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Peak rate of stormwater runoff from highways

by Dr J A Anderson

The aim of this paper is to show that an equation proposed by Swinnerton[9] for the peak rate of runoff from motorways cannot be justified and its validity for general application is open to question. It is shown that the peak rate of runoff from highway catchments would increase with increasing gradient to a power of about + 0.25.

Work carried out by Swinnerton on motorway stormwater drainage systems produced a formula for peak rate of runoff given by this equation

(1)

$$Q = 0.0034\, I_{15}^{0.998}\, IA^{-2.51}\, TA^{3.63} L^{-0.253}\, S^{-0.974}$$

where Q is the peak flowrate in ft^3/s
I_{15} is the maximum rainfall intensity of 15 minutes duration during the storm
IA is the impermeable area in acres
TA is the total area in acres
L is the length of catchment in feet
S is the average longitudinal slope of the catchment

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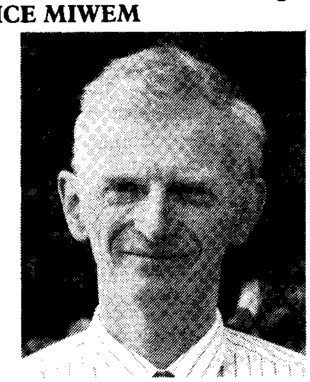

John Anderson is a principal lecturer in civil engineering in the Department of Civil Engineering and Building at Coventry Polytechnic. He graduated from Cambridge University in 1960 and joined Coventry City Engineer's department for a two year training period followed by a further two years working mainly on bridges and associated structures.

In 1964, he moved to the then Lanchester College of Technology and taught a variety of subjects including structures, water resources and public health engineering. His main interests are now in the areas of surface water drainage and public health engineering, and he has carried out consulting work on a wide range of topics.

Eight motorway sites were selected for monitoring: four on the M1 motorway, two on the M45 and two on the M6 motorway. Rainfall at each of the sites was recorded by tilting-syphon gauges and the runoff gauged by means of a standing wave flume in the outfall pipe. All the sites from which data was obtained were similar in character: impervious carriageways and hardshoulders, pervious verges and cutting slopes. The catchments ranged in length from 600 ft up to 2100 ft and in gross area from 0.36 acres to 6.5 acres, and pavements were of both asphalt and concrete construction. The data was collected during the period 1960-1965.

The dependence of the peak rate of runoff on various combinations of meteorological parameters and site characteristics was investigated by means of multiple linear regression analysis. The best result obtained was given by equation (1) hereafter call the Swinnerton equation, which explained 92% of the variance in the peak runoff. This equation was subsequently published in a paper entitled "A dimensionless hydrograph design method for motorway stormwater drainage systems" by Swinnerton et al[10] in 1972. In this paper, peak rates of runoff were estimated for the 12 short duration, high intensity storms recorded after the re-opening of several of the experimental sites in November 1969. The Swinnerton equation gave an average error in estimating the peak rate of runoff of approximately 20%. However it should be noted that ten out of the twelve storms occurred on two catchments on the M1 both with asphalt carriageways and with almost identical gradients of approximately 1 in 220.

The Swinnerton equation is quoted in at least one reputable textbook[7] dealing with highway drainage, and the associated hydrograph design method is described in two text books[7,8]. In both cases, there is no discussion on the effect of catchment slope on the peak rate of run off.

Historical development

Late in the last century, engineers developed empirical formulae to determine design discharges from storm drains[3]. For natural catchments many such formulae took the general form

(2)

$$Q = CAI\left(\frac{S}{A}\right)^{x}$$

where
Q is the peak discharge
C is a coefficient depending on climatic and physiographic conditions of the watershed
A is the drainage area
I is the average rainfall intensity
S in the slope of the drainage basin
x is an exponent which was usually between 0.25 and 0.50

For example, in the well-known Bürki-Ziegler formula[3], x = 0.25 giving

$$Q = CA^{0.75}\, I\, S^{0.25}$$

The C value varied from 0.20 for pervious rural areas to 0.75 for highly impervious built-up areas. About 100 empirical formulae have been collected by Chow[2]. Because of the development of other methods for runoff determination, use of such empirical formulae is not recommended in modern engineering design practice for urban stormwater runoff.

In 1962, Viessman and Geyer[11] proposed the following relationship

$$Q \propto A^{0.95}\, S^{0.17}$$

More recently, in the Flood Studies Report[5] for natural catchments in the British Isles the formula proposed for mean annual flood Q is given in terms of catchment and storm characteristics based on regression analysis as

$$\bar{Q} = C\ AREA^{0.94}\ STMFRQ^{0.27}\ SOIL^{1.23}\ RSMD^{1.03}\ S1085^{0.16}\ (1+LAKE)^{-0.85}$$

where
C is the regional coefficient
AREA is the area in square kilometres
STMFRQ is the stream frequency in junctions/km^2
SOIL is the soil index
RSMD is the net one day rainfall of five year return period
S1085 is the stream slope between 10% to 85% of main stream length
LAKE is the fraction of the catchment draining through a lake or reservoir

Written is simplified in terms, this equation becomes

(3)

$$\bar{Q} \propto A^{0.94} I^{1.03} S^{0.16}$$

It should be noted that the data for the Flood Studies Report is based on relatively large natural catchments.

Examination of the Swinnerton Formula

For simplicity, consider an impermeable rectangular area of length L and width B

then IA = TA = A say

and A = B x L

$$Q = 0.0034\, I_{15}^{0.998} A^{-2.51} A^{3.63} L^{-0.253} S^{-0.974}$$

$$\simeq 0.0034\, I_{15} \frac{A^{1.12}}{L^{0.25} S} = 0.0034\, I_{15} \frac{(BL)^{1.12}}{L^{0.25} S}$$

$$Q \simeq 0.0034 \frac{I_{15} A}{S} \left(\frac{B}{L}\right)^{1/8}$$

For a given rectangular shape

(4)

$$Q \propto \frac{I_{15} A}{S}$$

Comparing equation (4) with previous equations (3) and (2) shows good similarity for the powers of A and I, but exceedingly poor agreement for the power of slope S.

In the Flood Studies Report formula, see equation (3), S is to the power + 0.16, whereas in equation (4) the power of S in-1.0

ie Q is inversely proportional to the slope.

For example, consider a hypothetical catchment which could be tilted to either a 1% or 10% slope.

Based on the Flood Studies formulae;

$$\frac{Q \text{ for } 10 \text{percent slope}}{Q \text{ for } 1 \text{ percent slope}} = \left(\frac{10}{1}\right)^{0.16} = 1.45$$

Based on the Swinnerton equation;

$$\frac{Q \text{ for } 10 \text{ percent slope}}{Q \text{ for } 1 \text{ percent slope}} = \left(\frac{10}{1}\right)^{-1.0} = 0.1$$

The discrepancy between the two results is a factor of 14.5. Even though the Flood Studies formula is based on results for natural catchments, it does indicate that peak runoff would increase with increasing catchment gradient.

Other methods of design

Two other methods will be used:

(i) The Rational Method, and (ii) a more exact solution based on the dynamic equations of motion and continuity, for a particular highway drainage system[1].

The Rational Method

In Britain, the introduction of this method was attributed to Lloyd-Davies in 1906[4], and applied to storm water design calculations. The Rational Method is based on the understanding that the average rainfall intensity during a storm is inversely related to the storm duration, and to obtain the design peak runoff from a catchment the storm duration should be limited. In order to maximise the area contributing to the runoff, the storm duration is taken as being equal to the time of concentration T_c. The time of concentration is defined as the time taken for the flow from the furthest point to reach the point under design.

It is assumed that the rainfall intensity is constant during time T_c and the peak flow Q occurs at the time T_c.

Based on the continuity of flow the peak runoff can be written

$$Q = C\, I\, A$$

and is known as the Lloyd-Davies formula

where

A = catchment area upstream of the design point

I = average rate of rainfall during the time of concentration

C = coefficient of runoff dependent on catchment characteristics.

The units for flow rate in the Lloyd-Davies formula depend on the individual units of measurement for I and A.

Consider a single pipe of diameter D draining a catchment of impermeable area A and length L.

For simplification, ignore the time of entry to the pipe and assume that the rainfall intensity[6] can be written in the form

$$I = \frac{a}{b+T}$$

where

a and b are constants, T = storm duration. The peak flow is generated by a storm whose duration is equal to the time of concentration =

$$\frac{L}{V}$$

where

V = mean velocity of flow in the pipe flowing full.

Using Manning's formula

$$V = \frac{1}{n} R^{2/3} S^{1/2}$$

which is usually satisfactory for drainage design

where

n = coefficient of surface roughness

R = hydraulic radius (= D/4)

$$T = \frac{L}{V} = \frac{nL}{\left(\frac{D}{4}\right)^{2/3} S^{1/2}} = \frac{e}{D^{2/3} S^{1/2}}$$

where

e is a constant

$$\text{therefore } I = \frac{a}{b + \dfrac{e}{D^{2/3} S^{1/2}}}$$

(5)

$$\text{Peak flow} = AI = \frac{Aa}{b + \dfrac{e}{D^{2/3} S^{1/2}}}$$

As the slope S increases, the denominator reduces and therefore the peak flow increases.

Solution based on hydraulic computation

In a recent paper[1], the author considered the hydraulic design of road-edge surface channels of triangular cross-section. Rainfall intensities are based on the Bilham rainfall formula using a 50% summer profile storm[5] with a one year return period. Assuming instantaneous runoff into the channel, the following results were obtained for catchments of length 200m and 1000m each of 10m width.

Catchment 1 200m long by 10m wide

slope	peak flowrate
1%	53 l/s
10%	93 l/s

$$\left(\frac{10}{1}\right)^x = \frac{93}{53} = 1.75$$

hence $x = 0.24$

and $Q = 265\, A\, S^{0.24}$

where

Q = peak flowrate in litres per second

A = impermeable area in hectares

S = catchment slope in percent

Catchment 2 1000m long by 10m wide

slope	peak flowrate
1%	110 l/s
10%	208 l/s

$$\left(\frac{10}{1}\right)^x = \frac{208}{110} = 1.89$$

hence $x = 0.28$

and $Q = 110\, AS^{0.28}$

where, Q A and S are defined as for catchment 1.

Discussion of results

For a natural catchment, the Flood Studies report provides the relationship

$$\bar{Q} \propto A^{0.94} I^{1.03} S^{0.16}$$

which indicates that the peak annual flowrate would increase with catchment gradient to the power of approximately + 0.16.

For an impermeable catchment of a carriageway using results of a hydraulic computation, which ignores surface retention and any other losses

$$Q \propto A\, S^x$$

where x is of the order of + 0.25

The value of x in the Swinnerton formula is -1.0 and therefore cannot be supported on a rational basis. However in the concluding remarks of the paper by Swinnerton et al[10], because the coefficients in the Swinnerton equation were obtained using "best fit" statistics it is stated that "Engineers must therefore guard against attempting either to place a physical interpretation on the equation obtained or to extrapolate the equations greatly beyond the range of data from which they were derived". Unfortunately this caveat is not mentioned in later textbooks[7,8] which support the Swinnerton method.

Conclusions

On the basis of the Rational Method, and the more exact computational analysis, the peak runoff for a given impermeable highway catchment would be expected to increase with increasing gradient to a power in the region of + 0.25.

It is concluded that the use of the Swinnerton formula for peak flowrate may lead to inaccurate values, and therefore cannot be recommended for applications outside the scope of the original investigations.

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