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ANTHROPOGENIC ECOSYSTEM OF GREEN ROOFS FROM THE PERSPECTIVE OF RAINWATER MANAGEMENT

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ABSTRACT

In Bielsko-Biała (Poland), thanks to the initiative of the originator and architect, a green intensive roof was created on a shopping centre. This roof primarily serves as a garden that enhances the qualities of the residential area, but also as a means of absorbing some rainwater and slowing down the runoff. The water collects in the rainwater retention tank located under the building. Rainwater also evaporates, and its surface runoff is slowed down as it passes through the vegetation on the green intensive roof. This paper addresses some of the operational problems of a selected green roof. The Water Law introduces the obligation to pay charges for the reduction of natural terrain retention. Shopping centres usually occupy large areas of land, but their roofs are rarely used for rainwater management and the installation of biologically active surfaces. Green roofs undoubted advantage is the increase of biologically active surface in urban areas. It is also an oxygen-producing surface as well as reducing urban heat islands and attractive place for honeybees and butterflies. The roof in question meets the requirements of a retention facility mentioned in the Water Law Act. It is a multifunctional system for rainwater management. The analysis suggests that the roof under study is not a self-sustaining ecosystem and requires human intervention.

Key words: environment, green roof, rainwater, architecture, anthropogenic ecosystem

INTRODUCTION

In recent years, continued urbanisation has led to economic development, but has also put enormous pressure on existing infrastructure in cities (Lin & Zhu, 2018). Today, most of the world's population lives in urban areas characterised by a high degree of transformation, which negatively affects the quality of life. The substitution of natural elements by building materials such as concrete, cement or asphalt disturbs the balance of solar radiation and water in cities (Velázquez et al., 2019). In cities, we see excessive urban runoff (increased rainwater runoff) and flash urban floods and also problems of deteriorating water quality (Shafique & Kim, 2017; Shafique, Azam, Rafiq, Ateeq & Luo, 2020). Given the above, there is a great need for a green and sustainable practice to help redress the balance by allowing green spaces, such as green roofs to enable water evaporation and infiltration (and thus reduce surface runoff) in urban areas (Shafique et al., 2020). In urban areas, roof area accounts for about 40–50% of the total urban impervious surface (Stovin, 2010). These areas offer great opportunities for the application of green roofs to promote sustainability and a cleaner environment in urban areas (Berardi, Ghaffarian Hoseini & Ghaffarian Hoseini, 2014; Teotónio, Silva & Cruz, 2018; Shafique et al., 2020). For this reason, green roofs should be

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widely used in urban environments. They contribute to urban regeneration (Versini, Gires, Tchiguirinskaia & Schertzer, 2020), and are also recognised as multifunctional tools that can provide multiple ecosystem services (Francis & Jensen, 2017) to counter climate change or unsustainable urbanisation. They are particularly important in thermal regulation (Ouldboukhitine, Belarbi & Sailor, 2014; Suter, Maksimović & van Reeuwijk, 2017), can mitigate the urban heat island effect (Bowler, Buyung-Ali, Knight & Pullin, 2010; Velázquez et al., 2019), are important for biodiversity (Madre, Vergnes, Machon & Clergeau, 2014; Versini et al., 2020), have a positive impact on urban air quality (Speak et al., 2012), but most importantly have an impact on urban water management (Versini et al., 2016, 2020). Green roofs significantly reduce stormwater runoff by mitigating the peak and volume of runoff (Speak, Rothwell, Lindley & Smith, 2012; Zhan et al., 2015; Palermo, Turco, Principato & Piro, 2019). Additionally, they can also affect the aesthetic and social aspects of a city (Jungels, Rakow, Allred & Skelly, 2013). However, green roof implementations (including material extraction, raw material production, construction, operation, maintenance and recycling) can create a number of environmental and economic burdens (Law, Diemont & Toland, 2017).

The paper focuses on operational problems using the example of a selected ornamental green roof. Green roofs can be classified as anthropogenic ecosystems that are biologically active. The research hypothesis is that the selected research object meets the requirements of a biologically active area, which is defined in the Regulation of the Minister of Infrastructure of 12 April 2002 on technical conditions to be met by buildings and their location (Rozporządzenie Ministra Infrastruktury z dnia 12 kwietnia 2002 r.).

MATERIAL AND METHODS

Site description

The research object was an intensive green roof located on the Sfera II Shopping Centre in Bielsko-Biała. The town is located in the southern part of the Śląskie Voivodeship (49°49′21″N 19°02′40″E). The city of Bielsko-Biała covers an area of approx. 124.51 km², including residential areas: 16.4%, service areas: 2.6%, industrial and warehousing areas: 3.6%, communication areas: 11%, agricultural land: 14.6%, woodland: 24.2%, urban greenery: 2.2%, and other areas: 25.4%. The town's area is located within two climatic zones: Subcarpathian (foothills) and Carpathian (mountains), which results in irregular weather conditions, including high temperature fluctuations in the annual cycle. The prevailing winds during the year are westerly and south-westerly, with south-westerly and southerly winds more frequent in winter (e.g. the hurricanes), and westerly and north-westerly winds prevailing in summer. The greatest cloud cover occurs from November to January, and the greatest number of sunny days occurs between the end of summer and the beginning of autumn.

Description of the research object

The roof on the Sfera II Shopping Centre functions primarily as a garden, making the residential area more attractive. Plants planted on the roof are mostly watered with water collected in a rainwater storage tank. These waters are pre-treated by entering the tank through a layer of plants growing on the roof and a biologically active layer (Boas Berg, Radziemska, Adamcová & Vaverková, 2017; Boas Berg, Jeznach, Radziemska, Adamcová & Brtnický, 2018).

A residential development has been designed and built on the roof. The architect Ireneusz Hendel is the creator of this concept. The residential estate's inner garden has an area of 2,300 m². It is an intensive garden with trees such as birches, hornbeams and maples. Smaller plants include rose bushes, wild vines and lavender. The garden areas are covered with different species of grass. This roof is also a biodiverse roof. Honeybees have been observed there during blossom periods and blackbirds have been observed nesting in tree stands (Boas Berg et al., 2017; Boas Berg et al., 2018).

Type of green roof used – structure and elements

The construction of the roof layers is characteristic of an intensive roof. The roof surface (in the communication area, traffic routes) allows pedestrian traffic. Concrete paving stones have been used in this section. The concrete paving is 0.06 m thick and laid on a stoneware bed (6 mm fraction) and a 0.03 m thick sand bed. The 0.25-metre thick layer of aggregate stone (0–16 mm) is used on the roof. The filter layer consists of a 200 g geotextile filter fabric, which is loosely laid on the drainage layer, with longitudinal and transverse overlaps of approximately 0.20 m. In the garden part of the roof, special layers are used to allow large plants such as shrubs or small trees to grow. The vegetation layer consists of a 0.35 m thick substrate. Similar to the pedestrian section of the roof, the garden section of the roof has similar protective and safety layers. The next filtering layer is made of 200 g filtering geotextile, loosely laid on the drainage layer, with longitudinal and transverse overlaps of approx. 0.2 m. The next drainage layer consists of a DiaDrain-40 mat with a technological overlap, which is laid loosely on the protective layer and the depressions are filled with expanded clay aggregate – a special water-absorbing material (Boas Berg et al., 2017; Boas Berg et al., 2018).

The protective layer against mechanical damage consists of synthetic fibre $d = 0.8–1.0$ mm. It is loosely laid on the root barrier layer, with transverse and longitudinal overlaps of at least 0.10 m. The next root barrier layer is made of soft PVC $d_{\min}$ 0.8 mm, shaped like a tight sump and resting loosely on the substrate, with welded joints with a 0.05 m overlap. Like the pedestrianized section (Fig. 1), the roof covering is double-layered and made of bituminous felt. The first layer is a welded, reinforced, root-resistant bitumen membrane. The second layer consists of a welded asphalt membrane with additional root barrier in the form of copper foil $d = 0.1$ mm. The next element is the venting or separating layer consisting of point bonding of the first roofing layer to the thermal insulation. The next necessary layer is the thermal insulation consisting of polystyrene boards of the EPS 200-036 type, 0.24 m thick. This is followed by a vapour barrier made of roofing felt with aluminium foil, point-bonded to the construction layer. The final base layer is made of cold bituminous binder. The base of the entire roof is a 0.35 m thick reinforced concrete floor (according to the structural design – Fig. 2). The vegetation, which makes up the vegetation layer, consists of grasses, mosses, perennials, shrubs and trees. The plants are irrigated automatically. Drip irrigation is used for shrubs and perennials, and sprinklers for lawns and trees. Irrigation control is automatic and depends on soil moisture. The substrate layer under the trees was increased to 0.70 m (Boas Berg et al., 2017; Boas Berg et al., 2018).

Fig. 1. Intensive green roof. Visible pedestrian section and vegetation section (elaboration and photos by A. Boas Berg, 2018)

Fig. 2. Technical documentation of the intensive green roof on the Sfera II Shopping Centre (photo reproduction by A. Boas Berg, 2018)

Rainwater management on the premises of the shopping centre in Bielsko-Biała

Rainwater from paved surfaces on the roof of Sfera II Shopping Centre and from the roof itself, including the green roof, should theoretically be partially pre-treated by passing through the biologically active layer. In the underground part of the building (under the building), there is a rainwater harvesting tank (Fig. 3).

The tank is made of watertight concrete walls. On the active side, the tank is additionally protected with HydroStop waterproofing materials. In the adjacent room, there is a hydrophore room from which so-called grey water is pumped for watering the greenery located on the roofs and inside Sfera II Shopping Centre and for flushing the toilets accessible to the customers of the shopping centre. The grey water system is independent of the mains water system. Rainwater consumption for toilets is metered. According to the Regulation of the Ministry of Infrastructure of 14 January 2002 on determining average norms of water consumption (Rozporządzenie Ministra Infrastruktury z dnia 14 stycznia 2002 r.) – water consumption in toilets per device monthly is 3 m^3. There are 48 units connected, hence the estimated annual water consumption for the toilets is 1,728 m^3, and the water consumption for irrigation is 138,000 m^3 annually (60 l·m^{-2} annually).

RESULTS AND DISCUSSION

The roof in question meets the requirements of a retention facility mentioned in the Water Law Act (Ustawa z dnia 20 lipca 2017 r. Prawo wodne). It is a multifunctional system for rainwater management. The analysis suggests that the roof under study is not a self-sustaining ecosystem and requires human intervention. The roof must be systematically monitored, and drainage systems must be maintained and cleaned. This is the only way it can fulfil its function as a system and biologically active area, as stipulated in the previously mentioned Regulation of the Minister of Infrastructure of 12 April 2002.

In the academic literature, much attention has been paid to assessing the amount of runoff from green roofs, and a certain amount of attention has also been paid by researchers to water quality from green roofs (Teemusk & Mander, 2007; Hathaway, Hunt & Jennings, 2008; Getter & Rowe, 2009; Van Seters, Rocha, Smith & MacMillan, 2009; Alsup, Ebbs & Retzlaff, 2010; Carpenter & Kaluvakolanu, 2011; Gregoire & Clausen, 2011). Green roofs can theoretically reduce stormwater pollution by absorbing and filtering pollutants as they are covered with soil and vegetation (Berndtsson, 2010; Wang, Tian, & Zhao, 2017). Meera and Ahammed (2006) showed that conventional roof

Fig. 3. Rainwater harvesting tank under the Sfera II Shopping Centre (photos by A. Boas Berg, 2018)

runoff exceeds drinking water guidelines and that particle-related contaminants in conventional roof runoff contribute to the toxicity of sediment accumulation (Van Meter & Mahler, 2003). For example, metal roofs have been found to be a source of cadmium and zinc, and applied asphalt is a source of lead in roof runoff (Beck, Johnson & Spolek, 2011). In this light, green roofs can improve water quality. It is extremely rarely pointed out that green roofs (even intensive ones, i.e. roof gardens) are not a self-sustaining ecosystem. Extensive green roofs are characterised by a shallow substrate, which makes it difficult to optimise a specific function due to limitations in plant biomass potential and species selection (Xie, Lundholm & MacIvor, 2018). In addition, the shallow substrate is not sufficient to clean itself completely and independently as in a natural ecosystem. The soil in a garden or park on the ground naturally cleans itself. In contrast, roof gardens (intensive green roofs) are too shallow to sufficiently clean themselves of pollutants from rainfall or animals. Animal urine and faeces are toxic to succulent green roof plants. In addition, pet urine can cause damage to the bark of young trees. For this reason, there should be a total ban on dogs or cats in the roof garden.

Another problem is that roof gardens are not self--sustaining ecosystems. The complex ecological dynamics inherent in natural ecosystems are not directly replicated on a green roof. Plants on green roofs must withstand harsh environmental factors such as temperature fluctuations, drought and strong winds (Cook--Patton, 2015). In natural communities, multiple pests diminish plant performance, including disease, invasive weeds, and herbivory. While these threats are not often assessed on green roofs, they have the potential to similarly harm green roof plant communities, especially because green roof plants are already stressed by abiotic factors that may limit their ability to respond defensively (Cook-Patton, 2015). The world academic literature is scarce on studies of disease incidence and the impact of pests and pathogens on green roof vegetation. While pests have so far been ignored in green roof research, it is likely that they weaken plants. Therefore, an intensive green roof must be constantly monitored and managed by specialists in order to promote biodiversity, prevent plant diseases, and keep the plants in good condition. Lack of nutrients can also weaken plants. Green roofs lack substances available in the natural ecosystem.

The operational problem is proper plant care depending on whether it concerns sedum mats - in extensive roofs, or trees and shrubs – in intensive roofs. The green roof requires the use of appropriate plants and substrates (Liu et al., 2019). Using an unsuitable substrate can suppress plant growth (www.dachyplaskie.pl).

It has been established over many years of research that *Otiorhynchus sulcatus* is an issue on the studied roof. The genus *Otiorhynchus* is a hyper-diverse genus of Palaearctic root weevils (Curculionidae: Entiminae). The adults of this species cannot fly, and the larvae feed underground; most are polyphagous, and many are major pests of various crops (Majka & MacIvor, 2009). This pest cannot be eradicated by spraying, due to the limited garden area and the housing development on the aforementioned roof. For this reason, it was decided to use an alternative method on the roof in question, namely the introduction of nematodes into the substrate over the entire roof surface.

Selected operational problems of green roofs

Green roofs are an old concept involving the construction of a roof garden to improve biodiversity (Shafique, Kim & Rafiq, 2018). Green roofs are more sustainable than a conventional roof. However, this only applies to green roofs that have been done correctly (Shafique et al., 2020). One of the main operational challenges is the use of inadequate drainage (Tadeu, Simões, Almeida & Manuel, 2019). In Poland, the warranty for physical defects in real estate is three years. The warranty is statutory and therefore independent of the will of the parties. However, even considering the protection for physical defects, a green roof cannot be built just with the warranty period in mind. If a green roof is poorly constructed (for example by using inadequate drainage), it can result in the need to demolish the defective roof and entail high rebuilding costs. Therefore, it is so important for professionals to work together already at the design stage. Figure 4 illustrates the housing development and the roof garden.

An important element for green roofs is the correct calculation of the allowable floor loads. These loads are not the same at different points on the roof.

Builders' recommendations must be considered to prevent a construction failure. Extensive roofs are easier to install and lighter in weight, making them feasible to install on existing traditional roofs (Manso, Castro-Gomes, Paulo, Bentes & Teixeira, 2018). Intensive green roofs with a rich diversity of plants varying with grasses, perennials, shrubs and trees (Newton, Gedge, Early & Wilson, 2007; Manso et al., 2018). Due to the heavy weight, creating roofs on existing buildings poses risks and challenges (Castleton, Stovin, Beck & Davison, 2010; Vacek, Struhala & Matějka, 2017). A very important construction aspect is the proper installation of waterproofing. If waterproofing is not installed correctly, it may become ineffective in preventing roots from breaking through it. A waterproofing that is not resistant to root overgrowth cannot adequately function on a green roof and therefore additional materials (e.g.: anti-root films) must be used, which increases the installation costs (She & Pang, 2010). In Poland, there are no standards to determine the resistance of a given material to root overgrowth. On the other hand, you can find a list of root-resistant materials on the German Landscape Development and Landscaping Research Society e.V. (FLL) website. Accordingly, to avoid operational problems (root overgrowth), waterproofing of the highest quality should be used.

The materials used for green roof layers were studied by Bianchini and Hewage (2012). The green roof layers and materials are similar among manufacturers, but each manufacturer has developed its own system. General data on green roof systems are available; however, in most cases, substrate composition, production process, installation process and technical data are kept a trade secret (Bianchini & Hewage, 2012). Another issue with intensive roofs is the proper protection of trees and shrubs. They should have special underground and aboveground reinforcements to prevent uprooting in high winds (Fig. 5).

As the trees are not rooted as in natural or semi-natural conditions (park, garden), human intervention is necessary. Trees need to be inspected for adequate rooting. They need to be monitored and appropriately cared for (pruned) so that they do not overgrow. This protective measure must be checked and properly maintained (repaired if necessary).

Ordinary soil should not be used in the substrate, as it usually contains floating particles (e.g. clay) which accumulate on the layers below (filter fabric) and reduce its filtering properties and cause water stagnation. Neither should too much peat be used. In intensive green roofs, the proper choice of layers is an extremely important aspect. The choice of layers

Fig. 4. Residential development and roof garden on the Sfera II Shopping Centre (photo by A. Boas Berg, 2021)

Fig. 5. Trees secured with special strips on Sfera II Shopping Centre (photo by A. Boas Berg, 2021)

Fig. 6. The water drainage system on Sfera II Shopping Centre (photos by A. Boas Berg, 2021)

is critical in terms of the functioning of the roof space in question (fire routes, circulation paths, roof garden, etc.). The layers must be chosen so that the entire roof system functions efficiently and allows the planted vegetation to grow and develop.

As for irrigation, it is automatic on the studied roof and, in line with the idea of the green roof, rainwater collected under the building is used for irrigation. A common operational problem is siltation of drainage systems – pluvia roof drainage systems (Fig. 6).

The green roof in question experienced a clogged drainage system in 2019/2020. Rainwater was not draining into the underground harvesting tank. This increased the running costs of the building, which included watering the garden with tap water and the cost of repairing the roof and cleaning and unclogging the drainage system. Following the remedial work carried out in 2021, rainwater is again properly drained into an underground tank and is used to water the roof garden.

CONCLUSIONS

On the example of the analysis carried out on the selected green roof in Bielsko-Biała, it was confirmed that green roofs are a very good solution for highly urbanised city areas for many reasons. Their undoubted advantage is the increase of biologically active surface in urban areas. It is also an oxygen-producing surface as well as reducing urban heat islands and is an attractive place for honeybees and butterflies. However, it should be stressed that not only architects and engineers, but also specialists in landscape architecture or horticulture should be involved in the design of green roofs. Intensive roofs have a sufficient vegetative layer to allow the planting of grasses, perennials, shrubs and trees. However, on the selected green roof the trees need additional protection. Green roofs are a typical anthropogenic ecosystem where humans (human civilisation) decide on the composition of the soil profile, the composition of the vegetation, and the water regime. These factors interact with each other and confront the surrounding ecosystems. The results of the interactions and confrontations further shape the development of the green roof ecosystem. The quality of biodiversity and the representation of suitable plant species are essential for the sustainability of the roof garden ecosystem. It has been confirmed that on the Sfera II Shopping Centre meets the requirements of a biologically active area but is not self-sustaining ecosystem.

Authors' contributions

Conceptualisation: A.B.B. and J.W.; methodology: A.B.B. and J.W.; validation: A.B.B., E.H. and J.W.; formal analysis: A.B.B. and M.C.; investigation: A.B.B. and J.W.; resources: A.B.B., E.H. and J.W.; data curation: A.B.B., M.C. and J.W.; writing – original draft preparation: A.B.B. and J.W.; writing – review and editing: A.B.B. and J.W.; visualisation: A.B.B.; supervision: J.W.

All authors have read and agreed to the published version of the manuscript.

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ANTROPOGENICZNY EKOSYSTEM ZIELONYCH DACHÓW Z PERSPEKTYWY GOSPODAROWANIA WODAMI OPADOWYMI

STRESZCZENIE

Centra handlowe zajmują zwykle duże powierzchnie zabudowy, jednak ich dachy są rzadko wykorzystywane w celach związanych z zagospodarowaniem wód opadowych i rzadko zakłada się na nich powierzchnie biologicznie czynne. W Bielsku-Białej, dzięki inicjatywie pomysłodawcy i architekta, powstał zielony dach intensywny na galerii handlowej. Dach ten przede wszystkim pełni funkcję ogrodu uatrakcyjniającego walory osiedla mieszkaniowego, ale również przejmuje część wód opadowych i spowalniania ich odpływ. Woda gromadzi się w zbiorniku przeznaczonym do retencjonowania wód opadowych, znajdującym się pod budynkiem. Wody opadowe ulegają także ewaporacji, a ich spływ powierzchniowy ulega spowolnieniu dzięki temu, że przechodzą przez roślinność znajdującą się na zielonym dachu. W pracy zwrócono uwagę na niektóre problemy eksploatacyjne wybranego zielonego dachu. Postawiono hipotezę badawczą, że wybrany obiekt badawczy spełnia wymagania terenu biologicznie czynnego.

Słowa kluczowe: środowisko, zielony dach, woda deszczowa, architektura, ekosystem antropogeniczny