Advisory Committee on Water Information

HYDROLOGY SUBCOMMITTEE

Hydrologic Frequency Analysis Work Group

The Hydrologic Frequency Analysis Work Group is a work group of the Hydrology Subcommittee of the Advisory Committee on Water Information (ACWI). The Terms of Reference of this work group were approved by the Hydrology Subcommittee on October 12, 1999 and are available on the ACWI web page. The work group was formed to provide guidance on issues related to hydrologic frequency analysis and replaced the Bulletin 17B Work Group that had existed since 1989. The Hydrologic Frequency Analysis Work Group is open to individuals from public and private organizations. The current members of the work group are also given on the ACWI web page. The initial objectives of the work group are to

- Develop a set of frequently asked questions and answers on the use of Bulletin 17B guidelines,
- Prepare a position paper that provides guidance on determining the most appropriate methodology for flood frequency analysis for ungaged watersheds, and
- Prepare a position paper on methodologies for flood frequency analysis for gaged streams whose upstream flows are regulated by detention structures.

In response to the second objective above, the work group has prepared a paper that provides some guidance on evaluating flood frequency estimates for ungaged watersheds. This paper, entitled "Evaluation of Flood Frequency Estimates for Ungaged Watersheds" is provided below for informational purposes. This is not a guideline or standard but a possible approach for evaluating the reasonableness of flood frequency estimates for ungaged watersheds.

Any comments on this paper should be provided by email to Will Thomas, Chairman of the Hydrologic Frequency Analysis Work Group, at *wthomas@mbakercorp.com*.

ACWI Advisory Committee on Water Information — MEETINGS NEWS

Evaluation of Flood Frequency Estimates for Ungaged Watersheds

Wilbert O. Thomas, Jr.
Michael Baker, Jr.

Michael M. Grimm
Federal Emergency Management Agency

Richard H. McCuen
University of Maryland

Introduction

Two approaches for estimating the magnitude and frequency of flood discharges for ungaged watersheds are those methods based on statistical (regression) analysis of data collected at gaging stations and deterministic rainfall-runoff models that use rainfall input and algorithms to convert rainfall excess to flood discharges. Flood Insurance Guidelines and Specifications for Study Contractors (Federal Emergency Management Agency (FEMA, 1995) is an example of guidelines that describe the use of both regional regression equations and rainfall-runoff models for estimating flood discharges for flood insurance studies and map revisions. FEMA recommends the use of the most recent regional regression equations published by the U. S. Geological Survey (USGS), if these equations are applicable for the studied streams. Where regional regression equations are not applicable due to flow regulation, flood detention storage, rapid watershed development, or other unique basin characteristics, FEMA recommends the use of a rainfall-runoff model.

This paper describes an approach for evaluating flood discharges from regression equations and rainfall-runoff models and judging the reasonableness of discharges using a measure of uncertainty such as the standard error. Example cases from flood insurance studies are described to illustrate how uncertainty is used in the selection of a final discharge estimate. This approach could be used for other analyses such as the design of bridges and culverts for ungaged watersheds where frequency estimates are available from both regression equations and rainfall-runoff models.

Objective of Review Procedures

The estimation of flood discharges for floodplain management is just one example of the need for flood frequency analyses for ungaged watersheds. In an effort to expedite the processing of flood insurance studies, FEMA recommends the review of flood discharges prior to their use in hydraulic and mapping analyses. The 1-percent annual chance (base flood) discharge is used by FEMA to define the Special Flood Hazard Areas, those areas inundated by the base flood, on Flood Insurance Rate Maps (FIRMs). The intent of the hydrologic review is to obtain agreement on the base flood discharge prior to the hydraulic analysis to avoid revisions to the hydraulic and mapping analyses because of subsequent hydrologic revisions. This approach to review is similar to analyses for design of hydraulic structures (bridges, culverts, levees, dams, etc.) where the hydrologic analysis is completed and reviewed prior to the design and construction of the hydraulic structure.

Often flood frequency estimates are available from previous studies or are developed for the ongoing study by different methods for comparison purposes. The objective of the following review procedures is to determine which estimates are reasonable and can be used in floodplain management. These procedures are intended as general technical guidance for judging the reasonableness of flood discharges and not as a set of rules to be followed strictly. The review procedures provide a framework for evaluating flood discharges and provide some quantitative guidance for selecting a flood estimate. Engineering judgement is needed in the application of these review procedures as this is not a "cook-book" approach. There is no intent to imply that the examples provided are inclusive of all situations or that other input data, such as rainfall data, should not be investigated.

The intent of the review procedures is not to identify a best method for a region or best method under given watershed conditions but to identify a reasonable estimate for a given application. It is assumed that different methods can provide reasonable estimates and that no one method is universally superior.

Most hydrologic analyses have the potential for being used for flood insurance studies even though they were undertaken for other purposes. For example, hydrologic analyses performed for the design of a new bridge or culvert are often later submitted to FEMA by the State Department of Transportation to revise the FIRM through the Letter of Map Revision process. Hydrologic analyses for flood insurance studies are used to illustrate the review procedures.

Description of Hydrologic Methods

The review procedures primarily involve the comparison of flood frequency estimates from rainfall-runoff models to those from regression equations and gaging station data. Rainfall-runoff models used for design purposes and floodplain management are usually based on a single-event design storm with the assumption that the rainfall frequency equals runoff frequency. This approach also assumes that the design rainfall events have uniform spatial distribution over the watershed and a specified temporal distribution. These models are typically not calibrated to observed flood data. Given these assumptions and those involving antecedent moisture and infiltration rates, there is uncertainty in characterizing the frequency of flood discharges from rainfall-runoff models based on the design-event approach.

However, estimates from other methods such as continuous simulation models are sometimes used in design of hydraulic structures and in floodplain management (Brown and Steffen, 1997). Continuous-simulation rainfall-runoff models account for changes in soil moisture between storm events and use historical rainfall and other climatic data to estimate peak flows. Frequency analyses are then performed on the simulated peak flows to determine design discharges such as the 1-percent chance flood. These models are often assumed to be more accurate than other methods for estimating the magnitude and frequency of design flood discharges because they are calibrated to observed data, estimate antecedent moisture conditions from observed data, and rely on the temporal and spatial distributions of historical rainfall. However, the flood data used for calibration often lack a major flood. Thomas (1987) has shown that frequency curves generated from a continuous rainfall-runoff model used by USGS (Dawdy and others, 1972) for extending flood records on small watersheds tend to exhibit less variance than frequency curves based on observed flood data. Conclusive evidence of greater accuracy of continuous simulation models, particularly for extreme floods, has not been reported. Additionally, continuous-simulation models are not commonly used because of their significant data requirements and the time and effort involved in their calibration. However, it should be noted that recent improvements in development of data bases and GIS technology enable the user to apply continuous simulation models with considerable less effort than in the past.

Regression equations are developed by relating flood discharges at gaging stations to watershed and climatic characteristics using least-squares regression techniques. If the regression equations are applicable to a given stream, then reasonable estimates of the magnitude and frequency of flood discharges should be obtained. A pilot test was conducted to compare procedures for estimating flood discharges for natural watersheds in the Midwest and Northwest USA (U.S. Water Resources Council (USWRC, 1981)). Analyses for these two regions indicated that regression equations provided more unbiased and reproducible estimates of flood discharges than rainfall-runoff models such as HEC-1 and TR-20. Even though regression equations are calibrated to gaging station data, they may provide biased flood estimates if they are based on outdated gaging station data or do not include explanatory variables unique to the watershed of interest.

Accuracy of Discharge Estimates

In addition to the flood estimates themselves, the accuracy or uncertainty of the estimates is considered in making decisions about reasonable estimates. Uncertainty exists in all methods and, therefore, it is advisable to compare all estimates and use the accuracy of each estimate in deciding the best discharge estimate to use. When comparing discharge estimates computed using different methods (e.g., rainfall-runoff models and regional regression equations), the various estimates are considered reasonable if they are within a predefined error band. The standard error is recommended as a predefined error band for judging the reasonableness of flood discharges since this measure of uncertainty is easy to compute, is frequently used, is often reported in the literature and is better understood by engineers and hydrologists.

The standard error of flood discharges from gaging station data can be determined using procedures described by Kite (1988). The standard error of gaging station estimates can also be estimated using 84-percent one-sided confidence limits as described in Bulletin 17B (IACWD, 1982). The approach by Kite (1988) is favored since this approach considers the uncertainty in the skew coefficient while the Bulletin 17B approach does not. The standard errors of estimate or prediction of the USGS regression equations are given in regional flood frequency reports (e.g., Dillow, 1996).

The standard error of rainfall-runoff model estimates is not usually known, although the USWRC report (1981) suggested that it is larger then the standard error of regression estimates. This is due, in part, to the fact that rainfall-runoff models based on a single-event design storm are not usually calibrated to regional data. Confidence limits or standard errors of flood discharges from rainfall-runoff models can be estimated if an equivalent years of record is assumed for the flood discharges as described by the USACE (1996) as part of risk-based analyses. However, there is no established practice of estimating the uncertainty of flood estimates from rainfall-runoff models by this or any other procedure.

The standard error of the flood discharge is not the only factor in determining significant differences for floodplain mapping. The change in elevation of the base flood is also very important as discussed in FEMA 37 (FEMA, 1995). Standard errors of flood discharges from regression equations and limited gaging station data often exceed 40 percent. Since flood depths are proportional to the approximate square root power of discharge, this implies that a 40 percent change in discharge translates to about a 20 percent change in depth (or elevation). If flood depths exceed 5 feet, then a 20 percent change is about plus or minus one foot which is usually considered significant in the National Flood Insurance Program. Base flood depths in the main channel usually exceed 10 feet even for small streams so plus or minus one standard error in the base flood discharge is likely to transform to a significant change (on the order of 2 feet) in water-surface elevation.

The review procedures described herein are often applied to the flood discharges prior to the hydraulic analyses or determination of water-surface elevations. As described earlier, the motivation for the review procedures from a FEMA perspective was to obtain consensus on flood discharges prior to hydraulic analyses. However, the change in base flood elevations resulting from a standard error change in the base flood discharge can quite likely be determined from prior (effective) hydraulic analyses.

It is possible that the base flood discharges may be statistically insignificant, yet there is a significant change in the water-surface elevations. Under these conditions, the decision about the appropriate elevation to use should be based on hydraulic considerations such as the best modeling approach or the most current hydraulic data.

Hydrologic Analysis Based on a Rainfall-Runoff Model

Flood discharges are updated for flood insurance studies for several reasons such as the availability of a more physically-based rainfall-runoff model, updated regression equations, or changing land-use or hydraulic conditions. The proposed base flood discharges from a rainfall-runoff model should be compared to flood discharges at gaging stations with watershed characteristics within the range of those for the studied stream(s), to base flood discharges from USGS regression equations (if they are applicable), to the effective discharges used for previous flood insurance studies in that community, and to discharges computed from other available hydrologic analyses. Flood frequency estimates for the gaging stations used in this evaluation should be made in accordance with the methodology presented in Bulletin 17B, *Guidelines For Determining Flood Flow Frequency* (Interagency Advisory Committee on Water Data (IACWD), 1982). If the watershed under study is urbanized, then the regional regression equations should be adjusted for urbanization using procedures such as those described by Sauer and others (1983) and Jennings and others (1994). The urban equations developed by Sauer and others (1983) are applicable nationwide and were based on observed and modeling data through 1978. It may be time to update these equations using more recent data and current statistical procedures.

The regression equations are considered applicable for evaluating rainfall-runoff model estimates if the watershed, climatic, and urbanization characteristics for the studied streams are within the range of those of the gaging stations used to develop the equations and regulation by flood detention structures does not significantly effect flow rates. The applicability of the regression equations can be determined from a plot of the explanatory variables, as illustrated in Figure 1, for data for the Piedmont Region in Maryland. The Piedmont Region is that area between the Appalachian Mountains of western Maryland and the Fall Line that runs from Washington, DC, through Baltimore to the northern extremes of the Chesapeake Bay.

Figure 1

As illustrated in Figure 1, an ungaged watershed with a drainage area of 0.5 square miles and a forest cover of 70 percent is outside the cloud of the data and is, therefore, an extrapolation of the regression equations. Note that the drainage area and forest cover are individually within the limits of the data, but the combination of a small watershed with high forest cover is not represented in the data set.

The gaging stations used in the evaluation of rainfall-runoff model estimates should also have watershed characteristics that are within the range of the characteristics of the studied streams. Base flood discharges for gaging stations can be obtained from recently published USGS regional flood reports. It may be appropriate to update the flood frequency estimates for the gaging stations using Bulletin 17B guidelines (IACWD, 1982). Decisions on whether to update the station frequency curves are dependent upon factors such as the existing length of record, the time since the analyses were last updated, and whether major floods have occurred since the last update. The gaging station and regression estimates are used to judge the reasonableness of the rainfall-runoff model estimates.

The base flood discharges from rainfall-runoff models, gaging station data, regression equations and previous (effective) flood insurance studies are plotted against drainage area on logarithmic paper to determine if the proposed rainfall-runoff model discharges are reasonable. The error bars of plus or minus one standard error should be shown about the gaging station or regression estimates. The review procedures are illustrated using data submitted for flood insurance studies for two communities.

Application in Lake County, California

The first example is for a study of selected streams in Lake County in California. The proposed discharges were estimated using the U.S. Army Corps of Engineers (USACE) HEC-1 model (USACE, 1990). Two of the studied streams, Adobe and Highland Creeks, have gaging stations upstream of flood-control reservoirs. The reaches of these streams that are to be mapped are downstream of the reservoirs. USGS regression equations documented in Waanenen and Crippen (1977) were applied to the unregulated (upstream) reaches of the studied streams.

The effective base flood discharges used in previous flood insurance studies are compared in Figure 2 with discharges from the HEC-1 model, gaging station data, and USGS regression estimates. The effective base flood discharges either are for the studied streams or for other streams in the county with similar drainage areas. The gaged data are based on 24 years of record each for Adobe Creek (6.36 square miles) and Highland Creek (11.9 square miles). The vertical bars about the gaged data represent plus and minus one standard error computed by methods given in Kite (1988), i.e., 27 percent for Adobe Creek and 30 percent for Highland Creek. The vertical bars for the USGS regression estimates represent plus one standard error of estimate (66 percent from Waananen and Crippen, 1977). Only the plus standard errors are shown for the USGS regression equations because the HEC-1 discharges for the unregulated stream reaches are greater than those for the regression equations.

Figure 2

For the unregulated reaches of the studied streams, the proposed HEC-1 discharges are within one standard error of the USGS regression estimates. The same is generally true for the gaging station data except one of the HEC-1 discharges is situated slightly below the one-standard-error bound for the Highland Creek gaged data. If most of the HEC-1 estimates are within the standard error bound of the gaging station and regression estimates, then logic dictates that the HEC-1 estimates are reasonable.

The three proposed discharges clearly outside the one-standard-error bound are for regulated reaches of Adobe and Highland Creeks. The regulated estimates are shown in Figure 2 to evaluate if the base flood discharges for the regulated reaches are less than those for the unregulated reaches for a comparable drainage area. Given the comparison in Figure 2, FEMA concluded that the proposed HEC-1 base flood discharges are reasonable for use in the hydraulic analysis. The conclusion implies that the differences in the unregulated discharges from the HEC-1 model and gaging station and regression estimates are not significantly different. Therefore, the proposed HEC-1 discharges were used for floodplain mapping.

In the Lake County, California example, the HEC-1 model or some deterministic model is needed since two of the streams, Adobe and Highland Creeks, are regulated by reservoirs. The example described above was just part of the review process to judge the reasonableness of the HEC-1 inflow peak discharges to the reservoirs. Additional review considerations were the reasonableness of the starting reservoir elevations for the base flood routings and the shape and volume of the inflow hydrographs.

Application in St. Francis County, Arkansas

The second example is in Forrest City in St. Francis County, Arkansas. The proposed discharges were estimated using a HEC-1 model (USACE, 1990) and balanced design storms based on rainfall data from U.S. Weather Bureau (USWB) TP-40 (USWB, 1961), rainfall losses calculated using the Natural Resources Conservation Service (NRCS) runoff-curve-number method, kinematic-wave calculations for routing the rainfall excess to the main collector channels, and normal-depth-storage routing.

The HEC-1 discharges were compared to gaging station data and regression equations developed by Hodge and Tasker (1995). Forrest City lies in two hydrologic regions as defined by Hodge and Tasker (1995): Region C represented by Crowleys Ridge where the channel slopes are steep and Region D which is the remains of the old alluvial floodplain of the Mississippi River where channel slopes are flat. Regression estimates were determined for the studied streams by weighting the regression estimates for Regions C and D proportional to the drainage area in each region.

Figure 3 compares the HEC-1 discharges, the weighted regression estimates, and gaging station data in Regions C and D. As illustrated in Figure 3, the HEC-1 base flood discharges over predict in comparison with the area-weighted estimates from the USGS regression equations and with gaging station data even within Region C (region of steep channel slopes). In fact, the HEC-1 discharges are generally greater than the USGS weighted regression estimates plus one standard error of prediction. The weighted standard error of prediction varies with watershed characteristics and was estimated using a computer program provided by Hodge and Tasker (1995). The average standard error of prediction for the studied streams is 45 percent and the vertical bars extending from the weighted regression estimates represents plus 45 percent. Only the plus standard errors are shown since the HEC-1 estimates are greater than the regression estimates.

Figure 3

The HEC-1 base flood discharges were considered to be too high for the following hydrologic reasons: use of saturated antecedent moisture conditions, inappropriate application of kinematic wave routing computations, and runoff-curve numbers that are higher than those used in previous studies in the region. On the basis of the comparisons given in Figure 3, FEMA concluded that the proposed HEC-1 base flood discharges were inappropriate. This conclusion is supported by the HEC-1 discharges being outside the standard error bounds of the weighted regression estimates and high in comparison to gaging station data. Since the USGS regression equations are applicable to the studied streams and a flood hydrograph is not needed, FEMA's recommendation was to use the regression equations for the flood insurance study. An alternative approach to using the USGS regression equations is to revise the HEC-1 model so that the model base flood discharges fall within one standard error of prediction of the weighted regression estimates. The use of the USGS regression equations was considered more cost effective than revising the HEC-1 model.

Hydrologic Analysis Based on Regional Regression Equations

Regional regression equations are frequently used in estimating base flood discharges for flood insurance studies. As with rainfall-runoff models, the regional regression equations should be evaluated before using the base flood estimates. Regression estimates should be compared to the effective discharges for the community, to base flood discharges from other regression equations published by USGS and other agencies that are applicable for the region, and to base flood discharges at gaging stations in the vicinity of the community. In general, the proposed regression estimates should be based on the most recent equations published by the USGS. If the most current USGS regression equations are not used, then reasons should be given as to why the other equations are more appropriate.

An example where an earlier version of the USGS regression equations may be more appropriate is in southern Arizona. Regression equations developed by Eychaner (1984) are based on drainage area, channel slope, and basin shape. More recent equations published for southern Arizona by Thomas and others (1994) are based on only drainage area. Evaluations of flood insurance studies in southern Arizona have indicated that the regression equations developed by Eychaner (1984) provide more accurate estimates of base flood discharges than Thomas and others (1994) for long, narrow, watersheds with flat channel slopes.

As noted earlier, the regression equations should be adjusted for urbanization, if appropriate. Procedures for making these urban adjustments are described in Sauer and others (1983) and Jennings and others (1994). If the urbanization factors for the studied streams are outside the range of the regression equations or if the watershed is undergoing rapid land-use change, then the effects of urbanization should be evaluated using a rainfall-runoff model. The base flood discharges for gaging stations used to evaluate the regression estimates should be determined as described above under the section on rainfall-runoff models.

The base flood estimates from the above sources should be plotted against drainage area on logarithmic paper similar to the examples in Figures 2-3. The proposed discharges are considered reasonable if the regression equations are applicable, were applied correctly, and are consistent with the gaging station data used in the evaluation.

USGS regression equations for some states were last updated in the mid- to late 1970's. These regression equations may not be indicative of the current flood discharges if major floods have occurred since publication of the regression equations. An example of this is California where some of the regional equations developed by Waananen and Crippen (1977) do not reflect major floods that occurred in different parts of the State in 1980, 1983, 1986, 1995 and 1997. The USGS is in the process of updating the 1977 regression equations. As described above, an approach for evaluating if regression estimates are reasonable is to compare these estimates to updated gaging station data in the region.

Future Research Needs

Procedures are well documented for determining the standard error of gaging station and regression estimates. Confidence limits can be estimated for flood discharges from rainfall-runoff models but assumptions about the equivalent years of record are needed (USACE, 1996). Future research should be oriented to determining the accuracy of flood discharges estimated from single (design) event rainfall-runoff models since the use of these models is prevalent in hydraulic design and floodplain management. If the accuracy of flood discharges from rainfall-runoff models could be objectively determined, then the feasibility of weighting these estimates with regression estimates could be evaluated.

Additional research is needed to determine the most appropriate criteria for distinguishing between flood estimates based on different hydrologic methods. One standard error was chosen because it is often available and more understood by engineers and hydrologists. Additional statistical criteria as well as economic and hydrologic criteria should be evaluated in judging the reasonableness of flood discharges for ungaged watersheds.

Summary

Procedures for evaluating flood discharges based on rainfall-runoff models and regional regression equations were described. Two examples of using the standard error (or standard error of prediction) of flood discharges to judge the reasonableness of flood discharges were presented. In the first example, the proposed HEC-1 base flood discharges were rejected for hydrologic reasons and were shown to be reasonable (within one standard error) in comparison to USGS regression equations and gaging station data. In the second example, the proposed HEC-1 base flood discharges were shown to over predict (outside one standard error of prediction) in comparison to USGS regression equations and gaging station data. The USGS regression equations were recommended for use because this was a more cost-effective approach than revising the HEC-1 model.

The review procedures described in this paper are considered an approach for determining reasonable estimates for flood discharges for ungaged watersheds. The procedures are predicated on the assumption that flood estimates that differ by less than one standard error (of estimate or prediction) are not significantly different. The choice of one standard error represents a statistical criterion and is used because this uncertainty measure is often available. Other statistical criteria, such as 50-percent confidence limits (75-percent one-sided limits) or 90-percent confidence limits (95-percent one-sided limits), could be adopted and the review procedures proposed herein could still be used. As more experience is obtained with the use of these review procedures, it may be worthwhile to revise the statistical criteria. These statistical criteria could be replaced by economic or hydrologic criteria, if such values could be agreed upon, were readily available, and were properly verified.

References

Brown, J. W., and Steffen, J. P., 1998, *Innovative Floodplain Mapping Procedures Utilized by DuPage County, Illinois*: Proceedings of the Association of State Floodplain Managers, May 18-22, 1998, Milwaukee, Wisconsin, pp. 403-409.

Dawdy, D. R., Lichty, R. W., and Bergmann, J. M., 1972, *A Rainfall-Runoff Simulation Model for Estimation of Flood Peaks for Small Drainage Basins*: U.S. Geological Survey Professional Paper 506-B, pp. B1-B28.

Dillow, J. J. A., 1996, *Techniques for Estimating Magnitude and Frequency of Peak Flows in Maryland*: U.S. Geological Survey Water-Resources Investigations Report 95-4154, 55 p.

Eychaner, J.H., 1984, *Estimation of magnitude and frequency of floods in Pima County, Arizona, with comparisons of alternative methods*: U.S. Geological Survey Water-Resources Investigations Report 84-4142, 69 p.

Federal Emergency Management Agency, 1995, *Flood Insurance Guidelines and Specifications for Study Contractors*: FEMA 37, Washington, DC.

Hodge, S.A., and Tasker, G.D., 1995, *Magnitude and Frequency of Floods in Arkansas*: U.S. Geological Survey Water-Resources Investigations Report 95-4224.

Interagency Advisory Committee on Water Data, 1982, *Guidelines For Determining Flood Flow Frequency*: Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, U.S. Geological Survey, Reston, Virginia, 183 p.

Jennings, M.E., W.O. Thomas, Jr. and H.C. Riggs, 1994, *Nationwide Summary of U.S. Geological Survey Regional Regression Equations for Estimating Magnitude and Frequency of Floods for Ungaged Sites, 1993*: U.S. Geological Survey Water-Resources Investigations Report 94-4002, 196 p.

Kite, G.W., 1988, *Frequency and Risk Analysis in Hydrology*: Water Resources Publications, Littleton, Colorado, 257 p.

Sauer, V.B., W.O. Thomas, Jr., V.B. Stricker, and K.V. Wilson, 1983, *Flood Characteristics of Urban Watersheds in the United States*: U.S. Geological Survey Water-Supply Paper 2207, 63 p.

Thomas, B.E., Hjalmarson, H.W., Waltemeyer, S.D., 1994, *Methods for estimating magnitude and frequency of floods in the southwestern United States*: U.S. Geological Survey Open-File Report 93-419, 211 p.

Thomas, W. O., Jr., 1987, *Comparison of Flood-Frequency Estimates Based on Observed and Model-Generated Peak Flows*: ***in*** Hydrologic Frequency Modeling, Proceedings of the International Symposium on Flood Frequency and Risk Analyses, May 14-17, 1986, Baton Rouge, LA, D. Reidel Publishing Company, pp. 149-161.

U.S. Army Corps of Engineers, 1990, *HEC-1 Flood Hydrograph Package, User's Manual: CPD-1A*, Hydrologic Engineering Center, Davis, California, 410 p.

U.S. Army Corps of Engineers, 1996, *Risk-based Analysis for Flood Damage Reduction Studies*: EM 1110-2-1619, Department of the Army, Washington, DC.

U.S. Water Resources Council, 1981,*Estimating peak flow frequencies for natural ungaged watersheds – A proposed nationwide test*: Hydrology Subcommittee, U.S. Water Resources Council, 346 p.

U.S. Weather Bureau, 1961, *Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years*: Technical Paper 40, Washington, DC, 115 p.

Waanenen, A. O., and J. R. Crippen, 1977, *Magnitude and Frequency of Floods in California*: U.S. Geological Survey Water-Resources Investigations 77-21, 96 p.

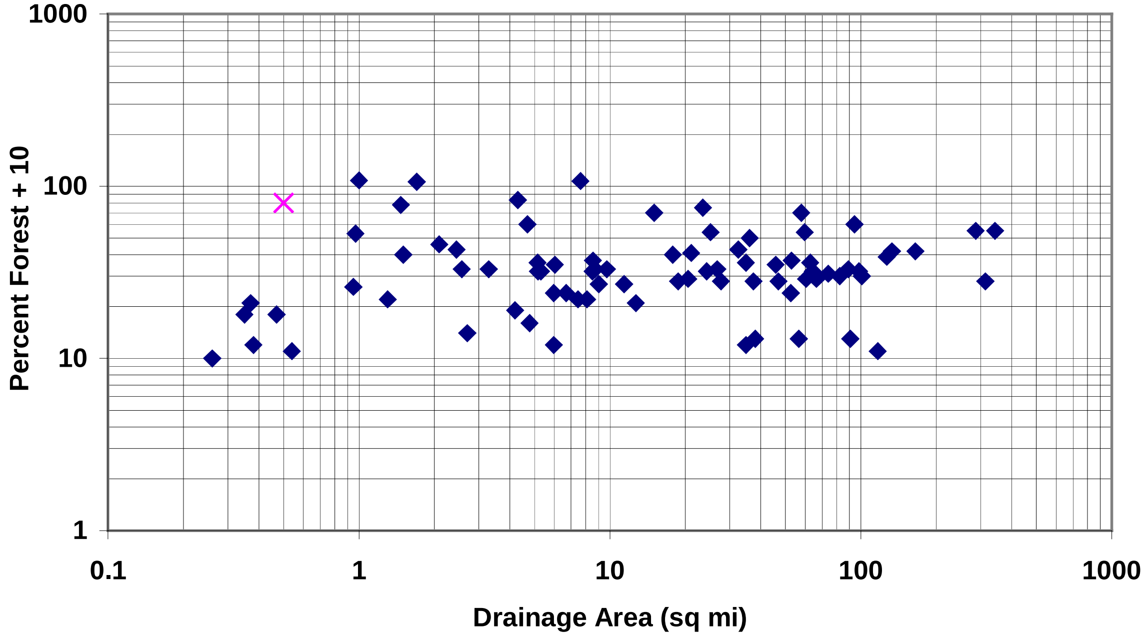

Figure 1. Relation between explanatory variables for regression equations in the Piedmont Region of Maryland.

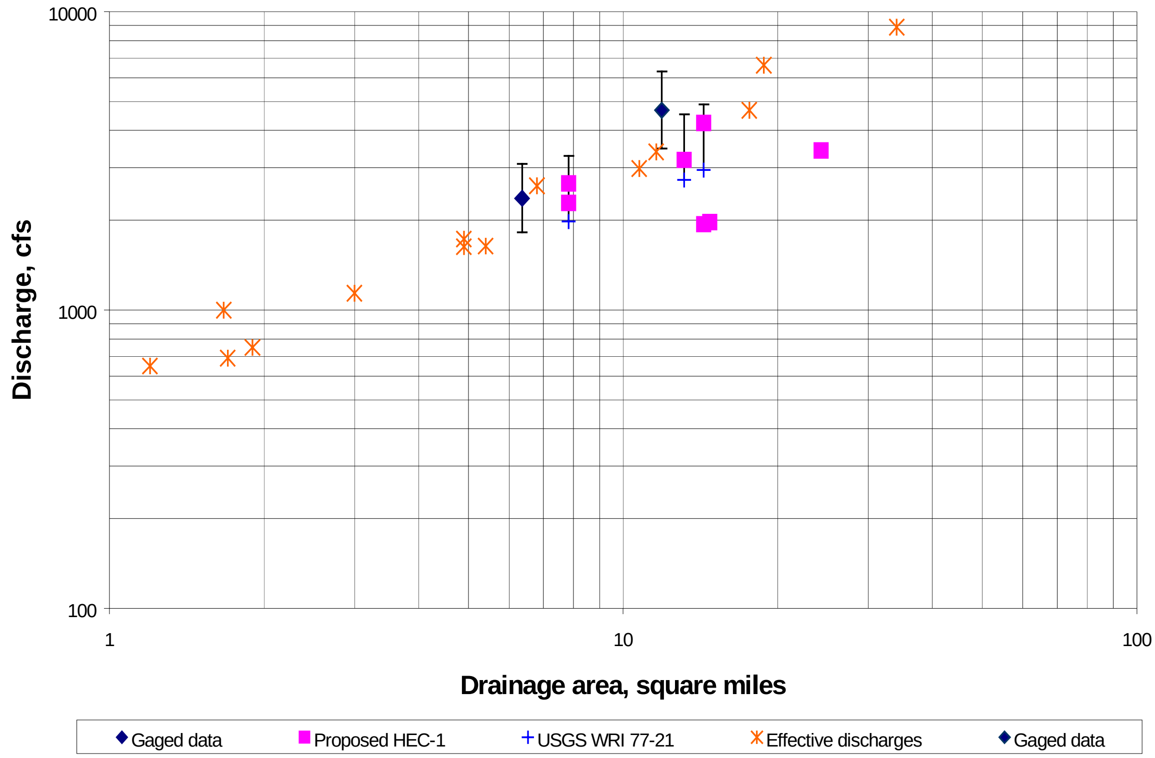

Figure 2. Evaluation of base flood discharges in Lake County, northern California.

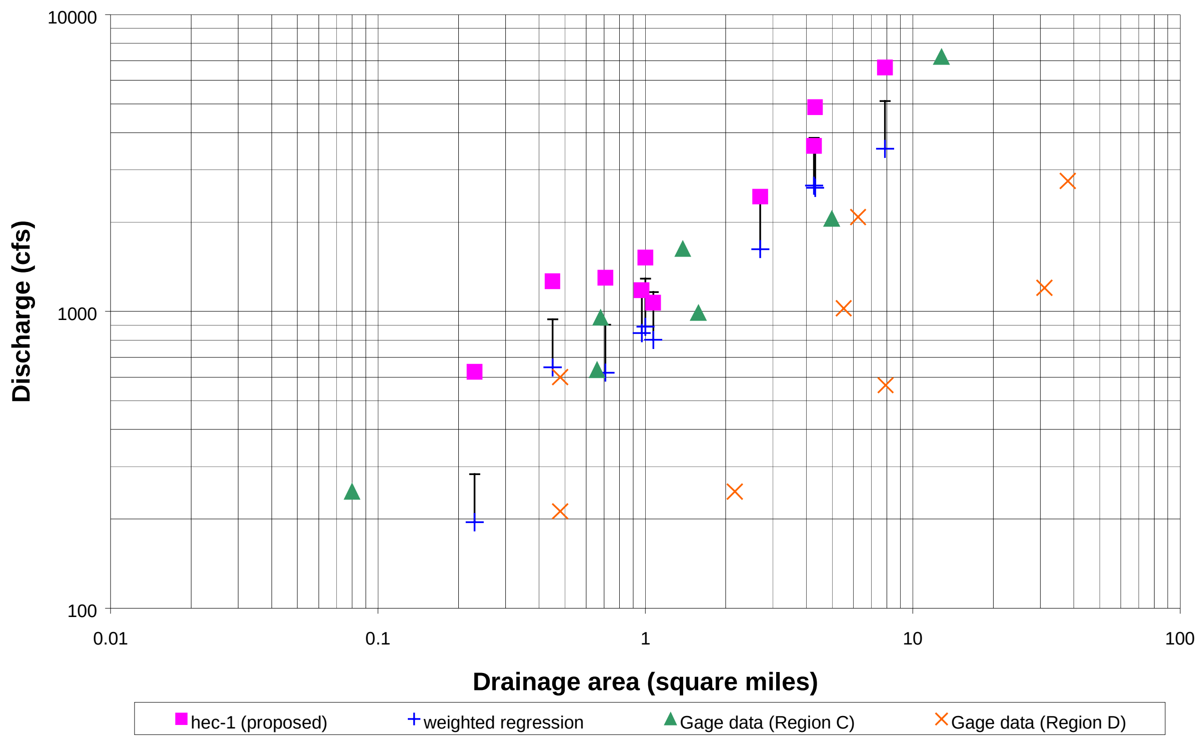

Figure 3. Evaluation of base flood discharges in Forrest City, Arkansas.