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Calculation of losses from rainfall falling in the design of culverts and drainage systems on highways

In this article, the problem of calculating the loss of atmospheric precipitation to the earth surface in the design of culverts and drainage systems of objects on highways is analysed. To account for the initial losses in runoff due, it is proposed to use an index level of soil moisture, which takes into account the type of soil and the initial level of moisture. An equation for calculating the rain lost through runoff from rainfall and soil type that takes into account the land use and the initial moisture level is developed. The validation of the proposed equation shows that it can be used to determine the flow losses in the design of drainage systems on highways.

Introduction

In Ukraine, meteorological phenomena can occur year in any area and cover large areas. The most common of them is heavy rains, which in some cases are catastrophic and cause heavy losses. In spite of this in, especially in recent times, drainage systems that divert rainfall from the surfaces of streets and roads have been neglected our country. As a result, the number of cases of flooding in low places has dramatically increased, especially in urban areas. According to hydrological design, drainage systems are based on the calculation of the maximum flow of the integral hydrograph showing peaks and flood volumes. Design methods are generally based on assumptions that take into account the ratio of precipitation and runoff (Brockenbrough *et al*. 2003; Kang *et al*. 2009).

A number of various researches provides an evaluation of the model for culverts water drainage under the motorway on different parameters. An economic assessment for culverts is presented in the following research: Fragkakis *et al*. 2015; Perrin *et. al*. 2004. The model to evaluate water mains performance under the motorway is presented in the research of Delgado-Ramos *et al*. 2014. A risk management approach for safety assessment of culvert is presented in following articles (Syachrani *et al*. 2010; Najafi *et al*, 2011; Najafi *et al*. 2010).

In this article, the existing research and publications related to the problem of calculating the loss of atmospheric precipitation to the earth's surface in the design of culverts and drainage systems of objects on highways will be analysed.

To calculate the losses due to runoff, the following calculation tools will be used: runoff coefficient, equation infiltration, empirical relationships SCS (SCS 1975) and HEC-1 (Feldman 1995).

There are many analytical expressions that take into account the intensity of infiltration time. Most of them have exponential or power-law form.

On the basis of field observations, the US Department of Agriculture Soil Conservation Service obtained an empirical relation between the potential reserves of soil moisture, S, and the runoff curve number, CN. In accordance with this method, the depth of runoff according to the following equation is valid if $P > 0.2S$

and Q = 0 if P ≤ 0.2S:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad (1)$$

Where Q is the depth of runoff, P is the layer accumulated rainfall, I_a is the initial loss of rainfall, which is absent runoff until the moment when the accumulated rainfall does not exceed the value I_a (I_a = 0.2S), and S is the potential reserve of moisture in the soil.

$$S = 25.4 * \left(\frac{1000}{CN}\right) - 10 \quad (2)$$

At the same time, recent studies performed (Hawkins et al. 2002) to determine the ratio of Ia to S on the basis of numerous data on the amount of precipitation for a large number of pools in the United States shows that this ratio varies depending on rain and watershed, and that the assumed value of 0.2 exceeds the relations obtained for Ia to S in more than 90 percent of cases. Therefore, the author recommends a ratio of 0.05 as their estimation.

Some studies have attempted to relate the rainfall–runoff model's initial conditions to different external indicators of soil moisture as estimated using in situ, satellite and modelled data (Beck *et al*. 2009; Brocca *et al*. 2009a; Brocca *et al*. 2009b; Brocca *et al*. 2011; Coustau *et al*. 2012; Graeff *et al*. 2012; Tramblay *et al*. 2010; Tramblay *et al*. 2011; Tramblay *et al*. 2012). Many studies have investigated the relationship between soil moisture and runoff, and indirectly determined the potential benefit of analysing soil moisture conditions for rainfall–runoff modelling (e.g. Penna *et al*. 2011; Matgen *et al*. 2012; Graeff *et al*. 2012).

In a number of researches (Beck *et al*. 2009; Brocca *et al*. 2009a; Brocca *et al*. 2011) conducted rainfall–runoff modelling in Italy, Luxembourg and Australia to investigate the relationship between modelled and observed antecedent wetness conditions. A recent study (Massari 2014) introduced a simplified continuous rainfall–runoff model, which uses satellite soil moisture data to identify the initial wetness conditions of a catchment to simulate discharge hydrographs (Nekrep Matjaž 2002).

In Ukraine, the most common method of accounting for the absorption of the surface storm water runoff in the catchment area of the underlying soil used in road design are described in the work of Protodjakonova, Boldakova and others. Their presentation and classification of the soil and ground absorbance category formed the basis of the "Instruction on the calculation of runoff from small basins" (BCH 63-76 1976) and distinguished six kinds of soil category ground absorbance. Each type of soil has its own standard curve. To describe the process of forming a layer in the catchment runoff curve, stroke rain P = f (t) and loss absorption curve S = f (P) were united by the "touch". The total value of the loss of rainfall runoff, Q, can be expressed as the difference between precipitation, P, and runoff, S.

The analysis methods used to calculate the losses in runoff show that they have certain drawbacks. Therefore, it was proposed to determine the runoff coefficient by a number of empirical formulae, the accuracy of the results of which are in some cases in serious doubt (Panjen 1996).

The parameters and coefficients of the equations and empirical relationships to determine the infiltration of water into the soil are usually determined by field studies and depend on the nature of the soil. It should be noted that in solving engineering problems in most cases we do not have detailed information for determining the above parameters and ratios due to a lack of available data.

Experience generalisation of experimental data showed the suitability of the application as the coefficient of runoff due, infiltration equations and empirical relationships. Some preferences deserve empirical relationships, especially the method (SCS) of the US Department of Agriculture, as it allows the flow losses to be determined even in the absence of the water balance model or observational data for a more accurate water balance model.

From our point of view, the expressions for determining infiltration do not currently fully take into account the physical processes that occur during each phase during the development infiltration.

Therefore, the purpose of this work is to develop a more physically justified expression to determine the loss of rain runoff considering each phase of water infiltration into the soil.

Calculation of losses in runoff due

Influence of soil moisture on determining the losses in runoff due

One of the most important factors that influences the formation of rainfall runoff is the nature of the underlying surface, which determines the intensity of the surface retention and water infiltration into the soil. It is possible to distinguish four phases of infiltration *natural conditions* irrigation rain. As a result, the rain runoff loss value, S, can be considered as the sum of the losses at the absorption step and the filtration step.

There is a functional relationship between field moisture capacity (FM), total moisture capacity (TM) and the porosity of the soil, since the packing density and composition of the aggregate have a dominant effect on the field moisture capacity.

It is known that the natural moisture in the soil overlying the upper crust thickness is more or less constant, depending on its type. This allows us to obtain the relation between moisture capacity of natural moisture soil (MNM) and total moisture capacity (TM) (Table 1).

Table 1

Characteristics of the soil and the level of the index values of the soil moisture

Ground	ρ, kg / m^3	W, %	P, %	FM:TM, %	MNM:TM, %
Broken stone soil	1750	2	33.96	94.18	83.87
	1900	6	28.30	87.16	46.88
Gravelly soil	1700	2	35.85	95.18	85.69
	1900	8	28.30	87.16	33.45
Sand	1500	8	43.40	91.21	63.56

	1600	12	39.62	94.81	46.35
Sandy loam	1500	10	43.40	91.21	56.65
	1600	15	39.62	94.81	34.24
Clay	1500	20	43.40	91.21	22.08
	1600	30	39.62	94.81	0.00
Loam	1500	14	43.40	91.21	42.82
	1600	19	39.62	94.81	18.09
Topsoil	1200	20	54.72	65.01	21.15
	1300	25	50.94	75.61	11.82

Rainfall runoff from fallen rain depends on the moisture content in the soil obtained from previous rainfall. In this connection, the ratio between field moisture capacity (FM), total moisture capacity (TM), can be regarded as an indicator of the soil moisture to dry soil conditions and the ratio between the natural soil wetness humidity (MNM) and total moisture capacity (TM) as an indicator of humidity natural moisture of the soil.

Determination of the loss of rain from runoff equation

Consider the mechanism of runoff formation. The total amount of rain lost through runoff, S, can be expressed as the difference between precipitation, P, and runoff, Q, *i.e.* S = P - Q.

When filling the entire pore space of soil water for a certain period of time, an increase in the amount of rain lost through runoff will be observed. In other words:

$$S_{n+1} = S_n + S_n kn = S_n\left(1 + kn\right) \quad (3)$$

where S_n is the original amount of rain lost through runoff; S_{n+1} is the backfilled amount (initial amount, together with a gain) of rain lost through runoff; k is the coefficient of growth, expressed as a fraction of the period; and n is the number of compounding periods.

Then the formula takes the form of the formula for the calculation of compound interest:

$$S_{n+1} = S_n\left(1 + \frac{k}{n}\right)^{nt} \quad (4)$$

where t is the time accrual period (in this case equal to 1, since this is the period during which the value of the rain lost through runoff reaches the maximum possible amount of moisture retained in the soil at the appropriate humidity of the soil).

The result is the exponential growth of relations S_s/S and:

$$\frac{S_s}{S} = e^k \text{ or } \frac{S}{S_s} = e^{-k} \tag{5}$$

where S is the amount of rain lost through runoff; S_s is the maximum possible amount of moisture retained in the soil at the appropriate soil moisture level.

Equation (5) can be expressed as the total amount of rain lost through runoff in the absorption and filtration steps as the ratio:

$$S = S_s\left[1 - \exp\left\{\ln(0.5) - \left(\frac{P}{S_s}\right)\right\} - \exp\left\{\ln(0.5) - \left(\frac{P}{\exp\{-S_s\}}\right)\right\}\right] \tag{6}$$

The resulting expression displays infiltration as a process of filling the soil pore water and the simultaneous impact of water into the underlying layer, which takes into account the soil type, land use and its initial moisture level.

If the time accrual period is equal to one then the values of the intensity of infiltration losses are equal. As a result, the intensity of infiltration strongly (and nonlinearly) depends on the initial intensity of infiltration, rainfall intensity, and is given by:

$$q = f_0\left[1 - \exp\left\{\ln(0.5) - \left(\frac{i}{f_0}\right)\right\} - \exp\left\{\ln(0.5) - \left(\frac{i}{\exp\{-f_0\}}\right)\right\}\right] \tag{7}$$

where f_0 is the initial intensity of infiltration; and i is the intensity of the rain.

The initial infiltration rate ratio ($f_0 = S_s/t$) is the maximum possible amount of moisture retained in the soil at the appropriate soil moisture level, the period of time during which the value of the rain lost through runoff reaches the maximum possible amount of moisture.

The dependence of the rain lost through runoff from rainfall for different values of potential soil moisture reserves is represented graphically in Fig. 1.

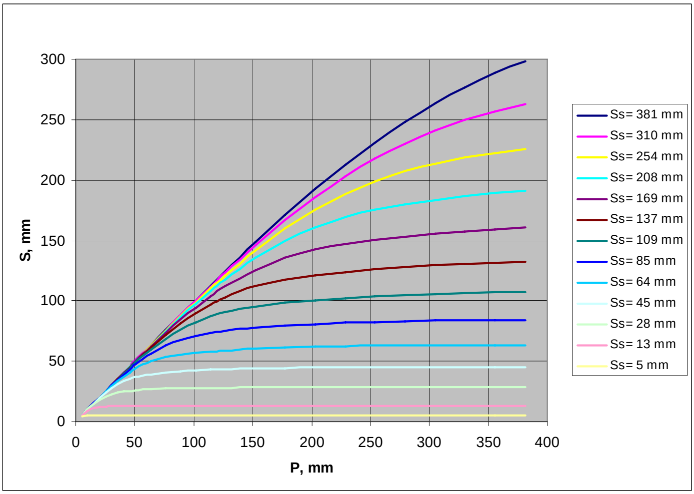

Fig. 1. Dependence of rain lost through runoff for different values of S_s (mm)

As can be seen from Fig. 1, a reduction in the level of soil moisture and an increase in the values of the potential supply of soil moisture increases the rain lost through runoff.

Check the validity of the equations

To check that the recommended equation (7) is satisfactory, laboratory determination of the rate of filtration of water in the soil was carried out. As a soil sample, we used sand with density 1600 kg/m^3 and a natural moisture content of 10%. As results of approximation of the data were determined for the equation parameters Horton and water absorption rate was calculated in the soil, depending on the time, see. Fig. 2.

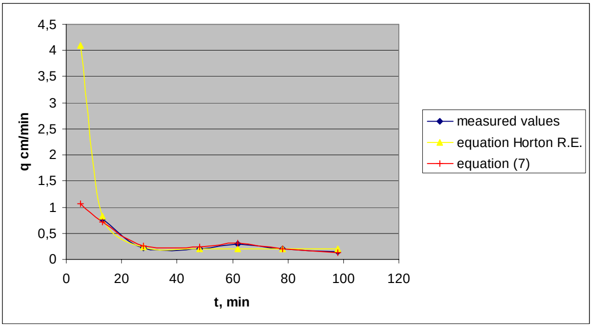

Fig. 2. The velocity of water absorption into the soil (q, cm / min) versus time (t, min)

Then, using the relation (7) is defined the value of the intensity of the infiltration, which allowed us to obtain the rate equation of the water to infiltrate a function of time.

As clearly illustrated in Fig. 2, the obtained dependence of the rate of water infiltration into the soil over time describes the process of absorption and filtration fairly well ($r^2 = 0.99$).

Validation of equations (6, 7) was carried out by comparison of theoretical and empirical data from a natural experiment in the Kurakhovo Donetsk region.

The experimental area is an open space with bare soil (loam) on which there is practically no vegetation.

During artificial sprinkling, the flow of water on the plot (precipitating layer of water) and the amount of runoff (loss flowing from the site) were determines.

Following the results of the processing of the results were obtained depending the layer runoff (Q, mm) on the value of of precipitation (P, mm) (see. Fig. 3) according to field measurements and calculated using the equation SCS and the equation (6).

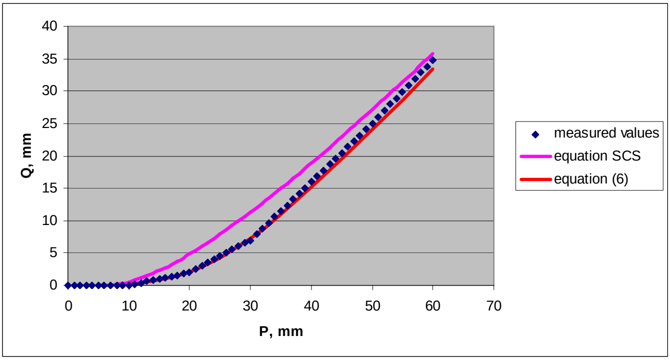

Fig. 3. The dependence of layer runoff (Q, mm) on the value rainfall (P, mm)

Comparison of these curves shows that the results of the calculations using the author's equation and the data from field measurements give very similar values with a correlation coefficient of 0.99. They are slightly different from the values of the SCS model, but if the SCS values are compared with the calculated values according to formula (6) or with the measurement data there is a correlation coefficient of 0.96.

A good approximation of the measured results by the author's data model and the SCS equation (6) (r^2 = 0.96–0.99) suggests that the resulting ratio can be used to determine the flow losses in the design of drainage systems on highways.

Conclusions

(1) Experience generalisation of experimental data provides expressions to determine flow losses in the form of the coefficients of runoff, infiltration equations or empirical relationships that do not fully take into account the physical processes that occur during each phase in the development of water infiltration into the soil.

(2) To take into account the initial loss of precipitation, it is proposed to use the index of the level of soil moisture, which takes into account the type of soil and the initial level of moisture.

(3) The resulting expression displays infiltration as a process of filling the soil pore water and the simultaneous impact of water into the underlying layer, which takes into account the soil type, land use and its initial moisture level.

(4) It is established that the loss values runoff are equal intensity infiltration into the ground if the accrual period is equal to one.

(5) A more realistic equation was developed, taking in to account the intensity of water infiltration into the soil, namely the intensity of rainfall and the potential value of soil moisture.

(6) The validation of equations (6, 7) suggests that the expressions obtained describe the process of absorption and filtration of water in the soil fairly well (r^2 = 0.99) and can be used to determine the runoff losses in the design of drainage systems on highways.

(7) In this work, a methodological model was developed for calculating the loss of precipitation to the earth's surface for further mathematical modelling of surface runoff.

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