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Limitations in the Curve Number Method to Characterize Small-Storm Rainfall-Runoff Transformations for Use with the Stochastic Empirical Loading and Dilution Model

By Gregory E. Granato

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This report, the associated computer applications, and data provide tools and techniques for developing planning-level estimates of stormflows at sites receiving highway runoff. This information is vital for assessing the potential for adverse effects of runoff on receiving waters throughout the Nation and it should provide transportation agencies with the tools and information to improve project delivery without compromising environmental protection.

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Introduction

The Natural Resources Conservation Service curve-number (CN) method has several limitations that reduce its applicability for stochastic runoff quality modeling. Planners and decisionmakers need information to assess potential effects of runoff from highways and other storm-discharge facilities. The curve-number method for estimating large-storm runoff has been successfully used to design hydraulic structures such as retention ponds and road culverts for decades. However, in many areas of the United States, only a small proportion of rainfall-runoff events meet criteria that are well suited for characterization by curve number methods. The curve number method has been used for runoff-quality analysis, but in most cases rainfall-runoff mechanisms may not be well characterized by the assumption of Hortonian infiltration-excess overland flow (Appendix4 Overview of Stormflow-Generation Mechanisms That May Be Used to Refine Estimates of Runoff-Coefficient Statistics).

The SCS-NRCS curve number method is designed as an empirical method for estimating flood volumes from small ungaged basins to facilitate flood-control project design but it also has been used for many different purposes (Ogrosky and Mockus, 1964; Mockus, 1972; Kent 1973; Cordery and Pilgrim, 1983; Natural Resources Conservation Service, 1983; 1986; Hawkins and others, 1985; Pilgrim and Cordery 1993). The CN method is widely used because it is simple to implement with commonly available soil, land-use, and precipitation data (Rallison and Miller, 1981; Hawkins and others, 1985; Tsakiris and Agrafiotis, 1988; Pilgrim and Cordery 1993; Michaud and Sorooshian, 1994; Mack, 1995; Grove and others, 1998; King and others, 1999; Kottegoda and others, 2000; Garen and Moore, 2005; Limbrunner and others, 2005; Merz, and others, 2006; Carter and others, 2007). This method works well for flood-control design, but the method has been extended tor many other uses (Rallison and Miller, 1981; Pilgrim and Cordery 1993). It is used for different catchment types, land uses, topographies, and geologies (Kottegoda and others, 2000). The CN method is commonly used because it facilitates analysis of the potential effects of land-use land-cover changes and implementation of runoff controls (Brander and others, 2004; Wang and others, 2005; Carter and others, 2007). It is commonly used for highway-design applications (McCuen and others 2002). It is used to optimize placement of infiltration BMPs in a watershed (Perez-Pedini and others, 2005). The CN method also is used for water-quality analyses including TMDL development (Shoemaker and others, 2005).

The CN method is an integral part of many rainfall runoff models. It is widely accepted and used because it is implemented in several early open-source runoff models including the Project Formulation-Hydrology program (TR-20), the Urban Hydrology for Small Watersheds program (TR-55), the Hydrologic Engineering Center Flood Hydrograph (HEC-1) program, and the Storage Treatment Overflow Runoff Model (STORM) (U.S. Army Corps of Engineers, 1976; 1990; Natural Resources Conservation Service, 1983; 1986). CN methods are used in a number of water-quality management models including the Agricultural Non-Point Source Pollution Model (AGNPS); the Dynamic Watershed Simulation Model (DWSM); the Erosion-Productivity Impact Calculator (EPIC); the GIS-Based Phosphorus Loading Model (GISPLM); the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS); the Generalized Watershed Loading Functions (GWLF); the Hydrologic Evaluation of Runoff model (HER); the Long-term hydrologic impact assessment model (L-THIA); the Pesticide Root Zone Model (PRZM); the Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds—Urban Catchment Model (P8-UCM); and the Soil and Water Assessment Tool (SWAT)(Williams and others, 1983; Carsel and others, 1985; Haith and Shoemaker, 1987; Young and others, 1987; 1989; Harbor, 1994; Mack, 1995; Shoemaker and others, 1997; Grove and others, 1998; Neitsch and others, 2002; Borah and Bera, 2003; Garen and Moore, 2005; Limbrunner and others, 2005; Shoemaker and others, 2005; Wang and others, 2005; Nachabe, 2006). Some studies indicate that models that use the CN method may not be as accurate for modeling a particular storm event as other runoff-modeling methods (Trommer and others, 1996; Zarriello, 1998; Fennessey and others, 2001). The CN method, however, was not designed to model relatively small storms or a particular storm event (Kent 1973; Pilgrim and Cordery 1993).

This appendix is an overview of the CN method and an evaluation of the potential application of the CN method for use in the stochastic empirical loading and dilution model (SELDM). The CN method is evaluated here because this method commonly is used by highway engineers to design culverts, highway structures, and structural stormwater BMPs (McCuen and others 2002). The CN method also is evaluated here because it has been used in other runoff and water-quality models. The CN method is evaluated using data from sixteen stations in the SiteStormV01.mdb database on the CD-ROM accompanying this report that have data from 9 or more storm events and a published CN value estimated using the hydrologic soil groups and land-cover data.

Evaluation of the Curve Number Method for Use with SELDM

In theory, a CN-method storm-flow estimate would be more accurate than a runoff coefficient estimate for a given precipitation event because the CN method is based on imperviousness, soil properties, and land cover. However, studies indicate that soil properties and land cover may not always be satisfactory explanatory variables for estimating runoff production. For example, Sharma and others (1980) did 26 infiltration tests in different soils in different locations within a small basin in Oklahoma and found no discernable pattern in infiltration values with respect to these variables. Cordery and Pilgrim (1983) looked at rainfall-runoff data from 50 basins with different climates and determined that information about land cover and soil characteristics did not characterize rainfall-runoff transformations. Merz, and others (2006) examined data from 50,000 storm events in 337 Austrian catchments and determined that that the spatial distribution of runoff coefficients is highly correlated with mean annual precipitation volume but is poorly correlated with soil type and land use. This may be because the mean annual precipitation volume may be correlated with dominant storm flow production mechanisms in different areas. Consistent application of the CN method depends on the consistency of available input data. For example, Hjelmfelt and others (2001) indicate that soils with similar properties have been classified into different hydrologic soil groups because of variations in soil-classification interpretations in different areas of the United States and at different times.

CN estimates also may be affected by the difference between DCIA and TIA in a basin. If the DCIA can be accurately specified, the CN of these impervious areas are set equal to 98 (Natural Resources Conservation Service, 1986). The rest of the impervious area discharges overland flow to adjacent impervious areas, which effectively reduces the CN of these impervious surfaces and increases the CN of the adjacent pervious areas. This is because the impervious overland flow increases the effective precipitation input to pervious areas receiving runoff from adjacent impervious areas. Within the documentation for the Urban Hydrology for Small Watersheds program (TR-55), the Natural Resources Conservation Service (1986) provides a decision tree and two nomographs to adjust composite CN estimates for contributing areas within a drainage basin. As previously discussed, however, soil compaction caused by development can substantially change the permeability of soils (Felton and Lull, 1963; Taylor, 1982; Gregory and others, 2006), which could result in misspecification of the appropriate hydrologic soil group and as a result, the appropriate CN values for the nominally pervious land covers in developed areas.

Applicability of the CN method may be limited in some cases because it is formulated under the assumption of infiltration-excess overland flow ***(*****Appendix4*****)*** from the entire basin (Ogrosky and Mockus, 1964; Mockus, 1972; Kent 1973; Rallison and Miller, 1981; Mack, 1995; Kottegoda and others, 2000; Mishra and Singh, 2004; Shoemaker and others, 2005). As such the curvilinear rainfall-runoff relations used in the CN method produce estimates of runoff that commonly are too low for small precipitation values (Michaud and Sorooshian, 1994; King and others, 1999). The CN method may not work well in low CN basins that have a relatively large proportion of the subsurface storm flow components in comparison to surface-runoff storm flows (Rallison and Miller, 1981; Mack, 1995).

Hjelmfelt and others (2001) indicate that curve numbers derived from precipitation-runoff data will not converge to a characteristic value if runoff from a basin is dominated by partial source-area stormflow mechanisms. Several studies indicate that unadjusted CN estimates are not a good approximation for humid basins dominated by partial-area saturation overland flow, but that the CN method can be adapted to account for differences in rainfall runoff processes (Steenhuis and others, 1995; Nachabe, 2006; Schneiderman and others, 2007). However, Mishra and Singh (2004) indicate that there are fundamental limits to the use of a characteristic maximum infiltration value (*S*) is used to model partial-area saturation overland flows.

The CN method was designed for analysis of runoff from large flood-producing storms that approximate the assumption of infiltration-excess runoff from a large proportion of the watershed (Ogrosky and Mockus, 1964; Mockus, 1972; Hawkins, 1975; Bondelid and others, 1982; Cordery and Pilgrim, 1983; Hawkins and others, 1985; Grove and others, 1998; Hjelmfelt and others, 2001; Garen and Moore, 2005). Natural Resources Conservation Service (1983) indicates that the CN method is suitable for storms that are large enough to produce substantial flooding. Miller and Viessman (1972) use runoff coefficients for small storms (less than 2 inches) and curve number methods for larger storms on the assumption that impervious surfaces are the sole source of small-storm runoff and pervious surfaces will contribute runoff in larger storms. Hawkins and others (1985) suggest a ratio of precipitation to maximum potential infiltration (*S*) greater than 0.46 for analysis of storm-event data to derive a characteristic CN value. This would be about 11 in of rain for a CN of 30, 4.6 in of rain for a CN of 50, about 1.2 in of rain for a CN of 79, and about 0.24 in of rain for a CN of 95. Hjelmfelt and others (2001) indicate that rainfall-runoff based CN estimates will converge to a representative data if precipitation totals are greater than 2 in. Walker and others (2001) indicate that annual flood events should be used to develop CN estimates based on rainfall-runoff data. Schneider and McCuen (2005) use a lower-bound of one inch of rain to select storms for statistical analysis of CN values.

The synoptic precipitation statistics in **table 8** (of the main report) indicate that, throughout the United States, most storms will not meet the large-storm thresholds commonly used to apply the CN method for hydraulic design purposes. The probability of exceeding a given precipitation value can be estimated with the statistics in table 5 for the 15 rain zones in the conterminous United States by assuming that synoptic storm-event volumes follow a 2-parameter exponential distribution with a lower limit of 0.1 inch. These estimates indicate that about 40 to 80 percent of precipitation volumes will be less than 0.5 in of rain, about 72-97 percent of precipitation volumes will be less than 1 in of rain, and about 93 to 99.9 percent of precipitation volumes will be less than 2 in of rain.

The CN method has been used in lumped (or composite) and distributed CN models (Stuebe and Johnston, 1990; Michaud and Sorooshian, 1994; Grove and others, 1998; Moglen, 2000; Mishra and Singh, 2004; Garen and Moore, 2005). In a lumped CN model, runoff from an entire basin is calculated from the area-weighted-average precipitation volume using one area-weighted-average CN. In a distributed CN model, the precipitation volume is used to calculate runoff from individual land use or land cover parcels within a basin. The precipitation volume in a distributed CN model can be the area-weighted-average or distributed precipitation volume depending on available information. Distributed CN models are increasingly used because GIS systems greatly facilitate the process of quantifying CN values from geographic land use, land cover, and soil-property data sets. In theory, distributed CN models should provide better estimates than lumped models because runoff contributions from different areas can be specified. For example, several studies indicate that lumped CN models produce runoff estimates that are less than distributed CN model estimates for small precipitation values but that results converge for very large storms because a large proportion of the basin is contributing water to flood flows (Bondelid and others, 1982; Michaud and Sorooshian, 1994; Grove and others, 1998; Moglen, 2000; Garen and Moore, 2005). Grove and others (1998) indicate that distributed curve-number values can be 100 percent higher for very small storms because the composite number does not account for the proximity of different CN parcels. CN values derived from rainfall and runoff data are lumped for the basin upstream of the runoff-measurement point, but distributed CN models allow the modeler to calibrate-runoff volume performance for different storms by providing more fitting parameters. Wilcox and others (1990) indicate that uncalibrated distributed-parameter models do not provide substantial benefits over lumped CN models. For example, King and others (1999) indicate that uncalibrated distributed CN models may under predict runoff volumes. Moglen (2000) indicates that, in his study, the distributed models, which account for spatial variation in curve numbers and flow aggregation from contributing areas in the watershed, produce results that are similar to composite CN model runoff estimates. Stuebe and Johnston (1990) found that drainage-area specification uncertainty, which is implicit in GIS methods for watershed delineation, accounted for the biggest difference in runoff volume estimates between manually-derived composite-CN runoff estimates and automatically-derived (GIS) distributed-CN runoff estimates for 6 watersheds in South Dakota. Distributed CN models may allow the user to adjust for different stormflow producing mechanisms in different areas of the drainage basin, but this type of adjustment cannot be done for uncalibrated CN models developed with standard CN tables (Mishra and Singh, 2004).

Although the CN method has limits, its use in many water-quality and BMP models indicates that results from the method may be sufficient for developing planning-level water-quality estimates. The curve number method is effectively an empirical single-parameter relation between rainfall depth (P) and runoff depth (Q) developed from the theory of infiltration-excess overland flow. The CN method is well documented in manuals, textbooks and reference books with tables of characteristic CN values for different land covers (Ogrosky and Mockus, 1964; Mockus, 1972; Kent 1973; Rallison and Miller, 1981; Natural Resources Conservation Service, 1983; 1986; Hawkins and others, 1985; Pilgrim and Cordery, 1993; McCuen and others 2002). The runoff-depth (Q) for a given rainfall depth (P) is estimated from information on an initial abstraction (Ia), and the maximum potential infiltration (S) of an area, each of which is normalized by basin area to be expressed in units of depth (for example inches). The generalized equation for the relationship between precipitation and flow for a given drainage basin is

$$Q = (P - Ia)^2 / (P - Ia + S) \qquad (5\text{-}1)$$

The initial abstraction is the amount of precipitation retained on the watershed before runoff begins (Ogrosky and Mockus, 1964; Mockus, 1972; Kent 1973; Aron and others, 1977; Rallison and Miller, 1981; Natural Resources Conservation Service, 1983; 1986; Bosznay, 1989; Ponce and Hawkins, 1996; Kottegoda and others, 2000; Woodward and others, 2003; Mishra and Singh, 2004; Jacobs and Srinivasan, 2005; McColl and Aggett, 2007). Ia includes interception, depression storage, and the infiltration that occurs before the onset of runoff. It is recognized, however, that the Ia also is a function of the hydrologic characteristics of the watershed, local climate, season, antecedent wetness, and storm characteristics. For design purposes Ia commonly is expressed as a function of the estimated maximum potential infiltration of the watershed to eliminate the necessity for estimating both variables. This is expressed in the equation

$$Ia = \lambda S \tag{5-2}$$

in which λ is the proportionality factor. It is recognized that the proportionality factor is a variable, but a standard value of 0.2 was empirically developed as the best fit value for scattered data from small watersheds (Ogrosky and Mockus, 1964; Mockus, 1972). Several studies indicate that a λ of 0.2 commonly may be too high (Aron and others, 1977; Woodward and others, 2003; Jacobs and Srinivasan, 2005). Different researchers have examined λ as a deterministic variable or a random variable with values ranging from 0.0005 to 0.49 (Aron and others, 1977; Hjelmfelt, 1991; Ponce and Hawkins, 1996; Bosznay, 1989; Becciu and Paoletti, 2000; Kottegoda and others, 2000; Woodward and others, 2003; Mishra and others, 2004; Mishra and Singh, 2004; Schneider and McCuen, 2005; Jain and others, 2006). For example, Woodward and others (2003) examined data from about 12,500 storms at 134 sites and determined that λ is not a constant from storm to storm, or watershed to watershed, and that the median λ value was about 0.05. The λ that is used to calculate Ia has a large effect on small precipitation volumes and on watersheds with low CNs (with high S values).

The maximum potential infiltration rate, S, is the amount of precipitation that would be retained in the watershed (once runoff begins) if the storm were to continue indefinitely. The S value for a given watershed can be calculated from tabulated values of CN on the basis of land cover characteristics. For an ungaged watershed, the S value (in inches) can be calculated from tabulated CN values with the equation

$$S = (1000/\mathrm{CN}) - 10 \tag{5-3}$$

In theory, S can range from zero (with a CN of 100) to infinity (as CN approaches 0) (Mockus, 1972; Kent, 1973; Kottegoda and others, 2000). In practice, the NRCS tables for CN values for average hydrologic conditions range from 98 (an S value of about 0.2) for paved parking lots to 6 (an S value of about 157) for contoured pastures in good condition on soils with high infiltration rates (Ogrosky and Mockus, 1964; Natural Resources Conservation Service, 1986; 2004). **Equation (5-3)** indicates that S is a deterministic variable, which is completely dependent on land-surface characteristics. However, NRCS recognizes that S is a variable that can vary seasonally and from storm to storm as a function of antecedent conditions (Ogrosky and Mockus, 1964; Mockus, 1972; Natural Resources Conservation Service, 1986; 2004). Furthermore, it is recognized that storm event characteristics also may affect the apparent *S* value. For example, infiltration rates are affected by the rainfall intensity, but rainfall intensity was neglected in the formulation of the NRCS runoff calculation methods because little information was available in rural areas when the methods were developed (Rallison and Miller, 1981). S can be calculated with rainfall and runoff data for a given storm using the equation

$$S = 5\ (P + 2Q \pm (4Q^2 + 5PQ)^{0.5}) \qquad (5\text{-}4)$$

if λ is assumed to equal 0.2; and

$$S = (P/\lambda) + ((Q(1 - \lambda))/2\ \lambda^2) \pm (1/(2\ \lambda^2))(Q^2\ (1\text{-}\ \lambda)^{\ 2} + 4\ \lambda PQ)^{0.5}) \qquad (5\text{-}5)$$

if λ is assumed to be variable (Schneider and McCuen, 2005). In these equations the square-root term should be subtracted from the first two terms to calculate the value *S* unless *Q* is equal to zero.

Storm to storm variability in *S* and therefore the CN has been recognized from the development of the CN method but this variation was simplified to a three-tier antecedent moisture condition (AMC), which is also known as the antecedent runoff condition (ARC) (Ogrosky and Mockus, 1964; Mockus, 1972; Kent 1973; Rallison and Miller, 1981; Hawkins and others, 1985; Hjelmfelt, 1991; McCuen, 2002; Mishra and others, 2004; Kottegoda and others, 2000). AMC-I represents dry conditions, AMC-II represents normal or average conditions, and AMC-III represents wet conditions. Tabulated CN values are based on the normal or average conditions AMC-II (Ogrosky and Mockus, 1964; Mockus, 1972; Natural Resources Conservation Service, 1986; 2004). Hawkins and others (1985) derive equations to calculate CN values for each AMC. In reality, however, antecedent moisture conditions represent a continuum rather than a three tier system, the AMC tier system does not represent field conditions, and the average CN values are commonly used for design purposes (McCuen and Bondelid, 1981; Kottegoda and others, 2000; McCuen, 2002; Mishra and others, 2004; Merz, and others, 2006;). Kent (1973) indicates that the AMC-I and AMC-III conditions represent bounding lines on the scatter among *P* and *Q* values used to estimate values used in the CN tables. Similarly, Hawkins and others (1985) describe the CN values for these AMC conditions as the 90 percent confidence interval of a continuous distribution of CN values. Hjelmfelt (1991) describes these AMC conditions as extremes of the distribution of random variation in CN among different storms at a given site.

CN relations between *P* and *Q* are, increasingly, being treated as stochastic rather than deterministic variables (Sharma and others, 1980; Hawkins and others, 1985; Haan, and Wilson, 1987; Hjelmfelt, 1991; Becciu and Paoletti, 2000; Kottegoda and others, 2000; McCuen, 2002; Schneider and McCuen, 2005; Young, and Carleton, 2006). For example Sharma and others (1980) indicate that the frequency distributions of *S* may be better approximated by a lognormal than by a normal distribution. Hawkins and others (1985) indicate that the probability distribution of event runoff exceeding zero may be approximated by a lognormal distribution. Haan and Wilson (1987) indicate that the distribution of *S* values can be approximated a lognormal distribution within each AMC class. Hjelmfelt (1991) indicates that the population of *S* values may be approximated by a lognormal distribution. Kottegoda and others (2000) use a truncated normal distribution to approximate the population of CN values for their study area. McCuen (2002) indicates that a gamma distribution may approximate variations in the population of values calculated as 100-CN. Schneider and McCuen (2005) used lognormal frequency methods to examine potential effects of random variations in λ. Stochastic methods to characterize relations between *P* and *Q* with the CN method may improve results of water-quality modeling efforts (Young, and Carleton, 2006).

Using CN values that are estimated from land cover and soil properties, can result in substantial runoff-estimate errors even on small homogenous drainage areas. For example, Fennessey and others (2001) examined data from 37 test basins and found that the CN values estimated from hydrologic soil groups and land cover were “within reason” of the CN values calculated from rainfall-runoff data at only 22 of these sites. The potential accuracy of CN values estimated from hydrologic soil groups and land cover data by the author of the source documents in the SiteStormV01.mdb database were compared to CN values calculated from measured rainfall-runoff data. Sixteen stations in the SiteStormV01.mdb database that have data from 9 or more storm events and a published estimate of the CN value (hydrologic soil groups and land cover) were selected for analysis. The query qryRvCNCalculate in the database was used to calculate the maximum potential infiltration (*S*) and CN values from rainfall-runoff data using **equation 5-5**. The query calculates CN values from rainfall-runoff data using initial-abstraction proportionality factor λ values of 0.01, 0.05, 0.10, 0.15, 0.2, and 0.25. The CN values in the boxplots on **figure 5-1** show the variability of CN values from storm to storm and the difficulty in calculating a representative lumped CN value for a drainage basin using land cover and soil properties. The CN values in the boxplots on **figure 5-1** were calculated for rainfall runoff events using the NRCS recommended initial-abstraction proportionality-factor (λ) of 0.2. The CN values which were estimated from land cover and soil properties, are lower than the 25th percentile of CN values calculated using rainfall-runoff data for 13 of the 16 sites (**fig. 5-1**). The figure also indicates the random nature of the rainfall-runoff processes, which are not characterized by using a single CN value.

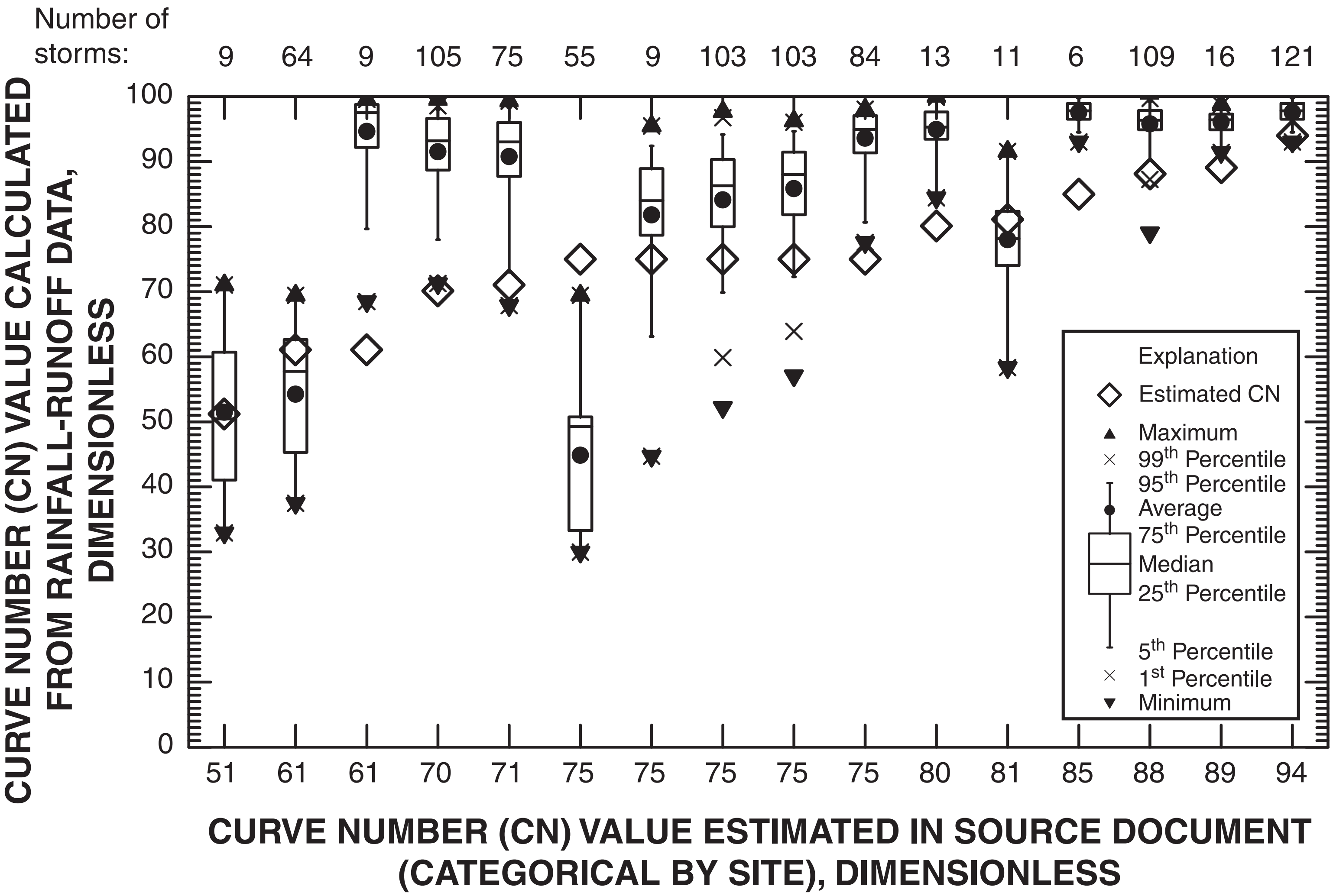

Figure 5-1. Boxplot showing the population of curve-number values calculated from rainfall-runoff data in comparison to the curve number value estimated using the hydrologic soil groups and land-cover data.

The CN method may not characterize runoff volumes for small storm events, especially in basins with runoff events that are not dominated by infiltration-excess runoff flow. This is because the CN method was developed to estimate runoff for large storm events under the assumption of infiltration-excess runoff flows. The CN-based rainfall-runoff relation (**eq. 5-1**) commonly produces low runoff-volume estimates for small storms. About 66 percent of the storms in the SiteStormV01.mdb database have precipitation volumes that are less than 1 inch. For example, **Figure 5-2** indicates that the curvilinear CN curve produces low runoff estimates for small storms. Furthermore, with the exception of the site with an estimated CN of 89, the shape of the CN curve does not approximate the scatter of the rainfall-runoff data for these study sites. This may indicate that the infiltration-excess runoff mechanism may not be predominant except for the site with the highest impervious fraction. **Figure 5-2** also indicates that, for these sites, an initial-abstraction proportionality-factor of 0.05 generally produces better runoff estimates than 0.2 for the storms with precipitation volumes that are less than 1 inch.

SELDM is designed to use runoff-coefficient statistics to generate a random population of stormflow volumes from a random population of precipitation volumes. Volumetric runoff coefficient methods rather than the curve number method were selected because the CN method is not well suited for use with SELDM. The CN method provides conservative runoff estimates for large storm events, but rainfall-runoff analyses conducted for this study indicate that most storms do not meet the large-storm criteria. Furthermore, the CN method is based on the assumption that runoff occurs from infiltration-excess overland flows, which is not the dominant stormflow generating mechanism for undeveloped areas in many parts of the country (appendix flow mechs.).

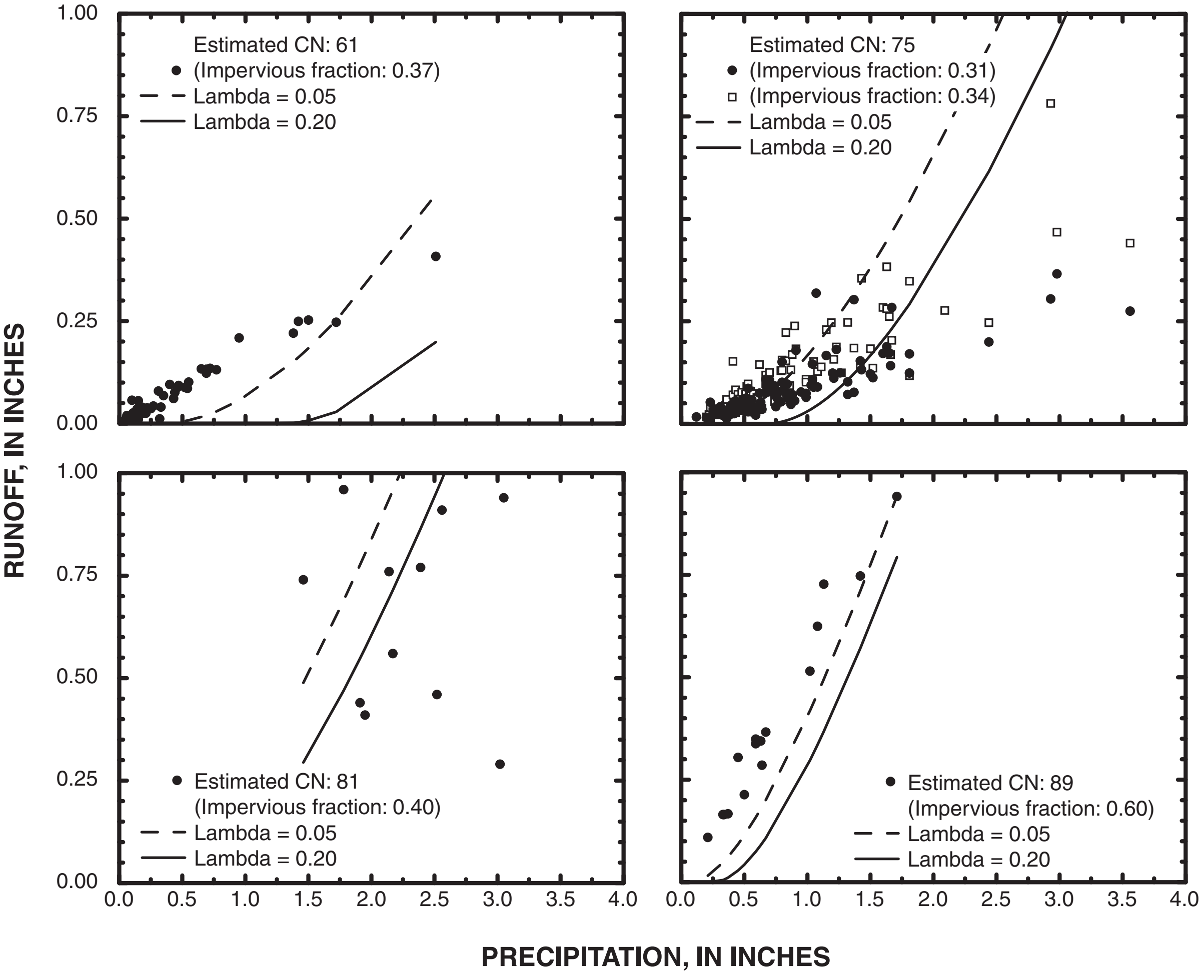

Figure 5-2. Graphs showing rainfall-runoff data and the theoretical curve-number (CN) relations with initial abstraction proportionality factors (Lambda) of 0.2, which is the National Resources Conservation Service (NRCS) recommended value, and 0.05, which has been proposed in several studies (for example,Woodward and others, 2003). The theoretical CN rainfall-runoff relations are based on CN values estimated from hydrologic soil groups and land-cover data.

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