Proceedings of ECOpole

DOI: 10.2429/proc.2013.7(1)013 2013;7(1)

Bartosz KAŹMIERCZAK[1]

MODELLING OF DISCHARGES FROM STORM OVERFLOWS ON A COMBINED SEWAGE SYSTEM

MODELOWANIE ZRZUTÓW ŚCIEKÓW Z PRZELEWÓW BURZOWYCH NA KANALIZACJI OGÓLNOSPŁAWNEJ

Abstract: A simulation of the functioning of a modern overfall with a throttling pipe on a combined sewage system was conducted in this work. For the modelling of storm overflow activity a combined drainage area of F = 50 ha was suggested. The overfall was loaded with sewage and wastewater. A typical, triangular hydrograph of the wastewater inflow to the storm overflow was applied here. The given hydraulic model of storm overflow activity includes a series of characteristic, occurring in sequence phases of filling and emptying of the overfall chamber. The phases were distinguished with the description of boundary conditions in reference to the precisely determined range of variables during the fillings and flows. On the basis of the formulated hydraulic and mathematical models of the storm overflow activity, a computer programme for the numerical simulation of the functioning of the aforementioned overflows was developed.

Keywords: storm overflow, combined sewage system, mathematical modelling

Introduction

Storm overflows are mainly applied in combined sewage systems in order to protect sewage-treatment plants from hydraulic overload and operation efficiency decline, as well as to reduce the dimensions of a trunk sewer behind an overflow. A hydraulic task of a storm overflow is the distribution of the maximum sewage inflow stream Q_d to the object, into two separate streams [1-3]:

- Q_o - outflow to the sewage-treatment plant ($Q_o = Q_d - Q$),
- Q - outflow to the receiver ($Q = Q_d - Q_o$).

So far, traditional lateral storm overflow constructions have been applied in sewage systems. They consist of low overflow edges, which are placed at the height of a regular fulfilment next to the boundary stream in the inflow drain, without appliances used to throttling of the outflow towards the sewage - treatment plant. Hydraulic efficiency of these overflows is low, and therefore the length of the overflow edges is sizeable, because of high inertia (velocity) of the flowing sewage in the inflow drain and overflow chamber. The unconventional constructions - with high overflow edges and outflow stream throttling appliances - constitute an alternative for the conventional lateral overflows. Throttling appliances, such as throttling pipes, systems of elbows, bends or hydrodynamic regulators enable the accumulation of the sewage in the overflow chamber and in the inflow drain. Unconventional overflows have gained an advantage over the traditional ones due to the following facts [3]:

- flow velocity reduction in the range of the overflow chamber and the increase of hydraulic efficiency, and therefore significant reduction of the overflow edge length,
- high level of protection of the sewage-treatment plant from hydraulic overload,

[1] Institute of Environmental Protection Engineering, Wrocław University of Technology, pl. Grunwaldzki 9, 50-370 Wrocław, email: bartosz.kazmierczak@pwr.wroc.pl

- the use of channel retention in reducing the time and frequency of the overflow activity throughout the year.

Storm overflow designing

While designing storm overflows, qualitative, as well as quantitative criteria of the receiver water protection must be taken into consideration. The criteria can be expressed by the allowed number of storm discharges during the year (their duration or allowed volume), or by the admissible concentration and/or the load of pollution drained off in storm discharges to the receiver. In case of storm overflows, the limited value of the average annual number of sewage discharges, depending from the type of sewage system and the receiver constitutes an obligatory quantitative criterion in Poland. As an example, in municipal sewage system the wastewater from the storm overflows might be drained off to the inland surface waters - moving or marginal, unless the average annual number of runs of the particular overflows exceeds 10 - according to the Ordinance of the Minister of Environment of 2006 [4]. In the absence of design data needed to verify the above quantitative criterion, the sewage from storm overflows in the municipal combined sewage system can be entered to the waters if this system delivers the sewage to the sewage-treatment plant with PE under 100 000, and at the beginning of the overflow activity, the volume stream of the mingled inflow sewage is at least four times greater than the average daily in a year stream of sewage in the period of no precipitation $Q_{śc(p.b.)}$.

With regard to the above criteria, the value of the boundary volume stream Q_{gr} in the drain before the overflow, determining the initiation of the sewage discharge to the receiver can be represented by the following model [3]:

$$Q_{gr} = Q_{śc(p.b.)} + Q_{dgr} + \sum Q_{oi}$$

where: $Q_{śc(p.b)}$ - authoritative sewage inflow stream in the period of no precipitation (domestic sewage, industrial liquid waste and incidental and infiltration waters), Q_{dgr} - boundary stream of the wastewater inflow from the direct drainage area, ΣQ_{oi} - total number of inflows from the storm overflows situated at higher locations.

It must be considered that with the maximum (design) wastewater inflow to the overflow $Q_{d(max)}$, the outflow from the overflow towards the sewage-treatment plant $Q_{o(max)}$ will be larger than the stream Q_{gr}, as a result of accumulation of the waste flowing over the overflow edge. Therefore, it is permitted:

- $Q_{o(\max)} = \beta Q_{gr} = (1.2 \div 1.5) Q_{gr}$ - in Poland [5],
- $Q_{o(\max)} = \beta Q_{gr} = (1.1 \div 1.2) Q_{gr}$ - in Germany [1, 6].

The value of the boundary stream Q_{dgr} can be determined with dilution method, the crux of which is the initial waste dilution coefficient n_{rp} (at the initial point of flowing over the overflow edge), defined as:

$$n_{rp} = \frac{Q_{dgr}}{Q_{śc(p.b.)}}$$

thus

$$Q_{dgr} = n_{rp} \cdot Q_{śc(p.b.)}$$

In Poland storm overflows applied in municipal combined sewage systems (in agglomerations with PE ≤ 100000) should be designed for the initial dilution value of $n_{rp} \geq 3$, then the boundary outflow towards the sewage-treatment plant can be defined as [3, 7]:

$$Q_{gr} = (1+ n_{rp})\, Q_{\acute{s}c(p.b.)} + \sum Q_{oi}$$

The computational scheme for storm overflow is shown in Figure 1.

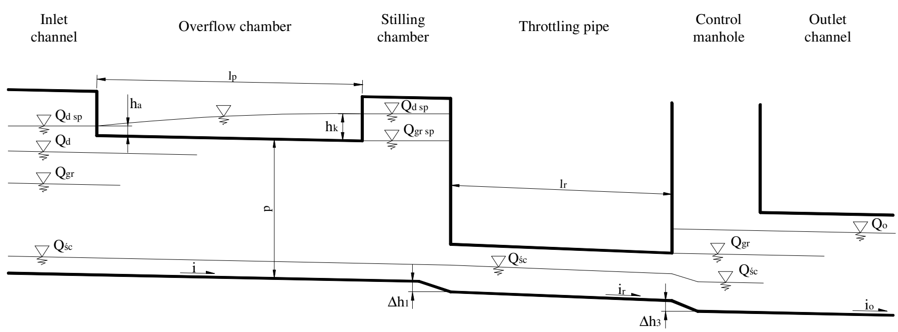


Fig. 1. Computational scheme for a non-conventional storm overflow

In order to design the algorithm applied in dimensioning of the improved storm overflows with a throttling pipe in a combine sewage system, the following course of operation was established [3]:

- for the sewage stream in no precipitation periods $Q_{\acute{s}c(p.b.)}$ a throttling pipe diameter is selected - taking into consideration its conditions of self-cleaning;
- for the boundary volume stream Q_{gr} of the sewage inflow flowing towards the overflow, the proper height of the side overflow edge is assumed - taking into consideration the hydraulic conditions of subcritical flow occurrence in the range of the overflow, and subsequently the necessary length of the throttling pipe is calculated;
- for the maximum stream Q_d the required distribution of the flows on the overflow:
  - for the assumed outflow (through the throttling pipe) flowing towards the sewage-treatment plant: *eg* $Q_o \in [1.1Q_{gr};\ 1.2Q_{gr}]$ the losses in the throttling pipe and the height of the overflow layer h_k at the end of the overflow are calculated;
  - for the outflow stream (through the overflow) flowing towards the receiver: $Q = Q_d - Q_o$ and for the calculated height h_k the height of the overflow layer h_a is determined iteratively at the beginning of the overflow, as well as the length of the overflow edge l_p.

Hydraulic and mathematical models of a storm overflow

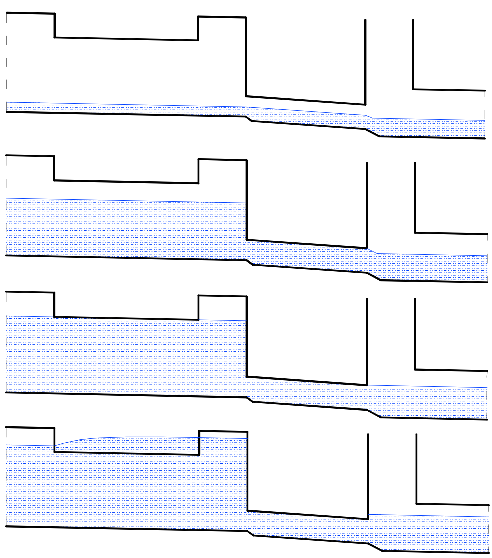
Designing of discharging objects, such as storm overflows, has been based on the maximum flows - the quasi-determined ones. Therefore the variability of the sewage stream is not taken into account as a function of time. At the stage of designing it is not possible to answer the questions concerning the multiplicity of the overflows activity during the year, or their activity time and the volume of discharges. The control of these parameters is possible only through hydrodynamic modelling [3, 8-12].

The assumed model of a storm overflow functioning includes a hydraulic description of the following processes: the inflow of the sewage to the object, the outflow to the sewage-treatment plant, the overflow through the side edge to the receiver, as well as the retention in the overflow chamber. The volume (V) change of the sewage accumulated in the overflow chamber in the time (t) can be defined as:

$$dV(t) = Q_d(t)dt - Q_o(t)dt - Q(t)dt$$

The sewage outflow stream Q_o flowing towards the sewage-treatment plant, as well as the sewage discharge stream Q flowing through the side overflow, are both dependent from the overflow chamber fulfilment height H. The sewage outflow volume stream flowing through the throttling pipe (under pressure) towards the sewage-treatment plant is calculated digitally, by the solution of a system of equations concerning hydraulic losses (Fig. 1):

$$\begin{cases} \Delta H_o(Q_o) = \left(\zeta_w + \lambda \dfrac{l_r}{d_r} + \alpha_r \right) \dfrac{8Q_o^2}{g\pi^2 d_r^4} \\ H - p = H_o(Q_o) + \Delta H_o(Q_o) - (il_u + p + \Delta h_1 + i_r l_r + \Delta h_2) \end{cases}$$



Boundary conditions in the range of fulfilments:
$0 < H(t) < d_r - \Delta h_1$
Boundary conditions in the range of flows:
$Q_d(t) < Q_{gr} \wedge Q_d(t) = Q_o(t) \wedge Q(t) = 0$

Boundary conditions in the range of fulfilments:
$d_r - \Delta h_1 \leq H(t) < p$
Boundary conditions in the range of flows:
$Q_d(t) < Q_{gr} \wedge Q_d(t) > Q_o(t) \wedge Q(t) = 0$

Boundary conditions in the range of fulfilments:
$H(t) = p$
Boundary conditions in the range of flows:
$Q_d(t) = Q_{gr} = Q_o(t) \wedge Q(t) = 0$

Boundary conditions in the range of fulfilments:
$H(t) \leq p + h_k$
Boundary conditions in the range of flows:
$Q_d(t) > Q_o(t) > Q_{gr} \wedge Q_o(t) \leq 1.2Q_{gr} \wedge Q(t) \leq Q$

Fig. 2. Overflow chamber filling phases

The sewage discharge to the receiver occurs when the fulfilment H exceeds the overflow edge height p and it is calculated from the model:

$$Q = \frac{2}{3} l_p \mu \sqrt{2g}\ (H - p)^{3/2}$$

where μ - side weir discharge coefficient $\mu \in [0.5; 0.6]$.

The given hydraulic model of a storm overflow activity includes a series of characteristic, occurring in sequence phases of filling (Fig. 2) and emptying (in analogy) of the overflow chamber. The phases were distinguished with the description of boundary conditions in reference to the precisely determined range of variables during the fulfilments and flows.

Exemplary storm overflow functioning simulation

For the modelling of a storm overflow activity, a combined drainage area of F = 50 ha was suggested. Making an assumption that a substitute (weighted average) run-off coefficient of the rain from the drainage area amounts ψ = 0.25, its reduced surface that takes part in the rain water run-off formation, will amount F_{zr} = 12.5 ha. An average population density of 150 inhabitant per one hectare was assumed, thus a number of inhabitants was estimated to be about 5000. On the basis of the German recommendations [13, 14], a unit rate (on an inhabitant) q_j = 0.005 dm^3/s was assumed as an authoritative (maximum per hour) domestic wastewater outflow. Hence the domestic wastewater outflow stream flowing from the model drainage area was estimated as 0.038 m^3/s. Furthermore, t = 20 minutes was assumed as the flow time in the trunk sewer, authoritative to the overflow design. The wastewater stream was calculated from the formula for the maximum precipitation amount in Wroclaw conditions (in [mm]) [15, 16], assuming design rainfall frequency C = 2 years:

$$h = -4.583 + 7.412 t^{0.242} + \left(97.105 t^{0.0222} - 98.675\right)\left(-\ln\frac{1}{C}\right)^{0.809}$$

The result of the calculation is the maximum sewage inflow stream flowing towards a storm overflow $Q_{m(C)}$ = 1.512 m^3/s. Thus the total sewage inflow volume stream flowing towards the storm overflow amounts $Q_d = Q_{d(\max)}$ = 1.550 m^3/s. The division of sewage streams was designed on the basis of dilution method, assuming n_{rp} = 5, taking into account the verification of the number of allowed storm discharges to the receiver, smaller than 10 in a year. The boundary sewage inflow stream flowing towards the overflow, according to (4), amounts: $Q_{gr} = (1 + 5)Q_{śc(p.b)}$ = 0.228 m^3/s.

On the basis of the assumed sewage division on the overflow and by the assumption that the maximum sewage outflow volume stream flowing towards the sewage-treatment plant can amount $Q_o = 1.2Q_{gr}$ = 0.274 m^3/s, the following storm overflow parameters were determined:

- an egg-shaped inflow drain 1.20 x 1.80 m with the slope of the drain bottom i = 1.00‰,
- a overflow edge with the height p = 1.20 m and length l_p = 2.56 m (μ = 0.523),
- a throttling pipe with the diameter d_r = 0.40 m, length l_r = 58.0 m and the bottom slope i_r = 2.50‰,
- an egg-shaped outflow drain: 0.60 x 0.90 m^2 with the bottom slope i_o = 1.67‰.

A typical, triangular hydrograph of the sewage inflow towards the storm overflow was applied here (Fig. 3).

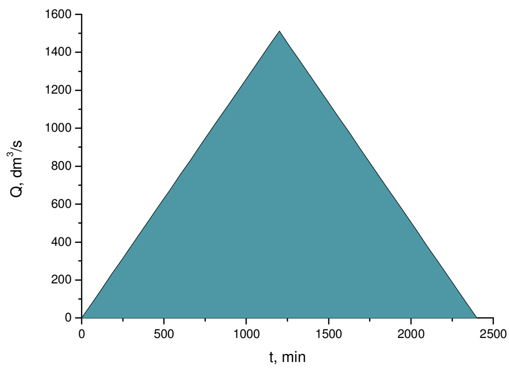


Fig. 3. The assumed hydrograph of wastewater inflow towards a storm overflow

On the basis of the formulated hydraulic and mathematical models of the storm overflow activity, a computer programme for the numerical simulation of the functioning of the aforementioned overflows was developed. The results of the simulation with the applied loads were presented in Table 1. On account of a high number of result data (one second time interval), only the data for the crucial moments of the simulation were presented in Table 1: simulation start (t = 0 s), sewage discharge start (t = 195 s), maximum temporary sewage discharge (t = 1200 s), sewage discharge end (t = 2252 s) and simulation end (t = 2400 s).

Table 1

The results of the simulation of a storm overflow functioning

t, [s]	Q_d [m^3/s]	Q_o [m^3/s]	Q [m^3/s]	ΣV_d [m^3]	ΣV_o [m^3]	ΣV [m^3]
0	0.038	0.038	0.000	-	-	-
195	0.284	0.229	0.008	31.4	26.5	0.0
1200	1.550	0.274	1.275	953.5	284.4	662.8
2252	0.224	0.228	0.004	1886.2	553.2	1328.1
2400	0.038	0.045	0.000	1905.5	577.4	1328.1

With the applied load the overflow starts discharging the sewage into the storm drain at 195 s. At 1200 s the maximum temporary sewage discharge $Q_{(max)}$ = 1.275 m^3/s occurs. The sewage discharge lasts until 2252 s (over 34 minutes). The total volume of the sewage discharged to the receiver in this time amounts V = 1328.1 m^3, whereas towards the sewage-treatment plant flows the volume of V_o = 577.4 m^3 (the total inflow towards the overflow V_d = 1905.5 m^3). The hydrographs of the sewage flow and discharge were presented in Figure 4.

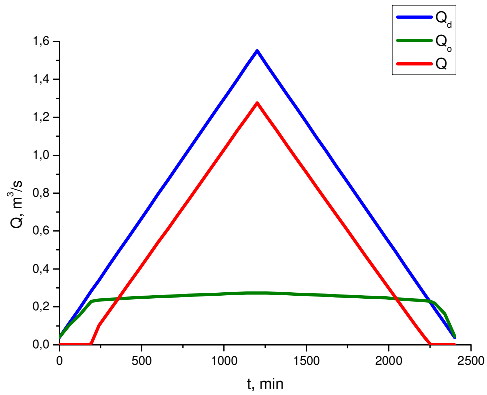


Fig. 4. The hydrographs of the sewage inflow towards the overflow, the outflow towards the sewage-treatment plant and the outflow to the storm drain through the overflow

The hydrographs in Figure 4 confirm an appropriate protection level of the sewage-treatment plant from the hydraulic overload through the application of throttling on a storm overflow. The maximum outflow stream towards the sewage-treatment plant amounts Q_o = 0.274 m^3/s, and therefore exactly 1.2Q_{gr}.

Conclusions and summary

Current methods of designing storm overflows do not take into account the frequency of storm discharges to the receiver, as well as they do not offer the possibility of their duration and volume determination and thus they do not allow for the assessment of pollution load that is drained off in discharges towards receivers. The simulations of storm overflows functioning allow for determination of these parameters for already designed overflow and for any assigned load. Therefore they constitute a valuable instrument supporting the process of designing this type of objects, as it has been proved in this work.

The simulation of a storm overflow functioning on a combined sewage system, conducted in this work, proved a high level of sewage-treatment plant protection from a hydraulic overload by the application of modern, unconventional storm overflows. Irrespective of the assigned load, sewage outflow stream towards the sewage-treatment plant is stabilized on a demanded level.

References

[1] Arbeitsblatt ATV-A111: Richtlinien für die hydraulische Dimensionierung und den Leistungsnachweis von Regenwasser-Entlastungsanlagen in Abwasserkanälen und -leitungen. Hennef: GfA; 1994.

[2] Fidala-Szope M. Surface Waters Protection from the Rain Water and Separate Sewage Systems Discharges. Warsaw: IOŚ; 1997.

[3] Kotowski A. The Principles of Safe Dimensioning of Sewage Systems. Warszawa: Seidel-Przywecki; 2011.

[4] Ordinance of the Minister of Environment dated 24 July 2006 on the conditions that must be fulfilled when entering sewage into waters or land, and on exceptionally harmful substances. Journal of Laws No. 137 of 31 July 2006, item 984.

[5] Błaszczyk P. The Principles of Sewage Systems Planning and Designing in Municipal and Industrial Agglomerations and Large Cities. Warsaw: IKŚ; 1983.
[6] Arbeitsblatt ATV-A128: Richtlinien für die Bemessung und Gestaltung von Regenentlastungs-anlagen in Mischwasserkanälen. Hennef: GfA; 1998.
[7] Kotowski A. Design of separators and high side weirs for storm sewers. Ochrona Środow. 2000;22(2):25-30.
[8] EN 752: Drain and sewer systems outside buildings, 2008.
[9] Kaźmierczak B, Kotowski A.: Verification of Storm Water Drainage Capacity in Hydrodynamic Modeling. Wrocław: The Publishing House of Wrocław University of Technology; 2012.
[10] Kaźmierczak B, Kotowski A, Dancewicz A. Verification of storm sewerage sizing methods with the hydrodynamic model SWMM 5.0 for the municipality of Wrocław. Ochrona Środow. 2012;34(2):25-31.
[11] Słyś. D, Stec A. Hydrodynamic modelling of the combined sewage system for the city of Przemyśl. Environ Protect Eng. 2012;38(4):99-112. DOI: 10.5277/EPE120409.
[12] Rossman LA. Storm Water Management Model. User's Manual. Version 5.0. Cincinnati: United States Environmental Protection Agency; 2010.
[13] Arbeitsblatt DWA-A118: Hydraulische Bemessung und Nachweis von Entwässerungs-systemen. DWA, Hennef, 2006.
[14] Schmitt T. Kommentar zum Arbeitsblatt A 118 "Hydraulische Bemessung und Nachweis von Entwässerungssystemen". Hennef: DWA; 2000.
[15] Kotowski A, Kaźmierczak B, Dancewicz A. The modelling of precipitations for the dimensioning of sewage systems. The Publishing House of the Civil Engineering Committee the Polish Academy of Sciences. Studies in Engineering no. 68, Warsaw; 2010.
[16] Kaźmierczak B, Kotowski A. Depth-Duration-Frequency rainfall model for dimensioning and modelling of Wrocław drainage systems. Environ Protect Eng. 2012;38(4):127-112. DOI: 10.5277/EPE120411.

MODELOWANIE ZRZUTÓW ŚCIEKÓW Z PRZELEWÓW BURZOWYCH NA KANALIZACJI OGÓLNOSPŁAWNEJ

Instytut Inżynierii Ochrony Środowiska, Politechnika Wrocławska

Abstrakt: W pracy przeprowadzono symulację działania nowoczesnego przelewu z rurą dławiącą na kanalizacji ogólnospławnej. Na potrzeby modelowania działania przelewu burzowego zaproponowano modelową zlewnię ogólnospławną o powierzchni F = 50 ha. Przelew obciążono ściekami bytowo-gospodarczymi oraz deszczowymi. Założono typowy, trójkątny hydrogram dopływu ścieków deszczowych. Model działania przelewu burzowego ujmuje szereg charakterystycznych i występujących kolejno faz napełniania i opróżniania komory przelewowej, które zostały wyróżnione opisem warunków brzegowych w odniesieniu do ściśle określonego zakresu zmiennych w czasie napełnień i przepływów. Na podstawie sformułowanych modeli hydraulicznego i matematycznego funkcjonowania przelewów burzowych opracowano program komputerowy do numerycznej symulacji działania przedmiotowych przelewów.

Słowa kluczowe: przelew burzowy, kanalizacja ogólnospławna, modelowanie matematyczne