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EVALUATION OF URBAN STORMWATER RUNOFF QUALITY

The methods for determining the quality of stormwater were reviewed from the viewpoint of their applicability in Poland. A simple method for calculation of pollutograms and annual load of contaminants in stormwaters is proposed. The method is based on the statistically determinable relationships between the runoff intensity of the contaminants and the volumetric runoff intensity on the one hand, and the time since the beginning of runoff and duration of dry weather, on the other one. The method of computing pollutographs in cases when only the maximum runoff intensity can be estimated is also proposed. The identification of parameters was based on investigations carried out in Warsaw. The analysis of experimental data from three catchment areas in the city of Rzeszów has proved that the volumetric runoff intensity is the parameter most important statistically affecting pollutographs.

NOTATIONS

A, B, C, D, a, n, m, q — regression coefficients,
$C_{m,i}$ — pollutant concentration measured at Δt_i intervals,
$\bar{C}_{w,k}$ — weighted average of pollutant concentration in the k-th subcatchment,
F_k — total area of the k-th subcatchment,
h_r — annual precipitation height,
L_i — flow of the pollutants washed out at the Δt_i interval,
$L_{\max}$ — maximum flow of the mass of pollutants during a single runoff,
L_t — annual pollutant load,
M — number of Δt_i intervals,
N — number of samples to be analyzed,
n — number of subcatchments,
Q_i — rate of volumetric flow over the Δt_i intervals,
$Q_{m,i}$ — flow rate measured at Δt_i intervals,
$Q_{\max}$ — peak flow,
T — duration of the annual stormwater runoff,
T_d — time elapsed from the last storm,

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t — time elapsed which passed from the beginning of runoff,
Δt_i — sampling time,
Ψ_k — annual runoff coefficient for the k-th subcatchment,
η_i — dimensionless coefficient of pollutant washed out by the stormwater runoff over the Δt_i interval.

1. INTRODUCTION

So far the problem of the urban stormwater runoff quality evaluation has not been solved explicitly.

There are two different approaches concerning mathematical description of the stormwater runoff concentration of pollutants and their loads. The form of mathematical description can be stated by two approaches: according to the model of accumulation of a street pollutant washed outside the catchment area and transported through drainage system or by means of experiment only, without attempting to reach mathematical generalization.

The former way leads to the method, which can be called a conceptual one, and the latter to the statistical method. The examples of the conceptual method are the EPA Storm water Management Model [4, 10], Cincinnati Urban Runoff Model [11], Suspended Solids Model for Stormwater Runoff [11], and the method of evaluation of stormwater pollutant concentration developed by PAJDZIŃSKA [9].

The application of conceptual methods requires identification of a numbeı of random parameters, such as: rate of accumulation of pollutants [4], coefficients expressing dust and dry litter mass as the values of the given type of pollution [9], velocity of leaching of pollutants by stormwater [11] and critical shear stress [12]. The above parameters are determined by optimization.

Due to the complexity of the stormwater runoff, conceptual methods do not take into account some factors, which can affect stromwater pollution loads. These factors include: sedimentation of suspended solids in the low discharge period, scouring of deposit from the bottom of sewers, manholes and road drain catchpits as well as the quality of infiltration water. Hence, each time initial assumptions should be checked. This can be done — using a statistical criterion — by comparing the computed values of concentrations and loads with the experimental data. If significant errors occur, the initial assumption should be verified and the identification procedure repeated. This involves troublesome and expensive investigations.

Statistical methods do not require separate identification and verification, as their accuracy has been estimated on the basis of experimental data. They may be applied if the categories of land use of the examined and planned catchment area are similar and the measuring range is taken into account.

In both methods hydrographs should be determined. They are computed by using hydrological models, and the way in which the hydrographs are determined depends on the method of evaluation of pollutographs. If the conceptual method is used the deterministic hydrological model, simulating nonsteady-state flow rate at any point of the sewer network should be applied. If the pollutographs are determined by the statistical method, the application of hydrological model is sufficient and easier in practice.

Generally speaking, the choice of the method is determined by their application and practical possibilities of identification of parameters and evaluation of hydrograms. Hence, it seems advisable to present a simple method of evaluation of the concentrations and loads of stormwater pollutants adapted to the amount of information, usually available in preliminary design of the sewer system [7].

Table 1

Characteristics of the area under study
Charakterystyka badanych obszarów

Catchment areas	Land use category	Area [ha]	Area [%]	Average slope of catchment areas [%]
Mixed, residential and industrial catchment in Warsaw "A"	total area	300	100.0	4
	housing estate	83	27.6	
	industrial establishments and warehouses	119	39.8	
	services and municipal establishments	36	12.0	
	streets	19	6.3	
	lawns	43	14.3	
Two one-way streets in Rzeszów "B"	total area	1.35	100.0	21.4
	asphalt roads and pavements	0.44	32.6	
	concrete roads and pavements	0.12	8.9	
	lawns	0.79	58.5	
Double-way streets in Rzeszów "C"	total area	4.16	100.0	4.3
	asphalt roads and pavements	2.55	61.13	
	lawns	1.61	38.70	
Housing estate in Rzeszów "D"	total area	1.83	100.0	23.1
	asphalt roads and pavements	0.26	14.2	
	concrete roads and pavements	0.42	22.9	
	roofs	0.34	18.4	
	lawns	0.81	44.3	

2. METHODS

The investigations involved the quality and quantity of stormwater runoff from the large residential and industrial catchment area in Warsaw and from three small catchment areas in Rzeszów.

The three-year investigations in Warsaw and two-year ones in Rzeszów included the measurements of the stormwater flow intensity and the concentration of contaminants.

The stormwater flow intensity was continually recorded by means of two limnigraphs. For chemical analysis, the runoff from the catchment area in Warsaw was sampled automatically at ten-minute intervals using the Rock and Tylor apparatus. In Rzeszów the samples were collected by means of a specially constructed apparatus. The sampling time varied within 5–10 min.

The characteristics of the catchment areas under study is presented in tab. 1. The concentration of stormwater pollutants is characterized by the following indices: total suspended solids, BOD_5, COD, and grease. In the Warsaw catchment area lead was also determined. The indices mentioned enable the reliable estimation of the stormwater discharge effects on the receiving stream [2, 3].

3. ANNUAL POLLUTANT LOADS

In preliminary planning and designing of sewage systems it is necessary to determine annual pollutant loads in order to evaluate the amount of sludge collected in the receiving streams or in sedimentation and retention tanks.

While designing the stormwater overflows, it is necessary to estimate the total volume of sludge collected during wet weather in a municipal wastewater treatment plant.

Information concerning the amounts of stormwater sludge is necessary in solving problems of sludge accumulation and its disposal. The annual pollutant loads can be calculated from the simple formula:

$$L_t = 10^{-2} h_r \sum_{k=1}^{n} \overline{C}_{w,k} \Psi_k F_k \qquad (1)$$

where:

L_t — annual pollutant load (kg/y),

h_r — annual precipitation (mm),

$\overline{C}_{w,k}$ — weighted average of the pollutant concentration in the k-th subcatchment (mg/dm^3),

Ψ_k — annual runoff coefficient for the k-th subcatchment site,

F_k — total area of the k-th subcatchment site (ha),

n — number of subcatchment sites.

To determine $\overline{C}_{w,k}$ the following equation was used:

$$\overline{C}_{w,k} = \frac{\sum_{i=1}^{N} 60 Q_{m,i} C_{m,i} \Delta t_i}{\sum_{i=1}^{N} Q_{m,i} \Delta t_i} \tag{2}$$

in which

$Q_{m,i}$ — flow rate measured in Δt_i time interval (dm^3/s),
$C_{m,i}$ — pollutant concentration measured in Δt_i time interval (mg/dm^3),
Δt_i — sampling time (min),
N — number of samples analyzed.

The third column in tab. 2 shows the values of $\overline{C}_{w,k}$ for each of the catchment areas studied.

Table 2

Annual average concentration
Średnie stężenia w ciągu roku

Catchment areas	Pollution indexes	Concentration: Weighted average $\overline{C}_{w,k}$ [g/m^3]	Concentration: Arithmetic mean $\overline{C}$ [g/m^3]	Number of samples
"A"	total solids	316	279	1250
	COD	241	184	567
	BOD_5	56	56	179
	grease	32	28	42
	lead	0.075	0.0043	40
"B"	total solids	1420	998	167
	COD	424	431	159
	BOD_5	35	64	158
	grease	23	18	81
"C"	total solids	1703	1470	79
	COD	453	280	70
	BOD_5	38	49	90
"D"	total solids	442	182	142
	COD	128	101	142
	BOD_5	33	39	142
	grease	3	3	48

It must be emphasized that the annual runoff coefficient in equation (1) differs from that used in rational method. According to the five-year investigations carried out in Warsaw, the annual runoff coefficient Ψ_k, defined as a ratio of the annual precipitation to the annual runoff, is about 53% of the maximum instantaneous runoff coefficient for a single runoff [4].

4. POLLUTION LOAD VERSUS RUNOFF

The relationship between the loads of the pollutants generated during 80 individual rainfalls and volumetric flow rate (figs. 1, 2) was expressed by the power function:

$$\eta_i = AQ_i^B, \quad i = 1, 2, \ldots, M \tag{3}$$

in which

η_i — dimensionless coefficient of pollutant washed out by the stormwater within the Δt_i time interval,
Q_i — volumetric flow rate within the Δt_i time interval (dm³/s/ha),
A, B — empirical coefficients specified in tab. 3,
Δt_i — time of sampling (min),
M — number of intervals Δt_i.

The coefficient η_i was defined by:

$$\eta_i = \frac{F_k T L_i}{1.157 \times 10^{-2} L_t} \tag{4}$$

where:

T — annual duration of stormwater runoff (days),
L_i — pollutants load washed out within the Δt_i time interval (g/s/ha),
1.157×10^{-2} — conversion factor,
F_k, L_t — parameters defined in formula (1).

By combining the formulas (3) and (4) we get:

$$L_i = \frac{1.157 \times 10^{-2} L_t \eta_i}{F_k T}. \tag{5}$$

If the hydrographs, Q_i, $i = 1, 2, \ldots, M$, and other parameters are known, the above formula can be used to determine the relationships between pollutant load and the runoff water flow.

When only a model of a peak urban runoff can be used, this formula should be simplified to the form:

$$L_{max} = \frac{1.157 \times 10^{-2} L_t \eta_{max}}{F_k T} \tag{6}$$

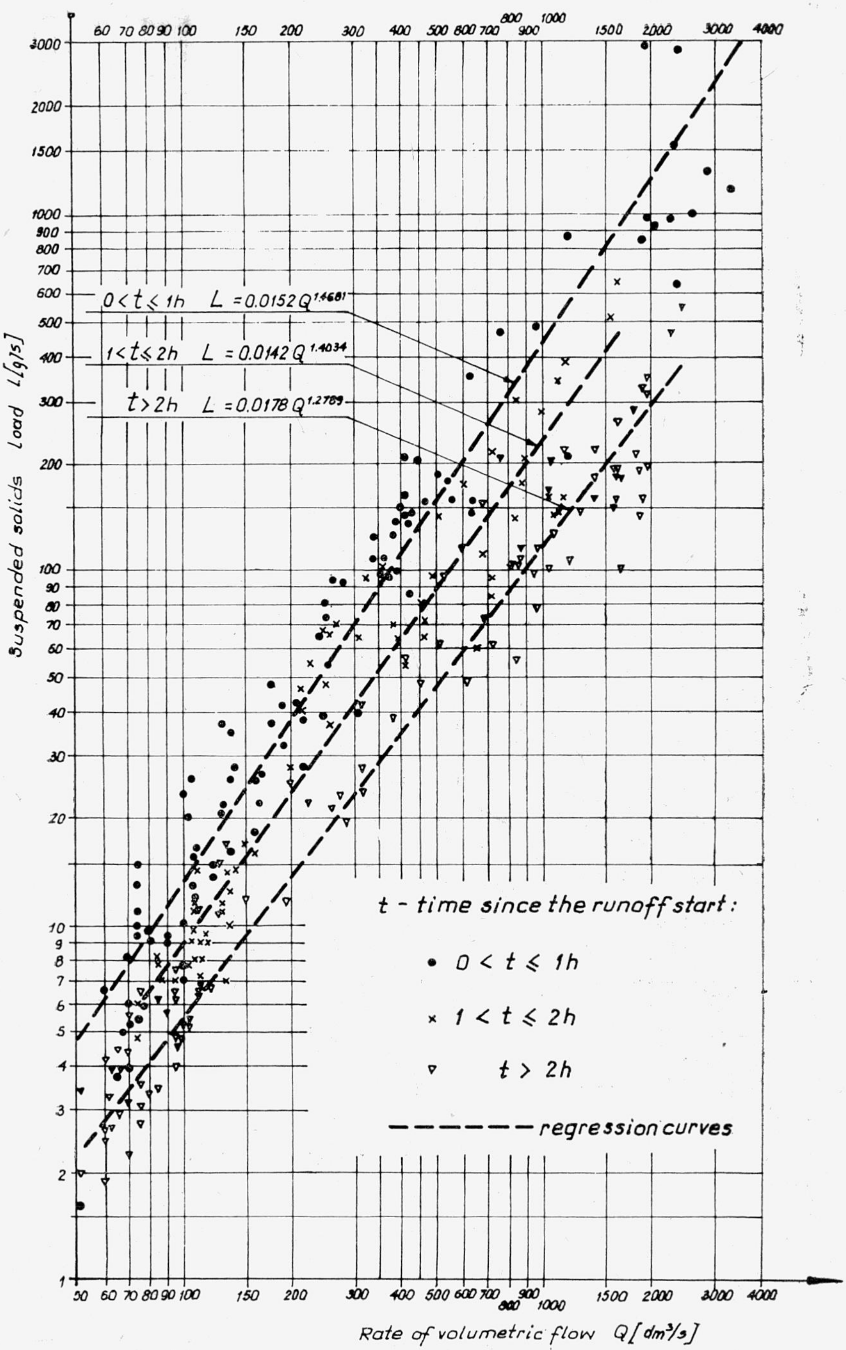

Fig. 1. Relation $L = f(Q)$ for various time intervals since the runoff start and for time from the last storm $T_d \leqslant 24$ h

Rys. 1. Ładunek zawiesiny w zależności od natężenia przepływu objętościowego dla różnych przedziałów czasowych: od początku spływu i od początku ostatniego opadu ulewnego $T_d \leqslant 24$ h

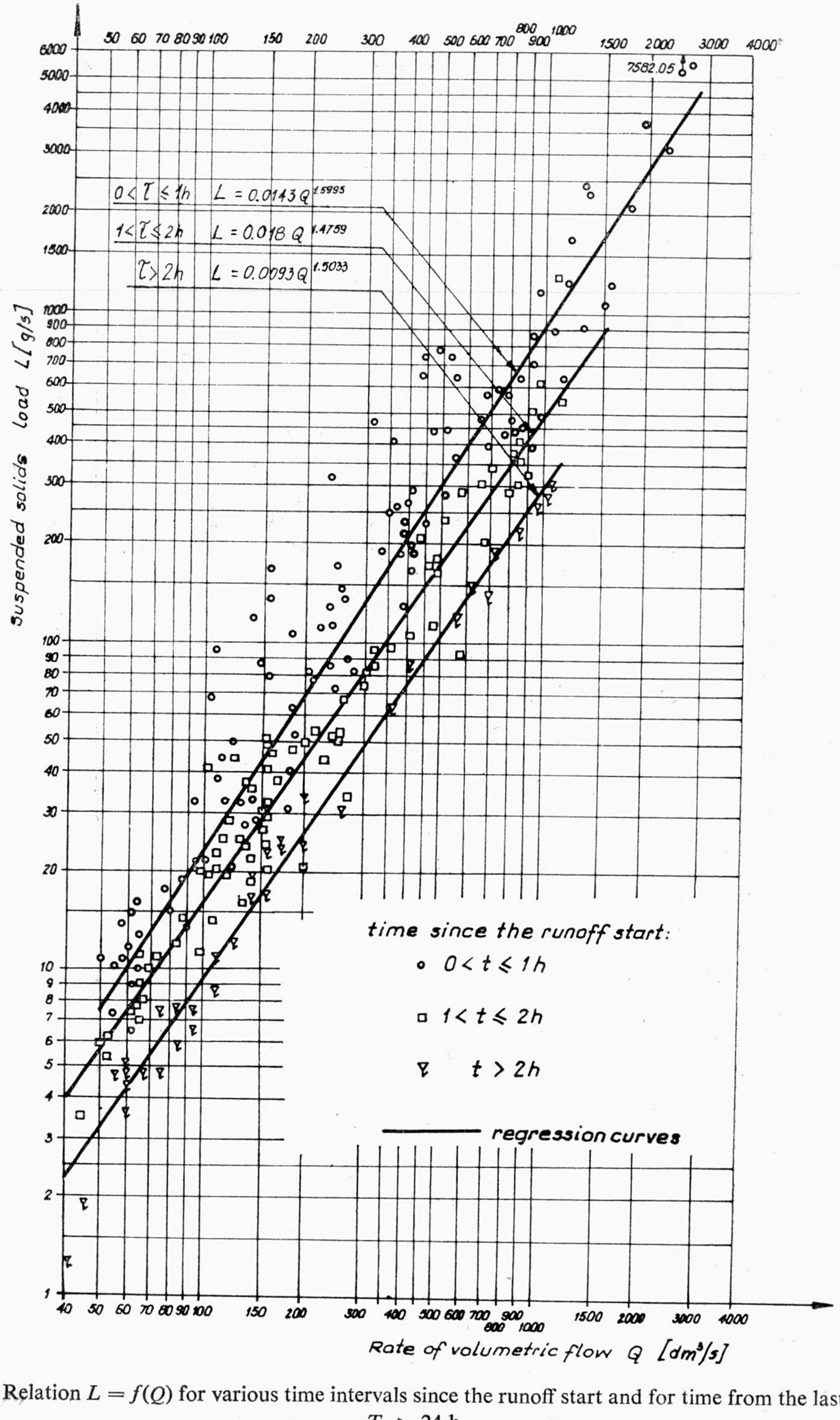

Fig. 2. Relation $L = f(Q)$ for various time intervals since the runoff start and for time from the last storm $T_d > 24$ h

Rys. 2. Ładunek zawiesiny w zależności od natężenia przepływu objętościowego dla różnych przedziałów czasowych: od początku spływu i od początku ostatniego opadu ulewnego $T_d > 24$ h where:

$\eta_{max} = CQ^D_{max}$,

Q_{max} — peak flow occurring after the period of dry weather not shorter than 24 h ($dm^3/s/ha$),

C, D — regression coefficients specified in tab. 4.

Tables 3 and 4 show a good agreement between experimental data and regression functions.

Table 3

Empirical coefficients and the fitness of the formula $\eta_i = AQ_i^B$*

Współczynniki empiryczne i stopień dopasowania do danych pomiarowych formuły $\eta_i = AQ_i^B$

Time since the last runoff termination [h]	Time since the runoff start [h]	Empirical coefficients		Determination coefficient r^2	Standard deviation [%]
		A	B		
Suspended solids					
$0 < T_d \leqslant 24$	$0 < t \leqslant 1$	1.3079	1.4681	0.94 ($p \geqslant 0.001$)	8.7
	$1 < t \leqslant 2$	0.8448	1.4034	0.92 ($p \geqslant 0.001$)	9.2
	$t > 2$	0.5206	1.2789	0.96 ($p \geqslant 0.001$)	8.1
$T_d > 24$	$0 < t \leqslant 1$	2.6036	1.5995	0.88 ($p \geqslant 0.01$)	9.0
	$1 < t \leqslant 2$	1.6193	1.4759	0.92 ($p \geqslant 0.001$)	7.4
	$t > 2$	0.9781	1.5033	0.96 ($p \geqslant 0.001$)	8.1
COD					
$0 < T_d \leqslant 24$	$0 < t \leqslant 1$	1.4311	1.3432	0.94 ($p \geqslant 0.001$)	11.8
	$1 < t \leqslant 2$	1.1878	1.4148	0.96 ($p \geqslant 0.001$)	10.4
	$t > 2$	0.9407	1.2557	0.96 ($p \geqslant 0.001$)	10.9
$T_d > 24$	$0 < t \leqslant 1$	2.7520	1.3528	0.96 ($p \geqslant 0.001$)	4.2
	$1 < t \leqslant 2$	1.9005	1.2572	0.92 ($p \geqslant 0.01$)	5.6
	$t > 2$	1.4728	1.2857	0.94 ($p \geqslant 0.001$)	10.8
BOD_5					
$T > 0$	$0 < t \leqslant 1$	1.8333	1.1572	0.83 ($p \geqslant 0.05$)	17.1
	$t > 1$	1.2776	1.1194	0.88 ($p \geqslant 0.02$)	20.2

* Measured range: $0 < Q_i \leqslant 11.2$ $dm^3/s/ha$.

Table 4

Empirical coefficients and the fitness of the formula $\eta_{max} = CQ_{max}^{D}$
Współczynniki empiryczne i stopień dopasowania do danych pomiarowych formuły $\eta_{max} = CQ_{max}^{D}$

Pollution indexes	Empirical coefficients		Determination coefficient	Standard deviation
	C	D	r^2	[%]
Suspended solids	3.5494	1.6588	0.92	9.1
COD	2.2973	1.3988	0.94	11.3
BOD_5	2.3413	0.0954	0.77	17.2

As an alternative method of experimental data analysis, a nonlinear model was used:

$$L = aQ^{n}T_{d}^{m}t^{q} \tag{7}$$

where:

Q — volumetric flow rate (dm^3/s),
L — pollutants' load (g/s),
t — time elapsed from the beginning of runoff (min),
a, n, m, q — regression coefficients.

Sequential analysis of multiple regression based on the experimental data from three catchment areas in Rzeszów has indicated that the flow rate may be assumed as the most significant parameter with probability 0.99 (tab. 5). The partial correlation coefficient $r_{Q,L}$ ranges within 0.75–0.90 as compared to 0.83–0.98 when all three variables are taken into account. Hence, it may be assumed that the flow rate is the only reliable predictor of the pollutants load in Rzeszów.

The time elapsing from the last precipitation was not important for two reasons: 1) the accumulation rate of pollutants is not a simple continuous function of time elapsed since the last storm runoff, 2) high frequency of relatively short dry weather periods.

On the other hand, the time elapsing since the beginning of runoff is not significant statistically because of highly varying rate of the pollutant removal from the streets, and especially from the road drain catchpits.

5. EXAMPLES OF PRACTICAL PROBLEM SOLUTIONS

1. Compute the annual load of the total suspended solids washed out from the streets of the area $F = 2$ ha from residential quarter $F_2 = 30$ ha. The maximum runoff coefficient for street is 0.8 and for the residential quarter 0.5. The annual precipitation h_r is 950 mm.

Solution: the values of annual runoff coefficients Ψ_1 and Ψ_2 are $0.53\times0.8 = 0.424$ and $0.53\times0.5 = 0.265$, respectively. From tab. 2 we find $\overline{C}_{w,1} = 1703$ mg/dm³ and $\overline{C}_{w,2} = 442$ mg/dm³. Substitution of the above data into formula (1) yields:

$$L_t = 10^{-2}\times950(1703\times0.424\times2+442\times0.265\times30) = 47101 \text{ kg/yr.}$$

Table 5

Empirical coefficients and the fitneess of eq. (7) based on data from the catchment areas in Rzeszów
Współczynniki empiryczne i stopień dopasowania do danych pomiarowych dla zlewni w Rzeszowie

Catchment areas	Regression coefficients				Partial correlation coefficients			Multiple correlation coefficients
	a	n	m	q	$R_{Q,td}$	$R_{T_d L}$	$R_{t,L}$	
				Suspended solids				
B	0.7571	1.2730	0.0764	0.1096	0.90	0.13	−0.34	0.915 ($p \geqslant 0.01$)
C	0.4474	1.1965	−0.1042	−0.0379	0.75	−0.11	−0.06	0.83 ($p \geqslant 0.01$)
D	0.1347	1.2269	0.1646	−0.1129	0.82	0.16	−0.21	0.902 ($p \geqslant 0.01$)
				COD				
B	0.3985	1.0278	0.0903	0.0674	0.90	0.18	−0.27	0.933 ($p \geqslant 0.01$)
C	0.2299	1.1342	0.0458	0.751	0.89	−0.11	−0.27	0.904 ($p \geqslant 0.01$)
D	0.0828	1.0493	−0.0244	−0.0141	0.90	0.13	−0.05	0.970 ($p \geqslant 0.01$)
				BOD_5				
B	0.0600	0.9392	−0.0213	−0.0614	0.84	−0.04	−0.21	0.943 ($p \geqslant 0.01$)
C	0.0774	0.6522	−0.0668	−0.0366	0.85	−0.19	−0.18	0.974 ($p \geqslant 0.01$)
D	0.0327	1.0159	0.0809	−0.0257	0.90	0.16	−0.10	0.982 ($p \geqslant 0.01$)

Table 6

Computed pollutograph
Obliczony polutogram

Time interval Δt_i [min]	10	20	30	40
Q_i [dm³/s·ha]	3.1	7.8	11.2	7.3
L_i [g/s·ha]	4.3	18.8	33.6	16.9

2. Compute the stormwater pollutograph from the residential-industrial catchment area $F_k = 280$ ha. The hydrograph Q_i (tab. 6), maximum runoff coefficient $\Psi = 0.5$, annual precipitation $h_r = 950$ mm, and sum of precipitation durations $T = 34$ days are given.

Solution: from the formula (1) we have $L_t = 222748$ kg/yr. Substituting the above data into the formula (5), we obtain L_i, as given in tab. 6.

6. SUMMARY AND CONCLUSIONS

From the investigations performed the following conclusions can be formulated:

1. Methods allowing the stormwater quality evaluation were reviewed. Statistical methods for calculating the annual pollutant load and pollutographs were developed.

2. The choice of the method for evaluation of those methods depends on the kind of models for evaluation of hydrographs.

If a parametric model of the hydrograph evaluation is available, the formula (3) can be used. If solely the maximum runoff is computed, the pollution load versus water flow curves can be estimated assuming that the loads of pollutants change linearly from zero to the maximum value during each runoff. The latter method can be particularly useful in preliminary planning.

The statistical model can be used for forecasting the loads discharged from similar and ungauged catchment areas.

3. The results presented suggest that in the case of an intensive erosion and the sedimentation of solids accumulated in the sewage system, the flow rate may be the statistically most significant parameter, affecting the flow of pollutants.

Results of this study cannot be applied uncritically to other watersheds. It may be expected that some of the fundamental concepts investigated in this study would be useful in further studies on urban stormwater quality.

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OKREŚLANIE JAKOŚCI ŚCIEKÓW DESZCZOWYCH

Dokonano przeglądu metod określania jakości ścieków deszczowych ze względu na ich praktyczne wykorzystanie w Polsce. Zaproponowano prostą metodę określania polutogramów i rocznego ładunku zanieczyszczeń ścieków deszczowych. Metoda opiera się na statystycznie określonym związku między natężeniem przepływu masy zanieczyszczeń a objętościowym natężeniem przepływu, czasem od początku odpływu i czasem pogody bezdeszczowej. Zaproponowano również sposób określania polutogramów wówczas, kiedy można oszacować jedynie maksymalne natężenie przepływu. Dokonano identyfikacji parametrów na podstawie badań w Warszawie. Analiza danych eksperymentalnych z trzech zlewni w Rzeszowie wykazała, że najbardziej statystycznie znaczącym parametrem, wpływającym na polutogramy, jest natężenie przepływu objętościowego.

BESTIMMUNG DER VERSCHMUTZUNG VON REGENABWÄSSERN

Gegeben ist eine Übersicht der Meßmethoden der Verschmutzungen von Regenabwässern unter dem Hinblick ihrer praktischen Anwendung in Polen. Vorgeschlagen wird eine einfache Methode der Pollutogrammbestimmung und der Jahresschmutzfracht. Sie stützt sich auf den statistischen Beziehungen zwischen der Schmutzfracht und der Durchflußmenge, der Abflußzeit seit Abflußbeginn und dem Dauer der Trockenperiode. Vorgeschlagen wird auch eine Pollutogrammbestimmung in Fällen, in denen nur eine Abschätzung des maximalen Abflußes möglich ist. Angeführt wird eine Identifizierung der Werte anhand von Meßwerten, die für Warschau ermittelt wurden. Eine Analyse von Experimenten an drei Einzugsgebieten in Rzeszów hat erwiesen, daß als wesentlichster Faktor, der auf die Pollutogramme einwirkt, die Abflußmenge anzusehen ist.

ОПРЕДЕЛЕНИЕ КАЧЕСТВА ДОЖДЕВЫХ СТОЧНЫХ ВОД

Произведён обзор методов определения качества дождевых сточных вод под углом возможности их практического использования в Польше. Предложен простой метод определения поллутограммов и годового груза загрязненний дождевых сточных вод. Метод опирается на статически определённой связи между расходом массы загрязнений и объёмным расходом, временем с начала стока и веременем погоды без дождя. Предложен также способ определения поллутограммов в случае, когда можно оценить только максимальных расход. Произведена идентификация параметров на основе исследований, произведённых в Варшаве. Анализ экспериментальных данных из трёх водосборных площадей в Жешове показал, что наиболее статистически значащим параметром, влияющим на поллутограммы, является объёмный расход.