Adjustment of Regional Regression Equations for Urban Storm-Runoff Quality Using At-Site Data

C. SHANE BARKS

Regional regression equations have been developed to estimate urban storm-runoff loads and mean concentrations using a national data base. Four statistical methods using at-site data to adjust the regional equation predictions were developed to provide better local estimates. The four adjustment procedures are a single-factor adjustment, a regression of the observed data against the predicted values, a regression of the observed values against the predicted values and additional local independent variables, and a weighted combination of a local regression with the regional prediction. Data collected at five representative storm-runoff sites during 22 storms in Little Rock, Arkansas, were used to verify, and, when appropriate, adjust the regional regression equation predictions. Comparison of observed values of storm-runoff loads and mean concentrations to the predicted values from the regional regression equations for nine constituents (chemical oxygen demand, suspended solids, total nitrogen as N, total ammonia plus organic nitrogen as N, total phosphorus as P, dissolved phosphorus as P, total recoverable copper, total recoverable lead, and total recoverable zinc) showed large prediction errors ranging from 63 percent to more than several thousand percent. Prediction errors for 6 of the 18 regional regression equations were less than 100 percent and could be considered reasonable for water-quality prediction equations. The regression adjustment procedure was used to adjust five of the regional equation predictions to improve the predictive accuracy. For seven of the regional equations the observed and the predicted values are not significantly correlated. Thus neither the unadjusted regional equations nor any of the adjustments were appropriate. The mean of the observed values was used as a simple estimator when the regional equation predictions and adjusted predictions were not appropriate.

Urban storm runoff has been determined to be a major source of nonpoint-source pollution. Urban engineers and planners need information on runoff quality at specific sites if they are to adequately assess the effects of storm runoff. The final rule implementing the Water Quality Act of 1987 requires municipalities with a population of 100,000 or greater to provide estimates of storm-runoff loads from urban areas to receiving streams (*1*). Because collection and analysis of urban storm-runoff data are expensive and time-consuming, a method for predicting urban storm-runoff quality at unmonitored sites is needed. To meet this need, regional regression equations for storm water quality constituents were developed from the existing data base of the Nationwide Urban Runoff Program (NURP) (*2*). These equations can be used to predict pollutant loadings at unmonitored sites. A procedure was developed using at-site data to adjust the regional regression equations to provide better local estimates of pollutant loadings.

In 1992, the U.S. Geological Survey (USGS), in cooperation with the city of Little Rock, Arkansas, began a study to characterize the storm-runoff quality and to investigate procedures for estimating storm-runoff loads and concentrations for selected constituents (*3*). Rainfall, discharge, and water-quality data were collected during representative storm events between June 1992 and January 1994 at five representative catchment areas in Little Rock. The local data collected were used to verify and adjust the regional regression equations for estimating storm-runoff loads and mean concentrations for selected water-quality constituents.

Water Resources Division, U.S. Geological Survey, 401 Hardin Road, Little Rock, Ark. 72211.

REGIONAL REGRESSION EQUATIONS METHOD

Regression equations to estimate urban storm-runoff quality were developed by USGS using regression analysis on the NURP data base (*4,5*). Separate sets of regression equations were developed for single-storm runoff quality and for mean annual runoff quality. The regression equations relate storm-runoff loads and mean concentrations (response variables) to easily measured physical, land use, and climatic characteristics (explanatory variables). Regional regression equations were developed for 11 constituents: chemical oxygen demand (COD), suspended solids (SS), dissolved solids (DS), total nitrogen as N (TN), total ammonia plus organic nitrogen as N (TKN), total phosphorus as P (TP), dissolved phosphorus as P (DP), total recoverable cadmium (CD), total recoverable copper (CU), total recoverable lead (PB), and total recoverable zinc (ZN). Three regional regression equations were developed for each constituent load and for each constituent mean concentration (*2*). The basis for the regional divisions was mean annual rainfall (Region I, less than 20 in.; Region II, 20 to less than 40 in.; Region III, equal to or greater than 40 in.).

Using the most significant explanatory variables, it was determined for all the storm-runoff load regression equations that logarithmic transformation was the best transformation for the response variable. The same equation used for the storm-runoff loads was used for the storm-runoff mean concentrations. The equations were developed using a stepwise regression analysis of the candidate explanatory variables. The final form of the regional regression equations was determined to be

$$Y = \beta_0' \times X_1^{\beta_1} \times X_2^{\beta_2} \ldots X_n^{\beta_n} \times \text{BCF} \quad (1)$$

where

Y = estimated storm-runoff load or mean concentration (response variable);
β_0' = regression coefficient that is the intercept in the regression equation;

$\beta_1, \beta_2, \ldots, \beta_n$ = regression coefficients;
$X_1, X_2, \ldots, X_n$ = physical, land use, or climatic characteristics (explanatory variables);
n = number of physical, land use, and climatic characteristics in the regression equation; and
BCF = bias correction factor.

The values of the coefficient of multiple determination (R^2) were generally larger for the Region I equations and smaller for the Region III equations and the standard errors of estimate (*SE*) were generally smaller for the Region I equations and larger for the Region III equations. This indicates that as mean annual rainfall increases, the ability to estimate storm-runoff quality decreases. An explanation for the larger R^2 and smaller *SE* values for Region I is that, in urban areas that have small mean annual rainfall, the pollutants accumulate and are less likely to be washed off completely during any storm. In areas that have larger mean annual rainfall, the pollutant accumulation can be washed off more completely by more frequent storms. This results in storms producing considerably smaller storm-runoff loads or mean concentrations than preceding storms with the same amount of rainfall.

ADJUSTMENT PROCEDURES FOR REGIONAL REGRESSION EQUATIONS USING AT-SITE DATA

When the regional regression equations are inaccurate for estimating storm-runoff quality in a particular city, local or at-site data may be used to adjust the regional equations to obtain more accurate results. Before using at-site data to adjust the regional equation predictions, certain attributes of the local data base should be considered. The sampled sites in the local data base should represent a wide range of physical and land use characteristics, and the storms sampled in the local data base should represent a wide range of storm characteristics. It is important that the explanatory variables at any unmonitored site for which an estimate is desired fall within the range represented by the local data base.

Four statistical methods, termed model adjustment procedures (MAPs) (*6*), for combining at-site data with the regional regression predictions were developed by USGS. All four of the MAPs are in the form of regression analysis. The response variable in the regression analyses is the observed storm-runoff load or mean concentration for a single storm. The explanatory variables used in the regression analyses are different for each procedure but include the predicted storm-runoff load or mean concentration values from the regional regression equations.

Single-Factor Regression Against Regional Prediction

Single-factor adjustment, or MAP-1F-P (*6*), is a modification of simple linear regression that can be used with a small calibration data set. In this procedure, the log-transformed observed values of storm-runoff load or mean concentration in the calibration data set (at-site data) are regressed against the corresponding log-transformed predicted values from the unadjusted regional equation using only one calibration coefficient as follows:

$$\log O = \beta_0 + \beta_1 \log P_u \quad (2)$$

where

O = observed values of storm-runoff load or mean concentrations,
P_u = predicted values of storm-runoff load or mean concentration from the unadjusted regional equation,
β_0 = single calibration coefficient, and
β_1 = regression coefficient forced to unity.

Using Equation 2 the value of β_0 can be computed as

$$\beta_0 = \overline{\log O} - \overline{\log P_u} \quad (3)$$

where the overbar denotes mean value.

The detransformation of Equation 2 becomes

$$P_{ai} = \beta_0' \times P_{ui} \times \mathrm{BCF} \quad (4)$$

where

P_{ai} = adjusted predicted value of storm-runoff load or mean concentration at unmonitored site *i*,
β_0' = 10^{β_0},
P_{ui} = unadjusted predicted storm-runoff load or mean concentration value using the regional equation at unmonitored site *i*, and
BCF = bias correction factor.

The BCF is calculated using

$$\mathrm{BCF} = \frac{1}{n} \sum 10^{e_i} \quad (5)$$

where e_i is the least-squares residual for observation *i* from the calibration data set, in log units, and *n* is the number of observations.

Regression Against Regional Prediction

In the second procedure, termed MAP-R-P (*6*), the log-transformed observed values are regressed against the log-transformed predicted values from the unadjusted regional equation in a standard linear regression:

$$\log O = \beta_0 + \beta_1 \times \log P_u \quad (6)$$

where β_0 and β_1 are coefficients determined from a simple linear regression analysis of the calibration data set.

The detransformation of Equation 6 becomes

$$P_{ai} = \beta_0' \times P_{ui}^{\beta_1} \times \mathrm{BCF} \quad (7)$$

Regression Against Regional Prediction and Additional Local Variables

In the third procedure, termed MAP-R-P-nV (*6*), the log-transformed observed values are regressed against the log-transformed predicted values from the unadjusted regional equation along with other independent variables in a multiple linear regression:

$$\log O = \beta_0 + \beta_1 \times \log P_u + \beta_2 \times \log V_1 + \ldots + \beta_{n+1} \times \log V_n \quad (8)$$

where $\beta_0, \beta_1, \ldots, \beta_{n+1}$ are coefficients determined from multiple linear regression analysis of the calibration data set and $V_1, V_2, \ldots, V_n$ are values of additional independent variables from the calibration data set.

The detransformation of Equation 8 becomes

$$P_{ai} = \beta_0' \times P_{ui}^{\beta_1} \times V_1^{\beta_2} \times \ldots \times V_n^{\beta_{n+1}} \times \text{BCF} \tag{9}$$

In this procedure the other independent variables included in the regression should be physical, land use, or climatic variables found to be significant but not included in the regional equation.

Weighted Combination of Regional Prediction and Local-Regression Prediction

In the fourth procedure, termed MAP-W (*6*), the storm-runoff quality prediction at an unmonitored site is calculated from an explicit weighting algorithm that weights the predicted value from the unadjusted regional equation with a predicted value based only on the local monitoring data:

$$P_{ai} = P_{ui}^{j_i} \times P_{loci}^{(1-j_i)} \times \text{BCF} \tag{10}$$

where j_i is a weighting factor between 0 and 1, which has a unique value for each unmonitored site, and P_{loci} is the predicted value at unmonitored site *i* based on at-site data.

The value for P_{loc} is estimated by performing a regression analysis of the local data base or simply using the mean of the observed values. The weighting factor, j_i, is a function of the variances of prediction at the unmonitored site *i* (V_{pi}):

$$j_i = \frac{V_{pi-loc}}{\left(V_{pi-loc} + V_{pi-u}\right)} \tag{11}$$

$$V_{pi-loc} = SE_{loc}^2 \times \left[1 + x_i \times \left(X'X\right)^{-1} \times x_i'\right] \tag{12}$$

$$V_{pi-u} = SE_u^2 \times \left[1 + z_i \times \left(Z'Z\right)^{-1} \times z_i'\right] \tag{13}$$

where

- V_{pi-loc} = variance of prediction at unmonitored site *i* for the local regression equation;
- V_{pi-u} = variance of prediction at unmonitored site *i* for the unadjusted regional equation;
- SE_{loc} = standard error of estimate (in log units) for the local regression equation;
- SE_u = standard error of estimate (in log units) for the regional (NURP) calibration data set for the unadjusted regional equation (*2*);
- x_i = $(1 \times p)$ row vector of the $p - 1$ explanatory variables used in the local regression, evaluated (in log units) for unmonitored site *i*, augmented by a 1 as the first element;
- X = $(n \times p)$ matrix of the $p - 1$ explanatory variables used in the local regression evaluated (in log units) for all *n* sites in the local calibration data set, augmented by a 1 as the first column;
- z_i = $(1 \times k)$ row vector of the $k - 1$ explanatory variables used in the regional regression, evaluated (in log units) for unmonitored site *i* augmented by a 1 as the first element; and
- Z = $(m \times k)$ matrix of the $k - 1$ explanatory variables used in the regional regression, evaluated (in log units) for all *m* sites in the regional (NURP) calibration data set, augmented by a 1 as the first column.

SE_{loc} is computed using the general formula for SE:

$$SE = \sqrt{\frac{\sum\left(\log O_i - \log P_i\right)^2}{n - (k + 1)}} \tag{14}$$

where

- SE = standard error of estimate of a regression equation for the calibration data set (in log units),
- O_i = *i*th observed value for the response variable in the calibration data set,
- P_i = *i*th predicted value for the response variable in the calibration data set,
- n = number of observations in the calibration data set, and
- k = number of explanatory variables in the regression equation.

Selection of Appropriate Regional Regression Equation Adjustment Procedure

The selection of the MAP is based on analysis of the local data base. The first steps in the data analysis are to perform the test for significance of the rank correlation coefficient, Spearman's rho (r_s), and to perform the signed rank test. If the test statistic from each of these tests is significant at the selected level, then MAP-1F-P or MAP-R-P is most appropriate. MAP-1F-P should be used if the calibration data set is small ($n < 20$).

If either of the test statistics is not significant at the selected level, then test for correlation between the response variable and other explanatory variables. If any of the correlations are significant, then MAP-R-P+nV or MAP-W may be used. If the MAPs and the unadjusted regional regression equations are inappropriate, then a simple estimator such as the mean or median value of the observed storm-runoff loads or mean concentrations may be used, or additional data may be collected to develop independent local regression equations.

VERIFICATION AND ADJUSTMENT OF REGIONAL REGRESSION EQUATIONS USING DATA COLLECTED IN LITTLE ROCK, ARKANSAS

The Little Rock data base is composed of storm-runoff data collected at five sites during 22 storms from June 1992 through January 1994 (*3*). Storm-runoff loads were calculated for COD, SS, TN, TKN, TP, DP, CU, PB, and ZN by multiplying sampled storm-runoff mean concentrations by the storm-runoff volumes and by a conversion factor. Predicted values of storm-runoff load and mean concentration for each of the monitored storms were computed from the regional regression equations for Region III (*2*). Comparison of observed storm-runoff load and mean concentration values in the Little Rock data base to predicted values from the regional regression equations showed large prediction errors for almost all constituents. Values for root mean square error (RMSE) range from

0.251 log units (63 percent) for TN load to over several thousand percent for CU load (Table 1). The RMSEs for the COD, TN, and TP load equations and the COD, TN, and TKN concentration equations are smaller than 0.36 log units (100 percent), which can be considered reasonable for water-quality prediction equations.

Differences between the observed values and the predicted values from the unadjusted regional equations are caused by variability in the Little Rock data base or by error in the regional equations, or both. For most of the constituents, the RMSE is too large to be reasonably explained by variability alone. Some of the prediction error is attributed to error in the regional equations due in part to differences in physiographic settings. In the NURP Region III data base, 8 of the 11 cities are in or very close to a coastal setting (*2*). Furthermore, most of the cities in the NURP Region III data base are larger and have been established longer than Little Rock. The regional regression equations also were developed from data collected approximately 20 years ago.

With such large errors, it is inappropriate to use several of the regional regression equations to estimate storm-runoff loads and mean concentrations in Little Rock. Therefore, where applicable, the regional regression equations should be adjusted using at-site data. Due to the size of the data set, the most appropriate adjustment procedure to be used was MAP-R-P. To apply MAP-R-P, there should be positive correlation and consistent direction of bias between observed and unadjusted predicted values. Values for these test statistics are presented in Table 1. For all of the load models, except TKN and DP, much of the variation in the observed values was explained by the regional equations. Of these models, the direction of bias of the unadjusted predicted values relative to the observed values was not consistent for COD, SS, TP, and ZN, thereby validating the unadjusted regional equations. For TN, CU, and PB, the direction of bias of the unadjusted predicted values relative to the observed values was consistent and positive; that is, the regional equations consistently overestimated the observed values, and MAP-R-P could be used to improve the estimates. Because the regional equations did not explain much of the variation in the observed values for TKN and DP, neither the MAP-R-P nor the regional equations were appropriate.

For the concentration models TP, DP, CU, and ZN, much of the variation in the observed values was explained by the regional

TABLE 1 Analysis of the Little Rock Data Base

Constituent name. model type	RMSE	O and Pu positively correlated		Consistent direction of bias		Direction of bias	Appropriate model
		r_s	Significant at 0.05?	p-value	Significant at 0.05?		
COD.LOAD	0.280	0.681	yes	1.168	no	NA	regional
SS.LOAD	.513	.534	yes	.286	no	NA	regional
TN.LOAD	.251	.745	yes	.026	yes	P	MAP-R-P
TKN.LOAD	.434	-.443	no	.664	no	NA	none
TP.LOAD	.310	.513	yes	.664	no	NA	regional
DP.LOAD	.585	-.270	no	.026	yes	P	none
CU.LOAD	3.277	.677	yes	.000	yes	P	MAP-R-P
PB.LOAD	1.158	.803	yes	.000	yes	P	MAP-R-P
ZN.LOAD	.424	.863	yes	.052	no	NA	regional
COD.CONC	.342	-.056	no	1.176	no	NA	none
SS.CONC	.590	-.277	no	.524	no	NA	none
TN.CONC	.323	.133	no	.189	no	NA	none
TKN.CONC	.336	.167	no	.383	no	NA	none
TP.CONC	.376	.522	yes	.078	no	NA	regional
DP.CONC	.409	.403	yes	.814	no	NA	regional
CU.CONC	.720	.540	yes	.000	yes	P	MAP-R-P
PB.CONC	1.210	.261	no	.000	yes	P	none
ZN.CONC	.432	.781	yes	.000	yes	P	MAP-R-P

[RMSE, root mean square error between observed values and predicted (from unadjusted regional equation) values, in log units; O, observed value; P_u, predicted value from unadjusted regional equation; r_s, Spearmans rho; 0.05, selected level of significance for the test statistic; COD, chemical oxygen demand; LOAD, storm-runoff load; SS, suspended solids; TN, total nitrogen as N; DP, dissolved phosphorus as P; TKN, total ammonia plus organic nitrogen as N; TP, total phosphorus as P; CU, total recoverable copper; PB, total recoverable lead; ZN, total recoverable zinc; CONC, storm-runoff mean concentration; NA, not applicable; P, positive (regional equation overestimates O)] equations. Of these models, the direction of bias of the unadjusted predicted values relative to the observed values was not consistent for TP and DP, thereby validating the unadjusted regional equations. For CU and ZN, the direction of bias of the unadjusted predicted values relative to the observed values was consistent and positive; therefore, MAP-R-P could be used to improve the estimates. For the remaining five constituents, COD, SS, TN, TKN, and PB, the regional equations did not explain much of the variation in the observed values, thus neither the MAP-R-P nor the regional equations were appropriate.

Coefficients were derived for the MAP-R-P (Table 2) using the Little Rock data base. *SE* for the MAP-R-P's ranged from 0.197 log units (48 percent) for the TN load model to 0.432 log units (130 percent) for the PB load model. The relatively large values of *SE* for some of the adjusted predictions may be unacceptable for some applications. The user may need to collect additional at-site data for these constituents and repeat the adjustment procedures or develop independent local regression equations.

EXAMPLE APPLICATION

In an example application, an engineer in Little Rock, Arkansas, needs to estimate a storm-runoff load for TN for an unmonitored site where the drainage area is 1.30 km^2 (0.50 mi^2); the impervious area is 40 percent, and the total storm rainfall for storm *i* is 2.79 cm (1.10 in.). The mean annual nitrogen load in precipitation in the Little Rock area is 15.9 kg of nitrogen per hectare (14.2 lb of nitrogen per acre). Using the regional regression equation for Region III (*2*), the engineer calculates the predicted storm-runoff load for TN as follows:

$$P_{ui}(\text{TN}) = 0.0459 \times 2.79^{0.776} \times 1.30^{0.474} \times 41^{0.611} \times 15.9^{0.863} \times 1.709$$

$$P_{ui}(\text{TN}) = 20.7 \text{ kg } (45.6 \text{ lb})$$

Before adjusting the estimate using MAP-R-P, the engineer should first consider whether the characteristics of unmonitored site and storm *i* are within the range of site and storm characteristics in the Little Rock data base (*3*). In this example, values for unmonitored site and storm *i* are within the range of the data base.

Using the MAP-R-P for the TN load model (Table 2), the engineer calculates the adjusted predicted value as follows:

$$P_{ai}(\text{TN}) = 0.737 \times 20.7^{0.958} \times 1.093$$

$$P_{ai}(\text{TN}) = 14.7 \text{ kg } (32.4 \text{ lb})$$

SUMMARY

Urban storm runoff has been determined to be a major source of nonpoint-source pollution. Urban engineers and planners need information on runoff quality at specific sites if they are to adequately plan for the effects of storm runoff. Regional regression equations were developed to estimate urban storm-runoff loads and mean concentrations for selected water-quality constituents. When the regional regression equations prove to be inaccurate for estimating storm-runoff quality in a particular city, at-site data may be used to adjust predictions from the regional equations to obtain more accurate results.

Four statistical methods were developed to adjust the regional regression equation predictions using at-site data. The four adjustment procedures are MAP-1F-P, a single-factor adjustment; MAP-R-P, a regression of the observed values against the predicted values; MAP-R-P+nV, a regression of the observed values against the predicted values and additional local independent variables; and MAP-W, a weighted combination of a local regression with the regional prediction. If the adjustment procedures and the unadjusted regional equations are inappropriate, then either a simple estimator such as the mean value of the

TABLE 2 Regression Coefficients and Error Statistics for Adjusted Models for the Little Rock Data Base

Constituent name, model type	Regression coefficients			Regression error statistics		
	β_0'	β_1	BCF	R^2	*SE*, log	*SE*, percent
TN.LOAD	$10^{-0.118}$	0.958	1.093	0.588	0.197	48
CU.LOAD	$10^{-2.726}$	.700	1.464	.469	.415	122
PB.LOAD	$10^{-1.044}$	1.268	1.627	.641	.432	130
CU.CONC	$10^{0.211}$	.408	1.124	.346	.215	53
ZN.CONC	$10^{-0.403}$	1.016	1.131	.577	.238	59

P_{ai}, adjusted predicted value of storm-runoff load or mean concentration for unmonitored site and storm *i*; β_0', regression coefficient that is the intercept in the regression equation; P_{ui}, predicted value of response variable from the unadjusted regional equation for unmonitored site and storm i; *BCF*, bias correction factor; R^2, coefficient of determination, calculated using log-transformed observed and predicted values; *SE*, standard error of estimate; TN, total nitrogen as N; LOAD, storm-runoff load, in pounds; CONC, storm-runoff mean concentration, in milligrams per liter; CU, total recoverable copper; PB, total recoverable lead; ZN, total recoverable zinc; equation form is:

$$P_{ai} = \beta_0' \times P_{ui}^{\beta_1} \times BCF$$

observed storm-runoff loads or mean concentrations may be used, or additional data may be collected to calibrate independent local regression equations.

Data collected at five representative sites during 22 storms in Little Rock, Arkansas, were used to verify, and, when appropriate, adjust the regional regression equations. Comparison of observed values of storm-runoff load and mean concentrations with the predicted values from the regional regression equations indicated large prediction errors for almost all constituent models ranging from 63 percent to more than several thousand percent. The root mean square errors for COD, TN, and TP load equations and COD, TN, and TKN concentration equations were less than 100 percent and can be considered reasonable for water-quality prediction equations.

The adjustment procedure MAP-R-P was used to adjust the TN, CU, and PB load equations and CU and ZN concentration equations. The unadjusted regional predictions were found to be appropriate for the COD, SS, TP, and ZN load equations and for the TP and DP concentration equations. For the TKN and DP load predictions and the COD, SS, TN, TKN, and PB concentration predictions, neither the regional equations nor the adjustment procedures were appropriate.

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