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ANALYSIS OF COMBINED SEWER FLOW STORAGE SCENARIOS PRIOR TO WASTEWATER TREATMENT PLANT

ANALIZA SPOSOBÓW RETENCJI ŚCIEKÓW Z KANALIZACJI OGÓLNOSPŁAWNEJ PRZED OCZYSZCZALNIĄ ŚCIEKÓW

Abstract: Combined sewer systems in cities are increasingly equipped with additional storage facilities or other installations necessary for keeping the wastewater treatment plants from overloading during wet weather and reducing combined sewer overflows into receiving waters. Effective methods for reducing such negative phenomena include the temporary storage of wet weather flow in an end-of-pipe separate tank or in a sewer system. In this paper, four scenarios of wastewater storage for the Group Wastewater Treatment Plant (GWWTP) in Lodz (Poland) have been analysed: a storage in a separate single tank located in GWWTP, a storage in the bypass channel in GWWTP, in-sewer storage, and a combination of the aforementioned variants, also with real time control (RTC) system introduced. The basic calculations were performed using the EPA's SWMM software for the period of 5 years (2004-2008). The chosen solution - storage in a separate storage tank - has been verified based on the inflow dataset from the years 2009-2013. The specific volume of the separate storage tank should be at least 22 m^3 per hectare of impervious catchment area, but it could be reduced if additional in-sewer storage with RTC were introduced. Both options allow the effective protection of receiving waters against discharge of untreated sewage during wet weather.

Keywords: combined sewerage, in-sewer storage, modelling, storage tank, RTC system, SWMM

Introduction

The functioning of combined sewer systems in cities during wet weather still poses many problems. An increasing degree of surface sealing in urban catchments and an increasing frequency of intense rainfalls result in the inability of existing sewer systems and wastewater treatment plants (WTTPs) to temporarily intercept considerable amounts of wastewater. In this situation a discharge of excess wastewater directly into receiving water bodies by combined sewer overflows (CSOs) in the sewerage systems or using by-pass channels in treatment plants without the required wastewater treatment is being practised. WTTPs usually have problems with treating significantly increased amount of wastewater during wet weather [1]. The biological treatment process is sensitive to any violent changes, including variations in quantity and composition of raw wastewater during rainy weather. In this respect, periods of intense precipitation and snowmelt are especially detrimental [2].

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Hydraulic overloading has a negative influence on treatment plant functioning, but the treatment process can be significantly improved by applying stormwater detention. The organization of this detention requires solving a number of technical and economic problems and usually depends on local conditions. There are several possibilities of wastewater storage in the sewer system: end-of-pipe, on-site, and in-sewer storage. In the case of a separate storage tank, the required effective volume usually ranges from several dozen to more than one hundred m^3 per hectare of impervious catchment area (m^3/ha_{imp}). Anta et al. [3] presented a comparative study for several combined sewerage catchments in Spain; the specific storage ranged from 20 to even 90 m^3/ha_{imp} depending on the annual rainfall and local situation. Todeschini et al. [4] determined that the optimum tank capacity, due to reducing pollution loads discharged into the receiving waters, is usually about 35-50 m^3/ha_{imp}. Calabro and Viviani [5] estimated the specific storage volume as 30-50 m^3/ ha_{imp} as optimal for capturing total suspended solids in on-line and off-line storage tanks. Temprano and Tejero [6], determined that bacteriological pollution of overflows produce the most adverse effect in the river and the needed storage volume is 45 to 180 m^3/ha_{imp}, more than in the case of other pollutants.

According to the previous analyses conducted by the authors regarding a densely built-up catchment [7], the addition of a single storage tank, with a specific volume of 50 m^3/ha_{imp}, makes it possible to reduce the frequency of a CSO to the level of 10 times per year, required in Poland according to the Regulation of the Minister of Environment [8]. This frequency should be confirmed by the measurements or by the long-term modelling of the system (for at least 10 years) using the real rainfall data. Additionally, a three-time dilution of dry weather flow at the beginning of a CSO spill should be guaranteed. For the same specific detention volume (50 m^3/ha_{imp}), the annual wastewater volume discharged via a CSO can be reduced by 60 %. The specific detention volume appeared to be greater in the case of smaller catchments. The analysis carried out for an urbanized catchment of a small town gave the result of 82 m^3/ha_{imp}. This is probably caused by an unfavourable ratio of wet to dry weather flow and in smaller towns with less water consumption per capita.

Formal regulations in Poland do not fully protect receiving water against pollution because they do not take pollutant loads into consideration. It is planned to introduce restrictions on the allowable pollutants' loads emitted into receivers. Therefore, to assess the impact on the receiver, at least the volume of discharges should be additionally determined. So, both indicators can be applied for assessment of receiving water quality impact, however, depending on local conditions they must be taken with caution [9].

A large detention tank to prevent combined sewer overflows significantly reduces the negative impacts on receiving waters associated with discharges during wet weather. According to Llopart-Mascaro et al. [10], the total annual mass of pollutants introduced into the receiving waters is reduced by 45 % - measured in terms of suspended solids and chemical oxygen demand - while the efficiency can be increased by 15 % in case of optimised performance. Stormwater may also be stored inside the sewer network. The analysis carried out by Guillon et al. [11], for sewerage in a densely populated department of 176 km^2 in Paris, showed that during the initial overflow, only 12.4 % volume of the system is mobilized and 79 % at first flooding, respectively. It means that the available volume enables the system to store a rainfall of 6.6 mm.

Extended in-sewer storage may lead to some problems in treatment plants, such as an increase in foul flush loads, disruption of treatment process efficiency for carbon, nitrogen and phosphorus removal, and the increase of screenings, grit and sludge masses

[12]. The analysis carried out by Jack and Ashley [13] highlighted that ammonia concentrations in the effluent from the treatment plant deteriorate rapidly under storm conditions, and a large storage volume (> 10,000 m^3) can serve to exacerbate this problem. Moreover, other problems connected with septic conditions can occur in the system. However, where the systems are designed and operated in accordance with current standards, the problems should not be insurmountable.

In order to reduce the total outflow from the catchment, it is necessary to implement a more sophisticated real time control (RTC) system or, at least, an optimised static throttling of tank outflow, which allows for the optimal use of available tank volume. Application of RTC offers great benefits for system operators and for the environment, particularly when water quality RTC is included in global RTC [14]. Regarding networks with large-volume collectors, the application of RTC for stormwater storage may be less expensive than the construction of additional storage tanks [15, 16]. Real time control enables enhancement of WWTP performance by balancing inflow loads and allowing the plant to operate closer to its design capacity [17]. Numerous studies show that by using a RTC system the wastewater treatment plant functioning can be significantly improved [18-20]. Choosing optimal variant of storage in sewer system and necessary volume should be made based on many parameters [21-23], among others costs (Life Cycle Cost) of storage reservoir construction and functioning [24].

Experimental

Study area

Lodz, one of the largest cities in Poland, is located in the central region, on the border of the watersheds of two major rivers. The average annual precipitation is 575 mm, and on average, there are 167 days of wet weather per year. The central part of the city is equipped with a combined sewer system which has been operating for more than 80 years, while newer areas on the outskirts are equipped with a separate system. The catchment area of combined sewerage is 43 km^2, 43 % of which is impervious. This system is equipped with 18 combined sewer overflows (CSOs) which, according to the legal requirements, should function up to 10 times per year. In Lodz, combined flow, without any local detention, is directed by the main sewer Polesie 15 into the Group Wastewater Treatment Plant (GWWTP). The biological stage of the GWTTP works in the MUCT system. The main sewer Polesie 15 is located on undeveloped areas (Fig. 1). All other trunk sewers (sanitary and combined) are connected directly or indirectly to it. This main sewer consists of two barrels of cross-section 2.45×2.47 m and the length of the sewer is approximately 2400 m.

Initial state of the Lodz Wastewater Treatment Plant

The average value of daily dry weather inflow to the GWWTP amounts about 180,000 m^3/d and the level of about 200,000 m^3/d is exceeded during wet weather conditions. In the present state, the main bottlenecks in the GWWTP are secondary clarifiers, which are susceptible to inflow increase, causing a rise of the activated sludge blanket level. The maximum capacity of primary settling tanks is about 600,000 m^3/d = 5.9 m^3/s. However, due to the limitations concerning the secondary clarifiers, for most wet-weather events inflow to the biological stage has to be limited to 5.0 m^3/s.

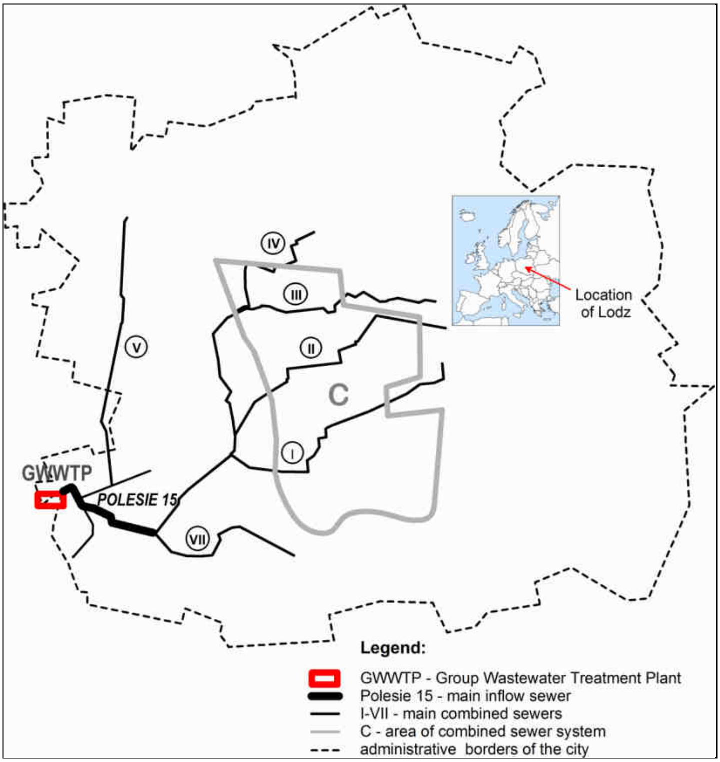

Fig. 1. Sewer system in Lodz

If the flow of wastewater during the rainfall is greater than the capacity of the wastewater treatment facilities, the excess wastewater is discharged via a bypass channel directly into the river. Such situation occurs at least 20 times a year. Treating such a phenomenon as the activation of additional combined sewer overflow (CSO) should be recognized that the limit of CSO frequency is exceeded.

For some rainfall phenomena, it is possible to increase the daily sewage flow through the biological part of the GWWTP up to 700,000 m^3/d. Calculations carried out with a dynamic simulation software SymOS [25] showed that at the time, a slight increase of the concentration of pollutants in the wastewater discharged from the plant (biologically treated) may occur, but the total pollution load discharged into receiving waters (from secondary clarifiers and a bypass channel) is smaller [2] (Fig. 2).

The analysis performed indicates the necessity of introducing storage into the system. Previous studies of the storage in the Lodz combined sewerage showed that the total necessary volume should be greater than 30,000 m^3 and this option is difficult to be implemented due to high investment costs and a lack of available space on the developed urban area. In this situation the detention by using a separate storage tank or in-sewer storage, may be an effective method for reducing discharges of untreated sewage into the receiving water. It can improve the operation of the GWWTP and reduce environmental pollution.

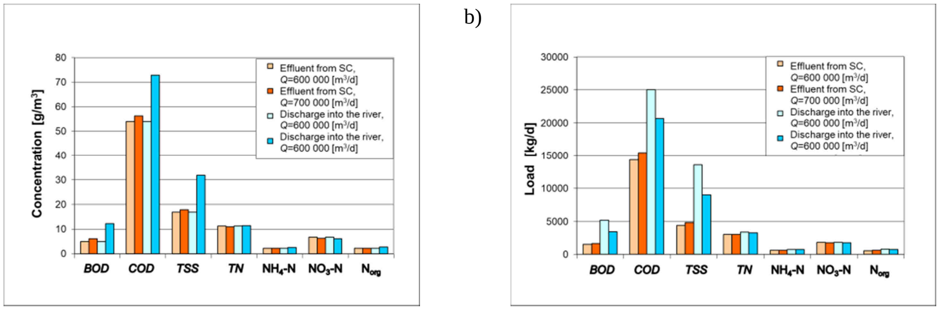

Fig. 2. a) The concentration and b) load of pollutants discharged into the receiving water for different variants of the GWTTP operation (simulation results for a rainfall of return period C = 1 year and duration t = 60 min). *BOD* - biological oxygen demand, *COD* - chemical oxygen demand, *TSS* - total suspended solids, *TN* - total nitrogen, NH_4-N - ammonia nitrogen, NO_3-N - nitrate nitrogen, N_{org} - organic nitrogen, SC - secondary clarifiers, Q - flow

Methodology of hydraulic analyses

In order to reduce the sewage flow into the biological part of the treatment plant during the wet weather the following scenarios of storage were analysed (Fig. 3):

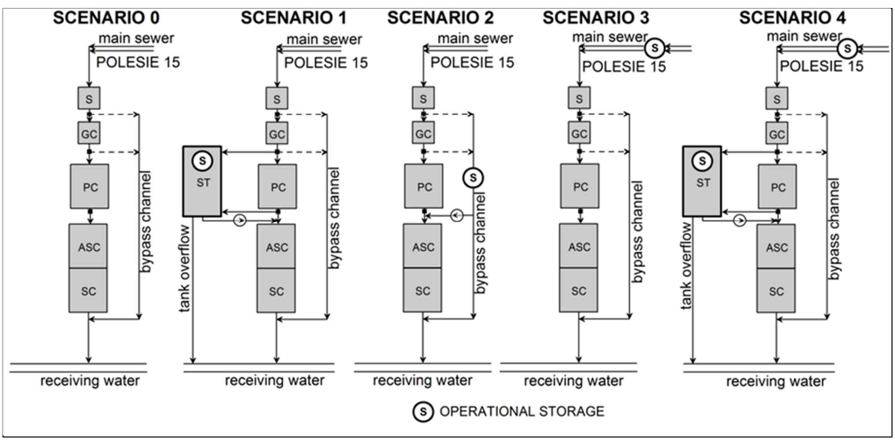

Fig. 3. Schemes of analysis scenarios of storage: S - screens; GC - grit chamber; PC - primary clarifiers; ASC - activated sludge chambers; SC - secondary clarifiers; ST - storage tank

0 - the present state

1 - a storage in a separate single tank located in WWTP - a gravitational inflow of wastewater after mechanical treatment, emptying by a pump with max. 24 hours storage, analysed total active volume V = 5000-40,000 m^3. It was assumed that the storage tank could be emptied by means of 3 pumps with a continuous capacity of 500 dm^3/s each. The pumps were started progressively, during the decreasing inflow to primary clarifiers (PC) after a storm, and in such a controlled way that the total inflow to the activated sludge chambers (ASC) was kept at the maximum allowable loading. The wastewater from storage tank is directed to ASC. However, as it has been demonstrated by Maruejouls et al. [26],

some portions of wastewater from storage tanks - at the beginning and the end of the tank emptying - contain solid particles of relatively high settling velocity. Therefore, depending on the settleability of particles, the tank needs to be emptied prior to primary clarifiers. Nevertheless, a change of the storage tank emptying operation does not change further analyses of the scenario under discussion.

2 - a storage in the bypass channel. The existing bypass channel can be used for wastewater storage by installation of a movable gate on its last segment prior to a receiving body and the use of a pump, pushing sewage back to the technological system. The active storage capacity of the bypass channel is about 4000 m^3. The calculations were performed on the assumption that it would be emptied with a pump of a capacity of 300 dm^3/s.

The wastewater would be directed to ASC.

3 - in-sewer storage - in the main sewer Polesie 15 with an optimised static throttling of the flow as a basic option. At present, the wastewater is transported in two barrels, but the hydraulic capacity of the main sewer is not fully used. The average dry weather wastewater depth in each barrel is about 0.35 m, corresponding to the mean flow of 1 m^3/s. It was assumed that the detention in the main sewer would be forced by 4 pairs of gates installed in both barrels in the existing rectangular inspection chambers. The lower edge of each of the gates is set at 0.35 m above the bottom, and the upper reaches the level of sewer ceiling. Under these circumstances, the dry weather sewage will be transported under the gates, but taking into account wastewater impoundments during wet weather, the flow downstream the gates under pressure will be increased to approximately 4 m^3/s. The total volume of the main sewer is about 30,000 m^3 but the usable storage volume is about 22,000 m^3. A scheme of detention in the main sewer is presented below (Fig. 4).

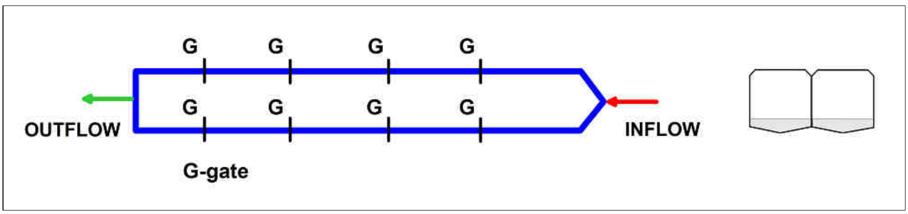

Fig. 4. Scheme and cross-section of the main sewer Polesie 15

4 - a combination of scenarios no. 1 and no. 3 - storage in a separate single tank and in-sewer storage.

The main criteria of assessment the effectiveness of each scenarios was the number of overflow of biologically untreated wastewater and reduction of overflow volume. The calculations for several storage options were performed using the EPA's Storm Water Management Model (SWMM) based on the continuous ultrasonic measurements of inflow to the GWWTP during 5 years (2004-2008). The ultrasonic flowmeter is systematically calibrated and guarantees precise measurements of flow with a measurement error less than 5 %. The use of these data directly for calculations made it possible to eliminate the necessity of elaborating the calibrated model of the whole combined system in the city. The software SWMM is widely used and guarantees high precision of dynamic simulation of the detention both in a separate tank and in-sewer. The calculation error obtained for hydrodynamic modelling was less than 0.5 %. The effectiveness of storage in a separate storage tank has been verified by the inflow dataset from the years 2009-2013. Because at present a separate storage tank of a volume of 15,000 m^3 is under construction, a combination of the storage in this tank and in the main sewer Polesie 15 with a local RTC system included has been analysed additionally (scenario 4bis). In order to force the effective detention in the sewer, the same 4 pairs of gates has been assumed, however the gates are movable. At initial position they allow a free maximum allowable flow to the biological part GWTTP and in case of greater inflow, the controlled gates are shifted down, throttling the flow and allowing for better use of available sewer volume. It was assumed that the maximum level of damming should not cause any flooding. In the event of such a threat anywhere along the profile of the main sewer, the gates are lifted.

Results and discussion

The results of calculations for the scenario 1 - in a separate storage tank - are shown in Figure 5. The effectiveness of the storage tank, represented by the reduction of the number of overflows, is proportional to the storage tank volume - but the improvement is relatively small for large volumes, especially for volumes greater than 20,000 m^3. This effectiveness strongly depends on the year of analysis, and the character of rainfalls which occurred during that given year. Based on the calculations for 5 years, it can be assumed that a storage tank with a volume of approximately 40,000 m^3 will provide the required reduction in the frequency of CSOs. This will also limit the volume of biologically untreated sewage discharged into the receiver by about one third. The total storage volume is equivalent to 22 m^3/ha$_{imp}$.

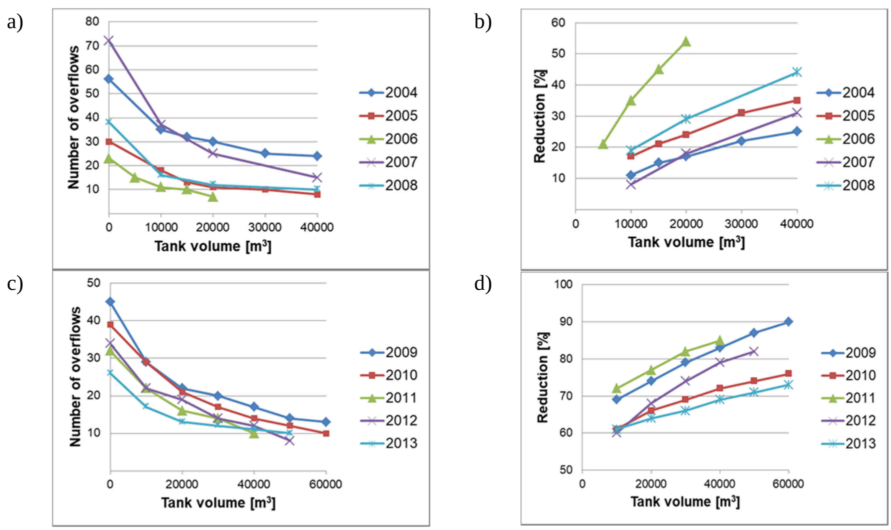

Fig. 5. Storage effects for scenario 1: a) number of overflows in 2004-2008, b) reduction of overflow volume in 2004-2008, c) number of overflows in 2009-2013, d) reduction of overflow volume in 2009-2013

The storage tank was usually emptied during a period less than 24 hours, except for one situation of two consecutive torrential storms in June 2007. The required volume of separate storage tank was confirmed by the calculations carried out for the data flows from the years 2009-2013, but in relation to the number of overflows, the volume reduction of overflows was significantly greater (Fig. 5).

In case of the use of the bypass channel (scenario 2) very low detention efficiency was observed (Fig. 6) because each year the number of overflows far exceeded the value of 10. That option, however, is not expensive and should be considered as additional to other scenarios.

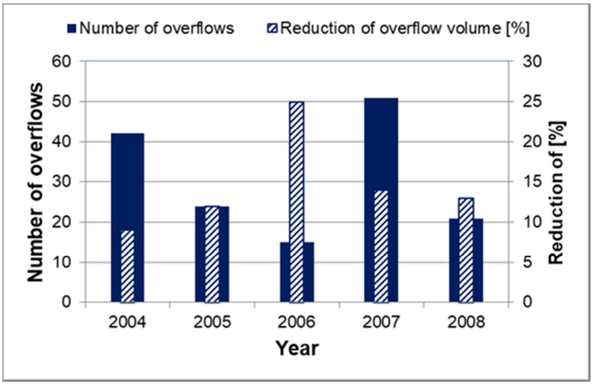

Fig. 6. Storage effect for scenario 2

The use of the main sewer Polesie 15 (scenario 3) for stormwater storage with static throttling did not give satisfactory results (Fig. 7). Although the detention volume of the sewer Polesie 15 was larger than that of the tank with a volume 20,000 m^3, the tank allowed for a more efficient reduction of the number of discharges. Good results can be achieved for scenario 4, i.e. for a combination of storage in the sewer Polesie 15, and in an end-of-pipe tank with a volume greater than 10,000 m^3 (Fig. 7).

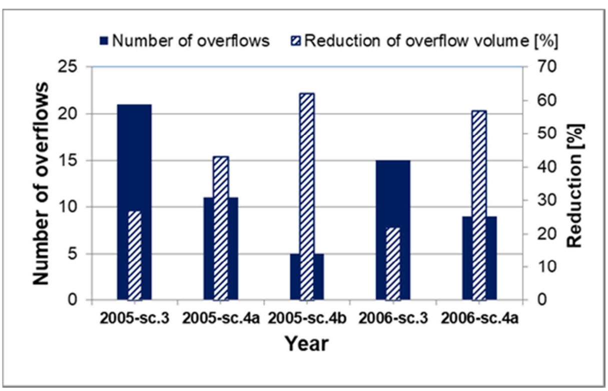

Fig. 7. Storage effect for scenario 3+4 (a - storage tank V = 10,000 m^3; b - storage tank V = 40,000 m^3)

The efficiency of storage in main sewer Polesie 15 can be distinctly increased in case of RTC system application. The storage effects in the separate storage tank of a volume

15,000 m^3, which is under construction now and in main sewer Polesie 15 with RTC are presented in Table 1.

Table 1

Storage effects in the separate storage tank of a volume of 15,000 m^3 and in main sewer Polesie 15 with RTC system

Year	Without detention (scenario 0)		With detention (scenario 4bis)			
	No. of overflow	Volume of overflows [m^3]	No. of overflow	Reduction [%]	Volume of overflows [m^3]	Reduction [%]
2004	56	3,813,000	14	96	1,443,000	62
2005	30	1,480,000	7	77	545,000	63
2006	23	487,000	0	100	0	100
2007	72	2,360,000	11	85	154,000	93
2008	38	1,186,000	3	92	8000	99
2009	68	2,909,000	18	74	574,000	80
2010	66	3,925,000	15	80	1,176,000	70
2011	52	1,997,000	15	31	347,000	83
2012	42	2,187,000	6	86	232,000	89
2013	40	2,863,000	11	72	956,000	67

The use of an end-of-pipe tank together with an in sewer storage can significantly reduce the volume of untreated sewage discharged from WWTP during wet weather, which certainly helps to protect of the quality of receiving water. The number of CSO events may, however, not every year be reduced to the required level. It strongly depends on the characteristics of the rainfall, but not always directly on the annual precipitation depth, which can be seen in Figure 8.

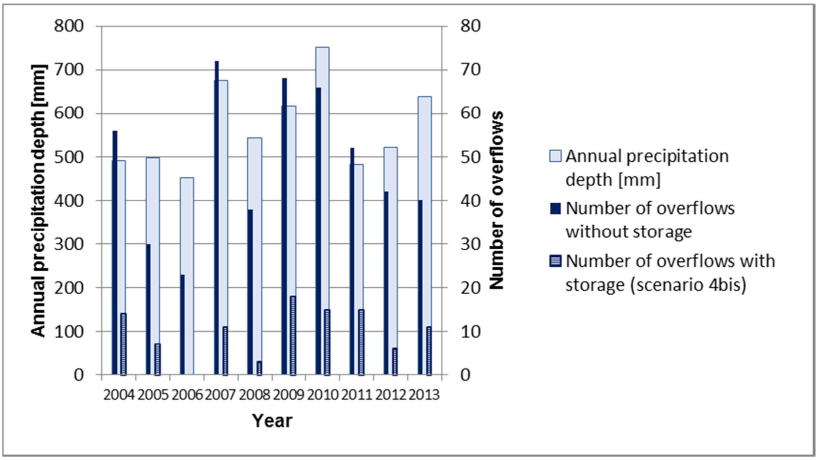

Fig. 8. Annual precipitation and number of overflows from the GWWTP into the receiving water in 2004-2013

In the period of 2004-2013 the precipitations were very differentiated, therefore analyses similar to the presented ones should be performed using long-term flow data. In general, the analysis of the functioning of CSOs focuses on periods with heavy rainfalls.

In a temperate climate zone however, periods of rapid increase of temperature in winter after a period of intense snowfall can cause frequent activation of storm overflows. It was observed in some years, particularly in January 2004, when CSO was activated 15 times.

Application of storage in main sewer Polesie 15 with RTC system has enabled to use the entire capacity of the sewer, i.e. more than 30,000 m^3. This option can be a very attractive solution for various reasons, primarily due to the reduction of investment costs. As previously mentioned the capacity of two-barrels' sewer is not fully used. It runs outside built-up areas, and the terrain relief allows for safe impoundment of wastewater using four pairs of gates. The future task is the development of optimal control of two-step storage and operation of the system. Regular cleaning of the sewer and removal of sediments accumulated as a result of wastewater storage will be necessary.

Application of two-step storage gives slightly different results in comparison to storage in the end-of-pipe tank of the same volume. Some storm inflows are effectively stored in the sewer Polesie 15 together with the separate tank of 15,000 m^3 (scenario 4bis) whereas for the option of an end-of-pipe tank (scenario 1) of a volume of 45,000 m^3 overflows have been observed despite the same effective storage volume. For some other rainfalls a reverse situation (i.e. no overflows from the tank 45,000 m^3 and excess overflows from the tank 15,000 m^3) can occur.

In choosing the optimal variant of storage for sewer system in Lodz - in addition to the formal requirements - the reliability, capital and operational cost of solutions, technical feasibility, and maintenance should be taken into account. In-sewer storage with RTC system, arranged in the main sewer, might probably eliminate the necessity of an end-of-pipe storage expansion, i.e. as added to the storage tank of 15,000 m^3. The detention scenarios should be, however, analysed in the future. This is due to the possible changes of the inflow quantity to the GWWTP. For several years a decrease of dry weather flow into the GWWTP has been observed. A decrease of stormwater amount in the future can be expected, too. Introduction of on-site retention and rainwater reuse, especially in newly-constructed buildings, should limit stormwater amount discharged from the sealed surface to the combined sewer system in the city. LID implementation in urban areas may be a cost-effective way of reduction of CSO activity [27] and is therefore this option is considered to be widely introduced in the city area.

The obtained specific volume of 22 m^3/ha_{imp} is lower than obtained for the catchments in city centre [3-6]. Probably two basic factors affect this result. The first one: the capacity of the biological stage of GWWTP which is able to treat 3.3 DWF (dry weather flow). The second one: the total catchment of Lodz is extended which causes the attenuation of inflow hydrographs in comparison to single catchments in the city centre or smaller towns.

Conclusions

The Group Wastewater Treatment Plant in Lodz is not able to treat significantly increased amounts of wastewater during wet weather, and as a result a part of the biologically untreated wastewater is discharged directly to receiving waters. Therefore, the formal requirements are not met, and the environment water receivers are being polluted. There is an urgent necessity to introduce a detention into the system to solve the problem. The use of EPA SWMM enabled a detailed hydraulic analysis of wastewater treatment plant and main inflow sewer based on the flow data from the period of 10 years and a reliable analysis of the problems arising in periods of wet weather including snowmelt inflow. The performed analyses show that an end-of-pipe storage tank with a minimum specific volume of 22 m^3 per hectare of impervious catchment area would be necessary. Based on the calculations for the years 2004-2009 the required volume of the tank is around 40,000 m^3, which has been confirmed by calculations for the years 2009-2013. It will then be possible to reduce the discharge of the biologically untreated wastewater to the receiving waters up to 10 times a year, which is consistent with the legal requirements in Poland. At the moment, at the GWWTP, a separate storage tank with a volume of 15,000 m^3 is under construction. The decision to build a next tank should be taken after assessing the effectiveness of the first one. In-sewer storage with RTC, arranged in the main sewer, might probably eliminate the necessity of an additional end-of-pipe storage.

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