Chapter 16
Ungauged Basin Analysis

16-1. General

a. Problem definition. Earlier chapters of this manual described various flood-runoff analysis models. Some of the models are *causal*; they are based on the laws of thermodynamics and laws of conservation of mass, momentum, and energy. The St. Venant equations described in Chapter 9 are an example. Other models are *empirical*; they represent only the numerical relationship of observed output to observed input data. A linear-regression model that relates runoff volume to rainfall depth is an empirical model.

(1) To use either a causal or empirical flood-runoff analysis model, the analyst must identify model parameters for the catchment or channel in question. Paragraph 7-3*e* described a method for finding rainfall-runoff parameters for existing conditions in a gauged catchment. Through systematic search, parameter values are found to yield computed runoff hydrographs that best match observed hydrographs caused by observed rainfall. With these parameter values, runoff from other rainfall events can be estimated with the model. A similar search can be conducted for routing model parameters, given channel inflow and outflow hydrographs.

(2) Unfortunately, as Loague and Freeze (1985) point out, "...when it comes to models and data sets, there is a surprisingly small intersecting set." The rainfall and runoff data necessary to search for the existing-condition calibration parameters often are not available. Streamflow data may be missing, rainfall data may be sparse, or the available data may be unreliable. Furthermore, for USACE civil-works project evaluation, runoff estimates are required for the forecasted future and for with-project conditions. Rainfall and runoff data are never available for these conditions. In the absence of data required for parameter estimation for either existing or future conditions, the stream and contributing catchment are declared ungauged. This chapter presents alternatives for parameter estimation for such catchments.

b. Summary of solutions. To estimate runoff from an ungauged catchment, for existing or forecasted-future conditions, the analyst can use a model that includes only parameters that can be observed or inferred from measurements, or extrapolate parameters from parameters found for gauged catchments within the same region. In practice, some combination of these solutions typically is employed, because most models include both physically based and calibration parameters.

c. Using models with physically based parameters. Model parameters may be classified as physically based parameters or as calibration parameters.

(1) Physically based parameters are those that can be observed or estimated directly from measurements of catchment or channel characteristics.

(2) Calibration parameters, on the other hand, are lumped, single-valued parameters that have no direct physical significance. They must be estimated from rainfall and runoff data. If data necessary for estimating the calibration parameters are not available, one solution is to use a flood-runoff analysis model that has only physically based parameters. For example, the parameters of the Muskingum-Cunge routing model described in paragraph 9-3*a*(6) are channel geometry, reach length, roughness coefficient, and slope. These parameters may be estimated with topographic maps, field surveys, photographs, and site visits. Therefore, that model may be used for analysis of an ungauged catchment.

d. Extrapolating calibration parameters. If the necessary rainfall or runoff data are not available to estimate calibration parameters using a search procedure such as that described in paragraph 7-3*e*, the parameters may be estimated indirectly through extrapolation of gauged-catchment results. This extrapolation is accomplished by developing equations that predict the calibration parameters for the gauged catchments as a function of measurable catchment characteristics. The assumption is that the resulting predictive equations apply for catchments other than those from which data are drawn for development of the equations. The steps in developing predictive relationships for calibration parameters for a rainfall-runoff model are as follows:

(1) Collect rainfall and discharge data for gauged catchments in the region. The catchments selected should have hydrological characteristics similar to the ungauged catchment of interest. For example, the gauged and ungauged catchments should have similar geomorphological and topographical characteristics. They should have similar land use, vegetative cover, and agricultural practices. The catchments should be of similar size. Rainfall distribution and magnitude and factors affecting rainfall losses should be similar. If possible, data should be collected for several flood events. These rainfall and

discharge data should represent, if possible, events consistent with the intended use of the model of the ungauged catchment. If the rainfall-runoff model will be used to predict runoff from large design storms, data from large historical storms should be used to estimate the calibration parameters.

(2) For each gauged catchment, use the data to estimate the calibration parameters for the selected rainfall-runoff model. The procedure is described in Chapter 7, and guidelines for application of the procedure are presented in Chapter 13 of this document.

(3) Select and measure or estimate physiographic characteristics of the gauged catchments to which the rainfall-runoff model parameters may be related. Table 16-1 lists candidate catchment characteristics. Some of these characteristics, such as the catchment area, are directly measured. Others, such as the Horton ratios, are computed from measured characteristics.

Table 16-1
Catchment Characteristics for Regression Models

Total catchment area
Area below lowest detention storage
Stream length
Steam length to catchment centroid
Average catchment slope
Average conveyance slope
Conveyance slope measured at 10% and 85% of stream length (from mouth)
Height differential
Elevation of catchment centroid
Average of elevation of points at 10% and 85% of stream length
Permeability of soil profile
Soil-moisture capacity average over soil profile
Hydrologic soil group
Population density
Street density
Impervious area
Directly-connected impervious area
Area drained by storm sewer system
Percent of channels that are concrete lined
Land use
Detention storage
Rainfall depth for specified frequency, duration
Rainfall intensity for specified frequency, duration
Horton's ratios (Horton 1945)
Drainage density (Smart 1972)
Length of overland flow (Smart 1972)

(4) Develop predictive equations that relate the calibration parameters found in step 2 with characteristics measured or estimated in step 3. In a simple case, the results of steps 2 and 3 may be plotted with the ordinate a rainfall-runoff model parameter and the abscissa a catchment characteristic selected in step 3. Each point of the plot will represent the value of the parameter and the selected characteristic for one gauged catchment. With such a plot, a relationship can be "fitted by eye" and sketched on the plot. Regression analysis is an alternative to the subjective graphical approach to defining a predictive relationship. Regression procedures numerically determine the optimal predictive equation. Details of regression analysis are presented in EM 1110-2-1415 and in most statistics texts, including those by Haan (1977) and McCuen and Snyder (1986).

(a) To apply a parameter-predictive equation for an ungauged catchment, the independent variables in the equation are measured or estimated for the ungauged catchment.

(b) Solution of the equation with these values yields the desired flood-runoff model parameter. This parameter is used with the same model to predict runoff from the ungauged catchment.

16-2. Loss-Model Parameter Estimates

a. Options. Two of the rainfall loss models described in Chapter 6 of this document are particularly useful for ungauged catchment analysis: the Green-Ampt model and the SCS model. The Green-Ampt model is a causal model with quasiphysically based parameters. The SCS loss model is an empirical model with parameters that have been related to catchment characteristics. Other loss models may be used if parameter-predictive equations are developed from gauged catchment data.

b. Physically based parameter estimates for Green-Ampt model. The Green-Ampt model is derived from Darcy's law for flow in porous media. The model predicts infiltration as a function of time with three parameters: volumetric moisture deficit, wetting-front suction, and hydraulic conductivity. In application, an initial loss may be included to represent interception and depression storage. Additional details of the Green-Ampt model are presented in Chapter 6.

(1) Brakensiek, and Onstad (1988), McCuen, Rawls, and Brakensiek (1981), Rawls and Brakensiek (1982a), Rawls, Brakensiek, and Saxton (1982b), Rawls and

Brakensiek (1983a), Rawls, Brakensiek, and Soni (1983b), and Rawls and Brakensiek (1985) propose relationships of the Green-Ampt model parameters to observable catchment characteristics, thus permitting application of the model to an ungauged catchment. The relationships define model parameters as a function of soil texture class.

(2) Texture class, in turn, is a function of soil particle size distribution. This distribution can be estimated from a sample of catchment soil. For example, a soil that is 80 percent sand, 5 percent clay, and 10 percent silt is classified as a loamy sand. For this texture class, Rawls and Brakensiek (1982a) and Rawls, Brakensiek, and Saxton (1982) suggest that the average saturated hydraulic conductivity is 6.11 cm/hr. The other parameters can be estimated similarly from the soil sample.

c. Predictive equations for SCS model parameters. The SCS loss model, described in detail in Chapter 6, is an empirical model with two parameters: initial abstraction and maximum watershed retention (maximum loss). Often both parameters are related to a single parameter, the curve number (CN). Using data from gauged catchments in the United States, the SCS developed a tabular relationship that predicts CN as a function of catchment soil type, land use/ground cover, and antecedent moisture. Table 16-2 is an excerpt from this table (U.S. Department of Agriculture (USDA) 1986).

(1) To apply the SCS loss model to an ungauged catchment, the analyst determines soil type from a catchment soil survey. For many locations in the United States, the SCS has conducted such surveys and published soil maps. The analyst determines existing-condition land use/ground cover from on-site inspection or through remote sensing. For future conditions, the land use/ground cover may be determined from development plans. The analyst selects an appropriate antecedent moisture condition for catchment conditions to be modeled (wet, dry, or average). With these three catchment characteristics estimated, the tabular relationship may be used to estimate CN. For example, for a residential catchment with 2-acre lots on hydrologic soil group C, the CN found in Table 6-6 for average antecedent moisture is 77. With this CN, the initial abstraction and maximum watershed retention can be estimated, and the loss from any storm can be predicted.

(2) Publications from the SCS provide additional details for estimating the CN for more complex cases.

16-3. Runoff-Model Parameter Estimates

a. Options. Chapter 7 presents a variety of models for estimating runoff due to excess rainfall. For an ungauged catchment, the analyst may use the kinematic-wave model, a UH model with physically-based parameters, or a UH model with predictive equations for the calibration parameters.

b. Physically based parameter estimates for kinematic wave model. The kinematic-wave model described in Chapter 7 is particularly well suited to analysis of an ungauged urban catchment.

(1) This causal model, which is described in further detail in HEC documents (USACE 1979, 1982, 1990a), represents the catchment rainfall-runoff process by solving theoretical equations for flow over planes. Catchment runoff is estimated by accumulating the flow from many such planes.

(2) Application of the model requires identification of the following parameters: catchment area, flow length, slope, and overland-flow roughness factor. The area, length, and slope are physically based and are estimated for existing catchment conditions from maps, photographs, or inspection. For forecasted-future condition, these parameters are forecasted from development plans. The overland-flow roughness factor is a quasiphysically based parameter that describes resistance to flow as a function of surface characteristics. Published relationships, based on hydraulic experimentation, are used to select this coefficient for existing or forecasted conditions. Thus all parameters of the kinematic wave model can be estimated without gauged data.

c. Physically based parameter estimates for Clark's IUH and SCS UH. Parameters of Clark's and the SCS empirical UH models have a strong link to the physical processes and thus can be estimated from observation or measurement of catchment characteristics. Clark's IUH accounts for translation and attenuation of overland and channel flow. Translation is described with the time-discharge histogram. To develop this histogram, the time of concentration is estimated and contributing areas are measured. Likewise, the SCS UH hydrograph peak and time to peak are estimated as a function of the time of concentration. The time of concentration, t_c, can be estimated for an ungauged catchment with principles of hydraulics. The SCS suggests that t_c is the sum of travel times for all consecutive components of the drainage conveyance system (USDA 1986).

That is,

$$t_c = t_1 + t_2 + ... t_m \qquad (16\text{-}1)$$

where

t_i = travel time for component *i*

m = number of components

Each component is categorized by the type of flow. In the headwaters of streams, the flow is sheet flow across a plane. Sheet-flow travel time is estimated via solution of the kinematic-wave equations. The SCS suggests a simplified solution. When flow from several planes combines, the result is shallow concentrated flow. The travel time for shallow concentrated flow is estimated with an open-channel flow model, such as Manning's equation. Shallow concentrated flow ultimately enters a channel. The travel time for channel flow is estimated also with Manning's equation or an equivalent model.

d. Predictive equations for UH calibration parameters. The procedure described in paragraph 16-1d can be used to develop predictive equations for UH model parameters for ungauged catchments. For example, Snyder (1938) related unit hydrograph lag, t_p, to a catchment shape factor using the following equation:

$$t_p = C_t \, (L \, L_{ca})^{0.3} \qquad (16\text{-}2)$$

where

t_p = basin lag, in hours

C_t = predictive-equation parameter

L = length of main stream, in miles

L_{ca} = length from outlet to point on stream nearest centroid of catchment, in miles

The value of C_t is found via linear regression analysis with data from gauged catchments. A wide variety of predictive equations for UH model calibration parameters have been developed by analysts. Table 16-2 shows example equations for Snyder's and Clark's UH parameters. In general, these equations should not be used in regions other than those for which they were developed. If they are, the analyst must be especially cautious. He or she should review derivation of the equations. Conditions under which the equations were derived should be examined and compared with conditions of the catchments of interest.

Table 16-2
Example UH Parameter Prediction Equations

Equation	Reference
$C_t = 7.81 / I^{0.78}$	Wright-McLaughlin Engineers (1969)
$C_p = 0.89 \, C_t^{0.46}$	Wright-McLaughlin Engineers (1969)
$R = c \, T_c$	Russell, Kenning, and Sunnell (1979)
$T_c / R = 1.46 - 0.0867 \, L^2/A$	Sabol (1988)
$T_c = 8.29 \, (1.00 + I)^{-1.28} \, (A/S)^{0.28}$	USACE (1982)

Note: In the above equations,

C_t = calibration coefficient for Snyder's UH (see paragraph 7-3*c*)

C_p = calibration coefficient for Snyder's UH (see paragraph 7-3*c*)

T_c = time of concentration, in hours

R = Clark's IUH storage coefficient, in hours

I = impervious area, in percent

L = length of channel/ditch from headwater to outlet, in miles

S = average watershed slope, in feet per foot

c = calibration parameter (for forested catchments = 8 - 12, for rural catchments = 1.5 - 2.8, and for developed catchments = 1.1 - 2.1)

A = catchment area, in square miles

16-4. Routing-Model Parameter Estimates

a. Candidate models. The routing models described in Chapter 9 account for flood flow in channels. Of the models presented, the Muskingum-Cunge, modified puls, and kinematic-wave are most easily applied in ungauged catchments. Parameters of each of these models are quasiphysically based and can be estimated from channel characteristics.

b. Physically based parameter estimates for modified puls routing model. The modified puls (level-pool) routing model is described in detail in Chapter 9-3. The parameters of this model, as it is applied to a river channel, include the channel storage versus outflow relationship and the number of steps (subreaches). The former is considered a physically based parameter, while the latter is a calibration parameter.

(1) For an ungauged catchment, the channel storage versus outflow relationship can be developed with normal depth calculations or steady-flow profile computations. In either case, channel cross sections are required. These may be measured in the field, or they may be determined from previous mapping or aerial photography. Both procedures also require estimates of the channel roughness. Again, this may be estimated from field inspection or from photographs. With principles of hydraulics, water-surface elevations are estimated for selected discharges. From the elevations, the storage volume is estimated with solid geometry. Repetition yields the necessary storage versus outflow relationship. These computations can be accomplished conveniently with a water-surface profile computer program, such as HEC-2 (USACE 1990b).

(2) The second parameter, the number of steps, is a calibration parameter. Paragraph 9-3*a* suggests estimating the number of steps as channel reach length/velocity of the flood wave/time interval (Eq. 9-13). Strelkoff (1980) suggests that if the flow is controlled heavily from downstream, one step should be used. For locally controlled flow typical of steeper channels, he suggests the more steps, the better. He reports that in numerical experiments with such a channel, the best peak reproduction was observed with:

$$NSTPS = 2\ L\ \frac{S_o}{Y_o} \qquad (16\text{-}3)$$

where

$NSTPS$ = number of steps

L = entire reach length, in miles

S_0 = bottom slope, in feet per mile

Y_0 = baseflow normal depth, in feet

So, for example, for a 12.4-mile reach with slope 2.4 ft/mile and Y_0 = 4 ft, the number of steps would be estimated as 15.

c. Physically based parameter estimates for kinematic wave model. The physical basis of the kinematic-wave model parameters makes that model useful for some ungauged channels. In particular, if the channels are steep and well-defined with insignificant backwater effects, the kinematic-wave model works well. These limitations are met most frequently in channels in urban catchments.

(1) The parameters of the kinematic-wave channel routing model include the channel geometry and channel roughness factor. The necessary channel geometry parameters include channel cross section and slope data. Since these are physically based, they may be estimated for existing conditions from topographic maps or field survey.

(2) For modified channel conditions, the geometry data are specified by the proposed design. The roughness generally is expressed in terms of Manning's *n*. This is a quasiphysically based parameter that describes resistance to flow as a function of surface characteristics. Published relationships predict this coefficient for existing or modified conditions.

d. Physically based parameter estimates for Muskingum-Cunge model. If the channel of interest is not steep and well-defined as required for application of the kinematic-wave channel routing model, a diffusion model may be used instead. In the case of an ungauged channel, the Muskingum-Cunge model is a convenient choice, since the parameters are physically based.

(1) Parameters of the Muskingum-Cunge channel routing model include the channel geometry and channel roughness factor. The necessary channel geometry parameters include channel cross section and slope data, which may be estimated for existing conditions from topographic maps or field survey.

(2) For modified channel conditions, the geometry data are specified by the proposed design. The roughness is expressed in terms of Manning's *n*.

16-5. Statistical-Model Parameter Estimates

In some hydrologic-engineering studies, the goal is limited to definition of discharge-frequency relationships. EM 1110-2-1415 describes procedures for USACE flood-frequency studies. Chapter 12 of this document summarizes those procedures and describes the statistical models used. All the models described are empirical. Observed data are necessary for calibration. Consequently, these statistical models cannot be applied directly to an ungauged catchment. Options available to the analyst requiring frequency estimates for an ungauged stream include development of frequency-distribution parameter predictive equations, and development of distribution quantile predictive equations.

a. Parameter predictive equations. The log Pearson type III distribution (model) is used for USACE annual maximum discharge-frequency studies. As described in Chapter 12, this model has three parameters. These are estimated from the mean, standard deviation, and skew coefficient of the logarithms of observed peak discharges.

(1) In the absence of flow data, regional-frequency analysis procedures described in paragraph 12-5*c* may be applied to develop distribution parameter predictive equations. As with the equations for rainfall-runoff model parameters, these equations relate model parameters to catchment characteristics. For example, for the Shellpot Creek Catchment, Delaware, the following predictive equation was developed (USACE 1982):

$$S = 0.311 - 0.05 \log A \tag{16-4}$$

where

S = standard deviation of logarithms

A = catchment drainage area, in square miles

With similar equations, other parameters can be estimated.

(2) To apply a distribution parameter-predictive equation for an ungauged catchment, the independent variables in the equation are measured or estimated for the ungauged catchment. Solution of the equation with these values yields the desired statistical distribution parameter. The frequency curve is then computed as described in EM 1110-2-1415 and Chapter 12.

b. Quantile predictive equations. The frequency-distribution quantiles for an ungauged catchment also may be defined with predictive equations. Such a predictive equation is developed by defining the frequency distributions for streams with gauged data, identifying from the distributions specified quantiles, and using regression analysis procedures to derive a predictive equation. For example, for the Red Lion Creek Catchment, Delaware, the following quantile predictive equation was developed (USACE 1982):

$$Q_{100} = 1040\ A^{0.91} \tag{16-5}$$

where Q_{100} = 100-year (0.01 probability) discharge.

16-6. Reliability of Estimates

The reliability of a runoff estimate made for an ungauged catchment is a function of the reliability of the flood-runoff model, the form of the predictive equation and its coefficients, and the talents and experience of the analyst.

a. Model reliability. Linsley (1986) relates the results of a 1981 pilot test by the Hydrology Committee of the USWRC that found that all runoff models tested were subject to very large errors and exhibited a pronounced bias to overestimate. He shows that errors of plus or minus 10 percent in estimating discharge for a desired 100-year (0.01 probability) event may, in fact, yield an event as small as a 30-year event or as large as a 190-year event for design. Lettenmaier (1984) categorizes the sources of error as model error, input error, and parameter error. Model error is the inability of a model to predict runoff accurately, even given the correct parameters and input. Input error is the result of error in specifying rainfall for predicting runoff or in specifying rainfall and runoff for estimating the model parameters. This input error may be due to measurement errors or timing errors. Parameter error is the result of inability to properly measure physically based parameters or to properly estimate calibration parameters. The net impact of these errors is impossible to quantify. They are identified here only to indicate sources of uncertainty in discharge prediction.

b. Predictive equation reliability. Predictive equations are subject to the same errors as runoff models. The form and parameters of the equations are not known and must be found by trial and error. The sample size upon which the decision must be based is very small by statistical standards because data are available for relatively few gauged catchments. Overton and Meadows (1976) go so far as to suggest that the reliability of a regionalized model can always be improved by incorporating a larger data base into the analysis. Predictive equations are also subject to input error. Many of the catchment characteristics used in predictive equations have considerable uncertainty in their measured values. For example, the accuracy of stream length and slope estimates are a function of map scale (Pilgrim 1986). Furthermore, many of the characteristics are strongly correlated, thus increasing the risk of invalid and illogical relationships.

c. Role of hydrologic engineer. Loague and Freeze (1985) suggest that hydrologic modeling is more an art than a science. Consequently, the usefulness of the results depends in large measure on the talents and experience of the hydrologic engineer and her or his understanding of the mathematical nuances of a particular model and the hydrologic nuances of a particular catchment. This position is especially true in estimation of runoff from an ungauged catchment. The hydrologic engineer must exercise wisdom in selecting data for gauged catchments, in estimating flood-runoff model parameters for these catchments, in establishing predictive relationships, and finally, in applying the relationships.