RUNOFF CURVE NUMBER VARIATION WITH DRAINAGE AREA, WALNUT GULCH, ARIZONA

J. R. Simanton, R. H. Hawkins, M. Mohseni-Saravi, K. G. Renard

ABSTRACT. *Runoff Curve Numbers (a measure of a watershed's runoff response to a rainstorm) were determined using three different methods for 18 semiarid watersheds in southeastern Arizona. Each of the methods produced similar results. A relationship was then developed between optimum Curve Number and drainage area of the watershed used. Curve Numbers decreased with increasing drainage area. This response is a reflection of spatial variability in rainfall and infiltration losses in the coarse-textured material of the channels associated with larger drainage basins.*
Keywords. *Runoff, Curve Number.*

Hydrologists are frequently concerned with runoff from rainstorms for purposes of structural design, for post-event appraisals, and for environmental impact assessment. The most widely used technique is the "Curve Number" method, developed by the United States Department of Agriculture (USDA), Soil Conservation Service (SCS) — now the Natural Resource Conservation Service (NRCS). This model is explained in the SCS National Engineering Handbook, Section 4, Hydrology, or "NEH-4" (USDA-SCS, 1985). The storm runoff depth is calculated from the expression:

$$Q = (P - 0.2S)^2/(P + 0.8S) \qquad P > 0.2S$$

$$Q = 0 \qquad P < 0.2S \qquad (1)$$

where Q and P are the storm runoff and rainfall depths, respectively (in mm), and S is a measure of watershed storage in mm, equal to 5/6 of the maximum possible difference between effective rainfall (P – initial abstraction, Ia) and runoff. The storage index S is transformed into the coefficient Curve Number (CN) by the equation:

$$CN = 25\,400/(254 + S) \qquad (2)$$

CN is a dimensionless index, and can vary from 0 (no runoff, $S = \infty$) to 100 (all rainfall becomes runoff, $S = 0$). Design estimates of CN based on the hydrologic soil groups, cover, and land use are given in the original agency documentation and subsequent publications. Knowing the soils, the watershed surface cover, vegetative cover, and rainfall depth, the corresponding runoff depth is calculated with equations 1 and 2.

Equation 1 can be solved for S in terms of P and Q:

$$S = 5[P + 2Q - (4Q^2 + 5PQ)^{1/2}] \qquad (3)$$

When specific values of P and Q are available, solution for S and substitution into equation 2 gives the observed CN for the event. When storm variability is considered, a CN for application in a specific locality can be obtained.

CURVE NUMBER VARIATION WITH DRAINAGE AREA

Simanton et al. (1973), working with data from plots and small watersheds (0.00069 to 227 ha) in southern Arizona, found that CN varied inversely with drainage area. This was an unexpected finding, and the results (given in table 1) express the relation as:

$$CN = kA^{-b} \qquad (4)$$

where k and b are fitting coefficients, and A was drainage area in acres (1 acre = 0.40 ha). CN was calculated from recorded event rainfall and runoff pairs by a least-squares fitting of equation 1. It should be noted from equation 4 that when A = 1, CN = k. Thus the "k" coefficient might be seen as the root CN found on small (0.40 ha) upland source areas.

Since the original study in 1973, additional years of data, more stations, and newer data analysis techniques have become available. In this study we have revisited the original problem for additional verification and reinforcement of the original findings.

Table 1. Simanton et al. (1973) CN-area prediction equations

Watershed Vegetation Cover	Prediction Equation	Standard Error (CN)
Brush-covered	$CN = 85.75A^{-0.0087}$	± 1.6
Grass-covered	$CN = 88.00A^{-0.0085}$	± 1.1
Combined grass and brush	$CN = 86.74A^{-0.0088}$	± 3.5

Note: A = drainage area in acres.

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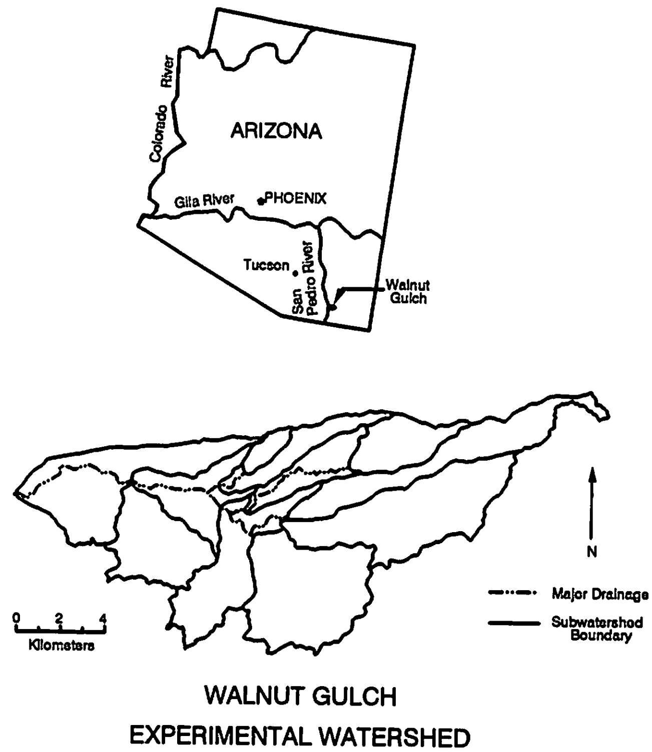

Figure 1–Location of the Walnut Gulch Experimental Watershed.

Table 2. General characteristics of selected watersheds in the Walnut Gulch Experimental Watershed, Tombstone, Arizona

Name	Area (ha)	Soil Series, Texture, and Vegetation Type
Plots	0.00069	Hathaway gravelly loam, grass/brush
105	0.182	Rillito/Laveen gravelly loam, brush
101	1.30	Rillito/Karro, brush
112	1.86	Bernardino/Hathaway gravelly loam, grass
103	3.68	Rillito/Laveen gravelly loam, brush
104	4.53	Rillito/Laveen gravelly loam, brush
215	36.9	Hathaway/Nickel, brush
223	48.4	Rillito/Laveen, brush
111	52.5	Bernardino/Hathaway gravelly loam, grass
220	60.4	Bernardino/Hathaway, grass
208	103.1	Hathaway/Bernardino, brush/grass
214	145.4	Hathaway/Bernardino, brush/grass
216	150.3	Hathaway/Bernardino, grass
207	151.4	Rillito/Cave/Tortugas, brush/grass
213	153.6	Graham/House Mountain, brush/grass
No. 4	228.7	Rillito/Laveen gravelly loam, brush
212	387.9	Cave/Rillito/Laveen/Tortugas, brush
No. 11	785.3	Hathaway/Bernardino/Nickel, brush/grass

Notes: The 100s are small flume or weir gaged watersheds; 200s are water level gaged stock tanks at watershed outlet. No. 4 and no. 11 are flume gaged major channeled watersheds.

Study Area, Data, and Methods

The study was conducted on the USDA, Agricultural Research Service's (ARS) Walnut Gulch Experimental Watershed in southeastern Arizona, USA (31°43′N, 110°41′W) (fig. 1). The watershed (150 km²) is representative of about 60 million ha of brush and grass rangeland found throughout the semiarid southwest and is considered a transition zone between the Chihuahuan and Sonoran Deserts. The watershed is an alluvial basin between isolated mountain blocks (Libby et al., 1970) and is typical of basin and range physiography in the western U.S. The alluvium consists of Tertiary and Quaternary aged deposits locally cemented by numerous calcrete layers.

Soils are generally well drained, calcareous, gravelly loams with large percentages of rock and gravel at the soil surface (Gelderman, 1970). Soil series sampled included Bernardino (a thermic Ustollic Haplargid), Cave (thermic, shallow Typic Paleothid), and Hathaway (thermic Aridic Calciustoll). In general, these series are of medium depth and well-drained, medium-textured soils derived from Quaternary alluvium. The uppermost 10 cm of the soil profiles contain up to 60% gravel and usually less than 40% gravel in the underlying parts of the profiles.

Average annual precipitation is about 300 mm with about 75% occurring as summer thunderstorms from July to mid-September (Osborn and Renard, 1988; Osborn et al., 1979). These thunderstorms are generally high intensity, short duration, limited in areal extent, and produce over 99% of the annual watershed runoff.

Major vegetation of the soil-slope complexes includes shrub species of creosote bush (*Larrea tridentata*), whitethorn (*Acacia constricta*), tarbush (*Flourensia cernua*), snakeweed (*Gutierrezia Sarothrae*), and burroweed (*Aplopappus tenuisectus*); and grass species of black grama (*Bouteloua eriopoda*), blue grama (*B. gracilis*), sideoats grama (*B. curtipendula*), and bush muhly (*Muhlenbergia porteri*).

Basic information about the watersheds used is given in table 2 and table 3 includes additional information on the duration and size of the rainfall and runoff records. These watersheds and data sets were chosen on the basis of data availability, consistency with the Simanton et al. (1973) study, and length of record. Event rainfall and runoff for which $Q > 0$ were used in this analysis.

Watershed Curve Numbers for the new data sets were determined by three different methods. Although the subsequent CN-area relationships are based on results from only one method (least squares), results from all three methods are presented for comparison.

Method I is the asymptotic method, which determines CN as an asymptotic limit for the CN calculated (using eq. 3) from ordered data pairs as P approaches ∞ (Hawkins, 1993). The equation:

Table 3. Data characteristics and runoff curve number

Watersheds		Event Data			Curve Number Fitting			
Name	Area(ha)	Period	No.	P (mm)	CN_∞	CN_{46}	N_{46}	CNLS
Plots	0.00069	-	-		-	-	-	89.27*
105	0.182	65-86	240	0.5-72.6	86.46	81.50	25	86.87
101	1.30	65-79	92	3.3-72.6	88.48	87.00	32	88.53
112	1.86	63-79	118	2.0-55.4	84.69	81.80	24	84.46
103	3.68	71-75	65	4.6-72.4	87.76	85.76	17	87.06
104	4.53	63-87	203	1.3-72.6	83.39	78.00	12	82.91
215	36.9	66-79	85	3.3-80.3	85.34	84.20	25	82.70
223	48.4	60-77	115	2.8-68.8	88.25	86.00	31	88.31
111	52.5	-	-	-	-	-	-	86.00*
220	60.4	59-77	21	5.1-45.5	78.40	n	n	78.20
208	103.1	69-79	68	5.3-46.7	84.91	n	n	80.26
214	145.4	61-79	109	2.5-50.0	87.15	83.80	33	86.73
216	150.3	66-78	69	3.8-57.9	76.86	73.30	4	76.51
207	151.4	59-77	98	1.5-49.5	79.85	78.00	6	79.86
213	153.6	69-79	39	10.4-52.8	71.76	n	n	70.10
No. 4	228.7	-	-	-	-	-	-	81.00*
212	387.9	69-79	65	3.3-50.8	77.42	n	n	74.91
No.11	785.3	82-87	37	10.2-80.3	78.73	69.50	1	70.58

Notes: "*" indicates values taken from Simanton et al. (1973).
"P" column gives the rainfall depth range (mm) of storm events used.
"n" indicates situations where criteria for calculation did not occur.
CN_∞ is the CN determined by the asymptotic method.
CN_{46} is the CN determined by the "(P/S) > 0.46" method.
N_{46} is the number of events for which (P/S) > 0.46, and which were used in the calculation of CN_{46}.
CNLS is the CN determined by the Least Squares method.

$$CN(P) = CN_\infty + (100 - CN_\infty)e^{-kP} \quad (5)$$

has been found to fit a wide variety of P-CN data sets, where CN_∞ is the constant value reached as P approaches ∞, and k is a fitting coefficient.

Method II is the "(P/S) > 0.46" method. It uses only event rainfall and runoff data for which (P/S) > 0.46, the theoretical point at which 90% of the occurrences of Q = 0 are avoided. This data censoring minimizes upward bias in CN calculation from this Q = 0 situation. The background for the method and the explanation of the trial-and-error procedure are described by Hawkins et al. (1985).

Method III (CNLS) is simply a least squares fitting of all the event rainfall and runoff depths to equation 1. In it, the quantity:

$$f(S) = \Sigma(Q_{ei} - Q_{oi})^2 \quad (6)$$

is minimized by variation of the storage index S, where Q_{ei} is the estimated runoff using a trial S value and an observed P_i in equation 1 and Q_{oi} is observed runoff corresponding to the observed P_i used to calculate Q_{ei}. This method is used throughout this article in order to be consistent with the Simanton et al. (1973) earlier work. Their original storm data points for several of the data sets were not available to recalculate CN by methods II or III. These are so indicated in table 3, which also presents the results of CN calculations.

The CNLS results are given in table 3 and the relation between watershed area and CN is shown in figure 2. This CN-area relationship is expressed by the linear regression model:

$$CN = 84.72 - 0.022 \times A$$

$$r^2 = 0.50 \quad \text{Std.Err.} = 4.3CN$$

$$A = \text{watershed area (ha)} \quad (7)$$

Analysis and Discussion

Figure 2 shows that Curve Numbers decrease about 2.2 units/100 ha of drainage area. The intercept of the fitted equation (eq. 7) can be interpreted as a base CN of about 85 for small upland source areas, i.e., a drainage area of 1 ha. This is about the same base CN that Simanton et al., (1973) found for an area of 0.4 ha (table 1).

The most obvious explanation for the relationship seen in equation 7 is channel transmission losses. For southwestern ephemeral streams, this has been dealt with by several authors (Wallace and Lane, 1978; Lane et al., 1980; Lane, 1985, 1990) and alone would explain the general nature of declining CNs with drainage area. Intermixed with this is the high variation of thunderstorm rainfall over short distances observed in southeastern Arizona (Smith, 1974; Osborn et al., 1979, 1980; Simanton and Osborn, 1980; Osborn, 1983). Under these conditions, areal watershed rainfall is seldom uniform and the average depth can be expected to decline as drainage area increases. Considering the role that drainage area plays in the findings here, rainfall spatial variability may be a major influence needing additional study.

For whatever reasons, the relation between CN and drainage area has some interesting implications. Using equation 3 and specific frequency rainfall depths, figures 3 and 4 have been assembled. Equation 7 was used with the different frequency rainfall amounts to determine runoff amounts as a function of drainage area. The results of this analysis are summarized in figure 3 for one-hour duration storms assumed to be the maximum point value within the Walnut Gulch watershed. Runoff at the watershed exit can be expected to be zero from drainage areas of several square kilometers. Figure 4 shows the net flow volume in cubic meters with drainage area for the same data. This suggests that the maximum flow volumes occur at drainage areas of about 400 to 650 ha. This finding might be useful in planning the design of small earthen impoundments in

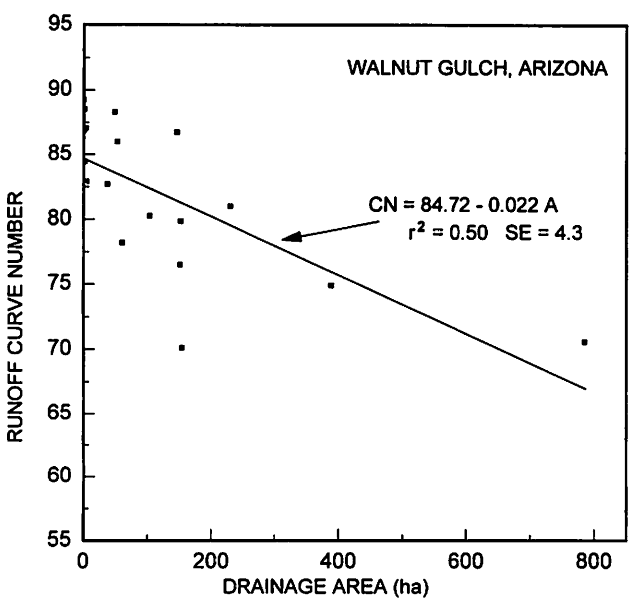

Figure 2–Plot of data-defined Curve Numbers with drainage area. The fitted line is CN = 84.72 – 0.022 × A, where A = ha, r^2 = 0.50, Std. Err. = 4.3 CN.

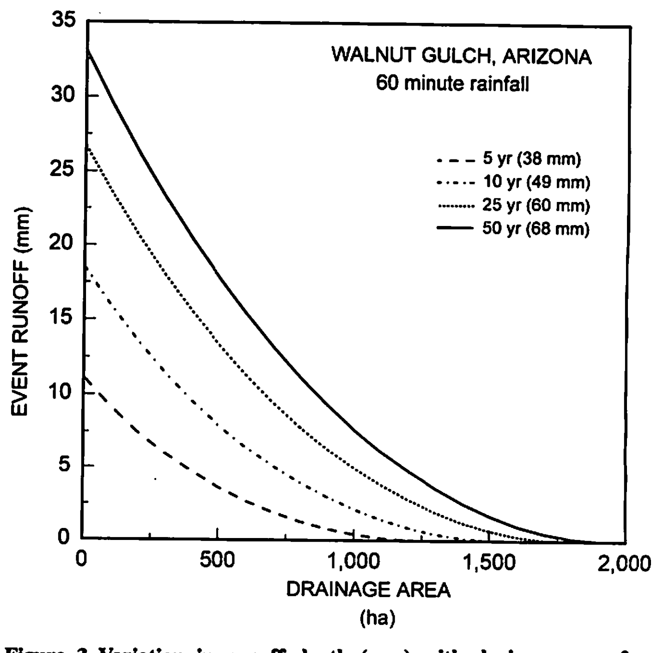

Figure 3–Variation in runoff depth (mm) with drainage area for various return period 60-min rainfall for the Walnut Gulch watershed.

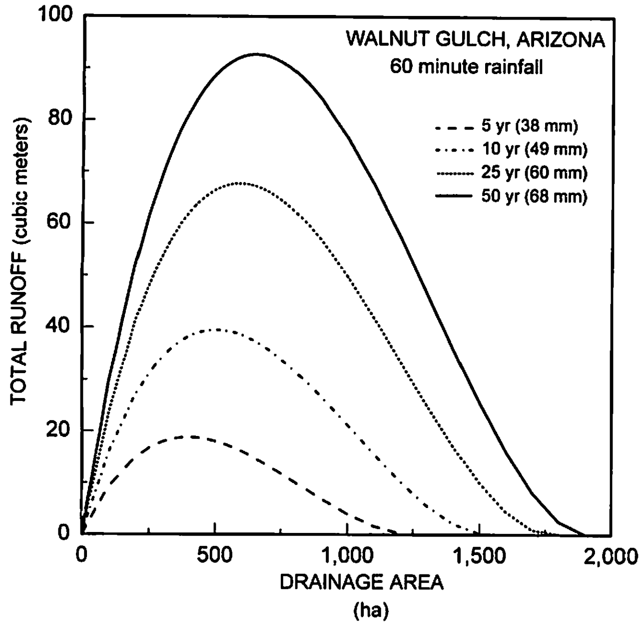

Figure 4–Runoff volume (m^3) of drainage areas for various return period 60-min rainfall for the Walnut Gulch watershed.

the region. It should be recognized in figures 3 and 4 that the CN used is a central tendency of the CN for that drainage area, and that a higher CN may occur under conditions of wet watersheds and high intensity storms.

CONCLUSIONS

This study resulted in two primary findings which may be summarized as follows:

1. Three different methods were used to determine Curve Numbers from 18 small watersheds in southeast Arizona. Each of the methods produced similar results and supported the Curve Number versus drainage area relationship.
2. Curve Number was observed to decrease with increasing drainage area for semiarid areas in southeastern Arizona. This Curve Number (runoff) reduction may result from spatial rainfall and flow abstractions in ephemeral channels (upland area runoff is absorbed in the porous channel alluvium).

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