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The use of bioretention cell to decreasing outflow from parking lot

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Abstract

The objective of the research was to look into the role that bioretention systems play in a decentralized management of stormwater runoff from the impervious areas. The study took place at a catchment of a low permeability and equipped with a combined sewer system. Two rainfall options were selected: actual rainfall intensity $q = 105.65 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{ha}^{-1}$ and a hypothetical rainfall with a probability of exceedance $p = 10\%$ and $q = 40.7 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{ha}^{-1}$. All calculations were carried out using the SWMM EPA program (storm water management model; Environmental Protection Agency). They have shown that the bioretention system reduces the cumulative flow rates by over 55% and the flood wave volume by over 54%. Moreover, it was found that, a precipitation pattern significantly influences runoff from the urban catchment.

Key words: *bioretention system, Euler hyetographs, sewage system, stormwater, SWMM, urban catchment*

INTRODUCTION

The human activity plays more and more important role in hydrological transformations of anthropogenically transformed watersheds. In the course of history, humans have caused major disruptions in a water circulation and a hydrological regime [BELLO *et al.* 2017]. The anthropogenic changes are multidimensional and very difficult to evaluate in an unbiased way because there is not much information available on the original background and the initial conditions [WAŁĘGA 2010]. Over the last two centuries, urban development has triggered changes in watershed hydrology that included a decrease of a natural filtering capacity of river basins (e.g., channelling of headwater streams, loss of floodplains and wetlands) and regulation of flows by dams and impoundments [O'DRISCOLL *et al.* 2010; RADECKI-PA-

WLIK *et al.* 2014]. Urban development strongly disturbs many hydrological processes through alteration of land covers, burial of streams, re-plumbing of watersheds with stormwater infrastructures and restoration and re-design of streams [HALE 2016]. Social consequences of stormwater infrastructures include a risk of flooding and water pollution [ASHLEY *et al.* 2005].

The reduction of flooding in urban areas traditionally involves upgrading of the existing drainage capacity. On the contrary, low-impact development (LID) is focused on rehabilitation of local urban hydrological cycles [SURMA 2015]. These techniques are based on expansion of pervious surfaces where stormwater infiltration into the ground can occur [LIZÁRRAGA-MENDIOLA *et al.* 2017; LOCATELLI *et al.* 2017]. Bioretention systems are landscaping features adapted to treat stormwater runoff at retrofit sites.

These solutions are linked in the best management practice as non-structural methods to achieve the overall goal of pollution prevention [FLETCHER *et al.* 2015]. Surface runoff is directed into a shallow landscaped hole that employs many pollutant removal mechanisms, which operate in forested ecosystems. The filter comprises a sand/soil bed of the depth of 7–19 cm, with a surface mulch layer. During storms, runoff temporarily accumulates from 2.5 to 4.0 cm above the mulch layer and then rapidly filters through the bed. Normally, the filtered runoff is collected by an underdrain and returned to the stormwater drainage system. The underdrain consists of a perforated pipe installed in a gravel jacket, along the filter bottom. In other cases, bioretention can be achieved by infiltration of runoff into native soils. This can be accomplished at sites with highly permeable soils, a low groundwater table, and a low risk of a groundwater contamination. The design features a “partial exfiltration” system that promotes greater groundwater recharge i.e. underdrains are only installed beneath a part of the filter or are eliminated altogether, thereby increasing a storm-water infiltration [CWP 2007; WAŁĘGA 2010; WAŁĘGA *et al.* 2013]. It is generally acknowledged that bioretention systems contribute strongly to reduction of a runoff pollution, so it is reasonable to analyse whether they may bring a relieve to stormwater drainage systems during torrential rains. Bioretention systems have some limitations: they can only be used to “accept” runoff from relatively small drainage areas up to 2 ha, they should comprise about 5–10% of their contributing drainage areas and be designed to completely drain within 48 hours after a rainfall event. Thus, bioretention areas without underdrains should rather not be used at the sites with soil infiltration rates lower than 6.35 mm per hour [CWP 2009].

The objective of this study was to evaluate the bioretention system and its impact on a decrease of the peak discharge and a volume of stormwater runoff from impervious areas. The analysis was based on discharge flow simulations during a real and a hypothetical precipitation episode carried out with the storm water management model (SWMM).

MATERIAL AND METHODS

The actual site with 96.3% of the impervious surface was studied. The site was located in Cracow and its characteristic features were: a surface area = 0.784 ha (7840 m²), an average slope = 2.80% (Fig. 1). The growing development of the city zone affects the climate by reduction of a wind speed BŁAŻEJCZYK [2013] and transparency of the atmosphere (dust) [WOJKOWSKI 2007] as well as by an increase of the average annual air temperature by about 0.3°C [PIOTROWICZ 2007]. In this area also heavy rainfalls, classified as torrential rains (>20 mm), occur. On the basis of the analysis of the maximum daily rainfalls TWARDOSZ [2000], it was found that high daily pre-

cipitations have been recorded from mid Apr. to 9th Sept., with the highest values, reaching 80 mm, observed from 25th May to 18th July. The highest daily precipitation measured in Krakow occurred on 9th Sept. 1963 and reached 99 mm. It amounted to 58.9% of the monthly total and to 12.7% of the annual total. The event occurred on a day with a cyclonic circulation from the east [CEBULSKA, TWARDOSZ 2016]. According to the study of NIEDŹWIEDŹ [1989], as much as 30 mm of rain fell during 5 min, which accounted for nearly 50% of the average monthly precipitation in this month. On the other hand, the height of this precipitation reached 92 mm within 30 min, which constituted 152% of the long-term average. During 20 min, the precipitation reached 76.5 mm, which according to the Chomicz classification indicated the third degree torrential rain – B3 [LEWIŃSKA 1964]. The reported average annual precipitation for Botanic Garden of Jagiellonian University in Krakow (Ogród Botaniczny Uniwersytetu Jagiellońskiego w Krakowie) station was 703 mm.

Surface runoff from the studied area, i.e. the parking lot covered with a bituminous surface, is discharged into the combined sewage system. The sewage collector is made of PVC pipes with a diameter of 0.4 to 0.5 m and it is connected to the main city sewer. The collector slope varies from 0.52 to 1.41%.

For the purpose of the analysis, the highest measured precipitation in the last pentad in the range of 10 min was assumed, which was registered on 16th Aug. 2015 in the botanical garden. The rain on this day lasted from 12:50 to 15:50 and a total of 54 mm of rain was measured [Zakład Klimatologii UJ 2016]; during 80 min of the event a recorded sum of rain was 50.7 mm (this sum of rain comprised 94% of a daily

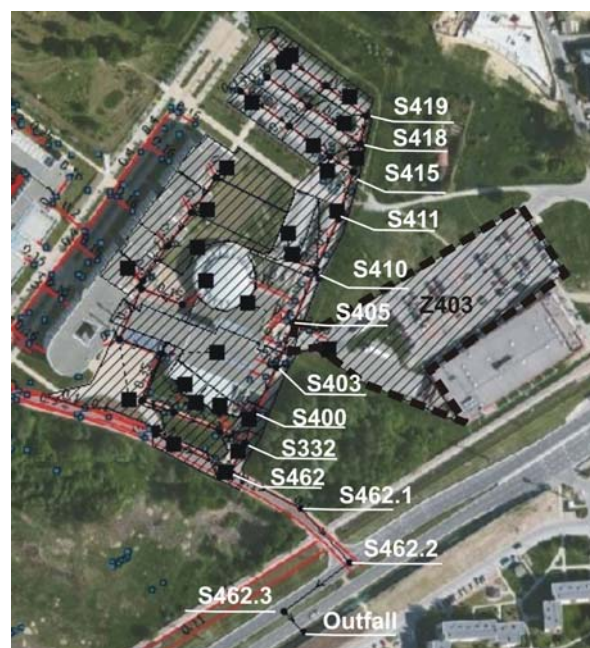


Fig. 1. Layout of the analyzed catchment, as input into the storm water management model: the catchment area is marked with a black dotted line; source: own elaboration

precipitation). The hypothetical precipitation with an exceeding probability of $p = 10\%$, calculated with the formula of BOGDANOWICZ and STACHY [1998], was also included in the study.

The duration of the precipitation was equal to the critical one, at which the maximum discharge from the entire system was obtained. The critical precipitation time was determined by iteration and simulations for a precipitation with a fixed probability but a different duration [MAIDMENT (ed.) 1993]. During iteration, a fixed precipitation distribution according to Euler type II [KOTOWSKI 2015] was used. The precipitation balance and its transformation in the stormwater drainage system was based on a hydrodynamic modelling performed with the storm water management model (SWMM), developed by the United States Environmental Protection Agency (US EPA) [JAMES *et al.* 2010; ROSSMAN 2015]. The input data in the SWMM model included the routes of stormwater collectors and combined sewer collectors together with their altitudes. The data was acquired from the design drawings and from the Department of Geodesy Town Hall at Krakow (Pol. Wydział Geodezji Miasta Krakowa). Discretization of the catchment basin into sub-catchment basins has been carried out and for each sub-catchment a discharge volume was determined. The discharge from each sub-catchment basin was directed to the manholes, in line with the slope. The catchment area as well as the elevations of manholes and inlets were determined from the elevation maps.

The width of the surface runoff is the basic parameter used in the SWMM model; its increase, observed after rainfalls of varying intensity, results in a higher discharge and a shorter time after which the maximum hydrograph is reached [ROSSMAN, HUBER 2016].

The width has been calculated using one of the methods recommended by EPA:

$$W = L + 2L(1 - Z) \quad (1)$$

Where: W = hydraulic width of a runoff route (m); L = length of the main collector (m); Z = coefficient of skewness (0.5 to 1) calculated from the formula:

$$Z = \frac{A_m}{A} \quad (2)$$

Where: A_m = larger of the two areas on each side of the channel (ha); A = total area of the catchment (ha).

At the site, the average slope (weighted average) was determined to identify runoff routes. According to Manning, the following surface runoff coefficient values were assumed: for asphalt pavements 0.011 and for parking concrete pavements 0.012 [MCCUEN 1989]. The surface retention was determined according to the ROSSMAN [2015], where the surface retention rates were: 1.27 mm for roofs and asphalt roads, 2.4 mm for parking lots and 5.08 mm for green areas.

Losses due to infiltration through permeable areas were the last parameter included in the runoff model.

They were calculated using the Green–Ampt method [CHOW *et al.* 1988] while the soil characteristics were assumed according to RAWIS *et al.* [1983]. Surface runoff from the sub-catchments was determined based on the model of a non-linear tank [ROSSMAN, HUBER 2016].

Transformation of a discharge flow inside a collector was modelled as an unsteady flow using a dynamic wave approach. A dynamic wave routing solves the complete one-dimensional Saint Venant flow equations and therefore produces the most theoretically accurate results. The equations comprise the continuity and momentum equations for channels and a volume continuity equation at nodes [KOWALSKA *et al.* 2013]:

$$\frac{\delta Q}{\delta t} + \frac{\delta}{\delta x} \left(\frac{\beta Q^2}{A} \right) + gA \frac{h}{\delta x} + g \frac{n^2 |Q|Q}{R_h^{4/3} A} = 0 \quad (3)$$

$$\frac{\delta A}{\delta t} + \frac{\delta Q}{\delta x} = 0 \quad (4)$$

Where: R_h = hydraulic radius (m); A = stream cross sectional area (m²); Q = flow rate (m³·s⁻¹); β = dimensionless velocity coefficient; n = roughness coefficient (s·m^{-1/3}); g = gravity (m²·s⁻¹); h = channel depth (m).

Based on the available literature sources – ASCE [1982], the coefficient of roughness $n = 0.013$ was assumed for a stormwater drainage system (PVC pipes and smooth concrete ducts).

Simulation of a bioretention system was carried out on the basis of mass balance equations, that describe changes of a water volume in each layer in time as a difference between the inflow and the discharge (Fig. 2). It was assumed that the surface of the bioretention system would represent 11.2% of the parking area.

The surface layer receives both a direct rainfall and a runoff from other watersheds. It loses water through: infiltration into the soil below, evaporation of any water stored in depression storage, vegetation, and by any surface runoff that might occur. The soil layer consists of a modified mix of soil that can support vegetative growth; it receives infiltration from the surface layer and loses water through evaporation and percolation into the storage layer below it. The storage layer consists of coarse crushed stone or gravel; it receives percolation from the soil above it and loses water by either infiltration into the underlying natural soil or by outflow through a perforated under-drain system [ROSSMAN 2014]. Due to the analysis of single rainfall episodes, the evapotranspiration losses have been ignored in the model calculations.

On the basis of maps showing elevation, terrain use and collector routes a water exchange between permeable and impermeable areas was determined. Three scenarios were taken into account:

- 1) surface runoff flows directly to a collector, regardless whether surfaces are permeable or impermeable;
- 2) surface runoff from a permeable surface flows onto an impermeable one and then to a collector;
- 3) surface runoff from an impermeable surface flows onto a permeable one and then to a collector.

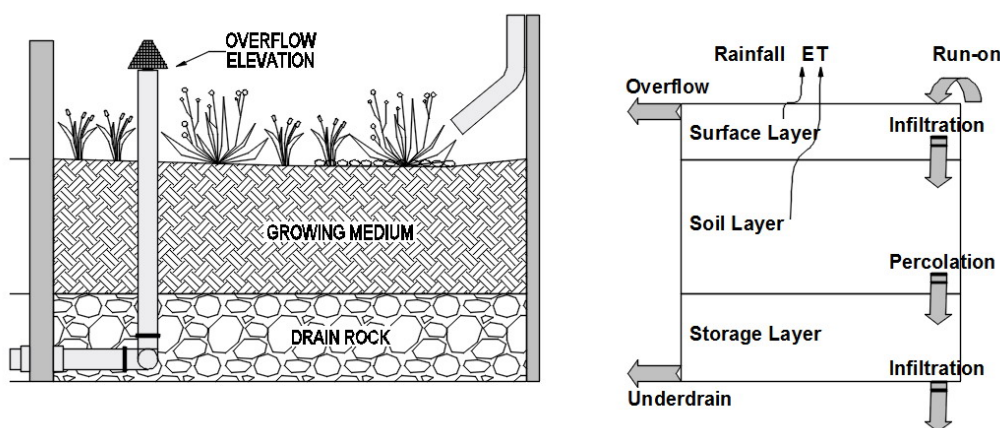


Fig. 2. Bioretention cell; source: ROSSMAN [2014]

Calculations were made for two precipitation episodes: an actual precipitation, which occurred on 16th Aug. 2015 and a hypothetical precipitation with a probability $p = 10\%$ and a critical duration time. The event on 16th Aug. 2015 was considered since it resulted in several floods in the analyzed area. In case of a hypothetical precipitation, the critical duration 180 min was assumed after a series of simulations of a system operation at different meteorological conditions.

RESULTS AND DISCUSSION

The total precipitation assumed for 16th Aug. 2015 was 50.7 mm and its duration was 80 min. The average rainfall intensity was $0.634 \text{ mm}\cdot\text{min}^{-1}$ ($q = 105.65 \text{ dm}^3\cdot\text{s}^{-1}\cdot\text{ha}^{-1}$); it corresponded to a probability of exceedance 5%, i.e. the frequency $c = 20$, calculated according to the formula presented by BOGDANOWICZ and STACHY [1998]. On the other hand, a hypothetical rainfall with a probability $p = 10\%$ and a critical time $t = 180$ min, as calculated from the Bogdanowicz and Stachy equation, was 44.0 mm. This corresponded to an average intensity of $0.244 \text{ mm}\cdot\text{min}^{-1}$ ($q = 40.7 \text{ dm}^3\cdot\text{s}^{-1}\cdot\text{ha}^{-1}$). As a result of simulations performed for the actual rainfall in the real conditions, the maximum discharge from the parking lot catchment (No. Z403) was $213.9 \text{ dm}^3\cdot\text{s}^{-1}$ and a wave volume was $V = 390 \text{ m}^3$. As a result of the actual precipitation, the maximum flow in a manhole was $424.8 \text{ dm}^3\cdot\text{s}^{-1}$ and the discharge volume was $V = 794 \text{ m}^3$. Therefore, it can be concluded that a runoff from the parking lot constitutes 50.3% of the discharge to the combined sewage system for the maximum flow and 49.1% for the runoff volume. This situation resulted in floods and water overflows from the drainage system, caused mainly by the intensive runoff from the parking area. Figure 3a shows the profile of the maximum fill level in the combined sewage collector during an actual precipitation. Most of the time the collector was working under pressure and 10 out of 15 wells were overflowing with water. In the well S403, where the parking lot runoff was also col-

lected, a water overflow occurred at a maximum intensity of $44.2 \text{ dm}^3\cdot\text{s}^{-1}$ and a volume of $V = 4 \text{ m}^3$.

In the case of a hypothetical precipitation in the real conditions, the maximum flow from the catchment area of the parking lot was $323.8 \text{ dm}^3\cdot\text{s}^{-1}$ and the wave volume was $V = 330 \text{ m}^3$. Higher flow rates are observed for a hypothetical precipitation compared to an actual precipitation intensity. In the case of a hypothetical precipitation, the Euler type II hyetograph was adopted, which results in higher precipitations in the initial phase. As shown by the studies of OLIVEIRA and STOLPA [2003], SZELĄG *et al.* [2014] or WAŁĘGA *et al.* [2012], the shape of the precipitation hyetograph plays a key role in a discharge flow resulting from hydrological modeling. For a hypothetical precipitation, the maximum flow was $437.7 \text{ dm}^3\cdot\text{s}^{-1}$, resulting in a discharge volume of $V = 646 \text{ m}^3$ in the manhole. During both a hypothetical precipitation and an actual precipitation a discharge from the parking lot contributes in a similar way to the total discharge from the catchment. Figure 3b shows the profile of the maximum water level in the combined sewage system main during a hypothetical precipitation. Most of the time the collector was working under pressure and 11 out of 15 wells accumulated water. In two adjacent wells S403 and S405 there was a water overflow with the maximum intensity of $210.9 \text{ dm}^3\cdot\text{s}^{-1}$ and a total volume of $V = 47 \text{ m}^3$.

The introduction of the bioretention system contributes to reduction of the peak floods and the discharge volume from the basin, as it can be seen from the drainage hydrograph (Fig. 4) prepared for the parking lot working with and without the bioretention system. The shape of flooding curve did not change significantly after the bioretention system was introduced, but culmination of flooding was reduced by 55.3%. The volume of the wave was also reduced from 390 to 170 m^3 (56%). The reduction of water volume was caused by retention of water in the soil bed and by interception and infiltration losses in the bioretention system; this way the sewage system would be less burdened. The maximum flow rate to sewerage well S405 was $311.4 \text{ dm}^3\cdot\text{s}^{-1}$, compared to

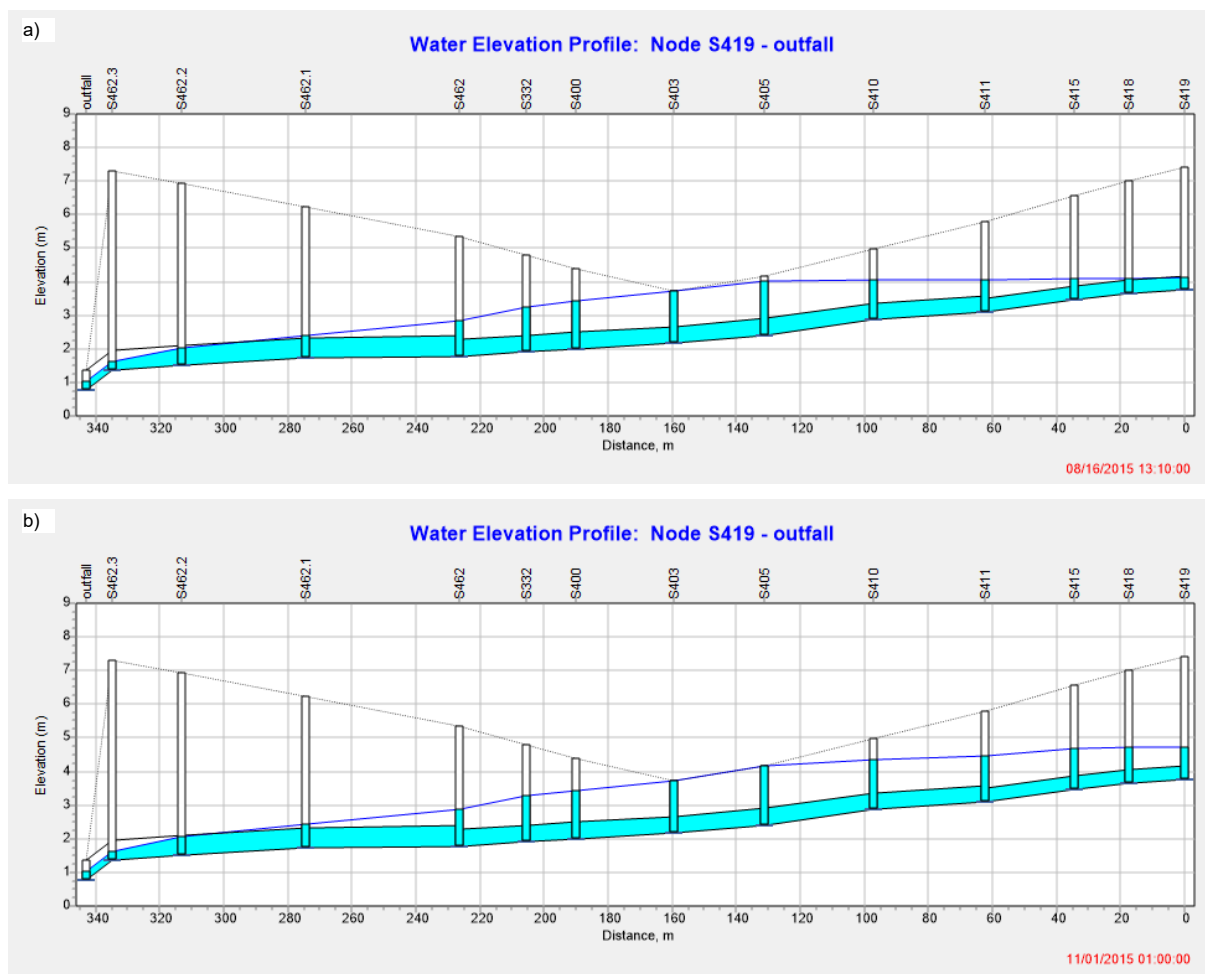


Fig. 3. Water elevation profile between the well S419 and the discharge point, at the maximum filling: a) on 16th Aug. 2015, b) during a hypothetical precipitation (without bioretention); source: own study

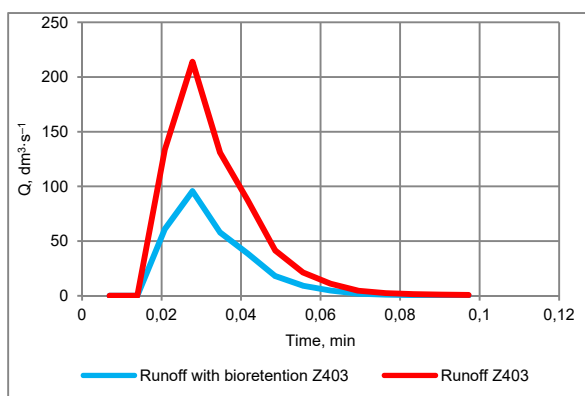


Fig. 4. Hydrographs of runoff from the parking lot – the options with and without bioretention on August 16, 2015; Z403 as in Fig. 1; source: own study

424.8 $\text{dm}^3 \cdot \text{s}^{-1}$ in case without bioretention. In turn, the discharge volume to this well was reduced by 223 m^3 , and thus by 28% compared to the original situation. The same shape of hydrograph in time, regardless of the presence of bioretention, is probably caused by the assumption that the excess water from the bioretention system will be drained off from the drainage basin, while the rest will undergo evapotranspiration.

Thus, the discharge from the bioretention system is not discharged into the sewage system and lower flows in the option with bioretention and without an outflow delay are observed (Fig. 4). Figure 5 shows the profile of the combined sewage system collector with the maximum water level for an actual precipitation and a bioremediation system employed. Comparing to the existing conditions it is obvious that the maximum water pressure in the collector is reduced; it results in a smaller number of wells with observed water accumulation (up to 7) and no water overflowing from the system. In the case of a hypothetical precipitation, a similar situation was observed – Figure 6. The maximum flow was reduced by 56% and the wave volume was reduced by 54.5%. In the well S405 the maximum flow was 436.3 $\text{dm}^3 \cdot \text{s}^{-1}$ and was reduced by only 1.4 $\text{dm}^3 \cdot \text{s}^{-1}$, i.e. by 0.3%. A wave volume in the well S405 was reduced by 160 m^3 or 24.8% as a result of the bioretention system. In the case of a hypothetical precipitation, with duration of $t = 180$ min, a small flooding the bioretention system occurred; the system lost its retention capacity, which resulted in a slight higher discharge from the catchment in the hydrograph descent phase if compared to the option without bioretention.

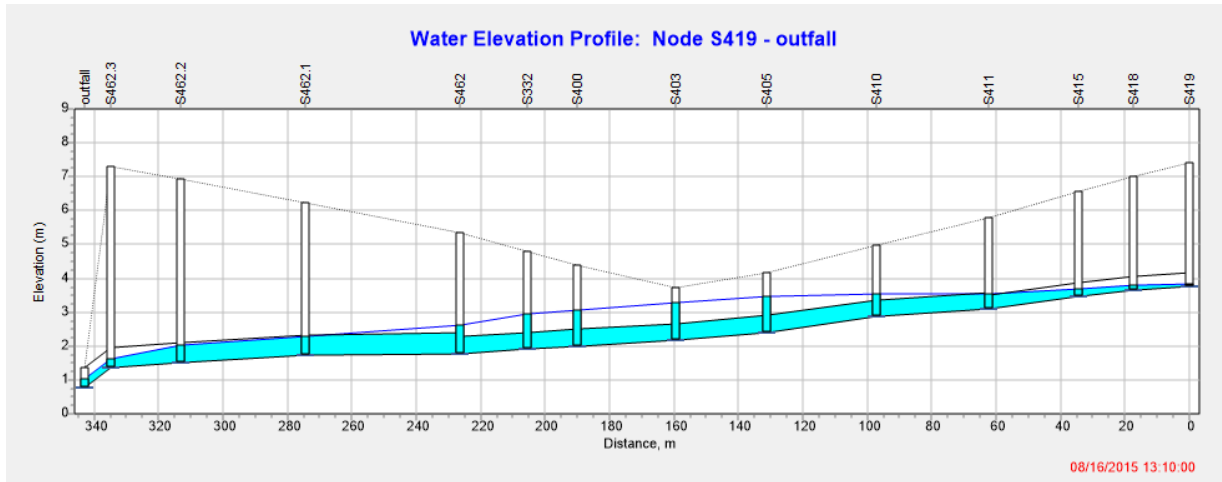


Fig. 5. Water elevation profile between the well S419 and the discharge point, at the maximum filling on 16th Aug. 2015 (with bioretention); S419 as in Fig. 1; source: own study

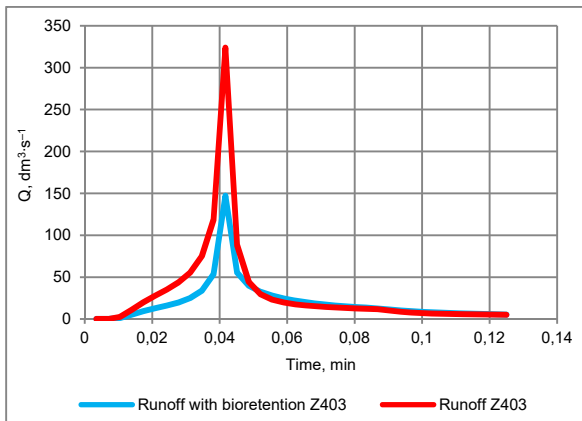


Fig. 6. Hydrographs of runoff from the parking lot – the options with and without bioretention for a hypothetical precipitation; Z403 as in Fig. 1; source: own study

It was found that in case of hypothetical precipitation, the water discharged to the well S405 comes mainly from the analyzed parking lot and is almost equivalent to the total discharge from the upper part

of the catchment, observed in the well S410 (Fig. 7). Assuming a form of a hypothetical precipitation hyetograph, with the maximum precipitation occurring at the beginning of the episode, a rapid loss of the catchment retention capacity above the well S405 was observed resulting in a large discharge to the well S405; all that took place despite of the bioretention system, which significantly reduced the discharge from the parking area.

As a result, a water level in the collector was slightly lowered, comparing to the one observed in the real episode – Figure 8.

Water cumulation was observed in 11 wells, as in the option without bioretention, though the maximum overflow $67.6 \text{ dm}^3 \cdot \text{s}^{-1}$ and a volume of $V = 4.0 \text{ m}^3$ were observed in the well S403, only. The overflow volume was reduced by 91% in this option. Therefore, it can be concluded that the bioretention system has brought a relief to the overloaded sewage system, significantly reducing the risk of flooding due to the torrential rain. During low-intensity rainfalls, that do not overload the sewage system, the bioretention system

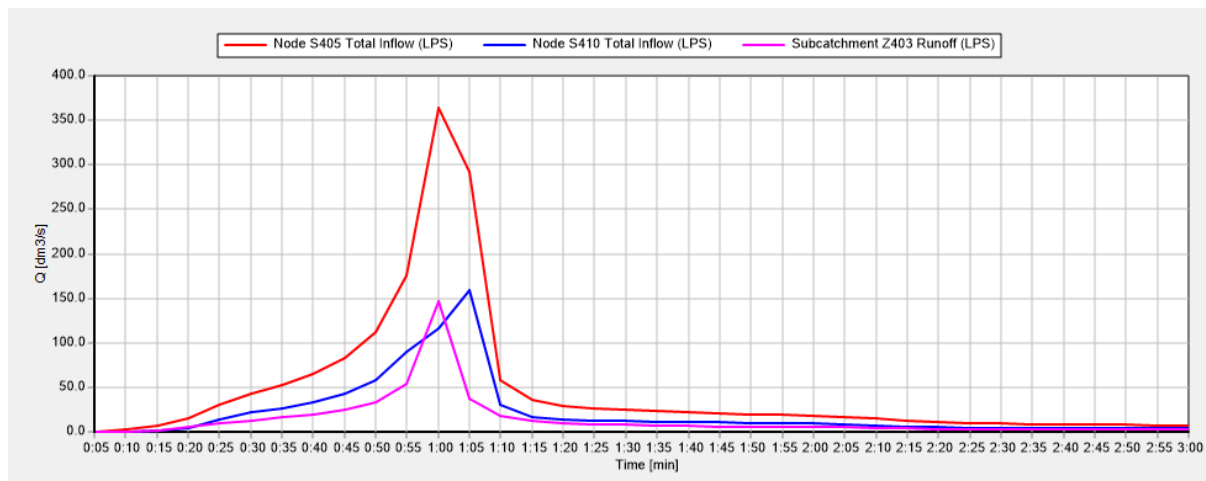


Fig. 7. Hydrographs of runoff (Q) in selected locations of the sewer system during a hypothetical precipitation; S405, S410, Z403 as in Fig. 1; source: own study

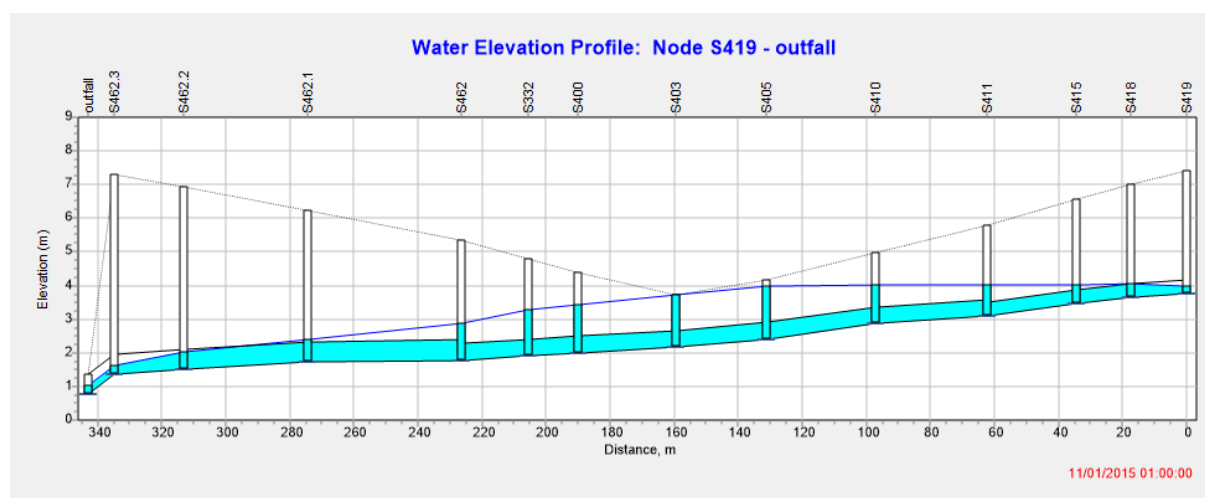


Fig. 8. Water elevation profile between the well S419 and the discharge point, at the maximum filling during a probable precipitation (with bioretention); S419 as in Fig. 1; source: own study

withholds the entire runoff, while at high air temperatures, the collected water is additionally removed through evapotranspiration. Bioretention areas can be used to “accept” stormwater runoff at a wide variety of development sites, including residential, commercial and institutional development sites in rural, suburban and urban areas [CWP 2009]. They are well suited to “accept” stormwater runoff from nearly all small impervious and pervious drainage areas, including local streets and roadways, highways, driveways, small parking areas and disturbed pervious areas (e.g., lawns, parks, community open spaces). Bioretention areas are one of the most effective low impact developments to reduce post-construction stormwater runoff rates, volumes and pollutant loads. They also provide a number of other benefits, including improvement of general aesthetics, wildlife habitat, urban heat island mitigation and air quality.

CONCLUSIONS

1. The bioretention systems contribute to a significant reduction of runoff and a volume of floods from low-permeable catchments. They should offer an alternative to classic solutions providing a relief to drainage systems in urbanized areas.

2. Precipitation significantly affects the drainage system. Adoption of the hypothetical hyetograph type II, proposed by Euler, leads to a situation where an intense precipitation at the beginning of the episode results in a rapid loss of retention capacity of the catchment, which in turn increases the water discharge from the catchment.

3. Application of professional computer programs, such as storm water management model, Environment Protection Agency (SWMM EPA), enables performing multivariate hydrodynamic calculations that consider also the influence of local rainwater management devices such as bioretention systems.

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Wykorzystanie systemów bioretencyjnych do zrównoważonego gospodarowania wodami opadowymi w obszarach uszczelnionych

STRESZCZENIE

Celem pracy jest ocena możliwości zastosowania systemu bioretencyjnego jako metody zrównoważonego gospodarowania wodami opadowymi w zlewniach uszczelnionych. Analizy prowadzono w zlewni silnie uszczelnionej wyposażonej w kanalizację ogólnospławną. Przyjęto dwa warianty opadu: pierwszy z opadem rzeczywistym o natężeniu jednostkowym $q = 105,65 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{ha}^{-1}$ i drugi z opadem hipotetycznym o prawdopodobieństwie przewyższenia $p = 10\%$ i $q = 40,7 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{ha}^{-1}$. Wszystkie obliczenia przeprowadzono w programie SWMM EPA (storm water management model; Environmental Protection Agency). Analizy wykazały, że zastosowanie systemu bioretencyjnego umożliwia redukcję przepływu kulminacyjnego o ponad 55% oraz ponad 54% zmniejszenie objętości fali. Ponadto stwierdzono, że przebieg opadu w istotny sposób wpływa na kształtowanie się odpływu w zlewni zurbanizowanej.

Słowa kluczowe: *hietogram Eulera, SWMM, system bioretencyjny, system kanalizacyjny, wody opadowe, zlewnia zurbanizowana*