A simplified dimensioning method for high-efficiency retention tanks

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Abstract. The article presents the results of research on the development of a simplified dimensioning method for sewage retention tanks equipped with a high-efficiency hydraulic system. The need to develop a new method is associated with the outdated rainfall model by Błaszczyk, which is the most popular model in Poland. According to the research made by numerous scientific centres, this model underrates the values of the maximum intensity of critical rains. As a consequence, its use affects the design of sewage systems and related facilities with insufficient hydraulic capacity.

1 Introduction

Urban spatial development is accompanied by problems related to the implementation of water and sewage management [1, 2]. Among these problems, the most important include the formation of so-called local municipal floods [3] and a lowered quality of sewage receiving bodies.

Municipal floods are very often caused by the insufficient hydraulic capacity of drainage systems, and generate significant material losses. In turn, the contamination of receiving bodies is most often associated with the discharge of a significant volume of sewage containing a large load of organic and inorganic compounds in a short time [4]. In both cases, the main stimulator is an increase in the volume necessary to discharge rainwater, which, among others, is caused by the sealing of the drainage area and the intensification of torrential rains.

Limiting or even the complete elimination of the negative effects of the presented problems can be obtained by using sewage retention facilities [5, 6]. Their ability to temporarily deposit excess liquid allows reducing the flow of sewage in buildings located below the tank to a level declared by the designer. This beneficial effect has made retention facilities an integral part of many urban investments [7, 8]. At the same time, it should be noted that every capital-intensive investment is required to execute a proper financial analysis [9, 10, 11].

On the other hand, the use of retention facilities requires a suitably adapted method to determine their necessary capacity. Nowadays, the most favourable solution seems to be the

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use of hydrodynamic modelling software for this purpose. Unfortunately, this requires dedicating a significant amount of work for the construction and calibration of the model, which in the case of small investments is unfavourable due to significant capital intensity. In such cases, a good alternative to achieve similar effects is the use of simplified methods based on the use of simple algebraic formulas.

The methods that are currently used in Poland for simplified dimensioning of tanks are based on the model rainfall by Błaszczyk [12], which is unreliable and should be replaced by another rainfall model, for example, by Bogdanowicz and Stachy [13]. Therefore, due to the update of rainfall models in Poland, the simplified dimensioning methods of retention tanks should also be updated.

2 Aim of the research

The aim of this manuscript is to develop calculation formulas that would allow determining the capacity of a retention tank equipped with the installation of retention facilities [6]. When determining them, the most current rainfall model by Bogdanowicz and Stachy for Poland was used [13].

3 Installation of retention facilities

The installation of retention facilities is a system of hydraulically connected ducts, the installation of which in any retention facility allows reducing the time necessary to obtain full hydraulic capacity of a building's outflow channel.

The application of the installation of retention facilities in classic retention tanks (Fig. 1a) allows obtaining the value of the volume stream of sewage that flows outfrom the tank that is close to the flow rate of sewage flowing to it already in the initial phase of its functioning. To illustrate this phenomenon, Figure 1b presents sewage inflow and outflow hydrographs for a tank equipped with the installation in question. As a result, the use of this solution translates into a reduction in the required retention capacity of the facility.

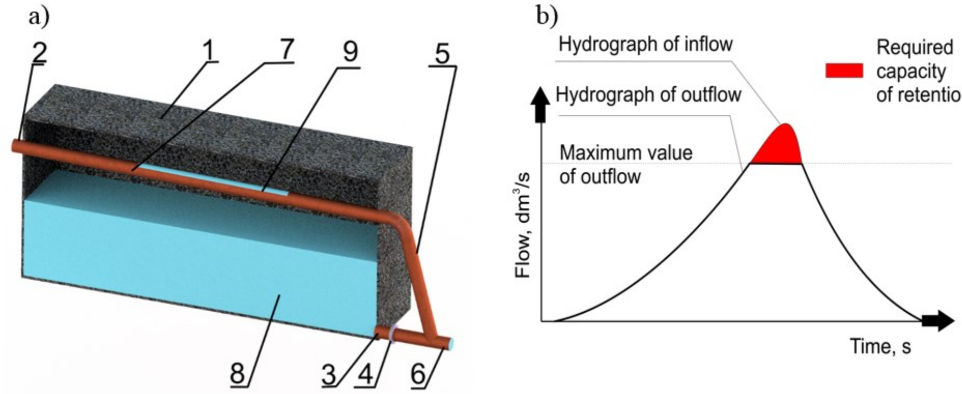

Fig. 1. a) Visualization of the cross-section of underground tank containing an installation which minimizes the required retention volume (1 – underground tank, 2 – inflow channel, 3 – first outflow channel, 4 – check valve, 5 – main channel, 6 – second outflow channel , 7 – overflow channel, 8 – retention volume, 9 – overflow), b) Inflow and outflow hydrograph for a tank containing installation which minimizes the required retention volume.

4 Selected rainfall models for Poland

The most popular formula in Poland that describes the intensity of rain q depending on its time t, the average annual height H, and frequency c is Błaszczyk's formula [12] described by formula (4.1).

$$q = \frac{6{,}631 \cdot \sqrt[3]{H^2 \cdot c}}{t^{\frac{2}{3}}} \tag{4.1}$$

where:

H - average annual height, mm;
c - frequency of rain, 1/c years;
t - reliable time of rainfall for a network, min.

However, this rainfall model has been deeply criticized in recent years. As research shows, it significantly reduces the intensity of rainfall, which is why it should no longer be used in the dimensioning of drainage systems in this form [14].

The probabilistic rainfall model by Bogdanowicz and Stachy [13], which is an alternative to Błaszczyk's formula [12], covers almost the whole of Poland. Depending on the assumed probability of rainfall p and the geographical region of Poland R, at a specific rainfall time t_{op} it allows determining the total rainfall height h_{max} according to the dependence (4.2).

$$h_{max} = 1{,}42 \times t_{op}^{0{,}33} + \alpha(R, t_{op}) \times (-ln\, p)^{0{,}584} \tag{4.2}$$

where:

h_{max} - the maximum total rainfall height of a determined time top and exceedance probability p, mm;
p - rainfall exceedance probability;
α (R , top) - parameter (scale) depending on the region of Poland R and time of rain t_{op}.

To use the presented formula (3.2), the region of Poland R for which the rainfall model is calculated should be designated first. The boundaries of Poland's division into regions: R1, R2, and R3 are presented in the works [15]. Whereas the scale parameter α, due to Poland's division into three regions, was described by six different formulas R and rainfall time top.

Research on the suitability analysis of this rainfall model for sewage system design was made by [15]. It was pointed out that although for rains with the frequency of c equal to one, this model is subject to a significant error but it is currently one of the most suitable models for drainage system design [15].

5 Dimensioning of retention facilities using the formula by Bogdanowicz and Stachy

The development of the dimensioning method of retention tanks equipped with the installation of retention facilities was based on the basic dependence describing the volume of sewage necessary to be deposited. This dependence is presented by formulas (5.1 and 5.2) and they show that the necessary retention capacity of a facility is equal to the surface area between the sewage inflow and outflow hydrographs [16].

$$V = maxS_{Tdj} \tag{5.1}$$

where:

$$S_{Tdj} = \int_0^{td} (A - B)dt \tag{5.2}$$

A - time-variable inflow of sewage to the tank, l/s;
B - time-variable outflow of sewage from the tank, l/s;
td- time after which the flow of sewage into the tank decreases to the level of the outflow intensity, min.

For tanks equipped with the installation in question, sewage inflow function *A* coincides with outflow function *B* to the value of the maximum sewage outflow from the tank (Fig. 1a).

In the development of simplified formulas, a simplified hydrograph of a trapezoidal sewage inflow was adopted, the lower base of which is equal to the time of rainfall authoritative for tank T_z increased by an authoritative time of rainfall for network t_s. In turn, its upper base corresponds to the time of rainfall authoritative for tank *Tz* decreased by the time of rainfall for network t_s (Fig. 2). Thus, the required capacity of the facility V corresponds to the surface area of the figure between the maximum value of sewage inflow to the tank (straight A1), and the determined value of sewage outflow from the tank (straight B1).

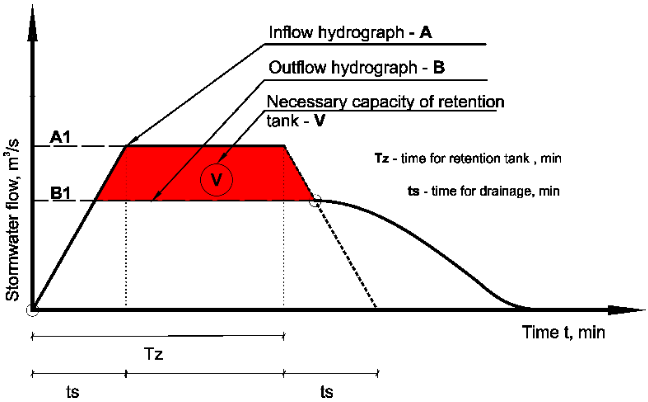

Fig. 2. The required retention capacity of the tank equipped with installations for retention facilities.

The developed simplified dimensioning method of retention tanks is based on the rainfall model by Bogdanowicz and Stachy. However, its form is heterogeneous because it makes its form dependent on the time of rainfall t and the region of Poland R. Hence there is a need to develop several different calculation formulas for individual regions and times of rainfall. To systematize them, they were given appropriate markings and are presented in Table 1.

Table 1. A list of equationmarkings for the dimensioning of retention tanks depending on region *R* and time of rainfall *t*.

Region Rainfall duration *t*, min	R1	R2	R3
5-30	Ia	IIa	Ia
30-60		IIb	
60-120		Ia	
120-720	Ib		
720-1080			
1080-4320	Ic		III

The procedure for determining individual calculation formulas is presented using the example of formula Ia. The remaining equations were determined in an analogous manner.

In accordance with the formulas (5.1 and 5.2), the necessary retention capacity corresponds to the surface area between the hydrograph of inflow *A* and outflow *B* (Fig. 3). Therefore, using the *installation of retention facilities*, the only task becomes determining the trapezoidal surface area above line *B1* (Fig. 2). For this purpose, the phenomenon of the similarity of triangles as in the work by [16] was used. The surface area of the desired figure can be divided into three simple geometrical figures: two identical rectangular triangles *P*1, and rectangle *P*2 (Fig. 3).

Triangle *P*1 is characterized by a base length of *x* and a height that is equal to the difference between the maximum values of the inflow and outflow of sewage *A*-*B*.Whereas, rectangle *P*2 has a height equal to the difference between *A* - *B* and a base with a length equal to the difference of time of rainfall for the dimensioning of the retention tank T_z and time of rainfall for the dimensioning of network t_s.

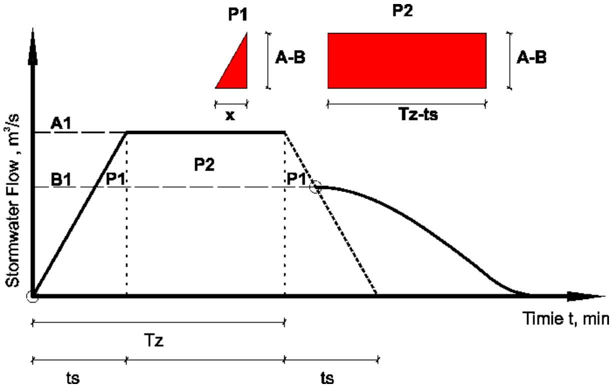

Fig. 3. Calculation schematic to determine the formula to calculate the required retention capacity.

Based on Figure 2 it can be concluded that the required retention capacity of the facility can be described by means of equation (5.3).

$$V = P1 + P2 + P1 \tag{5.3}$$

In turn, the surface areas of components *P1* and *P2* can be described using formulas (5.4 and 5.5).

$$P2 = (A - B) \cdot (Tz - ts) \tag{5.4}$$

$$P1 = \frac{x*(A-B)}{2} \tag{5.5}$$

The dimension of the bottom base of triangle *x* can be determined by using the similarity of triangles (5.6) and equation (5.7).

$$\frac{t_S}{A} = \frac{x}{A-B} \tag{5.6}$$

$$x = ts\frac{(A-B)}{A} \tag{5.7}$$

The last step was to determine the value of maximum inflow *A*. It depends on the rainfall intensity value and the area of the reduced drainage area. After substituting all values and adopting calculation formulas for the intensity of rainfall by Bogdanowicz and Stachy, six calculation formulas (5.8-5.13) were obtained for individual regions of Poland and time of rainfall *t* according to Table 1. The conversion of units was included in the equations.

Formula Ia

$$\begin{aligned} v &= \\ t_s &\cdot \left(\frac{\left(\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (4.693 \cdot \mathrm{LN}(T_z + 1) - 1.249) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z} - b \right)^2}{\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (4.693 \cdot \mathrm{LN}(T_z + 1) - 1.249) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z}} \right) \\ &+ \left(\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (4.693 \cdot \mathrm{LN}(T_z + 1) - 1.249) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z} - b \right) \cdot (T_z - t_s) \end{aligned} \tag{5.8}$$

Formula Ib

$$\begin{aligned} v &= \\ &= t_s \cdot \left(\frac{\left(\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (2.223 \cdot \mathrm{LN}(T_z + 1) + 10.639) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z} - b \right)^2}{\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (2.223 \cdot \mathrm{LN}(T_z + 1) + 10.639) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z}} \right) \\ &+ \left(\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (2.223 \cdot \mathrm{LN}(T_z + 1) + 10.639) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z} - b \right) \cdot (T_z - t_s) \end{aligned} \tag{5.9}$$

Formula Ic

$$\begin{aligned} v &= \\ &= t_s \cdot \left(\frac{\left(\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (3.01 \cdot \mathrm{LN}(T_z + 1) - 5.173) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z} - b \right)^2}{\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (3.01 \cdot \mathrm{LN}(T_z + 1) - 5.173) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z}} \right) \\ &+ \left(\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (3.01 \cdot \mathrm{LN}(T_z + 1) - 5.173) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z} - b \right) \cdot (T_z - t_s) \end{aligned} \tag{5.10}$$

Formula IIa

$$\begin{aligned} v &= \\ &= t_s \cdot \left(\frac{\left(\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (3.92 \cdot \mathrm{LN}(T_z + 1) - 1.662) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z} - b \right)^2}{\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (3.92 \cdot \mathrm{LN}(T_z + 1) - 1.662) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z}} \right) \\ &+ \left(\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (3.92 \cdot \mathrm{LN}(T_z + 1) - 1.662) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z} - b \right) \cdot (T_z - t_s) \end{aligned} \tag{5.11}$$

Formula IIb

$$\begin{aligned} v &= \\ &= t_s \cdot \left(\frac{\left(\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (9.16 \cdot \mathrm{LN}(T_z + 1) - 19.6) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z} - b \right)^2}{\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (9.16 \cdot \mathrm{LN}(T_z + 1) - 19.6) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z}} \right) \\ &+ \left(\Sigma\mathrm{F} \cdot \frac{\left(1.42 \cdot T_z^{0.33} + (9.16 \cdot \mathrm{LN}(T_z + 1) - 19.6) \cdot \left(-LN(p)\right)^{0.584}\right) \cdot 10}{T_z} - b \right) \cdot (T_z - t_s) \end{aligned} \tag{5.12}$$

Formula III

$$v = t_s \cdot \left(\frac{\left(\Sigma\mathrm{F} \cdot \frac{(1.42 \cdot T_z{}^{0.33} + (9.472 \cdot \mathrm{LN}(T_z + 1) - 37.032) \cdot (-LN(p))^{0.584}) \cdot 10}{T_z} - b \right)^2}{\Sigma\mathrm{F} \cdot \frac{(1.42 \cdot T_z{}^{0.33} + (9.472 \cdot \mathrm{LN}(T_z + 1) - 37.032) \cdot (-LN(p))^{0.584}) \cdot 10}{T_z}} \right) + \left(\Sigma\mathrm{F} \cdot \frac{(1.42 \cdot T_z{}^{0.33} + (9.472 \cdot \mathrm{LN}(T_z + 1) - 37.032) \cdot (-LN(p))^{0.584}) \cdot 10}{T_z} - b \right) \cdot (T_z - t_s) \tag{5.13}$$

where:

T_z - time of rain for retention tank dimensioning, s;
b -maximum intensity of sewage outflow from the tank, m^3/s;
t_s - time of rainfall for network dimensioning, s;
p – rainfall exceedance probability;
$\sum F$ - reduced surface area of drainage area being drained, ha.

The presented calculation formulas (5.8 - 5.13) allow determining the required capacity of retention tank V for a given length of rainfall time t. However, it will vary depending on the rainfall time for tank T_z adopted for the calculations. Therefore, to determine the required tank capacity, calculations should be made for different rainfall times T_z and the highest value should be chosen. This is presented in the example for the data: reduced surface area of drainage area $\sum F_{zr}$ - 25 ha, rainfall time authoritative for the network of T_s - 15 minutes, probability of rainfall p - 0.2, the maximum sewage outflow intensity from tank B - 0,5 m^3/s.

The presented data was introduced into calculation formula Ia (4.8), and then the required retention capacities V for rainfall times T_z from 0 up to 100 minutes were determined. The results obtained are shown in Figure 4.

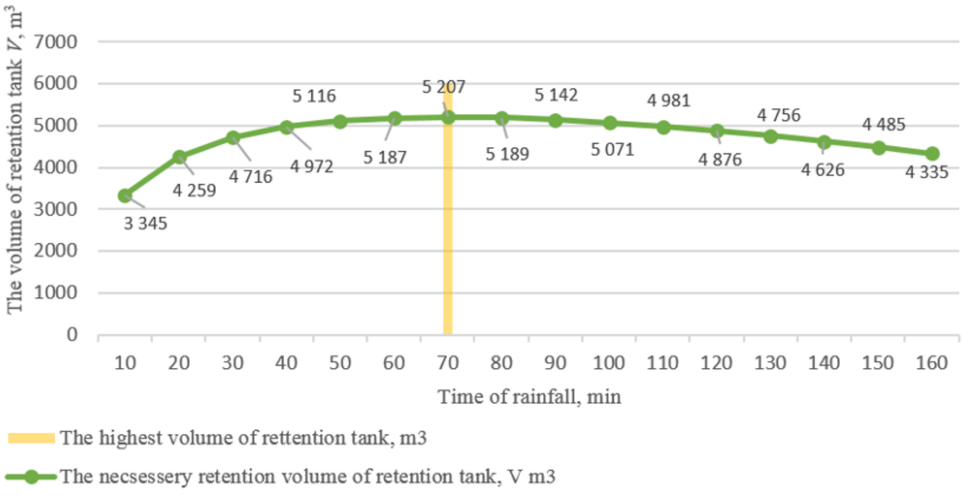

Fig. 4. The required tank retention capacities for different rainfall times T_z.

The presented data (Figure 3) shows that the largest required retention capacity of tank V amounting to 5 207 m^3 was obtained for a rainfall time of T_z 70 minutes.

The presented methodology for the dimensioning of retention tanks equipped with installations for retention facilities has been made for design cases in which the reliable time for the dimensioning of retention tanks $T_z$is longer than the time for dimensioning of network t_s.

6 Conclusions

The manuscript presents a simplified methodology for the dimensioning of retention facilities equipped with an installation for retention facilities. This methodology is based on the use of the newest rainfall model in Poland by Bogdanowicz and Stachy.

Due to the complex form of the rainfall model by Bogdanowicz and Stachy, which makes parameter α dependent on region R and rainfall time t, six calculation formulas for the tested retention tank were developed. The selection of an appropriate formula should be preceded by an analysis of the geographical location of the place for which a given tank will be designed, and an analysis of the critical rainfall time which will require reserving the largest retention capacity. The use of the presented method that is based on the newest rainfall model will increase the system's hydraulic safety.

The developed method can be used for design cases in which the rainfall time authoritative for the network is shorter than the rainfall time authoritative for retention tanks.

The next stage of the research will be to develop a formula that allows determining an authoritative rainfall time to carry out the dimensioning of the retention tank, which will allow omitting the search for the largest tank capacity for different lengths of rainfall time.

References

1. D. Słyś, A. Stec, Ecol. Chem. Eng. S **21**, 623-635 (2014)
2. S. Kordana, E3S Web Conf. **17**, 00042 (2017)
3. A. Stec, D. Słyś, Ecol. Chem. Eng. S **20**, 381-396 (2013)
4. M. Kida, S. Ziembowicz, P. Koszelnik, Sep. Purif. Technol. **192**, 457-464 (2018)
5. K. Pochwat, D. Słyś, S. Kordana, J. Hydrol. **549**, 501-511 (2017)
6. K. Pochwat, E3S Web Conf. **17**, 00075 (2017)
7. M. Starzec, J. Dziopak, *Underground Infrastructure of Urban Areas 4*, 181-191 (2018)
8. M. Starzec, J. Dziopak, D. Słyś, *Underground Infrastructure of Urban Areas 4*, 193-200 (2018)
9. D. Słyś, S. Kordana, Energ. Buildings **71**, 1-11 (2014)
10. A. Stec, A. Mazur, D. Słyś, E3S Web. Conf. **22**, 00168 (2017)
11. A. Mazur, D. Słyś, E3S Web. Conf. **17**, 00058 (2017)
12. W. Błaszczyk, W. Stamatello, Budowa miejskich sieci kanalizacyjnych (Arkady, Warszawa, 1967)
13. A. Kotowski, B. Kaźmierczak, A. Dancewicz, Modelowanie opadów do wymiarowania kanalizacji (PAN, Warszawa, 2010)
14. E. Bogdanowicz, J. Stachy, Maksymalne opady deszczu w Polsce: charakterystyki projektowe (IMiGW, Warszawa, 1998)
15. J. Dziopak, Analiza teoretyczna i modelowanie wielokomorowych zbiorników kanalizacyjnych (wyd. Politechniki Krakowskiej, Kraków, 1992)