A CONCEPTUAL MODEL OF THE SCS RUNOFF METHOD

By Stephen Priestley, E-mail: stephen.priestley@beca.com

ABSTRACT

The SCS (or NRCS) method, arising in the 1950's out of analysis of real data from large numbers of catchments across the USA, is one of the most commonly applied flood estimation methods. It is used in several regions within New Zealand and is the preferred method for the Auckland Region. The original approach was empirical and this paper presents a concept of the physical rainfall-runoff processes for the SCS method. It is based on the variable source area concept for promoting runoff. The variable source concept is based on part of the catchment contributing to runoff at an increasing rate with increasing rainfall. It can be demonstrated that a unique storage function can be defined across a catchment representing the catchment type (land use, soil type etc.). The concept provides a physical meaning for the runoff number (CN), and demonstrates that the storage (S) in the SCS method can be taken to represent the average storage across the catchment.

It is anticipated that this concept will aid an understanding of SCS applications and perhaps its use in continuous rainfall-runoff modelling.

KEYWORDS

Flood Estimation, SCS Runoff Method, NRCS Runoff Method.

PRESENTER PROFILE

Stephen Priestley is a senior technical director of Beca Ltd, Consulting Engineers, Auckland, New Zealand. He has 35 years of experience in hydrology, hydraulics and water related engineering.

1 INTRODUCTION

The aim of this paper is to present a concept of the physical rainfall runoff processes involved in the SCS method. (Originally developed by the USDA Soil Conservation Service – now the Natural Resources Conservation Service or NRCS).

The SCS method was developed in the 1950's and has survived in the intervening period, despite many other more physically based methods and the ability to solve complex issues with modern computers. It owes its endurance to its simplicity and a database of typical curve number (CN) values which cover a range of land uses and soil types. It makes comparison of the rainfall-runoff characteristics of differing levels of catchment development relatively straightforward.

The SCS method is intuitive. Its main attribute is that it exhibits increasing rates of runoff with increasing rainfall (whether depth or intensity). Those who have used continuing loss models (e.g. Horton or Green Ampt) will know the difficulty with model verification with known storm events, usually under predicting frequent events and over predicting the more extreme events. The SCS method typically yields some runoff during the more frequent events and more moderate runoff during extreme events. The SCS method for estimating a runoff event requires a rainfall profile (or hyetograph), a rainfall-runoff relationship and convolution using a unit hydrograph to produce a runoff hydrograph. This paper deals with the rainfall-runoff relationship.

2 BACKGROUND

The original SCS method was based on the following approach:

$$P' = Q + F \qquad (1)$$

where P' is rainfall depth from the start of an event, Q is the runoff depth and F is the losses.

It was then postulated that the runoff to rainfall function was proportional to actual and potential losses, where F was assumed to be the maximum potential losses i.e.

$$\frac{Q}{P'} = \frac{F}{S} \qquad (2)$$

By substituting (1) into (2) the SCS relationship was developed:

$$Q = \frac{(P')^2}{(P' + S)} \qquad (3)$$

The method also includes an initial abstraction (I_a) which was assumed to be equivalent to 0.2S. When introduced the following final form of the SCS method is:

$$Q = \frac{(P' - 0.2S)^2}{(P' + 0.8S)}$$

in which runoff is produced if Q > 0.2S.

The inclusive of I_a as equivalent to 0.2S is not universally accepted, as it often results in no runoff for smaller events. The modelling of smaller events (with say a frequency of less than a 2 year return period) is becoming more important when considering water quality.

Therefore for the purpose of this paper the following relationship will be used:

$$Q = \frac{P^2}{(P+S)} \qquad (4)$$

where $P = P' - I_a$, allowing for some potential initial abstraction.

A dimensionless form of Eqn 4 can be expressed as:

$$Q^* = \frac{P^{*2}}{(P^* + 1)} \qquad (5)$$

where $Q^* = Q/S$ and $P^* = P/S$.

The curve number (CN), which varies between 0 (i.e. no runoff) and 100 (i.e. total runoff) was introduced as:

$$CN = \frac{1000}{(10 + S)} \qquad (6)$$

where S is in inches and Eqn 6 has the following form for metric application in which S is in millimeters.

$$CN = \frac{1000}{(10 + S/25.4)} \qquad (7)$$

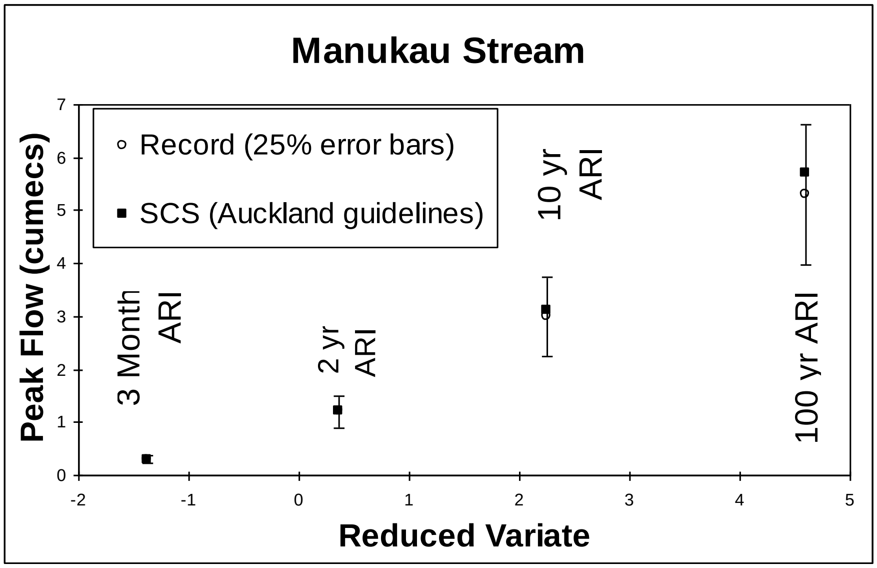
Much of the above and a good background to the SCS method are given in Hawkins et al (2009). This concise publication provides more information on the various derivations of the SCS method. Perhaps one of the more compelling derivations is by Yu (1998) which expressed the temporal rainfall intensity pattern as an exponential distribution and which expressed the spatial infiltration rate as an exponential distribution. While the clever manipulation of these assumed distributions yields the relationship in Eqn 4, the assumption of temporal rainfall intensity being an exponential distribution is questionable as most applications have an *a priori* assumed rainfall distribution. The assumed spatial distribution of infiltration is based on "partial area" or "variable source area" considerations. This is probably the key to better understanding the SCS method.

Boughton (1988) gives a good background to "variable source area" concepts and quotes many authors contributions to this subject. Basically in humid, temperate climates the Hortonian overland flow concept appears not to apply. Most rainfall infiltrates the ground to a degree. Areas near to the streams and stormwater systems become saturated and contribute to overland flow. As a storm continues, the areas of saturation expand thereby increasing the area that is producing runoff.

Areas with a good coverage of topsoil and vegetation will contribute more towards infiltration or sub surface flow, while slopes with a lesser coverage of topsoil and vegetation will contribute more towards saturated overland flow.

In the Auckland Region of New Zealand the Regional Council (ARC) now Auckland Council produced flood estimation guidelines (ARC (1999), Beca (1999)) as Technical Publication 108. A range of methods were evaluated and the SCS method was adopted. Verification of the method (including rainfall pattern, rainfall runoff relationship and unit hydrograph application) was achieved by comparing statistically derived flood peak flows from long term gauging sites with the SCS method using long term rainfall data. This verification was aimed at events from a 3 month to 100 year return periods. An example of the comparison is given in Figure 1.

Figure 1: Comparison of SCS Method with Gauging record (15 years)



It was noted that flood hydrology is not an accurate science. Consistency of approach and giving good guidance on flood estimation methods that a regulatory authority can have confidence in was important. The SCS method has provided that.

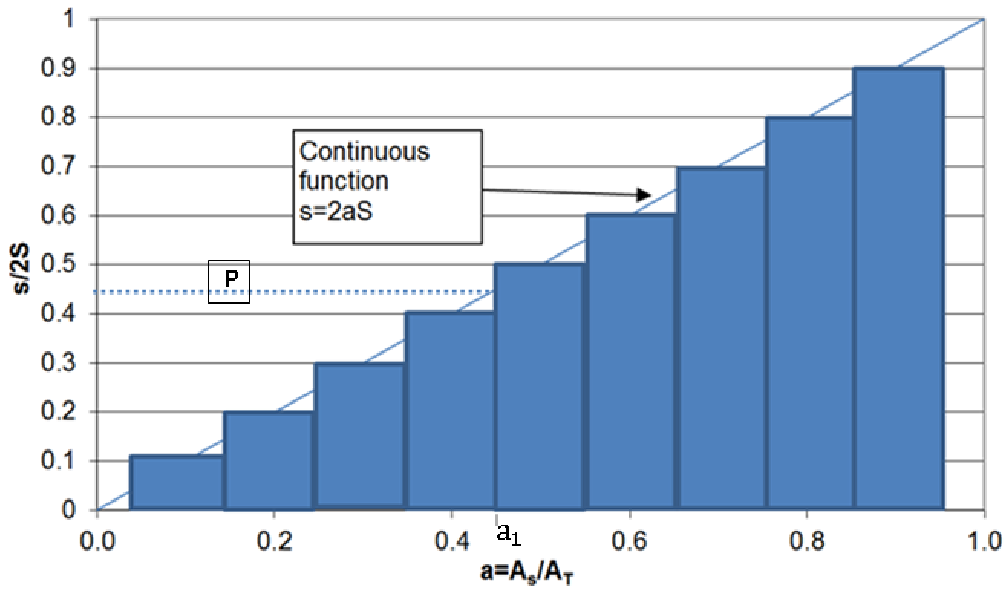
3 CONCEPT OF THE PHYSICAL PROCESSES

3.1 THE CONCEPT

Consider a catchment made up of a variety of storages (e.g. tin cans of various size scattered throughout the catchment). The larger storages would be representative of areas with permeable soils or areas with good topsoil and vegetative coverage. The smaller storages would be representation of low permeability soils or saturated overland flow areas.

A linear distribution of storages is illustrated in Figure 2 (a is the ratio of the area (As) with storages less than size s, A_T is the total catchment area and 2S is the maximum storage). The term 2S is used to make it equivalent to the term used in the SCS method (as S is the average storage across the catchment as will be demonstrated later). This linear distribution is not the concept being promoted but is included to illustrate the development of the method.

Figure 2: Distribution of Storage (S) across a Catchment (A_T)



For a progressive rainfall event, if P <2S then the following runoff relationships can be developed:

$$s = 2a\, S \qquad (8)$$

$$F = \int_0^{a_1} s\, da + (1 - a_1)P$$

$$= {a_1^2}/{2} + (1 - a_1)\, P \qquad (9)$$

$$\text{as } a_1 = \frac{P}{2S}$$

$$F = P - P^2/4S \qquad (10)$$

$$\text{As } Q = P - F$$

$$Q = P^2/4S \qquad (11)$$

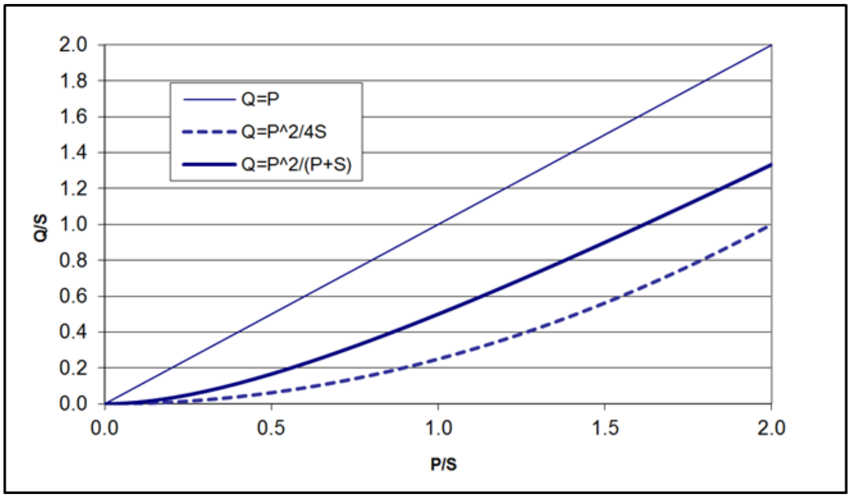
$$\text{and } \frac{\partial Q}{\partial P} = \frac{P}{2S} = a_1 \qquad (12)$$

$$\text{and } \frac{\partial F}{\partial P} = 1 - \frac{P}{2S} = 1 - a_1 \qquad (13)$$

For a given rainfall depth P, the value of a_1 represents the area of saturation or the fraction of the catchment contributing to the total runoff (Q). It also corresponds to the instantaneous runoff coefficient analogous to the coefficient used in the Rational Method.

The above relationship (Eqn 11) is compared to the SCS method in Figure 3 in a dimensionless form.

Figure 3: Comparison of different 'Partial Area" models.



This relationship is similar in form but not in result to the SCS method. It results in less runoff for the same P and S, but has been used as a basis of a runoff-relationship in flood estimation methods (e.g. ARC (1992); Institute of Hydrology (1979)).

An important outcome of the above development is Eqn 12 which can be shown to apply to any assumed continuous distribution of storage(s) across a catchment (as for example given in Eqn 8). That is the distribution of storages across a catchment is proportional to the first derivative of the runoff/rainfall relationship. Also the losses in the catchment system (F) are the integral of the storage relationship (e.g. Eqn 8) in the system.

If the SCS method is now investigated using the same approach.

$$Q = \frac{P^2}{(P+Q)} \qquad \text{(as given in Eqn 4)}$$

$$\frac{\partial Q}{\partial P} = \frac{2P}{(P+Q)} - \frac{P^2}{(P+S)^2} \qquad (14)$$

$$1 - \frac{\partial Q}{\partial P} = \frac{S^2}{(S+P)^2} \qquad (15)$$

If $a_1 = \dfrac{\partial Q}{\partial P}$ as given in Eqn 12 then

$$a_1 = 1 - \frac{S^2}{(S+P)^2} \qquad (16)$$

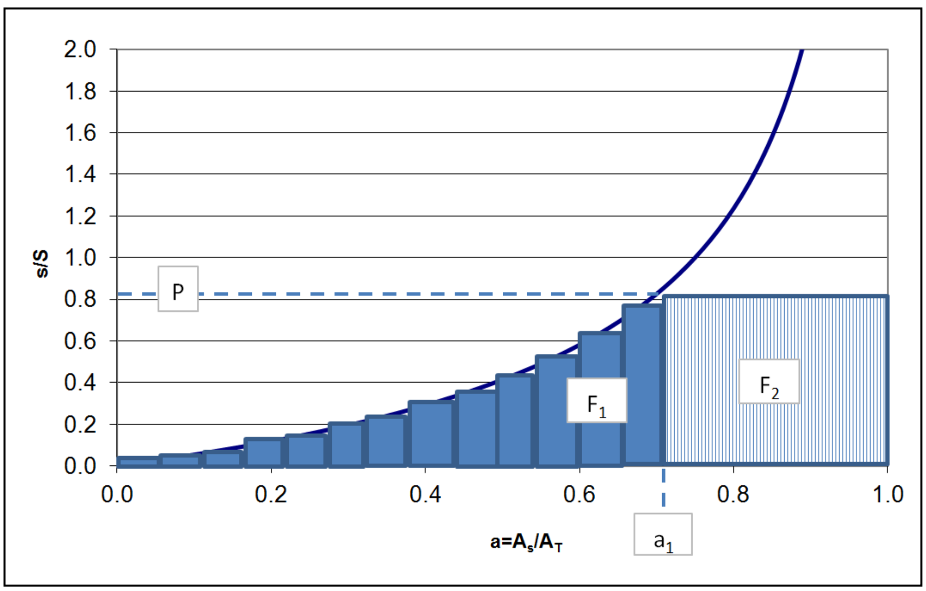
which yields

$$P = S\left(\frac{1}{(1-a_1)^{0.5}} - 1\right)$$

and the actual storage distribution across the catchment is therefore:

$$s = S\left(\frac{1}{(1-a_1)^{0.5}} - 1\right) \qquad (17)$$

Figure 4: Catchment losses for SCS method



To prove its applicability, as given by Figure 4:

$F = F_1 + F_2$

$$= \int_0^{a_1} s\,da + (1 - a_1)\,P \qquad (18)$$

$$F = \int_0^{a_1} S\left(\frac{1}{(1-a)^{0.5}} - 1\right) da + (1 - a_1)P \qquad (19)$$

$\therefore$ F = S [2-2(1-a_1)$^{0.5}$ – a_1]+(1-a_1)P (20)

$$\text{From Eqn 16 } (1 - a_1) = \frac{S^2}{(S+P)^2}$$

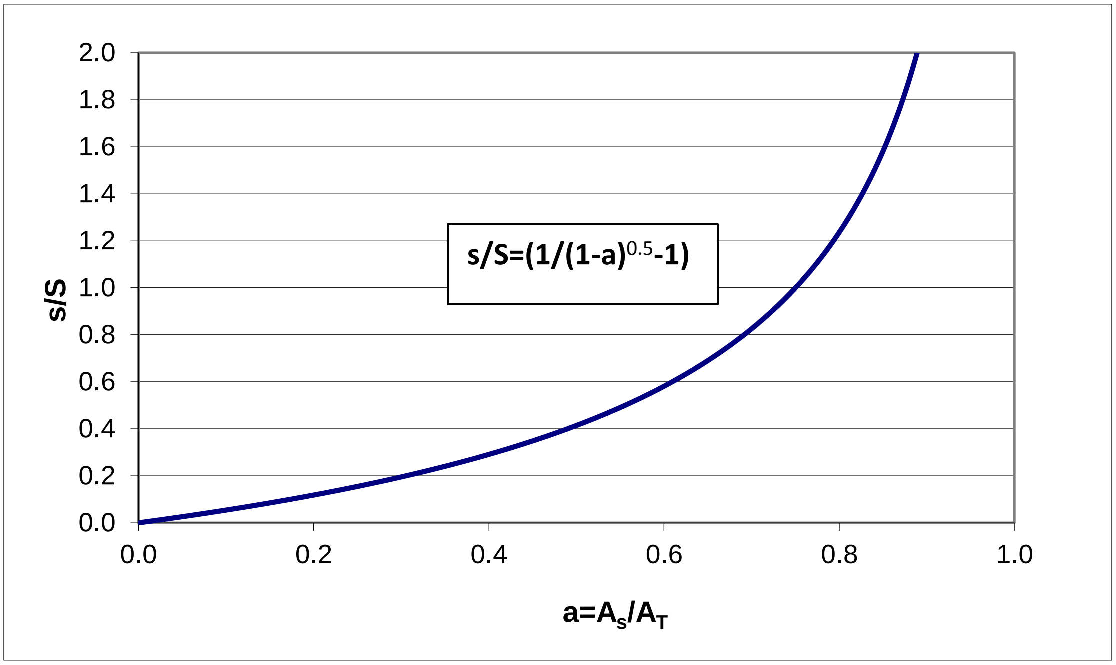
$$F = 2S - 2\,\frac{S^2}{(P+S)} - S + \frac{S^3}{(P+S)^2} + \frac{S^2P}{(P+S)^2} \qquad (21)$$

which if expanded out and terms cancelled the result is :

$$F = \frac{SP}{(P+S)} \quad \text{as given in Eqn 14} \qquad (22)$$

The storage distribution in dimensionless form for Eqn 17 is given in Figure 5.

Figure 5: Catchment Storage Relationship for SCS Method



The relationship for the distribution of storages across a catchment as given in Eqn 17 is also described as a similar relationship in Hawkins et al (2009). They described it as a continuous distribution form of infiltration storage.

Interesting outcomes of the above analysis are:

- Eqn 17 describes the unique distribution of storages across a catchment as given in Figure 5. It is considered that the above explanation of the physical processes could aid in applying the SCS method to continuous or water balance models. On the completion of a runoff event the amount of catchment storage is known. These storages can then be subject to evapotranspiration, baseflow and groundwater losses and be accounted for discretely, with subsequent soil/moisture accounting.

- Eqn 16 gives the relationship between the area of saturation (a_1) and the variables in the SCS Eqn 4 (i.e. P and S).

The area of saturation (a_1) is the instantaneous runoff coefficient and is directly proportional to the first derivative of the runoff/rainfall relationship (Eqn 15). The value of a_1 is analogous to the runoff coefficient in the Rational Method.

3.2 THE MEANING OF STORAGE (S)

The value of S can be shown to be the average value of storage(s) across the catchment.

$$\overline{\mathrm{s}} = \int_0^1 \mathrm{s}\,\mathrm{da} = \mathrm{S}\int_0^1 \left(\frac{1}{(1-\mathrm{a})^{0.5}} - 1\right)\mathrm{da} \qquad (23)$$

$$= \mathrm{S}$$

When s (or P) = S then 75% of the variable storages across the catchment are full and the runoff (Q) = losses (F) = P/2.

3.3 THE MEANING OF CN

CN varies between 0 (no runoff) and 100 (complete runoff). If the volumetric runoff coefficient (C_v) where considered to be Q / P then:

$$\frac{Q}{P} = C_v = \frac{CN}{100} = \frac{P}{\left(P + \left(\frac{100}{CN} - 1\right)254\right)} \qquad (24)$$

From Eqn 24, it can be shown that when P is 254 mm, C_v is CN/100. As 254 mm of rainfall would be considered an extreme event for most places, it could be said that CN is the volumetric runoff coefficient (in % terms) for extreme rainfall conditions. This helps give a practical sense of the CN value.

4 CONCLUSIONS

This paper may be considered as another attempt to rationalize the SCS method. Given its popularity of application, there is merit in understanding the method on a more conceptual basis. This paper presents the concept that a catchment can be represented as a series of variable size storages as illustrated in Figure 5. During an actual rainfall event, the smaller storages are filled resulting in runoff for which the runoff intensity increases as more storages are filled. The distribution of storages across the catchment is given by a unique relationship as given by Eqn 17. It can be demonstrated that this distribution of storages is proportional to the first derivative of the runoff (Q) / rainfall (P) relationship.

With the storage relationship developed in Eqn 17, the S term in the SCS method represents the average storage across the catchment. In addition, the CN term represents the volumetric runoff coefficient (in % terms) for a 254mm rainfall event – an extreme event for most places.

NOTATION

a = ratio of As /AT

As = catchment area with storage less than size S

A_T = Total catchment area (Figure 3)

CN = runoff number

F = losses to soil, interflow and subsurface flow

i = rainfall intensity

Ia = initial abstraction

P' = rainfall depth from the start of an event

P = P' – Ia

P* = P/S

Q = runoff depth

q = runoff rate

Q* = Q/S

s = storage at any point in a catchment

S = average storage across a catchment.

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