Theory and Building Practice

Vol. 2, No. 2, 2020

https://doi.org/10.23939/jtbp2020.02.010

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ELIMINATION OF FLOW RATE RESTRICTION FOR SYSTEM OF STORM WATER SEWAGE WITH THE HELP OF DRAG-REDUCING POLYMERS

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The flow-rate restriction for storm sewage network is substantiated. Possible causes of flooding of territories by storm water in the case of emergency and methods of storm waters management are considered. The article is devoted to an increase in throughput of storm sewage networks with the help of in-line storm water detention tank installed at the beginning of storm sewage network and drag-reducing polymers (DRP). It is proposed to introduce DRPs in the form of solution directly into the sewage network through a storm-water inlet or through a sewer manhole. The introduction is conducted from a tank (cistern) in which there is a device for preparing an aqueous solution from the raw materials of DRP. For a square (in horizontal plane) catchment, in the case of point-type water drainage, the numerical simulation of the work of a system of storm water sewage with the help of DRP has been carried out.

Key words: flow-rate restriction; flooding of territories, drag-reducing polymers, detention tank.

Introduction

In Ukraine, on the territories of multy-storey capital development (building) and in industrial zones, it is necessary to lay a storm sewerage of pipe-type (but not an open-channel type) that is regulated by SBN V.1.1-25-2009. With this, storm sewerage networks are of restricted flow-rate (Belousov, 1986; Orel, 2017a). The peculiarity of sewage collectors during removal of surface run-off from different catchments with different loading is forced-flow mode (Ignatchik, Kuznetsova, Fes'kova, & Senyukovich, 2019). This is accounted for by the fact that in such networks, besides gravitational flow under nominal flow rate, it is possible according to SBN V.2.5-75:2013 to accept (is admitted according to SSTU-N B V.2.5-61:2012) full filled pipe. Exceeding over the nominal flow rate of a storm sewerage networks can lead to flooding of territories (Malmur, 2019; Hrudka, Csicsaiova, Marko, Stanko, & Skultetyova, 2020) (Fig. 1).

It can be considered that storm sewage network usually works under gravitational head ΔH (Fig. 1). The characteristics of the pipeline for nominal flow rate of storm waters $Q_w(\Delta H)$ is represented by the curve 1, which passes through the point A, and the restriction of flow rate of storm sewage is represented by the straight line 2 (Fig. 2) (Orel, 2017a).

When in the segment of the storm sewage network the flow rate of storm waters exceeds the nominal value of $Q_w(\Delta H)$, then water level in the well rises to the top of its chimney by the altitude h (Kalicun, 1987) (Fig. 1). Under further increases in flow rate in the network, there arises a flood of land.

It is a value of flow rate no less than $Q_w(\Delta H + h)$ that corresponds to the gravitational head $(\Delta H + h)$, under which the network works with flood of territories. With this, the characteristics of pipeline is still described by the curve 1, but the flow rate corresponds to a greater than ΔH (Fig. 2) head. Eq. (1) defines the ratio of flow rates in this case is the following (Kalicun, 1987):

$$\frac{Q_w(\Delta H + h)}{Q_w(\Delta H)} = \sqrt{\frac{(\Delta H + h)/L}{(\Delta H)/L}} = \sqrt{1 + \frac{h}{\Delta H}}, \tag{1}$$

where L is the length of the segment of storm sewage network in this case of flood of territory. Since the ratio of heads $h / \Delta H > 0$, then $Q_w(\Delta H) < Q_w(\Delta H + h)$ always holds (Kalicun, 1987), i.e. the storm sewage network is unable to cope with the excess flow rate. Eq. (2) defines the excess flow rate which the storm sewage network is unable to cope (Orel, 2017a):

$$\Delta Q = Q_w(\Delta H + h) - Q_w(\Delta H). \tag{2}$$

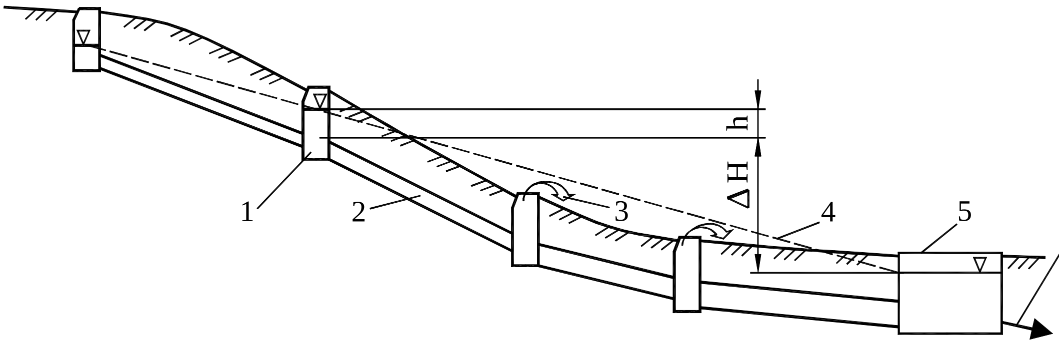

Fig. 1. Schematic diagram of segment of storm sewage network for the case of flood: 1 – water-intake or inspection well; 2 – pipeline; 3 – place of inflow of storm waters through storm water-inlet or through sewer manhole; 4 – piezometric line; 5 – tank or treatment facilities; 6 – outlet into pond (▼ – water level)

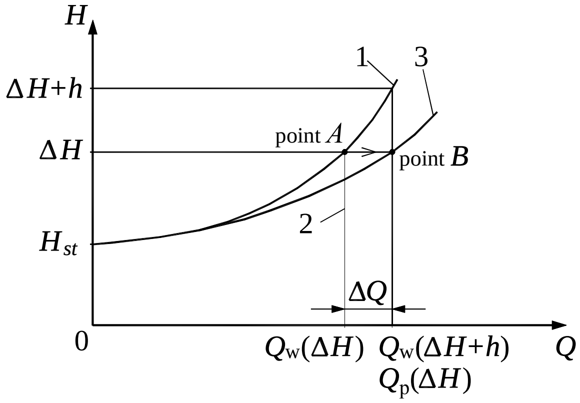

Fig. 2. Characteristics of pipeline of storm sewage network: 1 – without undertaking measures for elimination of flow rate; 2 – restriction of flow rate; 3 – with undertaking measures for elimination of flow rate (H_{st} is static head)

The causes of flood are the following (Tkachuk & Zhuk, 2012; Tkachuk, Salchuk, & Oleksiiuk, 2014; Rybalova, Bryhada, Matsak, & Zhuk, 2018):

– discrepancy between characteristics of the existing structures of storm sewage and the parameters of rain run-off which is formed within the catchment basins;

– absence or ineffective work of structures for retain, regulation, and treatment of storm waters;

– improper operation of structures of storm waters;

– removal of storm waters through general-purpose and combined systems of storm sewage;

– aging and wear-and-tear of storm sewage network;

– ineffective vertical planning of territories;

– increase in area of the territories with water-proof coatings;

– change in climate on the Earth.

One of the preventive measures for avoiding flood of territories and buildings is the ensurance of proper removal of storm waters according to SBN V.1.1-25-2009. In construction of a system of surface runoff removal, we should provide a whole range of ways of reduction of the surface run-off, since its operation consists in ensuring an effective and non-stop removal of storm waters and waters from melted snow according to SSTU-N B V.2.5-61:2012.

To avoid flood of land, it is necessary to undertake measures that return the storm sewage network into work under the gravitational head ΔH with the flow rate $Q_p(\Delta H)$ with undertaking the measures for elimination of its restriction of flow rate. The protection of territories against flood should be carried out by means of accumulation, regulation, removal of surface sewage waters (run-off) according to SBN V.1.1-25-2009. Eq. (3) defines the excess flow rate for the work of the storm sewage network with undertaking the measures for elimination of its restriction of flow rate (Orel, 2017a):

$$\Delta Q = Q_p(\Delta H) - Q_w(\Delta H)\,. \tag{3}$$

The new characteristics of pipeline corresponds in this case to the curve 3 (Fig. 2). The latter passes through the point B, which has been obtained by means of adding the excess flow rate ΔQ to the value corresponding to the point A in the curve 1 under the head ΔH (Orel, 2017a).

For a while, in Ukraine only scant attention is payed to the regulation of storm waters run-off. At the same time, this is an important state task abroad; the term “storm waters management” (control over storm waters flow) has become a key word in sci.-tech. literature abroad (Tkachuk & Zhuk, 2012). Therefore, it is expedient to search new methods of storm waters run-off.

In Ukraine, there are the following methods of storm waters management (control over water run-off) that is regulated by SSTU-N B V.2.5-61:2012:

– increase in duration of concentrating of surface run-off (increase in the roughness of surface and creation of buffer ponds);

– interception of portion of the stream (water-removal structures and accumulating ponds);

– reduction of water accumulation (water permeable coatings, filtration ponds (tanks), ploughing the area of water catchment basins, etc.

It is recommended to take into account the increase in the flood-carring capacity (throughput) of segments of collectors of storm sewage segments which work with elevation of water level in wells according to SBN V.2.5-75:2013. This is also one of the methods of storm waters management (Zhuk, Vovk, Popadiuk, & Matlai, 2015).

The installation of accumulating and detention tanks for storm sewage waters, erection of filtrating structures, application of systems of “green” (vegetated) roofs, permeable pavement, bio-ponds, artificial wetlands, etc. belongs to the world’s best operational practices in the branch of storm waters removal (Tkachuk & Zhuk, 2012; Osman, Takaijudin, Yusof, Goh, & Ghani, 2020).

Regulation of surface run-off with the purpose to avoid flood of territories and for increase in carring capacity of storm sewage networks by means of increase in diameters of pipelines or by means of laying a parallel by-pass (doubling) of pipelines in majority of cases is cost-ineffective (Sergaev, 2018). However, it is also possible to increase the carring capacity by means of reduction of hydraulic friction in networks. This can be achieved by means of sewer rehabilitation of pipes by means of coating their inner surfaces (Butin, 2015) or by introduction of drag-reducing polymers (DRP) into streams in transported in pipelines (Jelperin, Levental, Melcer, Sirotenko, & Malkenzon, 1976; Zhuk & Orel, 1995; Simonenko, Aslanov, & Dmitrenko, 2015).

The elimination of the aforesaid shortcomings in organization of a removal of storm waters from territories of populated areas calls for complicated and high-amount works (Tkachuk et al., 2014). In our opinion, the introduction of DRP into fluid flow can save a lot of labour and costs. Eq. (4) defines the increase in flow rate increment in the case of introduction of DRP (Ling & Abdulbari, 2017):

$$FI = \left(1 - \frac{Q_w}{Q_p}\right) \cdot 100\ \% . \tag{4}$$

Here, the ratio of flow rates is found based on the Eq. (5) (Hoyt, 1972):

$$\frac{Q_w}{Q_p} = \frac{\sqrt{\lambda_p}}{\sqrt{\lambda_w}} , \tag{5}$$

where λ_w , λ_p are the Darcy friction factor before and after the introduction of DRP, respectively. Eq. (6) shows it is the introduction of DRP into streams in transported in pipes fluid virtually increases the volume of a pipeline by virtual increase in its length (Hoyt, 1972):

$$\frac{L_p}{L_w} = \frac{\lambda_w}{\lambda_p} \tag{6}$$

and Eq. (7) shows it is that of its diameter (Hoyt, 1972):

$$\frac{D_p}{D_w} = \frac{\sqrt[5]{\lambda_w}}{\sqrt[5]{\lambda_p}} . \tag{7}$$

The amount of storm waters that corresponds to the excess flow rate, which cannot be carried through the storm sewage network, flows out through storm water inlets and hatches of wells.

According to SSTU-N B V.2.5-61:2012 the carring capacity of storm-water inlets is $Q_s = f(L_s, H_s, V_s)$, where L_s is the perimeter of the storm water inlet; H_s is the depth of water in front of the storm water inlet; V_s is the velocity of approach of water to the water inlet. During flooding of territory by storm waters as under emergency, the storm water inlets work being flooded with the head H_s. To reduce the water accumulation on surface by storm water run-off, it is necessary to remove storm sewage waters as soon as possible. Therefore, the use of DRP in a storm sewage network can be considered as such a method of storm water management as the reduction of storm sewage accumulation on runoff surface.

However the shortcoming of the use of DRP is the mechanical degradation (Belousov, 1986; Almuhametova, 2016) and increase in the length of the segment of gravitational flow with partial filling of pipeline (Almuhametova, 2016). Both the first and the second one reduce the effectiveness of storm waters management.

The purpose of the study

The purpose of this study is substantiation of expedience of the application of DRP for elimination of restriction of flow rate in storm sewage network with the help of the numerical simulation of the work of a system of storm sewage.

Materials and methods

It is possible to introduce DRP into a storm sewage network in the form of a solution (Zhuk & Orel, 1995) or in the form of liquid composition of polymers – thin-dispersion suspension and paste on the basis of polyetylenoxide or of polyacrilamide (PAM) (Simonenko et al., 2015).

It is only in case when the rate of polymer dissolution does matter, i.e. in short pipelines, that application of HAP in the form of a solution is expedient (Sulejmanova, 2007). Therefore, to obtain maximal hydrodynamic effect from the action of DRP solutions in long pipelines in small time intervals, it is necessary to perform their introduction simultaneously in several places along the pipeline (Simonenko et al., 2015). In our opinion, an DRP solution should be introduced directly into storm water inlets from cisterns in which there is a device for preparation of the solution (Fig. 3). The introduction is carried out with the help of a gear-pump, which prevents premature destruction of molecules of DRP (Belousov, 1986). It is possible to use mixing of water solutions of DRP in a mixer with eccentrically arranged smooth working part (Orel, Pitsyshyn, & Popadiuk, 2019; Orel, Pitsyshyn, & Popadiuk, 2020) and to use a gear-pump as a mettering pump for DRP solutions at the expense of frequency regulation (Orel, 2017b).

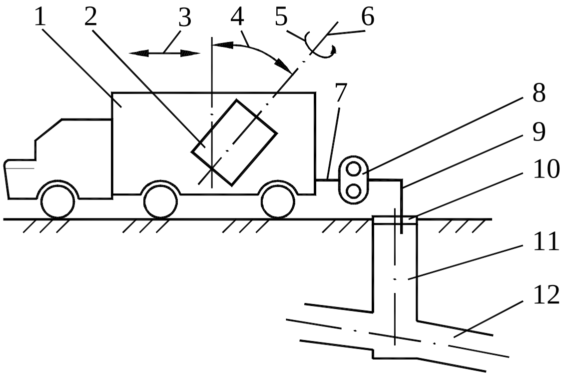

Fig. 3. Scheme of introduction of DRP solutions into a storm sewage network: 1 – cistern; 2 – working part of mixer; 3 – displacement of working part of mixer along axes of cistern; 4 – change in angle of inclination of axis of working part of mixer relative to the axes of cistern; 5 – rotation of working part of mixer about own axis; 6 – axis of working part of mixer; 7 – suction pipeline of gear-pump; 8 – gear-pump; 9 – pressure pipeline of gear-pump; 10 – storm water inlet; 11 – rain intake well; 12 – pipeline of storm sewerage network

The economic profit from the application of DRP solutions whose curve of effect of drag reduction $DR = f(C)$ has extremum (Fig. 4) when the maximal value $DR_{\max}$ is achieved at certain optimal concentration C_{opt} (Manzhay, Nosikova, & Abdusalyamov, 2015; Kashlach, Berezina, Smirnova, Berezina, Manzhai, & Fufaeva, 2019) can be obtained only for concentration $C \le C_{opt}$ (Semenov, 1991).

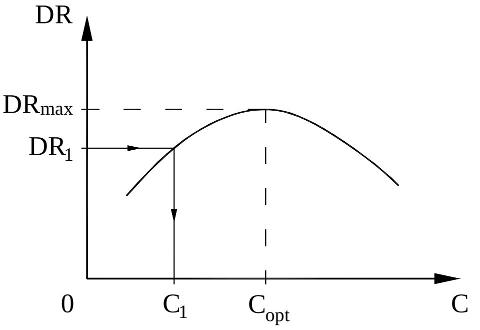

Fig. 4. Dependence of effect of drag reduction on action of DRP solutions

Eq. (8) defines the effect of drag reduction in the case of introduction of DRP-solutions whose concentration $C \le C_{opt}$ (Kashlach et al., 2019):

$$DR = 1 - \frac{Q_w^2}{(Q_w + \Delta Q)^2} = 1 - \frac{1}{\left(1 + \frac{\Delta Q}{Q_w}\right)^2}. \tag{8}$$

Eq. (9) defines the excess flow rate of storm sewage network

$$\Delta Q = Q_w \cdot \left(\frac{1}{\sqrt{1 - DR}} - 1 \right). \tag{9}$$

Eq. (10) defines the flow rate of storm waters under the use of DRP-solutions

$$Q_p = Q_w \cdot \frac{1}{\sqrt{1 - DR}}. \tag{10}$$

This formula had been obtained in (Belousov, 1986) as well.

Eq. (11) defines the drag reduction caused by action of DRP-solutions

$$DR = 1 - \frac{\lambda_p}{\lambda_w}. \tag{11}$$

The concentration of DRP-solutions can be determined from Fig.4. Eq. (12) shows the analytical dependence $DR = f(C)$ presented for $C \le C_{opt}$ (Belousov, 1986):

$$DR = DR_{\max} \cdot \frac{C}{a_1 + C} = \frac{C}{a_2 + b_2 \cdot C}. \tag{12}$$

where a_1, a_2 are the coefficients, kg/m³; $a_2 = \frac{a_1}{DR_{\max}}$; b_2 is the coefficient, $b_2 = \frac{1}{DR_{\max}}$.

Results and discussion

For a square (in plane) catchment basin with area $F = L \times B$ under point-type water removal we presented an example of storm waters management with the use of an in-line storm water detention tank installed at the beginning of storm sewage network (Mysak, Zhuk, & Petrushka, 2020) (Fig. 5) without introduction of DRP and with introduction of DRP for the data presented in Table 1. As DRP there is used a water solution of PAM whose concentration C = 500 ppm.

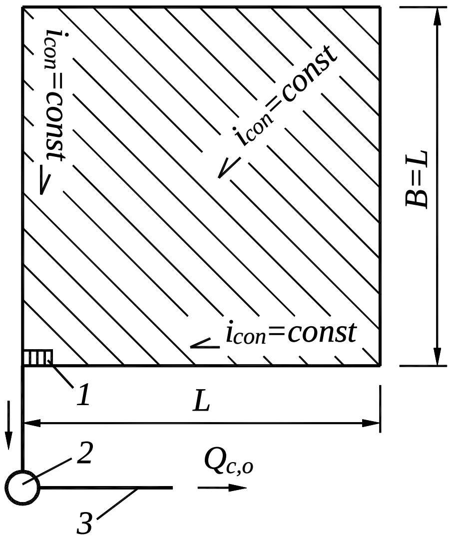

Fig. 5. Scheme of the tested square (in plane) catchment: 1 – storm-water inlet; 2 – in-line detention tank; 3 – outflow pipeline

The Table 1 gives the storm water management presented by means of an example of storm sewage network of Kharkiv city (Jelperin et al., 1976) provided the flow of storm sewage waters is gravitational at full filled pipe. The Darcy friction factor has been calculated according to the Eq. (13):

$$\lambda = 8 \cdot \frac{u_*^2}{V^2}. \tag{13}$$

where u* is dynamic velocity; V is mean storm water velocity.

In Ukraine, for Kharkiv city according to SBN V.2.5-75:2013, for the return period of $P = 1$ year, the 20 minute rainfall intensity $q_{20} = 104$ l/s per hectare, the exponent $n = 0.70$ in the intensity−duration formula by the Eq. (14):

$$q_r = \frac{A}{t_r^n}, \tag{14}$$

where q_r is the intensity of the design rainfall of the duration t_r; A is the dimensionless parameter by the Eq. (15):

$$A = q_{20} \cdot 20^n \cdot \left(1 + \frac{lg\, P}{lg\, m_r}\right)^{\gamma}, \tag{15}$$

where m_r is the average annual number of rainfall events; γ is the exponent; both depend from the climate conditions. A subcatchment basin whose area $F \le 1$ hectare and whose coefficient of run-off $\psi_{mid} = 0.95$ has been considered; the longitudinal slope of the catchment's surface is assumed to be uniform in all its points and equal to $i_{con} = 0.01$, and the roughness coefficient of the surface 0.014. As a detention tank a round (in plane) sewage well whose typical diameter was 2 m and the depth 5 m was used. The longitudinal slope of the outflow pipeline from the sewage well was taken of $i = 0.00307$, which differs from minimal slope $i_{\min} = 1/D_c = 0.00333$ no greater than by 7,8 %, where D_c is the diameter of outflow pipeline.

Table 1

Storm water management at gravitational flow at full filled pipe of storm sewage network of Kharkiv city (according to data from (Jelperin et al., 1976))

Parameter	Water	Water with aqueous PAM-solution
Diameter of outflow pipeline D_c, mm	300	
Relative roughness of outflow pipeline	0.004	
Length of outflow pipeline L_c, m	1922.5	
Mean velocity V, m/s	0.80	0.97
Outflow rate $Q_{c,o}$, l/s	56.52	68.53
Excess outflow rate which cannot be coped with by storm sewage network	$\Delta Q_{c,o} = 68.53 - 56.52 = 12.01$ l/s	
Reynolds' number	$2.05 \cdot 10^5$	$2.47 \cdot 10^5$
Dynamic velocity u_*, m/s	0.048	
Darcy friction factor	$\lambda_w = 8 \cdot \frac{0.048^2}{0.80^2} = 0.0288$	$\lambda_p = 8 \cdot \frac{0.048^2}{0.97^2} = 0.0196$
Virtual increase in outflow pipeline length	$(L_c)_p = 1922.5 \cdot \frac{0.0288}{0.0196} = 2824.9$ m; $\frac{(L_c)_p}{(L_c)_w} = \frac{2824.9}{1922.5} = 1.469$	
Virtual increase in outflow pipeline diameter	$(D_c)_p = 300 \cdot \frac{\sqrt[5]{0.0288}}{\sqrt[5]{0.0196}} = 324$ mm; $\frac{(D_c)_p}{(D_c)_w} = \frac{324}{300} = 1.080$	
Drag reduction under the use of aqueous PAM-solution	$DR = 1 - \frac{0.0196}{0.0288} = 0.319$ Remark: in data from (Jelperin et al., 1976) $DR = 0.280$.	
Outflow rate under the use of aqueous PAM-solution	$\Delta Q_{c,o} = 56.52 \cdot \left(\frac{1}{\sqrt{1-0.319}} - 1\right) = 11.97$ l/s; $(Q_{c,o})_p = 56.52 \cdot \frac{1}{\sqrt{1-0.319}} = 68.49$ l/s	
Increase in outflow rate	$FI = \left(1 - \frac{56.52}{68.49}\right) \cdot 100 = 17.5$ %; $\frac{(Q_{c,o})_p}{(Q_{c,o})_w} = \frac{68.49}{56.52} = 1.212$	

For the case of the above described conditions, with the help of the developed software (Zhuk et al., 2015), it has been found that no flood of territory can occur if storm waters was removed from catchment whose area is of $F_w = 6690$ m² and $F_p = 7973$ m² without and with use of PAM-solution, respectively. This corresponds to the linear sizes of catchment $L_w = 81.79$ m and $L_p = 89.29$ m, respectively.

The value of the ratio of maximum flow rates by with and without the use of aqueous PAM-solution is obtained $(Q_r)_p / (Q_r)_w = 1.132$ (Fig. 6), where Q_r is the runoff flow rate. The change of the flow rate in first stage of the hydrograph modelled by the sector method (Tkachuk & Zhuk, 2012; Zhuk et al., 2015; Mysak et al., 2020; Zhuk & Mysak, 2020) is described by power functions of the form $Q = k \cdot t^x$ with the exponent $x = 10/3$ in both cases and the coefficient $k - var$ (Zhuk & Mysak, 2020). The value of the ratio of coefficients by with and without the use of aqueous PAM solution is obtained $k_p / k_w = 0.875$.

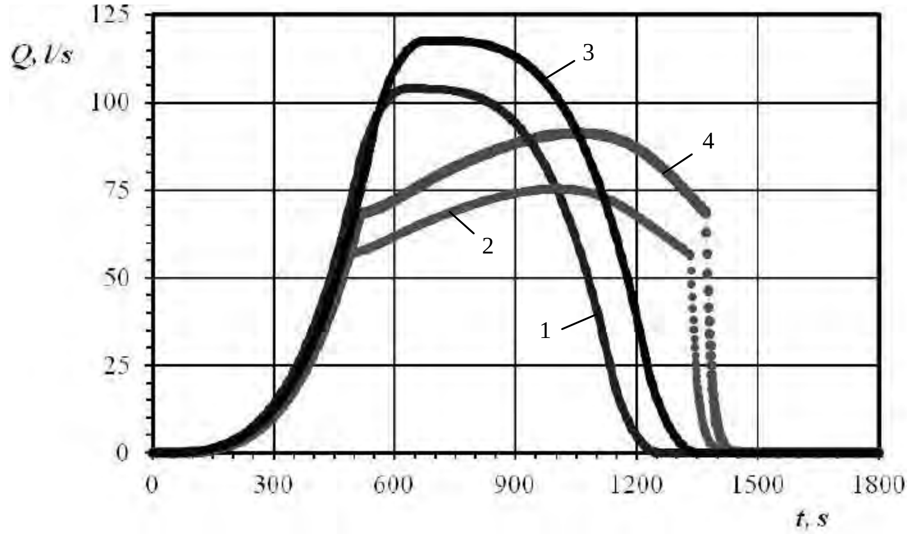

Fig. 6. Example of storm water management with the help of in-line detention tank installed in beginning of storm sewage network without (1, 2) and with (3, 4) the use of aqueous PAM-solution for square (in plane) catchment basin in point-type arrangement of water run-off: 1, 3 – surface runoff hydrograph; 2, 4 – flow-out from detention tank

The value of the ratio of beginning of flow-out from detention tank by without and with the use of aqueous PAM solution is obtained $(Q_{c,o})_p / (Q_{c,o})_w = 1.212$ (Fig. 6). The last value agrees with the calculated value of increase in outflow rate presented in Table 1.

Conclusions

The use of drag-reducing polymers in a storm sewage network can be considered as such a method of storm water management as the reduction of storm sewage accumulation on runoff surface.

By means of numerical simulation, it is established that under storm water management on small square (in plane) catchment basins with the help of in-line detention tank and the use of DRP enables to increase the area of the catchment basin, to increase the peak runoff flow rate and to increase the beginning of flow-out from detention tank. It can enable to reduce the loading of the storm sewage network in the projecting of the storm water runoff at the urban areas.

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УСУНЕННЯ ОБМЕЖЕННЯ ДОЩОВОЇ КАНАЛІЗАЦІЙНОЇ МЕРЕЖІ ЗА ВИТРАТОЮ ЗА ДОПОМОГОЮ ГІДРОДИНАМІЧНО АКТИВНИХ ПОЛІМЕРІВ

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Розглянуто можливі причини затоплення територій дощовими водами за надзвичайних ситуацій та методи управління дощовим стоком. Обґрунтовано уникнення затоплення місцевості вживанням заходів, які усувають обмеження дощової каналізаційної мережі за витратою. Використання гідродинамічно активних полімерів (ГДАП), які зменшують гідравлічне тертя в трубопроводах, запропоновано розглядати як метод управління дощовим стоком зменшенням накопичення зливових вод на поверхні водозбору. ГДАП збільшують об’ємну витрату трубопроводів і віртуально збільшують їхню довжину та діаметр. Стаття присвячена збільшенню пропускної здатності дощових каналізаційних мереж за допомогою регулювального резервуара для зливової води та ГДАП. Запропоновано використовувати ГДАП у вигляді водного розчину та вводити безпосередньо в дощову каналізаційну мережу крізь дощоприймач чи люк колодязя. Застосовуючи шестеренний насос як дозатор, введення проводять із цистерни, в якій пристрій для приготування розчину з вихідної сировини ГДАП має ексцентрично розташований гладкий робочий орган. Вказані пристрої не призводять до деструкції молекул ГДАП, що передчасно не зменшує ефекту від використання останніх. Управління дощовим стоком показано на прикладі квадратного в плані басейну стоку при точковій схемі водовідведення з використанням регулювального резервуара проточного типу, встановленого на початку дощової каналізаційної мережі діаметром 300 мм та довжиною 1922,5 м, та використання водного розчину поліакриламіду концентрацією 500 ppm (0,0005 кг/л). Математичне моделювання роботи системи дощової каналізації показало, що збирати дощовий стік за зазначених вище умов можна з басейну більшою площею, ніж без використання ГДАП за рахунок збільшення витрати поверхневого стоку та витрати відтоку з регулювального резервуара.

Ключові слова: обмеження за витратою, затоплення територій, гідродинамічно активні полімери, регулювальний резервуар.