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16. Abstract: <p>The Natural Resources Conservation Service (NRCS) runoff curve number method provides the basis for much hydraulic design, including that performed by the Texas Department of Transportation (TxDOT). An index, the runoff curve number, is used to represent the runoff-producing potential of soils in a given watershed. In current TxDOT practice, curve numbers depend on characteristics of the watershed such as land use, soil group, and antecedent-moisture conditions. The basic index so derived is modified for geographic location to include, theoretically, the sensitivity of the index to differences in climate. Furthermore, these curve numbers are assumed applicable for a wide range of additional design criteria such as drainage area precipitation duration, and precipitation intensity. Such assumptions have not been tested and there are considerable ramifications to the hydraulic design process if these assumptions do not hold. It hoped that several adjustments to standard curve numbers can be derived to account for the influence of the additional design criteria.</p>			
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**CLIMATIC INFLUENCE ON NRCS
CURV NUMBERS LITERATURE REVIEW**

by

David Thompson

Research Report Number 0-2104

conducted for

Texas Department of Transportation

by the

**CENTER FOR MULTICISCIPLINARY RESEARCH IN TRANSPORTATION
TEXAS TECH UNIVERSITY**

October 2000

IMPLEMENTATION STATEMENT

The literature review presented in this report represents the first step in examining the relation between Texas climate and the NRCS runoff curve number. Remaining tasks include completion of data collection, analysis of the collected data, and statistical interpretation of the results. Therefore, much work remains to be completed before implementation of results of the research can be completed.

What is clear from the literature review is that the NRCS examined the relation between climate and runoff curve number in the early 1980s, the results of which were published. However, since that time, significant new research in the development of runoff curve numbers has been completed by other researchers. Therefore, completion of the remaining tasks in project 0-2104 is important to use of NRCS runoff curve numbers by TxDOT designers for estimating runoff volume and discharge for hydraulic design.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

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SI* (MODERN METRIC) CONVERSION FACTORS

CONVERSIONS TO SI UNITS

APPROXIMATE CONVERSIONS FROM SI UNITS

How	Multiply By	To Find	Symbol		Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH					LENGTH				
	25.4	millimeters	mm	mm	millimeters	0.039		inches	in
	0.305	meters	m	m	meters	3.28		feet	ft
	0.914	meters	m	m	meters	1.09		yards	yd
	1.61	kilometers	km	km	kilometers	0.621		miles	mi
AREA					AREA				
	645.2	square millimeters	mm ²	mm ²	square millimeters	0.0016		square inches	in ²
	0.093	square meters	m ²	m ²	square meters	10.764		square feet	ft ²
	0.836	square meters	m ²	m ²	square meters	1.195		square yards	yd ²
	0.405	hectares	ha	ha	hectares	2.47		acres	ac
	2.59	square kilometers	km ²	km ²	square kilometers	0.386		square miles	mi ²
VOLUME					VOLUME				
	29.57	milliliters	mL	mL	milliliters	0.034		fluid ounces	fl oz
	3.785	liters	L	L	liters	0.264		gallons	gal
	0.028	cubic meters	m ³	m ³	cubic meters	35.71		cubic feet	ft ³
	0.765	cubic meters	m ³	m ³	cubic meters	1.307		cubic yards	yd ³
1000 l shall be shown in m ³ .									
MASS					MASS				
	28.35	grams	g	g	grams	0.035		ounces	oz
	0.454	kilograms	kg	kg	kilograms	2.202		pounds	lb
o)	0.907	megagrams (or "metric ton")	Mg (or "t")	Mg (or "t")	megagrams (or "metric ton")	1.103		short tons (2000 lb)	T
TEMPERATURE (exact)					TEMPERATURE (exact)				
	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C	°C	Celcius temperature	1.8C + 32		Fahrenheit temperature	°F
LUMINATION					ILLUMINATION				
	10.76	lux	lx	lx	lux	0.0929		foot-candles	fc
	3.426	candela/m ²	cd/m ²	cd/m ²	candela/m ²	0.2919		foot-Lamberts	fl
PRESSURE or STRESS					FORCE and PRESSURE or STRESS				
	4.45	newtons	N	N	newtons	0.225		poundforce	lbf
	6.89	kilopascals	kPa	kPa	kilopascals	0.145		poundforce per square inch	lbf/in ²

nal System of Units. Appropriate

(Revised September 1993)

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Climatic Influence on NRCS Curve Numbers Literature Review

Introduction

The Natural Resources Conservation Service (NRCS) curve number procedure is a method for estimating the depth of runoff from a depth of precipitation, given soil textural classification, land-use/land-cover, and an estimate of watershed wetness. TxDOT uses this procedure for design of drainage facilities associated with watersheds too large for application of the rational method and too small for application of regional regression equations.

The curve number procedure is based on the assumption that the ratio of watershed retention to maximum potential retention is the same as the ratio of runoff to the difference between gross precipitation and the initial abstraction,

$$\frac{F}{S} = \frac{Q}{P - I_a},$$

where:

F = watershed retention (L),
 S = maximum potential retention (L),
 Q = runoff (L),
 P = precipitation (L), and
 I_a = initial abstraction (L).

In the standard application of the curve number procedure, maximum potential watershed retention is taken as a function of an index, the runoff curve number (CN),

$$S = 254 \left(\frac{100}{CN} - 1 \right).$$

Furthermore, the initial abstraction is taken to be a linear fraction of the maximum potential retention,

$$I_a = 0.2S.$$

Finally, the runoff, Q , is solved for in the equation,

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

with the requirement that precipitation, P , exceeds initial abstraction, I_a .

Given runoff, Q , and precipitation, P , for a particular event, the maximum watershed retention can be computed by solving the rainfall-runoff equation for S (Hawkins, 1979b):

$$S = \left(P + 2Q - \sqrt{4Q^2 + 5PQ} \right)$$

Basic application of the procedure requires the analyst to determine hydrologic soil group from soil association, then look up a standard value for the runoff curve number for average watershed wetness from a table. Given a design precipitation or distribution of precipitation, values of runoff (in terms of watershed depth) can be computed.

A fundamental assumption (among many) is that the table value of curve number is for average watershed wetness, Antecedent Moisture Condition (AMC) II, which is not well defined in NRCS literature. Because the western portion of Texas is relatively dry and warm, and the eastern portion of Texas is relatively wet, a correction is applied to the AMC II curve number (CNII). This correction is derived from Figure 5A of the Texas Engineering Technical Note (Number 210-18-TX1). The source of this design aid was traced to work done by NRCS in the late 1970's and early 1980's as reported in Hailey and McGill (1983).

Researchers working under contract to TxDOT on Project 0-2104 conducted a review of the literature. Much of the literature comprised discussion of application of the CN procedure in various contexts. What became clear after reading several papers was that the exact procedures used by NRCS to develop the procedure were never published in the peer-reviewed literature. Consequently, the method and its development were never critically reviewed by the profession. Yet, because of the simplicity of its application and the backing of a Federal agency, the curve number method received widespread acceptance and is used frequently in engineering practice (Hawkins, 1978, among others).

General Literature on the Curve Number Procedure

Hawkins (1975) studied the impact of errors in CN estimate. Estimates of runoff using the curve number procedure are sensitive to both precipitation and CN. For precipitation depths up to 230 mm, he reported that errors in CN estimates affect computed runoff more than errors in precipitation estimates. Such errors are especially dangerous near the threshold of runoff (low runoff and low rainfall conditions).

Hjelmfelt (1980), taking notice of work by Schaake *et al* (1967) with the rational method, examined rainfall-runoff data from five moderate-sized watersheds (drainage areas from 193 to 400 square miles). Hjelmfelt used events documented by Dalrymple (1965) in which annual maximum peak runoff rates were reported with commensurate rainfall depths. These values were sorted independently (that is, not pair-wise) from greatest to least and were plotted on log-probability ordinates. Both variables were approximated by lognormal distributions. Hjelmfelt computed CN for each ranked pair (not necessarily from the same event), treating the CN procedure as a method for converting the distribution of rainfall events into a commensurate distribution of runoff events. With the exception of the Sonoita River watershed located in the semi-arid southwest, results were good. Renard (1981), in a comment on the Hjelmfelt's work, indicated that the poor results with the Sonoita River watershed could be attributable to the spatial distribution of precipitation (partial area runoff) and to the reduction of flow volume by streambed infiltration.

Ragan and Jackson (1980) used Landsat imagery to classify land-use/land-cover for application of the curve number procedure. Because the imagery is not capable of resolving to the same degree as presented in the standard NRCS table of curve number for land-use/cover, the authors developed a reduced table based on an analysis of the NRCS standard table, as shown on Table 1. They examined a portion of the Anacostia River basin near Washington, DC to test their methodology. Three teams estimated curve number independently for the watershed. The first team applied the standard approach and estimated a value of CNII of 63.5. The second team used aerial photography and a digital soil map and estimated a value of CNII of 68. The third team used Landsat imagery with an assumed Hydrologic Soil Group of B and arrived at an estimate of CNII of 64.

Table 1. Runoff curve number for use with Landsat imagery (Ragan and Jackson 1980).

Land Cover Description	Curve Number for Hydrologic Soil Group			
	A	B	C	D
Forest Land	25	55	70	77
Grassed Open Space	36	60	73	78
Highly Impervious (Commercial, Industrial, Large Parking Lot)*	90	93	94	95
Residential	70	74	83	87
Bare Ground	72	82	88	90
*Probably sufficient to use CNII=93 for all soils				

Wood and Blackburn (1984) studied application of the curve number method applied to rangelands in Nevada, Texas, and New Mexico with respect to classification of soils by hydrologic soil group. The investigators measured rainfall-runoff responses of 1 square yard plots for a variety of plant communities, soils, slopes, rainfall intensities, hydrologic soil groups, and antecedent moisture conditions. They compared measured runoff with runoff predicted by the curve number procedure for each measurement. A total of 1600 plots were tested with CNII values ranging from 50 to 90. They concluded that current classifications are a poor basis for estimating hydrologic response of rangelands and that modifications may only accentuate the problem.

White (1988) developed a distributed application of the curve number procedure and applied it to a southeastern Pennsylvania watershed. He superimposed a grid over the watershed, computed (or imputed) precipitation depth at each point, determined curve number at each point, then applied the curve number procedure to compute the runoff at each point in the grid network. Results of the effort were marginal in that use of CNII tended to result in underprediction of runoff volume.

Hjelmfelt (1991) reviewed the state of the art of the CN procedure and set out “to establish a logically consistent, experimentally verifiable system” within which engineers and hydrologists could assess and refine application of the approach.

- 1) S includes I_o : Early version of NEH-4 contained a definition for watershed retention that stated that S includes I_o . This was corrected in a subsequent revision of NEH-4.
- 2) Definition of AMCII: AMCII is the watershed moisture condition from which standard CN is defined. Adjustments are made to CNII to account for dry or wet conditions.
 - a) AMCII is defined as the average condition, however it is not clear what is to be averaged. NRCS indicates that the conditions were associated with annual floods. However, in other places in NEH-4, NRCS seems to imply that five-day antecedent rainfall should be averaged.
 - b) In NEH-4, NRCS demonstrated determination of CN from annual rainfall-runoff data. The CN that divides the plotting into two equal numbers of points is associated with AMCII. AMCI and AMCIII are defined using enveloping curves. No association with antecedent precipitation is discussed.
 - c) In NEH-4, NRCS displays a table for AMCI and AMCIII based on five-day antecedent rainfall. But, in TR-55, the term was changed to antecedent runoff conditions.

- 3) Physical basis for S : Hawkins (1978) suggested that S could be used to indicate a hydrologically active depth for accounting of soil moisture.
- 4) The CN method is an infiltration equation: NRCS did not intend the CN method to be an infiltration equation. Many authors attempted to relate the procedure to one of the many methods for estimating infiltration (or infiltration capacity). However, a match was obtained only for a constant rainfall rate and zero asymptotic infiltration rates (Chen, 1976 and Hjelmfelt, 1980a).

In general, when applied as a function to transform rainfall frequency to runoff frequency, the procedure worked reasonably well. This was particularly true when runoff was a substantial fraction of rainfall. When attempting to explain the scatter extant in plots of rainfall-runoff data, instead of attempting to explain results in terms of antecedent precipitation, it is better to consider S (CN) to be a random variable. Therefore, CNII can be associated with the median value (50%) and CNI and CNIII with the 10% and 90% probabilities, respectively. If short-duration data sets are to be used to determine CN, then estimates of CN are generally substantially greater than those presented in handbook tables. Therefore, the data sets should be censored based on rainfall depth to reduce the impact of "small" events on estimates of CN.

Along a similar line (though with an additional 5 years of experience), Ponce and Hawkins (1996) presented an excellent review of general rainfall-runoff theory and practice with respect to the CN procedure. Like Hjelmfelt (1991), they relate that NRCS developed the CN procedure from annual series of daily rainfall and storm runoff volumes. The standard value for CN (or S) was taken as the median (50%) curve through the computed curve numbers. They also suggest that variability in computed CN results from 1) the effect of spatial variability of storm and watershed properties, 2) the effect of temporal variability of the storm, 3) the quality of measured data, and 4) the effect of antecedent rainfall and associated soil moisture. As a result, potential retention, as computed from measurements of rainfall and runoff, includes the history of antecedent rainfall (or lack of it), seasonal variations in runoff properties, and unusual storm conditions.

To put this in context, then, the average design condition was designated AMCII and the associated curve number CNII. Choice of AMCI (and CNI) results in reduced runoff volume and choice of AMCIII (and CNIII) results in increased runoff volume. Orange County, CA, used an approach wherein high frequency events used reduced runoff (CNI), low frequency events used high runoff (CNIII), and medium frequency events used the standard approach (CNII).

Ponce and Hawkins (1996) commented on the two approaches for computing CN from rainfall-runoff measurements. First, the standard approach, which they referred to as the "annual flood series" method, uses select daily precipitation and corresponding runoff volume for the annual floods at a site. This procedure has the advantage in that it encompasses a wide range of values. However, these data are not readily available, the return periods of the rainfall and runoff are not necessarily the same, and there is only one measurement for each year of record.

In response, some researchers use return periods less than one year. However, this may cause errors in curve number estimates.

Another approach is to determine curve numbers from events in which the rainfall frequency is matched to the runoff frequency. Storm rainfall and runoff are sorted separately, realigned on rank-order basis, and curve number computed from the resulting frequency-matched pairs.

Shirmohammadi *et al* (1997) reported on a modification to the GLEAMS model. The original model used CNII, which was converted to CNI internally. Because of the tendency for the model to underpredict runoff, they modified the code to use CNII directly. For the application they examined (coastal plain of Maryland), results were much better with the modified code.

Calculation of Curve Numbers from Measurements

Hawkins (1973) examined rainfall-runoff relations for four mountainous watersheds. Computed CN tended to decrease with increasing precipitation depth. The author suggested that the storms studied were not large enough to fully develop the hydrologic relation implied in the runoff equation.

Hawkins (1979b) studied the hydrology of watersheds for which a constant CN could not be developed. He suggested that a relatively small source area could account for the runoff from the watershed.

Although not reported by NRCS in NEH-4, Rallison and Cronshey (1979) reported that NRCS personnel used annual maximum runoff events with associated recorded daily rainfall to compute estimates for the watershed retention, and hence, CN. This method of computation for the original studies is alluded to in Hailey and McGill (1983) as well.

Hawkins *et al* (1985) examined the relation between CN_I and CN_{III}. These relationships form the 10% and 90% cumulative probability distributions for runoff from a given precipitation depth. Given the interest in determining CN from observed rainfall-runoff sequences, and given the general undocumented concern about storm size requirements for application of the CN method and that early development was through annual maxima daily rainfall and runoff data, the authors continued by examining what constitutes a "large event." Smith and Montgomery (1980) suggest a lower bound for P/S of 0.4. Hjelmfelt (1984) suggested that a smallness threshold of $P < 0.456S$, or $Pr(Q/S > 0) = 0.90$, were S is defined on CN_{II}.

From Hawkins *et al* (1985), clearly, the threshold value for including the event says nothing about the probability of the event, which is geographically dependent. For example, for a CN_{II} of 99, $S=0.10$ in, and almost all storms would be considered large events. However, for a CN_{II} of 40, $S=15$ in and a storm depth of 3in would be considered small. This leads the authors to the observation that the censoring procedure results in lower estimates of CN_{II}. Furthermore, they observed that not all events are useful for determining CN. For example, for a site with CN_{II}=50, a storm depth of 4.6in would be required to achieve $P/S=0.46$. In addition, although the smallness threshold produces censors that minimize calculation bias, it also reduces the sample size, thereby increasing uncertainty in the results. Finally, the smallness threshold of $P/S>0.46$ suggests that at least one point that produces 12% runoff from a rainfall event is required to estimate the CN.

Bonta (1997) developed a procedure to use the probability distributions of precipitation and runoff to estimate S , from which CN can be computed. In comparison with the asymptotic approach of Hawkins (1993) and annual maximum approach used by NRCS (Rallison and Cronshey, 1979). He reported that results were similar to those derived using Hawkins asymptotic approach. He suggested that the derived-distribution method may have advantages if statistical precipitation data (such as from TP-40) are used with measured runoff data, and that the approach may have utility for regionalization of CN estimates.

Examples of Computed Curve Numbers

Hawkins and Ward (undated) examined rainfall-runoff relations on the Jornada Experimental Range in New Mexico. They used the asymptotic method (Hawkins, 1993) to compute runoff curve numbers for numerous events and subwatersheds located on the site. They compared computed CN with NEH-4 table values and table values from a local guide. Computed values of CN deviated substantially from values determined from either guidance. The authors suggested that the basic soil resource is of overriding importance in limiting hydrologic response with vegetation playing a smaller role.

Hawkins (1984) published results of studies of 110 watersheds for which both measurements of rainfall and runoff were available. In addition, sufficient watershed description was available that handbook CN could be estimated, at least in a rough sense. Observed CN was determined using the least-squares approach to construct a best estimate of S , from which CN was derived. Most of the CN derived exceeded 50. Analysis of results suggested that, although the correlation coefficient between observed and

estimated CN was statistically significant, substantial variance would not be described by a linear relation. This implied that substantial errors in predicted runoff might be incurred by application of the standard procedure.

Hauser and Jones (1991) studied rainfall and runoff from three field-sized watersheds at the Bushland, Texas, Agricultural Research Service Research Laboratory. They computed CN based on annual maximum runoff event from each watershed. They applied a modification to the method suggested by Hjelmfelt (1980). Hauser and Jones found no correlation between potential maximum retention and five-day antecedent rainfall for annual maximum runoff events. CNII values were estimated by fitting a lognormal distribution to

Modifications to the Curve Number Procedure

Because AMC is poorly defined, Hawkins (1978) examined the relation between antecedent moisture condition (AMC), curve number (CN) and the intra-storm processes evapotranspiration (ET) and drainage. He developed an approach such that, given estimates of ET and drainage, an estimate of CN could be developed that would be improved over the simpler NEH-4 estimates of CN based on AMC.

Hjelmfelt (1980a) studied the potential use of the CN procedure as an infiltration method. Previous authors had been critical of the CN procedure because of a dependence of implied infiltration rate on precipitation intensity (Smith 1976) which is in contrast with declining rate methods such as Horton's infiltration equation. However, if the precipitation rate is held constant, then infiltration rate, as predicted by the CN method, also declines with increasing precipitation. However, it does not approach a constant or final infiltration capacity. Hjelmfelt then went on to show that, for a constant precipitation rate, the CN method is equivalent to the Holtan-Overton infiltration equation.

McCuen and Bondelid (1981) used the rational method and TR-55 to derive a relation between runoff coefficient and CN. They observed that peak discharges estimated using the rational method are more sensitive to the runoff coefficient than commensurate peak discharges developed through TR-55 using the CN.

Hawkins (1982) examined the loss-rate function implicit in the CN procedure. He developed a mathematical relation between watershed mean loss rate (similar to a phi-index) and the CN. Because of the requirement for an initial abstraction equal to $0.2S$, mean watershed infiltration rate is limited to this value. Hawkins remarked that if the 0.2 multiplicative factor could be modified (or relaxed), then more reasonable values for mean watershed loss rates might be derived.

Hailey and McGill (1983) presented results of studies conducted on Texas watersheds to relate curve number to climatic factors. They observed that use of table values (CNII) resulted in designs that did not perform as expected, given the range in climatic conditions in Texas. The authors collected data from watersheds located at agricultural experiment stations and SCS flood control projects for further analysis. Locations of the SCS watersheds and flood control structures are shown on Figure 1. Using a simple hydrologic model developed by Williams and LaSeur (1976), they supplemented NRCS data with data from USGS gaging stations. The locations of the USGS gaging stations are shown on Figure 2.

They applied three methods for analysis of the collected data. The first procedure was to use annual storm rainfall and runoff data (the standard method) to estimate curve number. The second procedure was applied where daily runoff was available. In that case, the performed frequency analysis on two-day annual runoff (assuming that storm runoff would overlap 24-hour periods) and associate 2-day runoff frequency with daily rainfall frequency, then compute curve number. The third procedure was to

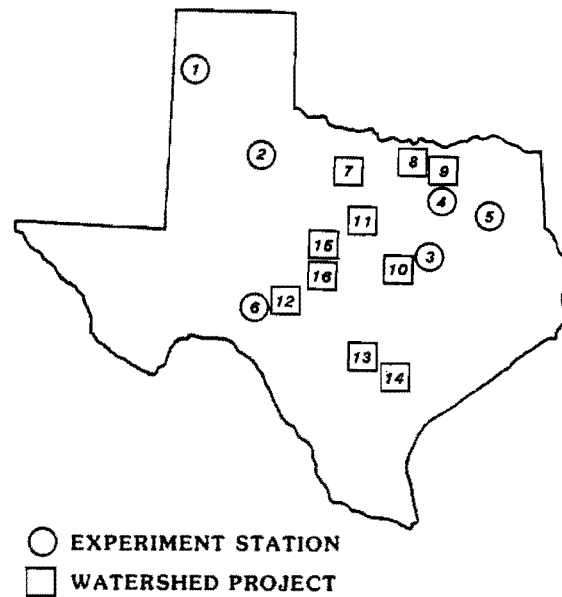


Figure 1. Locations of experiment stations and watershed projects (after Hailey and McGill, 1983).

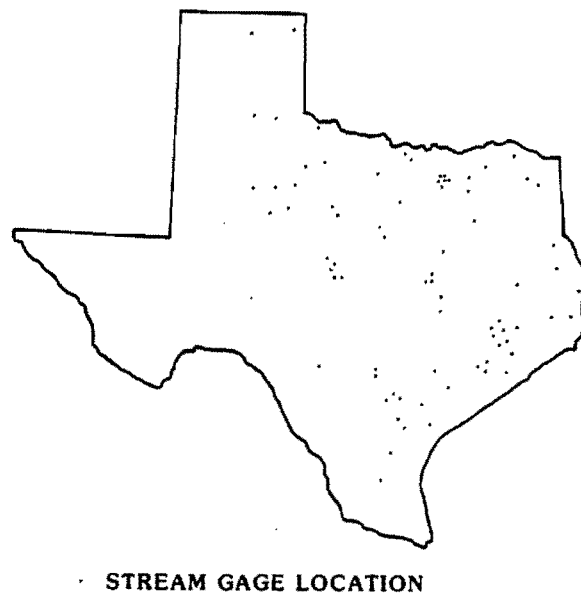


Figure 2. Stream gage locations (after Hailey and McGill, 1983).

examine the volume-duration-probability relation of runoff from USGS measurement stations. Two-day runoff volume was related to daily precipitation at the same frequency, then the curve number was computed.

Hailey and McGill (1983) then computed a weighting factor, X , for the equations $CN = CNI + X(CNII - CNI)$ if computed $CN < CNII$, or $CN = CNII + X(CNIII - CNII)$ if computed $CN > CNII$. The resulting CN was related to climatic index, defined as the ratio of average annual precipitation to the square of average annual temperature. A graphical depiction of the distribution of climate index is shown on Figure 3. Computed CN was approximately equal to CNII in regions where the climate index was near 1.0. Computed CN was approximately equally to CNI where climatic index as near 0.5. The results of these analyses are shown on Figure 4.

Hawkins *et al* (1985) examined relations between the enveloping curves for CNI and CNIII and the median curve for CNII. They suggested that the AMC categories might be interpreted as statistical error bands or envelope curves indicating the experienced variability in the rainfall-runoff relation. The implication, therefore, was that NRCS was using site antecedent moisture as a surrogate for all sources of variability not directly included in the CN model. This concept came from an earlier paper (Hjelmfelt *et al*, 1981), in which the idea was proposed that the AMCI, AMCII, and AMCIII relations described the 90%,

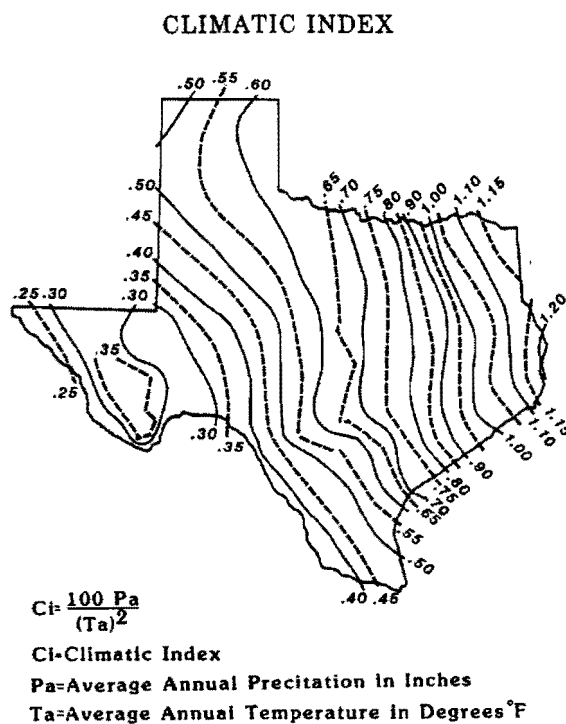
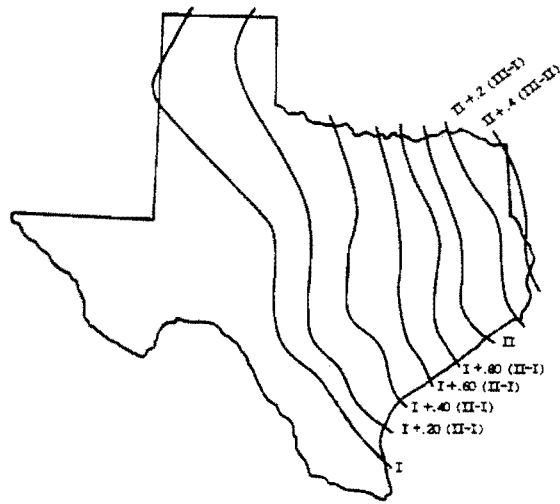


Figure 3. Climatic index for Texas (after Hailey and McGill, 1983).

50%, and 10% cumulative probabilities of runoff depth given rainfall depth. These relations are shown on Table 2.



AVERAGE CONDITION
RUNOFF CURVE NUMBERS

Figure 4. Curve number modified for climate index (after Hailey and McGill, 1983).

Table 2. Probability of runoff for P/SII (after Hawkins *et al* (1985)).

P/SII	Probability ($Q/SII > 0$)	Comments
0	0	
0.085	0.10	AMCIII
0.20	0.50	AMCII
0.456	0.90	AMCI
Infinity	1	

Hawkins *et al* (1985) mentioned a largely undocumented concern about storm size requirements for application of the CN method. Early development of the procedure relied on annual maximum daily rainfall and runoff data. Smith and Montgomery (1980) suggested that $P/S < 0.4$ poorly defines CN. Hjelmfelt (1982) suggested that a small storm is one where $P < 0.2SI$ and suggested that users censor small events from data sets to be used for analysis. From Hjelmfelt's work, $P/SII = 0.456$ corresponds to $Pr(Q/SII > 0) = 0.90$. This suggested an algorithm for computing CN:

1. Rank the events in decreasing order. Compute S and CN using the rainfall-runoff equation.
2. Check that $P/S > 0.46$.
3. If $P/S > 0.46$, proceed to the next largest storm in the calculation and update S to use the mean value of S computed as the process advances.
4. Include all events to the point where the last P/S exceeds 0.46.

The authors then applied the procedure to several example cases. They observed that this censoring procedure resulted in lower estimates of CN. Furthermore, not all events are useful for estimating CN. (For example, if $CNII = 50$, then to satisfy the requirement that $P/SII > 0.46$, a precipitation event of about

4.6 inches would be required!) Finally, the censoring process reduces effective sample size, thereby increasing uncertainty in the results, which is a function of $N^{0.5}$.

Bosznay (1989) suggested a modification to the CN procedure in which I_a is not a function of S . He used the combination of precipitation and initial abstraction, $P - I_a$, as a variable because it appears on both the numerator and denominator of the CN equation.

Chong and Teng (1986) examined the relation between maximum watershed retention, S , saturated infiltration rate, K_{sat} , and soil sorptivity, S_0 . They used a data set derived from operating a rainfall simulator on a test plot. CN is strongly related to K_{sat} but that the standard error of estimate was relatively large. The efficacy of the relations derived in the study was not discussed.

Hawkins (1993) developed his procedure for estimating CNII from measurements of rainfall-runoff data. This work was based on his earlier presentation of an investigation to determine an appropriate censoring level (Hawkins *et al*, 1985). Because of the sensitivity of runoff computations to CN estimates (Hawkins, 1975) and the difficulty of selecting CN from handbook values (Hawkins, 1984; Hossein *et al*, 1989), Hawkins recommended that local measurements of rainfall and runoff be used to estimate regional values of CN.

The algorithm presented in Hawkins *et al* (1985) was applied to a large number of watersheds. Watershed drainage area ranged from 4.0 to 4,600 acres. Numerous events were used from each watershed. Three behaviors of CN as a function of storm rainfall were observed. The first was labeled complacent and occurred when no asymptotic value of CN was approached. This was characteristic of watersheds which exhibited a partial area source (Hawkins 1979; Pankey and Hawkins 1981). The second was labeled standard and occurred when CN declined with increasing storm rainfall, but approached a constant, relatively stable value with increasing storm depth. The third was labeled violent and occurred when observed CN rose suddenly with increasing storm rainfall to approach asymptotically an apparently constant value. This behavior was thought to represent a threshold phenomenon when significant runoff did not begin until a certain depth of rainfall had occurred.

Implications for Project 0-2104

First, the work of Hailey and McGill (1983) is the basis for the NRCS Engineering Technical Note (210-18-TX5). This is the procedure currently in use by TxDOT for design activities requiring use of the NRCS curve number procedure. Hailey and McGill developed the adjustment procedure for CNII based on relations between observed CN and climatic index. Observed CN was developed using several methods from a variety of measured rainfall-runoff responses. At the time Hailey and McGill were executing their research, later work by Hjelmfelt and Hawkins was unavailable, hence Hailey and McGill were not able to take advantage of Hjelmfelt's frequency matching approach or of Hawkins' asymptotic algorithm.

Second, as a result of development of curve number technology following the work of Hailey and McGill, computation of observed curve numbers can be revisited. Hjelmfelt's concept of matching the frequency of observed rainfall with that of observed runoff, then using the curve number method as a transformation function between the two probability distribution functions, matches the way that curve numbers are used, namely as a predictive tool for estimating a design discharge. Furthermore, the asymptotic approach for computation of observed curve number, as developed by Hawkins, should result in additional values and increased confidence in curve number estimates.

Third, relatively few watersheds were available in the western one-third of the state. Consequently, little confidence can be placed in any adjustments proposed to design curve number for that portion of the state. Clearly, it would be beneficial to TxDOT and other design agencies that use curve numbers for predicting runoff from rainfall to collect and analyze data for this region.

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