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ESTIMATION OF DAILY RUNOFF COEFFICIENT OF THE PERVIOUS SURFACES FOR THE CLIMATE CONDITIONS OF THE CITY OF LVIV

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Abstract. The method of calculation of daily runoff coefficients based on the SCS USDA curve number method is presented in this paper. The calculated values of daily runoff coefficients for climatic and geological conditions of the city of Lviv for maximum daily rainfall events with a return period of 0.1–5 years are obtained.

Key words: stormwater runoff, daily runoff coefficient, pervious surface, return period, initial abstraction, potential maximum retention.

1. Introduction

Global climate change and ever-increasing urbanization are leading to a redistribution of territorial water balances and a deterioration of the ecological status of surface water bodies. The negative impact of human activity is significant even in areas with low population density far from big cities [1]. Surface runoff obtained from the highly urbanized impervious sub-catchments (e.g. the highway facilities) is one of the main sources of contamination of surface water [2].

The widespread use of improved impervious covers, compact urban development, and the problematic status of drainage networks cause the increasing flooding of urban areas. According to the report of the State Emergency Service of Ukraine, total economic losses of over UAH 300 mln were caused by the flooding in Ukraine in 2018. The number of meteorological emergencies in Ukraine has increased from 4 events in 2018 to 16 in 2019. These trends indicate the urgency of reviewing the design methods for stormwater drainage networks in urban areas.

One of the most important parameters in the modelling of stormwater runoff is the runoff coefficient, which is the ratio of surface runoff and the amount of precipitation. The runoff ratio is a function of the type of coverage, the depth of initial abstraction, the infiltration parameters of the soils, and the climatic conditions of the terrain. It is necessary to distinguish between 1) total runoff coefficient, which is the quantitative ratio of the annual or seasonal runoff volume and the corresponding rainfall amount; 2) daily runoff coefficient, as the ratio of the daily runoff volume and corresponding rainfall volume; 3) current estimated runoff coefficient, which is a time function of rainfall intensity and infiltration rate.

Ukrainian regulations [3], [4] recommend determining runoff coefficients, depending only on the surface cover, but without taking into account other above mentioned significant factors. This can cause significant errors in determining the hydraulic load on urban drainage systems. Modelling the operation of the wastewater treatment plants and most structures of the stormwater drainage system requires a scientifically based use of the daily runoff coefficients, corresponding to different periods of onetime excess of the daily depth of the precipitation (or return periods).

Today it is proven that the division of the territory only into pervious and impervious surfaces is too simplistic and gives false values in determining the runoff volume. The detailed description of impervious surfaces and the division of the cover type into effective impervious surfaces and unconnected impervious surfaces changes the value of the total runoff coefficient by 14 % [5]. It is particularly difficult to determine the runoff coefficient from water pervious urban areas (open spaces) since the numerical value of runoff coefficient depends on both the hydraulic parameters of the soil and the hydrological condition of the territory (e.g. density of plant, the height of curbs or other borders, etc.). Thus, the urgent task is to find optimal, proven multifactor methods of determining the daily runoff coefficients for the urban pervious covers for the precipitations of different return periods.

The purpose of the study is to analyze the multifactor methods for determining the daily runoff coefficient from the water pervious urban areas, which are tested enough, and to adapt the optimal method to the known methods of designing the stormwater drainage systems in Ukraine. It is of practical importance to use an adapted method for estimating the dependence of daily runoff coefficient of pervious surfaces within the city of Lviv as the function of the return period for the maximum daily depth of the precipitation layer, taking into account data on the distribution of different types of soil in the city.

In the design of stormwater drainage systems and structures the total runoff coefficient (annual or seasonal), the daily runoff coefficient, and the runoff coefficient for the maximum flow rate estimation are distinguished.

One of the main parameters for determining the annual volume of surface runoff is the total runoff coefficient ψtot, taking into account the mean annual losses due to the initial abstraction, infiltration, and evaporation. According to the Ukrainian regulatory documents [3] and [4], the value of the total runoff ratio coefficient ψtot depends on the surface cover only: for impervious surfaces 0.6−0.8 and 0.7 respectively; for soil surfaces – 0.1–0.2 and 0.25; for lawns – 0.02–0.1 and 0.1. This difference significantly affects the value of the estimated annual runoff volume. For example, the difference between estimated annual runoff volumes from the central part of the city of Lutsk is 7.2 % when using these two methods [6]. Sometimes, it is almost impossible to clearly classify the type of the cover, for example, the difference between the soil cover and lawns is blurry, there are no clear quantitative differences between them (in the density of vegetation, the degree of compaction or loosening of soil, presence of borders or fences, etc.). The classification of the cover type for the choice of runoff coefficient in abroad design practice is more detailed [7]. The runoff coefficients for return periods of 2–10 years for asphalt roads is 0.7−0.95, for brick pavement roads − 0.7−0.85, for playgrounds − 0.2−0.35, for railways − 0.2−0.35, for parks − 0.1−0.25, for lawns − 0.05−0.35, etc. There are also averaged values of the runoff coefficient for industrial, residential, and office areas. For longer return periods, special correction factors are used.

The annual runoff coefficient differs from the event runoff coefficients derived from individual storms, so as it takes into account also those rainfall events which did not produce any runoff. The annual runoff coefficient is, therefore, always smaller compared to the arithmetic mean of runoff coefficients derived from individual runoff-producing storms [8]. The method of the average annual runoff model is widely used for the description of the catchment, for the development of the water resources management plans, etc. [9].

In the world practice of the design of stormwater drainage systems, the runoff coefficient is often defined for the peak flow associated with the time of runoff concentration from the catchment [10].

There are several methods for determining the runoff coefficients for the estimated rainfalls. The maximum discharge of the stormwater runoff from urban areas in Ukraine is defermined using the runoff coefficient according to Belov's empirical formula [11], [12]:

$$\psi = z_{mid} q^{0.2} t^{0.1}, \tag{1}$$

where z_{mid} is the average value of a special dimensionless coefficient that characterizes the surface of the catchment; q is rainfall intensity, l/(s·ha); t is time elapsed since the beginning of the rainfall, min.

The Green-Ampt method and the Horton method, which allow modelling the change in the intensity of infiltration of permeable areas over time, are widely used in computer modelling of stormwater hydrographs, in particular in the SWMM program, [13]. The Green-Ampt method is a simplified quasi-physical method that is derived from Darcy's law and the mass conservation law for a laminar filtration flow. It is assumed that the depth of the water layer accumulated on the surface is constant over time, the soil is homogeneous, and the initial water content at all points of the soil is the same. In the empirical Horton's method, the infiltration rate is a function of three independent empirical variables that cannot be evaluated analytically. These parameters depend mainly on the type of soil and must be determined experimentally.

However, the runoff coefficient in the above-mentioned methods is determined as a function of the estimated rainfall intensity. Thus, these methods are suitable for the calculation of maximum second flow rates and the modelling of stormwater hydrographs. However, it is not entirely reasonable to use these values to determine the daily runoff coefficients, since rainfall with maximum daily depth is not identical to rainfall with maximum intensity.

The analysis shows that index methods are best suited for modelling daily runoff coefficients in urban areas. The most widespread index method is a curve number method (CN-method), presented in USDA regulation TR-55 [14]. This method allows us to take into account the economic purpose of the territory, the type of soil in the territory of the drainage basin, the height of the initial retention of runoff h_{in}, the height of the saturation layer h_s, as well as the ratio of these values and the estimated height of the rainfall layer of a certain repetition, for which it is necessary to find the daily volume of rain runoff.

The CN-method developed by SCS USDA and presented in [14] is the worldwide-spread index-type method of estimating the daily runoff coefficients for small urbanized watersheds. The CN-method is based on the hypothesis:

$$\frac{h_Q}{h_{exs}} = \frac{h_{exs}}{(h_{exs} + h_s)}, \tag{2}$$

where h_Q is the runoff depth; $h_{exs} = (h_p - h_{in})$ is the excessive layer depth defined as the difference of the precipitation depth h_p and the depth of initial abstraction h_{in}; h_s is the depth of the saturation layer which characterizes the maximum infiltration capacity of the runoff basin.

TR-55 recommends the simplest empirical correlation between the initial abstraction and the saturation depth: $h_{in} = 0.2\,h_s$. Then the runoff coefficient for the rainfall event with the precipitation depth h_p is:

$$\psi = \frac{h_Q}{h_p} = \frac{(1 - 0.2h_s / h_p)^2}{(1 + 0.8h_s / h_p)}. \tag{3}$$

The saturation depth h_s according to [14] is determined as a function of the dimensionless curve number of the *CN* parameter:

$$h_s = 0.0254 \cdot \left(\frac{1000}{CN} - 10 \right). \tag{4}$$

The *CN* parameter can be found from detailed tables, depending on the type of land by economic activity and the type of soils at the catchment. All soils due to the SCS classification are divided into 4 hydrological groups: A, B, C, D (Table 1).

Table 1

Values of the CNparameter for pervious urbanized open spaces for soils of different hydrological groups

Soil hydrologic groups according to SCS. Description of soils	Hydrologic condition		
	Poor (grass cover < 50 %)	Fair (grass cover 50−75 %)	Good (grass cover > 75 %)
Group A. Sand, loamy sand, or sandy loam. High infiltration rates even when thoroughly wetted. Coefficient of filtration greater than 7.6 mm/hr.	68	49	39
Group B. Silt loam or loam. Moderate infiltration rates when thoroughly wetted (3.8−7.6 mm/hr).	79	69	61
Group C. Sandy clay loam. Law infiltration rates when thoroughly wetted (1.3−3.8 mm/hr).	86	79	74
Group D. Clay loam, silty clay loam, sandy clay, silty clay, or clay. Very law infiltration rates when thoroughly wetted (<1.3 mm/hr).	89	84	80

2. Materials and Methods

Estimation of the dependences of daily runoff coefficient of pervious surfaces within the city of Lviv as the function of the return period is performed analytically using the following baseline data: 1) the actual values of the maximum daily rainfall depths depending on the return period; 2) data on the distribution of soils of different types in the city; 3) results of selective field studies on the degree of improvement and hydrological conditions of the runoff sub-catchments.

Data on maximum daily rainfalls in Lviv for the period from 1945 to 2018 were taken from the Report [15]. The principle of end-to-end precipitation depths ranging has been used in the processing of full-scale results for both the entire 1945–2018 period and for shorter, more recent periods (over the last 35 years and the last 20 years). As the calculated values of the depth of the precipitation layer are systematically increasing with the reduction and updating of the studied time range, the results obtained from data processing for the period from 1999 to 2018 are taken to estimate the daily runoff coefficients. Due to the existing tradition of describing maximum daily hydrometeorological parameters, the actual data were analyzed using the Weibull model. As a result of the analysis, a strong functional dependence (5) was obtained with a coefficient of determination $R^2 = 0.9966$:

$$h_p = 73.0 - 64.6e^{-0.742 \cdot P^{0.862}}, \text{ mm/day} \tag{5}$$

where *P* is return period, years.

A detailed description of the types of natural soils in the city of Lviv [16] indicates that they are mostly represented by sod-podzolic soils on ancient alluvial and water-glacial deposits, grey forest soils, mainly on loess-like deposits, black soil, peat soil and urban soil (Table 2).

Analysis of the composition and infiltration properties of soils makes it possible to organize them by hydrological groups according to the classification [14], which is presented in Table 2.

Table 2

Types of soils of different hydrology groups in the city of Lviv [16]

Type of soil	Proportion, %	Hydrology group of soil by SCS
1. Sod-hidden podzolic i slightly podzolic.	7.53	A
2. Sod-slightly podzolic with soil from rill and gully erosion (sandy loam).	0.54	B
3. Grey forest soils.	15.28	B
4. Dark grey podzolic soils.	0.72	B
5. Podzolic black soil on loess-like deposits.	5.30	B
6. Meadow, meadow chernozem, meadow carbonate soils	3.82	C
7. Lowland peat lands.	5.90	A
8. Urban soil in combination with reclaimed soil with humus bulk horizon.	60.91	B
Total:	100	

3. Results and Discussion

The modelling of the dependencies for the daily runoff coefficient by the above-described method is performed for the climatic and geological conditions of the city of Lviv. The maximum daily depth of the rainfall layer is found using the equation (5) for return period P in the range from 0.1 to 5 years. The analysis of the geological composition of soils indicates that soils in Lviv belong to three hydrological groups: A, B, and C (Table 2).

The results are presented as graphs of the dependence of daily runoff coefficient ψ for pervious surfaces as a function of the return period *P* for hydrologic soil groups A, B and C presented in Lviv (Fig. 1, 2, and 3, respectively).

Comparing the trends of the curves in these graphs, a regular increase of the daily runoff coefficient ψ is noticeable when P increases and in the direction from the good to the poor hydrologic condition of the pervious covers. Minimum values of the daily runoff coefficient correspond to soils of group A that are in good hydrological condition. The daily runoff coefficient increases from the soils of group A to group B and C, and when hydrologic condition changes from good to fair and further to the poor condition. The maximum estimated value of the daily runoff coefficient for the pervious surfaces in the city of Lviv during the return period P =5 yr. is ψ_{max} = 0.527 for the poor hydrologic condition of the surfaces with soils of type C.

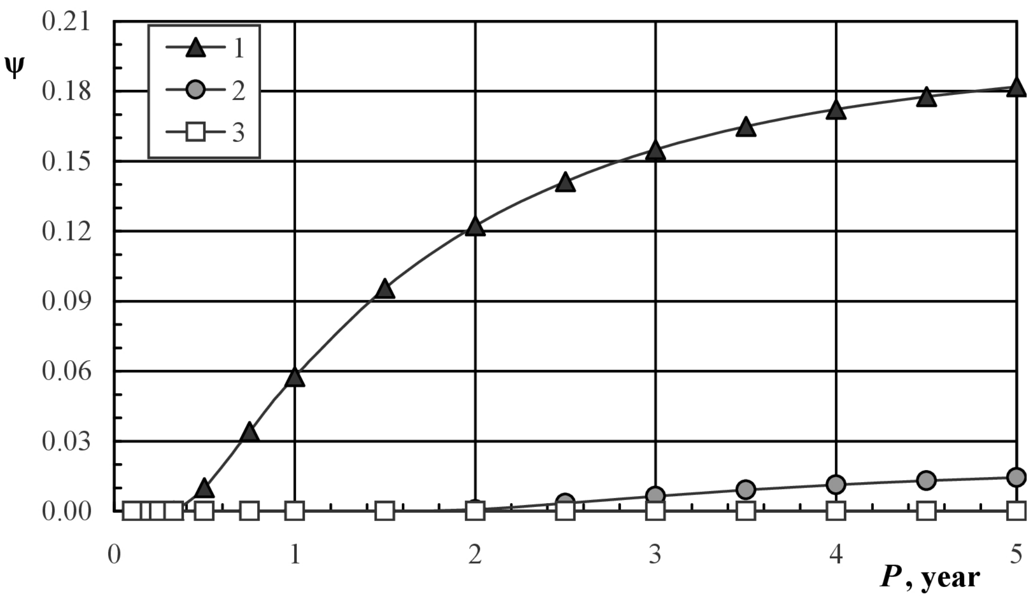

Fig. 1. Daily runoff coefficient ψ for pervious surfaces of the city of Lviv as a function of the return period *P* for soils of hydrologic group A: 1) poor condition; 2) fair condition; 3) good condition

The daily runoff coefficient for soils of hydrologic group A with the highest water permeability is shown in Fig. 1. The runoff coefficient ψ = 0 is obtained for the good hydrologic condition for the whole investigated range of return period $0 < P \leq 5$ yr.; for fair condition $\psi = 0$ if $P \leq 1.5$ yr., and for the poor condition the daily runoff is absent if $P \leq 0.33$ yr. Zero values of the daily runoff coefficient can be explained by the first boundary condition of runoff formation and correspond to cases when the daily depth of the precipitation layer h_p is less compared to the initial abstraction depth $h_o = 0.2$ hs.

The daily runoff coefficient depends almost equally on both the type of the soil and the hydrologic condition of the cover. For example, the daily runoff coefficient at the return period P = 5 yr. for soils of group C for the poor hydrologic condition is 1.93 times higher compared to the good condition (Fig. 3). On the other hand, for the same conditions, the ratio of the runoff coefficients for soils of groups C and A in the poor hydrologic condition is 2.89.

The ratio of the daily runoff coefficients for the poor and the fair hydrologic condition, as well as for the fair and good condition proved to be practically the same at the return periods $2 \leq P \leq 5$ yr. for soils of hydrologic group B (Fig. 2) and at $0.5 \leq P \leq 5$ yr. for soils of hydrologic group C (Fig. 3).

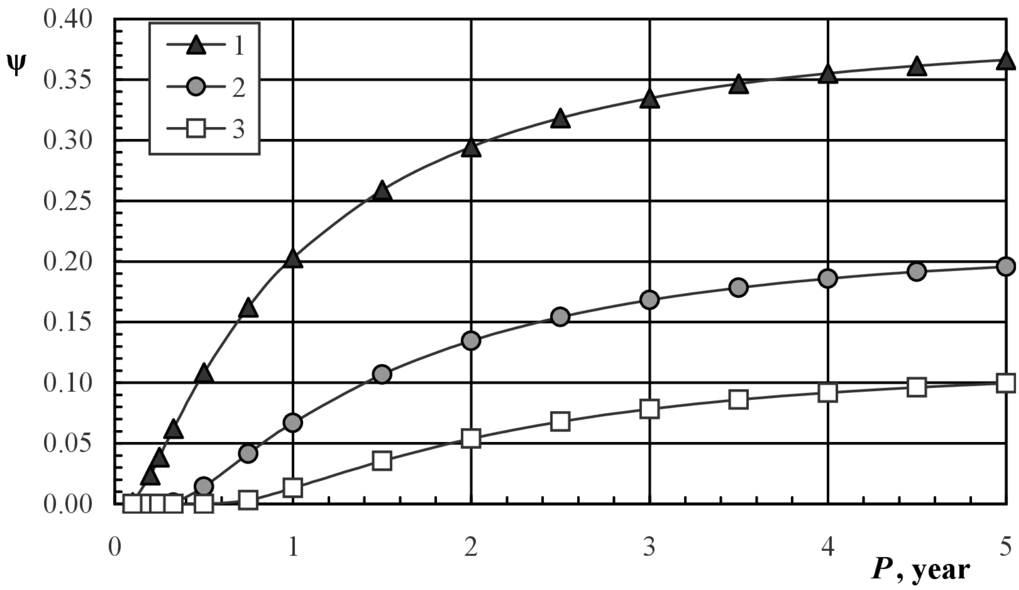

Fig. 2. Daily runoff coefficient ψ for pervious surfaces of the city of Lviv as a function of the return period *P* for soils of hydrologic group B: 1) poor condition; 2) fair condition; 3) good condition

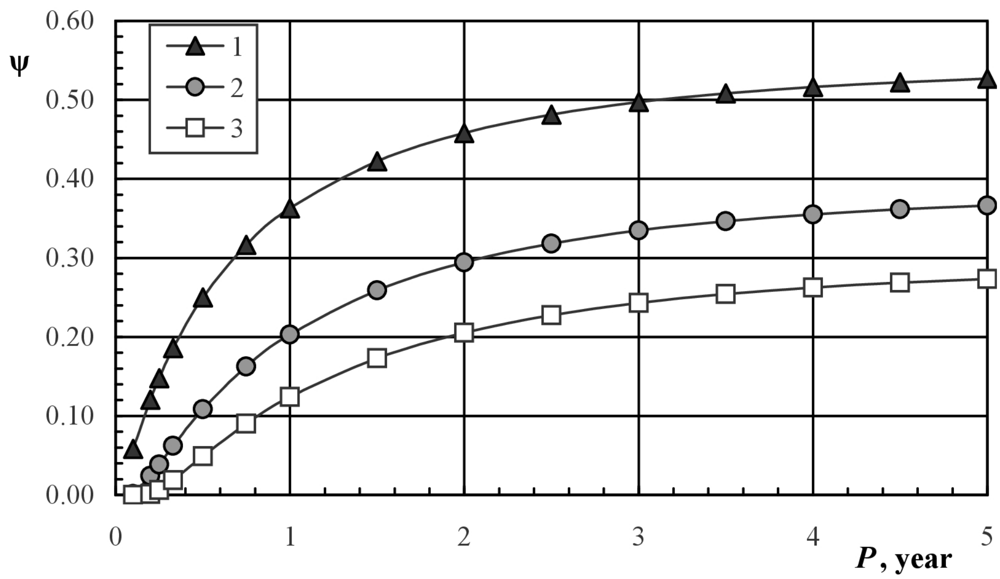

Fig. 3. Daily runoff coefficient ψ for pervious surfaces of the city of Lviv as a function of the return period *P* for soils of hydrologic group C: 1) poor condition; 2) fair condition; 3) good condition

The average value of the period P for designing the stormwater drainage networks is P = 1 yr., so a detailed analysis of the daily runoff coefficient is performed just for that baseline. For the soils of group A, with fair and good hydrological conditions at P = 1 yr., the surface runoff is absent, i.e. $\psi = 0$. The maximum daily runoff coefficient $\psi = 0.363$ corresponds to the soils of group C in poor hydrologic conditions, which is 1.79 times higher than for the soils of group B ($\psi = 0.203$) and 6.28 times greater compared to the soils of group A ($\psi = 0.058$) under the same hydrologic conditions.

The maximum relative difference between the values of daily runoff coefficients is obtained for the soils of group B: for poor hydrologic conditions the daily runoff coefficient $\psi = 0.203$ is 15.6 times larger than for good hydrological conditions ($\psi = 0.013$).

The numerical simulation of the weighted average values of the daily runoff coefficient ψ from the pervious surfaces in the city of Lviv was performed. Proportions of the coverage with soils of different groups according to Table 2 are: group A − 13.43 %, B − 82.75 %, and C − 3.82 % of the total area of the city. As a result, the average values of the daily runoff coefficient for the pervious covers in the city of Lviv are obtained for different return periods P, assuming that the proportion of each of the three hydrologic conditions is the same (Table 3).

Table 3

Average daily runoff coefficients for pervious surfaces in the city of Lviv

Return period *P*, yr.	Maximum daily depth of the precipitation h_p, mm	Average daily runoff coefficient ψ for hydrological conditions:			Total average daily runoff coefficient
		poor condition	fair condition	good condition	
0.1	14.66	0.00333	0.000005	0	0.0011
0.2	19.33	0.0244	0.00091	0.000005	0.0085
0.25	21.40	0.0376	0.00148	0.00024	0.0131
0.33	24.44	0.0587	0.00314	0.00071	0.0209
0.5	30.05	0.1006	0.0160	0.0019	0.0395
0.75	36.80	0.1510	0.0405	0.0060	0.0658
1	42.24	0.1897	0.0631	0.0156	0.0894
1.5	50.45	0.2433	0.0982	0.0360	0.1258
2	56.23	0.2776	0.1227	0.0524	0.1509
2.5	60.40	0.3007	0.1402	0.0648	0.1686
3	63.46	0.3168	0.1528	0.0740	0.1812
3.5	65.73	0.3283	0.1621	0.0809	0.1904
4	67.43	0.3367	0.1689	0.0860	0.1972
4.5	68.72	0.3429	0.1741	0.0899	0.2023
5	69.69	0.3476	0.1779	0.0928	0.2061

The results in Table 3 were analyzed using the Logistic Power model. It is customary to use this model to describe the distribution of annual and monthly precipitation in hydrology. The equation (6) was obtained to calculate the total average daily runoff coefficient for the pervious surfaces of the Lviv city as a function of the return period P:

$$\psi = \frac{0.229}{1+\left(P/1.328\right)^{-1.633}} \qquad (6)$$

Equation (6) has high validity criteria (standard deviation $\sigma = 0.001$, the determination coefficient R2 = 0.99986) and can be used for the scientifically based stormwater runoff modelling for the pervious part of the urbanized catchment of the city of Lviv at the daily scale level.

Conclusions

The multifactor methods used to determine the daily runoff coefficient from the water-pervious urban areas are analyzed taking into account: 1) maximum daily rainfall depths of different return periods; 2) groups of soil by water permeability; 3) the hydrological condition of pervious surfaces at the urbanized catchment. The method for the calculation of the daily runoff coefficient based on the SCS USDA curve number method, presented in this paper, complements the relevant Ukrainian regulatory requirements when designing the stormwater drainage systems. The calculated values of daily runoff coefficients for climatic and geological conditions of the city of Lviv for maximum daily rainfall events with a return period P = (0.1–5) years were obtained. There is a clear tendency of increasing the runoff coefficient in the direction from the soils of group A to groups B and C, as well as towards the deterioration of the hydrological condition of the pervious surfaces. The total average daily runoff coefficient was obtained in general for water-permeable coatings in the city of Lviv as a logistic power function (6) of the period of a onetime excess of *P*.

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