Evaluation of Alternative Hydrograph Methods for Hydraulic Design

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ABSTRACT

A protocol is established to evaluate nine methods for defining hydrographs. Data from one site are used. The context is a need for dynamic hydraulic analysis to downsize drainage structures resulting from designs developed by using conservative steady-state flow assumptions. In addition, the analysis addresses a situation in which measured rainfall or runoff data are missing at a site. Data are generated for a hypothetical site and data requirements and computational methods are evaluated. The test results indicate that Snyder's method and its modification by Constant are superior. The protocol appears to be general enough to use in a comprehensive evaluation of hydrograph generation methods for use in ungauged watersheds. The comprehensive evaluation would draw on a national database and would determine criteria for selecting appropriate hydrograph generation methods to support dynamic hydraulic analysis.

The objective of this paper is to propose a protocol for reviewing methods used to generate hydrographs of small to medium-sized ungauged watersheds. The hydrographs are used to design culverts, bridges, and storm sewers and for inputs to dynamic hydrologic simulations. Dynamic simulation is used to help safely economize drainage structures. Design selections that result from static or steady-state analysis tend to be larger because the influence of system storage is not exploited. Smaller system elements can be sized under dynamic hydraulic conditions because of the effects of temporary storage as well as the effects of dynamic interactions of drainage system elements.

For very small drainage areas, the rational method has become the standard for sizing drainage structures on the basis of peak flows. For larger drainage areas, in which basin storage characteristics need to be accounted for, several competing hydrograph methods have been proposed, each with its own set of adherents. No hydrograph method has yet emerged as a de facto standard. Thus, the objective of this paper is to examine various methods that can be used with microcomputers and to suggest a protocol by which further investigations might be conducted to encourage the adoption of one or more methods as de facto standards.

This paper is divided into four sections: background, a discussion of several hydrograph methods, application of the methods to hypothetical and actual watersheds, and conclusions and recommendations.

BACKGROUND

Procedures developed for hydraulic and hydrologic analysis span a rather broad range. Each procedure has its own strengths and weaknesses and its own set of devotees. Requirements for analytical consistency cause specific analytic procedures to emerge as standards. For example, in the area of floodplain backwater calculations, the U.S. Army Corps of Engineers HEC-2 model has become the de facto standard, accepted by both legal and technical professionals. More recently, the Federal Emergency Management Agency designated the FHWA-U.S. Geological Survey (USGS) WSPRO model as an acceptable method in this area. As a result of federal interagency committee decisions, the Log Pearson Type III extreme-value methods became the standard for flood-peak estimation of gauged stream flows. It is clear in specific cases that standard methods do not necessarily work as well as other alternatives; however, standard methods provide a uniform basis of comparison between studies and also ensure that errors of judgment in selecting alternatives are avoided.

Synthetic hydrographs have been developed because of a lack of stream-flow and rainfall data for many watersheds. The synthetic methods require significantly less data and effort to develop compared with construction of a hydrograph solely from actual gauge data. Unlike the examples cited earlier, no single synthetic unit hydrograph method is universally accepted throughout the United States because of the wide range of geographical and climatic regimes and different institutional approaches. It may be that it is now time to consider standardization of hydrograph generation methods.

The rainfall-runoff response of watersheds can influence the design of highway stream crossings and highway surface drainage systems. Sophisticated data analysis and modeling can be used to predict the response of a watershed to a precipitation event in the presence of adequately measured data. However, the use of synthetic unit hydrographs may be appropriate for watersheds for which there are no rainfall data. Watershed attributes are used instead.

A hydrograph is a continuous graph depicting the discharge from a watershed with respect to time. It characterizes the response of a watershed to a specific precipitation event and integrates geometric and climatologic factors.

A unit hydrograph is "the hydrograph that results from one inch of precipitation excess generated uniformly over the watershed at a uniform rate during a specified period of time" (1). Unit hydrographs are commonly used to predict peak discharge rates and the pattern of that discharge over time using the runoff produced during the precipitation event. For a

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unit hydrograph it is assumed that the runoff occurs from precipitation excess (i.e., the difference between precipitation and losses) and that the excess is created at a uniform rate and with a uniform spatial distribution (1).

For rainfall events producing an excess of other than 1 in. of runoff, the amount of excess rainfall is simply multiplied by the unit graph ordinates. It is assumed that the time base of the hydrograph remains unchanged and that the ordinates are directly proportional to the amount of rainfall. The shape of a unit hydrograph derived from measured data depends on the temporal and spatial distribution of rainfall excess.

The design approach for using unit hydrographs to secure design information for highway drainage is

- Select a method,
- Estimate the unit hydrograph from watershed characteristics,
- Select a return period,
- Estimate the rainfall excess or the peak flow associated with the return period, and
- Develop the hydrograph from the unit hydrograph and the rainfall excess or peak flow.

METHODS

Nine methods for developing synthetic unit hydrographs are examined. These methods and the agencies that use them are given in Table 1. There are, of course, other methods that are not investigated in this paper. Six common hydrologic-hydraulic models that incorporate eight of the nine methods are as follows:

TABLE 1 Synthetic Unit Hydrograph Methods Examined

Method	Reference	User Agency
Snyder's	*2, 3, 4*	Corps of Engineers
SCS		
Dimensionless	*1, 3*	Soil Conservation Service
Triangular	*1, 3*	Soil Conservation Service
Clark's	*5*	Corps of Engineers
Grey's	*2*	–
Constant's	*6, 7*	Corps of Engineers
SBUH	*8, 9*	–
HYMO	*2*	Agricultural Research Service
USGS dimensionless	*10, 11*	U.S. Geological Survey

Model and Developer	Method Used
HEC-1 [Corps (5)]	Snyder's, Clark's
TR-20 [SCS (1)]	SCS dimensionless
CDS [FHWA (10)]	USGS
HYMO [ARS (2)]	Grey's, HYMO
HYDRO [FHWA (7)]	Constant's
SSAD [Golding (8)]	SBUH

A discussion of each of the nine methods follows.

Snyder's Method

Snyder's method was developed for Appalachian watersheds ranging from 10 to 10,000 mi². It has been applied to watersheds in most of the continental United States.

The method uses seven input parameters: watershed area (A), overall length (L), length to watershed centroid (L_{CA}), volume of excess rainfall (Q), rainfall duration (D), and two empirical coefficients (C_p and C_t) to calculate peak flow (Q_p) and time to peak (t_p). The unit hydrograph is constructed by calculating 50 and 75 percent of the peak flow, the corresponding times, and the time at which the flow returns to zero (or base) flow. Spline techniques are used to fit the points into a smooth unit curve.

C_t, the first empirical coefficient, represents the variation of the unit hydrograph lag time with respect to watershed slopes and storage. A typical value used for C_t is 2.0. Values of C_t have been found to vary from 1.8 to 2.2 in the Appalachian highlands and from 0.4 in Southern California to 8.0 in the eastern Gulf of Mexico (3). Schultz (4) provides the values of C_t for several differing watershed types.

The second empirical coefficient is C_p, which represents the variation of unit hydrograph peak discharge with watershed slope, storage, lag time, and effective area. Values of C_p usually range from 0.4 to 0.94 with a typical value of 0.6 (3).

Soil Conservation Service (SCS) Methods

The SCS unit hydrograph methods were designed for watersheds from 0 to 2,000 acres. The dimensionless method was created by averaging a large number of hydrographs collected from watersheds across the continental United States and calculating a scaled table of dimensionless ordinates. The triangular method uses a simple application of the unit hydrograph theory for derivation of the hydrograph shape.

An important input parameter for determining the peak flow is the time of concentration (t_c) for the watershed. The SCS developed two methods to calculate t_c: the graphical and the curve number. The graphical method relates overland and channel slopes and topographical features to the velocities of the runoff. With these velocities and the overland and channel lengths, t_c is readily calculated. The curve-number method allows the input of more precise geographical and hydrological factors. This method reflects actual watershed characteristics and is one of the more detailed empirical means of evaluating watershed t_c.

A second direct input parameter in the SCS unit hydrograph methods is an empirical constant (K), which represents the fraction of the area under the rising limb of the hydrograph. A typical value of K is 484. This value represents a hydrograph with 3/8 of its area under the rising limb. The fraction is less for flat, swampy areas ($K \approx 300$) and greater for mountainous watersheds ($K \approx 600$).

Time of concentration and the constant K, along with A, D, and Q, allow the calculation of Q_p. Q_p and t_c are used to create the unit hydrograph shape.

Clark's Method

Clark's method routes the incremental runoff from a watershed through a linear reservoir and translates the data into hydrograph ordinates. Clark's method can be applied to a wide range of watershed areas.

The input parameters are A and t_c. These parameters are used to section the watershed along its primary watercourse into subareas containing equal travel times. The translated flows are then routed through storage that is assumed to be at the outflow location. An attenuation constant (R), evaluated at the point of inflection of the recession limb of the hydrograph, is defined by successive iterations of the method.

As a result of the iterative process, Clark's method lends itself to use on a computer. In addition, it offers the ability to make adjustments for changes in drainage characteristics without requiring a complete reworking of the problem.

Grey's Method

Grey's method was designed for Midwestern watersheds of 0 to 94 mi^2. This method consists of a two-parameter derivation and is sensitive to the accuracy of the input data. It does not lend itself to simple applications. It requires calculation of a gamma distribution parameter (Γ), construction of an S-curve, and routing of the curve for the desired time interval. The final calculated values do not require the use of empirical constants. A practical drawback is the amount of analysis time required to determine the ordinates of the hydrograph.

Constant's (Modified Snyder's) Method

Constant's method was developed by the Albuquerque District of the U.S. Army Corps of Engineers. It is a variation of the techniques used in Snyder's unit hydrograph method and, as such, is similar in application and data requirements. In Constant's method it is recognized that the rising limb of a unit hydrograph can be expressed as a parabolic function and that the falling limb can be expressed as a function of exponential decay. A general equation was developed by using curve-fitting techniques to include the points calculated by Snyder's method.

The inputs for the method are Q_p, A, t_p, and the desired time interval. These features allow Constant's method to be applied to any hydrologic technique that calculates Q_p and t_p (or, indirectly, t_c). The method can be used for any technique that closely simulates the available watershed data. It is a convenient method because it uses peak flow rather than rainfall excess as an input variable. The peak-flow return can be estimated by USGS ungauged techniques that use watershed attributes and have been developed by using regression analysis for most of the country.

Santa Barbara Method

The Santa Barbara unit hydrograph (SBUH) method is a linear reservoir routing method similar to Clark's. An important difference is that the SBUH method uses Horton's equation to calculate infiltration rates (and thus rainfall excess). This approach allows the creation of a hydrograph that is adjusted for an estimated volume of rainfall excess. The SBUH method also uses such watershed characteristics as fraction of impervious area, antecedent moisture conditions, and soil classification as input parameters. The requirement of a hyetograph necessitates more complete rainfall data than are required by other unit hydrograph methods.

HYMO Method

The HYMO method is a dimensionless unit hydrograph developed for the Agricultural Research Service (ARS). It is based on data from watersheds of 0.5 to 25 mi^2 located in Arkansas, Louisiana, Mississippi, Oklahoma, Tennessee, and Texas. The dimensionless unit hydrograph is synthesized by applying computed parameters to three segment equations. Input variables are A, Q, L, watershed width (W), elevation difference (SLP), and two empirical parameters (n,B). There are three calculated parameters; two are regional regression equations--one for t_p and a regional recession constant K_R--and the third parameter is for Q_p.

The empirical parameters are dimensionless and are related to the shape of the watershed. The parameter B is a function of n. It has a purpose and range similar to those of the SCS empirical constant (K) and is used to determine the peak flow. The parameter n is a function of K_R and t_p.

USGS Urban Method

The USGS developed a dimensionless unit hydrograph by using a method similar to that used to develop the SCS dimensionless unit hydrograph. The difference is that the USGS data used to develop the ordinates consisted of urban and western watershed characteristics (as opposed to the rural nationwide watershed characteristics of the SCS dimensionless hydrograph). The USGS method can be applied to urban watersheds of most sizes.

Input data necessary for the method include Q_p and time lag (t_l). Q_p can be determined by using USGS empirical equations. Time lag can be calculated by using USGS techniques (or indirectly from t_c or t_p). Input data are applied to a scaled table of ordinates to create the unit hydrograph shape.

Because t_l and Q_p are the only required input data, the method is similar to Constant's in its scant data requirements. Constant's method uses three inputs--Q_p, A, and t_p--and mathematical equations instead of a table of ordinates.

Standardized Test Case

Synthetic unit hydrograph methods discussed previously are applied to a hypothetical watershed (Figure 1). The hypothetical watershed was invented

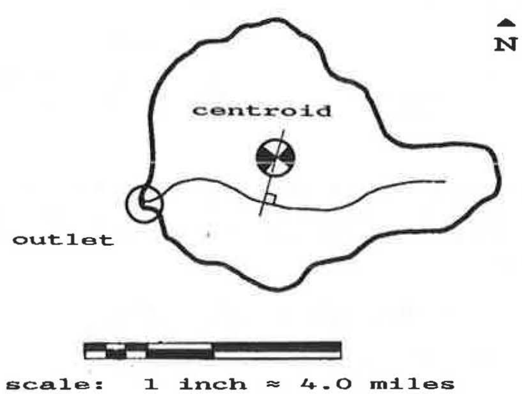

FIGURE 1 Hypothetical watershed.

to test the data requirements and complexity of the nine methods. It is ungauged and has the following characteristics:

- Drainage area (A) = 87.5 mi^2 (56,000 acres)
- Overland statistics
  - Forested, rural watershed with slope (S_o) of 1.5 percent
  - Length of watershed (L) = 8.3 mi from outlet to watershed divide
  - Width of watershed (W) = 12.0 mi at widest point
  - Length to centroid (L_{CA}) = 4.1 mi from outlet to centroid of watershed area

- Channel statistics
  - Grassy waterway ($n \simeq 0.030$) with a slope (S_c) of 0.7 percent
  - Length of channel (L_c) = 8.0 mi
- Volume of rainfall excess (Q) = 1.0 in.
- Duration of rainfall event (D) = 1.0 hr
- Time of concentration (t_c) = 10.8 hr (overland plus channel)

COMPARISON OF HYPOTHETICAL UNIT HYDROGRAPHS

Table 2 provides data and peak flows resulting from the application of the nine unit hydrograph methods to the hypothetical test case. The table is significant because it demonstrates the information that is required for each of the nine methods. Included in Table 2 are input parameters and watershed characteristics. For Snyder's method, a peak flow of 5,843 ft^3/sec was calculated assuming a C_t of 2.0 and a C_p of 0.6. This peak-flow value was also applied to Constant's and the USGS methods. Comparison of peak flows provides an indication of the degree of consistency of the various methods. Several analyses of data from actual sites are necessary for a sound comparison. The SBUH method could not be applied to the test case because of a lack of a suitable hyetograph; the need for data on rainfall versus time imposes a level of complexity that may be unwarranted for the intended use of a synthetic unit hydrograph method.

From a computational standpoint, all unit hydrograph methods except HYMO, Grey's, Constant's, and SBUH are relatively quick and easy. The methodology for HYMO is lengthy and complicated, but the results are consistent with those from other unit hydrograph methods. Grey's, Constant's, and SBUH methods require extensive calculations or a computer program, or both, to be practical.

All unit hydrograph methods except USGS use measurements of drainage area. The most common driving variable is rainfall excess. From a practical standpoint, this means that an analysis of rainfall, infiltration, and runoff must precede the development of a hydrograph. In contrast, Constant's and USGS methods are driven by peak flow. Peak flow is a convenient driving variable because its use eliminates determination of rainfall excess. Peak flow can be estimated by using

- The rational method for very small drainage areas (i.e., <300 acres). In this case the rainfall return period is assumed to be the hydrograph return period.
- USGS empirical regression equations that are developed for selected return periods. These equations are in widespread use across the country and are available in USGS publications.
- A frequency analysis of a nearby flow gauge, which can identify a flow with a given return period. This flow can be transferred to an ungauged site by using drainage-area ratios.

Overall, it can be seen from Table 2 that the SCS methods produce the highest peak flow, whereas Clark's method produces the lowest. All methods consistently develop a hydrograph volume of 1 in. over the watershed; this is a constraint and is necessary in order for a unit hydrograph to be considered valid.

The shapes of the unit hydrographs are shown in Figure 2. All the hydrographs appear qualitatively similar except those from the SCS triangular, Grey's, and USGS methods, which appear to depart significantly from the others. A comparison of the methods shows that

- Peak flows vary within a range of ±5 percent. It should be noted that peak flow from Snyder's method is used as input for peak flows for Constant's and USGS methods.
- All methods produce a volume consistent with the definition of a unit hydrograph.
- For all but SCS triangular, Grey's, and USGS methods, the hydrographs are similar in shape.
- The following differences exist with respect to computation: Snyder's, SCS dimensionless and triangular, Clark's, Constant's, HYMO, and USGS methods are relatively quick and easy to compute. Grey's and SBUH methods require significant computations to determine gamma-distribution parameters (Grey's) or to calculate infiltrations (SBUH).
- The following differences exist with respect to input data: There is some overlap, but different watershed attributes are used in the different methods. The peak-flow methods (Constant's and USGS) are convenient in that rainfall excess is not used and the methods directly input the peak flow.

COMPARISON OF UNIT HYDROGRAPHS WITH ACTUAL DATA

The synthetic unit hydrograph methods are compared with the actual data for a 910.9-acre (1.432-mi^2) subcatchment of the Bloody Run Catchment, located in the northwest section of Cincinnati, Ohio. The Bloody Run Catchment has been the subject of an

TABLE 2 Data Comparison for Standardized Test Case

	Method								
Parameter	Snyder's	SCS Dimensionless	SCS Triangular	Clark's	Grey's	Constant's	SBUH	HYMO	USGS
Peak flow Q_p (ft^3/sec)	5,843	6,062	6,062	5,741	5,852	5,843[a]		5,769	5,843[a]
Time of concentration t_c (hr)		10.8	10.8	10.8			X		
Time to peak t_p (hr)	6.25					6.25		6.4	
Time lag t_l (hr)									6.2
Lag-time factor C_t	2.0								
Peak-flow factor Cp	0.6								
Shape factor K		484	484						
Gamma distribution Γ					7.9				
Watershed factor B								420	
Shape factor n								5.2	
Computational interval δt (hr)						1.0	X		
Hyetograph i(t) (in./hr)							X		
Infiltration rate f(t) (in./hr)							X		
Fraction impervious Imp							X		

Note: X = data required but not run, as noted in text.

[a]Peak flow calculated indirectly (Snyder's method).

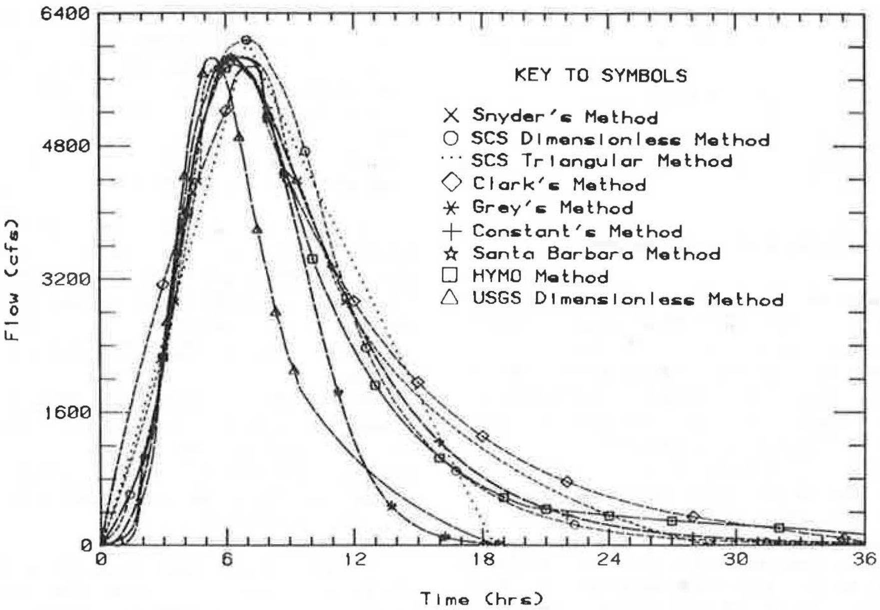

FIGURE 2 Unit hydrographs for standardized test case.

Environmental Protection Agency (EPA) report (12). These data were available to the authors and were used to demonstrate the methods described here.

The subcatchment is a urban drainage area consisting of primarily pasture and open parkland (24 percent) and single-family and multifamily residential (55 percent) and commercial (21 percent) property. The area is shown in Figure 3. The topography consists of rolling terrain (average slope is 4.8 percent) with ridges running east and west. The parameters for the Bloody Run subcatchment are as follows:

- Drainage area (A) = 1.423 mi^2 (910.9 acres)
- Overland statistics
  - Developed, urban watershed with slope (S_o) of 4.8 percent
  - Length of watershed (L) = 1.8363 mi from outlet to watershed divide
  - Width of watershed (W) = 0.8 mi
  - Length to centroid (L_{CA}) = 0.8755 mi from outlet to centroid of watershed area
  - Impervious area, 55 percent
- Channel statistics
  - Grassy waterway (n $\tilde{=}$ 0.030) with a slope (S_c) of 4.8 percent
  - Length of channel (L_c) = 1.5322 mi
- Volume of rainfall excess (Q) = 0.0174 in.
- Duration of rainfall event (D) = 1.0 hr
- Time of concentration (t_c) = 0.918 hr (overland plus channel)

The subcatchment contains a flow gauge and rainfall stations located near the subcatchment outlet from which data are measured. The storm-runoff event that is compared by using different synthetic unit hydrograph methods occurred on November 9, 1970, between 6:00 and 7:00 p.m. The average intensity of the rainfall event is 0.109 in./hr. The storm duration approximately equals the time of concentration; this enabled the authors to avoid the process of hydrograph separation that would be necessary to evaluate most natural storms and to estimate unit hydrographs. The resulting output hydrograph contained a volume of 0.0174 in. This volume is assumed to be due to the rainfall excess. The peak flow of the hydrograph was 9.72 ft^3/sec.

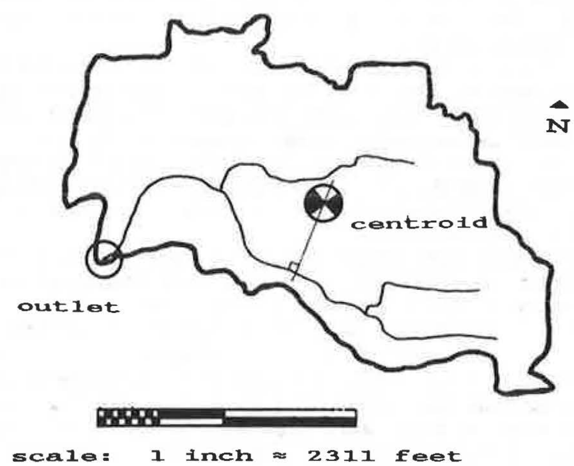

FIGURE 3 Bloody Run subcatchment watershed.

The verification rainfall is relatively light; that is, it is not a flood event. This implies that this particular verification measures the ability of the various methods to estimate an event with a low return period.

Figure 4 shows the hydrographs computed for the November 9, 1970, 6:00 p.m. rainfall event for the Bloody Run subcatchment. Qualitatively, the best-fitting hydrographs are the result of Snyder's and Constant's methods, both of which match the peak well and match the shape for the first 2 hr.

Clark's and the SBUH methods, both similar linear reservoir-routing methods, underestimate the peak but match the recession. Grey's method underestimates the peak and overestimates the recession. HYMO, SCS dimensionless and triangular, and USGS methods match the peak but underestimate the recession. HYMO matches the recession more closely than the others. The SCS triangular method visually appears to produce a poor approximation of a smooth hydrograph curve.

Table 3 presents a quantitative comparison of the methods. The data used to generate Figure 4 are analyzed by using a standard error (SE) test. The difference between the calculated and the observed

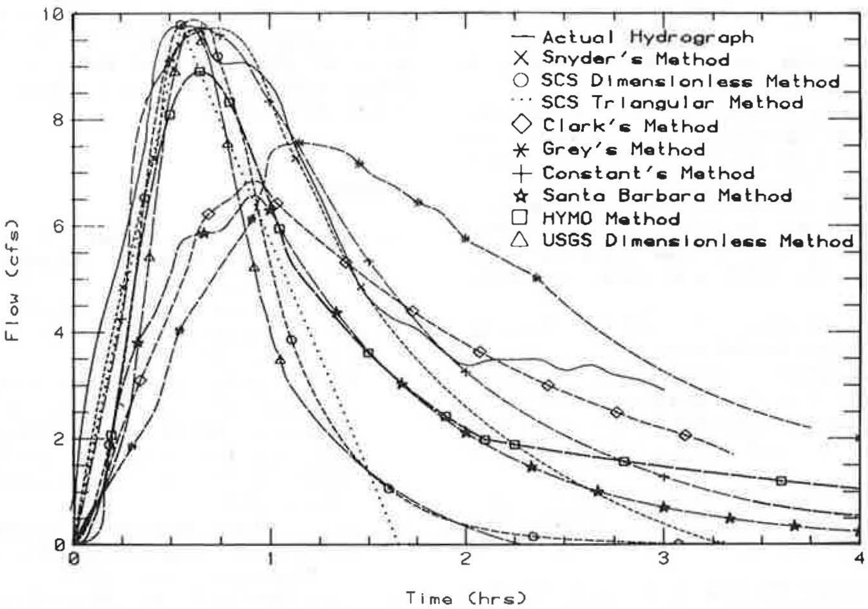

FIGURE 4 Unit hydrographs for actual test case.

TABLE 3 Quantitative Comparison of Unit Hydrograph Methods

Method	Peak Flow (ft^3/sec)	Standard Error
Actual data	9.72	–
Snyder's	9.67	0.53
Constant's	9.67	0.56
HYMO	8.89	1.51
Clark's	6.83	2.34
SBUH	6.56	2.45
SCS		
Triangular	9.87	2.56
Dimensionless	9.87	2.65
USGS	9.61	2.87
Grey's	7.54	3.12

values at 15-min intervals is squared and cumulated over the interval 0 to 2 hr. The square root of the cumulated value divided by the number of intervals (9) is reported as the SE in Table 3. This SE is similar to a chi-squared goodness-of-fit statistic. Also reported are the peak flows estimated by the various methods.

The standard errors indicate a relative ranking as follows:

- Snyder's and Constant's methods have SE's less than 1 ft^3/sec;
- SE for the HYMO method is between 1 and 2 ft^3/sec;
- SCS dimensionless and triangular, Clark's, SBUH, and USGS methods have SE's between 2 and 3 ft^3/sec; and
- Grey's method has an SE greater than 3 ft^3/sec.

It is notable that the SCS triangular method is slightly better in terms of SE than the SCS dimensionless and USGS methods. Thus the "un-eye-appealing" SCS triangular method provides a slightly better fit than either dimensionless method. However, all three methods have similar SE performance.

CONCLUSIONS AND RECOMMENDATIONS

A protocol for testing hydrograph generation methods is recommended:

- Assemble the alternative procedures and their documentation (nine methods are tested to check the protocol in this paper).
- Identify and assemble data on specific watersheds:
  - Input hyetograph,
  - Output hydrograph,
  - Land use and geometric data sufficient to estimate watershed attributes (similar to the information in Table 2).
- Provide quality control on the watershed.
- Specify a goodness-of-fit criterion or criteria (such as standard error of estimate or chi-square).
- Apply the watershed information to each watershed (independently of the input hyetograph and output hydrographs) to estimate the unit hydrograph for each alternative procedure.
- Employ the input hyetograph or rainfall excess to calculate a hydrograph from each unit hydrograph.
- Compare the calculated hydrograph with the measured hydrograph and determine goodness of fit.
- Analyze the goodness of fit and develop criteria for hydrograph method selection:
  - Focus on methods that are suitable for ungauged watersheds, and
  - Determine whether suitable methods can be applied universally or if they must vary according to geography or climate.

As an example of the protocol, an examination of nine hydrologic methods by using a hypothetical watershed to examine data requirements and methods and by using one actual runoff event to test performance indicates the following:

- Snyder's and Constant's methods performed best in terms of standard error of prediction. In practice, Snyder's method would be used with rainfall excess as the driving variable and Constant's method would be used with peak flow as the driving variable.

• HYMO method performed nearly as well as Snyder's and Constant's methods.

• USGS, SCS dimensionless, and SCS triangular methods all performed similarly. USGS method used the least data, and SCS dimensionless and triangular methods used the same data.

• Clark's and SBUH methods require considerable analysis and probably need computerized implementation. The other methods are simpler and, with the exception of Grey's, provided the same or better performance.

• Grey's method provided the least accurate results and was difficult to implement.

• The methods requiring a computer or significant calculation are Clark's, Grey's, Constant's, SBUH, and HYMO. Of these, Constant's gave the most accurate results and the most straightforward computations.

• The desk-top methods are Snyder's, SCS dimensionless and triangular, and USGS. Of these, Snyder's was the most accurate and easiest to implement.

The example presented in this paper demonstrates the feasibility of implementing the protocol on a large-scale test of many sites.

It is recommended that watershed data be assembled for evaluation with this protocol and that they be distributed across the country so as to represent various geophysical and climatologic regions. Assuming that this can be accomplished with approximately two sites per state, on the average, a database of 100 sites is implied.

Sources of data can be USGS studies, EPA Areawide Wastewater Management Studies, and state, local, and university studies.

Data assembly is expected to be a challenge; however, no new measurement program is recommended. It is the authors' experience that sufficient data exist and that it will take diligence and effort to assemble, check, tabulate, and refine these data into a uniform and consistent database for testing alternatives.

ACKNOWLEDGMENTS

Helen Mihm, GKY and Associates, assisted with the technical writing and editing. Sterling Jones, of FHWA, suggested the topic and encouraged the authors. M. Wacker, Wyoming Highway Department, provided further encouragement on the great significance of the topic to highway drainage engineers. Sandra Gillian and Linda Gough assisted in manuscript preparation.

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