mostly mismatched) P:Q pairs. While these new "ordered" pairs may not be as occurred in nature, each event component (P and Q) has the same calculated (i.e., plotting position) return period.

This puts the CN equation in the role of a function that transforms a rainfall frequency curve to a runoff frequency curve. Precedent for this tactic is found in the works of Schaake et al. (1967) who applied it in determining rational coefficients in an urban setting. This method per se - as applied to CNs - is treated later in this section. Thus, P:Q data has two forms; natural (paired as it occurred), and ordered (or re-matched as described here).

Rainfall depth effects: In essentially all cases – using both natural and ordered data sets - a residual relationship between the data-defined CN and the causative rainfall depth P is apparent. The data-defined CNs are not independent of the rainfall depth itself, and a distinct bias to high CNs at small rainfalls is evident. While this is evident upon closer examination in NEH4 examples and in the data used by Hjelmfelt et al. (1982), the phenomenon was first shown and demonstrated by Sneller (1985). It may be attributed to a mixture of data censoring, partial area effects, and to basic error in the model or the data. Data censoring results from the common practice of excluding from the data sets all rainfall events without direct runoff, thus assuring $P \geq 0.2S$, and $100/(1+P/2)<CN<100$. On the other hand, to the extent that any CNs are manifested at low rainfalls (for which there are many storms), they would – by definition – define high CNs. Additionally, partial area runoff, as from direct channel interception or from other impervious areas, can reproduce the declining CN action as well.

Springing from the above, several distinct CN-P response patterns have been observed, described, and labeled (Hawkins 1990, 1993). The dominating behaviors are:

Standard: Characterized by a declining CN with increasing P, but approaching a constant or near-stable value asymptotically at higher rainfalls. This is the most common case, and is found in most agricultural, urban, and rangeland settings where rainfall excess is thought to arise from infiltration processes. CN can be determined from such data. Because of sample size limitations from small data sets, not all show a well-defined fixed stable CN, but indicate an approach to it.

Complacent: This condition is also characterized by declining CN with increasing P, but *without* approaching a fixed equilibrium value in the period of record. This can be caused by small constant source areas as may arise from direct channel rainfall. It is commonly found with well-forested watersheds with baseflow. CN fitting is inappropriate in such situations. Such data are more aptly fit to Q=CP, with C values usually in the range of 0.005-0.070, rather than to the CN equation (Hawkins, 1973). Complacent behavior is apparently also widely found in urban watersheds, as clearly illustrated by Pitt (1999). This is especially cogent in the case of smaller storms which carry the bulk of urban non-point pollution.

Violent: This pattern is characterized by Complacent behavior with declining CNs at the lower rainfalls, but with a sudden change to a much higher runoff response at some threshold elevated rainfall depth. Typically, such threshold depths are in the range of 1.5 to 2.5 inches, and a higher near-constant CN is approached with increasing rainfall, typically in the 85-95 range.

These behaviors or responses to rainfall are illustrated by Figures 9 to 11.

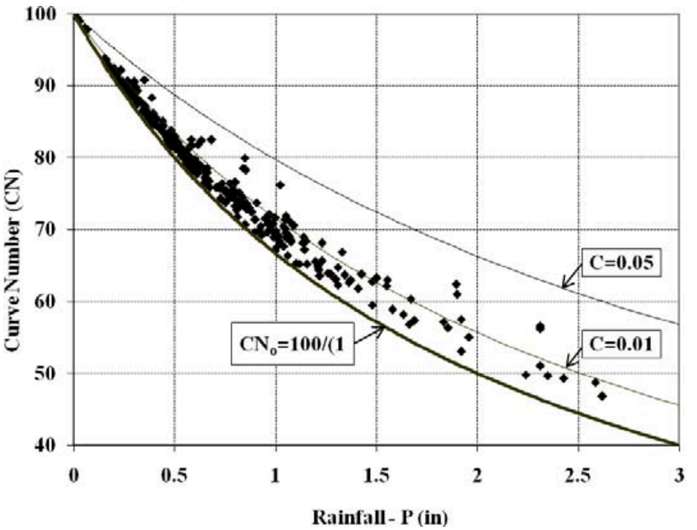
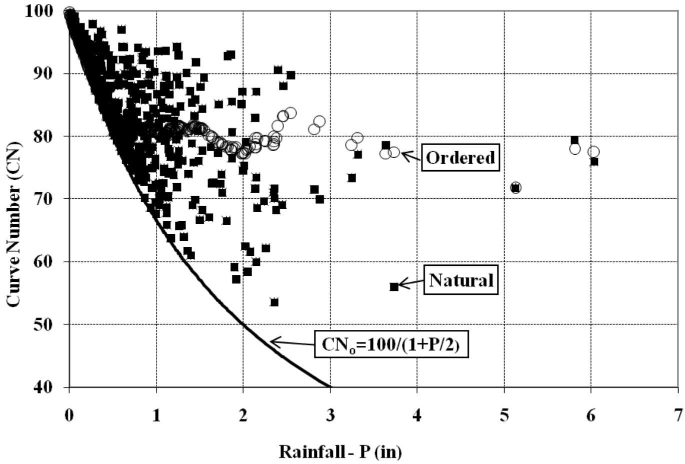


Figure 9. Complacent CN response to rainfall. The natural P:Q data from which these area drawn data are a composite for 13 small wild land (mainly forested) watersheds in Colorado, Utah, Arizona, and Idaho, totaling 313 events.

The data in Figure 9 are drawn from several different primary sources (see Springer and Hawkins, 2005). Note the similarity of response for natural (not ordered) data points, the lines of low runoff ratio C, and that no stable constant CN is apparent. In Figure 10, the drainage area for Hastings is 411 acres (166 ha), and the cover was a variety of rainfed row crops [data from USDA, Agricultural Research Service]. The drainage area for Zulu 15 was 1364 ha. Those data were supplied by Dr. Roland Schulze, University of Natal (now University of KwaZulu-Natal), Pietermaritzburg. The watershed is described by Hope (1980), and it has cover from a variety of rainfed agricultural crops, grasslands, and woodlands. The drainage area for Berea 6 in Figure 11 is 287 acres (116 ha), and the cover is a hardwood forest on "very shallow sandy loam soils." (details in see Hewlett et al., 1984). In Figures 10 and 11, CNs for natural (squares) and ordered (empty circles) data are shown.



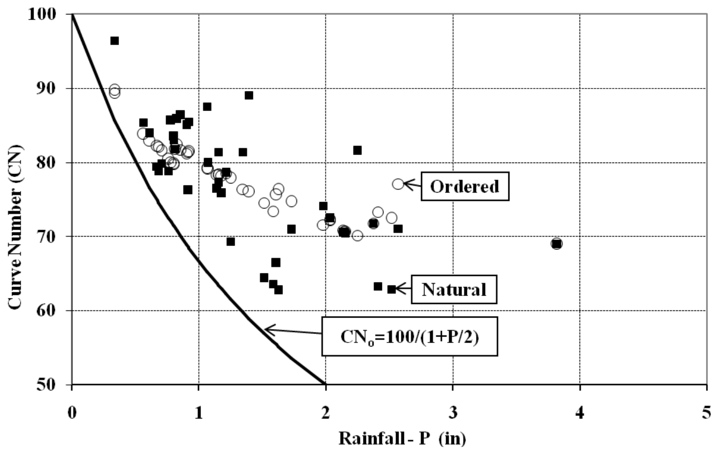


Figure 10. Standard CN response to rainfall. The upper figure is for Hastings, Nebraska, 44002 for 482 events from 1939 to 1967. The lower figure is for 44 events from Zulu 15 in South Africa.

The three main patterns above are observed with both natural and ordered data sets, though as shown it is more apparent with ordered data. However, only the Standard and Violent data cases are suitable for CN definition. The several phenomena and opportunities described above should be observed in extracting CNs from field data. For example, the rainfall–CN effect precludes determining mean CNs from small data sets, which will usually over-sample the smaller, high CN events, and thus lead to a high CN bias. The equilibrium values found at higher rainfalls will be more fitting to the higher rainfall design situation, and are a more stable measure of the watershed response. And finally, all watersheds do not follow the CN rainfall-runoff response pattern. Complacent behavior is not appropriate to the CN rainfall-runoff response.

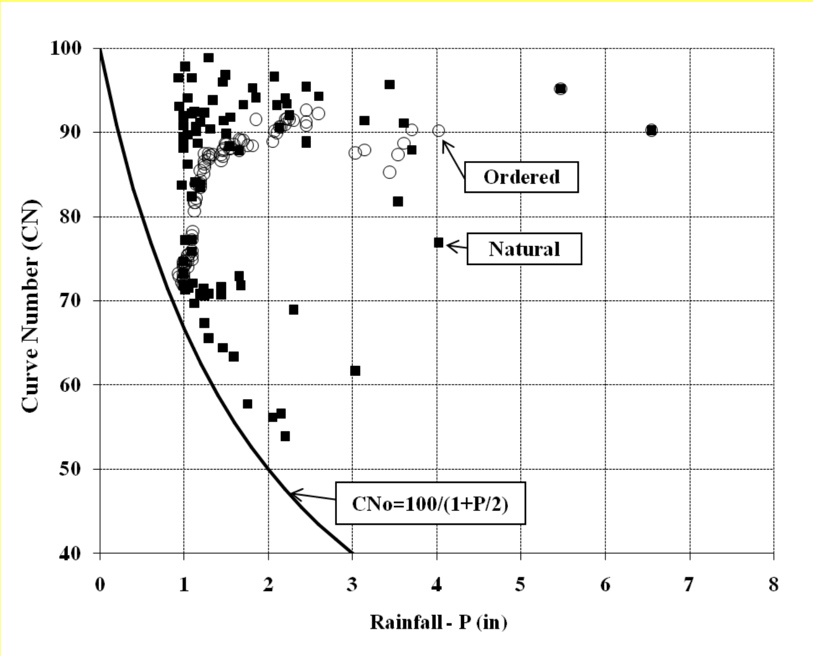


Figure 11. Violent CN response to rainfall. Illustrated by rainfall and runoff for Berea 6, Kentucky, covering 84 events from 1969-76 [data from USDA Forest Service].

Several other P-CN pattern clusters have also been observed, and are described here for perspective. The *Abrupt* pattern (or a low threshold form of Violent behavior), is characteristic of very highly urbanized and impervious watersheds, and is CN consistent. The *Inactive* grouping describes watersheds which show no event runoff over a long period of instrumentation. No CNs can be determined for this case. *Indeterminate* watersheds respond to rainfall, but in such a subdued manner that no clear or realistic association of rainfall data to runoff hydrographs can be made. These three categories are not relevant here. It should also be noted that the P-CN relationships described above also have corresponding expression in the P-Q plane (Hawkins, 1990a, b).

Alternatives to annual series: Most rainfall runoff data sets contain more than a single event per year sampling the rainfall-runoff process. Using an annual peak series provides only a single sample for an entire year, but respects the original NEH4 example and the accompanying notion that the method is intended only for annual peak calculation. In the interest of data economy (i.e., large samples) many investigators have used multiple events per year, on the assumption that the smaller storms express the same identifying hydrologic characteristics as do the annual flood events.

The above three considerations; data ordering, effects of rainfall depth, and sample selection/data censoring (i.e., annual series or complete series, and minimum storm size) dominate the choice of specific procedures applied.

Least Squares method: Here the task is to find the value of S such that it achieves the minimum value of the objective function, F, or

$$\text{Minimize } F = \Sigma[Q_{calc}-Q_{obs}]^2 \qquad [58]$$

where Q_{calc} is given from the CN runoff equation [1], including Q=0 for the P≤0.2S condition, and the observed rainfall P, (or P_{obs} to be consistent above). Recalling the high-CN low-P effects, a consideration here is the lower limit of rainfalls. It is common to use all $P_{obs}>1$ inch, for example, or to censor the data so that $P_{min}/S>0.46$ (Hawkins et al., 1985). It does treat the quantity of interest, i.e., the direct runoff, and is perhaps the most intuitive method, especially when using natural data. It provides easily understood and traditional goodness-of-fit measures; r^2 and S_e. Negative values of r^2 (as a measure of variance reduction) are possible, and there should be no trend of residual error with P. Both ordered and natural data may be so treated.

Perhaps the earliest effort with least squares was by Walker (1970), who used a trial-and-error least squares fitting to storm runoff data from several small watersheds in Utah's Wasatch Front. Simanton et al. (1973), Springer et al. (1980), Cooley and Lane (1981), Montgomery (1980) and Montgomery and Clopper (1983), Curtis et al. (1983), Bales and Betson (1980) also used least squares fitting to arrive at values of S, apparently without a lower limit to storm size.

Asymptotic method: This method builds on the observation of CN as a function of P, and inserts user judgment into a major role. It deals with CN directly, rather than Q, and with both natural and ordered data cases. Event CNs are determined for both the natural and ordered P:Q sets, and CN (Y-Axis) plotted against P (X-axis). To outline the lower limits, the $CN_o = 100/(1+P/2)$ should also be shown.

A. From inspection, if a well-defined constant CN is apparent for the higher P values, then that portion of the data is isolated and the mean CN determined. This may occur with Standard, Violent, or Abrupt cases. This is the preferred method.

B. If the constant CN is not apparent, but there is a recognizable partial trend towards such a steady-state condition, then asymptotic least squares fitting may be done to extend the trend to the stable value. For Standard cases, the fitting equation is

$$CN(P) = CN_\infty + (100-CN_\infty)\mathbf{exp}(-kP) \quad [59]$$

The decay equation is structurally the same as Horton's (1939) infiltration equation.

For Violent cases, the following has been used

$$CN(P) = CN_\infty [1-\mathbf{exp}(-kP)] \quad [60]$$

A variation on this is to use $P-P_{min}$ in the place of P, where P_{min} is determined by inspection or judgment for individual data sets. In both of the above the k's are fitting coefficients, and the fitted CN_∞ is taken as the target CN. The aim in both equations [59] and [60] is to extend the trend to an expected asymptotically constant CN value at higher rainfalls.

C. For Complacent data sets, several options are possible, depending upon user goals. First, the CN search might end, acknowledging that the data is inapplicable to the CN method. The simple linear function Q=CP usually fits such data sets nicely, and is more appropriate to the suspected source processes. Second, the Standard fitting might be done, (i.e., equation [59]) acknowledging the insecurity and inapplicability of such extrapolation. Third, the simple equation

$$CN(P) = CN_o + k(100-CN_o) \quad [61]$$

has been suggested and used (Hawkins, 1973), where CN_o is as previously defined, is 100/(1+P/2). With this form, as $P \rightarrow \infty$, $CN(P) \rightarrow 100k = CN_u$, which might be used as an identifying CN. These latter two (Standard fitting and Equation [61] above) should be seen as purely curve-fitting endeavors.

The k coefficients in equations [59]-[61] are not equivalent. The Complacent case is unsettling. It indicates low response, but with a large undeveloped, unmeasured runoff potential. While seemingly benign, it may perform as a lead-in to the high-response Violent pattern at some unknown higher threshold, above which runoffs and flood peaks may be orders of magnitudes greater. This rainfall threshold may be either just above the largest storm in the data set, or well beyond human experience. Thus, extending experienced Complacent behavior beyond the data to higher rainfalls contains some risk. This uncertainty, and the definition of the threshold based on storm and watershed factors, is worthy of further investigation.

For the Standard asymptotic fitting via equation 59, it is tacitly assumed that the CN_∞ - taken as the watershed CN - is appropriate for remote return period rainfalls (P). That is, that the equation with large values of P calculates CN(P) that closely approaches CN_∞.

This assumption has not been widely tested. In fact, McCutcheon et al. (2006) suggest that with the heavily forested watersheds of their experience, the transient values, i.e., CN(P), are important, and should be applied. This is tantamount to a non-constant, P-defined CN, a notion at some variance from the original concept of S as a limit of F, and from current practice and handbook values.

In addition, the runoff-response group assignments are made via judgmental inspection of plotted data. A declining CN with P without a hint of approaching a stable value might interpret as a Complacent pattern, a potentially Violent condition, or merely an incompletely developed Standard response. These should be treated differently.

From experience, ordered data gives the most consistent and reliable results, and makes better use of the available data resources. CNs determined for ordered data are usually1to 3 CNs higher than those from natural data. Also, from experience, a minimum sample size (N=number of P:Q events) is about 30, though some settings produce more consistent storm-to-storm behavior, and a smaller sample (ca 15) may suffice. As with most data requirements, more is better.

<u>Distribution matching method</u>: This method treats both P and Q as distributed (i.e., random) variables, and seeks the CN that best transforms the P distribution to the Q distribution via the CN runoff equation. This was first developed in several works by Hjelmfelt (1980b, 1983), Hjelmfelt et al. (1982), and Hjelmfelt et al. (1983). The P and Q distributions are displayed on lognormal plots, and the calculated transformation, or the CN that best recreates the Q distribution from the P distribution is determined visually. The Hjelmfelt (1980b) paper gives four examples with good fits, but an aberrant data set – displaying complacent behavior - was also shown, giving an early suggestion that not all data sets conform to either the distribution transform notion, or to the CN equation. However, this approach is in line with the frequency matching interpretation application mode of the CN method.

Enlargement and formalization of this approach was done by Bonta (1997) who used "derived distributions" and statistical testing to replace Hjelmfelt's visual fits. Using a trial-and error procedure varying CN, he used the Kolmogorov-Smirnov test to determine the best fit between the cumulative distributions of calculated P (back-calculated using observed Q and the CN equation) and observed P. The P:Q data was censored to $P/S>0.465$. He determined CNs for a number of Standard and Violent data sets, but was unable to achieve satisfactory fittings with Complacent data, which was in keeping with Hjelmfelt's findings. It should be noted that while the lognormal distribution was used, it is not intrinsically required by the CN method.

This general method of matching the observed and P-CN generated Q distributions has also been recently applied by McCutcheon et al. (2006) in determining CNs from forested watersheds in the southeastern US.

<u>Fitting to continuous and event hydrograph models</u>: As described elsewhere in this report, CNs are used frequently in continuous models in a soil moisture management mode, so the underlying CN(II) can be treated as a fitting variable. When so treated, a

descriptive CN can be determined via the usual techniques of model calibration. Also, when the flood peak is of primary interest in event hydrograph models, a CN can be chosen that produces the observed peak, regardless of the volume considerations. This approach was used by Titmarsh et al. (1989), and Titmarsh et al. (1995, 1996). This general model fitting method was also pursued - though not centered on flood peaks - by Garg et al. (2003).

However, insofar as these methods use CN with other interacting/competing components in the model, they mask/confuse the independent role of CN. Continuous models with assumption of soils moisture thresholds, drainage, and evapotranspiration are examples. Furthermore hydrograph models intertwine the direct runoff pulses and their sequences dictated by the CN equation with routing procedures. Thus, the elemental CN feature - a function of only P and Q - is not isolated in these cases.

CNs from rainfall simulation plots: While usually done to measure site infiltration properties, rainfall simulation plots offer a tempting avenue to utilize the accompanying P and Q data to provide CNs. In addition, the hope remains that CNs – like infiltration measures – are unique measures of site hydrology – and should be tightly related. Because of the small plot size, routing considerations are assumed to be minimal, and runoff is taken to be identical to rainfall excess. By their very nature they assure that overland flow is the dominating process. Additional positive attributes are the high quality of the rainfall measurement, usually at several points over the plot area and along the plot boundaries, and the ability to visually observe the flow generation in some detail.

Several problems exist in these attempts. First, the rainfalls applied are almost never a valid sample of the site's resident rainfall across all seasons, depths, durations, and intensity patterns. Applied rainfalls are usually at a fixed duration (0.5 to 1.0 hour are typical) and uniform intensity, typically 25, 50, 75, or 100 mm/hr. Additionally, infiltration capacities as measured in such environments are usually found to be intensity-dependent (Hawkins, 1982). While this is consistent with the CN equation, the CN equation leads to an infiltration rate form which achieves a stable equilibrium rate of zero, in contrast to observed positive steady-state values greater than zero for almost all reigning infiltration formulations. The P and Q generated may hang on what may be arbitrarily selected measurement protocols. In fact, CNs so generated tend to be inconsistent and variable with the above factors.

Nevertheless, such direct CN interpretations have been made and discussed by several investigators, including Sabol et al. (1982), Steichen (1983), Partsch and Jarrett (1991), and Kuntner (2002). A slightly different approach was used by Hawkins (1979a) who fitted the CN infiltration rate equation to plot infiltration rate data. Numerical infiltration-based simulations to simulate rainfall-runoff with real break-point rainfall data were performed by Pierson et al. (1995), and produced credible – though variable – CN:P relations.

Indirect fitting of CN to sprinkler infiltrometer data was done by Wood and Blackburn (1984) who compared predicted runoff Q (based soil and cover based handbook CNs) with observed runoffs from 1200 rainfall simulation plots runs at 12 range sites in

Nevada, Texas, and New Mexico. They found generally poor comparisons, and attributed these results to the inappropriate assignment of Hydrologic Soil Groups for arid rangelands.

Summary: In brief, the major methods for CN determination from watershed rainfall-runoff data are:

"*NEH4 Method*": *Means or medians* of groups of event CNs, with the *median* of annual q_p events being the default historical NEH4 handbook example. However this approach avoids the known tendency of found CNs to decline with storm depth P, and may bias towards high CNs. An inconvenient interpretation is that when using the annual q_p series, the median CN defines the 2-yr return period CN. Also, the use of only one event per year requires a corresponding long period of record to gain a statistically-comfortable large sample size. Because of this long-record requirement (one data point per year), shorter term or transient land use effects – such as fires, seasonal cropping practices, silviculture activities, and grazing, may be quite difficult to detect.

From an operational standpoint, one clear appeal of the method is its intrinsic simplicity. The historical precedent and authority issues make it the default standard. This method is most appropriate using natural data, though ordered data can be used.

Least Squares fits to a large number of P:Q events. This is a familiar curve-fitting technique that gives well-known goodness-of-fit statistics. However, the CN-P problem described directly above occurs here too, and the biasing effects of high CNs for small storms can be dealt with by using only the larger storms, such as P>1", or for P/S>0.46. Using natural data makes the best use of the least squares capabilities and is consistent with the original rhetoric that developed the CN equation: i.e., individual events and variability around a central trend.

Asymptotic fitting, which recognizes the different runoff response patterns and the observed CN-P relationships. It provides a CN_∞, or the CN as P (and its return period) approaches infinity, and the parameters for intermediate events. Also it recognizes that not all P:Q data sets fit comfortably to the CN equation, i.e., the Complacent case. This is the method recommended for NEH630 adaptation by the ARS/NRCS Curve Number Working Group. (Woodward et al. 2003). Ordered data has been found to work well with this method. Additionally, as practiced, it makes economical use of the data by selecting events form the entire data record, not jus the annual events.

Frequency curve transformation of P to Q via the CN equation meets the return period matching application of the CN method, but is not appropriate in all cases: in particular, if the annual flood peak CNs displays a trend with rainfall. This method is, however, fully appropriate to the P-Q return period matching mode of application.

Other methods are also found. Though not uncommon, fitting with continuous models or complete hydrograph models complexes the CN rainfall-runoff effects with other model processes, though this approach is not uncommon. There is little justification or fixed protocols for using rainfall simulation-infiltrometer results to find CNs with present techniques.

Methods comparisons: Given the several approaches to extracting CN from data described above, the CNs generated by each may be different, and make different fundamental definitions of CN. Thus, method used should be appropriate to the intended application. The best fit CN from an annual series analysis (the NEH4 method) may not make the best CN for use in continuous models. General response descriptions reflecting and runoff event variety might be best achieved with least squares fits to natural P:Q data sets.

In addition, the data choices (ordered vs. natural, annual peaks vs. all significant event, etc.) lead to different CNs, as will differences in the fitting criteria. For example, asymptotic fittings to ordered P:Q data usually give CNs 1-3 units above those for natural data. Outside of the "NEH4 method" - with known limitations as described previously - there does not seem to be a general consensus choice. As future data sets are developed, this should be a fruitful ground for further research and inquiry.

PERFORMANCE COMPARISONS

CN table comparisons: A measure of the method's utility is the ability to accurately estimate CNs from soils and land information, and thus the ensuing runoff response. Several studies have tested this feature. Hawkins (1984) compared handbook estimates against P:Q defined (mainly as means and medians) 110 watersheds, and found essentially no relationship overall. When land types were considered, the best estimates were for rain-fed agricultural watersheds, and the least accurate were for forested watersheds. Later, similar studies by Titmarsh et al. (1989, 1995, and 1996) used the entire hydrograph modeling process to make similar comparisons, and came to similar results, as shown in Figure 12. From these two studies, the CN tables and their use (soils) do not compare well with the reality suggested from gage data. It would be worthwhile to repeat these studies using current data-based CN identification techniques.

Studies giving similar results are also provided by Fennessey (2000), Fennessey et al., (2001), Hawkins and Ward (1998), and Bales and Betson (1980). A study by Woodward (2003) with 97 urban watersheds with at least three years of data gave a reasonable comparison between the *average* data-defined (average CNs for each site) and handbook (i.e., from TR55). The average data-defined CN for the 97 watersheds was 85, and from the handbook tables 86. CN correspondence for individual watersheds varied considerably. A plot of the results from Hawkins and Ward (1998) is given in Figure 13. This figure highlights a problem in such analyses: several different tables and charts in local or regional usage were available for the "handbook estimates," and gave different results.

On the other hand, as described previously, Hansen et al. (1981) used least squares to find CNs on 25 small watersheds in Montana, Wyoming, and South Dakota, and found general agreement with handbook values. They used the peak events plus any summer runoff events with greater than 6 mm of runoff.