Comparison of methods for estimation of 50-year peak discharge from a small, rural watershed in North Carolina

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Abstract Four applied hydrologic methods were used to estimate the 50-year peak storm discharge (Q_{50}) from a 15.8-ha agricultural (67%) and forested (33%) watershed in North Carolina, U.S.A. The methods (and Q_{50} results) were the NCDOT (North Carolina Department of Transportation) method (0.42 m^3/s), the USGS (U.S. Geological Survey) regression method (0.50 m^3/s), the rational method (1.2 m^3/s), and the NRCS (Natural Resources Conservation Service) TR-55 method (2.6 m^3/s). The wide range of results (coefficient of variation = 84%, factor of >6 between highest and lowest estimates) indicates significant inaccuracy in one or more of the methods, and presents a practical problem for use of the methods in the design of drainage systems. The NRCS method likely overestimates Q_{50}, and the NCDOT and USGS methods have other potential drawbacks for the study watershed. The least problematic approach in this case is probably the rational method. The best estimate of Q_{50} from the study watershed is likely ~1 m^3/s. The results suggest the importance of developing improved methods for estimation of peak storm discharge from small, rural watersheds.

Keywords Watershed · Runoff · Drainage · Peak discharge · North Carolina, U.S.A.

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Introduction

Quantitative knowledge of storm discharge (runoff) rates from watersheds is relevant to understanding and controlling a number of environmental processes, including erosion and sediment transport, pollutant loadings and travel times, and flooding and drainage. Accurate estimation of peak storm discharge rates from watersheds is especially important to the design of drainage works along roadways and related infrastructure (Wright and Paquette 1987; Mannering and Kilareski 1998). A variety of methods are available for estimation of storm discharge from watersheds and are used as aids in the design of roadway drainage (AASHTO 1999). Some are based on regional statistical relationships between measured storm discharge and watershed characteristics such as size (area) and land use; this approach has been popularized by the U.S. Geological Survey (Koltun and Roberts 1990; Bisese 1995; Pope and Tasker 1999), and is referred to here as the "USGS method". Other methods use rainfall statistics (Hershfield 1961) along with simple "runoff coefficients" or other empirical coefficients and algorithms for relating rainfall amounts and/or intensities to peak storm discharge rate; the most widely used of these methods are the "rational method" and the "Natural Resources Conservation Service (NRCS) method" (McCuen 1982; USDA 1986; Chow and others 1988; Viessman and others 1989; Bras 1990; NYSDOT 2000; ODOT 2002). The NRCS method is also known as the "TR-55 method", in reference to the report in which it was originally published, i.e., Technical Release 55 of the former USDA Soil Conservation Service (now the USDA NRCS).

The USGS, rational, and NRCS methods are all commonly used in the design of roadway drainage in the U.S. (Table 1). In this study, these three methods and a fourth specific to the North Carolina Department of Transportation (the "NCDOT method") were applied to a small, rural watershed adjacent to a state highway in North Carolina. Each method was used to estimate the 50-year peak storm discharge (Q_{50}, m^3/s) from the watershed; this frequency is significant because highway drainage works are often designed to protect against roadway inundation with a 50-year frequency (e.g., Mannering and Kilareski 1998; NCDOT 1999; ODOT 2002). The study was prompted by a fatal automobile accident on a flooded section of highway adjacent to the study watershed, a consideration relevant

Table 1
Four methods used to estimate Q_{50}

Method	Recommended by[a]	Parameters needed to estimate Q_{50}
NCDOT	NCDOT	Watershed area, location, length, and % forest cover
USGS	NCDOT, SCDOT, VADOT, ODOT, NYSDOT, FLDOT	Watershed area and location, land use/cover in some cases
Rational	NCDOT, SCDOT, VADOT, ODOT, NYSDOT, FLDOT	Watershed area, runoff coefficient, and time of concentration; 50-year rainfall intensity for a storm with duration equal to the time of concentration
NRCS	SCDOT, VADOT, NYSDOT	Watershed area, location, land use, and time of concentration; soiltype, hydrologic group, and drainage condition; 50-year 24-hour rainfall total

[a] As an example of use of the methods in hydrologic/drainage engineering, the second column indicates whether the method is recommended for some watersheds by the state departments of transportation in North Carolina, South Carolina, Virginia, Ohio, New York, and/or Florida (NCDOT, SCDOT, VADOT, ODOT, NYSDOT, and FLDOT, respectively). This is not intended to indicate whether these departments would recommend or concur with the specific application in this study. Sources: NCDOT (1973), VADOT (1980), NCDOT (1999), FLDOT (2000), NYSDOT (2000), SCDOT (2000), ODOT (2002)

to the overall costs associated with drainage design on this and other small watersheds. Q_{50} results from the four methods are reported below, along with discussion of some causes and implications for the wide range of results (a factor of >6 between the highest and lowest Q_{50} estimates).

Study site

The study watershed is in Cumberland County, North Carolina (Fig. 1). Its area (15.8 ha) and land use (67% forested and 33% agricultural fields) were determined from CCPD (2001), a composite of aerial photographs at 1:2400 scale with topographic contours. The watershed drains northward to a roadside drainage ditch along the south side of North Carolina highway 217 (NC217). At present two culverts (Fig. 1) carry drainage under NC217, though only culvert 1 (Fig. 1) was present at the time of interest for the analyses in this study (the time of the fatal automobile accident). At this time, all flow in the roadside ditch along the northern watershed boundary was toward culvert 1 from both east and west, and the agricultural areas were plowed and bare (no crop or significant crop residue). A very small, ephemeral channel which flows only after significant rainfall runs toward culvert 2.

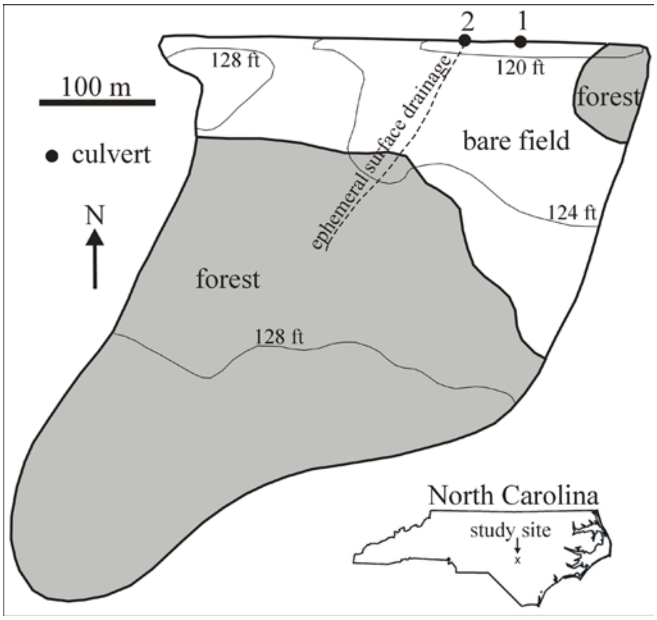

Fig. 1
Map of the study watershed. Agricultural fields are *white*, forest is shaded. Elevation contours (from CCPD 2001) indicate feet above sea level. The northern boundary of the watershed is a drainage ditch running along the south side of North Carolina highway 217 (NC217). At the time of interest for the study, culvert 2 was not yet installed and all drainage from the watershed converged at the inlet of culvert 1 (both culverts pass beneath NC217)

Estimation of Q_{50}

NCDOT method

This method is based on a series of hydrologic charts presented in NCDOT (1973). Data and analyses used in creating the charts are not presented in NCDOT (1973) or elsewhere in readily available NCDOT documents. The method is suggested and used by NCDOT for rural North Carolina watersheds less than one square mile (259 ha) in area (NCDOT 1999), and as such represents the officially-recommended method for the study watershed. Parameters needed to apply the method (Table 1) were determined from CCPD (2001).

USGS method

A number of USGS reports describe estimation of peak discharge based on regional statistical regressions of peak discharge against watershed area and, in some cases, other watershed characteristics such as land use (Sauer 1983; Guimaraes and Bohman 1988; Koltun and Roberts 1990; Bohman 1992; Bisese 1995; Mason and Bales 1996; Robbins and Pope 1996; Pope and Tasker 1999). Equations are generally developed for a specific physiographic-hydrologic region (e.g., the Coastal Plain of North Carolina) using stream-flow data from a number of watersheds in the region. The equations are then considered to be applicable to those watersheds and others in the same region. The study watershed falls within the Sand Hills region of southeastern North Carolina as defined in Pope and Tasker (1999). The relevant equation for this region (Pope and Tasker 1999) is $Q_{50} = 0.0747A^{0.69}$, where A is the watershed area in hectares (15.8 for the study watershed) and the units of Q_{50} are m^3/s. This equation represents the USGS method as applied in the present study.

Rational method

The rational method dates from the late 19th century (Kuichling 1889), and remains widely used for estimating peak discharge from small watersheds in the U.S. and elsewhere (VADOT 1980; Chow and others 1988; Viessman and others 1989; Bras 1990; FLDOT 2000; NYSDOT 2000; SCDOT 2000; ODOT 2002). The method is based on the equation Q = CIA, where Q is the peak discharge, C is a dimensionless runoff coefficient which depends on land use and recurrence interval, I is rainfall intensity, and A is the watershed area. Values of C are generally tabulated to give Q in ft^3/s when I is expressed in inches/hour and A in acres (e.g., Chow and others 1988; Viessman and others 1989). For a 50-year recurrence interval, Chow and others (1988) give C = 0.43 for low-slope (0–2%) cultivated land (33% of study watershed), and C = 0.35 for low-slope woodlands/forest (67% of the study watershed). In accord with standard practice, C for the full watershed (0.38) was computed as the weighted average of the C values for the two land uses, each weighted by its fraction of watershed area (Chow and others 1988).

The intensity generally recommended for use with the rational method is that applicable to the recurrence interval of interest (50 years in this case), for a storm with duration equal to the time of concentration (t_C) of the watershed (Chow and others 1988; Viessman and others 1989). The time of concentration is the hydrologic time of travel from the most remote point in the watershed to the watershed outlet (in this study, the latter point was the inlet of culvert 1). The time of concentration of the study watershed was estimated to be 1.5 h using methods in USDA (1986), discussed in further detail below. At a storm duration of 1.5 h, Hershfield (1961) gives 2.8 inch/h (71 mm/h) as the intensity for a 50-year rainfall at the study site. This was used with the watershed area and the runoff coefficient given above (C=0.38) to estimate Q_{50}.

NRCS method

The graphical NRCS method (USDA 1986) represents an updated version of an earlier method (USDA 1975; McCuen 1982). The method is widely used in applied runoff and drainage design problems, and remains a topic of active discussion in the technical literature of this area (Ponce and Hawkins 1996; Smith 1997; Moglen and Hartman 2001; McCuen and Okunola 2002). The NRCS method involves use of watershed soils and land use information to define a "curve number" (CN). CN is then used to estimate the amount (volume per area) of drainage from the watershed for a rainfall event having the annual probability of interest (in this case 0.02, for a recurrence interval of 50 years) and a duration of 24 h (i.e., the 50-year, 24-h rainfall). The estimated drainage is then used along with t_C and a standard assumed temporal distribution for the 24-h rainfall (USDA 1986) to compute Q_{50}. Additional details are given in USDA (1986) and Viessman and others (1989).

The 50-year, 24-h rainfall for the study site (191 mm) was found from Hershfield (1961). The study watershed contained six different combinations of soil type and land cover (Table 2), each with its own CN. The overall CN for the watershed (82) represents a weighted average of the CNs of the six subareas, with each of those six CNs weighted by the fraction of watershed area to which it applies. Using the curve number of 82 and the 50-year, 24-h rainfall total given above, Fig. 2-1 of USDA (1986) gives 137 mm as the amount of watershed drainage expected from the 50-year, 24-h storm.

Time of concentration (t_C) represents the hydrologic travel time to the watershed outlet (the culvert 1 inlet) along a 652-m flowpath from the most remote point on the watershed boundary. The value of t_C was estimated to be 1.5 h, using a combination of methods appropriate to different portions of the flowpath including (1) Manning's kinematic solution for travel time by overland "sheet" flow (USDA 1986, p. 3-3) in the headwater area, (2) a nomograph giving the velocity of shallow concentrated flow as a

Table 2
Soils and CN values of the study watershed. Weighted average CN (weighted by percent of watershed area) is 82. Data sources are indicated in the table notes

NRCS soil name[a]	NRCS hydrologic group[a]	NRCS land-use category[b]	NRCS drainage condition[c]	Percent of watershed[d]	NRCS curve number (CN)[e]
Lenoir	D	Woods	Poor	57.2	83
Wickham	B	Fallow agric. field	Not applicable	28.3	86
Wickham	B	Woods	Fair	6.0	60
Craven	C	Fallow agric. field	Not applicable	4.7	91
Craven	C	Woods	Fair	2.0	73
Tarboro	A	Woods	Good	1.8	30

[a] USDA (1984), Table 16, pp. 151–153, and Sheet 21, Inset A

[b] CCPD (2001) and USDA (1984) to show forest and agricultural land, and NCDOT video to show that the agricultural field was plowed and bare at the time of the automobile accident

[c] Soil descriptions in USDA (1984), pp. 36, 42, 73, and 91

[d] USDA (1984) for soils map (Sheet 21, Inset A), and CCPD (2001) for determination of watershed boundary

[e] USDA (1986), Table 2-2, pp. 2-5 to 2-7

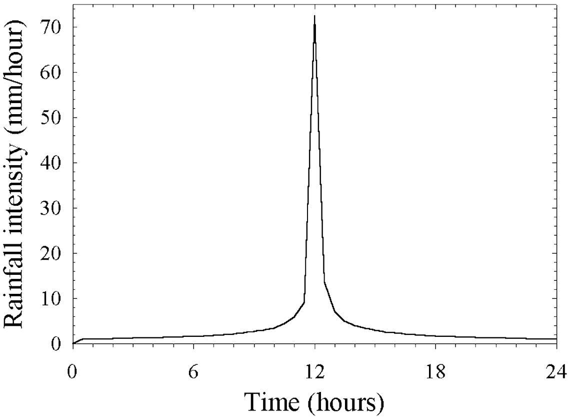

Fig. 2
50-year, 24-h rainfall total for the study site (191 mm, from Hershfield 1961), distributed over a 24-h period according to the temporal pattern (Type II) specified in the NRCS method (from USDA 1986, and McCuen 1982)

function of watershed slope (USDA 1986, Fig. 3-1) downstream of the headwaters, and (3) Manning's equation for flow in open channels (e.g., USDA 1986, p. 3-4; Chow and others 1988; Viessman and others 1989), to model flow through the NC217 roadside drainage ditch to the culvert 1 inlet. In this context, shallow concentrated flow refers to a form of overland flow in which the sheet flow has concentrated into shallow, natural drainage ways but not organized into discrete, well-defined channels. Q_{50} was determined using Exhibit 4-II and Eq. 4-1 of USDA (1986), based on the values given above for watershed area, CN, t_C, and the amount of discharge expected from the 50-year, 24-h rainfall.

Results and discussion

Estimates of Q_{50} from the four different methods are:

- NCDOT method: 0.42 m^3/s
- USGS method: 0.50 m^3/s
- Rational method: 1.2 m^3/s
- NRCS method: 2.6 m^3/s

The mean of the estimates is 1.2 m^3/s, and the coefficient of variation about the mean (standard deviation divided by mean) is 84%; the highest estimate is more than 6 times the lowest.

Two of the methods (NCDOT and USGS) are in close agreement, but application of each has a potential shortcoming. The development and performance of the NCDOT method are not fully documented in openly available publications. Such "in-house" methods may be based on a sound body of work and be effective in practice, but they must be fully documented if they are to allow for scientific, public, and/or legal scrutiny. The USGS method for this region was developed using stream-flow data from watersheds of 563 ha to 3.2×10^5 ha; its application to the 16-ha watershed in this study represents an extrapolation with a potentially significant and unknown uncertainty (NCDOT does not recommend this particular application of the USGS method). If the NCDOT method is sound (as the agency believes), its close agreement with the USGS method suggests that the extrapolation of the latter to the 16-ha study watershed did not involve a large error in Q_{50}. Although agreement between different methods is generally an encouraging result, in this case the agreement between the NCDOT and USGS methods does not alleviate concern over their use on small watersheds. There is little or no practical difference between results of the two methods in this case, but neither represents an ideal practice—one lacks available documentation and the other requires extrapolation (for watershed areas less than about 560 ha in this region of North Carolina).

Although the NRCS method is widely used and cited in the applied hydrologic literature, a number of technical concerns have been raised concerning the method (e.g., Pilgrim and Cordery 1993; Willeke 1997; Smith 1997; McCuen 2002). There is reason to believe the NRCS method may overestimate Q_{50} in this and possibly other cases; such overestimation would be consistent with the high Q_{50} value found here. The estimate of Q_{50} from the NRCS method depends on the assumption (embedded in the method) of a large central peak in the temporal distribution of the 24-h rainfall total (Fig. 2). The assumption of a large peak in the rainfall hyetograph leads directly to a large peak discharge estimate. Estimation of peak discharge in the context of the NRCS method requires a temporal distribution for rainfall, and the distribution contained in the method may be reasonable in some respects. However, other temporal rainfall distributions which are possible but not included in the method would lead to lower peak discharge estimates. The lowest peak discharge estimate would result from assuming that the 191 mm of rainfall used as input to the method fell evenly over 24 h. In this case, the 137 mm of expected discharge would also be approximately evenly distributed in time, and the peak discharge rate would be about 0.25 m^3/s (less than one tenth the NRCS estimate given above). Recent discussions with practicing engineers in North Carolina indicate that some do not use the NRCS method because of concern that it overestimates peak discharge.

With all four methods used, uncertainty arises through oversimplification of a complex hydrologic system (i.e., through model structure), and through selection of values for the parameters in the models. The best measure of uncertainty for all four methods would come from comparison of predicted and observed Q_{50}, with observed values determined from flood frequency analysis of long-term stream-flow records. This is not possible on the study watershed or any other watershed lacking a long-term stream-flow record over a period with stable land-use characteristics, but it has been done in previous studies for two of the methods (USGS and rational). With regard to the USGS method, Pope and Tasker (1999) state that the prediction uncertainty in their equation for Q_{50} in the Sand Hills region of North Carolina is about 50%. This was the typical deviation between a Q_{50} value predicted with the equation and the observed Q_{50} value on the same watershed; as such, it applies to the watersheds used in developing the equation. Uncertainty in prediction of Q_{50} for other watersheds in the region (e.g., the watershed in the present study) is probably larger, especially for watersheds significantly smaller or larger than those used by Pope and Tasker (1999) in development of their equation. In 63% of cases from a study of 271 watersheds in Australia, the rational method predicted peak discharges which deviated by >50% from peak discharges estimated from frequency analysis of observed hydrographs (Pilgrim and Cordery 1993); recurrence interval was not given for the peak discharges.

This comparison between predicted and observed peak discharge is not available for the NCDOT or NRCS methods, though other indicators of performance and uncertainty have been published for the NRCS method. McCuen (2002) reports a procedure for estimating confidence limits on curve number (CN) values, and provides a table of CN intervals for different confidence levels based on annual maximum peak discharges from a watershed in the Maryland Piedmont. He found lower and upper 95% confidence limits of 69.9 and 91.6, respectively, for a CN of 82 (the best estimate of CN in the present study). These limiting CN values lead to Q_{50} estimates of 2.0 and 3.2 m^3/s for the watershed in the present study. The lower value is still 67% above the nearest Q_{50} estimate by another method (1.2 m^3/s from the rational method). Also, Q_{50} "limits" computed in this way account for uncertainty in CN but not in t_C, rainfall amount, watershed area, or model structure (e.g., the simple structure of the model, the assumption of a large rainfall peak, etc.). Actual confidence limits on Q_{50} are no doubt wider. The approach is helpful in placing objective confidence limits on CN and showing the sensitivity of Q_{50} to CN. The latter aspect (sensitivity analysis) has also been addressed by Chen (1982) and Hawkins (1980). In a somewhat different means of assessing performance and uncertainty, Hoesein and others (1989) used the NRCS method in an "inverse mode", estimating CN values from observed peak discharges and rainfall data on 139 watersheds in Australia. CN values estimated in this way were in poor agreement with those determined in the standard way (through use of tables based on soil type, drainage condition, and land use/cover). This and other measures of performance and uncertainty raise concerns over the validity of the NRCS method (Pilgrim and Cordery 1993).

Although formal, direct assessment of accuracy is not possible with the four Q_{50} estimates presented, the results necessarily contain some information concerning accuracy: given the spread in the Q_{50} results, it is obviously not possible to consider all four methods to be accurate in this case (at least one must be considered significantly inaccurate). Also, there is no obvious path to a clear "best estimate" of Q_{50}. Given the results, a reasonable estimate for Q_{50} would be roughly 1 m^3/s (the mean of the four individual estimates, rounded to one significant digit). This is also approximately the value from the rational method, which may be the least problematic of the four methods although it too represents a significant simplification of the hydrology.

Although the best estimate of Q_{50} is probably bounded by the four values estimated, the four methods offer only very broad constraints within which an engineer or hydrologist would have to exercise judgment. This has important practical implications for drainage design and other applied hydrologic problems. Drainage design for the study watershed and adjacent roadway could be quite subjective, given the wide range of Q_{50} (a factor of more than 6) within which one would have to exercise professional judgment. A design based on the high end of the range may be more than adequate but unnecessarily expensive, whereas one based on the low end of the range may be inadequate (and possibly also unnecessarily expensive if it leads to drainage failure, as discussed below). Results from this study suggest that a better approach to estimation of peak discharge on small rural watersheds (smaller than about 50 ha) is needed to improve the design and performance of drainage works. This is consistent with the conclusions of other authors who focused on the NRCS method (Pilgrim and Cordery 1993; Smith 1997; Willeke 1997). Improved methods for estimation of peak discharge could also be useful in environmental applications other than drainage (e.g., in estimation of erosion and sediment transport, or pollutant travel time). Lacking improved methods, the results of this study should be considered when the same methods are used for drainage design in other small, rural watersheds.

The lack of available documentation makes it impossible to fully assess the NCDOT method. Full public documentation of the NCDOT and other in-house methods used by technical agencies is strongly recommended. This general recommendation is broadly applicable and not restricted to the NCDOT. It was, for example, one major conclusion of a university panel which reviewed technical analyses carried out by government agencies working on water management and ecosystem restoration in the Everglades (Graham and others 1997). A similar concern has been raised with regard to the NRCS method—although the method has been widely used and discussed in the literature, Willeke (1997) asserts that the data on which it rests and the analyses connecting those data to the procedures in the method have not been subject to external review.

Peak discharge methods for small watersheds may be thought to merit little attention, in part because the required drainage works are relatively inexpensive to build and infrequent high discharges are unlikely to cause major damage. However, the total human and economic cost of drainage failure from the 16-ha watershed studied here (including the fatality and post-accident investigations and lawsuit) was substantial. Because it is unlikely this was a unique case, additional resources may be justified to improve Q_{50} estimates from similar small watersheds.

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