Use of Quantitative and Qualitative Wastewater Monitoring in Water Protection on the Example of Lodz

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1. Introduction

In recent decades surface water protection has become particularly essential among others due to the decreasing world drinking water resources and simultaneously the growing population and its requirements for water quality. Water protection largely depends on the functioning of sewage systems, which should not only ensure the safe functioning of the city, but also determine the ecological safety of the receiver. Urban development, and therefore an increase of urbanized areas in the total catchment area, additionally highlights the impact of sewerage systems on water reservoirs. In the last two decades, both methods and devices used for monitoring wastewater systems have significantly progressed (Lvovaa et al. 2016, Di Lecce et al. 2017). It should be noted, however, that the functioning of sewage systems carried out wastewater from urban areas is associated with the occurrence and character of rainfall, which should therefore also be constantly monitored (Langeveld et al. 2013, Zawilski & Brzezińska 2014). In addition to changes in the character of precipitation as a consequence of climate variations, changes in air temperature are also observed. This affects in some way the temperature of rainwater directed to the sewage system and the temperature in the wastewater receivers. This may alter, among other things, the morphology of the receiver as well as the kinetics of the chemical reactions taking place in it.

Pollutants introduced by wastewater sewer systems largely affect the chemical and ecological state of reservoirs (Casadio et al. 2010, Caissie et al. 2014). Monitoring of sewer systems should therefore be carried out in terms of both the quantity and composition of transported sewage (Brzezińska et al. 2016). This is particularly important for the assessment of pollution load in surface waters pollution load coming from the sewage system, including the effect of cobined sewer overflows activation (Phillips et al. 2012, Bi et al. 2015), and

wastewater treatment plant (WWTP). Only comprehensive knowledge of pollutant emissions allows to fully control and effectively counteract the pollution of water receivers and promotes the proper functioning of the sewage system, even in conditions of variable flows caused by precipitation events.

The aim of this article is to present the needs and benefits of different forms of monitoring in order to widely understood protection of surface waters on the example of Lodz.

2. Analysis of needs, tasks and benefits resulting from the application of quantitative and qualitative monitoring

Urban development and the increasing incidence of extreme rainfall events leads to sewage systems, including WWTPs, being increasingly overloaded, which reduces their operational safety. The condition of optimal use of their technical capabilities and determining the necessary scope of modernization and expansion is knowledge of the hydraulic conditions of the network operation and the composition of flowing wastewater. The database required for this is facilitated by on-line devices. Until recently, on-line monitoring was most often carried out mainly in WWTPs to control treatment processes and its use in sewage disposal systems was sporadic and rarely de-scribe (Torres & Bertrand-Krajewski 2008).

Currently, on-line monitoring can be carried out using, among other things:
- rain gauges that allow determining rainfall characteristics,
- filling sensors and flow meters in channels,
- on-line sensors measuring one or several indicators of wastewater pollution simultaneously (multi-parameter sensors).

For effective control of the impact of wastewater sewer systems on receiver waters, it is important to define criteria for the selection of monitoring points (Thompson et al. 2011). Depending on the applied solutions a lot of information can be obtain, among others, for:
- recognition of the dynamics of flow variabilities in the sewers,
- composition of wastewater flowing through the sewage network both in dry and wet weather,
- monitoring of wastewater inflow to the treatment plant,
- calibration of computer programs used for network modeling,
- analysis of the "first flush" phenomenon of pollution in the sewage system,
- assessment of the functioning of sewage systems in the hydraulic aspect, as well as pollutant emission,
- Real Time Control system implementation (RTC) in sewer networks (Campisano et al. 2013).

In accordance with PN-EN 752: 2017 "External sewage systems", when conducting research and analyses relating to the functioning of sewage systems and determining the needs for their modernization, should be used simulation models that require accurate data from measurement campaigns. The use of on-line sensors measuring the concentrations of selected wastewater pollution indicators, especially in the case of combined sewer system (CSS), allows for a significant cost reduction of sampling, their transport and laboratory tests.

The use of quantitative and qualitative monitoring of wastewater sewer systems is extremely important for the functioning of WWTPs. Variations of quantity and composition of inflowing wastewater, sewer system modernization and changes within the catchment area may reflected in the inflow characteristic to the WWTP and influence on hydraulic and pollution load.

3. Methods and tools used in Lodz

3.1. Characteristics of Lodz wastewater sewer system and the scope of its monitoring

Lodz is equipped with mixed sewer system. A CSS (43 km^2) exist in the central districts and a separated system in the rest of the city. There are 18 combined sewer overflows (CSOs), which discharge excess raw wastewater directly to Lodz rivers during heavy rainfall. The main receiver of all wastewater from the city, both the treated wastewater from the Lodz treatment plant and the raw wastewater coming from heavy rainfall, which is directed to the receiver from CSOs is the Ner River. Currently, all overflows are equipped with flow meters, which allow to monitor the functioning of these facilities, determine the frequency of their activity and the volume of discharged wastewater (Fig. 1a).

In addition the measurements mentioned above carried out by the network operator, the monitoring of the sewer system in Lodz is also carried out by the Institute of Environmental Engineering and Building Installations at the Lodz University of Technology at two research stations:

- the station on the J1 overflow equipped with a flow meter and on-line sensors (Solitax and UVvis) for measuring the wastewater composition and a sampler for the automatic collection of wastewater samples,
- a station at the outlet from the stormwater drainage system of the "Liściasta" district with a rainwater settler, equipped at its inlet with a sampler for collecting wastewater, a wastewater fill sensor and flow velocity sensor in the sewer and at its outlet equipped with a sampler and a wastewater fill sensor in the settler.
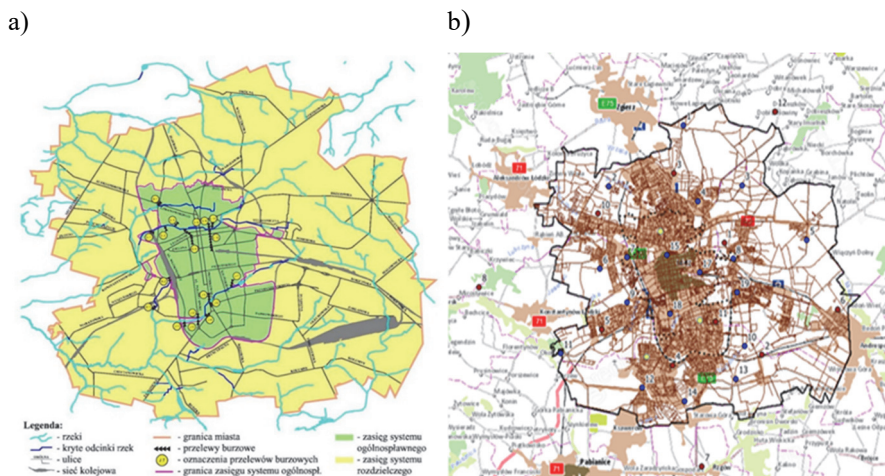
a)

b)

Fig. 1a. Location of combined sewer overflows in Lodz (Wierzbicki et al. 2010)
Fig. 1b. Location of rain gauges in Lodz (blue – Lodz Infrastructure Company rain gauges, red – University of Lodz, yellow – Lodz University of Technology)

3.2. Rainfall monitoring and its use

Lodz has an urban rain gauges network (18 devices) belonging to the Lodz Infrastructure Company. Additionally, three rain gauges belonging to the Lodz University of Technology and 12 rain gauges owned by the University of Lodz are located in the city (Fig. 1b). This type of data allows not only to determine the character of precipitation, but also to indicate the direction of precipitation and its spatial unevenness, which has a significant impact on the functioning of the sewage system. Much more favourable for the operation of the sewer system is opposite direction of rainfall movement in relation to the direction of wastewater flow (Zawilski & Brzezińska 2014). According to observations, during the year the air masses come to Lodz from the west (20% of observations), south-west (15%) and from the east (14%) (Kożuchowski 2011), which in some way helps in removal of excess stormwater from the city area.

Currently, cities increasingly need to have digital models of sewer networks. Thanks to them it is possible to assess their functioning, as well as determine the needs for modernization and design guidelines. According to the current requirements contained in the Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 on substances particularly harmful to the aquatic environment and the conditions to be met when discharging sewage into waters or ground, as well as when discharging rainwater or meltwater into waters or into water devices to assess the functioning of sewer systems in the case of lack of data from observation of their functioning over longer period of time, it is

recommended to use verified computer models. However, for these models to be useful and generate reliable results, it is required to correctly map the net-work and have accurate input data, including precipitation data, needed to calibrate the combined sewage and rainwater drainage network. Currently, many Polish cities do not yet have a pluviometric network, and have only, for example, one rain gauge (or only a few) for the entire city. In this case, it is difficult to determine the spatio-temporal characteristics of precipitation, which is especially important for large catchments area. That model calibration based only on one rain gauge usually causes over-statement of results (Zawilski 2012). Examples of the results of simulation flow rate in the sewage system in comparison with the actual rain-fall data (spatial precipitation, point precipitation) conducted in the use of the US EPA SWMM program at the outlet from the Bałutka catchment (609 ha) are shown in Figure 2. Results of the simulation of flow in the combined network for this catchment showed a better fit in the case of spatial precipitation, which con-firms the usefulness of using extensive rainfall monitoring in the city.
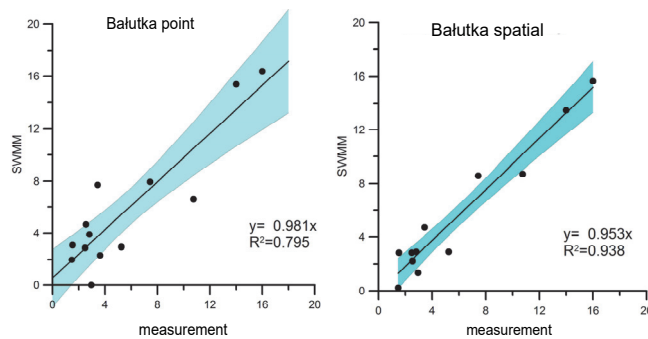

Fig. 2. Comparison of modeling results with real data of wastewater flow at the outlet of the Bałutka catchment area (flow stream in [m^3/s]) (Zawilski 2012)

3.3. Network flow monitoring

In most major cities in Poland, CSSs with overflows function in the cen-tral districts. Operation of these systems creates many problems, especially dur-ing the rainfall due to hydraulic over-load of sewers and with the pollution load discharged to the receiver. The flow meters located in the area of CSOs in Lodz, allow to determine both the frequency of their activity and the volume of dis-charged wastewater, which is particularly important in the case of surface water protection. According to RME, the number of activations of these facilities should not exceed 10 per year. Therefore, quantitative monitoring allows to de-termine the correct operation of overflows or, if necessary, to indicate exceed-ances in their functioning (Fig. 3).

Based on the measured data, the frequency of CSOs can be analysed at various time intervals. In Lodz, most CSOs usually operate in the summer months, and the volume of dis-charged wastewater is greatly varied. In example the B1 overflow in both June and July, works on average around 3.5 times, but the volume of wastewater emitted to the receiver is several times higher in June. Without quantitative monitoring, obtaining such information would be very difficult.
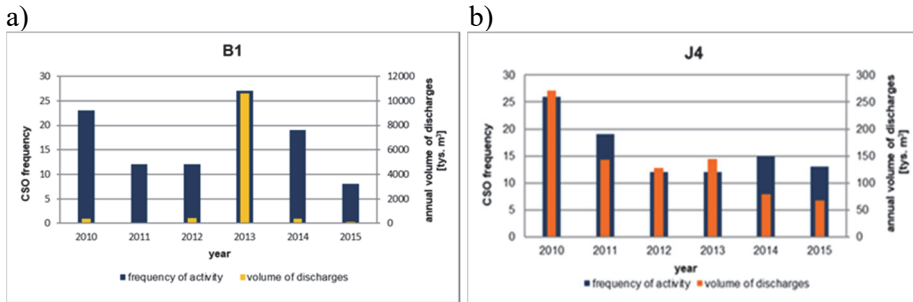
a)

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Fig. 3. Annual average frequency and volume of wastewater discharged by combined sewer overflow in the years 2010-2015, a) B1, b) J4 (Brzezińska 2019)

With this type of data, it is possible to determine the parameters relevant to the functioning of the network: flow variability (Fig. 4), hourly and daily unevenness coefficients, etc. The use of this data together with precipitation data in modeling systems enables their calibration. This allows, among others, to identify overloads and establish the required storage capacity of the system and the possible channel retention capacity.
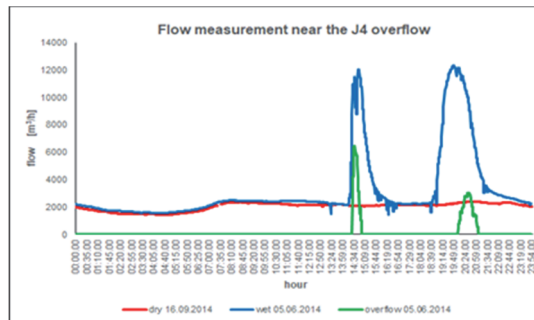

Fig. 4. Dynamics of flow variabilities during the day with dry and wet weather and an example of PB J4 functioning

3.4. Qualitative monitoring of wastewater in the sewage system

During measurements of the first tested indicator a method of measuring UV absorption with a wavelength of 254 nm (according to DIN 38402 C2) is used, while the measurement of the second one is carried out in a combination of the absorption process and infrared rays dispersion (according to DIN 27027). The probes are calibrated using the results of laboratory tests on the composition of the wastewater collected with the sampler installed on the bench. The data obtained from the monitoring also allow for the analysis of the concentrations of the measured indicators in dry and wet weather, as well as their changes depending on the day of the week, month, season, etc.

Data from quantitative and qualitative monitoring allow to assess pollution loads transported through the network and their variability during rainfall events (e.g. occurrence of the "first flush" of pollution). For example, the J1 transfer on 27-28.04.2013 caused the discharge of 2598 m^3 of untreated wastewater transporting 992 kg of total suspended solids and 658 kg of organic substances expressed as COD. Data analysis obtained from qualitative monitoring confirmed the occurrence of the first flush phenomenon (Fig. 5), whose capture to the retention tank and subsequent referral to the WWTP would significantly protect the receiver against the pollution inflow.
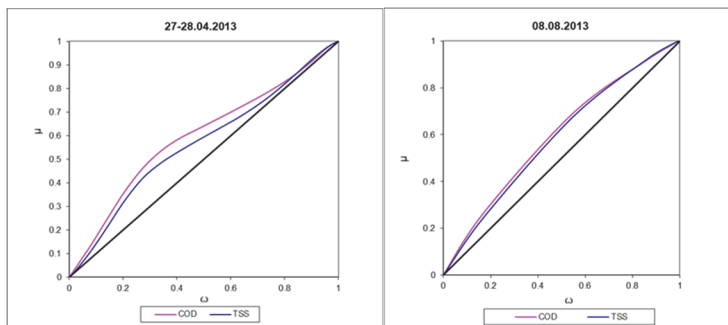

Fig. 5. An example of the occurrence of the first flush pollution phenomenon on the J1 overflow

The inflow of a large amount of pollutants in very short time, even if there are no toxic substances among them, can cause significant difficulties in the treatment process. Changes in the quality and quantity of sewage flowing into WWTP are not repeatable, they depend primarily on rainfall characteristic and the length of the dry weather period before precipitation, which determines the amount of pollution built-up on the catchment and wash-off during rainfall. Even

on the same catchment, in the case of different precipitation, the first flush phenomenon may not be observed, it may be pronounced or the so-called the last wave phenomenon may occur, moreover, the flow of pollutants may be different for basic quality parameters of sewage (Fig. 5).

3.5. The use of monitoring data for pollutant load prediction

Continuous monitoring of CSOs and storm water drainage outlets is costly, labour-intensive and sometimes complicated for technical reasons. That is why simpler, less expensive, but equally accurate methods for estimating the quantity and composition of wastewater emitted to the receiver are increasingly being sought (Hannouche et al. 2017, Montserrat et al. 2017). For this aim mathematical models are used, which allow to know and predict pollutant emissions and simultaneously limit the range of measurement campaigns. Based on the monitoring data, among others models for pollutant emissions from combined overflows and storm water drainage were developed for the Lodz catchment area. The predictive model of pollutant emissions from CSOs was based on three variables: height and maximum rainfall intensity and volume of wastewater discharged from CSO. These parameters were selected after a series of analyses using the Principal Component Analysis method (PCA) and multiple regression. On their basis, a mathematical formula to forecast the load of emitted pollutants for total suspended solids (TSS) and COD was developed (Brzezinska et.al. 2018). In addition to the parameters included in the model, other parameters such as the rainfall duration, its average intensity and the time of dry weather before precipitation were taken into account for the analysis. The results of the conducted analyses indicated that the above-mentioned parameters turned out to be less important. Pearson correlations between rainfall parameters and concentration as well as the load of TSS and COD were also made. The results showed practically no relationship between the concentration of the studied indicators and rainfall parameters, while strongly marked the dependence of the load on the height and maximum intensity of precipitation as well as volume of discharge, which was confirmed by the formula of the model.

$$L_{TSS} = 1.8 \cdot R_{depth}^{-0.37} \cdot i_{max}^{0.21} \cdot V_{CSO}^{0.97} \tag{1}$$

$$L_{COD} = 1.6 \cdot H_{op}^{-0.3} \cdot i_{max}^{0.22} \cdot V_{CSO}^{0.95} \tag{2}$$

where:
R_{depth} – rainfall height [mm],
i_{max} – maximum rainfall intensity [mm/h],
V_{CSO} – volume of discharged wastewater [m^3].

According to the developed model, the prediction of pollutant load emitted by a CSO depends mainly on the volume of wastewater in power close to 1. It should be remembered that for a single CSO event, the volume of wastewater has a various importance relative to the load of emitted pollutants. This is due to the fact that precipitation parameters and the "first flush" phenome-non significantly influance the concentration of pollutants in surface runoff and CSO. The proposed model provides reliable results on pollutant emissions ($R^2 = 0.79$ for TSS, and for COD $R^2 = 0.80$) in the case of the catchment area belong to J1 CSO for which it was developed (Fig. 6).
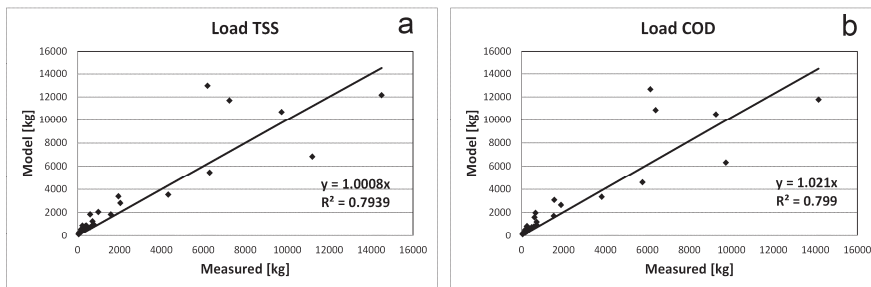

Fig. 6. Relationships between the measured values and model for J1 CSO: a) for TSS, b) for COD (Brzezinska at al. 2018)

For other catchments, this model can be used after adjusting the propor-cional coefficient, which depends, among others, on the catchment characteristics, the way it is managed, sources of pollution, and the characteristics of the wastewater system and the overflow itself.

4. Advantages and disadvantages

On-line quantitative and qualitative monitoring used in sewage systems allows, among others, for:
- limitation of measurement campaigns,
- limitation of costs of wastewater laboratory tests,
- creating a large measurement database for analyzing of the functioning network,
- capturing all occurring variabilities of amount and composition of wastewater in both dry and wet weather.

These advantages are particularly important in the case of storm water drainage and CSS due to the unpredictability of precipitation phenomena and high dynamics of changes in the composition of wastewater and rainwater in these systems. The large advantage of using measurements directly in the medium

is the high quality of the obtained data and the possibility of their transmission directly to e.g. a dispatcher, which allows making quick decisions regarding the operation of the system. It should be added that the simultaneous possession of rainfall monitoring gives the possibility of earlier network preparation and sewage treatment plant for sudden rainwater inflows. Despite the many benefits resulting form the use a such monitoring, some disadvantages should also be noted. Belong to them:

- still relatively high price, despite the dynamic development of measuring methods and technical solutions,
- sensors susceptibility to dirt, clogging and mechanical damage,
- lack of power supply or other factors preventing the measurement or causing erroneous data (e.g. indication of the instantaneous concentration value exceeding the repeatedly measured average minute concentration persistent for a very short time of the order of a minute or 2 minutes, most likely due to hanging up around the sensor of large things like rag, foil, etc),
- the need for periodic calibration for some types of equipment,
- in case of on-line sensors for measuring the pollution concentration indicators, limited range of indicators measured and the need to select it,
- location difficulties (e.g. lack of technical possibilities for mounting the sensor due to hydraulic conditions, no possibility of power supply, operational difficulties, difficulties with data transmission),
- difficulties associated with these installation (sewer condition, hydraulic conditions,sewer deposits),
- the need for periodic inspections and repairs.

Despite the possible operational problems and significant purchase costs, monitoring is already becoming the basis for suitable network management, especially in unforeseen situations, e.g. during heavy rainfalls. The benefits of having quantitative-qualitative monitoring (or even quantitative in the initial phase of its creation) are definitely higher than the potential disadvantages.

5. Conclusions

The examples of the on-line monitoring application included in the article have shown its great usefulness in determining rainfall characteristics, assessing of the wastewater sewer system functioning, and pollutant emissions directed to the receiver. Presented in this article the possibility of forecasting pollutant load (TSS and COD) directed to the surface waters e.g. form CSO's based on the data of rainfall and volume discharges can be a useful tool in the selection of effective methods of reducing emissions of pollutants getting into surface waters. On-line

measurements allow to build a wide base for these purposes. The city's monitoring gives the possibility to observe changes taking place in the sewer system in real time and to reduce the costs associated with the wastewater analysis process. Despite the presented operational problems, having quantitative and qualitative monitoring is cost-effective and increasingly necessary due to the protection of surface waters. Sustainable development of city drainage systems will require the use of various forms of monitoring, interrelated to one another (rainfalls, flows in the network as well as to wastewater composition).

References

Bi E.G., Monette F., Gachon P., Gaspéri J., Perrodin Y. (2015). Quantitative and qualitative assessment of the impact of climate change on a combined sewer overflow and its receiving water body, *Environmental Science and Pollution Research, 22,* 11905-11921.

Brzezińska, A., Sakson, G., Zawilski, M. (2016). Assessment of pollutant load emission from combined sewer overflows based on the online monitoring, *Environmental Monitoring and Assessment, 188(9)*, 502.

Brzezińska, A., Sakson, G., Zawilski, M. (2018). Predictive model of pollutant loads discharged by combined sewer overflows, *Water Science and Technology, 77*(7-8), 1819-1828.

Brzezińska, A. (2019). *Emission of pollutants from combined sewer ovelflows*. Monographs of the Lodz University of Technology, No. 2279.

Casadio, A., Maglionico, M., Bolognesi, A., Artina, S. (2010). Toxicity and pollutant impact analysis in an urban river due to combined sewer overflows loads, *Water Science and Technology, 61*(1), 207-221.

Campisano, A., Cabot, J., Muschalla, D., Pleau, M., Vanrolleghem, P.A. (2013). Potential and limitations of modern equipment for real time control of urban wastewater system, *Urban Water Journal, 10*, 300-331.

Caissie, D., Kurylyk, B.L., St-Hilaire, A., El-Jabi, N., MacQuarrie, K.T. (2014). Streambed temperature dynamics and corresponding heat fluxes in small streams experiencing seasonal, ice cover, *Journal of Hydrology, 519,* 1441-1452.

Di Lecce, V., Petruzzelli, D., Guaragnella, C., Cardellicchio A., Dentamaro, G., Quarto, A., Soldo, D., Dario, R. (2017). Real-time monitoring system for urban wastewater, July 2017, *Conference: 2017 IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems (EESMS).*

Hannouche, A., Joannis, C. & Chebbo, G. (2017). Assessment of total suspended solids (TSS) event load and its uncertainties in combined sewer system from continuous turbidity measurements. *Urban Water Journal, 17*(8), 789-796.

Keupers, I., Willems, P. (2013). Impact of urban WWTP and CSO fluxes on river peak flow extremes under current and future climate conditions, *Water Science and Technology, 67*(12), 2670-2676.

Kożuchowski, K. (2011). *Polish climate: a new look*. PWN Scientific Publisher, Warsaw, 1-292.

Langeveld, J.G., Schilperoort, R.P.S., Weijers, S.R. (2013). Climate change and urban wastewater infrastructure: there is more to explore, *Journal of Hydrolology, 476,* 112-119.

Lvovaa, L., Guanais, Gonçalvesa, C., Petropoulosa, K., Michelia, L., Volpea, G., Kirsanovb, D., Leginb, A., Viaggiud, E., Congestrid, R., Guzzellae, L., Pozzonie, F., Palleschia, G., Di Nataleb, C., Paolesse, R. (2016). Electronic tongue for micro-cystin screening in waters, *Biosensors and Bioelectronics, 80,* 154-160.

Montserrat, A., Hofer, T., Poch, M., Muschalla, D., Corominas, L. (2017). Using the duration of combined sewer overflow events for the calibration of sewer hydrodynamic models. *Urban Water Journal, 14*(8), 782-788.

Phillips, P.J., Chalmers, A.T., Gray, J.L., Kolpin, D.W., Foreman, W.T., Wall, G.R. (2012). Combined sewer overflows: an environmental source of hormones and wastewater micropollutants, *Environmental Science and Technology, 46*(10), 5336-5343.

Regulation of the Minister of the Environment of November 18, 2014 on the conditions which must be met during discharging wastewater into water or into the ground,, and on substances that are particularly harmful to the aquatic environment.

Thompson, K.E., Vamvakeridou-Lyroudia, L., Kapelan, Z., Savic, D. (2011). Optimal macrolocation methods for sensor placement in urban water systems," Exeter, UK.

Torres, A. & Bertrand-Krajewski, J.L. (2008). Partial Least Squares local calibration of a UV–visible spectrometer used for in situ measurements of COD and TSS concentrations in urban drainage systems, *Water Science and Technology, 57*(4), 581-588.

Wierzbicki, P., Waack-Zając, A., Koska, T. (2010). Hydrographic system of the city of Lodz, Scientific Notebooks of the Lodz University of Technology, *Civil Engineering, 1066*(61), 1-13.

Zawilski, M., Brzezińska, A. (2014). Areal rainfall intensity distribution over an urban area and its effect on a combined sewerage system, *Urban Water Journal, 11*(7), 532-542.

Zawilski, M. (2012). Analysis of the hydraulic load of the sewage system on a large urban catchment scale, Scientific Papers of Rzeszów University of Technology, *Civil and Environmental Engineering, 59*(2) / I, 237-247.

Abstract

Widely understood protection of water, and in particular surface waters, most exposed to direct pollution, requires many operations carried out both in the catchment area and in sewage systems as well as WWTPs. Due to its character and working conditions, it should be monitored not only in terms of hydraulics, but also in terms of the quality of transported wastewater. During atmospheric precipitation, large volumes of domestic and industrial wastewater as well as rainwater in various proportions flow through the canals, changing not only their quantity but also their composition. In such cases, the issue of monitoring becomes particularly vital. The article presents an analysis of the needs and tasks resulting from the application of quantitative and qualitative monitoring in the assessment of the functioning of sewage systems. Methods and tools used in Lodz that may be useful in water protection are presented. The benefits of using this type of solutions as well as the limitations and difficulties are discussed.

Keywords:
sewer system, wastewater monitoring, rainfall monitoring, predictive model

Stosowanie ilościowego i jakościowego monitorowania ścieków w ochronie wód na przykładzie Łodzi

Streszczenie

Szeroko rozumiana ochrona wód, a zwłaszcza wód powierzchniowych, najbardziej narażonych na bezpośrednie zanieczyszczenie, wymaga wielu działań przeprowadzanych zarówno w zlewni, jak i w systemach kanalizacyjnych oraz w oczyszczalniach ścieków. Ze względu na swój charakter i warunki pracy system kanalizacji należy monitorować nie tylko pod względem hydraulicznym, ale także pod względem składu transportowanych ścieków. Podczas opadów atmosferycznych przez kanały, w różnych proporcjach, przepływają znaczne ilości ścieków bytowych, przemysłowych oraz deszczowych, zmieniając przy tym także swój skład. W takich przypadkach kwestia monitorowania staje się szczególnie istotna. W artykule przedstawiono analizę potrzeb i zadań wynikających z zastosowania monitorowania ilościowego i jakościowego w ocenie funkcjonowania systemów kanalizacyjnych oraz metody i narzędzia stosowane w Łodzi, które mogą być przydatne w ochronie wód. Omówiono zalety korzystania z tego typu rozwiązań, a także ograniczenia i trudności.

Słowa klucze:
system kanalizacyjny, monitoring ścieków, monitoring opadów, model predykcyjny