Adjustment of Regional Regression Models of Urban-Runoff Quality Using Data for Chattanooga, Knoxville, and Nashville, Tennessee
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By ANNE B. HOOS and ANANT R. PATEL

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95–4140

Prepared in cooperation with the City of Chattanooga, Tennessee, the City of Knoxville, Tennessee, and the Metropolitan Government of Nashville and Davidson County

Nashville, Tennessee
1996
### CONVERSION FACTORS

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>inch (in.)</td>
<td>25.4</td>
<td>millimeter</td>
</tr>
<tr>
<td>foot (ft)</td>
<td>0.3048</td>
<td>meter</td>
</tr>
<tr>
<td>square mile (mi²)</td>
<td>259.0</td>
<td>hectare</td>
</tr>
<tr>
<td>square mile (mi²)</td>
<td>2.590</td>
<td>square kilometer</td>
</tr>
<tr>
<td>cubic foot (ft³)</td>
<td>0.02832</td>
<td>cubic meter</td>
</tr>
<tr>
<td>cubic foot (ft³)</td>
<td>28.317</td>
<td>liter</td>
</tr>
<tr>
<td>cubic foot (ft³)</td>
<td>28,317</td>
<td>cubic centimeter</td>
</tr>
<tr>
<td>pound (lb)</td>
<td>0.4536</td>
<td>kilogram</td>
</tr>
</tbody>
</table>

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

\[ °F = 1.8 \times (°C + 32) \]

### ABBREVIATIONS

- **ADD**: Number of antecedent dry days
- **BCF**: Bias correction factor
- **CD**: Total-recoverable cadmium
- **COD**: Chemical oxygen demand
- **Cp**: Mallow's coefficient
- **CU**: Total-recoverable copper
- **DA**: Total contributing drainage area
- **DP**: Dissolved phosphorus
- **DS**: Dissolved solids
- **IA**: Impervious area, as a percent of total contributing drainage area
- **INT**: Maximum 24-hour precipitation intensity that has a 2-year recurrence interval
- **LUC**: Commercial land use, as a percent of total contributing drainage area
- **LUI**: Industrial land use, as a percent of total contributing drainage area
- **LUN**: Nonurban land use, as a percent of total contributing drainage area
- **LUR**: Residential land use, as a percent of total contributing drainage area
- **MAP**: Model-adjustment procedures
- **MAP-1F-P**: Single-factor regression against regional prediction
- **MAP-R-P**: Model-adjustment procedures based on regression against prediction value alone
- **MAP-R-P+nV**: Regression against regional prediction and additional local variables
- **MAP-W**: Weighted combination of regional prediction and local-regression prediction
- **MAR**: Mean annual rainfall
- **MJT**: Mean minimum January temperature
- **MNL**: Mean annual nitrogen load in precipitation
- **NURP**: Nationwide Urban Runoff Program
- **O**: Observed values of storm-runoff load or mean concentrations
- **P_{ai}**: Adjusted-model predicted value of response variable for unmonitored site and storm i
- **P_{a}**: Predicted values of storm-runoff load or mean concentration from the unadjusted regional model
- **P_{ai}**: Predicted value of response variable from the unadjusted regional model for unmonitored site and storm i
- **PB**: Total-recoverable lead
- **r**: Correlation coefficient
- **r_s**: Spearman's rho
- **RMSE**: Root mean square error
- **SE**: Standard error of estimate
- **SEP**: Standard error of prediction
- **SS**: Suspended solids
- **TKN**: Total ammonia plus nitrogen as nitrogen
- **TN**: Total nitrogen
- **TP**: Total phosphorus
- **TRN**: Total storm rainfall
- **ZN**: Total-recoverable zinc
Adjustment of Regional Regression Models of Urban-Runoff Quality Using Data for Chattanooga, Knoxville, and Nashville, Tennessee

By Anne B. Hoos and Anant R. Patel

ABSTRACT

Model-adjustment procedures (MAP's) were applied to the combined data bases of storm-runoff quality for Chattanooga, Knoxville, and Nashville, Tennessee, to improve predictive accuracy of storm-runoff quality from urban watersheds in these three cities and throughout Middle and East Tennessee. Data for 45 storms at 15 different sites (5 sites in each city) constitute the data base.

Comparison of observed values \( O \) of storm-runoff load and event-mean concentration to the predicted values from the regional regression models \( P_u \) for 10 constituents shows prediction errors ranging from 59 to 806,063 percent. MAP's, which combine the regional model predictions with local data, are applied to improve predictive accuracy.

For 8 of the 10 load models, the variation in \( P_u \) explains much of the variation in \( O \) and the direction of bias of \( P_u \) relative to \( O \) is consistent and positive; that is, \( P_u \) consistently overestimates \( O \). The MAP based on regression against \( P_u \) alone, MAP-R-P, is therefore favored for most of the load models.

For 7 of the 10 concentration models, however, the variation in \( P_u \) does not sufficiently explain the variation in \( O \), and furthermore, correlation between \( O \) and each of the additional explanatory variables is not significant. None of the MAP's is, therefore, appropriate for the concentration models for these constituents. For three of the seven constituents, the prediction error is small enough that the analyst may use the regression model without adjustment. For the other four, a simple estimator such as the mean of the observed concentration values may be used, or additional data could be collected to calibrate a local model.

Standard error of estimate for the selected MAP's ranges from 0.263 log units (67 percent) to 0.677 log units (322 percent). Calibration results may be biased due to sampling error in the Tennessee data base. The relatively large values of standard error of estimate for some of the constituent models, although representing significant reduction (by at least 50 percent) in prediction error compared to estimation with \( P_u \), may be unacceptable for some applications. The user may wish to collect additional local data for these constituents and repeat the MAP analysis, or calibrate an independent local regression model.

INTRODUCTION

Urbanized areas are a major source of nonpoint-source pollution. The design of effective remedial programs requires information on pollutant loads from individual watersheds. The 1987 amendments to the Clean Water Act require cities with populations of more than 100,000:

* to characterize storm-runoff quality and quantity from representative storm-sewer outfalls during several storms; and

* to estimate annual and seasonal pollutant loading from each major storm-sewer outfall in the city.
In 1989, the U.S. Geological Survey, in cooperation with the city governments of Chattanooga, Knoxville, and Nashville, Tennessee, began a study to characterize the water quality of storm runoff and to evaluate procedures for estimating storm-runoff loads and concentrations for selected constituents. To meet the first objective, rainfall, streamflow, and water-quality data were collected during the period January 1990 through May 1993 at five sites in each of the three cities (Outlaw and others, 1994; and U.S. Geological Survey unpublished data). To meet the second objective, procedures were developed (Hoos and Sisolkak, 1993) to optimize predictive accuracy for storm-runoff quality by combining local data with regional regression models developed by Driver and Tasker (1990).

Purpose and Scope

This report presents the results of applying model-adjustment procedures (MAP's) to the combined data bases of storm-runoff quality from Chattanooga, Knoxville, and Nashville, Tennessee. Calibration coefficients are presented for 13 models: 10 load models and 3 concentration models. Simple estimators are presented for five constituent models for which the MAP approach could not be used. Also included are calibration error statistics, which can be used to compute the standard error of the adjusted prediction. An example illustrates the use of an adjusted model to estimate the load of total kjeldahl nitrogen in storm runoff from an unmonitored watershed.

Description of Study Area

Chattanooga and Knoxville lie within the Valley and Ridge physiographic province of Tennessee; Nashville lies partly within the Central Basin and partly within the Highland Rim physiographic provinces (fig. 1). The three cities share similarities in geology and climate. All three cities are underlain by limestone or alternating bands of limestone and shale, with predominantly gently to moderately sloping topography. Most soils are moderate- to fine-textured and are generally less than 20 feet thick. The smaller streams have well-defined channels cut into bedrock, except where they flow through the alluvial plain of large receiving water bodies. Modifications to small

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EXPLANATION

1 STUDY AREA LOCATION - Number refers to metropolitan area listed below:
   1 Chattanooga, Tennessee
   2 Knoxville, Tennessee
   3 Nashville, Tennessee

PHysiographic Divisions

A COASTAL PLAIN   E CUMBERLAND PLATEAU
B WESTERN VALLEY   F SEQUATCHIE VALLEY
C HIGHLAND RIM     G VALLEY AND RIDGE
D CENTRAL BASIN    H BLUE RIDGE

Figure 1. Locations of urban-runoff study areas and physiographic divisions in Tennessee.
stream channels to improve drainage are generally minimal.

Mean annual precipitation does not vary appreciably among the three cities, ranging from 47 to 53 inches (National Oceanic and Atmospheric Administration, 1980). Winter storms are of longer duration and greater total precipitation, but are less intense than summer storms. The coldest weather usually occurs during January; the mean minimum January temperature for the three cities ranges from 26 to 29°F (National Oceanic and Atmospheric Administration, 1980).

Acknowledgments

The authors gratefully acknowledge Tom Scott, City of Chattanooga, Ted Schuler, City of Knoxville, and Tom Palko and Gill Prichard, Metropolitan Government of Nashville, for providing data on basin characteristics, and for their support throughout this project. Tom Lopes, U.S. Geological Survey, made many revisions and improvements to the statistical-analysis software.

URBAN-RUNOFF DATA BASE FOR CHATTANOOGA, KNOXVILLE, AND NASHVILLE, TENNESSEE

The urban-runoff quality data base used for this report combines data from monitoring networks in Chattanooga, Knoxville, and Nashville, and is referred to as the Tennessee data base. Data for 45 storms at 15 different sites (5 sites in each city) make up the data base. Values of storm-runoff mean concentration for each storm were obtained from Outlaw and others (1994; and U.S. Geological Survey unpublished data) for chemical oxygen demand (COD), suspended solids (SS), dissolved solids (DS), total nitrogen (TN), total ammonia plus organic nitrogen as nitrogen (TKN), total phosphorus (TP), dissolved phosphorus (DP), total-recoverable cadmium (CD), total-recoverable copper (CU), total-recoverable lead (PB), and total-recoverable zinc (ZN). Values of storm-runoff load were calculated as the product of storm-runoff mean concentration and storm-runoff volume, and also were provided by Outlaw and others (1994, table 2).

For some of the storms represented in the data base, samples were collected only during the first 3 hours of the hydrograph; values for storm rainfall and storm-runoff volume were corrected to account for this. Storm rainfall (TRN) was calculated by summing rainfall amounts before and during sampling only; any rainfall after sampling was not included. Storm-runoff volume was calculated by summing volume during sampling. Finally, storms were not included in the analysis of storm-runoff loads if (1) a significant part of the runoff volume occurred after sampling stopped and (2) the after-sampling runoff could not be clearly defined as a separate runoff event, caused by rainfall after sampling. Basin characteristics in the data base include the following physical and land-use characteristics:

1. Total contributing drainage area (DA), in square miles.
2. Impervious area (IA), as a percent of total contributing drainage area.
3. Industrial land use (LUI), as a percent of total contributing drainage area.
4. Commercial land use (LUC), as a percent of total contributing drainage area.
5. Residential land use (LUR), as a percent of total contributing drainage area.
6. Nonurban land use (LUN), as a percent of total contributing drainage area.

Storm characteristics in the data base include:

1. Total storm rainfall (TRN), in inches.
2. Number of antecedent dry days (ADD), in days.

Climatic characteristics in the data base include:

1. Maximum 24-hour precipitation intensity that has a 2-year recurrence interval (INT), in inches.
2. Mean annual rainfall (MAR), in inches.
3. Mean annual nitrogen load in precipitation (MNL), in pounds of nitrogen per acre.
4. Mean minimum January temperature (MJT), in degrees Fahrenheit.

Values for basin characteristics were provided by the staffs of the Public Works Department of the three cities. Values for TRN were obtained from Outlaw and others (1994; and U.S. Geological Survey unpublished data). Values for ADD were determined from the daily rainfall record for each monitoring basin; days for which rainfall amounts were smaller than 0.05 inch were considered dry days. Values for MAR and MJT were obtained from the National Oceanic and Atmospheric Administration (1980), for INT from Hershfield (1961), and for MNL from the National Atmospheric Deposition Program/National Trends Network Coordination Office (1990).

Predicted values of storm-runoff load and event-mean concentration for each of the monitored storms...
were computed from the basin, storm, and climatic characteristics and from the single-storm regression models for region III (Driver and Tasker, 1990, tables 1 and 5). Predicted values for the constituent DS, for which Driver and Tasker did not develop a region III model, were computed from region II models.

MAP's can be expected to provide more accurate estimates (as compared to the regional models) of urban-runoff quality at a wide range of unmonitored sites only if the local data base used for the adjustment represents a wide range of physical, land-use, and storm characteristics. The minimum, maximum, and median values of these characteristics in the Tennessee data base are presented in table 1. For TRN, the range and median are determined from all 45 observations in the data base; these values may be slightly different for data sets from which certain storms were excluded.

Table 1. Ranges of values of each explanatory variable in the data base for Chattanooga, Knoxville, and Nashville, Tennessee

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRN, inches</td>
<td>0.08</td>
<td>1.28</td>
<td>0.36</td>
</tr>
<tr>
<td>DA, square miles</td>
<td>0.01</td>
<td>7.31</td>
<td>52</td>
</tr>
<tr>
<td>IA, percent</td>
<td>9.6</td>
<td>94</td>
<td>53</td>
</tr>
<tr>
<td>LUI, percent</td>
<td>0</td>
<td>96</td>
<td>16</td>
</tr>
<tr>
<td>LUC, percent</td>
<td>0</td>
<td>91</td>
<td>6</td>
</tr>
<tr>
<td>LUR, percent</td>
<td>0</td>
<td>100</td>
<td>16</td>
</tr>
<tr>
<td>LUN, percent</td>
<td>0</td>
<td>57</td>
<td>10</td>
</tr>
<tr>
<td>INT, inches</td>
<td>3.2</td>
<td>3.8</td>
<td>3.5</td>
</tr>
<tr>
<td>MAR, inches</td>
<td>47.1</td>
<td>53.0</td>
<td>47.3</td>
</tr>
<tr>
<td>MNL, pounds of nitrogen per acre</td>
<td>14</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>MJT, degrees Fahrenheit</td>
<td>26</td>
<td>29</td>
<td>27</td>
</tr>
<tr>
<td>ADD</td>
<td>0</td>
<td>32</td>
<td>4</td>
</tr>
</tbody>
</table>

For the characteristics IA, LUC, LUN, MAR, and MJT, the range and median values in the Tennessee data base were similar to those in the Nationwide Urban Runoff Program (NURP) region III data base (compare to Driver and Tasker, 1990, table 4). Maximum and median values for TRN and LUR, however, were smaller in the Tennessee data base than in the NURP region III data base. Maximum and median values for DA, LUI, INT, and MNL were larger in the Tennessee data base than in the NURP region III data base.

ADJUSTMENT OF REGIONAL REGRESSION MODELS

Comparison of observed values (O) of storm-runoff load and event-mean concentration in the Tennessee data base to the predicted values from the regional regression models (P_a) shows large prediction errors for almost all constituent models. Comparison could not be made for CD, for which most observed values were below the minimum reporting level. Values of root mean square error (RMSE) range from 0.239 log units (59 percent) for TN event-mean concentration, to 1.842 log units (806,063 percent) for PB load (table 2, column 1). For each constituent model, RMSE is compared to calibration error for the unadjusted regional model (standard error of the estimate reported by Driver and Tasker, 1980, tables 2 and 6) to evaluate whether the regional regression can be used for sites represented by the Tennessee data base. For only three models, COD, DS, and TN event-mean concentration, RMSE is smaller than, or almost equal to, the corresponding standard error of the estimate, indicating that these three models may be used without adjustment.

Large values of RMSE are due to error in the regional models or to sampling error in the Tennessee data base. Sampling error occurs when the sites and storms in the data base do not represent typical storm-runoff conditions in the three cities. Average storm size in the data base (median TRN is 0.36 inch) is smaller than the average storm size in the three cities (between 0.60 and 0.80 inch, according to Steurer and Nold, 1986). In addition, many monitoring sites in the data base are in watersheds that may be too large (median DA is 0.52 mi^2) for these sites to be considered as storm-runoff discharge points, because discharge during storms at these sites may contain a substantial volume of base flow along with storm runoff.

For most constituents, however, RMSE is too large to be reasonably explained by sampling error alone; some of the error must be due to error in the regional models. Model error is probably not caused by temporal trend in runoff quality in the elapsed time between data collection for NURP (1979-83) and data collection for the Tennessee data base (1990-93), because the RMSE's for the Knoxville NURP data base
Table 2. Exploratory data analysis of the Tennessee data base

[RMSE, root mean square error between observed and predicted (from unadjusted regional model) values of the response variable, in log units; Acceptably small? is evaluated by comparing RMSE with standard error of the estimate for the unadjusted regional model (published in Driver and Tasker, 1990, tables 2 and 6); $r_p$, Spearman's rho; 0.005 is the selected level of significance for the test statistic; O, observed value of the response variable; $P_O$ predicted value from the unadjusted regional model; TRN, total storm rainfall; DA, total contributing drainage area; IA, impervious area; LUI, industrial land use; ADD, antecedent dry days; COD, chemical oxygen demand; SS, suspended solids; DS, dissolved solids; TN, total nitrogen; TKN, total ammonia plus organic nitrogen as nitrogen; TP, total phosphorus; DP, dissolved phosphorus; CU, total-recoverable copper; PB, total-recoverable lead; ZN, total-recoverable zinc; LOAD, storm-runoff load; CONC, storm-runoff mean concentration; P, positive (model overestimates O); model-adjustment procedures (MAP's) explained in Hoos and Sisolak (1993)]

<table>
<thead>
<tr>
<th>Constituent and model type</th>
<th>RMSE, log</th>
<th>RMSE, percent</th>
<th>Acceptably small?</th>
<th>$r_s$</th>
<th>Significant at 0.005?</th>
<th>Correlation of bias</th>
<th>$O$ positively correlated</th>
<th>Consistent direction of bias</th>
<th>Correlation of variable with $O$</th>
<th>$O$ significantly correlated with any variable?</th>
<th>Best MAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD.LOAD</td>
<td>0.639</td>
<td>277</td>
<td>N</td>
<td>0.766</td>
<td>0.0001</td>
<td>Y</td>
<td>P</td>
<td>0.408</td>
<td>0.727</td>
<td>-0.310</td>
<td>0.542</td>
</tr>
<tr>
<td>SS.LOAD</td>
<td>1.106</td>
<td>2,558</td>
<td>N</td>
<td>0.878</td>
<td>Y</td>
<td>0</td>
<td>Y</td>
<td>0.607</td>
<td>0.669</td>
<td>-0.460</td>
<td>0.414</td>
</tr>
<tr>
<td>DS.LOAD</td>
<td>0.655</td>
<td>295</td>
<td>N</td>
<td>0.860</td>
<td>0.001</td>
<td>Y</td>
<td>P</td>
<td>0.509</td>
<td>0.822</td>
<td>-0.500</td>
<td>0.461</td>
</tr>
<tr>
<td>TN.LOAD</td>
<td>0.930</td>
<td>985</td>
<td>N</td>
<td>0.735</td>
<td>Y</td>
<td>0</td>
<td>Y</td>
<td>0.463</td>
<td>0.810</td>
<td>-0.410</td>
<td>0.508</td>
</tr>
<tr>
<td>TKN.LOAD</td>
<td>0.575</td>
<td>218</td>
<td>N</td>
<td>0.715</td>
<td>Y</td>
<td>.185 (&lt;0.005)</td>
<td>N</td>
<td>0.444</td>
<td>0.799</td>
<td>-0.420</td>
<td>0.494</td>
</tr>
<tr>
<td>TP.LOAD</td>
<td>0.798</td>
<td>531</td>
<td>N</td>
<td>0.747</td>
<td>Y</td>
<td>0.001</td>
<td>Y</td>
<td>0.458</td>
<td>0.773</td>
<td>-0.480</td>
<td>0.485</td>
</tr>
<tr>
<td>DP.LOAD</td>
<td>0.741</td>
<td>417</td>
<td>N</td>
<td>0.587</td>
<td>Y</td>
<td>1</td>
<td>N</td>
<td>0.440</td>
<td>0.767</td>
<td>-0.510</td>
<td>0.420</td>
</tr>
<tr>
<td>CU.LOAD</td>
<td>1.635</td>
<td>119,597</td>
<td>N</td>
<td>0.889</td>
<td>Y</td>
<td>0</td>
<td>Y</td>
<td>0.309</td>
<td>0.755</td>
<td>-0.250</td>
<td>0.648</td>
</tr>
<tr>
<td>PB.LOAD</td>
<td>1.842</td>
<td>806,063</td>
<td>N</td>
<td>0.695</td>
<td>Y</td>
<td>0</td>
<td>Y</td>
<td>0.398</td>
<td>0.725</td>
<td>-0.180</td>
<td>0.639</td>
</tr>
<tr>
<td>ZN.LOAD</td>
<td>0.880</td>
<td>772</td>
<td>N</td>
<td>0.897</td>
<td>Y</td>
<td>0</td>
<td>Y</td>
<td>0.346</td>
<td>0.609</td>
<td>-0.120</td>
<td>0.650</td>
</tr>
</tbody>
</table>

COD.CONC 0.324 86 Y 0.010 N 0.233 N -.444 0.610 .071 -.110 0.142 N Use as is
SS.CONC 0.754 440 N 0.158 N 0.001 Y P 0.295 0.257 -.330 -0.052 -0.094 N None
DS.CONC 0.287 74 Y 0.327 N 0.003 Y P -0.171 0.469 -.400 0.158 0.205 N Use as is
TN.CONC 0.239 59 Y 0.257 N 0.291 N -0.232 0.144 0.034 -0.062 0.192 N Use as is
TKN.CONC 0.435 131 N 0.359 N 0 Y P -0.277 0.008 0.008 0.061 0.127 N None
TP.CONC 0.518 177 N -0.055 N 0.233 N 0.078 0.462 0.500 0.068 0.123 Y R-P+nV
DP.CONC 0.504 169 N -0.253 N 0.451 N -0.108 0.244 0.257 -0.093 0.179 N None
CU.CONC 1.107 2,573 N 0.395 Y 0 Y P 0.365 0.321 0.349 0.406 0.237 N R-P
PB.CONC 1.432 22,956 N 0.034 N 0 Y P -1.166 0.137 0.158 0.368 0.008 N None
ZN.CONC 0.424 126 N 0.744 Y 0 Y P -0.399 -0.200 0.070 0.405 0.080 N R-P

*None of the MAP's considered can be expected to provide more accurate estimates than the unadjusted regional model. Alternatives are to collect additional data to calibrate a local model, or use a simple estimator such as mean or median value.
(Hoos and Sisolak, 1993, table 4) and for the Tennessee data base (table 2) are comparable. The load and event-mean concentration models for PB are an exception: RMSE for the Tennessee data base far exceeds RMSE for the Knoxville NURP data base, indicating a change in PB loading characteristics in storm runoff over time. Because values of load and event-mean concentration of PB in the Tennessee data base are smaller than values in the Knoxville NURP data base, the change over time is a downward trend, possibly caused by reduction of lead emissions in automobile exhaust.

The model error for some constituents may be caused by differences in physiographic setting: 8 of the 11 cities in the NURP region III data base are in, or are very close to, a coastal setting. Topography and geology are important controls on storm-runoff quality, even in urban areas. Furthermore, most cities in the NURP region III data base are larger and older than the three Tennessee cities.

It is, therefore, inappropriate to use the regional regression models to estimate storm-runoff quality in Tennessee for most constituents. An estimating technique based only on the Tennessee data base, however, regression models to estimate storm-runoff quality in the NURP region III data base are larger and older than the three Tennessee cities.

It is, therefore, inappropriate to use the regional regression models to estimate storm-runoff quality in Tennessee for most constituents. An estimating technique based only on the Tennessee data base, however, would be simple and empirical, because the maximum data set size is 45. An additional available option is the use of model-adjustment procedures (MAP's) to combine the regional model predictions with local data, thereby effectively increasing the size of the local data base. The reader is referred to Hoos and Sisolak (1993) for detailed description and evaluation of four possible MAP's. Hoos and Sisolak developed a scheme, based on exploratory data analysis of the local data base, for selecting the appropriate MAP for each constituent model (fig. 2).

The selection scheme was modified slightly for this analysis. The MAP that weights \( P_u \) with a prediction from a local regression model, MAP-W, was excluded from consideration because the weighting coefficient could not be calculated reliably. The reason for this is that the matrix of explanatory variables from the NURP region III calibration data set is unavailable.

### Exploratory Data Analysis

The MAP selection scheme based on exploratory data analysis (fig. 2) was applied to the Tennessee data base to select the most appropriate MAP for each constituent model. Values for test statistics are presented in table 2. For most of the load models, the variation in \( P_u \) explains much of the variation in \( O \), and the direction of bias of \( P_u \) relative to \( O \) is consistent and positive; that is, \( P_u \) consistently overestimates \( O \). The MAP based on regression against \( P_u \) alone, MAP-R-P, is therefore favored for most of the load models. The MAP based on regression against \( P_u \) and additional local variables, MAP-R-P+nV, is favored for the TKN and DP load models.

For the event-mean concentration models, MAP-R-P is favored for CU and ZN, and MAP-R-P+nV is favored for TP. For the remaining seven constituents, the variation in \( P_u \) does not sufficiently explain the variation in \( O \) and, furthermore, correlation between \( O \) and each of the additional explanatory variables is not significant. None of the MAP's is, therefore, appropriate for the concentration models for these seven constituents. For three of the seven constituents, COD, DS, and TN, the prediction error is small enough that the analyst may use the regional regression model without adjustment. For the other four, SS, TKN, DP, and PB, a simple estimator such as the mean of the observed concentration values may be used, or additional data could be collected to calibrate a local model.

The three models for which MAP-R-P+nV was favored (TKN load, DP load, and TP event-mean concentration) required additional exploratory analysis: multiple regression analysis of all possible combinations of five explanatory variables was done to determine the most suitable regression model. The explanatory variables considered in this analysis were TRN, DA, IA, LUI, and ADD. Inclusion of \( P_u \) in all of the multiple regressions was forced by regressing the residuals from the regression, \( O \) against \( P_u \) against all possible combinations of the residuals from five regressions (each of the five explanatory variables against \( P_u \)).

The best combination of explanatory variables was selected for each size category (table 3) based on values of \( r^2 \) and \( C_p \): largest \( r^2 \) and smallest \( C_p \). (The reader is referred to Draper and Smith, 1981, for a detailed description of Mallow's coefficient, \( C_p \).) Ideally, the most suitable regression model from among the best in each size category would be selected by comparing \( r^2 \) and \( C_p \). For the Tennessee data base, however, the size of the calibration data set constrained the choice to the size category \( n = 1 \) or, in the
case of TP event-mean concentration, to \( n \leq 2 \), where \( n \) is the number of explanatory variables (table 3).

**Calibration and Error Analysis**

Observations in the Tennessee data base were used to derive coefficients for the selected MAP for each constituent model (table 4). Calibration error is reported as standard error of the estimate (SE); SE measures how well the estimated values from the MAP agree with the observed values for the calibration data set. Calibration results may be biased due to sampling error in the Tennessee data base.

\( SE \) for the selected MAP's ranges from 0.263 log units (67 percent), for the ZN event-mean concentration model, to 0.677 log units (322 percent), for the SS load model. The relatively large values of \( SE \) for adjusted models for some of the constituent models, although representing significant reduction (by at least 50 percent) in prediction error compared to estimation with \( P \_u \), may be unacceptable for some applications. Furthermore, values of \( r^2 \) for adjusted models for TP, CU, and ZN event-mean concentration are small (0.264, 0.185, and 0.381, respectively). The user may wish to collect additional local data for these constituents and repeat the MAP analysis, or calibrate an independent local regression model.

\( SE \) for adjusted load models is larger than for the corresponding adjusted concentration model. Compare, for example, \( SE \) for the adjusted CU load model, 135 percent, to \( SE \) for the adjusted CU concentration model, 79 percent. This disparity should not encourage the user, however, to use an estimate from the adjusted CU concentration model, in conjunction with an estimated runoff volume, to estimate CU load. \( SE \) values are larger for load models partly because the variation in load values is naturally greater, which is caused in turn by the greater variability in values of runoff volume.

Figure 2. Flowchart for selection of model-adjustment procedure (MAP) based on exploratory data analysis of the calibration data set (from Hoos and Sisolak, 1993).

**Table 3:**

- \( P_u \): Predicted values of storm-runoff load or mean concentration from the unadjusted regional model.
- \( O \): Observed values of storm-runoff load or mean concentration.
- \( f_r \): Spearman's rho.
- \( n \): Number of observations.
- MAP-IF-P: Single-factor regression against regional prediction.
- MAP-R-P: Regression against regional prediction and additional local variables.
- MAP-R-P+NV: Regression against regional prediction and additional local variables.
- MAP-W: Weighted combination of regional prediction and local-regression prediction.

**Table 4:**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>SE (log units)</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP event-mean concentration</td>
<td>0.263</td>
<td>0.264</td>
</tr>
<tr>
<td>ZN event-mean concentration</td>
<td>0.677</td>
<td>0.381</td>
</tr>
<tr>
<td>SS load</td>
<td>0.677</td>
<td>0.381</td>
</tr>
<tr>
<td>CU load</td>
<td>0.677</td>
<td>0.381</td>
</tr>
</tbody>
</table>
Table 3. Multiple regression analysis of data sets for which MAP-R-P+nV is favored

Regression analysis forces inclusion of the predicted value from the unadjusted regional model, $P$; $n$, number of explanatory variables; $C_p$, Mallows's coefficient (Draper and Smith, 1981); $r$, correlation coefficient; TKN, total ammonia plus organic nitrogen as nitrogen; DP, dissolved phosphorus; TP, total phosphorus; LOAD, storm-runoff load; CONC, storm-runoff mean concentration; TRN, total storm rainfall; DA, total contributing drainage area; IA, impervious area; LUI, industrial land use; ADD, antecedent dry days.

<table>
<thead>
<tr>
<th>Constituent name. model type</th>
<th>Best $n=1$</th>
<th>Best $n=2$</th>
<th>Best $n=3$</th>
<th>Best $n=4$</th>
<th>All variables $(n=5)$</th>
<th>Most suitable model</th>
<th>Selected variables</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Variable</td>
<td>$C_p$</td>
<td>$r^2$</td>
<td>Variable</td>
<td>$C_p$</td>
<td>$r^2$</td>
<td>Variable</td>
<td>$C_p$</td>
</tr>
<tr>
<td></td>
<td>IA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DP.LOAD</td>
<td>DA</td>
<td>9.51 .299</td>
<td>TRN</td>
<td>6.59 .376</td>
<td>TRN</td>
<td>5.37 .422</td>
<td>TRN</td>
<td>5.54 .438</td>
</tr>
<tr>
<td></td>
<td>IA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP.CONC</td>
<td>IA</td>
<td>1.34 .234</td>
<td>DA</td>
<td>.58 .271</td>
<td>TRN</td>
<td>2.14 .262</td>
<td>TRN</td>
<td>4.00 .246</td>
</tr>
<tr>
<td></td>
<td>IA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^1$Data set size constrains $n$ to 1.

$^2$Data set size constrains $n$ to 2 or less.
Table 4. Calibration coefficients and error statistics for selected model-adjustment procedures for the data base for Chattanooga, Knoxville, and Nashville, Tennessee

(Model-adjustment procedures (MAP's) and bias correction factor (BCF) explained in Hoos and Sisolak (1993); r, correlation coefficient; SE, standard error of the estimate; RMSE, root mean square error between observed and predicted (from unadjusted regional model) values of the response variable; COD, chemical oxygen demand; SS, suspended solids; DS, dissolved solids; TN, total nitrogen; TKN, total ammonia plus organic nitrogen as nitrogen; TP, total phosphorus; DP, dissolved phosphorus; CD, total-recoverable cadmium; CU, total-recoverable copper; PB, total-recoverable lead; ZN, total-recoverable zinc; LOAD, storm-runoff load, in pounds; CONC, storm-runoff event-mean concentration, in milligrams per liter (except for CD, CU, PB, and ZN, which are in micrograms per liter); $P_u$, predicted value of response variable from the unadjusted regional model for unmonitored site and storm i; DA, drainage area, in square miles; IA, impervious area, in percent; --, not calculated)

<table>
<thead>
<tr>
<th>Constituent name, model type</th>
<th>Best MAP</th>
<th>Equation form</th>
<th>Calibration coefficients</th>
<th>Calibration error statistics</th>
<th>Prediction error without MAP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\beta_0$ $P_u$</td>
<td>$\beta_1$ $P_u$</td>
<td>$\beta_2$ $P_u$</td>
<td>$\beta_3$ $P_u$</td>
</tr>
<tr>
<td>COD.LOAD R-P $\beta_0 P_u$</td>
<td>10^-0.650</td>
<td>1.068</td>
<td>1.506</td>
<td>0.679</td>
<td>0.451</td>
</tr>
<tr>
<td>SS.LOAD R-P $\beta_0 P_u$</td>
<td>10^-5.224</td>
<td>1.114</td>
<td>2.164</td>
<td>.629</td>
<td>.677</td>
</tr>
<tr>
<td>DS.LOAD R-P $\beta_0 P_u$</td>
<td>10^-4.80</td>
<td>.961</td>
<td>1.520</td>
<td>.725</td>
<td>.453</td>
</tr>
<tr>
<td>TN.LOAD R-P $\beta_0 P_u$</td>
<td>10^-1.54</td>
<td>1.688</td>
<td>1.576</td>
<td>.613</td>
<td>.484</td>
</tr>
<tr>
<td>TKN.LOAD R-P $\beta_0 P_u$</td>
<td>10^-2.85</td>
<td>.421</td>
<td>0.747</td>
<td>.642</td>
<td>.450</td>
</tr>
<tr>
<td>TP.LOAD R-P $\beta_0 P_u$</td>
<td>10^-2.57</td>
<td>1.235</td>
<td>2.948</td>
<td>.629</td>
<td>.639</td>
</tr>
<tr>
<td>DP.LOAD R-P $\beta_0 P_u$</td>
<td>10^-1.24</td>
<td>.143</td>
<td>1.157</td>
<td>.560</td>
<td>.633</td>
</tr>
<tr>
<td>CD.LOAD None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CU.LOAD R-P $\beta_0 P_u$</td>
<td>10^-2.54</td>
<td>1.052</td>
<td>1.395</td>
<td>.763</td>
<td>.443</td>
</tr>
<tr>
<td>PB.LOAD R-P $\beta_0 P_u$</td>
<td>10^-1.853</td>
<td>1.609</td>
<td>1.897</td>
<td>.709</td>
<td>.516</td>
</tr>
<tr>
<td>ZN.LOAD R-P $\beta_0 P_u$</td>
<td>10^-1.74</td>
<td>1.059</td>
<td>1.778</td>
<td>.648</td>
<td>.533</td>
</tr>
</tbody>
</table>
Table 4. Calibration coefficients and error statistics for selected model-adjustment procedures for the data base for Chattanooga, Knoxville, and Nashville, Tennessee—Continued

<table>
<thead>
<tr>
<th>Constituent name, model type</th>
<th>Best MAP</th>
<th>Equation form</th>
<th>Calibration coefficients</th>
<th>Calibration error statistics</th>
<th>Prediction error without MAP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\beta'_0$, $\beta'_1$, $\beta'_2$, $\beta'_3$, $BCF$</td>
<td>$r^2$, $SE$, $SE$, $RMSE$, percent</td>
<td></td>
</tr>
<tr>
<td>COD.CONC</td>
<td>Use as is</td>
<td>$P_{ui}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS.CONC</td>
<td>None$^b$</td>
<td></td>
<td>$\beta'_0$, $\beta'_1$, $\beta'_2$, $\beta'_3$, $BCF$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS.CONC</td>
<td>Use as is</td>
<td>$P_{ui}$ (region II)</td>
<td>$\beta'_0$, $\beta'_1$, $\beta'_2$, $\beta'_3$, $BCF$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TN.CONC</td>
<td>Use as is</td>
<td>$P_{ui}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TKN.CONC</td>
<td>None$^b$</td>
<td></td>
<td>$\beta'_0$, $\beta'_1$, $\beta'_2$, $\beta'_3$, $BCF$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP.CONC</td>
<td>R-P+nV</td>
<td>$\beta'<em>0 \times P</em>{ui} \times BCF$</td>
<td>$10^{-0.347}$, 0.198, 0.264, 0.186, 1.510</td>
<td>0.264$^a$, 0.397, 114, 177</td>
<td></td>
</tr>
<tr>
<td>DP.CONC</td>
<td>None$^b$</td>
<td></td>
<td>$\beta'_0$, $\beta'_1$, $\beta'_2$, $\beta'_3$, $BCF$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD.CONC</td>
<td>None$^b$</td>
<td></td>
<td>$\beta'_0$, $\beta'_1$, $\beta'_2$, $\beta'_3$, $BCF$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CU.CONC</td>
<td>R-P</td>
<td>$\beta'<em>0 \times P</em>{ui} \times BCF$</td>
<td>$10^{-0.099}$, 0.524, 1.241</td>
<td>.185, .302, 79, 2,573</td>
<td></td>
</tr>
<tr>
<td>PB.CONC</td>
<td>None$^b$</td>
<td></td>
<td>$\beta'_0$, $\beta'_1$, $\beta'_2$, $\beta'_3$, $BCF$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZN.CONC</td>
<td>R-P</td>
<td>$\beta'<em>0 \times P</em>{ui} \times BCF$</td>
<td>$10^{-0.075}$, 0.832, 1.261</td>
<td>.381, .263, 67, 126</td>
<td></td>
</tr>
</tbody>
</table>

$^a$r$^2$ value differs from value reported in table 3. In the regression analysis for table 3, the response and explanatory variables were transformed to residuals of regression against $P_u$ (see text for explanation).

$^b$See suggested estimator in table 5.
The predictive accuracy of the MAP for a particular unmonitored site and storm \( i \) is estimated by the standard error of prediction (SEP). The \( \text{SEP}_i \) is computed as a function of the \( \text{SE} \) of the MAP as well as the difference between explanatory-variable values for the unmonitored site and the mean values of the calibration data set. The equations for computing \( \text{SEP}_i \) for each MAP are presented in Hoos and Sisolak (1993, Supplement C).

Simple estimators are given in Table 5 for the constituents for which model adjustment was not appropriate.

**Table 5. Simple estimators for constituents for which models were not adjusted**

<table>
<thead>
<tr>
<th>Constituent name, model type</th>
<th>Simple estimator: mean of observed value*</th>
<th>Calibration error: standard deviation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS.CONC</td>
<td>65</td>
<td>3.74</td>
</tr>
<tr>
<td>TKN.CONC</td>
<td>1.04</td>
<td>1.95</td>
</tr>
<tr>
<td>DP.CONC</td>
<td>.165</td>
<td>2.51</td>
</tr>
<tr>
<td>CD.CONC</td>
<td>&lt;1</td>
<td>--</td>
</tr>
<tr>
<td>PB.CONC</td>
<td>16.9</td>
<td>2.51</td>
</tr>
</tbody>
</table>

* Computed from log-transformed data, then detransformed.

**EXAMPLE APPLICATION**

An estimate of TKN storm-runoff load is needed for an unmonitored site and storm \( i \) in Hixon, Tennessee: DA is 0.20 square mile, LUN is 30 percent, and TRN is 0.3 inch. MAR for the Hixon area is 53 inches. First, the TKN load model for region III (Driver and Tasker, 1990, table 1) is used to calculate the value for unmonitored site and storm \( i \) predicted from the unadjusted regional model \( (P_{ui}) \):

\[
P_{ui} (\text{TKN}) = 199,572 \times TRN^{(0.875)} \times DA^{(0.393)} \times (LUN + 2)^{(0.082)} \times MAR^{(-2.643)} \times 1.736;
\]

\[
P_{ai} (\text{TKN}) = 199,572 \times 0.3^{(0.875)} \times 0.20^{(0.393)} \times 32^{(0.082)} \times 53^{(-2.643)} \times 1.736;
\]

\[
P_{ai} (\text{TKN}) = 2.36 \text{ pounds}
\]

Before adjusting this estimate with results from the MAP analysis, consideration should first be given to whether the characteristics of unmonitored site and storm \( i \) are within the range of site and storm characteristics in the Tennessee data base (presented in table 1). In this example, values for unmonitored site and storm \( i \) are within the range for the data base.

The selection procedure based on exploratory data analysis (fig. 2) favors MAP-R-P+nV for the TKN load model (table 2) with DA as the additional explanatory variable (table 3). Calibration of MAP-R-P+nV yields values of \( 10^{0.285} \), 0.421, 0.747, and 1.528 for \( \beta_0 \), \( \beta_1 \), \( \beta_2 \), and \( BCF \), respectively (table 4). \( P_{ai} \) is adjusted to \( P_{ai} \) using these coefficient values, the value for DA (0.20 square mile), and the MAP-R-P+nV adjustment equation (table 4):

\[
P_{ai} (\text{TKN}) = \left( 10^{0.285} \times P_{ui} (\text{TKN})^{0.421} \times DA^{(0.747)} \times 1.528; \right.
\]

\[
P_{ai} (\text{TKN}) = \left( 10^{0.285} \times 2.36^{(0.421)} \times 0.20^{(0.747)} \times 1.528; \right.
\]

\[
P_{ai} (\text{TKN}) = 1.27 \text{ pounds}
\]

where \( P_{ai} \) = adjusted model-predicted value of storm-runoff load for unmonitored site and storm \( i \). Therefore, the adjusted estimate of TKN load for a 0.3-inch storm at unmonitored site \( i \) is 1.27 pounds.

Annual and seasonal urban-runoff load at the unmonitored site \( i \) can be estimated by calculating \( P_{ai} \) for a recorded series of storms, thereby producing a synthetic record of storm loads. The synthetic record is reduced to an estimate of mean annual load by first summing loads from each storm, then dividing by the number of years in the period of synthetic record. Mean seasonal load can be estimated by summing loads only from the season of interest before dividing by the number of years of record.

**SUMMARY**

This report presents the results of applying model-adjustment procedures (MAP's) to the combined data bases of storm-runoff quality from Chattanooga, Knoxville, and Nashville, Tennessee (Tennessee data base). Data for 45 storms at 15 different sites (5 sites in each city) constitute the data base.
Comparison of observed values \( (O) \) to the predicted values from the regional regression models \( (P_u) \) shows large prediction errors for almost all constituent models. Discrepancies between \( P_u \) and \( O \) are caused by error in the regional models or by sampling error in the Tennessee data base. Some sampling error may be present: average storm size in the data base is smaller than the average storm size in the three cities, and many monitoring sites in the data base are in watersheds that may be too large for these sites to be considered as storm-runoff discharge points.

For most constituents, however, the prediction error is too large to be reasonably explained by sampling error alone; some of the error must be due to error in the regional models. MAP's, which combine the regional model predictions with local data, are applied to improve predictive accuracy.

For most of the load models, the variation in \( P_u \) explains much of the variation in \( O \), and the direction of bias of \( P_u \) relative to \( O \) is consistent and positive; that is, \( P_u \) consistently overestimates \( O \). The MAP based on regression against \( P_u \) alone (MAP-R-P) is favored for most of the load models. The MAP based on regression against \( P_u \) and additional local variables (MAP-R-P+nV) is favored for only the TKN and DP load models.

For the event-mean concentration models, MAP-R-P is favored for CU and ZN, and MAP-R-P+nV is favored for TP. For the remaining seven constituents, the variation in \( P_u \) does not sufficiently explain the variation in \( O \) and, furthermore, correlation between \( O \) and each of the additional explanatory variables is not significant. None of the MAP's is appropriate for the concentration models for these seven constituents. For three of the seven constituents, COD, DS, and TN, the prediction error is small enough that the analyst may use the regional regression model without adjustment. For the other four, SS, TKN, DP, and PB, a simple estimator such as the mean of the observed concentration values may be used, or additional data could be collected to calibrate a local model.

\( SE \) for the selected MAP's ranges from 0.263 log units (67 percent), for the ZN event-mean concentration model, to 0.677 log units (322 percent), for the SS load model. Calibration results may be biased due to sampling error in the Tennessee data base. The relatively large values of \( SE \) for adjusted models for some of the constituent models, although representing significant reduction (by at least 50 percent) in prediction error compared to estimation with \( P_u \), may be unacceptable for some applications. The user may wish to collect additional local data for these constituents and repeat the MAP analysis, or calibrate an independent local regression model.

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