes, possible implementation of plants increasing biodiversity and ecological processes;
- The 0–1 scale refers to the intensity of the influence of a factor where 0 is high and 1 is low, for example, implementation and maintenance costs, or where 0 is low and 1 is high, for example, interference with the ground;
- The 1–2 scale refers to the intensity of the influence of a factor or a size of the area/element where 1 is low/small, and 2 is high/large, for example, retention capacity, required distance from buildings;
- The 1–2 scale refers to the size of the area/element where 1 is large and 2 is small, for example, large space needed for implementation, scale of the solution, and complexity of its form.

The first level of the assessment of blue and green infrastructure solutions concerned each of the two aspects individually. Points obtained for each factor were added together to form a total overall score for each solution, with a maximum of 9 points in the spatial and 6 points in the functional aspect. The general assessment in both aspects together allowed for the prioritization of individual blue and green infrastructure solutions according to the decreasing number of points (a maximum of 15 points) in the final ranking. They were classified into three groups in relation to the possibility of their implementation in residential areas: high (80%–100% of the maximum score), medium (60%–79% of the maximum score) and low (≤59% of the maximum score).

3. Results

3.1. Spatial aspect

The blue and green infrastructure solutions assessed in the spatial aspect could score from a minimum of 4 up to a maximum of 9 points for 5 different factors, including the division of points into groups as follows: 8–9 points for high-value solutions, 6–7 points for medium-value solutions, and 4–5 points for low-value solutions. The results are presented in Table 1.

Only 4 blue and green infrastructure solutions obtained the highest number of points (8 or 9): green roofs, both types of rain gardens (applied on the surface and in containers), and permeable pavements. All of them do not require significant space for implementation and much distance from buildings, and their interference with the ground can be much limited. They can replace hard structures or collect runoff water. Other 4 solutions, such as sealed surface water reservoirs, water squares, but also grassed retention and infiltration basins, and wetland ponds, fall into the low-value spatial group and obtained the lowest number of points (4 or 5). Three of them were poorly rated in all factors due to the large space requirements, preferred large scale and complexity of the solution needed for better operation, and high interference with the ground. Spatial factors are crucial for their selection, including the impossibility of their implementation in small areas. The group with a medium spatial value included 6 blue and green infrastructure solutions which obtained an average number of points (6 or 7): street-side bioretention basins, infiltration trenches and grassed swales, infiltration boxes, infiltration wells and underground water reservoirs. They obtained a different number of points for the selected factors. Most of them do not require much space for implementation including spot objects such as infiltration wells, but the linear shape of infiltration trenches and grassed swales makes them suitable for narrow but long spaces (roads, paths), which is a significant limitation. Three underground blue and green infrastructure solutions (infiltration boxes, infiltration wells and underground water reservoirs) strongly interfere with the ground. However, the above-mentioned reservoirs do not require much distance from buildings or can be even integrated with architecture.

3.2. Functional aspect

The blue and green infrastructure solutions assessed in the functional aspect could score from a minimum of 1 up to a maximum of 6 points for 5 different factors, including the division of points into groups as follows: 5–6 points for

Table 1
Assessment of blue and green infrastructure solutions in terms of the spatial aspect

Blue and green infrastructure solution	Space needed for implementation (1–2 pts)	Required distance from buildings/construction (1–2 pts)	Size of solution (1–2 pts)	Shape of solution (1–2 pts)	Interference with the ground (0–1 pts)	Sum (4–9 pts)
Rain gardens in containers	2	2	2	2	1	9
Green roofs	2	2	2	1	1	8
Rain gardens on the ground	2	2	2	1	1	8
Permeable pavements	2	2	2	1	1	8
Street-side bioretention basins	2	1	2	1	1	7
Infiltration wells	2	1	2	2	0	7
Infiltration boxes	2	1	2	1	0	6
Infiltration trenches	1	1	2	2	0	6
Grassed swales	1	1	2	2	0	6
Underground water reservoirs	1	2	2	1	0	6
Sealed surface water reservoirs	1	2	1	1	0	5
Wetland ponds	1	1	1	1	0	4
Grassed retention and infiltration basins	1	1	1	1	0	4
Water squares	1	1	1	1	0	4

high-value solutions, 3–4 points for medium-value solutions, and 1–2 points for low-value solutions. The results are presented in Table 2.

Only 2 blue and green infrastructure solutions (sealed surface water reservoirs and underground water reservoirs) were classified to the low-value functional group and obtained 2 points – they have a high potential for rainwater retention due to their usually large size highlighted in the spatial aspect. Unfortunately, they were rated very poorly in other factors, especially for high implementation costs and low contribution to sustainable processes resulting from many limitations or the inability to introduce greenery. The group with a medium functional value included 7 blue and green infrastructure solutions, and they scored 3 or 4 points: rain gardens on the ground and in containers, street-side bioretention basins, water squares, green roofs, infiltration boxes, infiltration wells and wetland ponds. As most solutions with a low functional value, most representatives of this group were also poorly rated in the same factors related to high implementation costs and no contribution to sustainable processes. Only green roofs generate high maintenance costs. At the same time, they function with vegetation, just like rain gardens in containers, street-side bioretention basins and wetland ponds. But only three solutions – infiltration wells, permeable pavements and infiltration boxes – contribute to other processes besides retention such as rainwater infiltration or treatment. In the functional context of shaping residential areas, the highest-value group included the following 5 blue and green infrastructure solutions with the highest number of points (5): retention and infiltration water reservoirs, street-side bioretention basins, infiltration trenches and grassed swales, and rain gardens on the ground. All of them obtained the maximum number of points in relation to the factors such as maintenance costs, which are assessed as low, and contribution to sustainable processes (rainwater infiltration or treatment). All solutions classified to this group function together with vegetation, thus increasing biodiversity. Only some of them have been negatively assessed in relation to one factor, for example, grassed retention and infiltration basins as they generate higher implementation costs.

3.3. Valorization of blue and green infrastructure solutions

The comprehensive assessment in relation to the total number of points obtained for spatial and functional aspects shows that none of blue and green infrastructure solutions received the maximum (15) or the minimum (5) number of points in the complex rating in the two aspects. The division of points into individual groups is as follows: 12–15 points for high-value solutions, 9–11 points for medium-value solutions, and 8 points or less for low-value solutions, as presented in Table 3.

The following 3 solutions are assessed as most-valuable for implementation in residential areas: rain gardens on the ground, rain gardens in containers, and street-side bioretention basins. All of them obtained a similar number of points (12 or 13). Especially due to their small size and easy adaptation to most constraints, they have generally limited requirements in both spatial and functional aspects, and

Table 2
Assessment of blue and green infrastructure solutions in terms of the functional aspect

Blue and green infrastructure solution	Retention capacity (1–2 pts)	Contribution to water infiltration, treatment, etc. (0–1 pts)	Implementation cost (0–1 pts)	Maintenance costs (0–1 pts)	Plants implementation (0–1 pts)	Sum (1–6 pts)
Grassed retention and infiltration basins	2	1	0	1	1	5
Street-side bioretention basins	1	1	1	1	1	5
Infiltration trenches	1	1	1	1	1	5
Grassed swales	1	1	1	1	1	5
Rain gardens on the ground	1	1	1	1	1	5
Wetland ponds	2	0	0	1	1	4
Rain gardens in containers	1	0	1	1	1	4
Infiltration wells	1	1	1	1	0	4
Water squares	2	0	0	1	0	3
Green roofs	2	0	0	0	1	3
Permeable pavements	1	1	0	1	0	3
Infiltration boxes	1	1	0	1	0	3
Sealed surface water reservoirs	2	0	0	0	0	2
Underground water reservoirs	2	0	0	0	0	2

Table 3
Collective assessment of blue and green infrastructure solutions

Blue and green infrastructure solution	Spatial aspect (1–9 pts)	Functional aspect (1–6 pts)	Sum (5–15 pts)	Recommended implementation – value
Rain gardens in containers	9	4	13	high
Rain gardens on the ground	8	5	13	high
Street-side bioretention basins	7	5	12	high
Permeable pavements	8	3	11	medium
Green roofs	8	3	11	medium
Infiltration wells	7	4	11	medium
Infiltration trenches	6	5	11	medium
Grassed swales	6	5	11	medium
Infiltration boxes	6	3	9	medium
Grassed retention and infiltration basins	4	5	9	medium
Underground water reservoirs	6	2	8	low
Wetland ponds	4	4	8	low
Sealed surface water reservoirs	5	2	7	low
Water squares	4	3	7	low

thus offer many possibilities for implementation in various types of space (spot, linear or extensive). Especially rain gardens on the ground and street-side bioretention basins have a potential to connect them into more developed systems covering much area.

The other 7 blue and green infrastructure solutions classified as mid-value in the context of their implementation in residential areas represent the largest group. They obtained 9 or 11 points each. Some of them were higher rated in relation to the spatial aspects, for example, permeable pavements, green roofs and infiltration wells, due to their quite easy adaptation to spatial limitations. At the same time, they were evaluated as mid-value in the functional aspect, which results from their high implementation and/or maintenance costs, as well as no possibility of introducing plants. However, two blue and green infrastructure solutions stand out against this background, namely infiltration boxes and grassed retention and infiltration basins, which obtained the lowest number of points (only 9) mainly due to high implementation costs and high interference with the ground.

The third group of the least valuable blue and green infrastructure solutions for sustainable stormwater management in residential areas includes the following 4 solutions: both surface and underground water reservoirs, wetland ponds, and water squares. Most of them were rated low in the spatial aspect, especially due to their high interference with the ground, large size necessary to initiate complex environmental functions and thus much space needed for their implementation or distance from buildings. In the functional aspect, especially both types of sealed water reservoirs obtained the lowest number of points in relation to four factors due to no contribution to processes such as water infiltration or treatment, high implementation and maintenance costs, and no possibility to implement vegetation.

4. Discussion and conclusion

The approach presented in this study contributes to the discussion on the need to implement solutions based on sustainable stormwater management which meets the aims of the European Green Deal [1], at the level of planning and designing specific spaces such as housing estates as they cover much space within cities and are inhabited by large urban populations. The results of the assessment of the discussed blue and green infrastructure solutions, due to many possible limitations in their implementation in the spatial and functional aspects, may be helpful in understanding their role in the sustainable development of housing estates dominated by high intensity of buildings and impermeable surfaces.

Housing estates both require and have the potential for the introduction of sustainable solutions of different scale and intensity of operation to support the creation of a resilient environment [37,68,69]. It should also be noted that the implementation of blue and green infrastructure components primarily affects their functioning in those areas at the local level [70]. However, due to the significant share of those areas within cities, as well as the vicinity and possible connections with others through water retention systems, they grow in importance in making the environment of whole cities more sustainable [36,37]. Regarding the individual features, many of the presented blue and green infrastructure solutions provide opportunities to overcome the potential spatial and functional limitations typical of residential areas. Therefore, their variety may be assessed as an asset, which allows to highlight their role in comprehensive rainwater management even in areas with numerous constraints [30,71–73]. Thus, they may support the trend towards multi-directional and intelligent flood management in cities [74]. The implementation of various solutions of different size, shape and contribution to diverse ecological processes by adapting them to the key limitations may also create an opportunity to renew the natural structures of water balance within residential areas through improved rainwater retention and larger permeable surfaces [75].

The results of this pilot study show that many solutions were rated as medium-value in both aspects. The diverse number of points obtained in relation to individual factors proves that the limitations identified in the spatial context can be compensated for by the advantages resulting from the functional aspect, and vice versa. At the same time, this indicates great possibilities of using various solutions as alternatives, eliminating their constant duplication, thus supporting comprehensive rainwater management [71–73]. In this context, greater availability of diverse solutions should be perceived as an advantage facilitating the complicated process of their selection for areas with numerous constraints [29]. Furthermore, the lowest rated blue and green infrastructure solutions still have some value and should not be disregarded in shaping housing estates. Therefore, the presented study mentions that the key is to make careful decisions based on a well-thought-out selection of solutions to the individual characteristics of a space. Sustainable water management in housing estates requires a conscious selection of blue and green infrastructure components based on their individual features and especially the possibilities in adaptation to spatial and functional limitations to intensify the processes of mitigation the negative effects of climate change. The approach related to application of the European Green Deal principles can benefits both the urban environment and city dwellers [16,24,26]. An increasing number and scope of implemented blue and green infrastructure components in residential areas may also support an achievement of many sustainable development goals (SDGs) – not only Goal 6: which is to ensure availability and sustainable management of water and sanitation for all, but also Goal 13: which urges to take urgent action to combat climate change and its impacts, Goal 15: which is to protect, restore and promote sustainable use of terrestrial ecosystems, halt and reverse land degradation and halt biodiversity loss, as well as Goal 3: which aims at ensuring healthy lives and promote well-being for all [2].

The research on comparison of blue and green infrastructure components in urban flood mitigation is focused mostly on large-scale analyzes [76] and there is a lack of detailed data related to their implementation in the units such as housing estates, especially in their open spaces. Some more complex literature reviews include terminology, general characteristics of features or functions of these solutions [27,28,77,78]. Only selected studies analyses them in a more complex manner, but mostly in the context of designing urban public spaces [29,79]. Regarding the growing role of sustainable water management for more resilient cities, the research on the assessment of blue and green infrastructure solutions initiated in this study should be extended on more components useful for residential units to better understand their positive impact. However, even these preliminary results can support planning and design processes as the management of rainwater in residential areas depends on well-matched components and their flexibility in terms of possible implementation of sustainable solutions [73,80,81]. At the same time, the improvement of the quality of design practices [82–85] may convince planners and designers to pay more attention to the aims of the

European Green Deal strategy [1] and encourage them to support the transformation of urban environment towards a circular economy [3]. Redefining the scenario of modernization of existing and the creation of new housing estates focused on building so necessary flexibility in sustainable initiatives [86] is possible by wider implementation of blue and green infrastructure systems. The knowledge on their values should be used as a tool raising the awareness of many stakeholders and decision-makers (local community, managers and developers) [40,69,87]. At the same time, it may help broaden social participation in the creation of residential areas [13,38] and gain general acceptance for the promoted sustainable approach [32,88,89]. Without social agreement as well as the knowledge of scientists, the functioning of residential areas will remain significantly limited [74].

Summing up, the approach presented in this paper intends to highlight that blue and green infrastructure solutions require a comprehensive assessment to understand their limitations in spatial and functional terms in relation to their implementation in residential areas. The use of an uncomplicated quantitative evaluation method allowed to conduct a preliminary study, with the assumption that the number of factors can and should be extended in order to more fully recognize constraints associated with the implementation of blue and green solutions in those areas. Therefore, research in this area should be further developed.

The conducted study aimed at drawing attention to the importance of the spatial and functional aspects in the implementation of blue and green infrastructure solutions in housing estates, and at the same time presenting the available components which may increase the sustainable approach. It may help professionals (planners and designers) to strengthen their practices and role in the development of urban residential areas towards more circular in water management. This study therefore makes a contribution to the presentation of the value of selected elements of blue and green infrastructure and increases the knowledge related to the possibilities of their conscious use to support sustainable development of cities as part of European Green Deal concept.

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