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RESEARCH OF MAIN ANALYSIS PARAMETERS OF INFILTRATION AREAS CONNECTING TO THE STORM DRAINAGE SYSTEM

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Abstract: Infiltration areas with permeable pavements are one of the most effective modern methods of stormwater management on urban areas that permit accumulation of rainfall directly at place of precipitation. The paper justifies the expediency of inclusion of infiltration areas in the storm drainage system to ensure the effective stormwater management on urban areas. Thus, the aim of this paper is to calculate infiltration areas' basic parameters following the experimental and theoretical studies undertaken by authors. Based on these studies, a mathematical model of filling and emptying of base layer of infiltration areas by connecting them to the rain drainage systems is determined. As a result the formulae of calculation of the stormwater volume that detained on the infiltration areas, and the drainage discharges that came in the rain drainage system are received and verified. Moreover, obtained results permit to realize stormwater management on urban areas that depend on parameters of infiltration areas and pipe capacity of drainage system.

Key words: stormwater management, infiltration areas, permeable pavements, runoff volume, drainage discharge.

1. Introduction

In recent years, in the cities all over the world, urban areas' flooding resulted by rainfall is increasingly observed. In Ukraine, the flooded areas as a result of rainfall expand on the territory of more than 500 towns and cities and cover the area of about 200 thousand hectares (11% of the total area of these settlements). The potential flooded areas can cover more than 150 thousand hectares of built-up territories. In more than 20 major cities flooded areas exceed 1000 hectares (Ihnatenko and Zuzanska, 2012).

The main problems of stormwater disposal from urban areas in Ukraine are:

- increasing the percent of areas with impervious pavement;
- lack and inadequate technical condition and treatment of the rain drainage system;
- lack of government program of stormwater disposal;
- irrational approach to the issue of stormwater disposal, that focused on their fast interception and discharging into sewer system.

The works of many scientists are dedicated to the estimation issue of formation and regulation of stormwater runoff on urban areas (Alekseev and Kurhanov, 2000; Ferguson, 2005; Tkachuk and Zhuk, 2012). These scientists have made a significant contribution to the estimation of the runoff discharges calculation by limiting intensity method (Alekseev and Kurhanov, 2000), and research of the some methods and operation processes of facilities in stormwater regulation (Ferguson, 2005; Tkachuk and Zhuk, 2012). However, the issues of optimization of rain drainage system through an integrated approach to the stormwater management (interception and disposal) and purification are still unresolved (Tkachuk and Shevchuk, 2015a).

In developed countries of Europe and the North America the stormwater management of runoff in urban areas has taken a 'green' approach due to the emergence of urban flooding, which collect, store, treat, redistribute and/or recycle water (Astebol et al., 2004). Examples of these techniques are swales, filter strips, wetlands, ponds and infiltration areas. These methods reduce the maximum load on the existent drainage system, and delay pollution, prevent the flooding of areas. One of these methods is a construction of infiltration areas with permeable pavements for temporary interception and followed by stormwater infiltration in the drainage system pipes. The using of the modern permeable pavements for such urban areas as parking lots, various driveways, and lawns can significantly increase the areas, and the volume of temporarily intercepted rainwater can be used with permeable pavements (Scholz and Grabowiecki, 2007).

The use of infiltration areas with the rain drainage system allows at the design stage reducing the diameter

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of the new pipe and decreasing the networks value. Other infiltration areas' advantages are environmental compatibility and increasing the attractiveness of territories, etc. (Dierkes et al., 2002; Astebol et al., 2004).

Measures of stormwater management should set the priority of permeable pavements over the impervious pavements, only if the certain conditions do not limit it. Consequently the entire green tracks of Germany, which according to the survey account for 380 km single track of grass store more than 560 000 m^3 precipitation water with considerable microclimatic effects. Potentially at least 1 150 km of Germany's tram tracks are greenable which equals an area of about 287.5 ha. If this area was greened, annual water retention of 1.55 million m^3 would be possible (Schreiter and Kappis, 2013). In 2011 United States Environmental Protection Agency (EPA, 2011) accepted the Stormwater Management Program and 47.3% of its 479 state projects allowed for the using of infiltration areas with permeable pavements. The most of them are modernization of existent pavements, such as parking lots, pavements, trails, etc.

In comparison to traditional drainage systems, storm water retention and infiltration is a sustainable and cost effective process, which is suitable for urban areas (Andersen et al., 1999; Dierkes et al., 2002). Also they provide more effective peak flow reductions (up to 42%) and longer discharging times. There is also a significant reduction of evaporation and surface water splashing (Booth and Leavitt, 1999; Pagotto et al., 2000; Abbot and Comino-Mateos, 2003; Scholz, 2006). Moreover, infiltration areas with permeable pavement have many potential benefits such as reduction of runoff, recharging of groundwater, saving water by recycling and prevention of pollution (Pratt et al., 1999; Pagotto et al., 2000; Abbot and Comino-Mateos, 2003). This corresponds to the requirements of Water Frame Directive if the status of groundwater quality is not disturbed (Directive 2000/60/EC).

Many methods of calculation of infiltration areas are very simplified and do not introduced to many important factors (AMEC Earth and Environmental, 2001; DWA German Association for Water, 2005; CDT, 2013; DDE, 2013). In particular the time of filling (2 hours) (DDE, 2013) or emptying (72 hours) (CDT, 2013) of the porous structure of the area is therefore likely to be empirical and not corresponded the real conditions. Some methods don't introduce to fraction of impervious pavement (AMEC Earth and Environmental, 2001) and calculation of parameters of drainage system (DWA German Association for Water, 2005). Very often the calculation recommendations of the runoff volume intercepted by pavements are given in not full extent or are completely unavailable. This disputes the effectiveness of permeable pavements use in the stormwater management.

Thus, the aim of this paper is to calculate infiltration areas' basic parameters (the volume of intercepted stormwater; the time of filling and emptying of the porous structure of the area; the admeasurement of the reducing of maximum stormwater discharge that includes the amount of water in the drainage system pipelines) following the experimental and theoretical studies undertaken by authors. Therefore, the experimental part of the presented research includes testing of a fragment of infiltration area on the surface of which was imitated artificial "rainfall" with different intensity, estimates drainage water discharge The results of experimental and theoretical studies were compared.

2. Materials and methods

2.1. Experimental studies

We conducted laboratory tests on the laboratory rig, which is actually a fragment of infiltration area (Fig. 1), which can be arranged on any flat area, for example, parking lot. Rainfall flows to the infiltration area in the form of rain drops and an additional input from surrounding areas. Along perimeter or its larger sides there can be arranged tray that ensuring steady distribution of rainwater throughout the area. A pavement surface composed of structural units with void areas that are filled with grass turf.

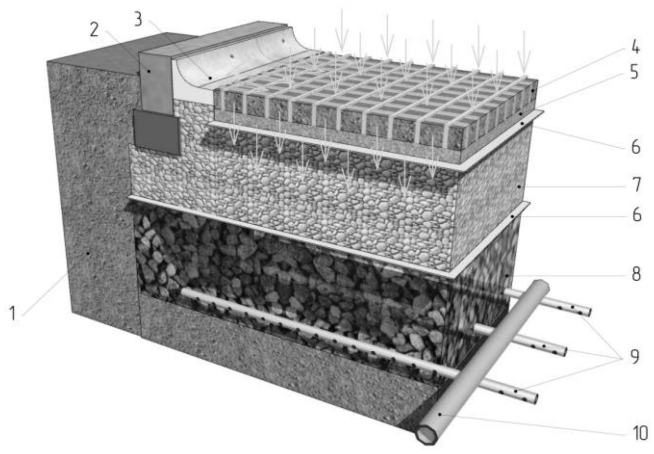


Fig. 1. Model of infiltration area: 1 – underlying soil; 2 – kerb; 3 – opened tray; 4 – plastic paving grids; 5 – bedding layer; 6 – geotextile; 7 – structural base layer; 8 – storage base layer; 9 – drainage pipes; 10 – manifold

For realization of experiment laboratory rig was designed and constructed (Fig. 2). The experimental model with using plastic paving grids was placed on a container which size was 600×400×500 mm. The type of base course was accepted in accordance with the recommendations (AMEC Earth and Environmental, 2001; DWA German Association for Water, 2005; CDT, 2013; DDE, 2013) and it had such construction as modular paving grid with void areas that were filled grass turf – thickness 50 mm; bedding layer of sand – thickness 30 mm; geotextile layer; structural base layer of gravel – thickness 200 mm; geotextile layer; storage base layer of gravel – thickness 150 mm; drainage layer of gravel and pipe separated by micromesh – thickness 20 mm.

The structure of the soil substrate of void areas consisted of 80% of sifted soil (sieve size 5 mm) and 20% of washed sand, 0.1-2 mm in diameter. The structure of the bedding layer consisted of washed sand, 0.1-2 mm in diameter. The structure of the structural base layer consisted of gravel, 2-40 mm in diameter. The storage base layer consisted of gravel, 10-40 mm in diameter. Non-woven, needle-punched geotextile was used with a fibre area weight of 200 g/m^2. Drainage layer consisted of gravel, 20-40 mm in diameter. Before the beginning of experiment drainage layer was filled with water and the waterline on piezometer tube stood on the datum point. Therefore, during the experiment, the volume of water in this layer was not introduced to the calculations.

During the experiment rainfall were imitated on the surface with intensity i = 2.3; 4.8 and 9.0 mm/min, and this intensity corresponded discharges q = 550, 1150 and 2160 ml/min (Fig. 3).

2.2. Theoretical studies

The water impoundment process of infiltration area on basis of the constant time rainfall intensity i_r = const and the unavailability of the subgrade bottom and side walls infiltration is represented through drainage water discharge in time t, in min, when the base is impounded by the formula (1):

$$Q_{dr} = k_{dim} \cdot i_r \cdot F_t \cdot \left(1 - e^{-\varepsilon \cdot t}\right) \quad (1)$$

where: k_{dim} is a dimension coefficient, i_r is a rainfall intensity, ($i_r \approx$ const), in mm/min; F_t is a total runoff area, in m^2; ε is a non-dimensional parameter that depends on the gravel base course characteristics and is estimated by the formula (2) (Tkachuk and Shevchuk, 2015):

$$\varepsilon = \frac{k_e \cdot K_f}{p \cdot H} \quad (2)$$

where: k_e is an equivalence coefficient characterizing drainage conditions through gravel base course of infiltration area, K_f is a filtration coefficient of gravel base course, in mm/min; p is a porosity of gravel base course, H is a total height of gravel base course, in mm.

The equivalence coefficients k_e depend on the conditions of water drainage and disposal from infiltration areas. Their values are regulated users over the range $k_e = 0..k_{e.\max}$. Thus, $k_e = 0$ when there isn't water diversion from infiltration area, and $k_e = 0..k_{e.\max}$ when there is the regulation of water discharge on the outlet pipe to the drainage system structures. The value $k_{e.\max}$ = 0.3 was determined experimentally during tests on laboratory facility in conditions of gravity filtration (Tkachuk and Shevchuk, 2015b).

Drainage water discharges (after the end of the rainfall) are calculated by the formula:

$$Q_{dr} = Q_0\left(1 - b \cdot \left(t_r - t_0\right)\right) \quad (3)$$

where: Q_0 is an initial stormwater discharge in time t_r (end of the rainfall), in ml/min; t_r / t_0 is a time of the rainfall end/beginning, in min; b is a parametric variable that takes into account the emptying conditions.

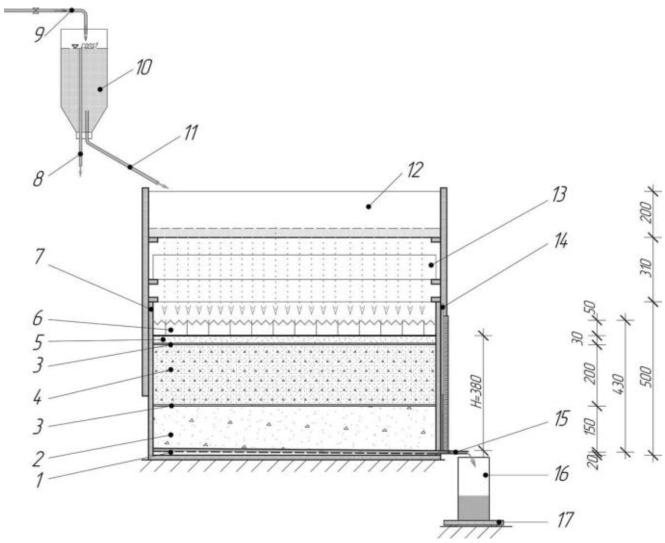
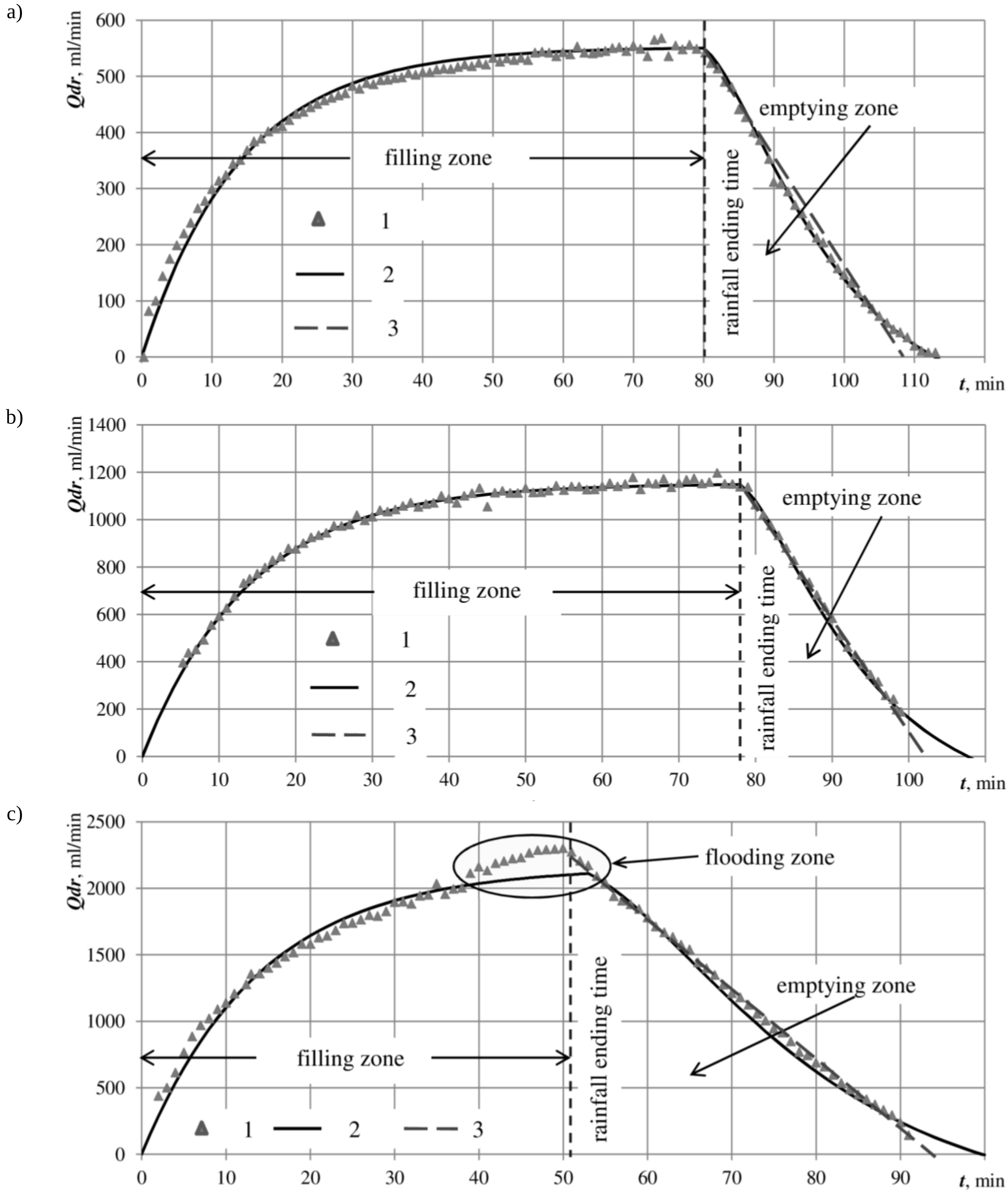


Fig. 2. Scheme of experimental rig: 1– drainage layer; 2 – storage base layer; 3 – geotextile; 4 – structural base layer; 5 – bedding layer; 6 – plastic paving grid; 7 – supporting structure; 8 – spillage tube; 9 – water feed pipe; 10 – reservoirs for water; 11 – water feed pipe on rig; 12 – tank for rainfall imitation; 13 – removable tray; 14 – piezometer tube; 15 – drainage pipe; 16 – measuring jug; 17 – scales Elenberg KS130.



1 – experimental points; 2 – theoretical curves; 3 – curves of simplified function

Fig. 3. The graph of time variation of drainage discharges on experimental rig for runoff intensity, where: a) i = 2.3 mm/min; b) i = 4.8 mm/min; c) i = 9.0 mm/min.

3. Results and discussion

Comparison of experimental data of stormwater discharge time changes for different admeasurement of the water intake, and theoretical curves built by formulae (1) and (3), estimated by t-test (Montgomery, 2001) and showed their complete concurrency (Fig. 3). Thus, the analytical functions (1) and (3) should be seen as a mathematical model of regulation stormwater discharge on the infiltration areas. The study results made it possible to assess the rainwater volume that can be intercepted on infiltration areas. Whereas, by its functional application infiltration areas are facilities for regulation of the rainwater discharges in front of the rain drainage systems, the water volume of accumulating space and drainage discharge can be determined by the formulae (4) and (5):

$$W_{dr} = k_{dim} \cdot \psi_{mid} \cdot i_r \cdot F_t \cdot t_\partial \cdot e^{-0.43 \cdot \varepsilon \cdot t_r} \cdot (1 + \varepsilon \cdot t_r)^{-\Delta t'_r} \quad (4)$$

$$Q_{dr} = k_{dim} \cdot \psi_{mid} \cdot i_r \cdot F_{run} \cdot \left(1 - e^{-\varepsilon \cdot t_r \cdot (1 + e^{-\varepsilon \cdot t_r} \cdot \Delta t'_c)} - \frac{\varepsilon \cdot t_r}{2} \cdot e^{-2 \cdot \varepsilon \cdot t_r} \cdot \Delta t'_r\right) \quad (5)$$

where $\Delta t'_r$ is a relative duration of infiltration area interception.

Formulae (4) and (5) can be transformed in following equations (6) and (7):

$$W_{dr} = k_{dim} \cdot \psi_{mid} \cdot F_t \cdot A \cdot k_h \quad (6)$$

$$Q_{dr} = k_{dim} \cdot \psi_{mid} \cdot F_t \cdot A \cdot k_q \quad (7)$$

where: k_h i k_q are variation coefficients of accumulated rainfall layer height and drainage discharge based on the estimated rainfall duration and calculated by formulae of a mathematical model of infiltration areas (Tkachuk and Shevchuk, 2015a):

$$k_h = t_r^{1-n} \cdot e^{-0.43 \cdot \varepsilon \cdot t_r} \cdot (1 + \varepsilon \cdot t_r)^{-\frac{\Delta t_r}{t_r}} \quad (8)$$

$$k_q = t_r^{-n} \cdot \left(1 - e^{-\varepsilon \cdot t_r \cdot \left(1 + e^{-\varepsilon \cdot t_r} \cdot \frac{\Delta t_r}{t_r}\right)} - \frac{\varepsilon \cdot t_r}{2} \cdot e^{-2 \cdot \varepsilon \cdot t_r} \cdot \frac{\Delta t_r}{t_r}\right) \quad (9)$$

or calculated by simplified formulae (10) and (11):

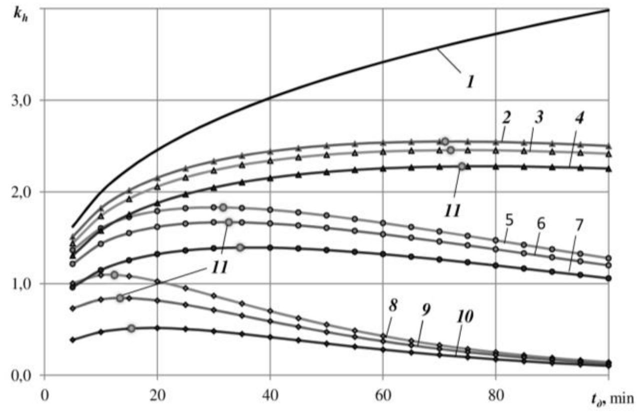
$$k_h = t_r^{1-n} \cdot e^{-\left(0.45 + 0.65 \cdot \frac{\Delta t_r}{t_r}\right) \cdot (\varepsilon \cdot t_r)^{0.9}} \quad (10)$$

$$k_q = t_r^{-n} \cdot \left(1 - e^{-1.1 \cdot (\varepsilon \cdot t_r)^{0.9}}\right) \quad (11)$$

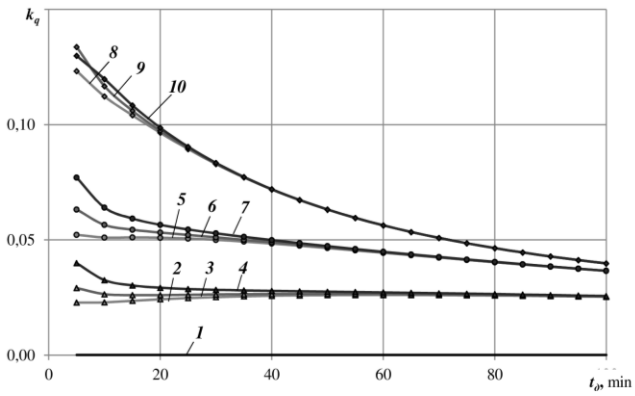
where Δt_r is a duration of continuous runoff formation on infiltration area or a concentration time of runoff from the most remote points of the territory and can be determined as the estimated duration of the runoff flow on surface and trays, in min.

According to formulae (8) and (9) Figure 4 shows an example of dependency graph k_h = f(t_r) and k_q = f(t_r) for ε = 0, 0.01, 0.025 and 0.075 and Δt_r = 5, 10 and 20 min with the value of the parameter n = 0.7 in the range of real data 0.6..0.75 (DBN, 2013).

a)



b)



1 – calculation data of (8) and (9) for ε = 0; 2, 3 and 4 – the same for ε = 0.01 and Δt_r = 5, 10 and 20 min; 5, 6 and 7 – the same for ε = 0.025; 8, 9 and 10 – the same for ε = 0.075; 11 – points of maximum values of k_h parameters calculated by (8)

Fig. 4. The graph of equation: a) k_h = f(t_r), b) k_q = f(t_r).

The data of Figure 4a show that the value of the parameter k_h has the maximum. This value determines the estimated value of rainwater volume W_{dr} that should be intercepted on infiltration site. A mathematical analysis of the function (10) was conducted to find the maximum parameter k_h. It showed following empirical equation to determine the estimated duration of rain $t_{r.est}$ which corresponded to maximum k_h:

$$t_{r.est} = 3.7 \cdot \frac{1-n}{\varepsilon^{0.9}} + 0.2 \cdot \Delta t_r. \quad (12)$$

When the rainwater volume W_{dr}, in m^3, which should be intercepted on infiltration area, is known the total base layer height, in m, will be estimated as:

$$H = \frac{W_{dr}}{F_{in} \cdot p} \quad (13)$$

where F_{in} is an area of infiltration site, in m^2, which is calculated as:

$$F_{in} = \psi_{mid} \cdot k_{in} \cdot F_t, \quad (14)$$

where k_{in} is a correlation coefficient of rainfall intensity to the drainage intensity on the infiltration site, $k_{in} \leq 0.1$.

The diameter and slope of pipes are calculated according to the values drainage discharges Q_{dr} drainage system (DBN, 2013).

The dimensions of parameters of received formulae are represented in Table 1.

Table 1. Dimensions of main parameters of infiltration areas.

№	Parameter	Value min	Value max	Reference
1	K_f (mm/min)	20	100	(AMEC Earth and Environmental, 2001; Ferguson, 2005); personal experimental studies
2	p	20	40	(AMEC Earth and Environmental, 2001; Ferguson, 2005)
3	H (m)	0,3	1,3	(AMEC Earth and Environmental, 2001); personal experimental studies
4	k_e	0	0,3	personal experimental studies
5	F_{in}/F_t	1:1	1:3 1:10	(AMEC Earth and Environmental, 2001); personal experimental studies
6	i_r (mm/min)	0	10	personal experimental studies
7	ψ_{mid}	0,8	1,0	(DBN, 2013); personal experimental studies

4. Summary of the results

The problems of runoff disposal from urban areas become significant. Change of approach toward stormwater management is an actual priority. One of these methods is using of infiltration areas with permeable pavements, that reduce runoff volume directly at place of precipitation and they are the most conductive maintenance of water balance.

But many methods of calculation of infiltration areas do not introduced to many important factors and are very simplified. Very often the calculation recommendations of the runoff volume intercepted by pavements are given in not full extent or are completely unavailable. Some methods do not introduce to calculation of parameters of drainage system with connection of infiltration areas.

Based on experimental and theoretical studies, a mathematical model of filling and emptying of stormwater infiltration areas' aggregate by connecting them to the rain drainage systems is determined. This mathematical model of stormwater discharge regulation on infiltration areas is represented by obtained analytical functions (1) and (3).

The functions (6)-(12) determine dependence between the rainwater volumes intercepted on the infiltration area and drainage discharges that flow from them in the rain drainage system. This allowed to determine the size and operating parameters of rainwater regulation facilities on urban areas and estimate dependence of infiltration areas parameters from the method of stormwater disposal and drainage capacity of existing facilities of drainage system. Input them to the rain drainage system allows to provide effective stormwater management on urban areas, accumulate rainfall directly at place of precipitation, reduce the maximum water discharge that determine pipe diameters and sizes of facilities of rain drainage system.

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