Heliyon 6 (2020) e05687

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Mathematical model for the duration of runoff formation determined from the road surface

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ARTICLE INFO

Keywords:
Civil engineering
Construction engineering
Safety engineering
Water treatment
Wastewater management
HIGHWAY
Rain
Runoff coefficient
Precipitation
Coverage
Slope
Runoff

ABSTRACT

Introduction: Many scientists were engaged in the problems of studying the runoff formation conditions from the water-intake basins area and studying the operation of rainwater drainage systems and its calculations. Among them: Alekseev M. I., Belov M. M., Dykarevskyi V. S., Kurganov A. M., Zhuk V. M., Tkachuk S. G., Salchuk V. L., Tkatchuk O. A., Shevchuk O. V., Dziopak J., James W., Horton R., Huber W., Mays L. W., Rossman L. A., Weitman D. [1–9] and others. The drainage systems calculation is implemented based on empirical or semi-empirical studies for pipes or open water bodies. Unlike the generally accepted conditions for the urban city areas drainage elements calculation, highways have the features of runoff and the formation of maximum runoff. Artificial surfaces of surface runoff are characterized by low water absorption, significant longitudinal and transverse slopes. According to State Building Norms DBN V.2.3–4:2015 «Highways. Part I. Design. Part II. Construction», the largest longitudinal slope for a category I road is 40 %, the carriageway transverse slope on straight sections is 25 %. In the world of engineering practice there is no single generally accepted approach to the construction of hydrographs of rainwater inflow to surface drainage structures. Therefore, the question remains open in terms of establishing the estimated rain duration and the surface runoff volume from the roads surface in particular.

Goal and problem: To explore and establish the main factors and their parameters for the surface runoff formation from road surfaces.

Research methods: In engineering practice, forecasting the estimated rain duration is defined as the time from its beginning to the time of collection by the drainage system. This research is based on the prediction method and analysis of the factors, which influence the effluents movement on the coating surface of the linear in the plan water-intake basins. Conducting research with the forecasted natural meteorological phenomenon and at the minimum estimated rain intensity values according to climatic conditions of Ukraine.

Results: The analysis of known methods for duration of surface runoff formation determining performed. For its determination, it is suggested to take into account the surface wetting duration and the influence of the viscous component of the friction force between the runoff layers. An analytical dependence for the surface runoff formation duration determining for highways with asphalt concrete pavement and variable longitudinal slope in the range from 0‰ to 30‰ is obtained. The influence of wastewater viscoelastic properties is determined. The influence of the calculated precipitation intensity on the surface runoff formation duration for linear water-intake basins is determined.

Conclusions: A mathematical model for determining the surface runoff formation duration for linear water-intake basin, namely highways, taking into account the estimated highway slope, the width of the carriageway, the estimated rainfall. A comparative analysis with existing methods is performed.

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https://doi.org/10.1016/j.heliyon.2020.e05687
Received 6 August 2020; Received in revised form 29 October 2020; Accepted 4 December 2020

1. Recent research and publications analysis

The work of Soviet and Ukrainian scientists is devoted to determining the rainwater flow, which enters the estimated cross section [1, 2, 3, 5, 10, 11, 12, 13, 14, 28, 29] as well as international research [6, 7, 8, 9, 15, 16, 17, 24, 25, 26, 27] etc.

According to Ukrainian norms in force State Building Norms DBN V.2.5–75:2013 «Sewerage. External networks and structures. Basic design statements», the time of surface concentration of rain runoff should be calculated or taken in settlements in the absence of intra-quarter closed rain networks, equal to 5–10 min, and in their presence - 3–5 min. The time of surface concentration recommended to be taken as 2–3 min when calculating the intra-quarter drainage network. The duration of surface runoff formation corresponds to its formation time and reaching the calculated cross section.

However, all research is limited to the empirical determination of the estimated rain runoff volume. Among the dependencies for the calculation of surface runoff formation time, the most famous is the Abramov-Chigorin formula [10]. It is obtained for rains with a decreasing power law of intensity change over time:

$$t_{con} = \left(\frac{1.5 \cdot n_m^{0.6} \cdot L_{con}^{0.6} \cdot 166.7^{0.5}}{Z_{mid}^{0.3} \cdot i_{п.кв}^{0.3} \cdot A^{0.5}}\right)^{1/(1-0.5n)}, \tag{1}$$

where

n_m – surface roughness coefficient of the runoff basin;

L_{con} – runoff basin length, m;

Z_{mid} – runoff basin surface coefficient;

$i_{п.кв}$ – runoff basin surface slope;

A, n – empirical coefficients describing the power law of rain intensity change ($q = A/t_n$) and depend on the region climatic features.

It is impractical to take into account the basin surface coefficient, which is actually decisive for the runoff coefficient, as well as the surface roughness coefficient when determining the flow rate. The introduction of the data characterizes the percentage of runoff retention, which does not reach the drainage elements. They give a generalized notion of the rain runoff amount that will decrease in general, rather than per unit time.

The Overton-Meadows formula is widely used in foreign engineering practice specifically to calculate the time of film flow formation [18]:

$$t_{con} = \frac{5.476 \cdot (n_1 \cdot L)^{0.8}}{P_2^{0.5} \cdot i^{0.4}}, \tag{2}$$

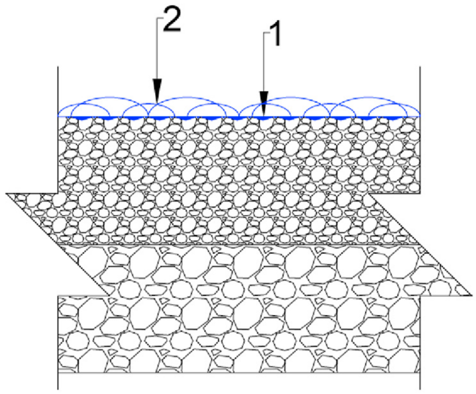
where

n_1 – effective surface roughness coefficient;

L – flow length, m;

P_2 –the precipitation layer height of 24-hour rain with a frequency of 2 years, mm;

i – geodetic slope of the area, m/m.



1 – roughness's filling; 2– contact surface wetting.

Figure 1. Components of the duration of surface runoff formation.

The engineering practice of Ukraine also uses the method, which is covered in [19] and Building Regulations SNiP 2.05.08–85 “Aerodromes”:

$$t_{con} = \left(\frac{2,41 \cdot n_* B_{роз}}{\Delta^{0,72} \Psi^{0,72} J_{роз}^{0,5}}\right)^{\frac{1}{1,72-0,72n}}, \tag{3}$$

where

n_* – roughness coefficient;

$B_{роз}$ – estimated width of the water-intake area, m;

Δ – parameter equal to the intensity of one-minute rain of the accepted recurrence, mm/min, and determined by the formula (5):

$$\Delta = \frac{20^n \cdot q_{20}(1 + ClgP)}{166,7}, \tag{4}$$

Ψ – runoff coefficient;

$J_{роз}$ – estimated slope of the water-intake area.

The one of the defining characteristics is the effect of coating roughness in all the formulas above. The study of rational duration determination of the surface runoff formation is performed in the work.

2. Presentation of the main research material

The duration of surface runoff formation depends on two parameters: the time spent on the surface wetting and the runoff duration on the wetted surface from the farthest point of the basin to the drainage channel:

$$t_{con} = t_{зМ} + t_{д}. \tag{5}$$

where,

$t_{зМ}$ – duration of the contact surface wetting;

$t_{д}$– duration of runoff on the wetted surface from the farthest point of the basin to the drainage channel.

To determine the surface runoff formation duration, consider how the runoff movement is formed. Before the beginning of the runoff movement on a covering, it is possible to allocate two stages: roughness's filling and contact surface wetting (Figure 1).

The measure of wetting of the surface is the equilibrium angle, which forms a drop with a solid surface. It is defined as the angle between the solid body surface and tangent at the contact point of the three phases (Figure 2).

Wetting solid surface with a liquid can be represented as a result of the action of surface tension forces. The wetting perimeter is the boundary of the interaction of three phases: solid (3), liquid (1), gas (2) [20].

A liquid better wets a solid surface when the adhesion forces between its molecules are smaller (cohesion) and the greater the adhesion forces to the solid body surface. The wetting criterion can be determined through the work of adhesion and the work of cohesion.

Consider the forces influencing the fluid at the time of movement on the coating (Figure 3). When the fluid moves on an inclined surface, it is affected by gravity, elastic force and friction force. According to Newton's second law, the equation of motion has the form (7):

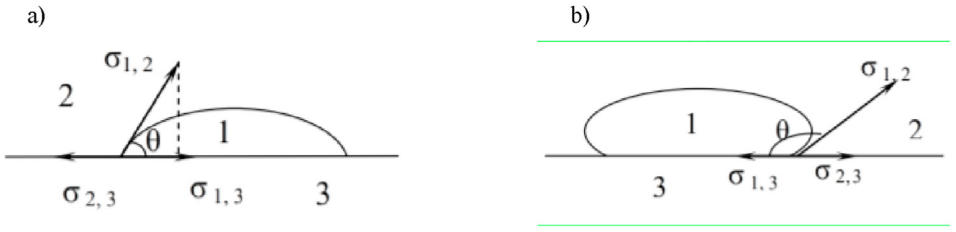
$$G + T + P = F, \tag{6}$$

where

G – gravity;

T – the viscosity of the liquid;

P – force of elasticity.



a – effective wetting; b – inefficient wetting

Figure 2. Wetting and contact angle.

The movement of the wastewater elementary volume occurs under the action of applied forces and forces of inertia. Then the differential equation of its motion has the form:

$$\rho\frac{\partial U}{\partial t}=\mu\frac{\partial^2 U}{\partial h^2}, \tag{7}$$

where,

ρ – fluid density;

U – elementary movement;

μ – dynamic viscosity coefficient of the liquid;

h – the liquid layer thickness.

If in the left part (7) for elementary (unit) volume, we have an analogue with the left part II of Newton's law:

$$m\cdot a=F, \tag{8}$$

where,

m – weight (liquid);

a – acceleration;then in the right part (7) there must be a force or tension (force acting per surface area unit of the elementary volume):

$$\tau=\mu\frac{\partial U}{\partial z}. \tag{9}$$

To determine the origin of the second-order derivative in the right-hand side of expression (7), consider the basic equations of Navier-Stokes hydrodynamics (10)–(12) and the condition of continuity (13) [21]:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=\rho X-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right), \tag{10}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=\rho Y-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right), \tag{11}$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=\rho Z-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right), \tag{12}$$

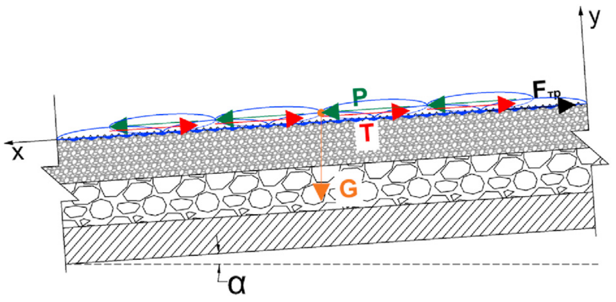


Figure 3. For the equation of the liquid motion on the surface determination.

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}+\frac{\partial u}{\partial z}=0. \tag{13}$$

where

ρ – fluid density;

X, Y, Z – external forces components,

p – pressure,

u, v, w – speed components.

Gravity and pressure change are neglected for viscous liquids [4], therefore:

$$X=Y=Z=0, \tag{14}$$

$$\frac{\partial p}{\partial x}=\frac{\partial p}{\partial y}=\frac{\partial p}{\partial z}=0. \tag{15}$$

In the case of fluid unsteady motion only along some direct, velocity will have a component only in the direction of this straight line. Taking its direction along the X-axis, and perpendicular to the Y-axis for

$$u=u(y,t), \tag{16}$$

get a simple differential equation:

$$\frac{\partial U}{\partial t}=\nu\frac{\partial^2 U}{\partial h^2}, \tag{17}$$

where V- kinematic viscosity coefficient

$$\nu=\frac{\mu}{\rho}. \tag{18}$$

The moment of rain runoff movement will occur at a certain amount of runoff on the surface. Thus, during the movement of surface runoff, the force of friction resistance is the force between the wetted surface and the runoff [21] (Figure 4).

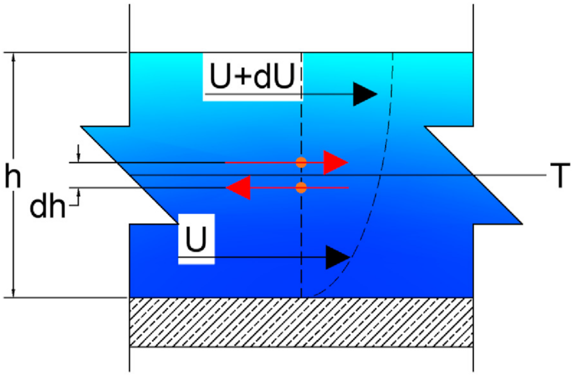


Figure 4. Scheme of fluid layers relative motion. T – shear resistance, viscosity, intramolecular interaction, which prevents movement between two layers of fluid; U – the liquid's lower layer speed; $U + dU$ – the liquid's upper layer speed.

The runoff layer changes over time, so the friction force between the fluid layers will look like this:

$$T = \mu \cdot S \cdot \frac{dl}{dt}, \tag{19}$$

where,

T – friction between layers of liquid;

μ - dynamic viscosity coefficient of the liquid;

l – displacement of the top layer of the liquid.

S – friction area.

Taking into account (18), the viscosity strength of the Newtonian fluid takes the form:

$$T = \rho \cdot \nu \cdot S \cdot \frac{dl}{dt}. \tag{20}$$

Horizontal component of gravity:

$$G = m \cdot sin\alpha \cdot \frac{d^2 l}{dt^2}. \tag{21}$$

Component of the elasticity force:

$$P = A \cdot l. \tag{22}$$

where, A – modulus of elasticity.

Substituting (20), (21) and (22) in (6) we obtain:

$$m \cdot sin\alpha \cdot \frac{d^2 l}{dt^2} + \rho \cdot \nu \cdot S \cdot \frac{dl}{dt} + A \cdot l = F, \tag{23}$$

F = const,

Given that the elementary volume of a liquid is taken into consideration, with the size ∂h and expressing the liquid density through the ratio of body weight to its volume, we obtain:

$$m \cdot sin\alpha \cdot \frac{d^2 l}{dt^2} + \frac{\nu \cdot m}{h} \cdot \frac{dl}{dt} + A \cdot l = F. \tag{24}$$

After the transformations, Eq. (24) takes the form:

$$\frac{d^2 l}{dt^2} + 2n \cdot \frac{dl}{dt} + k^2 l = F_1, \tag{25}$$

where

$$n = \frac{\nu}{2(h \cdot sin\alpha)}. \tag{26}$$

$$K = \sqrt{\frac{A}{m \cdot sin\alpha}}. \tag{27}$$

$$Q = \frac{F}{m \cdot sin\alpha}. \tag{28}$$

With the initial conditions:

$$l(0) = h_0, \frac{dl}{dt}(0) = V_0. \tag{29}$$

Eq. (25) is a linear inhomogeneous equation of the second order with constant coefficients. The general solution of this equation:

$$l = u + l_1, \tag{30}$$

where

u – general solution of a homogeneous differential equation;

l_1 – any partial solution of an inhomogeneous differential equation.

The general solution of the inhomogeneous equation has the form (30):

$$l = C_1 \cdot e^{r_1 t} + C_2 \cdot e^{r_2 t} + \frac{Q}{k^2}. \tag{31}$$

Constants C_1, C_2 are determined from the initial conditions (32):

$$C_1 = \frac{r_2\left(l_o - \frac{F_1}{k^2}\right) - V_0}{2w}, \tag{32}$$

$$C_2 = \frac{r_1\left(l_o - \frac{F_1}{k^2}\right) - V_0}{2w}. \tag{33}$$

Substitute the found values of C_1, C_2, form (32) and (33) into the general solution (31) and write the solution with the initial conditions (29):

$$l = \frac{r_2\left(l_o - \frac{F_1}{k^2}\right) - V_0}{2w} \cdot e^{r_1 t} + \frac{r_1\left(l_o - \frac{F_1}{k^2}\right) - V_0}{2w} \cdot e^{r_2 t} + \frac{Q}{k^2}. \tag{34}$$

At variable intensity of rain:

$$F = \alpha \cdot t, \tag{35}$$

where α – the coefficient of intensity change, which characterizes the runoff amount that makes the surface layer to move.

Taking into account (26), (27), (35) and after transformations, Eq. (24) can be represented as:

$$\frac{d^2 l}{dt^2} + 2n \cdot \frac{dl}{dt} + k^2 \cdot l = q \cdot t. \tag{36}$$

After transformations, we have a linear inhomogeneous differential equation of the second order with constant coefficients, where:

$$q = \frac{\alpha}{m}, \tag{37}$$

with such initial conditions:

$$l(0) = 0, \quad \frac{dl}{dt}(0) = 0. \tag{38}$$

The general solution of the linear inhomogeneous differential Eq. (36) will have the form:

$$l = u + l_1, \tag{39}$$

where

u – general solution of a homogeneous differential equation;

l_1 – any partial solution of an inhomogeneous differential equation.

The characteristic equation of the corresponding homogeneous Eq. (36) has the form (40):

$$r^2 + 2nr + k^2 = 0, \tag{40}$$

$$n^2 - k^2 \leq 0. \tag{41}$$

Since the water viscous properties are much smaller than the elastic ones, the solution of the homogeneous equation is a function:

$$u = e^{-nt}(C_3 cosw_1 t + C_4 sinw_1 t), \tag{42}$$

where C_3, C_4 – arbitrary constants, determined from the initial conditions (38);

The partial solution of the inhomogeneous differential equation has the form:

$$l_1 = \frac{q}{k^2} t - 2n \frac{q}{k^4} \tag{43}$$

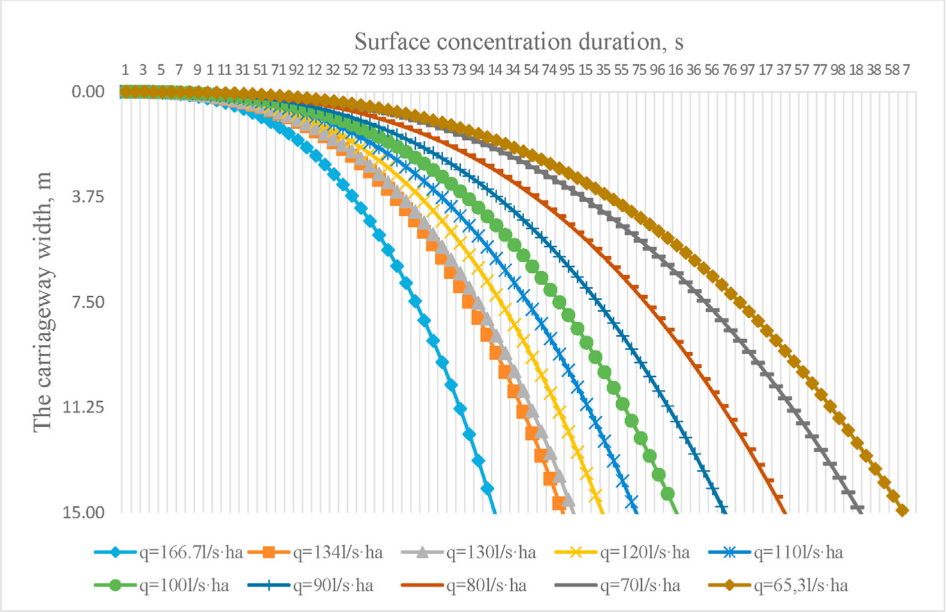
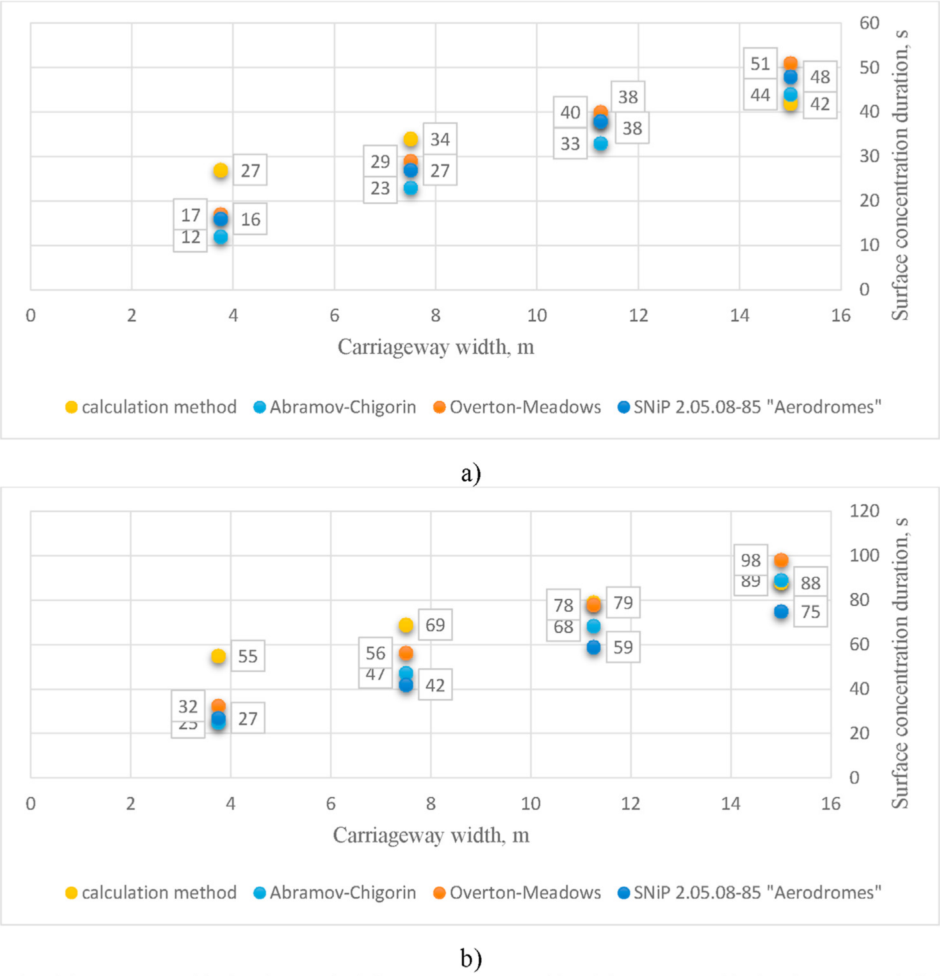
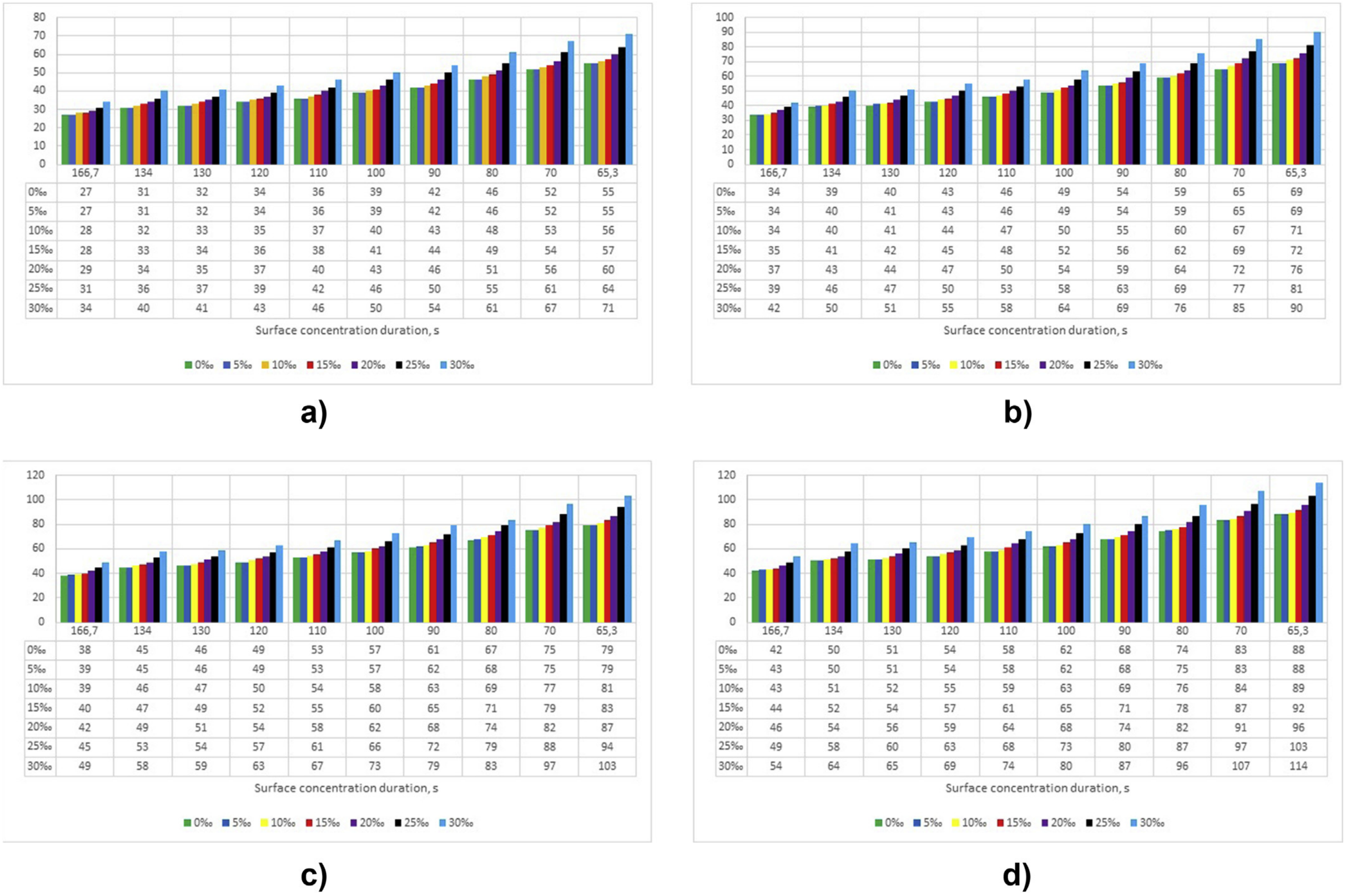


Figure 5. The surface runoff formation duration while the rain intensity changes.



a) with $q = 166{,}7$ l/s·ha (1 mm/min) b) with $q = 65{,}3$ l/s·ha (0,39 mm/min)

Figure 6. Calculation of t_{con} with different methods.



a)

	166,7	134	130	120	110	100	90	80	70	65,3
0‰	27	31	32	34	36	39	42	46	52	55
5‰	27	31	32	34	36	39	42	46	52	55
10‰	28	32	33	35	37	40	43	48	53	56
15‰	28	33	34	36	38	41	44	49	54	57
20‰	29	34	35	37	40	43	46	51	56	60
25‰	31	36	37	39	42	46	50	55	61	64
30‰	34	40	41	43	46	50	54	61	67	71

b)

	166,7	134	130	120	110	100	90	80	70	65,3
0‰	34	39	40	43	46	49	54	59	65	69
5‰	34	40	41	43	46	49	54	59	65	69
10‰	34	40	41	44	47	50	55	60	67	71
15‰	35	41	42	45	48	52	56	62	69	72
20‰	37	43	44	47	50	54	59	64	72	76
25‰	39	46	47	50	53	58	63	69	77	81
30‰	42	50	51	55	58	64	69	76	85	90

c)

	166,7	134	130	120	110	100	90	80	70	65,3
0‰	38	45	46	49	53	57	61	67	75	79
5‰	39	45	46	49	53	57	62	68	75	79
10‰	39	46	47	50	54	58	63	69	77	81
15‰	40	47	49	52	55	60	65	71	79	83
20‰	42	49	51	54	58	62	68	74	82	87
25‰	45	53	54	57	61	66	72	79	88	94
30‰	49	58	59	63	67	73	79	83	97	103

d)

	166,7	134	130	120	110	100	90	80	70	65,3
0‰	42	50	51	54	58	62	68	74	83	88
5‰	43	50	51	54	58	62	68	75	83	88
10‰	43	51	52	55	59	63	69	76	84	89
15‰	44	52	54	57	61	65	71	78	87	92
20‰	46	54	56	59	64	68	74	82	91	96
25‰	49	58	60	63	68	73	80	87	97	103
30‰	54	64	65	69	74	80	87	96	107	114

Figure 7. Dependence of t_{con} on q_{20} and longitudinal highway slope.

The general solution of the inhomogeneous differential equation will look like:

$$u = e^{-nt}(C_3 cosw_1 t + C_4 sinw_1 t) + \frac{q}{k^2}t - 2n\frac{q}{k^4}. \tag{44}$$

Constants C_3, C_4 can be found from the initial conditions (38):

$$C_3 = 2n \cdot \frac{q}{k^4}, \tag{45}$$

$$C_4 = \frac{V_0 + 2n^2 \cdot \frac{q}{k^4}}{w}, \tag{46}$$

where

$$w^2 = n^2 - k^2. \tag{47}$$

The partial solution of the inhomogeneous differential Eq. (36), which satisfies the initial conditions (38) has the form:

$$l = e^{-nt}\left(2n \cdot \frac{q}{k^4} cosw_1 t + \frac{V_0 + 2n^2 \cdot \frac{q}{k^4}}{w} sinw_1 t\right) + \frac{q}{k^2}t - 2n\frac{q}{k^4}. \tag{48}$$

where l – movement that carries the flow at the settlement area “b”.

Using formula (48), we plot a graph (Figure 5) of the change of the runoff elementary volume position over time at different calculated rainfall intensity and according to of State Building Norms DBN V.2.3–4:2015 requirements to the carriageway cross section.

We check the obtained results by comparing the calculated indicators of different methods with those obtained by us, using formulas (1, 2, 3 and 48) (Figure 6).

Significant influence on the results of calculations by formulas (1, 2, 3) have an indicator of the roughness of the coating and the slope of the site. As a result, at the initial stage we have inflated indicators of velocity - shorter duration of surface runoff formation. The results of calculations by formulas (1, 2, 3) have a linear relationship. In the calculations according to formula (48), the initial parameter of flow inhibition is friction of runoff with wetted surface, friction between liquids, which is present over the entire width of the catchment, and reducing the duration of surface runoff depends on rain intensity and length of the calculated area. The result of the calculation by formula (48) is characterized by a power dependence (Figure 5).

The dependences of the surface concentration duration on the precipitation intensity constructed taking into account the influence of the longitudinal profile [22]. The range of estimated rain intensity adopted according to State Building Norms DBN V.2.5–75:2013 “Sewerage. External networks and structures. The main statements of the design.”, and the calculated value of $q = 1$ mm/min $= 166.7$ l/s ha is taken into account on the condition of compliance [23] with the natural meteorological phenomenon when the rain lasts more than 30 min (Figure 7).

3. Conclusions

The analysis of the calculating methods for the surface runoff formation duration is carried out, the absence in the calculations of the parameter that characterizes the coating wetting and the runoff movement along it revealed.

A mathematical model for calculating the surface runoff formation duration from road pavement (48) with a water-intake area width of 3.75–15 m and longitudinal slopes 0–30‰ developed. Analytical studies of the effect of viscoelastic properties ratio of runoff water performed. A comparative analysis of the calculation model for calculating the surface runoff formation duration performed at the estimated values of 65.3 l/s ha and 166.7 l/s ha, which corresponds to the minimum regulated value of the estimated precipitation intensity in the regions of Ukraine and natural meteorological phenomena, respectively.

Declarations

Author contribution statement

Vladyslav Havryshchuk: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Volodymyr Kaskiv: Performed the experiments; Analyzed and interpreted the data.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

I would like to thank Kravchuk Andriy Mykhailovych, Doctor of Technical Sciences, Professor of the Department of Water Supply and Sewerage, Kyiv National University of Construction and Architecture.

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