5

HYDROLOGY OF MIDSIZE CATCHMENTS

A midsize catchment is described by the following features: (1) rainfall intensity varies *within* the storm duration; (2) storm rainfall can be assumed to be uniformly distributed in space; (3) runoff is by overland flow and stream channel flow; and (4) channel slopes are steep enough so that channel storage processes are small (see Chapter 9).

A catchment possessing some or all of the above properties is *midsize* in a hydrologic sense. Since rainfall intensity varies within the storm duration, catchment response is described by methods that take explicit account of the temporal variation of rainfall intensity. The most widely used method to accomplish this is the unit hydrograph technique. In an nutshell, it consists of deriving a hydrograph for a unit storm (the unit hydrograph) and using it as a building block to develop the hydrograph corresponding to the actual effective storm hyetograph.

In unit hydrograph analysis, the duration of the unit hydrograph is usually a fraction of the time of concentration. The increase in time of concentration is due to the larger drainage area and the associated reduction in overall catchment gradient. The latter has the effect of increasing runoff diffusion.

The assumption of uniform spatial distribution of rainfall is a characteristic of midsize catchment analysis. This assumption allows the use of a lumped method such

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The assumption of uniform spatial distribution of rainfall is a characteristic of midsize catchment analysis. This assumption allows the use of a lumped method such as the unit hydrograph.

Unlike midsize catchments, for large catchments rainfall is likely to vary spatially, either as a general storm of concentric isohyetal distribution covering the entire catchment with moderate rainfall or as a highly intensive local storm (thunderstorm) covering only a portion of the catchment.

An important feature of large catchments that sets them apart from midsize catchments is their substantial capability for channel storage. Channel storage processes act to attenuate the flows while in transit in the river channels. Attenuation can be due either to longitudinal storage (for inbank flows) or to lateral storage (for overbank flows). In the first case, the storage amount is largely controlled by the slope of the main channel. For catchments with mild channel slopes, channel storage is substantial; conversely, for catchments with steep channel slopes, channel storage is negligible. Since large catchments are likely to have mild channel slopes, it follows that they have a substantial capability for channel storage.

In practice, this means that large catchments cannot be analyzed with spatially lumped methods such as the unit hydrograph, since these methods do not take explicit account of channel storage processes. Therefore, unlike for midsize catchments, for large catchments it is necessary to use channel routing (Chapter 9) to account for the expanded role of river flow in the overall runoff response.

As with the limit between small and midsize catchments, the limit between midsize and large catchments is not immediately apparent. For midsize catchments, runoff response is primarily a function of the characteristics of the storm hyetograph, with concentration time playing a secondary role. Therefore, the latter is not well suited as a descriptor of catchment scale. Values ranging from 100 to 5000 km^2 have been variously used to define the limit between midsize and large catchments. While there is no consensus to date, the current trend is toward the lower limit. In practice, it is likely that there would be a range of sizes within which both midsize and large catchment techniques are applicable. However, the larger the catchment area, the less likely it is that the lumped approach is able to provide the necessary spatial detail.

It should be noted that the techniques for midsize and large catchments are indeed complementary. A large catchment can be viewed as a collection of midsize subcatchments. Unit hydrograph techniques can be used for subcatchment runoff generation, with channel routing used to connect streamflows in a typical dendritic network fashion (Fig. 5-1). Such a computationally intensive procedure is ideally suited to solution with the aid of a computer. Examples of hydrologic computer models using the network concept are HEC-1 of the U.S. Army Corps of Engineers and TR-20 of the USDA Soil Conservation Service. These and other computer models are described in Chapter 13.

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In practice, channel-routing techniques are not necessarily restricted to large catchments. They can also be used for midsize catchments and even for small catchments. However, the routing approach is considerably more complicated than the unit hydrograph technique. The routing approach is applicable to cases where an increased level of detail is sought, above that which the unit hydrograph technique is able to provide—for instance, when the objective is to describe the temporal variation of streamflow at several points *inside* the catchment. In this case, the routing approach may well be the only way to accomplish the modeling objective.

The hydrologic description of midsize catchments consists of two processes: (1) rainfall abstraction and (2) hydrograph generation. This chapter focuses on a method of rainfall abstraction that is widely used for hydrologic design in the United States: the Soil Conservation Service (SCS) runoff curve number method. Other rainfall abstraction procedures used by existing computer models are discussed in Chapter 13.

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With regard to hydrograph generation, this chapter centers on the unit hydrograph technique, which is a defacto standard for midsize catchments, having been

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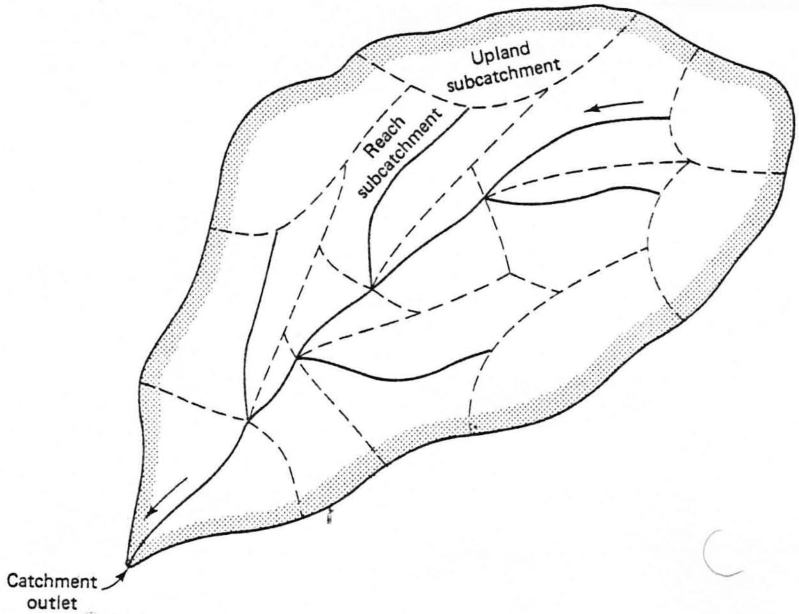

Figure 5-1 Subdivision of large catchment into midsize upland and reach subcatchments.

used extensively throughout the world. The SCS TR-55 method, also included in this chapter, has peak flow and hydrograph generation capabilities and is applicable to small and midsize urban catchments with concentration time in the range 0.1-10.0 h. The TR-55 method is based on the runoff curve number method, unit hydrograph techniques, and simplified stream channel routing procedures.

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This chapter is divided into three sections. Section 5.1 describes the runoff curve number method. Section 5.2 discusses unit hydrograph techniques, including unit hydrographs derived from measured data and synthetic unit hydrographs. Section 5.3 deals with the TR-55 graphical method for peak-discharge determinations.

5.1 RUNOFF CURVE NUMBER METHOD

The runoff curve number method is a procedure for hydrologic abstraction of storm rainfall developed by the U.S. Natural Resources Conservation Service (formerly *Soil Conservation Service*) [21]. In this method, total storm runoff depth is a function of total storm rainfall depth and an abstraction parameter referred to as runoff curve number, curve number, or *CN*. The curve number varies in the range 0-100, being a function of the following runoff-producing catchment properties: (1) hydrologic soil type, (2) land use and treatment types, (3) hydrologic surface condition, and (4) antecedent moisture condition.

The runoff curve number method was developed based on daily rainfall P (in.) and its corresponding runoff Q (in.) for the annual floods at a given site. It limits itself to the calculation of runoff depth and does not explicitly account for temporal variations of rainfall intensity. In midsize catchment analysis, the temporal rainfall distribution is introduced at a later stage, during the generation of outlet

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Runoff Curve Number Equation

In the runoff curve number method, potential runoff (i.e., total rainfall) is referred to as P; actual runoff is referred to as Q. Potential retention (or, in NRCS's use, "potential maximum retention") is referred to as S; actual retention is defined as $(P - Q)$, with $(P - Q) \leq S$.

The method assumes a proportionality between retention and runoff, such that the ratio of actual retention to potential retention is equal to the ratio of actual runoff to potential runoff:

$$\frac{P - Q}{S} = \frac{Q}{P} \tag{5-1}$$

This assumption underscores the conceptual basis of the runoff curve number method, namely the asymptotic behavior of actual retention toward potential retention for sufficiently large values of potential runoff.

For practical applications, Eq. 5-1 is improved by reducing the potential runoff by an amount equal to the initial abstraction I_a. The latter consists mainly of interception, surface storage, and some infiltration, which take place before runoff begins.

$$\frac{P - I_a - Q}{S} = \frac{Q}{P - I_a} \tag{5-2}$$

Solving for Q from Eq. 5-2:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{5-3}$$

which is physically subject to the restriction that $P \geq I_a$ (i.e., the potential runoff minus the initial abstraction cannot be negative).

To simplify Eq. 5-3, initial abstraction is related to potential maximum retention as follows:

$$I_a = 0.2S \tag{5-4}$$

This relation was obtained based on rainfall-runoff data from small experimental watersheds. The coefficient 0.2 has been subjected to wide scrutiny. For instance, Springer et al. [18] evaluated small humid and semiarid catchments and found that the coefficient in Eq. 5-4 varied in the range 0.0 to 0.26. Nevertheless, 0.2 is the standard initial abstraction coefficient recommended by SCS [21]. For research applications and particularly when warranted by field data, it is possible to consider the initial

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$$I_a = KS \tag{5-5}$$

/ λ

in which K = initial abstraction parameter.

/ λ

With Eq. 5-4, Eq. 5-3 reduces to:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{5-6}$$

which is subject to the restriction that $P \geq 0.2S$.

Since potential retention varies within a wide range (0-∞), it has been conveniently mapped in terms of a runoff curve number, an integer varying in the range 0-100. The chosen mapping equation is:

$$S = \frac{1000}{CN} - 10 \tag{5-7}$$

in which CN is the runoff curve number (dimensionless), and S, 1000, and 10 are given in inches. To illustrate, for CN =100, S = 0; and for CN = 0, S = ∞. Therefore, the catchment's capability for rainfall abstraction is inversely proportional to the runoff curve number. For CN = 100 no abstraction is possible, with runoff being equal to potential runoff, i.e., total rainfall. For CN = 0 the catchment's abstractive capability is infinite, and runoff is reduced to zero.

in which CN is the runoff curve number (dimensionless) and S, 1000 and 10 are given in inches. To illustrate, for $CN = 100$, $S = 0$; and for $CN = 1$, $S = 990$ in. Therefore, the catchment's capability for rainfall abstraction is inversely proportional to the runoff curve number. For $CN = 100$ no abstraction is possible, with runoff being equal to total rainfall. On the other hand, for $CN = 1$ practically all rainfall would be abstracted, with runoff being essentially equal to zero.

With Eq. 5-7, Eq. 5-6 can be expressed in terms of CN:

$$Q = \frac{[CN(P + 2) - 200]^2}{CN\,[CN(P - 8) + 800]} \tag{5-8}$$

which is subject to the restriction that $P \geq (200/CN) - 2$. In Eq. 5-8, P and Q are given in inches. In SI units, the equation is:

$$Q = \frac{R[CN(P/R + 2) - 200]^2}{CN\,[CN(P/R - 8) + 800]} \tag{5-9}$$

which is subject to the restriction that $P \geq R[(200/CN) - 2]$. With $R = 2.54$ in Eq. 5-9, P and Q are given in centimeters.

For a variable initial abstraction, Eq. 5-8 is expressed as follows:

$$Q = \frac{[CN(P + 10K) - 1000K]^2}{CN\{CN\,[P - 10(1 - K)] + 1000(1 - K)\}} \tag{5-10}$$

which is subject to the restriction that $P \geq (1000K/CN) - 10K$. An equivalent equation in SI units is:

$$Q = \frac{R[CN(P/R + 10K) - 1000K]^2}{CN\{CN\,[P/R - 10(1 - K)] + 1000(1 - K)\}} \tag{5-11}$$

which is subject to the restriction that $P \geq R[(1000K/CN) - 10K]$.

A graph of Eqs. 5-8 and 5-9 is shown in Fig. 5-2. This figure is applicable only for the standard initial abstraction value, $I_a = 0.2S$. If this condition is relaxed, as in Eqs. 5-10 and 5-11, Fig. 5-2 has to be modified appropriately.

replace for

/ λ

(12 times)

Estimation of Runoff Curve Number From Tables

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Estimation of Runoff Curve Number From Tables

With rainfall P and runoff curve number CN, the runoff Q can be determined by either Eq. 5-8 or Eq. 5-9 or from Fig. 5-2.

For ungaged watersheds, estimates of runoff curve numbers are given in tables supplied by federal agencies (SCS, Forest Service) and local city and county departments. Tables of runoff curve numbers for various hydrologic soil-cover complexes are widely available. The hydrologic soil-cover complex describes a specific combination of hydrologic soil group, land use and treatment, hydrologic surface condition, and

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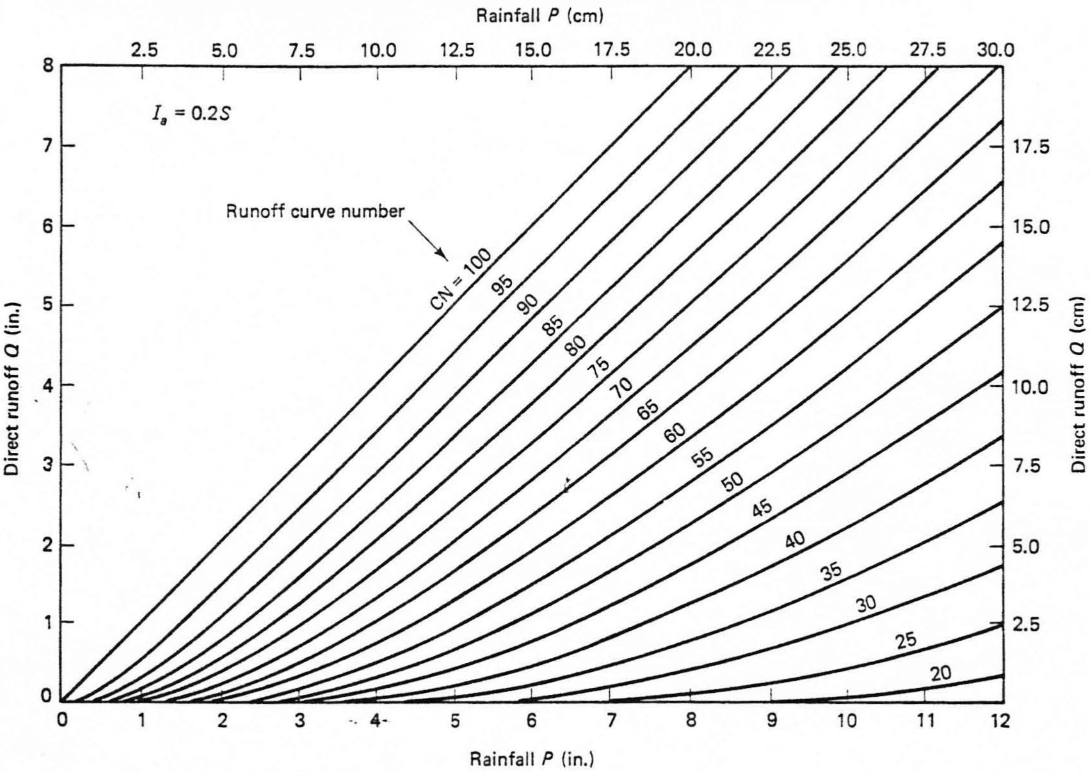

Figure 5-2 Direct runoff as a function of rainfall and runoff curve number [21].

antecedent moisture condition. All these have a direct bearing on the amount of runoff produced by a watershed. The hydrologic soil group describes the type of soil. The land use and treatment describes the type and condition of vegetative cover. The hydrologic condition refers to the ability of the watershed surface to enhance or impede direct runoff. The antecedent moisture condition accounts for the recent history of rainfall, and consequently it is a measure of the amount of moisture stored by the catchment.

/class
/surface

Hydrologic Soil Groups. All soils are classified into four hydrologic soil groups of distinct runoff-producing properties. These groups are labeled A, B, C, and D.

Group A consists of soils of low runoff potential, having high infiltration rates even when wetted thoroughly. They are primarily deep, very well drained sands and gravels, with a characteristically high rate of water transmission.

Group B consists of soils with moderate infiltration rates when wetted thoroughly, primarily moderately deep to deep, moderately drained to well drained, with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.

Group C consists of soils with slow infiltration rate when wetted thoroughly, primarily soils having a layer that impedes downward movement of water or soils of moderately fine to fine texture. These soils have a slow rate of water transmission.

Group D consists of soils of high runoff potential, having very slow infiltration rates when wetted thoroughly. They are primarily clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay layer near the surface, and shallow soils overlying impervious material. These soils have a very slow rate of water transmission.

Maps showing the geographical distribution of hydrologic soil types for most areas in the United States are available either directly from SCS or from pertinent local agencies. Additional detail on U.S. soils and their hydrologic soil groups can be found in NEH-4 [21].

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Land Use and Treatment. The effect of the surface condition of a watershed is evaluated by means of land use and treatment classes. Land use pertains to the watershed cover, including every kind of vegetation, litter and mulch, fallow (bare soil), as well as nonagricultural uses such as water surfaces (lakes, swamps, and so on), impervious surfaces (roads, roofs, and the like), and urban areas. Land treatment applies mainly to agricultural land uses, and it includes mechanical practices such as contouring or terracing and management practices such as grazing control and crop rotation. A class of land use/treatment is a combination often found in a catchment.

The runoff curve number method distinguishes between cultivated land, grasslands, and woods and forests. For cultivated lands, it recognizes the following land uses and treatments: fallow, row crop, small grain, close-seed legumes, rotations (from poor to good), straight-row fields, contoured fields, and terraced fields. Additional detail on these land use and treatment classes can be found in NEH-4 [21].

Hydrologic Condition. Grasslands are evaluated by the hydrologic condition of native pasture. The percent of areal coverage by native pasture and the intensity of grazing are visually estimated. A poor hydrologic condition describes less than 50 percent areal coverage and heavy grazing. A fair hydrologic condition describes 50 to 75 percent areal coverage and medium grazing. A good hydrologic condition describes more than 75 percent areal coverage and light grazing.

Woods are small isolated groves or trees being raised for farm or ranch use. The hydrologic condition of woods is visually estimated as follows: (1) poor—heavily grazed or regularly burned woods, with very little litter and few shrubs, (2) fair—grazed but not burned, with moderate litter and some shrubs, and (3) good—protected from grazing, with heavy litter and many shrubs covering the surface.

Runoff curve numbers for forest conditions are based on guidelines developed by the U.S. Forest Service. The publication *Forest and Range Hydrology Handbook* [23] describes the determination of runoff curve numbers for national and commercial forests in the eastern United States. The publication *Handbook of Methods for Hydrologic Analysis* [24] is used for curve number determinations in the forest-range regions in the western United States.

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Antecedent Moisture Condition. The runoff curve number method has three levels of antecedent moisture: AMC I, AMC II, and AMC III. The dry antecedent moisture condition (AMC I) has the lowest runoff potential, with the soils being dry enough for satisfactory plowing or cultivation to take place. The average antecedent moisture condition (AMC II) has an average runoff potential. The wet antecedent moisture condition (AMC III) has the highest runoff potential, with the catchment being practically saturated by antecedent rainfalls. Prior to 1993, the appropriate AMC level was based on the total 5-d antecedent rainfall, lands, and woods and forests. For cultivated lands, it recognizes the following land uses and treatments: fallow, row crop, small grain, close-seed legumes, rotations (from poor to good), straight-row fields, contoured fields, and terraced fields. Additional detail on these land use and treatment classes can be found in NEH-4 [21].

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TABLE 5-1 SEASONAL RAINFALL LIMITS FOR THREE LEVELS OF ANTECEDENT MOISTURE CONDITION (AMC) [21]

AMC	Total 5-d Antecedent Rainfall (cm)	
	Dormant Season	Growing Season
I	Less than 1.3	Less than 3.6
II	1.3 to 2.8	3.6 to 5.3
III	More than 2.8	More than 5.3

Note: This table was developed using data from the midwestern United States. Therefore, caution is recommended when using the values supplied in this table for AMC determinations in other geographic or climatic regions.

Tables of runoff curve numbers for various hydrologic soil-cover complexes are in current use. Table 5-2(a) shows runoff curve numbers for urban areas, Table 5-2(b) shows them for cultivated agricultural areas, Table 5-2(c) shows them for other agricultural lands, and Table 5-2(d) shows them for arid and semiarid rangelands. Runoff curve numbers shown in these tables are for the average AMC II condition. Corresponding runoff curve numbers for AMC I and AMC III conditions are shown in Table 5-3.

Using Eq. 5-7, Hawkins et al [8] have expressed the values in Table 5-3 in terms of potential maximum retention. They correlated the values of potential maximum retention for AMC I and III with those of AMC II and found the following ratios to be a good approximation:

$$\frac{S_{\mathrm{I}}}{S_{\mathrm{II}}} \cong \frac{S_{\mathrm{II}}}{S_{\mathrm{III}}} \cong 2.3 \tag{5-12}$$

This led to the following relationships:

$$CN_{\mathrm{I}} = \frac{CN_{\mathrm{II}}}{2.3 - 0.013\, CN_{\mathrm{II}}} \tag{5-13}$$

$$CN_{\mathrm{III}} = \frac{CN_{\mathrm{II}}}{0.43 + 0.0057 CN_{\mathrm{II}}} \tag{5-14}$$

which can be used in lieu of Table 5-3 to calculate runoff curve numbers for AMC I and AMC III in terms of the AMC II value.

TABLE 5-2(a) RUNOFF CURVE NUMBERS FOR URBAN AREAS[1] [22]

Cover Description		Curve Numbers for Hydrologic Soil Group:			
Cover Type and Hydrologic Condition	Average Percent Impervious Area[2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.)[3]:					
Poor condition (grass cover less than 50%)		68	79	86	89
Fair condition (grass cover 50 to 75%)		49	69	79	84
Good condition (grass cover greater than 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curves and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only)[4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-in. sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
$\frac{1}{8}$ ac. or less (town houses)	65	77	85	90	92
$\frac{1}{4}$ ac.	38	61	75	83	87
$\frac{1}{3}$ ac.	30	57	72	81	86
$\frac{1}{2}$ ac.	25	54	70	80	85
1 ac.	20	51	68	79	84
2 ac.	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation)[5]		77	86	91	94
Idle lands (curve numbers (CNs) are determined using cover types similar to those in Table 5-2(c)).					

Notes:

[1]Average antecedent moisture condition and $I_a = 0.2S$.

[2]The average percent impervious area shown was used to develop the composite *CN*s. Other assumptions are as follows: Impervious areas are directly connected to the drainage system; impervious areas have a $CN = 98$; and pervious areas are considered equivalent to open space in good hydrologic condition. *CN*s for other combinations of conditions may be computed using Fig. 5-16 or 5-17.

[3]*CN*s shown are equivalent to those of pasture. Composite *CN*s may be computed for other combinations of open space cover type.

[4]Composite CN's for natural desert landscaping should be computed using Figs. 5-16 or 5-17 based on the impervious area percentage ($CN = 98$) and the pervious area *CN*. The pervious area *CN*s are assumed equivalent to desert shrub in poor hydrologic condition.

[5]Composite *CN*s to use for the design of temporary measures during grading and construction should be computed using Figs. 5-16 or 5-17, based on the degree of development (impervious area percentage) and the CNs for the newly graded pervious areas.

TABLE 5-2(b) RUNOFF CURVE NUMBERS FOR CULTIVATED AGRICULTURAL LANDS[1] [22]

Cover Description			Curve Numbers for Hydrologic Soil Group:			
Cover Type	Treatment[2]	Hydrologic Condition[3]	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured and terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T + CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T + CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

Notes:

[1]Average antecedent moisture condition and $I_a = 0.2S$.

[2]*Crop residue cover* applies only if residue is on at least 5% of the surface throughout the year.

[3]Hydrologic condition is based on combination of factors that affect infiltration and runoff, including: (1) density and canopy of vegetated areas; (2) amount of year-round cover; (3) amount of grass or close-seeded legumes in rotation; (4) percent of residue cover on the land surface (good hydrologic condition is greater than or equal to 20%); and (5) degree of surface roughness. *Poor:* Factors impair infiltration and tend to increase runoff. *Good:* Factors encourage average and better than average infiltration and tend to decrease runoff.

TABLE 5-2(c) RUNOFF CURVE NUMBERS FOR OTHER AGRICULTURAL LANDS[1] [22]

Cover Description		Curve Numbers for Hydrologic Soil Group:			
Cover Type	Hydrologic Condition	A	B	C	D
Pasture, grassland, or range-continuous forage for grazing[2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow-continuous grass, protected from grazing and generally mowed for hay	—	30	58	71	78
Brush—brush-weed grass mixture with brush being the major element[3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30[4]	48	65	73
Woods—grass combination (orchard or tree farm)[5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods.[6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30[4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

Notes:

[1]Average antecedent moisture condition and $I_a = 0.2S$.

[2]*Poor:* less than 50% ground cover on heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: more than 75% ground cover and lightly or only occasionally grazed.

[3]*Poor:* less than 50% ground cover.
Fair: 50 to 75% ground cover.
Good: more than 75% ground cover.

[4]Actual curve number is less than 30; use $CN = 30$ for runoff computations.

[5]*CN*s shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the *CN*s for woods and pasture.

[6]*Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.