PEAK RATE FACTORS FOR FLATLAND WATERSHEDS

J. M. Sheridan, W. H. Merkel, D. D. Bosch

ABSTRACT. *Improved hydrologic design and modeling relationships are needed for predicting storm runoff response from watersheds with low–gradient drainage networks in coastal regions of the southeastern United States. Specifically, there is a need for developing guidelines for defining synthetic unit hydrographs required for hydrologic modeling applications on flatland watersheds. To develop this information 46 storm events from eight experimental watersheds located in the southeastern U.S. Coastal Plain and Flatwoods regions were evaluated. A relationship was developed between watershed unit hydrograph peak rate factors and two readily measured watershed characteristics, drainage area and main channel slope. This relationship provides a simple, easy–to–use tool that is compatible with hydrologic methods commonly used for estimating watershed–scale storm response. The relationship will provide improved hydrologic design and modeling capabilities required for natural resource and environmental quality planning and management on ungaged flatland watersheds in the southeastern United States.*

Keywords. *Hydrology, Storm runoff, Coastal Plains, Flatwoods, Unit hydrograph.*

Watersheds in coastal regions of the southeastern United States are characterized by permeable surface soils and low–gradient drainage networks. These areas of low topographic relief have long been considered problematic for determining hydrologic response characteristics at the watershed scale. For the USDA Natural Resources Conservation Service (NRCS) and for other agencies with natural resource and environmental quality planning and management responsibilities, there is a need for improved methodologies for predicting storm runoff response for watersheds in southeastern U.S. coastal regions. Specifically, there is a need for developing approaches for defining alternative, synthetic unit hydrographs (UH) for watersheds in regions with low topographic relief. The objective of the current study is to develop improved methods for defining synthetic unit hydrographs that are needed for hydrologic design and modeling applications on ungaged flatland watersheds in the southeastern United States.

BACKGROUND

SYNTHETIC UNIT HYDROGRAPH METHODS

Unit hydrographs (UH) are the primary tool for estimating runoff hydrographs resulting from storm rainfall. For applications on ungaged watersheds, synthetic UH methods are required. Some of the more frequently cited synthetic UH methods were developed by Clark (1945), Snyder (1938), and Mockus (1957). Hjelmfelt (1995), in an evaluation of the basis of these UH methods, demonstrated their similarities and showed that the methods have a common basis of development. Hjelmfelt concluded, however, that the synthetic UH methods are limited by the fact that little guidance is available for estimating UH parameters required for applications on ungaged watersheds.

THE SCS STANDARD UNIT HYDROGRAPH

The synthetic UH developed by Mockus (1957), often referred to as the Soil Conservation Service (SCS) standard UH, is the most frequently cited of the synthetic UH methods and is required for hydrologic design by statutes in some states or localities. The SCS standard UH is defined by the relationship:

$$q_p = PRF \times A \times Q/t_p \tag{1}$$

where

q_p = UH peak rate of flow (ft^3/s)
A = watershed drainage area (mi^2)
Q = runoff volume (in.)
t_p = UH time to peak (h)

$$PRF = 645.3 \times K \tag{2}$$

where

K = $(2/[1 + t_r/t_p])$
t_r = UH time of recession (h)

In the peak rate factor (PRF) relationship (eq. 2), the constant 645.3 results from conversion of discharge units from area–depth in inches to cubic feet per second. The quantity "K" results from geometric considerations in

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computation of the volume under the triangular unit hydrograph shape assumed by Mockus. Mockus also assumed a t_r/t_p ratio of 1.67 based on analyses of flood hydrographs from small agricultural watersheds in the Midwestern United States. Consequently, K is fixed at 0.75 and a PRF of 484 results. Mockus indicated that a UH with a PRF of 484 was representative of small agricultural watersheds in the United States. The assumption regarding the ratio of the unit hydrograph time of recession to the time to peak results in a UH with 38.5% of the runoff volume occurring on the rising side of the hydrograph. Conversion of the Mockus UH PRF from the original units (ft^3 per $s/mi^2/in.$) to metric units (m^3 per $s/km^2/mm$) results in a PRF of 0.208. It should be noted, however, that while a metric equivalent equation of the SCS UH relationship is practicable, the existing literature provides PRFs in standard units and most applications require PRF inputs in standard units.

The synthetic UH developed by Mockus is the basis of the NRCS UH methodology detailed in Chapter 16 of the National Engineering Handbook (NEH–4), Section 4, “Hydrology” (SCS, 1972). NEH–4 indicates that PRF may vary with terrain, ranging from 300 for flat, swampy watersheds to 600 for steep terrain (metric equivalent PRF values are computed as 0.129 and 0.258, respectively). However, no guidelines are presented for selecting the appropriate PRF for watersheds with conditions departing from those for which the original UH parameters were developed.

The SCS standard UH has been widely cited in hydrologic and water quality modeling. Current versions of AGNPS, an agricultural non–point source, watershed–scale water quality model (Young et al., 1989), for example, permit the user to specify a UH PRF that is termed the “K–coefficient.” If a value is not specified, AGNPS uses the SCS standard 484 (metric equivalent – 0.208) as the default value.

FIELD TESTING OF THE SCS STANDARD UH

As estimates of storm event peak flows computed using the SCS standard UH were compared with field data, it became apparent that some of the observed differences could be attributed to use of a standard UH for all watershed conditions (Woodward et al., 1995). Welle et al. (1980), in one of the first studies to address this topic for applications on Coastal Plain watersheds, reported a mean PRF of 284 (metric equivalent – 0.122) based on an evaluation of storm events from four watersheds in the Delmarva Peninsula of the eastern United States. Later studies by McCuen and Bondelid (1983), Meadows and Chestnut (1983), and Capece et al. (1988) also reported that the standard SCS UH over–predicted storm runoff rates for applications within coastal regions. The synthetic unit hydrograph defined by the 284 PRF (metric equivalent – 0.122) became known as the Delmarva UH and was subsequently recommended by the NRCS as an alternative to the SCS standard UH for hydrologic applications on flatter watersheds.

ARS–NRCS UNIT HYDROGRAPH WORK GROUP

A 1989 USDA Agricultural Research Service (ARS) and NRCS National Hydrology Workshop concluded that development of appropriate UHs for regions with differing terrain from the Midwestern United States, where the SCS standard UH was developed, was a primary hydrologic research need (Woodward et al., 1995). An ARS–NRCS Unit Hydrograph Work Group was subsequently formed which identified the coastal regions of the southeastern United States as one of the primary problematic regions for application of the SCS standard UH method. Initial results of the ARS–NRCS UH Work Group evaluations of selected storm events from seven watersheds in the Coastal Plain and Flatwoods regions of the southeastern United States indicated a considerable range in PRF (Sheridan and Merkel, 1993). The observed range in PRFs resulted in a hypothesis that development of a single regional PRF was not a likely outcome. Further, a premise emerged that effective relationships for determining watershed PRFs would need to be based on the respective watershed characteristics.

METHODS AND ANALYSES

Previous research has shown that a synthetic UH can be defined by two parameters, the unit hydrograph peak flow rate and the time to peak (Henderson, 1963). If those two parameters are adequately defined, then the exact form of the UH is unimportant and a triangular approximation is satisfactory (Rodriguez–Iturbe and Valdes, 1979). Previous work has shown that hydrograph time parameters for flatland watersheds can be estimated using simple watershed characteristics (Sheridan, 1994). Therefore, the primary need for developing improved methods for defining synthetic UHs for flatland watersheds is development of a predictive relationship between watershed characteristics and UH PRFs. Statistical analyses were performed in this study to relate PRFs for gaged flatland study areas to watershed physical characteristics and thereby develop improved relationships for predicting UH PRFs for ungaged watersheds in southeastern coastal regions.

AVAILABLE HYDROLOGIC DATABASES

To determine the appropriate PRFs for the flatlands experimental watersheds, selected storm data sets were assembled for six upper Coastal Plain watersheds (Little River, Ga.), one lower Coastal Plain watershed (Ahoskie Creek, N.C.), and one Coastal Flatwoods watershed (Taylor Creek, Fla.). Watersheds were restricted to those with drainage areas equal to or less than 52.0 km^2 (20 mi^2).

USDA–ARS has conducted hydrologic research in the southeastern United States since 1965, when the Southeast Watershed Research Laboratory (SEWRL) was established. In 1967, the SEWRL instrumented Little River Watershed (LRW) as the primary experimental watershed. The LRW is a 334 km^2 (129 mi^2) predominately agricultural basin located in central south Georgia. The LRW features a dense rainfall monitoring network and permanent flow–measurement controls located at seven subwatersheds ranging in area from 2.6 to 115 km^2 (1 to 44 mi^2).

Additionally, USDA–ARS has developed hydrologic databases for agricultural watersheds at two other locations within southeastern U.S. coastal regions: Taylor Creek Watershed in south Florida and Ahoskie Creek Watershed in North Carolina (fig. 1). Two subwatersheds, Taylor Creek W–3 and Ahoshie Creek A–4, have proven useful in regional hydrologic analyses despite having short hydrologic records and lacking permanent flow–measurement controls (Sheridan, 1997).

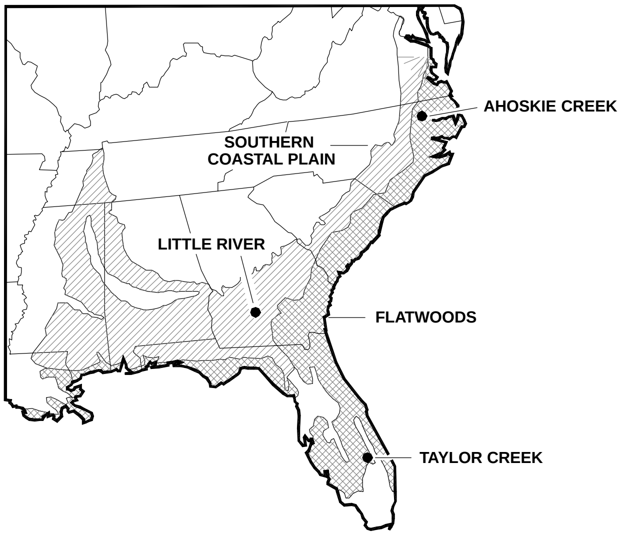

Figure 1. USDA–ARS experimental watersheds in southeastern U.S. Coastal Plain and Flatwoods regions.

SELECTION OF STORM EVENTS

Selected storm events were restricted to single peak events with peak flows equal to or exceeding the mean annual flow (MAF) and with relatively uniform rainfall distribution over the gaged area. Storm event data for the Taylor Creek Watershed were restricted to records collected prior to implementation of channel improvement and flood control programs (Knisel et al., 1985). Four to nine storm events from each watershed were available for UH optimizations (table 1).

WATERSHED DESCRIPTIVE DATA

Descriptive data for Little River Watershed include standard watershed characteristics and computed geomorphic indices developed based on measurements from 7.5–min USGS quad sheets (Sheridan and Ferreira, 1992). Watershed descriptive data for Taylor Creek Watershed (W–3) and Ahoskie Creek Watershed (A–4) were reported by Knisel et al. (1985) and USDA (1977), respectively. Descriptive data for the study watersheds are summarized in table 2.

UNIT HYDROGRAPH OPTIMIZATION

A storm hydrograph optimization computer program (MSHO Unit Hydrograph Optimization Program, Version 3050) developed for unit hydrograph studies by Williams (1968) was used to obtain UH PRF for selected storm events. The Williams program fits unit hydrographs using a gamma function and an exponential recession curve. The program performs parameter optimization using Davidon's method and offers several options for rainfall partitioning schemes. For this study, the NRCS Runoff Curve Number method was used to partition storm rainfall.

Table 1. Selected storm event data for flatland watersheds.

Location	Watershed	Drainage Area (km^2)	No. of Events	Mean Peak Rate Factor	Coeff. of Variation
Little River, Ga	M	2.6	4	269	18
(Upper Coastal Plain)	K	16.7	8	309	20
	J	22.1	7	371	7
	I	49.9	9	356	14
	N	15.7	4	476	13
	O	15.9	6	417	21
Ahoskie Creek, N.C. (Lower Coastal Plain)	A–4	6.7	4	256	30
Taylor Creek, Fla. (Flatwoods)	W–3	40.7	4	174	21

Table 2. Watershed descriptive data for flatland watersheds.

Watershed Characteristics	Watershed							
	M	K	J	I	N	O	A–4	W–3
Drainage area (km^2)	2.62	16.65	22.12	49.91	15.67	15.93	6.73	40.67
Channel length (km)	2.41	8.73	10.30	12.71	6.60	6.11	3.06	8.53
Relief ratio (m/m)	0.81	0.50	0.45	0.39	0.60	0.68	0.56	0.10
Channel slope (%)	0.35	0.29	0.25	0.22	0.36	0.37	0.32	0.10
Length–width ratio (km/km)	4.44	3.20	2.71	2.24	2.00	2.18	3.55	3.30
Stream frequency (No./km^2)	3.96	2.64	2.93	3.32	7.60	6.50	0.38	0.51
Drainage density (km/km^2)	2.78	2.50	2.58	2.69	2.96	3.20	0.76	0.72
Melton ratio (km^2/km^2)	0.51	0.42	0.44	0.46	0.87	0.63	0.66	0.98

STATISTICAL ANALYSES

Watershed mean UH PRFs obtained from hydrograph optimizations on selected storm events were regressed on watershed physical characteristic and geomorphic data. Independent parameters entered into the regression analyses included watershed drainage area, main channel length, basin slope indices (relief ratio and channel slope), watershed shape (length–width ratio), and geomorphic measures of stream network characteristics (stream frequency, drainage density, and the Melton Ratio). The Melton ratio, also termed the relative channel density, is defined as the ratio of stream frequency to the square of the network drainage density. Standard linear stepwise regression procedures (Draper and Smith, 1981) were employed on log–transformed dependent and independent parameters using Statistical Analysis System (SAS) software (SAS Institute, Inc., 1989). Statistical limits for parameter retention in stepwise regression analyses were set at the 0.10 level.

RESULTS

Linear regression analyses of log–transformed UH PRFs and watershed characteristics indicate that the best single parameters for explaining the variation in PRFs for flatland watersheds are the stream network parameters, stream frequency and drainage density (table 3). However, the best single parameter model explained only 69% of the observed variation in PRFs.

Stepwise regression analyses were then performed to determine the best multiple parameter model to explain the variation in PRF values. Results of stepwise regression analyses indicate that the best two parameter model for the flatland watersheds is:

$$PRF = 0.211 \times CS^{\mathbf{0.882}} \times DA^{\mathbf{0.264}} \; (R^2 = 0.89) \qquad (3)$$

where

PRF = peak rate factor

Table 3. Regression of flatland watershed characteristics on UH peak rate factors (PRF).

Independent Variable	Coefficient of Determination (r^2)
Stream frequency	0.693[a]
Drainage density	0.661[b]
Channel slope	0.506[b]
Relief ratio	0.456
Length–width ratio	0.249
Melton ratio	0.071
Channel length	0.046
Drainage area	0.001

[a] Probability of a greater F value is < 0.01.

[b] Probability of a greater F value is < 0.05.

CS = main channel slope (%), measured at 10 and 85% of total main channe1 length

DA = watershed drainage area (km^2).

The F statistic, used to test the significance of the two–parameter regression model, results in a probability of a greater F–value of 0.004.

While multiple regression procedures indicate that a three–parameter model based on channel slope, drainage area, and a stream network parameter explains a greater portion of the variation in UH PRF, the third parameter does not meet statistical significance tests for retention in the stepwise regression analysis. Therefore, the two–parameter model based on channel slope and drainage area is accepted as the best regression model for estimating UH PRF for low–gradient watersheds in the southeastern United States.

Equation 3 is presented in the required metric units. An equivalent equation developed in standard, or English, units that are typically required for hydrologic and water quality modeling applications is presented in the Appendix.

DISCUSSION

Mean PRFs obtained for watersheds in the upper Coastal Plain range approximately between the SCS standard UH PRF of 0.208 (484) and the alternative UH PRF of 0.122 (284). The mean PRF for the Florida Flatwoods watershed, 0.075 (174), is well below either the low PRF of 0.129 (300) recommended by NEH–4 for flat, swampy watersheds or the 0.122 (284) PRF of the SCS alternative UH. The range of observed PRF confirms previous hypotheses regarding the feasibility of developing a single regional UH for coastal regions of the southeastern United States and also indicates the need to relate PRF to the respective watershed characteristics.

Multiple regression analyses indicate that UH PRFs for flatland watersheds have a strong, direct relationship with changing channel slope and are less sensitive to changing watershed drainage area. The PRFs for flatland watersheds may be estimated using the two–parameter regression model (eq. 3) and the required independent parameter inputs. Parameter inputs should generally not exceed the ranges of parameter values entered into the regression analyses. Table 4 is a tabulation of PRF values predicted using equation 3 and a range of drainage areas and channel slopes for flatland watersheds.

Equation 3, when applied on small watersheds with channel slopes (~0.1%) similar to those reported for watersheds in the Flatwoods region of Florida by Capece et al. (1988), produces PRFs (table 4) comparable to those reported by Capece, which were in the range of 0.03 to 0.04.

The relationship developed for estimating PRF for ungaged, flatland watersheds results in a unique UH for each watershed. The required parameter inputs are readily measured watershed characteristics. This approach, which is compatible with established NRCS hydrologic methodologies, removes the restriction that t_r is equal to ($1.67 \times t_p$) contained in Mockus' original work and thereby addresses one of the major criticisms of the SCS standard UH (i.e., use of a single, or standard, UH for all watershed conditions).

CONCLUSIONS

Evaluations of unit hydrographs developed for selected storm events on small, agricultural watersheds in the Coastal Plain and Flatwoods regions of the southeastern United States indicate that PRFs range from near the SCS standard UH PRF of 0.208 (484) to well below the SCS alternative UH PRF of 0.122 (284). These results also indicate that use of a single regional synthetic UH is not a viable solution for estimating storm runoff response on watersheds in coastal regions of the southeastern United States.

A relationship for estimating UH PRF for flatland watersheds was developed by statistical analyses of selected storm event data from gaged watersheds in the southeastern U.S. Coastal Plain and Flatwoods regions. The resulting relationship, which is based on two readily measured watershed characteristics (drainage area and channel slope), explained 89% of the observed variation in PRFs for these watersheds.

The PRF relationship, together with previously developed hydrograph time parameter relationships for flatland watersheds (Sheridan, 1994), provides information needed by NRCS and others for characterizing hydrologic response for watersheds in the Coastal Plain and Flatwoods regions of the southeastern United States. These relationships provide simple, easy–to–use tools that are compatible with current NRCS methodologies for estimating storm runoff. The relationships provide improved hydrologic and water quality modeling capabilities required for natural resource and

Table 4. Watershed peak rate factors (PRF) for flatland watersheds.

	Peak Rate Factor (PRF), cms/km^2 /mm (cfs/mi^2/in.)					
	Watershed Drainage Area, km^2 (mi^2)					
Channel Slope (%)	2.6 (1.0)	5.2 (2.0)	7.7 (3.0)	13.0 (5.0)	25.9 (10.0)	51.8 (20.0)
0.05	0.019(45)	0.023(54)	0.026(60)	0.030(69)	0.035(82)	0.043(99)
0.1	0.036(83)	0.043(99)	0.048(111)	0.054(126)	0.065(151)	0.078(182)
0.2	0.066(153)	0.079(184)	0.088(204)	0.100(233)	0.121(281)	0.145(336)
0.3	0.094(219)	0.113(262)	0.126(292)	0.144(334)	0.173(401)	0.207(481)
0.4	0.121(282)	0.146(338)	0.162(376)	0.186(431)	0.222(517)	—

environmental quality applications on low–gradient watersheds of the southeastern United States.

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APPENDIX

The regression model for predicting PRF for flatland watersheds, in standard units, is:

$$\mathrm{PRF} = 631.7 \times \mathrm{CS}^{0.882} \times \mathrm{DA}^{0.264} \qquad (R^2 = 0.89)$$

where

PRF = peak rate factor
CS = main channel slope (%), measured at 10 and 85% of total main channel length
DA = watershed drainage area (mi^2).