The rational method revisited

ALAN A. SMITH
Department of Civil Engineering, McMaster University, Hamilton, Ont., Canada L8S 4L7

AND

KEN-BECK LEE
Engineering Department, District of Surrey, 14245-56th Avenue, Surrey, B.C., Canada V3W 1J2

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Despite the increasing availability of more-sophisticated methods for simulating rainfall–runoff events, the 'rational method' continues to be used as a design tool in many municipal engineering offices. This paper examines the basic assumptions of the method and shows how hydrographs from impervious areas can be accurately simulated by a simple convolution process using the rectangular response function implied in the rational method. The use of the dynamically varying response function appears to give improved results. Moreover, in the example illustrated, routing of the runoff through a hypothetical reservoir appears to be unnecessary.

For pervious areas, a method is suggested whereby the runoff coefficient is varied as a function of the time-dependent storage potential in the soil. For events with modest rainfall abstractions, the method appears to give good agreement with observed runoff hydrographs, but inclusion of a routing process through a cascade of reservoirs seems to be necessary in this case.

Key words: computer, design, hydrology, rainfall, rational, runoff.

Malgré la disponibilité croissante de méthodes plus sophistiquées pour simuler les épisodes pluie–ruissellement, la méthode rationnelle est toujours utilisée comme outil de design par plusieurs municipalités. L'article examine les hypothèses fondamentales de la méthode et montre comment des hydrogrammes de section imperméable peuvent être simulés avec précision par une convolution simple utilisant la fonction de réponse rectangulaire qu'implique la méthode rationnelle. L'utilisation d'une fonction de réponse variable dans le temps semble améliorer les résultats. De plus, dans l'exemple montré, le laminage du ruissellement par un réservoir hypothétique ne paraît pas nécessaire.

Pour les aires perméables, une méthode est suggérée dans laquelle le coefficient de ruissellement est modifiée en fonction de la variation temporelle du potentiel d'emmagasinage du sol. Pour des épisodes de précipitation dont les pertes sont faibles, la méthode semble en accord avec des hydrogrammes observés mais l'inclusion d'un laminage du ruissellement par une cascade de réservoirs semble requise.

Mots clés: ordinateur, design, hydrologie, pluie, méthode rationnelle, ruissellement.

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1. Introduction

Analysis and design of storm water drainage systems frequently relies on event simulation that approximates the rainfall–runoff process. Simulation is achieved by means of a mathematical model, the complexity of which may range from the simplest rule-of-thumb approach to sophisticated algorithms requiring substantial data to be implemented. The engineer must exercise considerable judgement in selecting the level of complexity appropriate to a specific problem. As the complexity of the model increases, the risk of not representing the system is reduced but the difficulty of obtaining a solution is increased. (See discussion by Overton and Meadows (1976, Chapt. 1).)

The 'rational method' represents the extreme end of the spectrum in terms of simplicity and has been in use for over a century, having been introduced to North America by Kuichling (1889). The method is 'rational' in the sense that it relates runoff per unit area to the rainfall intensity as opposed to purely empirical techniques, which attempt to correlate peak discharge to basin characteristics.

Frequent criticisms of the rational formula are (1) that it is too sensitive to the subjective choice of runoff coefficient C; (2) that it assumes a constant rainfall intensity; and (3) that at best, it provides only a peak discharge rather than a runoff hydrograph, which is essential for storage detention or water quality considerations.

A review of the assumptions underlying the rational method and its use is helpful in that it allows some relaxation of the limiting restrictions and provides a means of improving the method. An 'upgraded' rational method could be of value to engineers in that it provides a valuable basis for design as distinct from analysis or simulation, which usually requires the drainage system to be 'guestimated' in advance. Secondly, the method still finds much favour with engineers who have a practical idea of the magnitude of runoff coefficient to be expected.

2. Basic assumptions

The following assumptions are made in the rational method:

1. A rainfall event is represented as an average uniform intensity over the entire rainfall duration.

2. The rainfall−runoff characteristics of the catchment are homogeneous and given by the coefficient C, which is, moreover, constant with respect to time.

3. The rate of change of the contributing area is constant so that the accumulated tributary area increases and decreases linearly and symmetrically with time.

Under the first assumption, a typical equation for the average rainfall intensity may be expressed as

$$[1] \qquad i = a/(t_r + b)^c$$

where i = average intensity (mm/h or in./h), t_r = storm duration (h or min), and a, b, and c are coefficients dependent on the geographical location of the basin, on the units used, and on the probability of occurrence of the storm.

Further, under the second assumption, the effective rainfall becomes uniform and constant over the entire rainfall duration, and can be expressed as

$$[2] \qquad i_{\text{eff}} = C \cdot i$$

where C is the runoff coefficient.

The third assumption (linear change of contributing area) implies a response function of rectangular shape, i.e.,

$$[3] \qquad u(t) = \mathrm{d}A/\mathrm{d}t = A/t_c$$

It follows that the resultant outflow hydrographs will be of triangular or trapezoidal shape and symmetrical as shown in Fig. 1. Chien and Saigal (1974) use a similar approach although an error in their case 3 (i.e. when $t_r < t_c$) was reported by Walesh (1975).

The resultant outflow hydrograph can be expressed by a simple convolution, viz.,

$$[4] \qquad Q(t) = \int_0^{t \leq \min(t_c, t_r)} i_{\text{eff}}(\tau) \cdot u(t - \tau) \cdot \mathrm{d}\tau$$

where τ is the time with respect to which the integration is carried out.

For $i_{\text{eff}}(\tau)$ = constant = $C \cdot i$ this results in the convolution of two rectangular functions, so that

$$[5] \qquad \begin{aligned} Q_{\text{peak}} &= C \cdot i \cdot A && \text{at } t = t_c \text{ for } t_r \geq t_c \\ &= C \cdot i \cdot A(t_r/t_c) && \text{at } t = t_r \text{ for } t_r < t_c \end{aligned}$$

2.1 Criterion for maximum discharge

Based on these three assumptions, the peak discharge will be a maximum if the storm duration t_r is selected

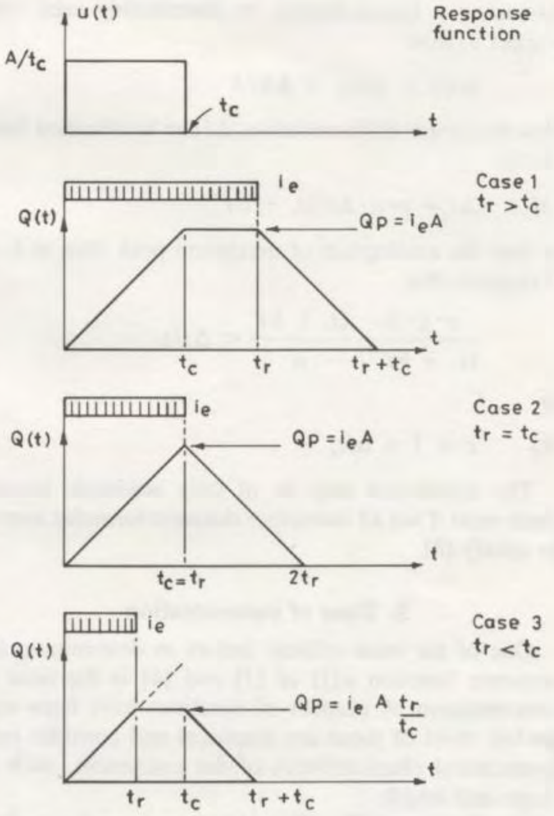

FIG. 1. Hydrographs produced by rectangular response function and constant effective rainfall intensity of different durations.

to be the same as the time of concentration of the catchment t_c. The validity of this assumption may be tested as follows, considering in turn the two cases of $t_r > t_c$ and $t_r < t_c$.

Case a: $t_r > t_c$

The rainfall intensity i given by [1] will be reduced but the tributary area A cannot be exceeded. Thus the peak flow will be reduced.

Case b: $t_r < t_c$

Assume that the contributing area is reduced by ΔA and the average rainfall intensity is increased by Δi. The increase in peak runoff is then given by

$$[6] \qquad \begin{aligned} \Delta Q &= (A - \Delta A)(i + \Delta i) - Ai \\ &= -\Delta A \cdot i + A \cdot \Delta i - \Delta A \cdot \Delta i \end{aligned}$$

The requirement for the peak flow to be a maximum when $t_r = t_c$ is that $\Delta Q < 0$, which, neglecting second order terms, is that

$$A \cdot \Delta i < \Delta A \cdot i$$

or

$$\Delta i / i < \Delta A / A$$

Assuming a linear change in contributing area with respect to time

$$\Delta i/i < \Delta t/t_c = \Delta A/A$$

Now by simple differentiation, Δi can be obtained from [1] as

$$[7] \quad \Delta i = c \cdot a \cdot \Delta t/(t_r + b)^{c+1}$$

so that the assumption of maximum peak flow at $t_r = t_c$ requires that

$$\frac{c \cdot a \cdot \Delta t}{(t_r + b)^{c+1}} \frac{(t_r + b)^c}{a} < \Delta t/t_c$$

or

$$[8] \quad c < 1 + b/t_c$$

The conclusion may be of only academic interest since most if not all intensity−duration formulae appear to satisfy [8].

3. Time of concentration

One of the most critical factors in determining the response function $u(t)$ of [3] and [4] is the time of concentration. A number of equations have been suggested; most of these are empirical and consider only geometrical characteristics of the catchment, such as slope and length.

Henderson and Wooding (1964) presented a method based on the kinematic wave whereby the time to equilibrium can be predicted in terms of the catchment length, the stage−discharge equation, and the intensity of the effective rainfall. Using the Manning flow resistance equation the stage−discharge relationship for sheet flow can be expressed as follows:

$$[9] \quad q = \frac{M^{1/3}}{n} y^{5/3} s^{1/2}$$

where q = discharge per unit breadth (length^2/s), n = Manning coefficient (length$^{-1/3} \cdot$s), y = depth of flow (length), s = energy or bed gradient, and M = length units per metre (e.g. $M = 3.28$ if length is in feet).

Differentiation of [9] yields an expression for the wave velocity $v_w = dq/dy = dx/dt$, which can be combined with the rate of rainfall accumulation $dy/dt = i_{eff}$ to give an equation that an integration enables the time to equilibrium or time of concentration to be found as shown in [10]:

$$[10] \quad t_c = t_{equ} = \frac{1}{M^{0.2}} \frac{(L \cdot n)^{0.6}}{s^{0.3} i^{0.4}} \text{ (s)}$$

where L = flow length of the catchment.

Further details of the development of [10] can be found in the original reference by Henderson and Wooding (1964).

Equation [10] is more usually written in the form

$$[11] \quad t_{equ} = \frac{kL^{0.6} n^{0.6}}{s^{0.3} i^{0.4}} \text{ (min)}$$

where the coefficient k takes a value dependent on the units employed. For example, $k = 0.939$ for L in ft, i in in./h; or $k = 6.989$ for L in m, i in mm/h.

4. A dynamic response function

Having decided on a method for finding the time of concentration (or time to equilibrium), the next problem is the choice of effective rainfall intensity that should be used in [11]. For nonuniform effective rainfall hyetographs, two approaches are possible:

1. The average effective rainfall intensity may be found over the duration of the effective rainfall.
2. A variable response function may be used in which the time of equilibrium is recalculated for each value of effective rainfall intensity.

The second method is reasonable in situations in which $(t_c/t_r) \ll 1$ and may be implemented as shown in the following algorithm.

4.1 Algorithm

1. Define the catchment as an equivalent rectangular plane in terms of area A, flow length L, and vertical drop H.
2. Define Manning's n.
3. Select the time step dt.
4. Set up and zero the array $Q(k)$, $k = 1, 2, \ldots,$ NQ to hold the accumulated contributions to the runoff hydrograph.
5. Set hyetograph counter $j = 1$, ($j = 1, 2, \ldots,$ NR).
6. Read the effective rainfall intensity $i_{eff}(j)$ and calculate the corresponding time of concentration $t_c(j)$ by [11].
7. Express the time of concentration $t_c(j)$ in terms of time step dt, i.e., $n = \text{INT}(t_c/dt) + 1$.
8. Accumulate contributions to the flow hydrograph elements.

$$Q(k) = Q(k) + i_{eff}(j) \cdot A \cdot dt/t_c(j), \quad k = j \text{ to } j + n - 1$$

$$Q(k) = Q(k) + i_{eff}(j) \cdot A \cdot (t_c(j) - (n-1)dt)/t_c(j), \quad k = j + n$$

9. Increment $j = j + 1$; if $j \leq$ NR go to step 6.
10. Output array Q correcting for units if necessary.

The calculation in step 8 is equivalent to the convolution process simplified for the case of constant effective rainfall $i(j)$ and response function given by A/t_c. A slight correction is required in the last time step if the duration of rainfall is not an exact multiple of the time step dt.

5. The C coefficient

One of the major criticisms of the rational method is the difficulty of accurately selecting a value for the runoff coefficient C. The single coefficient can only approximate the various abstractions due to interception, depression storage, and infiltration. In particular, observation of rainfall−runoff events or the examination of other infiltration models suggests that runoff coefficient must depend not only on the catchment but also on the antecedent conditions of the soil and the intensity of the rainfall. Moreover, it seems clear that, for a specific rainfall event, the runoff coefficient is initially small and increases as depression storage and potential storage in the soil is filled. Hoad (reported by Fair *et al*. (1971)) suggested empirical curves whereby C increases with elapsed time from the start of rainfall. Thus, according to Hoad,

[12] $C = t/(t + 8)$, impervious areas
$C = 0.5t/(t + 15)$, 'improved pervious' areas

where t is the elapsed time in minutes.

More recently, one of the authors (Lee 1980) generalized Hoad's equation using two parameters, i.e., ultimate runoff coefficient C_∞ and 60 min runoff coefficient C_{60}:

[13] $$C(t) = \frac{t}{\dfrac{60}{C_{60}} - \dfrac{60}{C_\infty} + \dfrac{t}{C_\infty}}$$

For example, assuming $C_\infty = 1.0$ and $C_{60} = 0.6$ for typical impervious areas, the runoff coefficient C can be expressed by

[13a] $$C(t) = \frac{t}{40 + t}$$

Assuming $C_\infty = 0.8$ and $C_{60} = 0.3$ for typical pervious areas, the runoff coefficient equation becomes

[13b] $$C(t) = \frac{t}{125 + 1.25t}$$

The above equations have been used to simulate rainfall−runoff events monitored in Surrey, British Columbia, Canada. The results of the simulation were very satisfactory (Lee *et al*. 1985).

Other empirical tables and curves are in use by some municipalities in Canada to reflect the fact that C is dependent on the magnitude of the rainfall and varies throughout the storm.

5.1 Limits on C

Most popular infiltration models attempt to relate the infiltration capacity to the amount of potential storage remaining in the soil. Holtan's model (Holtan 1965), the SCS method (Soil Conservation Service 1975), and the 'moving curve' application of Horton's equation (Horton 1933) all attempt to model the degree of saturation of the soil and to relate infiltration capacity inversely to this.

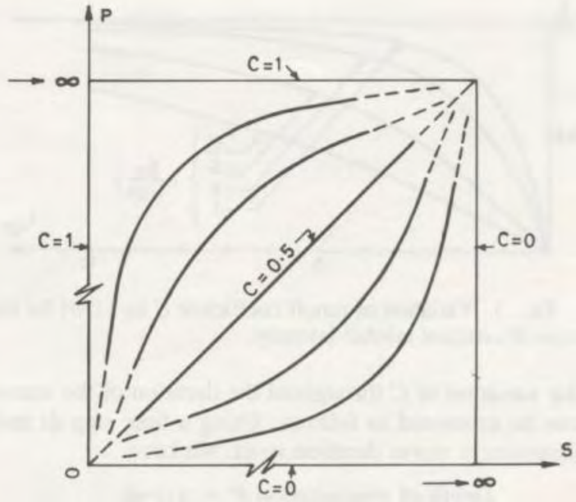

FIG. 2. Intuitive relation between runoff coefficient C, accumulated precipitation depth P, and potential storage depth S.

A similar approach can be used to describe the variation of C during a rainfall event. Defining P as the accumulated depth of rainfall at any time and S as the potential storage depth remaining in the soil at any time, certain limiting conditions can be intuitively applied to the runoff coefficient C during the progress of a rainstorm:

1. $C \cong 0$ when $P \cong 0$, $S > 0$ (i.e. at $t = 0$)
2. $C \to 1.0$ as $P \to \infty$, $S > 0$ (i.e. at $t \to \infty$)
3. $C \to 0.0$ as $S \to \infty$, all P
4. $C \to 1.0$ as $S \to 0.0$, all P

Qualitative description of the relation

[14] $C = f(P,S)$

may follow the general lines indicated in Fig. 2. For finite values of P and S, one of the simplest functional forms that describes such a diagram is given as follows:

[15] $C = (P - k_1)/(P + k_2 \cdot S)$

or more simply (setting $k_1 = 0$, $k_2 = 1$),

[15a] $C = P/(P + S)$

where C, P, and S are all time-dependent values.

5.2 Variation under constant rainfall

For the special case of constant rainfall intensity i,

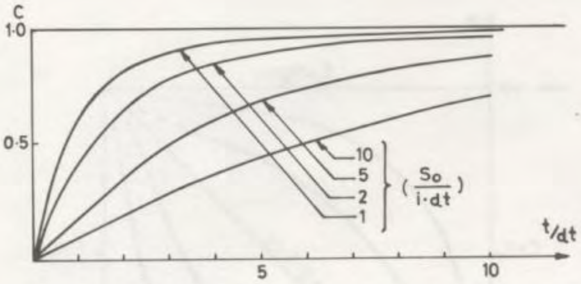

FIG. 3. Variation of runoff coefficient C by [15a] for the case of constant rainfall intensity.

the variation of C throughout the duration of the storm can be examined as follows. Using a time step dt and assuming a storm duration $n \cdot dt$, we have

$$\text{Depth of precipitation } P = n \cdot i \cdot dt$$

$$\text{Runoff depth } q = \sum_j (C(j) \cdot i \cdot dt), \quad j = 1-n$$

Setting the initial storage potential at $t = 0$ as S_0, the updated storage potential is given by $S = S_0 - P + Q$. Equation [15a] is then

$$[16] \quad C(j) = \frac{P(j)}{P(j) + S(j)} = \frac{j \cdot i \cdot dt}{j \cdot i \cdot dt + S_0 - j \cdot i \cdot dt + \sum_{k=1}^{j} C(k) \cdot i \cdot dt}$$

$$[17] \quad C(j) = \frac{j}{(S_0/i \cdot dt) + C(j) + \sum_{k=1}^{j-1} C(k)}$$

Equation [17] is a quadratic in $C(j)$ and can be solved as a function of the nondimensional elapsed time $j = t/dt$ with $(S_0/i \cdot dt)$ as a parameter. Figure 3 shows the form of the function for various values of $(S_0/i \cdot dt)$ from 1.0 (negligible storage) to 10.0 (large storage).

5.3 Variation under nonuniform rainfall

For the more usual case of variable rainfall intensity, the solution for the runoff coefficient must be obtained for each time step, updating the values of total precipitation and remaining storage potential. Using the simple model $C = P/(P + S)$, C, P, and S can be assigned the following average values within the jth time interval:

$$[18] \quad \begin{aligned} P &= P(j-1) + i(j) \cdot dt/2 \\ dS(j) &= i(j) \cdot dt \cdot [1 - C(j)] \\ S &= S(j-1) - dS(j)/2 \\ C(j) &= P(j)/[P(j) + S(j)] \\ &= \frac{P(j-1) + i(j) \cdot dt/2}{P(j-1) + i(j) \cdot dt/2 + S(j-1) - [1 - C(j)]i(j) \cdot dt/2} \end{aligned}$$

from which $C(j)$ may be obtained as the positive root of the quadratic:

$$[19] \quad a_1 \cdot C^2 + a_2 \cdot C + a_3 = 0$$

where $a_1 = i(j) \cdot dt/2$, $a_2 = P(j-1) + S(j-1)$, and $a_3 = -P(j-1) - i(j) \cdot dt/2$.

5.4 Estimation of storage potential

It may be argued that the uncertainty with respect to the runoff coefficient is now transferred to the initial storage potential. The value of S_0, however, has physical meaning which may be related to the soil properties or antecedant conditions. The relationship between S_0 and the SCS curve number CN is well known (Soil Conservation Service 1975), i.e.,

$$[20] \quad S_0 = 1000/\text{CN} - 10 \text{ (in.)}$$

although care must be taken to convert when units other than inches are employed. A working approximation that relates S_0 to the overall runoff factor may be derived from the SCS equation for abstractions,

$$[21] \quad Q = (P - 0.2S)^2/(P + 0.8S)$$

where Q is the depth of effective rainfall. Thus, in terms of $C_{ave} = Q_{max}/P_{max}$ the value for S_0 can be estimated approximately as follows:

$$[22] \quad S_0 = P_{max}\{5 + 10C_{ave}[1 - (1.25/C_{ave} + 1)^{0.5}]\}$$

Thus, if the engineer's experience suggests that a particular area should yield a runoff fraction of some approximate value for a storm of known total depth, the corresponding value of S_0 may be estimated. It is of course more appropriate to gain some insight for values of S_0 as a function of soil type and antecedent conditions and obtain C_{ave} as the dependent variable. It must be noted that the SCS model treats the value of S in [21] as a constant, and consequently as the value of C_{ave}

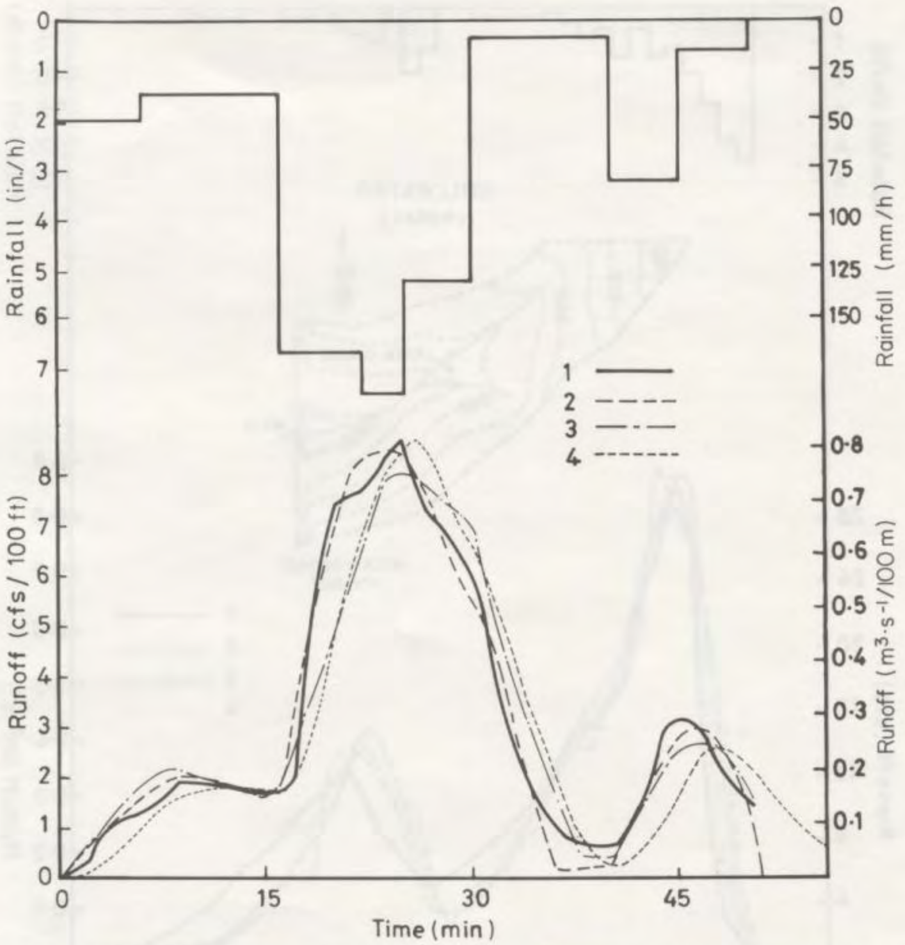

FIG. 4. Observed and simulated hydrographs obtained using different response functions. Concrete surface 500 ft (152.4 m) long; grade $s = 1\%$; assumed $n = 0.013$ (after U.S. Corps of Engineers 1954). (1) Observed hydrograph, (2) dynamic rational response, (3) static rational response, (4) dynamic SCS triangular response.

reduces, the approximation of [22] gets progressively poorer. For impervious areas, the value of S_0 for impermeable areas may be set to the surface depression storage with reasonable results.

6. Examples

The following examples are presented to demonstrate the application of the methods suggested in the previous sections, to illustrate certain shortcomings of such a simplified technique.

6.1 Impervious area

The first example considers an impervious, idealized surface to test the performance of the dynamic rational response function without the added complication of the mechanism for modelling the rainfall abstractions. The test is one of many carried out by the U.S. Corps of Engineers (1954), and also reported by Overton and Meadows (1976). The runoff surface was 500 ft long with a gradient of 1.0% and an assumed roughness represented by a Manning $n = 0.013$. Figure 4 shows the simulated rainfall hyetograph, which is quite complex and intense, delivering 2.305 in. in 50 min. In addition to the observed (measured) runoff hydrograph, Fig. 4 shows three computed hydrographs: (1) observed (i.e. measured) runoff hydrograph; (2) computed using a dynamic rectangular response function with time of concentration given by [11] for the rainfall intensity in each time increment; (3) computed using a constant rectangular response function based on [11], but using the average rainfall intensity; and (4) computed using the SCS method of a triangular response function with a dynamically varying time of concentration.

One of the striking features of the result is the surprisingly good agreement obtained by the first-mentioned method. The 'static' or constant response function based on the average intensity of 2.767 in./h is noticeably inferior. This difference is emphasized by

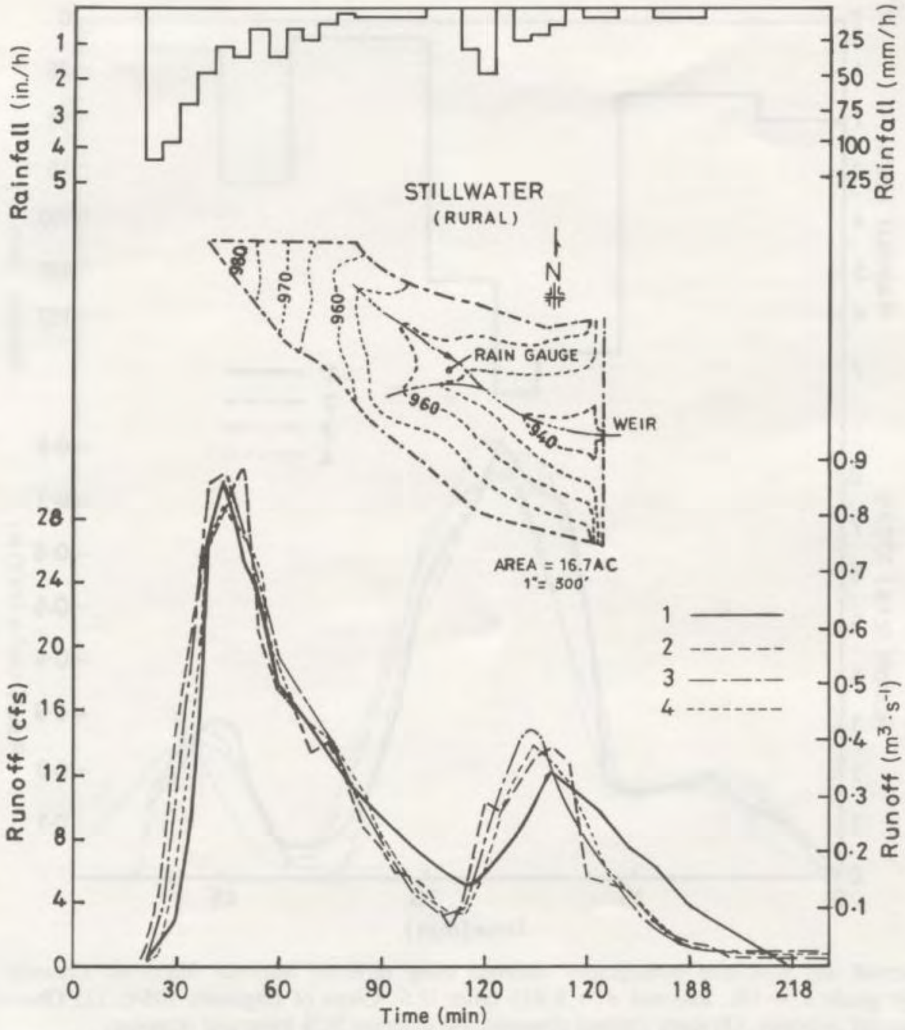

FIG. 5. Observed and simulated hydrographs (after USDA, Agricultural Research Service 1964). (1) Observed hydrograph, (2) dynamic rational response (n = 0.2), (3) dynamic rational response (n = 0.1) lagged through three 1 min reservoirs, (4) dynamic SCS triangular response (n = 0.1).

the extreme and abrupt variations in rainfall intensity. More surprising is the inferior result obtained by means of the triangular response function. Since the triangular response represents an approximation to a rectangular response routed through a hypothetical cascade of reservoirs, it appears that for such an idealized catchment with no infiltration and negligible depression storage, the theoretical rectangular response function yields a very reasonable approximation to the observed runoff.

6.2 Pervious area

A second example is illustrated in Fig. 5, which uses one of the experimental catchment results reported by the USDA, Agricultural Research Service (1964) (also reported by Terstriep and Stall 1974). The catchment in this case is a real one, of fairly regular shape and slope and subjected to an intense double-peaked storm of total depth 2.21 in. The topological characteristics of the catchment are noted in Fig. 5, although it should be noted that the flow length L is subject to some uncertainty as is the average slope. All of the terms in the quantity $(L \cdot n/s^{1/2})$ of [11] are subject to some uncertainty and sensitivity testing may be confined to any one of these. In this case, the Manning n value was chosen to be in the range 0.1−0.2. The reported storm event yielded a high runoff owing to nearly saturated antecedent moisture conditions. The calculation of abstractions was therefore based on a value of potential storage depth of 0.52 in., which corresponds to a SCS curve number of 95. The latter value in turn corresponds to a regular (i.e. type II) curve number of 87, which is appropriate for cultivated ground or pasture.

Figure 5 shows various trials together with the measured runoff hydrograph. All of the simulated hydrographs were generated using the dynamic rectangular response function. The result with the rather high value of $n = 0.2$ simulated the main peaks reasonably but the hydrograph is of an unnatural and irregular shape, especially in the recession limbs, which exhibit stepwise discontinuities corresponding to the pulses of rainfall. In order to obtain a reasonable result, it was found necessary to choose a lower value of $n = 0.1$ (which in turn produces shorter times of concentration and higher peaks) and route the resulting hydrographs through a cascade of linear reservoirs with a total lag of 3 min. Tests with lower values of n and longer lag times yielded roughly similar results. It therefore appears that, in contrast to the previous example, natural catchments which exhibit significant infiltration and surface depression storage must be modelled with a response function that embodies some form of routing function.

Another feature of this example is the fact that the second peak is high by a factor of 25%. This is almost certainly due to the fact that the volume-dependent runoff coefficient of [15a] is incapable of modelling the saturated hydraulic conductivity of the soil (e.g. f_c) and yields values of runoff coefficient C approaching 1.0 as the storage potential is saturated.

7. Conclusions

In the wake of more sophisticated methods of analyzing rainfall−runoff events, the traditional rational method has fallen into disrepute. However, it continues to be used in design offices, probably on account of its suitability for design purposes and because the user has developed an intuitive feel for the value of C to be applied in specific situations. This paper has attempted to show how some of the simple notions of the rational method can be used in a way which yields more reasonable runoff hydrographs from complex storms and which represents the process of rainfall abstractions in a way—albeit empirical—that represents a significant improvement on the crude application of a constant runoff coefficient.

One of the standard procedures in the rational method is the choice of a storm duration equal to the time of concentration. It can be shown that this will result in a maximum peak flow only if the condition of inequality [8] is satisfied. When using a nonuniform design hydrograph or historic storm, this criteria becomes less meaningful, especially when a nonlinear mechanism is used to represent rainfall abstractions. More importantly, when the design problem involves detention storage, it is important that the hyetograph duration be considerably in excess of the time of concentration. The appropriate storm duration to maximize the required detention storage is dependent on rainfall abstractions, catchment response function, etc., and cannot be predicted by a general rule.

Use of the rectangular response function implied by the rational method, in conjunction with uniform rainfall intensity, results in hydrographs of trapezoidal (or triangular) shape in Fig. 1. Convolution with a nonuniform hyetograph of effective rainfall intensity will produce a runoff hydrograph that is a reasonable approximation. A key feature of this approach is the determination of the time of concentration. This can be done by means of [11] derived from the kinematic wave equation. A simple approach is to compute t_c as a function of the average intensity of the effective rainfall. Alternatively, it is suggested that the use of a dynamically varying response function produces a more accurate runoff hydrograph, which in general is more 'peaky' than that generated by the constant response function. One of the examples supports this notion, and moreover, suggests that routing of the resultant runoff hydrograph is unnecessary when the surface exhibits negligible depression storage.

The variation of the runoff coefficient C over the duration of rainfall has been fairly widely recognized. Time dependency as suggested by Hoad (reported by Fair *et al.* (1971)) appears to be inappropriate for irregular hyetographs. Equation [15a] suggests a simple empirical method, which gives acceptable results for events with reasonably high runoff ratios. The volume-dependent runoff coefficient is undeniably empirical and cannot be claimed to represent the physical process of infiltration by any stretch of the imagination. It resembles the SCS infiltration method in that it assumes runoff to be proportional to precipitation (either gross or effective) but differs from the SCS equation [21] in that it uses the dynamically varying soil storage potential instead of the initial value. The total soil storage is assumed to include the surface depression storage that is satisfied over the duration of the storm and not as an initial abstraction. It thus avoids the uncertainty as to the appropriateness of assuming the initial abstraction I_a to be 20% of the storage potential S as debated by Aron (1982) and Hawkins (1978). It does not avoid criticisms of the type offered by Smith and Woolhiser (1971) concerning attempts to represent the physical process of infiltration by a model that is concerned mainly with the overland flow component of rainfall.

It has some attraction, however, in that it uses the runoff coefficient beloved of many design engineers, it may encourage direct or indirect measurement of the soil storage potential, which is unarguably the most significant physical parameter, and it avoids the use of curve numbers that are tied to a particular system of units and that are often regarded with a certainty that is unjustified by the test data on which they are based.

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List of symbols

A	area of catchment
a, b, c	coefficients in intensity−duration formula [2]
C	runoff coefficient
C_{ave}	average value of C over a rainfall−runoff event
CN	SCS curve number
i	rainfall intensity
i_{eff}	effective rainfall intensity
k	coefficient of proportionality
L	flow length over a catchment
M	units specifier (length units per metre)
n	Manning roughness coefficient
P	depth of precipitation
P_{max}	maximum depth of rainfall
Q	discharge; depth of effective precipitation
Q_{max}	maximum depth of runoff (effective rainfall)
Q_{peak}	peak runoff of flow
R	hydraulic radius
S	potential soil storage depth
S_0	initial value of S at $t = 0$
s	channel gradient
t	elapsed time
t_c	time of concentration
t_r	duration of rainfall
$u(\ )$	response function
V	velocity of flow