Evaluation of Peak Discharge Transposition

By Richard H. McCuen,[1] Member, ASCE, and Benjamin S. Levy[2]

Abstract: Discharge estimates obtained from gauged data are generally considered to be more accurate than model-estimated discharges. While most designs do not occur at the location of a gauging station, many designs are required at sites near but not at the gauged location. Transposition methods transfer discharge estimates from a gauged location to a nearby location on the same river. Despite their frequency of use, little is known about their accuracy and sensitivity. Because the state of Maryland is considering using discharge transposition, an assessment of the accuracy and sensitivity of two methods was undertaken: the area-ratio method and Sauer's weighting function method. Gauged data from nine states were used to evaluate the two methods for recurrence intervals of 2, 10, and 100 years. The criterion used to reject a data pair on the basis of time-sampling variation was when the T-year flood for the larger drainage area was less than the T-year flood for the smaller drainage area. Approximately 50% of the station pairs of gauged data had to be discarded because the data were collected during different periods, which is known as the time-sampling-variation problem. Sauer's method provided slightly better accuracy than the area-ratio method. Sensitivity analyses of the two methods are used to assess their rationality. Overall, both methods provide improved accuracy when the ungauged site is near the gauged site. The accuracy results suggest that Sauer's method can be reasonably applied if the drainage area of the ungauged site is within ±25% of the area of the gauged station, but the sensitivity analysis suggests that the method should be applied with caution because of its potential irrationality.

INTRODUCTION

The cost of estimating peak discharges and flood hydrographs for design work has declined with the advent and increased use of GIS programs. In spite of the increased efficiency afforded by this automation, the relative cost of data collection and analysis is still significant for agencies that must make numerous estimates with limited resources. Peak discharge transposition provides an alternative for estimating peak discharges at ungauged locations by transferring discharge information from a gauged location to an ungauged location. The ungauged site must be on the same stream and within a reasonable distance of a gauged site, and the streamflow record must be of sufficient length to perform a frequency analysis.

Transposition methods are commonly used by engineering companies and government agencies. The U.S. Water Resources Council report (1981), which referred to transposition as a transfer method, indicated that it was the fourth most frequently used category of 16 design methods in the private sector and the third most frequently used by state highway agencies. In spite of its frequent use, the accuracy of peak discharge transposition has not been studied.

Transposition Methods

The three most frequently used procedures for peak discharge transposition are (1) river profile graphs, which are graphs of peak discharge using gauged estimates plotted against river mile with discharge interpolated between gauges (e.g., Flippo 1977); (2) Sauer's weighting-function method (Sauer 1973; Thomas 1987), which is presented frequently in USGS discharge-frequency reports (e.g., Dillow 1996); and (3) the drainage area-ratio method, which has the form

$$q_u = q_g(A_u/A_g)^n \quad (1)$$

where q indicates peak discharge; A indicates drainage area; n is an empirical constant; and the subscripts g and U denote the gauged and ungauged sites, respectively.

Sauer's weighting-function method uses the following form:

$$q_{uw} = R_w q_{ur} \quad (2)$$

in which q_{uw} = weighted estimate of the discharge at the ungauged site; q_{ur} = discharge at the ungauged site estimated using the USGS state regression equation for the region in which the gauge lies; and R_w is a weight defined by

$$R_w = R - \frac{2(R - 1)|A_g - A_u|}{A_g} \quad (3)$$

where R is defined by

$$R = \frac{q_{gw}}{q_{gr}} \quad (4)$$

where q_{gr} = discharge estimated for the gauged site using the USGS state regression equation; and q_{gw} = weighted peak flow estimate using the flood frequency estimate q_g and the regression-equation estimate q_{gr} for the gauged site, which are related by

$$q_{gw} = \frac{q_g N_g + q_{gr} N_r}{N_g + N_r} \quad (5)$$

in which N_g and N_r = actual record length used to compute q_g and the equivalent record length of the regression equation, respectively. Values of N_r, which are a function of the return period and the accuracy of the USGS state regression equation, are given in the USGS reports. Sauer's weighting-function method of (2)–(5) cannot be used when the drainage area of the ungauged site differs by more than 50% of the drainage area at the gauged location. This limitation is implicit in the weighting function of (3). Sauer's method uses the USGS state regression equations (Jennings et al. 1994); thus any assumptions that underlie the regression equations should be met.

Objectives

It is enticing to adopt peak discharge transposition methods because they are simple to use and require minimal input data. Currently, a major limitation is the lack of documentation on their accuracy and sensitivity. In order to confidently apply transposition methods, knowledge of the accuracy of trans-

[1]Prof., Dept. of Civ. Engrg., Univ. of Maryland, College Park, MD 20742-3021.

[2]Grad. Res. Asst., Dept. of Civ. Engrg., Univ. of Maryland, College Park, MD.

Note. Discussion open until December 1, 2000. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on April 1, 1998. This paper is part of the ***Journal of Hydrologic Engineering***, Vol. 5, No. 3, July, 2000. ©ASCE, ISSN 1084-0699/00/0003-0278–0289/$8.00 + $.50 per page. Paper No. 18023.

J. Hydrol. Eng., 2000, 5(3): 278-289

position methods is needed. Specific aspects of peak discharge transposition that need investigation are

1. What are the implications of time-sampling variation to the use of transposition with short-record gauged estimates?
2. Does the relative accuracy vary both within a state and from state to state?
3. Does the relative accuracy vary significantly with return period?
4. How far upstream and downstream from a gauge can transposition be effectively used?
5. Do the larger data requirements of Sauer's method provide better accuracy than the less data-intensive area-ratio method?
6. What is the sensitivity of the two transposition methods?

Furthermore, a basis in accuracy for the 50% area limitation of Sauer's weighting-function method has not been documented (Wilbert O. Thomas Jr., personal communication, 1998). A study of these needs was undertaken, with the results provided herein.

DATABASE

The state of Maryland is considering allowing the use of peak discharge transposition. Because the streamgauge database in Maryland was not sufficient either to calibrate the area-ratio method or adequately assess the accuracy of the two methods, streamgauge data were compiled for the following states: Florida (Bridges 1982), Georgia (Stamey and Hess 1992), Kentucky (Choquette 1988), Maryland (Dillow 1996), New York (Lumia 1991), Ohio (Koltun and Roberts 1990), Pennsylvania (Flippo 1977), Tennessee (Weaver and Gamble 1993), and Virginia (Bisese 1995). The number of station pairs for each state is as follows: Florida, 54; Georgia, 104; Kentucky, 43; Maryland, 6; New York, 97; Ohio, 70, Pennsylvania, 27; Tennessee, 54; and Virginia, 17. Data from Pennsylvania were not used for the overall analysis because 100-year discharges for many stations were not included in the Flippo's report (1977). Only six station pairs were available for Maryland and about half of these suffered from time-sampling-variation problems; therefore, data for Maryland were also not included in the overall analysis. In addition to an analysis of the data combined from seven states, individual analyses were made for each of the seven states. Most of the conclusions are based on the combined analysis, which represents a database of 439 station pairs.

While data were available for other return periods, analyses were made using 2-, 10-, and 100-year return periods. These three return periods cover the range of most design work, and it seems reasonable to expect that results for the intermediate return periods (i.e., 5-year, 25-year, 50-year) will show similar results.

The calibration and assessment of the accuracy of the peak discharge transposition methods require streamgauge records from two gauges on the same river. The sites must be free of controls between the stations and representative of the hydrology of the region. Log-Pearson type III peak discharge estimates for the three return periods and the corresponding drainage areas are necessary to calibrate and evaluate the accuracy of (1). The input for the regression equations, including the drainage area, and the gauged and equivalent record lengths are necessary to evaluate Sauer's weighting function method. These data are available in the USGS reports.

Time-Sampling Variation

Temporal variations in rainfall and land use over the duration of flood records from different time periods can cause considerable variation in the log-Pearson type III flood characteristics. This introduces time-sampling variations that were shown to be very significant in compiling the data for assessing the accuracy of the transposition methods. The most obvious example is where the T-year flood for the larger drainage area is less than the T-year flood for the smaller drainage area.

The USGS reports show that the streamgauge records for many of the watershed pairs in the databases are not for the same periods of time. For example, Maryland records include historic floods from as early as 1884. For Pennsylvania and Virginia, historical floods from as early as 1787 and 1862, respectively, are part of the records that were used to develop the log-Pearson type III frequency curves. Some records were discontinued as early as the 1930s while other gauges were not installed until the 1960s. These examples of data problems were evident in all 10 states used in this study.

Data pairs for which time-sampling effects were obvious were not used in any of the analyses. The criterion used to reject a data pair on the basis of time-sampling variation was when the T-year flood for the larger drainage area was less than the T-year flood for the smaller drainage area. Approximately 50% of the paired records in Pennsylvania, Virginia, and Maryland were identified as suffering from time-sampling variation problems. Specific proportions were not developed for the other states, but the number of rejected station pairs was also about 50% of the available pairs. After station-pairs affected by time-sampling variation were removed, the database included 439 station-pairs in seven states.

Assessment Criteria

Two criteria were used to evaluate the data. First, the relative bias R_b is the average ratio of the difference between the predicted Y_p and measured Y_m discharges to the measured discharge:

$$R_b = \frac{1}{N} \sum \frac{(Y_p - Y_m)}{Y_m} \tag{6}$$

where N = number of station-pairs. For example, a negative relative bias would indicate that the transposition method, on the average, underpredicts. The relative bias is a measure of the systematic error variation.

The relative standard error R_e, which is the second goodness-of-fit, is defined as

$$R_e = \left[\frac{1}{N - 1} \sum \left(\frac{(Y_p - Y_m)}{Y_m} \right)^2 \right]^{0.5} \tag{7}$$

The relative standard error is a measure of the nonsystematic error variation.

The two goodness-of-fit statistics are expressed in relative form because the measured discharges in the data sets vary over several orders of magnitude. In relative form, the values of the statistics are less affected by the watersheds with large discharge magnitudes. Further, the relative statistics enable comparisons to be made both across drainage-area ratios and between transposition models.

WITHIN-STATE VARIATION

The USGS divides each state into regions based on the results of the regression analyses. Because relative statistics were used in the analyses, within-state differences were not expected to be significant. However, a preliminary analysis of the Pennsylvania data was conducted to test whether within-state variation was significant.

Flippo (1977) identified eight hydrologic regions in Pennsylvania, with these being subdivisions of the four major river basins (Delaware, Susquehanna, Potomac, and Ohio). Al-

J. Hydrol. Eng., 2000, 5(3): 278-289

TABLE 1. Variation of Area-Ratio Transposition Coefficient *n* in Pennsylvania

River basin (1)	Sample size (2)	2-year			10-year		
		n (3)	S_e/S_y (4)	R^2 (5)	n (6)	S_e/S_y (7)	R^2 (8)
Delaware	5	0.7732	0.282	0.921	0.8092	0.391	0.847
Susquehanna	13	0.8095	0.225	0.950	0.8011	0.210	0.956
Ohio	8	0.8093	0.226	0.949	0.8068	0.266	0.929
All four basins[a]	27	0.7880	0.256	0.935	0.8043	0.257	0.934

[a]Includes one watershed from Potomac River basin.

though the database was not large enough to evaluate the variation between the eight regions, the number of station-pairs in three of the four river basins was sufficient to assess whether or not the exponent of the area-ratio transposition method (1) was unique to the region.

A sufficient number of pairs of gauges for the Delaware, Susquehanna, and Ohio basins allowed the calibration of n of (1) (Table 1). The empirically derived n values show very little variation between the river basins and suggest that a coefficient of 0.8 is a realistic transposition coefficient for Pennsylvania. The empirical analyses provide reasonable accuracy, with coefficients of multiple determinations (R^2) generally above 0.93 and standard error ratios (standard error of estimate divided by the standard deviation of the criterion variable) less than 0.3. Because the data for the 2-year and 10-year return periods showed that the coefficient n did not vary across the three river basins, analyses for the remainder of the study did not attempt to examine within-state variation. This seems to have been a reasonable decision given that the between-state variation, with the exception of Florida, was small.

EFFECT OF DRAINAGE-AREA RATIO

A fundamental assumption of transposition methods is that the drainage area for which an estimated discharge is needed has similar characteristics to those for the gauged watershed. It seems reasonable to expect that this assumption would be less realistic as the difference in the two drainage areas, A_g and A_u, increases. The weighting function of (3) limits the use of Sauer's method such that the drainage area of the ungauged station must differ by no more than 50% of the gauged area. The area-ratio method of (1) does not have a mathematical limitation, unlike with Sauer's method. Therefore, it was necessary to assess whether the area-ratio method had a practical limit beyond which it would not perform well. It was also of interest to assess the extent to which the 50% limit of (3) was a practical limit or whether a more restrictive limit would be more accurate for practical applications. In our analyses, we purposely applied Sauer's method beyond the limit (±50%) that he recommended to see how it would perform. In practice, it should not be applied beyond this limit.

The effect of the drainage area ratio on the relative accuracy (7) and relative bias (6) of peak discharge estimates was evaluated for both transposition methods. This was done by dividing the data into groups of similar drainage area ratio and computing the relative bias and accuracy [(6) and (7)] of the two transposition methods for each interval. Where the number of station pairs was sufficiently large, drainage-area-ratio intervals for A_u/A_g were created for area ratios less than 1.0 at an increment of 0.1 (i.e., A_u/A_g = 0–0.1, 0.1–0.2, 0.2–0.3, . . . , 0.9–1.0). The separation ratios for area ratios greater than 1.0 are the reciprocal for the separation points below 1; thus, separation points of 1/0.9, 1/0.8, 1/0.7, etc., were used for A_u/A_g greater than 1. For states where sample sizes were small, such as Virginia, larger intervals had to be used.

Because of the large sample size, the data for the 439 station pairs provides the most useful results. The statistics of (6) and

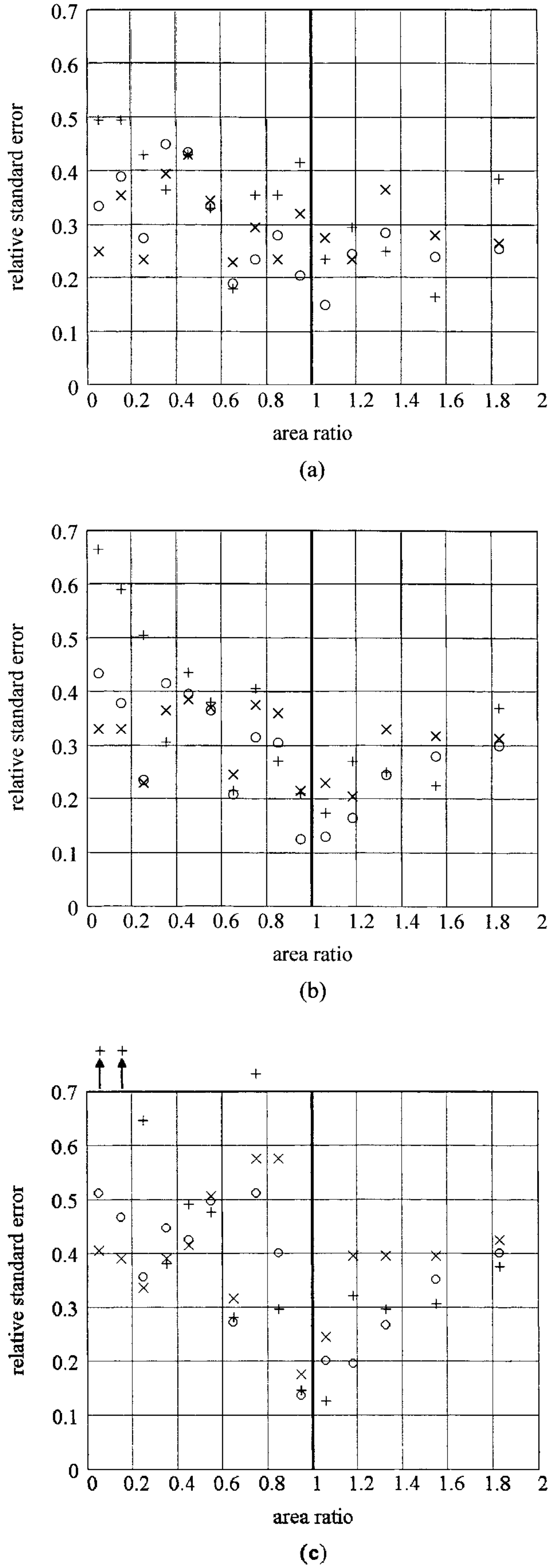

FIG. 1. Comparison of Relative Standard Error of Sauer's Method (○), Area-Ratio Method (×), and USGS Regression Equation (+) versus Area Ratio (A_u/A_g) for (a) 2-Year, (b) 10-Year, and (c) 100-Year Return Periods

J. Hydrol. Eng., 2000, 5(3): 278-289

(7) were computed for the 2-year, 10-year, and 100-year return periods using the values predicted by the two transposition methods and the USGS state regression equations. Fig. 1 shows the average relative standard error ratios for (1) the area-ratio method, (2) Sauer's method, and (3) the USGS regression equation estimates. Fig. 1 shows only values for area ratios less than 2.0; this is to more clearly show the results and because transposition is not recommended beyond this range. The values in Fig. 1 are plotted at the center point of each interval; for example, the relative standard error for the 0.8-to-0.9 interval is shown at a ratio of 0.85. Several comparisons should be made: (1) Sauer's method versus the USGS regression equation estimate by itself; (2) Sauer's method versus the area-ratio method; and (3) for both the area-ratio and Sauer's methods, comparisons within the 50% bounds and outside of the bounds.

The worth of the gauged data is indicated by a comparison of Sauer's method and the USGS regression equation estimates. The transposition of the gauged discharge estimate can be considered useful if the relative standard error for Sauer's method is smaller than the relative standard error from the regression-equation values alone. Thus, the difference between the two relative standard errors within the intervals of A_u/A_g is of interest. For the 2-year and 10-year return periods, Figs. 1(a and b) suggest that Sauer's method generally provides better estimates than the regression equations, although the improvement is minimal and probably not significant beyond the range of area ratios from 70–125%. For the 100-year discharges [Fig. 1(c)], the results are mixed such that it is difficult to conclude that estimates transposed with Sauer's method are better than discharges computed with the USGS equation. While the improvement for the three return periods is marginal outside the 70–125% range, Sauer's method generally gives better estimates than the regression equations alone, so transposition is warranted.

One objective of this study was to assess whether the complexity of Sauer's method provided substantial improvement over the less data intense area-ratio method. This can be assessed with a comparison of the average relative standard errors of the two methods. Sauer's method generally provides better accuracy than the area-ratio method within the 50% constraint inherent to the weighting function of Sauer's method. Beyond this range, the added complexity of Sauer's method does not provide greater accuracy than the area-ratio method. For $A_u/A_g < 0.50$, the area-ratio method provides better accuracy than Sauer's method, as should be expected because Sauer's method is not applicable beyond the 50% limit. The area-ratio method gives better accuracy than the USGS equation for $|A_u/A_g| < 50\%$.

COMPARISON ACROSS RETURN PERIODS

The results for the database combined from the eight states can be used to assess the variation in accuracy with return period. The preliminary analysis based on the application of the area-ratio method with the Pennsylvania data (Table 2) suggested that return period was not expected to be an important factor for model accuracy. In general, the results shown by comparison of the three parts of Fig. 1 for the seven-state analysis suggest that the relative accuracy does vary with return period. The mean relative standard errors generally range from about 20–40%, with values slightly less for area ratios near 1. However, the relative standard error generally gets poorer with increase in return period. This is true for all three return periods included in the analysis. All of the relative biases are low, generally less than 10%.

TABLE 2. Variation of Area-Ratio Transposition Coefficient (n) with Return Period for Pennsylvania (R^2 = Coefficient of Determination; S_e/S_y = Standard Error of Estimate Divided by Standard Deviation of Criterion Variable)

Return period (years) (1)	Sample size (2)	n (3)	S_e/S_y (4)	R^2 (5)
2	27	0.788	0.256	0.935
10	27	0.804	0.257	0.934
25	17	0.823	0.416	0.827
50	9	0.822	0.415	0.828
100	9	0.804	0.520	0.730

COMPARISON ACROSS STATES

Analyses were made for each of the seven states, with the relative bias and relative standard error computed for each return period and the selected drainage area ratios, A_u/A_g. Tables 3 and 4 include results for all seven states combined as well as those for Florida, Georgia, and Tennessee. The results for the other four states are similar, so they are omitted for reason of space. Except for Florida, the results are quite similar, with relative standard errors generally in the range from 0.2 to 0.4 and relative biases less than 15% in absolute value. The analyses for Florida showed much poorer accuracy, probably because of the higher standard errors for the USGS regression equations for Florida. In Florida, the relative standard errors were 40–160% for area ratios within the $\pm 50\%$ limit.

Analyses for Pennsylvania and Virginia were given additional consideration because of their proximity to Maryland. The results of the Pennsylvania data for the area-ratio transposition method of (1) are shown in Table 5. The area-ratio method provides similar levels of accuracy for all drainage area ratios between 0.2 and 1.0. In general, the area-ratio method provided slightly better results than the Sauer's method (Table 6). Specifically, the relative biases and relative standard errors are smaller for the area-ratio method, but the differences are probably not hydrologically meaningful.

The coefficient n of (1) was fitted with the 17 pairs of gauges in the Virginia data base. For the 2-year and 100-year discharges, the values of n were 0.629 and 0.852, respectively. For the 2-year analysis, the goodness-of-fit statistics were $S_e/S_y = 0.096$ and $R^2 = 0.991$. The corresponding values of S_e/S_y and R^2 for the 100-year discharges were 0.229 and 0.948, respectively. These goodness-of-fit statistics indicate a reasonable level of prediction accuracy. The values of n (0.629 and 0.852) show greater variation across return periods with the Virginia data than for the Pennsylvania data (Tables 1 and 2); however, the goodness-of-fit statistics are comparable.

The accuracy of both transposition methods for the Virginia data is similar to that for Pennsylvania. The relative biases are generally less than 10%, and the relative standard errors are generally less than 25%. In Virginia, the accuracy of estimates of the 2-year discharge are slightly better than those for estimates of the 100-year discharges.

ACCURACY FOR MARYLAND

Streamflow records in Maryland include only six station pairs that can be used to independently assess the transposition methods. Analyses were made for both the 2-year and 100-year magnitudes. Six station pairs is inadequate to calibrate n of (1). Therefore, based on the results from Pennsylvania and Virginia, a value of 0.8 was used for the area-ratio method with the Maryland data. Table 7 provides the relative bias and accuracy computations for the area-ratio method. Table 8 gives the corresponding statistics for Sauer's method. Values for the 2-year and 100-year events are included in both tables in order of increasing drainage area ratio. When using the area-ratio method, the relative errors ranged from 7 to 20% for the 2-

J. Hydrol. Eng., 2000, 5(3): 278-289

TABLE 3. Relative Bias and Relative Standard Error Statistics for Sauer's Method as Function of Drainage Area Ratio (A_u/A_g)

	All States							Florida						
		Relative Bias			Relative Standard Error				Relative Bias			Relative Standard Error		
Area-Ratio	N	2	10	100	2	10	100	N	2	10	100	2	10	100
0.05	51	-0.002	0.056	0.077	0.338	0.428	0.509	4	0.057	0.016	0.064	0.737	0.694	0.673
0.15	67	0.029	0.016	0.021	0.388	0.372	0.462	5	-0.114	-0.198	-0.177	0.620	0.579	0.561
0.25	58	0.017	0.024	0.035	0.275	0.238	0.359	10	0.096	0.098	0.178	0.244	0.192	0.339
0.35	69	0.113	0.090	0.075	0.451	0.417	0.446	10	0.268	0.292	0.413	0.924	0.785	0.696
0.45	51	0.046	0.065	0.054	0.436	0.390	0.426	5	0.680	0.741	0.870	1.291	1.184	1.244
0.55	54	0.054	0.078	0.117	0.333	0.365	0.496	8	0.174	0.357	0.643	0.438	0.613	1.030
0.65	35	-0.010	0.001	0.033	0.191	0.205	0.271	3	-0.208	-0.079	0.054	0.348	0.306	0.402
0.75	26	0.051	0.104	0.170	0.232	0.307	0.508	5	0.262	0.475	0.746	0.451	0.682	1.160
0.85	19	0.096	0.118	0.176	0.280	0.303	0.400							
0.95	9	0.127	0.076	0.028	0.203	0.124	0.136	5	0.227	0.279	0.392	0.378	0.431	0.669
10.00	51	0.044	0.109	0.142	0.489	0.567	0.682	4	0.183	0.265	0.548	0.970	1.138	1.598
6.67	67	0.040	0.034	0.066	0.448	0.397	0.479	5	-0.088	-0.134	-0.072	0.675	0.667	0.708
4.00	58	0.016	0.026	0.032	0.317	0.266	0.348	10	0.003	0.010	0.086	0.248	0.211	0.319
2.85	69	0.070	0.074	0.069	0.316	0.326	0.379	10	0.018	0.076	0.202	0.400	0.415	0.462
2.22	51	0.038	0.060	0.071	0.262	0.271	0.355	5	-0.073	0.090	0.279	0.480	0.551	0.691
1.82	54	-0.012	0.003	0.028	0.255	0.298	0.400	8	-0.029	0.135	0.364	0.375	0.491	0.788
1.54	35	0.007	0.042	0.094	0.241	0.278	0.353	3	-0.162	-0.156	-0.118	0.220	0.263	0.405
1.33	26	0.056	0.006	-0.034	0.283	0.245	0.267	5	-0.088	-0.147	-0.155	0.274	0.322	0.413
1.18	19	-0.082	-0.040	0.005	0.244	0.165	0.196							
1.05	9	-0.100	-0.074	-0.040	0.149	0.130	0.198	5	-0.177	-0.098	-0.005	0.240	0.125	0.161

TABLE 3. (*Continued*)

Area-Ratio	Georgia							Tennessee						
	N	Relative Bias			Relative Standard Error			N	Relative Bias			Relative Standard Error		
		2	10	100	2	10	100		2	10	100	2	10	100
0.05	12	-0.102	-0.043	0.043	0.268	0.358	0.478	7	-0.072	-0.134	-0.192	0.318	0.366	0.486
0.15	24	-0.003	-0.011	0.053	0.322	0.286	0.356	8	-0.196	-0.204	-0.289	0.420	0.444	0.488
0.25	14	0.026	0.017	0.050	0.357	0.316	0.511	5	0.143	0.087	-0.035	0.229	0.220	0.553
0.35	19	-0.047	-0.015	0.026	0.223	0.185	0.274	7	-0.128	-0.156	-0.176	0.238	0.302	0.285
0.45	7	-0.225	-0.164	-0.097	0.306	0.241	0.192	6	0.047	0.045	-0.113	0.190	0.284	0.357
0.55	9	-0.064	-0.077	-0.040	0.270	0.141	0.240	7	-0.050	-0.058	-0.063	0.281	0.366	0.427
0.65	8	0.095	0.132	0.207	0.265	0.275	0.371	8	0.009	-0.032	-0.067	0.116	0.154	0.217
0.75	5	0.050	0.062	0.081	0.180	0.174	0.294	3	0.008	-0.067	-0.113	0.148	0.093	0.155
0.85														
0.95	6	-0.008	-0.071	-0.071	0.115	0.103	0.111	3	0.090	0.073	0.096	0.253	0.206	0.272
10.00	12	-0.097	-0.033	0.044	0.385	0.441	0.468	7	-0.049	-0.113	-0.208	0.395	0.368	0.448
6.67	24	-0.066	-0.060	0.044	0.318	0.275	0.328	8	-0.173	-0.146	-0.209	0.398	0.427	0.490
4.00	14	-0.042	-0.039	-0.026	0.402	0.300	0.378	5	0.109	0.091	-0.008	0.213	0.135	0.255
2.85	19	-0.024	0.009	0.014	0.164	0.183	0.252	7	-0.090	-0.046	0.017	0.322	0.318	0.270
2.22	7	-0.138	-0.164	-0.156	0.191	0.204	0.200	6	0.019	0.068	0.038	0.139	0.177	0.200
1.82	9	-0.137	-0.131	-0.096	0.218	0.230	0.200	7	0.013	-0.043	-0.039	0.221	0.190	0.186
1.54	8	-0.077	-0.017	0.058	0.268	0.318	0.361	8	0.140	0.154	0.210	0.211	0.213	0.307
1.33	5	0.064	0.085	0.073	0.244	0.192	0.168	3	-0.040	-0.046	0.027	0.237	0.274	0.233
1.18														
1.05	6	-0.121	-0.051	0.003	0.209	0.106	0.120	3	-0.146	-0.138	-0.181	0.222	0.173	0.298

J. Hydrol. Eng., 2000, 5(3): 278-289

TABLE 4. Relative Bias and Relative Standard Error Statistics for Area-Ratio Method as Function of Drainage Area Ratio (A_u/A_g)

	All States							Florida						
		Relative Bias			Relative Standard Error				Relative Bias			Relative Standard Error		
Area-Ratio	N	2	10	100	2	10	100	N	2	10	100	2	10	100
0.05	51	-0.129	0.068	0.244	0.495	0.662	0.991	4	-0.138	-0.389	-0.563	0.513	0.568	0.692
0.15	67	-0.051	0.035	0.098	0.493	0.590	0.713	5	0.337	0.254	0.087	0.845	0.830	0.710
0.25	58	-0.003	0.085	0.169	0.429	0.506	0.643	10	0.365	0.329	0.281	0.826	0.835	0.901
0.35	69	-0.069	-0.038	-0.003	0.293	0.301	0.381	10	0.090	0.031	-0.037	0.336	0.287	0.282
0.45	51	-0.017	0.008	0.040	0.433	0.436	0.492	5	0.872	0.726	0.608	1.327	1.280	1.276
0.55	54	0.036	0.082	0.124	0.333	0.379	0.471	8	0.314	0.322	0.323	0.630	0.665	0.751
0.65	35	-0.040	-0.018	0.007	0.179	0.215	0.278	3	0.029	0.158	0.266	0.087	0.313	0.518
0.75	26	0.002	0.097	0.252	0.355	0.403	0.739	5	0.329	0.516	0.785	0.840	0.851	1.292
0.85	19	0.082	0.040	0.029	0.353	0.269	0.298							
0.95	9	0.217	0.144	0.085	0.419	0.213	0.147	5	0.358	0.287	0.250	0.526	0.402	0.421
10	51	0.100	-0.060	-0.155	0.604	0.560	0.626	4	0.569	0.666	1.047	1.548	1.181	1.625
6.67	67	0.117	0.029	-0.005	0.660	0.629	0.763	5	0.118	-0.015	-0.044	1.159	0.780	0.521
4	58	0.020	-0.047	-0.100	0.410	0.387	0.428	0	-0.168	-0.157	-0.114	0.371	0.404	0.432
2.85	69	0.091	0.054	0.049	0.541	0.513	0.620	10	-0.072	-0.056	-0.010	0.249	0.284	0.363
2.22	51	0.068	0.034	0.023	0.359	0.342	0.432	5	-0.353	-0.270	-0.167	0.536	0.535	0.572
1.82	54	0.004	-0.028	-0.053	0.386	0.369	0.372	8	-0.182	-0.168	-0.125	0.309	0.366	0.438
1.54	35	0.025	0.019	0.012	0.168	0.221	0.302	3	-0.047	-0.148	-0.211	0.097	0.246	0.338
1.33	26	0.036	-0.037	-0.099	0.250	0.254	0.295	5	-0.128	-0.265	-0.330	0.324	0.415	0.499
1.18	19	-0.010	0.008	0.033	0.294	0.268	0.319							
1.05	9	-0.139	-0.119	-0.077	0.233	0.169	0.123	5	-0.233	-0.210	-0.177	0.315	0.276	0.264

TABLE 4. (*Continued*)

	Georgia							Tennessee						
		Relative Bias			Relative Standard Error				Relative Bias			Relative Standard Error		
Area-Ratio	N	2	10	100	2	10	100	N	2	10	100	2	10	100
0.05	12	-0.240	-0.314	-0.326	0.417	0.370	0.353	7	-0.170	0.534	1.250	0.709	1.574	2.605
0.15	24	-0.004	-0.140	-0.155	0.383	0.302	0.391	8	-0.291	-0.022	0.202	0.395	0.374	0.678
0.25	14	0.028	-0.061	-0.065	0.272	0.226	0.287	5	-0.191	-0.014	0.058	0.277	0.316	0.443
0.35	19	-0.169	-0.164	-0.109	0.302	0.299	0.341	7	-0.114	-0.076	-0.084	0.300	0.192	0.217
0.45	7	-0.195	-0.140	-0.079	0.268	0.200	0.158	6	-0.070	-0.002	0.015	0.131	0.207	0.357
0.55	9	0.009	-0.034	-0.025	0.279	0.212	0.307	7	-0.099	0.052	0.153	0.189	0.274	0.574
0.65	8	0.084	0.069	0.085	0.214	0.191	0.223	8	-0.143	-0.122	-0.132	0.169	0.168	0.208
0.75	5	-0.023	-0.060	-0.026	0.122	0.097	0.179	3	-0.023	-0.015	-0.003	0.123	0.129	0.188
0.85														
0.95	6	0.075	-0.015	-0.054	0.177	0.081	0.136	3	0.099	0.120	0.176	0.185	0.183	0.324
10	12	0.182	0.196	0.116	0.537	0.319	0.187	7	0.289	0.044	-0.105	0.656	0.596	0.626
6.67	24	-0.028	0.089	0.160	0.428	0.408	0.587	8	0.346	0.161	0.052	0.616	0.479	0.465
4	14	-0.079	0.004	0.012	0.325	0.293	0.334	5	0.135	0.085	0.100	0.250	0.298	0.463
2.85	19	0.165	0.167	0.120	0.339	0.334	0.380	7	0.110	0.116	0.150	0.302	0.249	0.302
2.22	7	0.191	0.105	0.012	0.331	0.216	0.154	6	0.018	0.034	0.069	0.121	0.192	0.275
1.82	9	-0.010	0.020	0.025	0.247	0.212	0.248	7	0.080	-0.006	-0.004	0.190	0.200	0.321
1.54	8	-0.094	-0.081	-0.096	0.185	0.165	0.194	8	0.132	0.153	0.190	0.169	0.211	0.296
1.33	5	0.005	0.041	0.020	0.117	0.086	0.175	3	0.008	0.026	0.030	0.132	0.129	0.188
1.18														
1.05	6	-0.068	0.008	0.057	0.137	0.079	0.155	3	-0.091	-0.101	-0.125	0.155	0.155	0.230

J. Hydrol. Eng., 2000, 5(3): 278-289

TABLE 5. Goodness-of-Fit Statistics across Drainage Area Ratios Using Area-Ratio Method for Pennsylvania

Drainage area ratio (1)	Sample size (2)	Relative Bias		Relative Standard Error	
		2-year (3)	10-year (4)	2-year (5)	10-year (6)
0.0–0.2	6	0.157	0.174	0.226	0.253
0.2–0.4	9	−0.040	0.026	0.127	0.147
0.4–0.5	5	−0.043	−0.030	0.088	0.111
0.5–0.7	4	0.001	−0.002	0.044	0.122
0.7–1.0	3	0.122	0.031	0.176	0.113

TABLE 6. Goodness-of-Fit Statistics across Drainage Area Ratios Using Sauer's Weighting-Function Method in Pennsylvania

Drainage area ratio (1)	Sample size (2)	Relative Bias		Relative Standard Error	
		2-year (3)	10-year (4)	2-year (5)	10-year (6)
0.0–0.2	6	0.031	0.088	0.259	0.291
0.2–0.4	9	−0.037	0.017	0.180	0.237
0.4–0.5	5	0.205	0.130	0.354	0.273
0.5–0.7	4	−0.072	−0.061	0.169	0.145
0.7–1.0	3	0.180	0.148	0.286	0.318
1.0–1.5	3	−0.078	0.013	0.194	0.266
1.5–2.0	4	−0.039	0.006	0.137	0.059
2.0–2.5	5	0.178	0.041	0.292	0.191
2.5–5.0	9	0.023	−0.276	0.149	0.375
>5.0	6	−0.026	−2.536	0.212	3.770

year events and from 4 to 55% for the 100-year events. When using Sauer's weighing-function method, the errors ranged from 6 to 20% for the 2-year event and 5 to 31% for the 100-year event. In light of the accuracy statistics for the seven states, these relative standard errors suggest that the two methods would provide similar levels of accuracy in Maryland.

TIME-SAMPLING VARIATION

The effect of time-sampling variation on the accuracy of the area-ratio and Sauer's methods was assessed for the six Maryland station pairs (Table 9). The proportion of overlap of the paired stations was compared to the relative bias for both transposition methods. For example, one station pair (01596500 and 01598000) has record lengths of 42 and 24 years, respectively, but only 2 of the 24 years for which data were available at the short-record site (01598000) were from years of record at the long-record site, therefore, the overlap percentage is 8% (2/24).

The percentage overlap is shown in Table 8 for each station pair. The relative errors for the 2-year and 100-year errors from Tables 7 and 8 are also given in Table 9. Three of the six station pairs have a 100% overlap (i.e., the years of the short record length were all years when data were collected at the long-record station), with the other three gauges having overlaps of less than 10%. For the area-ratio method, the median average errors for the 2-year and 100-year events are 9% and 10%, respectively, for the three 100%-overlap station pairs and 11% and 35% for the three less-than-10% overlap station pairs. For Sauer's method, the median values are 11% and 23% for the 2-year and 100-year events for the 100%-overlap station pairs and 17% and 25% for the less-than-10%-overlap station pairs. These results suggest that Sauer's method is slightly less sensitive to time-sampling variation, most likely because it makes use of the regression estimates. For both transposition models, the accuracy is better when time-sampling variation is not a problem. This implies that, when transposition is to be applied, the gauge record should be reviewed to ensure that it includes a representative range of discharges.

SENSITIVITY OF TRANSPOSITION METHODS

Sensitivity analyses are useful for identifying the rationality of model components and measuring the relative importance of various parameters. Relative sensitivity is defined as the percentage change of one factor that results from a 1% change in a second factor (McCuen 1973). Therefore, a relative sensitivity of unity indicates that a change in one factor will cause an equal percentage change in a second factor. Expressing sensitivities in relative form $(\partial Y/Y)/(\partial X/X)$, rather than in absolute form $(\partial Y/\partial X)$, is useful because relative sensitivities are dimensionless and, therefore, values for different models or different variables within one model can be compared. The absolute sensitivities $(\partial Y/\partial X)$ of different X variables, such as drainage area and record length, cannot be compared, because the X variables will generally have different dimensions.

Sensitivity of Area-Ratio Transposition

The relative sensitivity of q_u to q_g for the area-ratio method (1) equals 1. Therefore, a 1% change in q_g causes a 1% change in q_u. The absolute change will depend on the multiplier $(A_u/A_g)^n$. A relative sensitivity of 1 is generally considered to be large, but it is inherent in the structure of (1). The unit relative sensitivity for the area-ratio method can be compared with relative sensitivities computed using Sauer's method.

TABLE 7. Assessment of Errors with Area-Ratio Transposition Method Using Maryland Streamgauge Data Assuming Large Watershed is Gauged

USGS gauge numbers (1)	Area (mi^2) (2)	2-Year				100-Year			
		Actual flow (ft^3/s) (3)	Predicted flow (ft^3/s) (4)	Error (ft^3/s) (5)	Relative error (6)	Actual flow (ft^3/s) (7)	Predicted flow (ft^3/s) (8)	Error (ft^3/s) (9)	Relative error (10)
0159 3500	38.0	1,340	1,439	99	0.074	10,500	10,090	−410	−0.039
0159 4000	98.4	3,080				21,600			
0159 6500	49.1	1,460	1,746	286	0.196	6,000	9.314	3,314	0.552
0159 8000	115	3,450				18,400			
0159 6000	287	8,100	8,806	706	0.087	39,500	43,694	4,194	0.106
0160 0000	596	15,800				78,400			
0158 6500	91.0	2,510	2,243	−267	−0.107	12,300	13,480	1,180	0.096
0158 7000	165	3,610				21,700			
0159 5500	225	7,470	6,667	−803	−0.108	38,500	32,512	−5,988	−0.156
0159 6000	287	8,100				39,500			
0164 2000	665	16,900	15,437	−1,463	−0.087	39,900	53,774	13,876	0.348
0164 3000	817	18,200				63,400			

J. Hydrol. Eng., 2000, 5(3): 278-289

TABLE 8. Assessment of Errors with Sauer's Weighting-Function Transposition Method Using Maryland Streamgauge Data Assuming Large Watershed is Gauged

USGS gauge numbers (1)	Area (mi^2) (2)	2-Year Actual flow (ft^3/s) (3)	2-Year Predicted flow (ft^3/s) (4)	2-Year Error (ft^3/s) (5)	2-Year Relative error (6)	100-Year Actual flow (ft^3/s) (7)	100-Year Predicted flow (ft^3/s) (8)	100-Year Error (ft^3/s) (9)	100-Year Relative error (10)
0159 3500	38.0	1,340	1,186	−154	−0.115	10,500	7,924	−2,576	−0.245
0159 4000	98.4	3,080				21,600			
0159 6500	49.1	1,460	1,546	86	0.059	6,000	6,299	299	0.050
0159 8000	115	3,450				18,400			
0159 6000	287	8,100	7,307	−793	−0.098	39,500	31,290	−8,210	−0.208
0160 0000	596	15,800				78,400			
0158 6500	91.0	2,510	2,833	323	0.129	12,300	15,096	2,796	0.227
0158 7000	165	3,610				21,700			
0159 5500	225	7,470	6,214	−1,256	−0.168	38,500	26,488	−12,012	−0.312
0159 6000	287	8,100				39,500			
0164 2000	665	16,900	13,446	−3,454	−0.204	39,900	50,010	10,110	0.253
0164 3000	817	18,200				63,400			

TABLE 9. Effect of Time-Sampling Variation on Accuracy

Gauge number (1)	Record length (2)	Overlap length (3)	Overlap proportion (%) (4)	RELATIVE ERROR (%) Area-Ratio Method 2-year (5)	Area-Ratio Method 100-year (6)	Sauer's Method 2-year (7)	Sauer's Method 100-year (8)
0159 3500	58	42	100	7	4	11	25
0159 4000	42						
0159 6500	42	2	8	20	55	6	5
0159 8000[a]	24						
0159 6000	26	16	100	9	11	10	21
0160 0000	16						
0158 6500	26	24	100	11	10	13	23
0158 7000[a]	24						
0159 5500	41	2	8	11	16	17	31
0159 6000	26						
0164 2000	35	2	6	9	35	20	25
0164 3000	62						

[a]Gauge currently located downstream of reservoir.

Sensitivity of Sauer's Method

Sauer's method involves variables other than the two drainage areas, namely, the record lengths and the regression discharges. As a result, the sensitivities of Sauer's method will depend on the magnitudes of these other factors. The relative sensitivities of q_{uw} of (2) were computed as a function of three ratios: (1) the record length ratio, $R_n = n_g/N_r$, where N_r is the equivalent record length of the regression estimates; (2) the gauged-site discharge ratio, $R_q = q_g/q_{gr}$; and (3) the area ratio, $R_a = A_u/A_g$, where the subscript gr refers to the regression estimate at the gauge and the subscripts g and u refer to the gauged and ungauged sites, respectively. Because q_{uw} of (2) is the design discharge, its sensitivity to the three discharges q_{ur}, q_g, and q_{gr} are of interest. The relative sensitivity functions are computed from (2) to (5):

$$S_{ur} = 1.0 \quad (8a)$$

$$S_g = w_1(1 - w_3)R_q(q_{ur}/q_{uw}) = w_1(1 - w_3)R_q/R_w \quad (8b)$$

$$S_{gr} = -S_g \quad (8c)$$

in which $w_1 = N_g/(N_g + N_r)$; $w_2 = 1 - w_1$; $w_3 = 2|A_u|/A_g$; and S_{ur}, S_g, and S_{gr} are the relative sensitivities of q_{uw} to q_{ur}, q_g, and q_{gr}, respectively. The relative sensitivity S_{ur} seems unreasonably high, but like the area-ratio relative sensitivity of 1, it is the result of the structure of Sauer's model.

The gauged discharge q_g should be important to predicting q_{uw} when the record length ratio R_n is large and the ungauged site is near the gauged site (i.e., R_a is near 1.0). The sensitivity surface of Fig. 2 shows that the weighted discharge q_{uw} at the ungauged site has a maximum relative sensitivity to the gauged estimate q_g of 0.91 at the area ratio of 1 and for high record length ratios. For low record length ratios, especially when R_a is not near 1, the weighted discharge q_{uw} becomes less sensitive to the gauged discharge estimate. This decline in sensitivity is rational. However, the relative sensitivity of q_{uw} to q_g is always less than that to q_{ur} even when the record length ratio is large and R_a is near 1.0, which is where the gauged discharge q_g is expected to be more important than the regression estimate q_{ur}. This suggests that q_{ur} is more important than q_g even at the gauged site. This irrationality is the result of the weighting structure, especially (2).

The reason for this greater sensitivity to q_{ur} than to q_g under

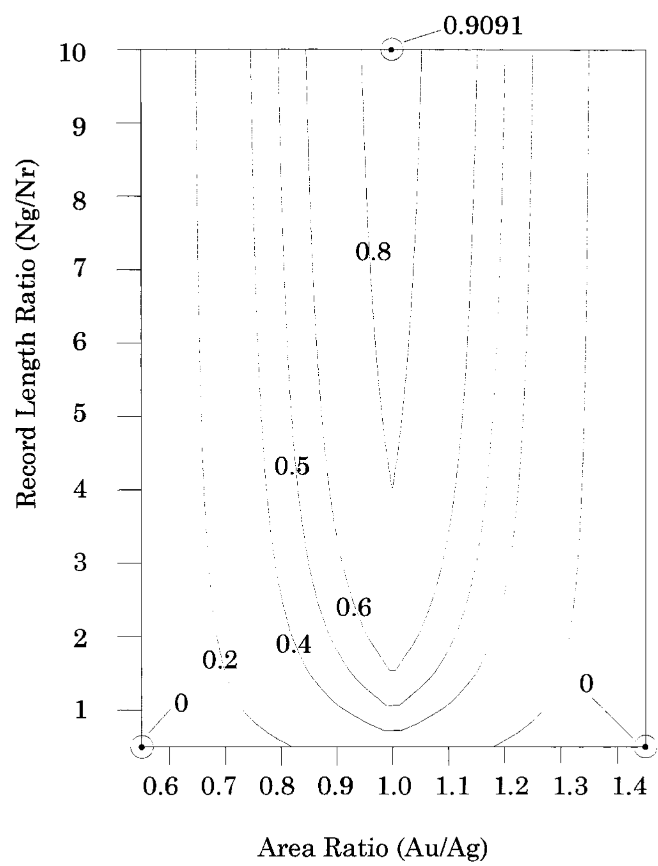

FIG. 2. Relative Sensitivity Surface of Sauer's Weighted Discharge (q_{uw}) at Ungauged Site for Selected Area Ratios and Record Length Ratios

J. Hydrol. Eng., 2000, 5(3): 278-289

these conditions is more easily understood by combining (2)–(5) into one equation:

$$q_{uw} = q_{ur}[w_3 + w_2(1 - w_3)] + q_g[(1 - w_2)(1 - w_3)(q_{ur}/q_{gr})] \quad (9)$$

in which $w_2 = 1 - w_1 = N_r/(N_r + N_g)$. This relationship shows that the ratio of the two regression estimates contributes to the weight applied to the gauged estimate. Eq. (9) also shows that the ungauged-site regression estimate q_{ur} has an independent effect that makes it generally more important than the gauged estimate. The gauge estimate q_g should be considerably more important when the record length ratio is large, especially when N_r is small and when A_u approaches A_g. Fig. 2 shows that the sensitivity of the ungauged estimate with respect to the gauge estimate q_g drops considerably, as expected, when the record length ratio is small.

For large values of the record length ratio N_g/N_r, the weighting function is not very sensitive to the record length ratio. In Fig. 2, the relative sensitivity isolines are nearly parallel to each other for record length ratios greater than 4. Only for small record length ratios does the relative sensitivity change with record length ratio for any given area ratio. This means that the sensitivity of q_{uw} does not change much for the longer record lengths as the length of the gauge record increases.

Sauer's method is not very sensitive to values of either the record length ratio or the area ratio for values of the area ratio A_u/A_g near the 50% and 150% limits, as expected. A low sensitivity is inherent to the weight of (3) with less emphasis placed on the gauged discharge estimate at the 50% limit (i.e., $A_u/A_g = 0.5$ or 1.5), which is rational.

The relative sensitivity function of (8*c*) indicates that the gauged regression estimate q_{gr} has the same importance as that of the gauge estimate. This seems rational given the balance of (5). The negative sign only indicates an inverse relationship. It seems irrational that the gauged-site regression estimate q_{gr} should have the same level of importance as q_g for large record length ratios.

These irrationalities are inherent to Sauer's model structure. In spite of some positive aspects of the method, the irrationalities suggest that a better model could be developed.

DISCUSSION AND CONCLUSIONS

Within the area ratio intervals of 70 to 125%, Sauer's method provided better accuracy than either the regression equations or the area-ratio method. It also has several advantages, including the 50%-area limitation and the fact that its weighting function decreases the significance of the gauged site as the distance between the two sites increases. The latter advantage is possibly a more rational assumption than a weight that is independent of the distance between gauges. Sauer's method has the additional advantage of using watershed characteristics in addition to the drainage area in weighting the gauged estimate. Specifically, the regression-equation discharges q_{gr} and q_{ur} may involve variables such as land use factors (e.g., percentage of forest cover or runoff curve number), watershed slope, or rainfall indicies. While this is a conceptual advantage, it implies that Sauer's method will require more input data when the regression equations use more predictor variables than drainage area. Thus, the weighting accounts for factors other than area that are important in the discharge. If transposition is to be used, Sauer's method is preferable to the area-ratio method. However, we recommend limiting its use to $\pm 25\%$ rather than $\pm 50\%$ of the gauged drainage area (i.e., area ratios from 0.75 to 1.25). Outside of this range, transposition does not make a substantial improvement in accuracy.

The sensitivity analysis provides important support for the empirical analysis of the data from seven states. Specifically, the plot of Fig. 2 shows that the relative sensitivity to the gauged estimate declines considerably outside the area ratio interval from 0.75 to 1.25. This is similar to the implications of the plots of the relative standard error ratio shown in Fig. 1.

A major difference between the area-ratio method and Sauer's weighting-function method is that the former uses the gauged estimate as the primary discharge variable while Sauer's method uses the regression equation estimate at the ungauged site (q_{ur}) as the primary discharge variable. The sensitivity analysis indicate that the relative sensitivity of q_u to q_g for the area-ratio method is always equal to 1. Similarly, Sauer's method has a mean relative sensitivity of 1 for q_{uw} with respect to q_{ur}. In some cases, the regression equation estimate has a small equivalent years of record (as small as 2 years in one region of Maryland). In such cases, it may not be rational that q_{ur} has such a high sensitivity. The sensitivity of q_g in Sauer's method may be much less than that of q_{ur} even when it is based on a longer record length.

The goodness-of-fit statistics given in Tables 3 and 4 suggest that peak discharge transposition is a reasonable method of estimating discharges at ungauged locations under certain conditions. First, the gauged record should have a sufficient record length that time-sampling variation will not reduce the likelihood of reasonable accuracy. The record length should be of sufficient length to include years of record with high discharges. Second, both channel and watershed characteristics for the ungauged location should be similar to those at the gauged site. Third, the ungauged location should be on the same river as the gauged location. Transposition to a site on a tributary of the river on which the gauge is located was not tested and is, therefore, not recommended. This assumption was made in selecting the stations used in the evaluation of the two methods reported herein.

The attractiveness of Sauer's method stems from its theoretically desirable characteristic of weighting gauged from a nearby site with regionally developed information in the form of the USGS regression equations. Statistical theory suggests that the mean square error of the weighted discharge would be lower than that for either of the independent inputs. It then follows that a user might wish to know if transposition is sufficiently better than using the regression estimate by itself. That is, how much more accurate are q_{uw} estimates made with (2)–(5) over values of q_{ur} alone? The results suggest that within the area ratio range of 0.75 to 1.25, transposition is of value. Outside of this range, the worth of transposition is marginal, at best.

ACKNOWLEDGMENTS

The writers appreciate the important comments contributed by Wilbert O. Thomas Jr., of the Michael Baker Corporation, Alexandria, Va. Much of the data was compiled by Jill Lehman and Keith Ramsey. Their assistance is very much appreciated.

APPENDIX. REFERENCES

Bisese, J. A. (1995). "Methods for estimating the magnitude and frequency of peak discharges of rural, unregulated streams in Virginia." *USGS Water-Resour. Investigations Rep. 94-4148*, U.S. Geological Survey, Richmond, Va.

Bridges, W. C. (1982). "Technique for estimating magnitude and frequency of floods on natural-flow streams in Florida." *WRI Rep. 82-4012*, U.S. Geological Survey, Tallahassee, Fla.

Choquette, A. F. (1988). "Regionalization of peak discharges for streams in Kentucky." *WRI Rep. 87-4209*, U.S. Geological Survey, Louisville, Ky.

Dillow, J. J. A. (1996). "Technique for estimating magnitude and frequency of peak flows in Maryland." *WRI Rep. 95-4154*, U.S. Geological Survey, Towson, Md.

Flippo, Jr., H. N. (1977). "Floods in Pennsylvania." *Bull. No. 13*, Department of Environmental Resources, Harrisburg, Pa.

Jennings, M. E., Thomas, W. O. Jr., and Riggs, H. C. (1994). "Nationwide summary of U.S. Geological Survey regional regression equation for

estimating magnitude and frequency of floods for ungauged sites, 1993.'' *WRI Rep. 94-4002*. U.S. Geological Survey, Reston, Va.
Koltun, G. F., and Roberts, J. W. (1990). ''Techniques for estimating flood-peak discharges in rural, unregulated streams in Ohio.'' *WRI Rep. 89-4126*, U.S. Geological Survey, Columbus, Ohio.
Lumia, R. (1991). ''Regionalization of flood discharges for rural, unregulated streams in New York, excluding Long Island.'' *WRI Rep. 90-4197*, U.S. Geological Survey, Albany, N.Y.
McCuen, R. H. (1973). ''The role of sensitivity analysis in hydrologic modeling.'' *J. Hydrology*, 18, Feb., 37–53.
Sauer, V. B (1973). ''Flood characteristics of Oklahoma streams.'' *WRI Rep. 52-73*, U.S. Geological Survey, Oklahoma City, Okla.
Stamey, T. C., and Hess, G. W. (1992). ''Techniques for estimating magnitude and frequency of floods in rural basins of Georgia.'' *WRI Rep. 93-4016*, U.S. Geological Survey, Atlanta, Ga.
Thomas, Jr., W. O. (1987). ''Techniques used by the U.S. Geological Survey in estimating the magnitude and frequency of floods.'' *Catastrophic flooding*, L. Mayer and D. Nash, eds., Binghamton Symposium in Geomorphology, No. 18, Allen and Unwin, Boston, 267–288.
U.S. Water Resources Council. (1981). *Estimating peak flow frequencies for natural ungaged watersheds*, Washington, D.C.
Weaver, J. D., and Gamble, C. R. (1993). ''Flood frequency of streams in rural basins of Tennessee.'' *WRI Rep. 92-4165*, U.S. Geological Survey, Nashville, Tenn.

J. Hydrol. Eng., 2000, 5(3): 278-289