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Estimation of mean annual flood in New Zealand

George A. Griffiths and Alistair I. McKerchar

NIWA, P.O. Box 8602, Christchurch, New Zealand. (Corresponding author: George.Griffiths@niwa.co.nz)

Abstract

The Rational Method of flood estimation is used in an exploratory study to calculate values of mean annual flood in New Zealand basins. To improve applicability of the method and accuracy of the results a power law formula for time of concentration as a function of length, slope and average Manning roughness coefficient of the main channel is derived. It is calibrated employing data from 25 basins with widely differing areas, rainfall intensities and catchment characteristics. The formula explains 88% of the variance between the logarithms of measured and predicted values. A table for calculating the value of the catchment factor (ratio of runoff to rainfall) is compiled which is also designed for use in New Zealand. Rainfall intensities with two-year return periods are determined using the HIRDS(V3) computer programme.

With these new estimators for time of concentration and catchment factor, application of the Rational Method to calculate mean annual flood yields a root mean square error (RMSE) of ±27% between measured and predicted values for the 25 basins.

Performance of the Rational Method is compared to that of the McKerchar-Pearson estimator for mean annual flood using data from a further 10 basins, giving RMSE values of ±34% and ±90% for the two approaches respectively.

While further testing, calibration and development of the formulae is required, particularly regarding the computation of catchment factor values, application is relatively simple and the Method should result in a substantial improvement in both the accuracy of estimates of mean annual flood and the reliability of use of the index flood technique in ungauged New Zealand basins.

Keywords

Mean annual flood: flood runoff: rational method: design flood: flood estimation: statistical hydrology

Introduction

A number of approaches are used in New Zealand to estimate design flood magnitudes in basins where little or no flow data are available. Examples include the Rational Method, which is often employed for urban flood design, and TM61 (National Water and Soil Conservation Organisation, 1975), commonly used in the design of small structures such as culverts and minor bridges in ungauged catchments up to 1000 km^2 in area (Griffiths and McKerchar, 2008). Mention should also be made of a stormwater runoff estimation method calibrated for use in rural and urban basins up to 12 km^2 in area within the Auckland Region (Auckland Regional Council, 1999).

For ungauged catchments of all sizes anywhere in the country, the only design flood estimation procedure available is the index flood method applied in New Zealand by Beable and McKerchar (1982) and McKerchar and Pearson (1989). This method has two parts: estimation of mean annual flood, Q_m, and estimation of dimensionless flood frequency growth curves. Of these, prediction of Q_m is much the less accurate part. (Even so, McKerchar and Macky (2001) showed for a small sample of six New Zealand basins that the index flood technique gave superior results compared with the Rational Method and TM61.) Accordingly, if the accuracy of the index flood approach is to be improved, then one approach is to improve estimation of Q_m. Historically, three attempts have been made to predict Q_m nationally in ungauged basins. Beable and McKerchar (1982) developed sets of regression equations for Q_m as a function of catchment parameters and rainfall intensity; Mosley (1979) used morphological reach and cross-section variables to estimate Q_m for 73 South Island rivers. Both methods had large standard errors. McKerchar and Pearson (1989) drew contour maps of the value of $Q_m/A^{0.8}$ (McKerchar-Pearson estimator) in which A is catchment area, employing data from 343 basins. This analysis reduced the standard error of Q_m compared to previous efforts and remains the best estimation method available.

With the advent of the computer model HIRDS(V3) (Thompson, 2002) rainfall intensity, I, throughout New Zealand is now better defined than in earlier important work by Tomlinson (1980), owing mainly to a significant increase in both the number of automatic rainfall recording stations and length of record.

Herein we propose to employ the theoretically and dimensionally correct Rational Method, given by the formula $Q = CIA$, where Q is flood peak discharge and C is a catchment factor defining the ratio of runoff to rainfall, to estimate Q_m. This method assumes that the return periods (RP) of I and Q are the same and that the critical duration for I is the time of concentration, t_c, defined as the time after commencement of rainfall excess when all portions of the drainage basin are contributing simultaneously to flow at the outlet (Pilgrim and Cordery, 1993).

The purpose of this paper is to explore whether this approach will improve the accuracy of estimation of Q_m and thus the index flood method.

The aim is to provide designers with an easy to use and more reliable tool to calculate the magnitude of mean annual flood in ungauged New Zealand catchments.

Theory

The model we adopt to estimate Q_m is a particular case of the Rational Method and is defined by

$$Q_m = 2.78 \times 10^{-3}\, C_m\, I_r\, A \qquad (1)$$

in which C_m (%) is the catchment factor corresponding to Q_m (m^3/s), I_r (mm/hr) is the 2-year return period rainfall intensity with a duration equal to t_c (hrs), and A has units of km^2. In Eq. 1 the theoretical return period of Q_m, which we adopt herein, is actually 2.33 years for the Generalised Extreme Value distributions fitted to New Zealand annual maximum flood peak data by McKerchar and Pearson (1989). (Note that the magnitude of Q_m at a site is estimated as the average of the annual maxima.) The difference in the two return periods as regards rainfall intensity usually gives rise to a difference in magnitude of the order of 10%, as the slope of the relevant magnitude versus return period curves is slight at these values and we accept it bearing in mind application of Eq. 1 as HIRDS(V3) lists only 2-yr, 5-yr and higher return periods. In what follows a formula for t_c is selected for calibration and a table is presented for choosing values of C_m.

Time of concentration

TM61 recommends use of three empirical formulae developed in the United States for calculating t_c in New Zealand. Auckland Regional Council (1999) gives the only formula calibrated for local conditions – in this case in the Auckland region. We prefer to adopt a formula of Henderson and Wooding (1964) because of its strong theoretical basis (involving kinematic wave theory) and after modification calibrate it for use nationally. Their formula, which considers rain of constant intensity falling on a steep impermeable surface, can be expressed as (Woolhiser and Liggett, 1967)

$$t_c = L_s^{0.6}\, n^{0.6} \ / I^{0.4}\, S^{0.3} \tag{2}$$

In applying Eq. 2 to natural basins we take L_s as the length of the main channel (from headwaters to site of interest), S as main channel average slope, and n as the average value of the Manning roughness coefficient for the main channel. Now, the presence of I in Eq. 2 is inconvenient, as its evaluation requires a duration to be specified. To eliminate I, we note that extreme rainfall intensity of a given return period is inversely proportional to the square root of the duration (Stedinger et al., 1993), that is

$$I \sim t_c^{-0.5} \tag{3}$$

where we have chosen a duration equal to t_c. Because the Rational Method assumes t_c to be the critical duration, we may substitute for I in Eq. 2 using Eq. 3 and thus arrive at the model

$$t_c > a\, L_s^b\, S^c\, n^d \tag{4}$$

where we have replaced the exponents in Eq. 2 by constants a, b, c, d to be evaluated using, for instance, log-linear regression techniques and New Zealand data.

Catchment factor

Turner (1960) produced a table for calculating catchment factor values that is used widely overseas in applications of the Rational Method (Laurenson, 1967). Here we adopt his categories, but to suit New Zealand conditions we have employed our knowledge of the behaviour of New Zealand catchments to modify the weights or scores assigned to some of the categories. Moreover, we have substituted descriptions of hydrological processes, particularly storage processes of various kinds, rather than list soil and vegetation types (Table 1). To use Table 1, you select a category and thus a score for each catchment characteristic and add up the resulting five numbers to obtain a value of C_m. The scores listed in Table 1 are default values; intermediate values may be assigned where detailed knowledge of basin behaviour is available.

Application

The formula for t_c (Eq. 4) is now calibrated and the performance of Eq. 1 for Q_m is tested using data from New Zealand rivers and streams. The predictive accuracy of our method (Eq. 1) is also tested and compared with that of McKerchar and Pearson (1989), which employs the McKerchar-Pearson estimator for Q_m.

Data selection

Twenty-five catchments of widely differing size and hydrologic, geologic and physiographic characteristics were selected from New Zealand areas ranging from Northland to Fiordland. Details of hydrological recording stations or sites, record length and hydrologic and basin properties are given in Table 2. Basin area was obtained from Walter (2000); Q_m was computed from flow records as the average of instantaneous, maximum annual flood peak discharges; L_s was measured from digital 1:50,000 scale topographic maps

Table 1 – Estimation of Catchment Factor, C_m, for use in Equation 1. Default values of C_m are bracketed. Intermediate values may be selected depending on knowledge of catchment behaviour.

Catchment characteristics	Runoff producing characteristics			
Rainfall intensity	(30) >30 mm/hr	(20) 21-30 mm/hr	(10) 11-20 mm/hr	(5) ≤ 10 mm/hr
Relief	(20) Very steep rugged country Channel slope >0.05	(5) Rugged hilly country Channel slope 0.01 – 0.05	(0) Rolling country Channel slope 0.004 – 0.009	(0) Relatively flat land Channel slope <0.004
Surface and subsurface storage	(25) Negligible depression/ detention/ subsurface storage	(15) Low depression/ detention/ subsurface storage. Well defined stream network	(5) Moderate depression/ detention/ subsurface storage	(0) Significant depression/ detention/ subsurface storage
Infiltration	(15) Negligible infiltration capacity. No effective vegetation cover. Rapid overland and subsurface flow	(10) Low rate of infiltration and high rate of overland and subsurface flow	(5) Moderate rate of infiltration and of overland and subsurface flow	(0) High rate of infiltration. Low rate of overland and subsurface flow
Vegetation	(10) No effective vegetation cover	(5) Low canopy/ interception/ litter storage	(5) Moderate canopy/ interception/litter storage	(0) Significant canopy/ interception/litter storage

(NZMS 260 series) and S was calculated using the equal area method (National Water and Soil Conservation Organisation, 1975). At least six hydrographs of smoothly rising floods with peak values near Q_m in magnitude were used to compute t_c – taken as the average of the times of rise of the hydrographs. The t_c values at a site were quite variable owing mainly, perhaps, to differing antecedent wetness and storage conditions and spatial and temporal characteristics of the relevant flood-generating storms. Estimation of spatially averaged n values was more subjective and often difficult and needs very careful consideration. We found the method given in Chow (1959, p 109), of summing n values corresponding to elements of channel roughness to give a composite value, to be a satisfactory approach. We supported this approach with information from ground and aerial photographs, Google Earth and the channel roughness estimation manual of Hicks and Mason (1998). Rainfall intensity was calculated for the measured values of t_c using HIRDS(V3) (available on the Internet at http://hirds.niwa.co.nz/) applied at the centroid of the relevant catchment.

Calibration and testing of formulae

The data listed in Table 2 were used to conduct a log-linear regression fit of Eq. 4, giving the result

$$t_c = 80.1 L_s^{0.624} \; S^{-0.215} n^{1.86} \qquad (5)$$

Table 2 – Hydrologic and physiographic characteristics of selected New Zealand basins and calculation of t_c and Q_m.

River and site name	Site Number (Walter, 2000)	Length of record yrs	Catchment area km² A	Main channel length km L_s	Main channel slope S	Manning coefficient n	Time of concentration (measured) hr t_c	Rainfall intensity (2 yr RP) mm/hr I	Mean annual flood (measured) m³/s Q_m	Catchment factor (Table 1) % C_m	Predicted tc (Eq. 5) hr	Predicted Qm (Eq. 1) m³/s
Maungaparerua at Tyrees Ford	3506	41	11.1	9.56	0.016	0.045	2.44	21.0	51.6	60	2.50	38.9
Orere at Br.	8604	32	40.8	18.6	0.012	0.030	1.63	19.4	59.4	30	1.90	66.0
Mangawhai at Omokoroa	13901	29	2.95	4.18	0.03	0.035	0.72	29.0	3.32	25	0.82	5.95
Waipaoa at Kanakania C/W	19716	35	1580	74.5	0.0033	0.045	10.0	6.6	1110	45	12.7	1305
Otane at Glendon	23209	46	24.3	10.2	0.006	0.050	3.20	11.4	11.4	20	3.93	15.4
Omakere at Fordale Rd	23210	47	54.4	21.5	0.005	0.065	10.8	6.8	54.6	45	10.6	46.3
Whareama at Nicholson Rd	25902	30	398	47.8	0.002	0.040	9.83	4.91	344	60	8.59	326
Whangaehu at Waihi	29244	43	36.3	17.5	0.004	0.050	4.14	7.95	27.3	25	5.99	20.1
Ohau at Rongomatane	32106	32	105	18.3	0.014	0.040	2.73	17.4	242	50	3.11	254
Whanganui at Te Porere	33347	42	28.2	16	0.037	0.050	1.62	19.2	31.8	30	3.51	45.2
Kai Iwi at Handley Rd	33502	32	192	44	0.0065	0.045	9.67	5.22	31.0	15	7.88	41.8
Punehu at Pihama	36001	39	29.5	31.4	0.031	0.045	3.52	13.9	39.6	40	4.56	45.6
Tahunaatara at Ohakuri Rd	1043428	43	210	37.3	0.0038	0.065	13.5	5.2	38.1	20	15.8	60.7
Te Tahi at Puketotara	1143427	29	3.11	6.19	0.05	0.035	1.23	20.0	3.46	20	0.94	3.46
Waitangi at SHBr.	43602	44	17.6	7.37	0.005	0.045	2.10	15.1	12.2	25	2.73	18.5
Waiwhiu at Dome Shadow	45702	43	8.03	6.56	0.017	0.040	1.82	21.5	30.8	55	1.57	26.4
Hunters at Weir	57022	31	5.02	5.51	0.04	0.050	2.40	10.0	2.28	20	1.77	2.79
Taylors at Borough Weir	60104	46	64.1	20.7	0.026	0.060	9.30	5.0	54.0	55	6.24	49.0
Stanton at cheddar Valley	64610	42	41.9	20.2	0.013	0.055	9.16	5.06	35.0	50	6.07	29.5
Avon at Gloucester St Br.	66602	28	38	14.1	0.001	0.040	6.27	5.3	17.9	35	4.65	19.6
Hukahuka at Lathams Br.	67602	23	12	5.59	0.073	0.085	3.83	8.1	8.19	30	4.22	8.11
Selwyn at Whitecliffs	68001	44	164	32.1	0.018	0.045	8.65	5.1	76.0	30	5.20	69.8
Nobles at Bull Creek Rd	74701	39	9.8	7.86	0.02	0.060	4.20	6.3	7.60	40	3.61	6.87
Spey at West Arm	79740	19	95.5	18.0	0.021	0.040	2.47	13.5	267	80	2.82	287
Arawata at County Br.	86301	19	971	76.1	0.006	0.040	9.80	12.0	2930	80	9.07	2591

with a correlation coefficient, r, of $r = 0.94$ (which explains 88% of the variance) and a standard error of the logarithms, SE (logs) of 0.135.

Again, using data listed in Table 2 with C_m values calculated using Table 1, the performance of Eq. 1 in predicting Q_m was assessed relative to measurements (Fig. 1). To quantify the performance of Eq. 1 the statistic

$$E = 100[Q_m(predicted) - Q_m(measured)]/Q_m(measured) \tag{6}$$

was calculated. The mean value of E is +10% and the root mean square error (RMSE) is ±27%.

Performance of formulae

To measure the performance of Eq. 1 compared to the McKerchar-Pearson estimator

$$Q_m = M_v A^{0.8} \tag{7}$$

where M_v is the areally weighted contour value for a given basin, a sample of 10 widely differing New Zealand catchments was selected (Table 3). None of the catchments in this sample was used in the analysis of McKerchar and Pearson (1989) nor in compiling Table 2. (It is of interest to note that M_v is proportional to the ratio of runoff to rainfall times a rainfall depth – see Appendix.) Figure 2 exhibits predicted versus observed values of Q_m for the basins of Table 3. For Eq. 7, E has a bias of +51% and a RMSE value of ±34%.

The performance of the Rational Method is clearly superior, which is not surprising given the inclusion of two additional and important contributing variables, namely I_r and C_m in the estimator for Q_m (Eq. 1). However, the RMS value is still substantial and could probably be further reduced as noted below. What on first view is surprising is that the Rational Method works quite well on larger basins, although the alternative rainfall-runoff approach, TM61 (Appendix), is employed in basins up to 1000 km^2 in area and only one basin in Table 1, Arawata, exceeds this size; the 24 remaining having a median area of 37 km^2. Similarly the median area of the basins in the test sample (Table 3) is 62 km^2.

The marked reduction in the RMSE achieved above by the Rational Method suggests that its use in the Index flood approach to flood estimation should significantly improve the accuracy of that approach.

Lastly, it is important to remember that stationarity of annual flood peak time series is assumed in the above analysis: predictions thus apply only to a climatic regime similar to the one for which the various formulae were calibrated. For recent developments on how, for instance, shifts in rainfall and flood regimes can be treated see Gray *et al.* (2005) and Ministry for the Environment (2008).

Future work

Refinement of the presented model (Eq. 1) by future workers is desirable in at least two areas. First, further testing of the model is needed using data from a much larger sample of basins for both the calibration of Eq. 4 for predicting t_c and evaluation of the performance of Eq. 1 for predicting Q_m. Second, following an approach taken originally by Horner and Flynt (1936) and termed the Probabilistic Rational Method (Pilgrim and Cordery, 1993), values of C_m could be calculated from measured values of I_r, A and Q_m, and presented as contours on topographic maps in similar fashion to the contours of $Q/A^{0.8}$ of McKerchar and Pearson (1989).

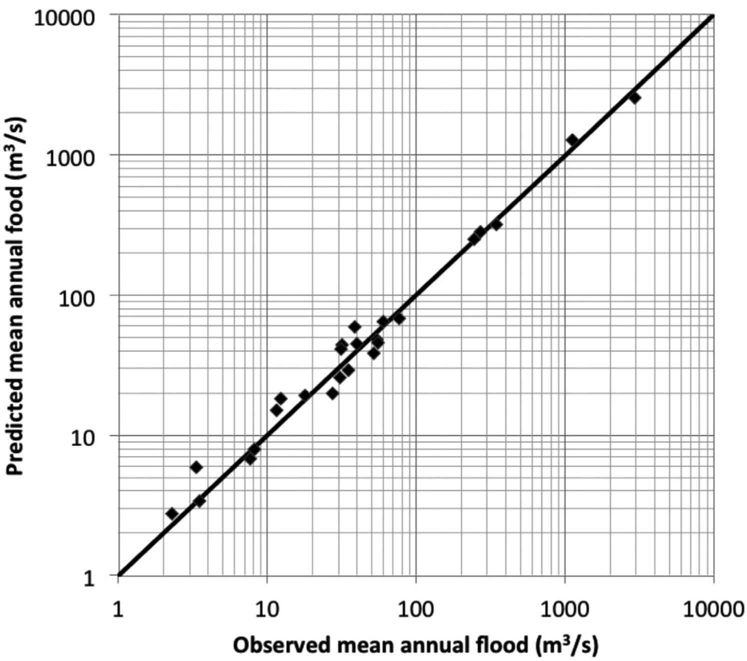

Figure 1 – Predicted values (Eq. 1) versus measured values of mean annual flood (Table 2).

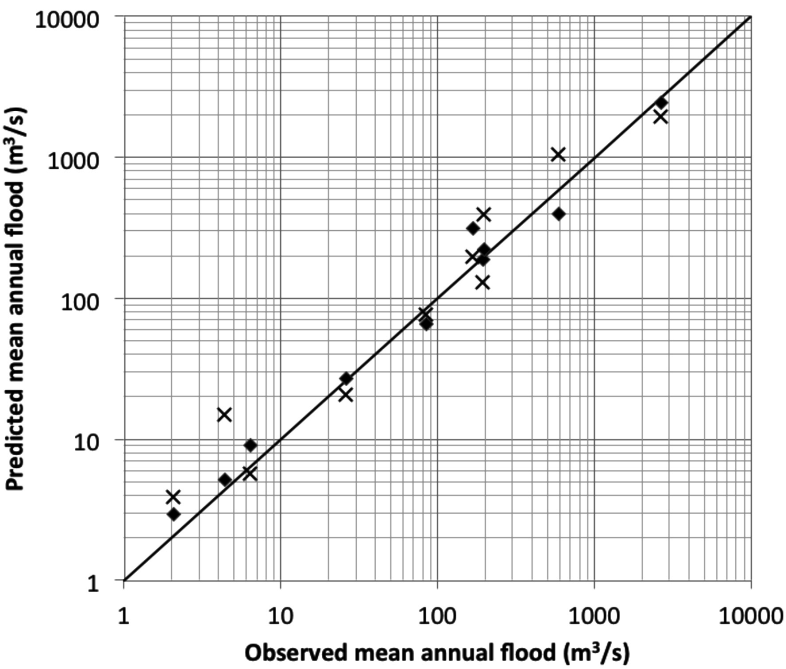

Figure 2 – Predicted values versus measured values of mean annual flood (Table 3). [Rational Method predictions (Eq. 1) are donated by (♦) and McKerchar-Pearson (Eq. 7) by (×).]

Table 3 – Hydrologic and physiographic characteristics of selected New Zealand basins used for comparing performance of Eq. 1 and the McKerchar-Pearson estimator (Eq. 7).

River and site name	Site Number (Walter, 2000)	Length record	Catchment area	Main channel length	Main channel slope	Manning coefficient	Time of concentration (Eq. 5)	Rainfall intensity (2 yr RP)	Mean annual flood (measured)	Catchment factor (Table 1)	Contour value for McKerchar-Pearson estimator	Mean annual flood predicted by Rational Method (Eq. 1)	Mean annual flood predicted by McKerchar-Pearson (Eq.7)
		yrs	km²	km			hr	mm/hr	m³/s	%		m³/s	m³/s
		N	A	L_s	S	n	t_c	I	Q_m	C_m	M_v		
Mangaheia at Willowbank	18913	32	40.3	14.9	0.016	0.035	2.06	15.0	83.9	40	4	75.6	77.0
McPhails at Waingake Rd	19779	27	3.98	3.62	0.015	0.035	0.86	19.0	4.34	25	5	5.26	15.1
Whenuakura at Nicholson Rd	34202	28	441	92.6	0.002	0.045	16.10	4.5	194	35	1	191	130
Otamakokore at Hossack Rd	2143401	24	40.1	16.0	0.007	0.055	5.96	8.3	6.39	10	0.3	9.25	5.75
Mangakahia at Titoki Br.	46626	24	798	83.2	0.002	0.04	12.10	6.1	591	30	5	474	1049
Awatere at Awapiri	60203	32	987	88.0	0.008	0.04	9.28	5.8	168	20	1.5	239	373
Heathcote at Buxton Tce	66612	21	63.9	9.8	0.015	0.045	2.56	7.8	25.9	20	0.75	27.5	20.9
Kakahu at Mitchells Weir No. 9	69633	30	2.75	3.2	0.091	0.05	1.05	13.0	2.06	30	1.75	2.98	3.93
Lyvia at Deep Cove	83201	22	59.5	14.4	0.068	0.06	4.03	17.1	196	80	15	226	394
Whataroa at SHB	89301	25	445	28.3	0.033	0.055	6.10	25.0	2650	80	15	2474	1971

Conclusions

The Rational Method may be usefully applied to estimate mean annual flood in ungauged catchments within New Zealand because for a sample of 25 diverse basins the bias between predicted and calculated values is 10% and the RMSE is ±27%.

The method depends on estimation of time of concentration; the derived formula for this variable, calibrated for New Zealand conditions, explains 88% of the variance amongst the logarithms of 25 measured values.

A table for reckoning the value of the catchment factor compiled for application to New Zealand basins should considerably reduce the subjectivity in selecting the relevant value.

An independent performance test, employing data from 10 catchments, shows that the Rational Method approach is more accurate than the McKerchar-Pearson estimator in predicting mean annual flood. Compared with the latter estimator bias is reduced by a factor of 3.6 and RMSE by a factor of 2.6.

Further testing of the proposed prediction method is needed using a much larger sample of catchments to refine estimation of catchment factor, time of concentration and thus mean annual flood. Nevertheless, the easy to use technique should significantly improve the accuracy of flood estimation in ungauged New Zealand basins employing the index flood approach.

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Appendix: Relationship between Rational Method and TM61

The TM61 formula (National Water and Soil Conservation Organisation, 1975: Griffiths and McKerchar, 2008) is

$$Q = kC_f \; R \; S_h \; A^{0.75} \qquad \text{(A1)}$$

where k is a constant whose value depends upon units employed and C_f is a co-efficient which depends on the physiography of a catchment; R and S_h are rainfall and catchment shape factors respectively. Now, $S_h = A/L^2$ where L is the direct length from the farthest point of the catchment to the outlet. From log-linear regression of the data in Table 1 we find that $L_s \sim A^{0.480}$ so we can take $S_h = 1$ as a good approximation. Moreover, R is a rainfall depth times a constant for given t_c, so we may write

$$R = It_c \qquad \text{(A2)}$$

Substitution for t_c in Eq. A2 using Eq. 5 and combination with Eq. A1 yields, with $S_h = 1$

$$Q = k \, C_r \, I \, L_s^{0.624} \, S^{-0.215} \, n^{1.86} \, A^{0.75} \qquad \text{(A3)}$$

and with $L_s \sim A^{0.5}$ Eq. A3 becomes

$$Q = (k \, C_f \, S^{-0.215} \, n^{1.86}) \, I \, A^{1.10} \qquad \text{(A4)}$$

which is very close to the Rational Method formula, $Q = C \, I \, A$, if $C = kC_f \, S^{-0.215} \, n^{1.86}$, that is if the ratio of runoff to rainfall adopted is the same.

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