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Surface Drainage System for Agricultural Water Sheed

by

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Abstract : *The suitability of surface drainage system, the hydrological parameters needed for design of surface drainage system, updating of SCS curve number and the SCS method for computation of design discharge during successive rainy days have been reviewed in this paper. A method for computation of peak discharge for which the surface drainage channel should be designed has been suggested.*

Introduction

Water and air, which compete for the same position in soil in the root zone, are both needed for plant growth. The soil moisture deficiency is abated through irrigation and the oxygen deficiency is done away with by providing drainage facilities in the agricultural field. It is convenient to divide overall drainage into two types : Land drainage and Field drainage. Land drainage is large scale drainage where the object is to drain surplus water from a large area by such means as improving the flow of the streams and river, excavating large open drains, erecting dykes and levees and pumping. Schemes of this nature are associated with large areas of low-lying land, frequently in coastal areas and involve major civil engineering work. Field drainage is removal of surplus water, that otherwise restricts crop growth, from agricultural land. The surplus water may accumulate because of rain or surface flow and can not naturally be drained away fast enough. The function of field drainage is directed towards accelerating or increasing the natural outflow, either on the surface by means of open drains or ditches or below the ground by a system of closed under drains.

Drainage System

The drainage system can be classified into surface and subsurface drainage systems. Although the basic objective of surface and subsurface drainage is to provide a drier soil for plant growth the way this is achieved is quite different. Surface drainage system removes water before it has entered the soil. Provision of surface drainage results in an increase in the surface runoff by which the amount of water going into storage in the soil is reduced. Subsurface drainage system removes water after it has entered the soil. Subsurface drainage aims at increasing the rate at which water can be drained from the soil so as to lower the water table for increasing the depth of drier soil above the water table. If the primary object is to avoid surface water logging then surface drainage is provieed. but if a permanent lowering of water table is desired besides removing the water from the root zone, a system of subsurface drain is often used.

Surface Drainage System

The natural development of stream system provides surface drainage for most sloping land. Areas that need artificial surface drainage are either nearly level or depressional. Surface drainage is the orderly removal of excess water from the surface of land through improved natural channels or constructed ditches and through shaping of the land surface. Surface drainage systems, when properly planned, eliminate ponding, prevent prolonged saturation and accelerate flow to an outlet without siltation or erosion of soil.

Surplus surface water may originate from irrigation or from precipitation. The surplus water from irrigation is generally caused by outflow from the lower ends of furrows or irrigation borders. It is found, in most cases, that the quantities of irrigation return flow are small and not critical to the design of surface drainage channel which can be conveniently excavated will generally prove to be greater than that required by the predicted rate of irrigation return flow. On the other hand the amount of surface water derived from precipitation which must be removed by a surface drainage system during the rainy season may be considereble, and therefore, critical in the design of surface drainage channel. Whenever rainfall intensity exceeds the infiltration rate of the soil, surplus water will collect on the ground surface. If the land is flat it will cause ponding. Some of the volume of ponded water will disappear without drainage after the rain stops because of continued infiltration and surface evaporation. The critical factor, therefore, is not the volume of water to be removed but the period of time which the crops can tolerate the ponding. Generally speaking, and for most crops shallow ponding for up to 24hr will not cause any serious damage. The tolerance limits of different field crops to ponding are as given in Table 1. If the fields are flooded from high water in a nearby river or from surface runoff at the foot of a nearby slope or hill, the problem is completely different and must be handled as a flooding rather than a drainage problem (Finkel, 1983).

Table 1 : Recommended period of disposal for different crops based on tolerance limit of crops to ponding (IS 8835–1978)

Name of Crop	Period of Disposal (in day)
Paddy	7 to 10
Maize, Bajra, and other similar crops	3
Sugarcane & Bananas	7
Cotton	3
Vegetables	1

Surface drainage system is comparatively simple to plan, design and construct and is usually rather inexpensive. All possible excess water from all sources should be removed before it percolates to the ground water table to create or intensity a more expensive subsurface drainage problem. The various conditions which causes surface drainage problems are :

(i) Uneven land surface with pockets or ridges which prevent or retard natural runoff. Slowly permeable soils magnify the problem.

(ii) Low-capacity disposal channels within the area which remove water so slowly that the highwater level in the channels causes ponding on the land for damaging period.

(iii) Outlet conditions which hold the water surface above ground level such as tide water elevation.

The traditional drainage system on heavy clay soils is surface drainage. Soils also need surface drains under any of the following situations :

(i) A hard pan or tight layer exists in the upper zone.

(ii) The sub soil within a depth of 100 cm remains dry even after an extended rainy period.

(iii) In tropical and subtropical area which receives high intense rainfall and where the soil is heavy and slow permeable.

The basic surface systems are :

(i) the random,
(ii) the parallel, and
(iii) the cross slope or diversion system

The system to be used will depend upon the requirement of the site.

Parameters for Surface Drainage

Factors for Converting Annual Maximum Series to Partial Duration Series :

For design of surface drainage system the amounts of water that have to be discharged must be known. If possible, these amounts should be assessed by direct measurements. If not, indirect method such as calculation of discharge from rainfall data will have to be used. As rainfall is extremely variable in time and space, the rainfall data covering long period and recored at various stations are needed from which a design rainfall is then transformed to a design discharge. The parameters which are required for finding the design discharge from rainfall data are presented here.

Drainage systems are usually designed based on a precipitation event which has a certain statistical frequency of occurrence. However, proposed systems are usually evaluated for their performance during a range of other events depending upon the importance of a system. While selecting a rainfall event with certain duration and frequency, an assumption is inherent that a given frequency rainfall of a critical duration will lead to same frequency runoff flood. Different rainfall events can lead to runoff events which do not have the same frequency of occurrence. Experience indicates that very intense storms are of short duration and are rare. Storm of long duration tend to be less intense. Extremely long storm supplying large amounts of rain are also rare. Drainage design needs qualification of the inverse relationship between intensity, duration and frequency. There are two methods for selecting data for analysis of extreme values. The first method considers the annual series in which the largest single event that occurred within each year of record is selected. In the annual series, year may be calendar year, water year, or any other consecutive 12 month period. The limiting factor is that one and only one place of event is accepted for each year. Use of the annual maximum series ignores the second and third highest events of a year even though they may be larger than the maximum of other years. The second method recognizes that the large events are not calender bound and that more than one large event may occur in the time unit used as a year. In a partial duration series, the largest N events are used regardless of how many may occur in the same year. The only restriction is that independence individual events be maintained. The number of events used is at least equal to the number of years of record. The partial duration series does not fit the extreme-value distribution and therefore can not be extrapolated by extreme value distribution function (Dunne and Leopolod, 1979). Instead, the return period and magnitude of the the partiai duration series can be plotted on semilogarithmic paper using the relation

$$T = (N+1)/M$$

in which,

T = is recurrence interval,

M = is the ranking, the events being arranged in discending order the highest event having the first ranking and

N = is number of events

The magnitude of the N year event can be determined from this plotting. This technique is particularly useful for estimating events of low recurrence interval from a short record.

For return periods greater than 10 years there is almost no difference between the partial duration series and annual maximum series. There is a difference, however, between the probabilities calculated from the two series for small events. Table 2 gives empirical factors for converting the magnitude of the partial duration series from that of the annual maximum series.

Table 2 : Empirical factors for converting rainfall magnitude calculated from the annual-maximum series to the partial-duration-series for the same recurrence interval

Recurrence Interval (Year)	Converting Factor
2	1.13
5	1.04
10	1.01
20	1.00

Factors for Converting Point Rainfall Values to Areal Average Values :

Averaging point-rainfall values of a given frequencies does not yield an areal average of the same frequency. It is not permissible to average the 10 year, 1 hour storm at five stations in a 100-square-miles basin to obtain the 10 year, 1 hour storm over the whole 100 square miles. The U.S. weather Bureau based on field study, has found the relationship as shown in Figure 1 between point rainfall of a specified duration (regardless of its frequency) and the average rainfall over areas upto 400 square miles. Once the magnitude of the rainfall of some frequency has been evaluated for one station located in an area of interest, the average rainfall for the area of interest can be obtained by multiplying it with appropriate value taken from the ordinate of Figure 1 (Vide Sheaffer et. al., 1982).

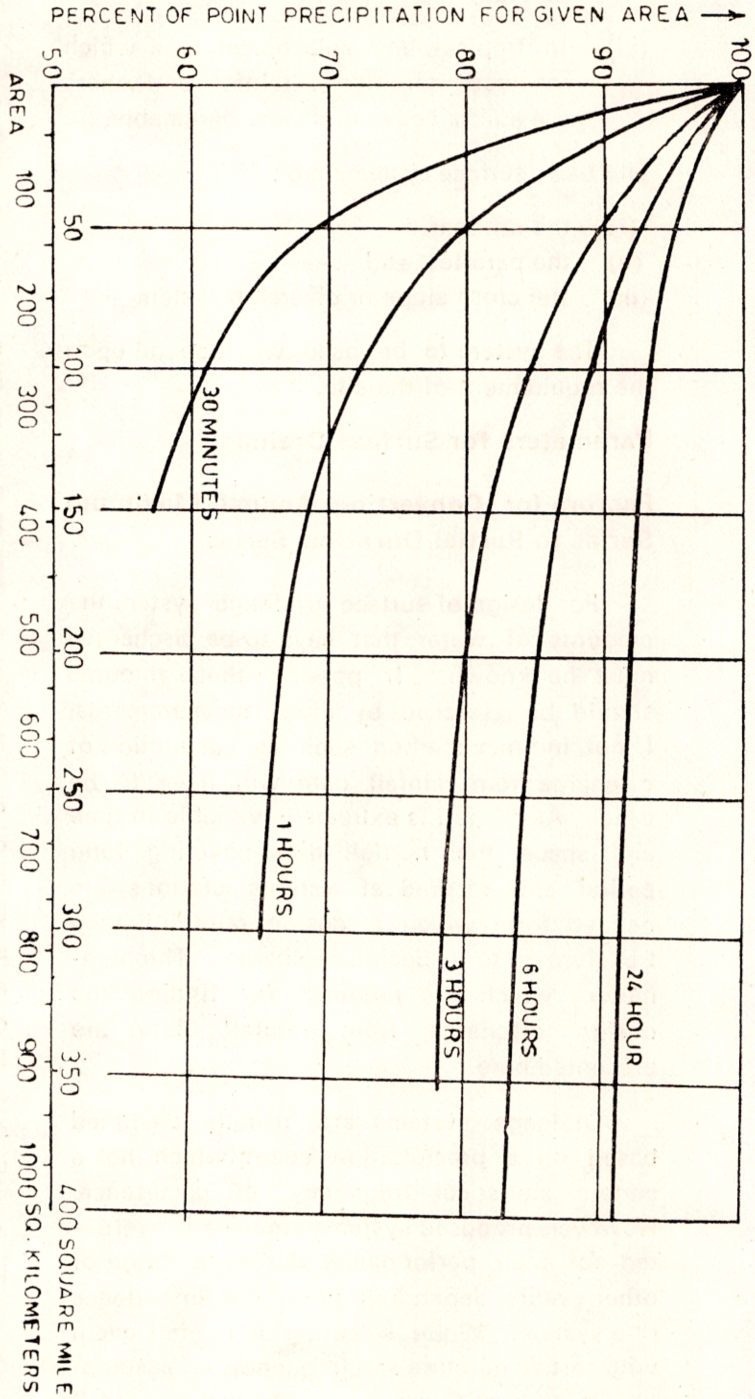


Fig. 1 : Areal Analysis Graph

Computation of Design Discharge

The storm runoff peak, volume and timing provide the basis for planning, design and construction of drainage facilities, Five basis approaches can be utilized for determining the character of storm runoff. They are :

(a) The rational Method,
(b) Synthetic Unit Hydrograph Procedure,
(c) Computer Simulation Modelling,
(d) Hydrologic Modelling, and
(e) SCS Method

Estimation of Direct Runoff from Storm Rainfall by SCS Method

The SCS method is widely used for designing surface drainage system. The principal application of the method is an estimating quantities of direct runoff from storm rainfall. The SCS rainfall-runoff relation uses the total of one or more storms occuring in a calendar day and nothing is used about the time distribution. The relation therefore excludes time as an explicit variable, which means that rainfall intensity is ignored. If every thing but storm duration or infensity is the same for two storms, the estimate of runoff is the same for both storms. (Mc Cuenes, 1982). Soil properties influence the process of generation of runoff from rainfall and they must be considered, even if only indirectly, in methods of runoff estimation. When runoff from individual storms is the major concern, as in flood prevention work, the properties can be represented by a hydrologic parameter : the minimum rate of infiltration obtained for a base soil after prolonged wetting. The influences of both the surface and the horizons of a soil are thereby included.

The infiltration rate is the rate at which water enters the soil at the surface conditions, and the transmission rate is the rate at which the water moves in the soil and which is controlled by the horizons. The hydrologic soils classification takes into consideration the minimum rate of infiltration for bare soil after prolonged wetting. The hydrologic soil groups as defined by SCS soil scientists, are :

A. Low runoff potential : Soils having high infiltration rates even when thoroughly wetted and consisting chiefly of deep, well to excessively drained sands or gravels. These soils have a high rate of water transmission of the order 7.5-11.5 cm/hr.

B. Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately course textures. These soils have a moderate rate of water transmission of the order 4-7.5 cm/hr.

C. Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water or soils with moderately fine to fine textures. These soils have a slow rate of water transmission of the order 0.13-4 cm/hr.

D. (High runoff potential). Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission of the order 0-0.13 cm/hr.

Besides, infiltration characteristics the antecedent moisture condition in a catchment governs significantly the fraction of storm precipifation which is converted to direct runoff SCS method recognises three stages of antecedent moisture condition which are :

AMC–I (Lowest runoff potential),

If the watershed soils are dry enough for satisfactory plowing or cultivation to take place, the moisture condition is classified as AMC-1.

AMC–II For the average condition, the soil moisture condition is classified as AMC-II

AMC–III (Highest runoff potential).

If the watershed is practically saturated from antecedent rains the moisture condition is considered as AMC-III. The AMC can be estimated from 5-day antecedent rainfall as indicated in Table 3 which give the rainfall limits by season categories.

Table 3 : 5-day antecedent rainfall (SCS, 1972)

AMC Group	Dormant season (cms)	Growing season (cms)
I	< 1.3	< 3.6
II	1.3 to 2.9	3.6 to 5.4
III	> 2.8	> 5.4

SCS method assumes the following rainfall-runoff relation which is shown schematically in Fig. 2 (a) and 2 (b).

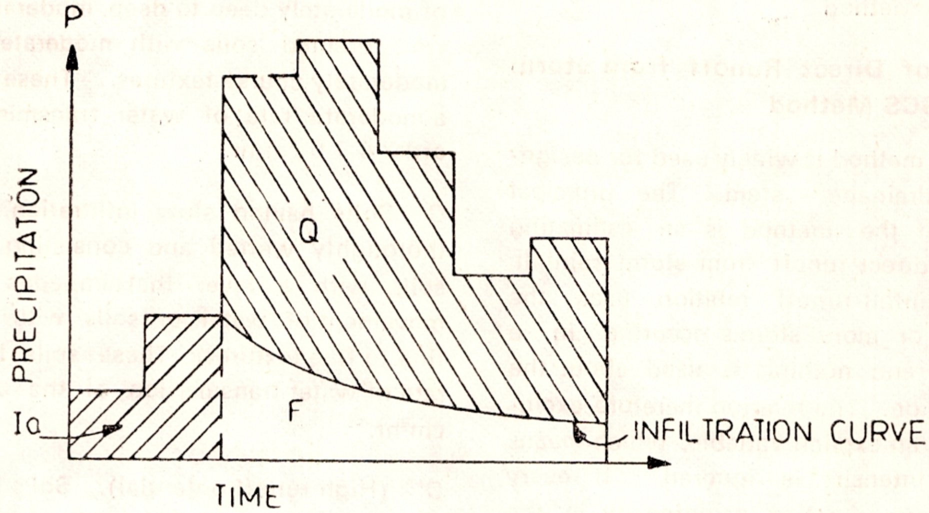


Fig. 2 (a) ; Relationship between Precipitation, Runoff & Retention

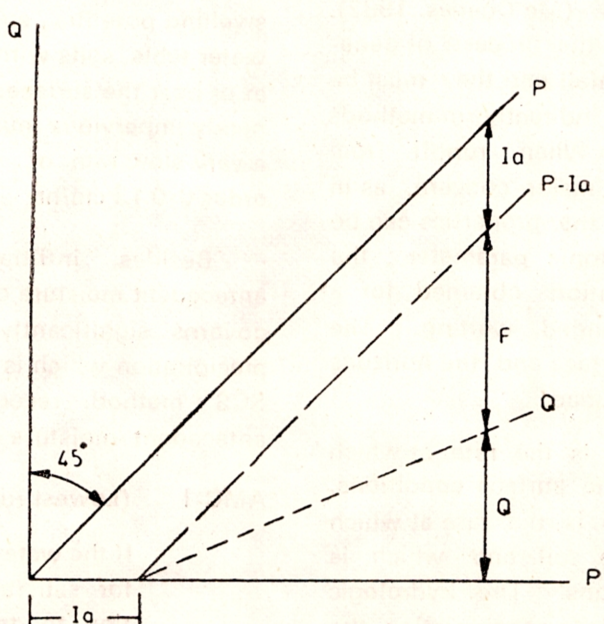


Fig. 2 (b) : A Mass Curve Representation of the SCS Rainfall Runoff Relationship

$$\frac{F}{S} = \frac{O}{P-I_a} \quad ...(1)$$

in which,

S = Potential maximum retention,

P = Volume of precipitation,

Q = Volume of runoff,

F = Actual retention

I_a = Initial abstraction which consists of interception, infiltration and surface storage all of which occur before runoff begins. The initial abstraction is a function of land use, and antecedent soil moisture condition.

The actual retention has been expressed as :

$$F = (P-I_a) - Q \quad ...(2)$$

Equations (1) & (2) have been combined and the following relation has been derived (SCS, 1956) :

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

An empirical relationship between I_a and S has been suggested which is based on analysis of rainfall and runoff data from several experimental watershed in USA and the relationship is given by :

$$I_a = 0.2S \quad ...(4)$$

Substitution of I_a value in equation (3) leads to

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)}\ ;\ P \geqslant 0.2S \quad ...(5)$$

Equation (5) is the hydrologic relation between storm rainfall, soil site storage, and storm runoff used in the SCS method of estimating direct runoff from storm rainfall. The direct runoff consists of channel runoff, surface runoff and subsurface flow (interflow). It does not include the baseflow component. In equation (5) the storage parameter, S, is an indicator of land condition. It may vary from zero for an impervious wateshed to infinite for a completely absorbent watershed. The value of S is still unknow. Based on analysis of rainfall runoff data in several watersheds having the same cover complex the storage in the form of curve number. CN, have been defined by SCS for various hydrologic cover complex. A hydrologic complex is a combination of a hydrologic soil group and a land use and treatment class.

The relation between curve number (CN) and storage index (S) is given by

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

Where CN is a dimensionless number, having no intrinsic meaning. It gives a convenient transformation of S to establish a 0 to 100 scale. The CN incorporates the effects of infiltration characteristics of the soil, land use and agricultural practices. Curve Numbers for different vegetative types and hydrologic soil groups are presented in Table 4 for AMC–II condition. The conversion factor to find curve number for other AMC conditions are given in Table 5.

Determination of Direct Runoff Consequent to Several Days Consequtive Rainfall

Direct runoff volume when rainfall continues for several days can be predicted using SCS method that has been outlined by Hawkins (1978). The procedure is described below which is based on updating the curve number by continuous accounting of storage.

Using the basic SCS rainfall runoff equation (5), expanding the numerator and applying polynomial division.

$$Q = P - S\,[1.2 - S/(P+0.8\,S)],\ P \geqslant 0.2\,S \quad ...(7)$$

It can be seen from the equation (7) that the possible difference (as $P \rightarrow \infty$) between rainfall (P) and direct runoff (Q) is not S but 1.2 S.

Let $V = 1.2\,S$

Table 4 — Runoff curve numbers for hydrologic soil-cover complexes
(Antecedent moisture condition II, and $I_a = 0.2$ S)

Cover: Land use	Cover: Treatment or practice	Cover: Hydrologic condition	Hydrologic soil group: A	B	C	D
Fallow	Straight row	-----	77	86	91	94
Row crops	"	Poor	72	81	88	91
	"	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	"	Good	65	75	82	86
	" and terraced	Poor	66	74	80	82
	" "	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	" and terraced	Poor	61	72	79	82
		Good	59	70	78	81
Close-seeded legumes 1/ or rotation meadow	Straight row	Poor	66	77	85	89
	" "	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	"	Good	55	69	78	83
	" and terraced	Poor	63	73	80	83
	" and terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	"	Fair	25	59	75	83
	"	Good	6	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		----	59	74	82	86
Roads (dirt) 2/		----	72	82	87	89
(hard surface) 2/		----	74	84	90	92

1/ Close-drilled or broadcast
2/ Including right-of-way.

Table 5 — Curve numbers (CN) and constants for the case $I_a = 0.2$ S

CN for condition II	CN for conditions I	CN for conditions III	CN for condition II	CN for conditions I	CN for conditions III
100	100	100	60	40	78
99	97	100	59	39	77
98	94	99	58	38	76
97	91	99	57	37	75
96	89	99	56	36	75
95	87	98	55	35	74
94	85	98	54	34	73
93	83	98	53	33	72
92	81	97	52	32	71
91	80	97	51	31	70
90	78	96	50	31	70
89	76	96	49	30	69
88	75	95	48	29	68
87	73	95	47	28	67
86	72	94	46	27	66
85	70	94	45	26	65
84	68	93	44	25	64
83	67	93	43	25	63
82	66	92	42	24	62
81	64	92	41	23	61
80	63	91	40	22	60
79	62	91	39	21	59
78	60	90	38	21	58
77	59	89	37	20	57
76	58	89	36	19	56
75	57	88	35	18	55
74	55	88	34	18	54
73	54	87	33	17	53
72	53	86	32	16	52
71	52	86	31	16	51
70	51	85	30	15	50
69	50				
68	48	84	25	12	43
67	47	83	20	09	37
66	46	82	15	06	30
65	45	82	10	04	22
64	44	81	05	02	13
63	43	80	00	00	00
62	42				
61	41				

This can be envisaged as the total storage available on the site for a given condition of soil vegetation and moisture status. At time t_1, the storage available is.

$$V_1 = 1.2\ S_1 = 1.2\ (1000/CN_1 - 10) \quad ...(8)$$

Any change in V_1, will be due to the actual evapotranspiration losses (ETA), rainfall (P) and runoff (Q) occuring at the time. So at time t_2

$$V_2 = V_1 + ETA_1 - (P_1 - Q_1) \quad ...(9)$$

Therefore,

$$V_2 = 1.2\ (1000/CN_1 - 10) + ETA_1 - (P_1 - Q_1) = 1.2\ S_2 \quad ...(10)$$

By definition.

$$CN_2 = \frac{1000}{10 + V_2/1.2}$$

Substituting value of V_2

$$CN_2 = \frac{1200}{1200/CN_1 + [ET_1 - (P_1 - Q_1)}$$

at time t_n

$$V_n = V_{n-1} + ETA_{n-1} - (P_{n-1} - Q_{n-1}) = 1.2\ S_n \quad ...(11)$$

Soil moisture storage by SCS method can be estimated by using equation (11) for any real value of P, Q and ETA.

Actual evapotranspiration can be estimated by the relationship :

$$ETA = \frac{ETP \times (\theta - WP)}{(FC - WP)} \quad ...(12)$$

where,

θ = Soil moisture (Volume ratio)

WP = Average wilting point (Volume ratio)

FC = Average field capacity (Volume ratio)

ETP = Potential evapotranspiration

Here WP and FC are the properties of the soil and ETP depends on metrological factors. However daily soil moisture shall vary depending upon the part of the precipitation retained by the catchment and the actual evapotranspiration occured during the day.

Once the curve numbers are updated, the daily surface runoff volumes can be known using the respective curvenumber making use of equation (5) and (6).

Let Q_1, Q_2, and Q_3 be the direct surface runoff volume on the first, second and the third day due to a storm that continues for three day as shown in Fig. 3. It may be noted that, according to Indian Standard, the surface drainage system is to be designed for a storm of three day duration. Let A be the area of the catchment and t_c is the time of concentration in fraction of a day. Let the rising limbs and falling limb of the hydrograph be straight lines. The peak discharge rates on different days can be estimated as given below

$$A\ Q_1 = 0.5 p_1 t_c + (1 - t_c)\ p_1$$

$$\text{or} \quad p_1 = AQ_1/(1 - 0.5\ t_c) \quad (13)$$

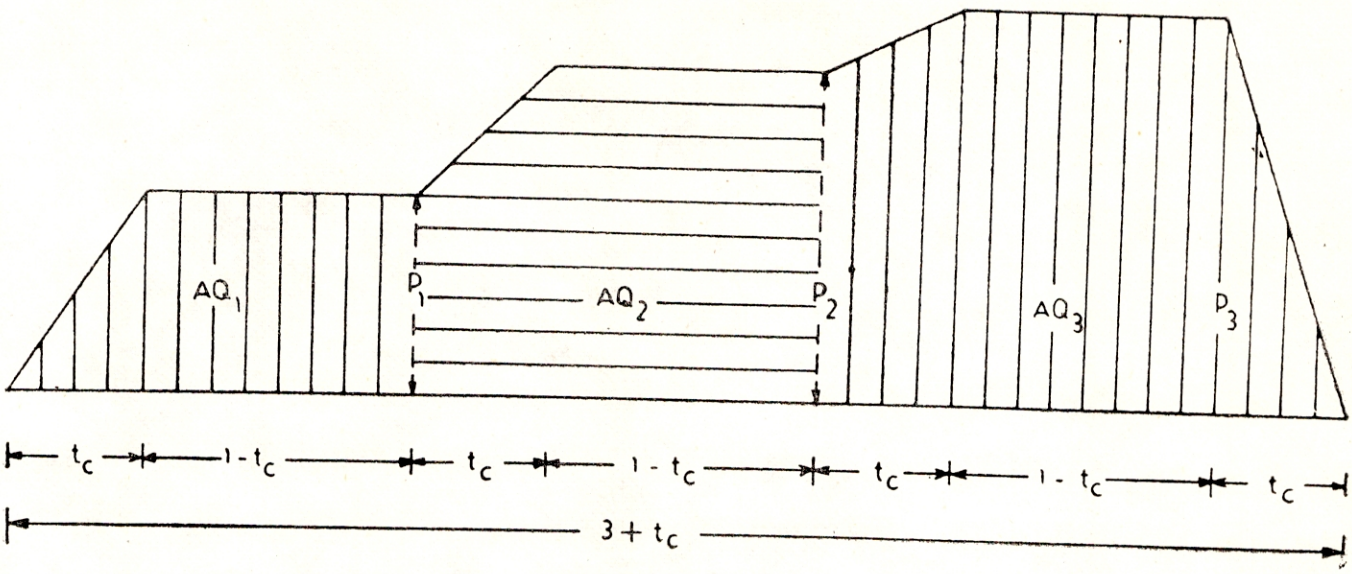
$$A\ Q_2 = 0.5\ t_c\ (p_1 + p_2) + (1 - t_c)\ p_2$$

$$\text{or} \quad p_2 = AQ_2/(1 - 0{,}5\ t_c) - 0.5\ t_c\ AQ_1/(1 - 0.5\ t_c)^2 \quad (14)$$

$$A\ Q_3 = 0.5\ t_c\ (p_3 - p_3) + (1 - t_c)\ p_3$$

$$\text{or} \quad p_3 = AQ_3/(1 - 0.5\ t_c) - 0.5\ t_c\ AQ_2/(1 - 0.5\ t_c)^2 + 0.25\ t_c^2\ AQ_1/(1 - 0.5\ t_c)^3 \quad (15)$$

The drainage channel should be designed for the highest peak discharge rate p_3 given in equation (15).



Q_1 = Direct runoff on the first day

Q_2 = Direct runoff on the second day

Q_3 = Direct runoff on the third day

Fig. 3 : Runoff Hydrograph consequent to a 3-day storm

Conclusions

The suitability of surface drainage system, the hydrological parameters needed for design of surface drainage system, updating of SCS curve number and the SCS method for computation of design discharge during successive rainy days have been reviewed in this paper. A method for computation of peak discharge for which the surface drainage channel should be designed has been suggested, However field verification of the proposed method of computation of design discharge would be necessary.

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