Modified NRCS Abstraction Method for Flood Hydrograph Generation

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Abstract: The NRCS abstraction method is based on two assumptions. The first is that the ratio of actual water retention after ponding to maximum potential retention after ponding is equal to the ratio of actual surface runoff to potential surface runoff. The second assumption is that the initial abstraction for the watershed is twenty percent of the maximum potential retention. This study shows that both assumptions violate continuity principles and proposes a modification that renders an elementary relationship accounting for all abstraction forms by dividing them into a variable and constant components. Consequently, the surface runoff computation becomes dependent on the soil initial moisture content and implicitly influenced by the initial abstraction, while retaining the advantage of the subjective selection of curve number from extensive database from which the NRCS method has gained popularity. A new time of concentration model is also proposed to extend the computation for flood hydrograph generation.

Keywords: Hortonian overland flow, Initial precipitation abstraction, Antecedent soil moisture, Time of concentration, Synthetic hydrograph.

Introduction

Hydrologic models have been used to synthesize surface runoff hydrographs in ungauged watersheds (e.g., Al-Qurashi *et al.* 2008; Öztürk *et al.* 2013; Petroselli and Grimaldi 2018; Paquet 2019). The computation requires the estimation of surface runoff depth from precipitation by subtracting interception by foliage, surface depression storage, soil infiltration, and evapotranspiration accounting for water evaporation from ground surface and transpiration through foliage. As time increases, transmission losses through soil infiltration dominates, which renders the computation of surface runoff via procedures considering event-based constant abstractions unreliable. The rainstorms are also intermittent, by which the initial abstraction and moisture content of soil will have a critical influence on surface runoff estimates. When the soil is dry, a frequent storm may not generate an appreciable surface runoff amount, but when the soil is saturated the storm may result in a flood.

The NRCS (2004) abstraction method (formerly, SCS 1972) has been widely mentioned in hydrologic textbooks for surface runoff estimation and implemented in software such as WinTR-55, WinTR-20, EPA-SWMM, and HEC-HMS. The development by a federal agency—the United States Department of Agriculture (USDA)—contributed to the method's popularity, because it received a degree of legal protection and support (Eli and Lamont 2010). Most importantly, the method computes the surface runoff in a simple manner accounting for all hydrologic abstractions by using a single parameter termed the curve number (Cronshey 1986). Extensive empirical database is provided and guidelines are given on a generally subjective basis for the selection of the appropriate curve number value. Among the criticisms reported, Hawkins *et al.* (2008) emphasized that the NRCS method has not properly predicted the initial abstraction for different intense storms, since it assumes that the hydrologic losses are event-based constant.

The method also is not considered an infiltration model, because it assumes that transmission losses are independent of time. A plethora of research has discussed the extent of the problem (e.g., Ponce and Hawkins 1996; Mishra and Singh 2002, 2003; Sahu *et al.* 2007; Grimaldi *et al.* 2013; Moglen *et al.* 2018; Hawkins *et al.* 2019).

The abstraction method has been extended by NRCS (2007) to generate flood hydrograph records in ungauged watersheds. The hydrograph method assumes a simple triangular representation of unit hydrograph with the triangle apex being the peak discharge. The procedure requires the estimation of time of concentration, which is the time for the water to travel from the hydraulically most remote point to the watershed outlet. Many empirical time of concentration equations are available, including that developed by NRCS (2010), but there is inconsistency among their performances (Sharifi and Hosseini 2011; Kaufmann de Almeida *et al.* 2017; Ravazzani *et al.* 2019). Applying an empirical equation requires regional constraints, because of existing uncertainty in watershed characteristics and hydrological processes (Efstratiadis et.al 2014), although the concept of hydrologic similarity is still ambiguous as there is not a standard criterion to consider justifying the similarity of two watersheds (Wagener *et al.* 2007).

This study will address two issues. The first is to modify the NRCS abstraction method while retaining the simple concepts from which it has gained popularity. The modification will consider that the hydrologic abstractions are composed of two components of event-based variable and constant. The variable component accounts for transmission losses estimated from a suitable soil infiltration model, while the constant component indicates the watershed potential for initial water retention relying on the concept of curve number. The second issue is to derive theoretically a new time of concentration model to extend the surface runoff computation for flood hydrograph generation. A numerical example will be provided to demonstrate the computation and results and to show how the two abstraction methods behave relative to the typical infiltration model.

NRCS Method

The rationale for the NRCS (2004) abstraction method is based on two assumptions. The first one is that the ratio of actual water retention after ponding F_a to the maximum potential retention after ponding S is equal to the ratio of actual surface runoff P_e to the potential surface runoff $P-I_a$

$$\frac{F_a}{S}=\frac{P_e}{P-I_a} \quad (1)$$

where I_a is the initial abstraction before ponding. The definition of S was made from the notion of a limiting loss $S=\lim_{P\to\infty} F_a$, which satisfies Eq. (1) when P and P_e sufficiently grow up resulting with $P_e/(P-I_a)\approx 1$. From the continuity principle

$$F_a=P-P_e-I_a \quad (2)$$

Combining Eqs. (1) and (2) gives

$$P_e=\frac{(P-I_a)^2}{P-I_a+S} \quad (3)$$

which is the basic surface runoff equation.

The second assumption for the NRCS method came to remove I_a as an independent variable by suggesting the linear relationship

$$I_a = \lambda S \quad (4)$$

where λ is the initial abstraction ratio. Through studies of many small agricultural watersheds, λ was found to be approximated by the average 0.2, by which Eq. (3) becomes

$$P_e = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad (5)$$

which requires that $P > 0.2S$; otherwise, $P_e = 0$. The surface runoff computation now involves only the maximum potential retention S, which varies in the range $0 \leq S \leq \infty$. For practical applications,S was related to the soil and cover condition for the watershed area through

$$S = \frac{1000}{CN} - 10 \quad (6)$$

where CN is the dimensionless curve number, varying in the range $0 \leq CN \leq 100$. Here, Eq. (6) represents the original model form where S is in inches.

Extensive empirical database is provided for the subjective selection of the CN based on watershed cover description, hydrologic soil group, and antecedent moisture condition. The watershed cover description is classified by cover type and hydrologic condition—of poor, fair, and good density of plant and residue cover on sample areas—with common categories such as agricultural, industrial, open spaces, paved parking, etc. The hydrologic soil group is classified as "A" with high infiltration rates (greater than 7.5 mm/h), "B" with moderate infiltration rates (3.75-7.5 mm/h), "C" with low infiltration rates (1.25-3.75 mm/h), and "D" with very low infiltration rates (0-1.25 mm/h). The antecedent moisture condition indicates the runoff potential before a storm event. The curve numbers in the database apply for an antecedent moisture condition with normal runoff potential AMCII. Based on the National Engineering Handbook

Section 4 (NEH-4) published in SCS (1972), the curve numbers were adjusted for a dry antecedent moisture condition with lowest runoff potential AMCI and for wet condition with highest potential AMCIII, which can be equivalently computed by (Chow *et al.* 1988)

$$CN(I)=\frac{4.2\,CN}{10-0.058\,CN} \quad (7)$$

and

$$CN(III)=\frac{23\,CN}{10+0.13\,CN} \quad (8)$$

The range for each antecedent moisture condition is tabulated in terms of dormant and growing seasons.

NRCS (2007) has extended the abstraction method to generate surface runoff hydrograph records in ungauged watersheds. The procedure is based on determining a triangular unit hydrograph with the characteristics

$$q_{peak}=\frac{2.08\,A}{t_{peak}} \quad (9)$$

$$t_{base}=2.67\,t_{peak} \quad (10)$$

$$t_{peak}=\frac{t_r}{2}+t_L \quad (11)$$

$$t_L=0.6\,t_c \quad (12)$$

where q_{peak} is the peak discharge per runoff depth in cubic meters per second per centimeter (m^3/s.cm), A is the drainage area in square kilometers (km^2), t_{peak} is the time to peak in hours (h), t_{base} is the base time, t_r is the storm duration, t_L is the lag time, and t_c is the time of concentration.

The triangular unit hydrograph is then transformed by using tabulated data into a more accurate curvilinear unit hydrograph.

Modified Abstraction Method

It should be noted that the two assumptions for the NRCS abstraction method do not satisfy continuity principles. This can be justified for the first assumption by recognizing that if abstractions after ponding arise from only soil infiltration, then F_a is equal to S and Eq. (1) becomes $P_e = P - I_a$, which is not true. The proportionality should result in $P_e = P - I_a - F_a$. The picture is complicated even further by Eq. (6), because it considers the maximum potential retention S as an event-based constant estimated from the curve number parameter. The event-based constant may properly simulate the runoff contribution from saturated overland flow (Ponce and Hawkins, 1996), when precipitation saturates the soil and raises the water table to the surface. Here, as $P \to \infty$ then $P_e \to P - I_a$ becomes acceptable. However, if S was rather considered an event-based variable, similar to typical infiltration models simulating the Hortonian runoff contribution from only surface overland flow, then as $P \to \infty$ the condition $P_e \to P - I_a - F_a$ prevails, because the soil equilibrium infiltration capacity will never be satisfied.

The second assumption suggests that the initial abstraction I_a is an event-based constant, indicating the watershed potential for initial water retention, which is quantified by the curve number parameter. This assumption was considered to simplify the surface runoff computation, because it is difficult to estimate the initial abstraction in practice. The initial abstraction can be related to a ponding time that considers all relevant hydrologic losses of interception, surface depression storage, and part of transmission losses of soil infiltration and evapotranspiration. The continuity here states that once the initial abstraction is satisfied at the ponding time, surface runoff begins. Deriving this relationship mathematically though is not straightforward, because transmission losses are variable but interception and depression storage remain somewhat constant from flood events, as they depend on surface topography and foliage of the system.

A possible manner to estimate the surface runoff contribution from surface overland flow is by presenting Eq. (2) of continuity in another equivalent form

$$P_e = P - F - S_o \quad (13)$$

where F is the cumulative infiltration for the soil, and S_o is the other remaining losses. The initial abstraction I_a is implicit in Eq. (13), which states that the surface runoff P_e exists once precipitation P is greater than hydrologic losses F and S_o; otherwise, $P_e = 0$. The equation divides the losses into two components of event-based variable F and constant S_o. The evapotranspiration loss is relatively small during flood events, by which it is considered here for practical reasons under the event-based constant component. The losses can then be estimated separately.

The cumulative infiltration F is the dominant source of losses during a flood event and can be estimated from any infiltration model applicable for a wide range of rainfall intensities greater or less than the initial soil infiltration capacity. The computation should account for the initial infiltration stage until the soil is fully satisfied at the ponding time, and then it accounts for the potential infiltration. The following explicit Green-Ampt model, developed by Almedeij and Esen (2014), can be adopted here

$$F = \psi \, \Delta\phi \left[\frac{1}{\left(\frac{i}{K} t^{¿} \right)^{-100} + \left(0.65 t^{¿} + \sqrt{0.25 t^{¿2} + 2 t^{¿}} \right)^{-100}} \right]^{1/100} \quad (14)$$

$$t^{¿}=\frac{Kt}{\psi\,\Delta\phi}$$

where t is the time, i is the rainfall intensity, K is the hydraulic conductivity, ψ is the capillary suction head at the wetting front, $\Delta\phi$ is the increase in moisture content as wetting front passes $\Delta\phi=\eta-\phi_i$, η is the porosity, and ϕ_i is the initial moisture content of dry soil before infiltration happens.

The event-based constant component S_o is difficult to estimate in practice. A rational quantitative assessment can be achieved by using the curve number parameter. This parameter, however, accounts for all losses including soil infiltration. The infiltration loss can be excluded, to some extent, by employing the curve number corresponding to the hydrologic soil group "D" with very low infiltration rate (0-1.25 mm/h) and wet antecedent moisture condition AMCIII as $C\,N_D(III)$. This parameter would indicate the remaining water retention, which is the surrogate for event-based constant losses. The following expression is suggested for the computation

$$S_o=S_v\left(1-e^{\frac{-it}{i\,t_p+S_v}}\right)(15)$$

where

$$S_v=\left(\frac{1000}{C\,N_D(III)}-10\right)$$

S_v is the maximum water retention excluding soil infiltration, and t_p is the ponding time due to soil infiltration. The variation pattern for Eq. (15) is shown in Fig. 1. Here, $it/(i\,t_p+S_v)=1$ approximates the condition when the precipitation depth is equal to the initial abstraction considering all relevant losses of event-based variable and constant. Equation (15) suggests that the water retention S_o begins from zero, increases with time until $S_o=0.63S_v$ when

$it/(it_p+S_v)=1$, and then starts asymptotically approaching the upper limit $S_o \approx S_v$. The asymptotic increase in S_v after the initial abstraction is satisfied $it/(it_p+S_v)>1$ may be reasonably referred to the contribution from the remaining part of evapotranspiration loss.

[Insert Fig. 1 here]

Equation (15) requires the estimation of the ponding time t_p due to soil infiltration. The implicit Green-Ampt infiltration model can be used

$$F-\psi\,\Delta\phi\ln\left(1+\frac{F}{\psi\,\Delta\phi}\right)=Kt$$

At ponding time, substituting by $t=t_p$ and $F=it_p$ yields

$$it_p-\psi\,\Delta\phi\ln\left(1+\frac{it_p}{\psi\,\Delta\phi}\right)=Kt_p$$

This equation can be solved to obtain t_p accurately (Almedeij and Esen 2014). An explicit approximation though can be derived here by using the first two terms of the power series expansion of the natural log term as

$$t_p=\frac{2K\psi\,\Delta\phi}{i^2}\,(16)$$

New Time of Concentration Model

The derivation of the unit hydrograph requires a time of concentration model, which depends on the watershed surface whether impervious or pervious. For impervious surfaces, the time of concentration can be defined as the time from the beginning of excess rainfall to that when inflow equals outflow (McCuen 2009). The factors influencing the estimation of time of concentration become the watershed average slope, surface roughness, longest stream path, and rainfall intensity. For pervious surfaces, the factors influencing the time of concentration estimation include also transmission losses mainly through soil infiltration. The estimation here also becomes more complicated by the presence of runoff contribution from saturated overland flow, which affects the flood hydrograph shape by extending further the time from the peak discharge until the end of the falling limb. This hydrograph pattern is common for many watersheds in humid areas, while for others including those in arid zones it is usually considered the result of Hortonian runoff contribution from only surface overland flow.

The available equations for pervious surfaces produce noticeable different results, by which the concept is still ambiguous. There is another reason for the observed discrepancy related to treating the time of concentration as a basin constant, rather than hydraulic variable, by excluding the rainfall intensity factor from the model. This is considered, although the factor is crucial for the model, to avoid an iterative solution, since both rainfall intensity and time of concentration are unknown. Michailidi *et al.* (2018) confirmed that the time of concentration is a negative power function of rainfall intensity. The inverse proportionality generates a decreasing curve that can be solved together with the intensity-duration-frequency curve for a given return period. Hence, increasing the design return period for water-related structures decreases the time of concentration, while disregarding this correlation can end up underestimating flood records and thus generating unreliable results for infrequent high-intensity events.

A time of concentration model is derived here for pervious surfaces with runoff contribution from only surface overland flow. The time of concentration t_c can be estimated from the equation of travel time between two points

$$t_c = \frac{L}{V} \quad (17)$$

where L is the longest stream path to watershed outlet, and V is the average overland flow velocity. Assuming a wide open channel with the hydraulic radius approaching water depth, the average overland velocity can be determined from the Manning equation

$$V = \frac{1}{n} y^{2/3} s_o^{0.5} \left(SI\, units \right) \quad (18)$$

where n is the dimensionless Manning roughness coefficient, y is the water depth in meters (m), and s_0 is the bottom slope in meter per meter (m/m). In this equation, V is in meters per second (m/s). Given that the overland flow per unit width q is

$$q = Vy$$

then Eq. (18) becomes

$$V = \frac{1}{n^{0.6}} q^{0.4} s_0^{0.3} \quad (19)$$

Continuity can be used to estimate q as schematically described in Fig. 2 for a control volume with inflow from rainfall $iL\cos\theta$ and outflow from both infiltration $fL\cos\theta$ and overland flow q

$$iL\cos\theta = fL\cos\theta + q$$

that can be written as

$$q = \left(i - f \right) L\cos\theta$$

Here, f is the potential infiltration rate after ponding, which is a function of time and soil properties. To simplify the complexity due to the presence of time in the derivation, f may be replaced by the soil hydraulic conductivity K

$$q=(i-K)L\cos\theta$$

This can be substituted in Eq. (19)

$$V=\frac{1}{n^{0.6}}\left[(i-K)L\cos\theta\right]^{0.4}s_0^{0.3}$$

and the above is then substituted in Eq. (17) to yield

$$t_c=\frac{(nL)^{0.6}}{\left[(i-K)\cos\theta\right]^{0.4}s_0^{0.3}}$$

If θ is very small, then this can be further simplified by assuming that $\cos\theta\approx 1$. Also it should be noted that the units for the time of concentration and rainfall intensity are in seconds and meters per second, respectively; however, it is common to present this equation by considering the corresponding units in minutes and millimeters per hour. Accordingly, this equation can be expressed as

$$t_c=6.99\frac{(nL)^{0.6}}{(i-K)^{0.4}s_0^{0.3}} \quad (20)$$

where t_c is in minutes (min), L in meters (m), i in millimeters per hour (mm/h), K in millimeters per hour (mm/h), and s_0 in meter per meter (m/m).

[Insert Fig. 2 here]

As mentioned previously, this derivation is valid for pervious surfaces with runoff contribution from surface overland flow. It is worth noting that the imposed simplification in terms of transmission losses through equilibrium infiltration capacity of K is useful for sufficiently undeveloped surfaces. For developed surfaces, the term K may be expressed by the rational coefficient C that reflects a general abstraction due to land use category. Equation (16) can then be rewritten by replacing the term $i-K$ in the denominator by Ci

$$t_c = 6.99 \frac{(nL)^{0.6}}{(Ci)^{0.4} s_0^{0.3}}$$

This yields a model similar to that obtained by Morgali and Linsley (1965), which was derived from finite difference methods and numerical techniques by solving partial differential equations of momentum and continuity for unsteady flow. Their model considers i as the excess rainfall intensity, which is compliant here with the term Ci.

Numerical Example

The proposed abstraction modification is based on using a typical infiltration equation and a subjective selection of curve number parameter that do not need to reprove their applicability. To demonstrate the computation and results, an example for a desert watershed is provided. In general, desert watersheds are ungauged, by which synthetic hydrograph methods become essential for hydrologic assessments. The desert hydrological regime is characterized by limited amounts of surface water and rare seasonal precipitations but torrential. The surface runoff is rapid and less restricted than that generated over similar slopes in humid catchments and will rapidly cease when the precipitation stops. The floodwater accumulation will be fast enough resulting in a risk of potential damage at downstream locations. The condition has been worsened by surface loose soil exposed to the flow, by which high sediment transport rates occur. Owing to the reason that the groundwater is considered fossil and subsurface water table is deep, runoff contribution from saturated overland flow is absent.

The example will generate the flood hydrographs for different return periods of 5-, 10-, 25-, 50-, and 100-year. The precipitation is assumed constant and uniformly distributed within the duration $t_r = 2$ h to simplify the computation for the two-hour unit hydrograph. A small basin is considered with the characteristics of $A = 1$ km^2, $L = 1340$ m, and $s_0 = 0.0108$. The surface area for the basin is undeveloped with a low vegetation cover composed of scattered plants that do not significantly intercept precipitation. To exclude soil infiltration contribution from the curve number parameter, the desert cover type with soil group "D" ($CN = 88$) and wet antecedent moisture condition AMCIII is used with $CN_D(III) = 94.4$. The following Manning and Green-Ampt parameters are considered for the soil with $n = 0.013$, $K = 3.4$ mm/h, $\psi = 167$ mm, $\eta = 0.5$, and $\phi_i = 0$. Initially, the time of concentration t_c and intensity i are obtained for the example from Fig. 3, as the intersection points from superimposing Eq. (20) on the given intensity-duration-frequency curves. The obtained t_c values are then used to determine the triangular unit hydrograph ordinates by solving Eqs. (9) to (12). Table 1 shows the design storms and triangular unit hydrograph parameters for the different return periods. Fig. 4 presents the curvilinear unit hydrographs transformed using the NRCS hydrograph method.

[Insert Table 1 here]

[Insert Fig. 3 here]

[Insert Fig. 4 here]

The flood hydrographs for the different return periods are estimated from the knowledge of the corresponding surface runoff depths P_e. Initially, the abstractions F and S_o are estimated from Eqs. (14) and (15), respectively. The ponding time t_p, which is required for S_o, was obtained from Eq. (16). The surface runoff P_e is then calculated from Eq. (13) for the given precipitation depth $P=i\,t_r$. The surface runoff P_e results are shown in Table 1. Fig. 5a presents the flood hydrographs, indicating the low runoff potential of the dry soil with the initial moisture content $\phi_i=0$. The hydrograph ordinates with 5-, 10-, and 25-year return periods are equal to zero since $P_e=0$. The hydrograph ordinates with 50-year return period resemble those for the unit hydrograph, because the surface runoff is very close to the one-centimeter unit depth from which the unit hydrograph was derived. It is worth comparing the results by re-plotting the hydrographs in terms of initial moisture content $\phi_i=0.4$. Here, Fig. 5b shows that the hydrograph ordinates with 5- and 10-year return periods are equal to zero since $P_e=0$, but those with the 25-year return period are not. Compared to those with initial moisture content $\phi_i=0$, the hydrograph ordinates with 50- and 100-year return periods have been highly increased with corresponding ratios of 2.78 and 1.64, which may explain the drastic impact of desert flash floods when two subsequent storms occur given that the second is major.

[Insert Fig. 5 here]

It is worth demonstrating how the modified and unmodified NRCS abstraction methods behave relative to the typical infiltration model. This can be presented by computing the variation of surface runoff P_e with respect to time for the case with 100-year return period and initial moisture content $\phi_i = 0.4$. Fig. 6 shows the results in terms of the ratio $P_e / (P - F)$. Apparently this ratio should not exceed one, because the denominator considers surface runoff with abstractions through only infiltration. For comparison purposes, the results from the unmodified NRCS method are presented in terms of four curve numbers representing the desert cover category with soil groups "A", "B", "C", and "D" equal to $CN =$¿ 63, 77, 85, and 88, respectively. To satisfy the case with initial moisture content $\phi_i = 0.4$, the curve numbers were adjusted for wet antecedent moisture condition AMCIII resulting with the corresponding values of $CN(III) =$¿ 79.66, 88.51, 92.87, and 94.4. As can be seen, the condition $P_e / (P - F) \leq 1$ is satisfied only for the modified NRCS method, while for the unmodified method it exceeds the limit by approaching asymptotically 1.11.

[Insert Fig. 6 here]

Conclusions

This study modified the NRCS abstraction method by accounting for all hydrologic losses in a different quantitative manner of two variable and constant components. The dominant infiltration loss is an event-based variable, estimated using a generalized Green-Ampt model applicable for a wide range of rainfall intensities greater or less than initial soil infiltration capacities. The concept of the curve number is useful for the event-based constant component, which depends on surface topography and foliage of the system. The evapotranspiration loss is relatively small during flood events, by which it was considered under this component. The proposed model for the event-based constant component though suggests that water retention starts to increase with time until it asymptotically approaches the upper limit. The asymptotic increase after the initial abstraction is satisfied may be reasonably referred to the contribution from the remaining part of evapotranspiration loss.

The new time of concentration model, which is valid for pervious surfaces with runoff contribution from surface overland flow, was proposed because empirical equations in the literature have different performances and the hydrologic similarity concept is ambiguous and difficult to justify for two watersheds. The model considers the time of concentration as a hydraulic variable rather than basin constant, which is relevant for the generation of different flood hydrograph scenarios. The longer the return period, the greater is the rainfall intensity and shorter time of concentration. The numerical example showed that substantial flows can be generated under extreme conditions when flood severity becomes influenced by a high initial moisture content of soil, which is the condition when two subsequent storms occur given that the second is major. The example also showed that the asymptotic behavior for the modified abstraction model coincides with the typical infiltration model simulating Hortonian overland flows.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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