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Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the Twin Cities metropolitan area, Minnesota, USA

Patrick L. Brezonik*, Teresa H. Stadelmann[1]

Department of Civil Engineering, Water Resources Center, University of Minnesota, Minneapolis, MN 55455, USA

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Abstract

Urban nonpoint source pollution is a significant contributor to water quality degradation. Watershed planners need to be able to estimate nonpoint source loads to lakes and streams if they are to plan effective management strategies. To meet this need for the twin cities metropolitan area, a large database of urban and suburban runoff data was compiled. Stormwater runoff loads and concentrations of 10 common constituents (six N and P forms, TSS, VSS, COD, Pb) were characterized, and effects of season and land use were analyzed. Relationships between runoff variables and storm and watershed characteristics were examined. The best regression equation to predict runoff volume for rain events was based on rainfall amount, drainage area, and percent impervious area ($R^2 = 0.78$). Median event-mean concentrations (EMCs) tended to be higher in snowmelt runoff than in rainfall runoff, and significant seasonal differences were found in yields (kg/ha) and EMCs for most constituents. Simple correlations between explanatory variables and stormwater loads and EMCs were weak. Rainfall amount and intensity and drainage area were the most important variables in multiple linear regression models to predict event loads, but uncertainty was high in models developed with the pooled data set. The most accurate models for EMCs generally were found when sites were grouped according to common land use and size. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Urban stormwater; Urban runoff; Diffuse-source pollution; Nutrients; Nitrogen; Phosphorus; Event-mean concentrations; Event loads

1. Introduction

Urban nonpoint pollution has been identified for many years as an important cause of surface water quality degradation in the United States. Sources of this pollution include precipitation, soil erosion, accumulation and wash-off of atmospheric dust, wash-off of street dirt, fertilizers and pesticides, and direct discharge of pollutants into storm sewers [1]. Urban growth has several detrimental impacts on receiving waters. It increases the impervious land area in a region, which decreases infiltration, increases runoff, and decreases the time during which runoff occurs. In addition, detrimental water quality changes in stormwater runoff accompany land-use changes coinciding with urbanization. Due to the impacts on receiving waters and the expense involved in obtaining monitoring data on nonpoint source pollution data, interest has grown in compiling/analyzing existing data to develop predictive models for urban stormwater loads and concentrations. Such models can aid planners and engineers make such loading estimates for unmonitored watersheds.

This sort of data summary and analysis was done on a coarse scale for the United States [2,3] and on a finer scale for several metropolitan areas and sites in them. Variability from one location to another and from storm to storm indicates the need for local data. Stormwater

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*Corresponding author.

E-mail address: brezo001@tc.umn.edu (P.L. Brezonik).

[1] Current address: Archer Engineers, Lee's Summit, MO, USA.

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quality was studied in the Twin Cities metropolitan area (TCMA) by Payne et al. [4], but a considerable amount of data have been collected since then. Much of the recent data has been obtained from small storm-sewered urban watersheds that drain to lakes and rivers. Compilation and analysis of these data is a necessary step in the development of predictive models for estimating stormwater runoff loads to lakes from watersheds in the TCMA.

To conduct the analysis, we compiled a database of urban and suburban runoff data for small watersheds in the TCMA. The data came from 15 previously published and unpublished studies. Our study had four objectives: (1) statistically characterize urban storm runoff loads and event-mean concentrations (EMCs) of 10 commonly measured constituents for TCMA watersheds; (2) evaluate seasonal variations in runoff loads and EMCs; (3) determine relationships between runoff volumes, loads and EMCs and storm and watershed characteristics; and (4) develop predictive equations relating runoff volumes, loads and concentrations to easily measured physical, land-use, and climatic characteristics of small watersheds.

2. Background

Studies throughout the United States have documented the impacts of urbanization on stormwater runoff. Yields of total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN) from intensive agriculture and urban areas in the Great Lakes region were 10–100 times greater than from forested and idle lands [5]. Annual yields of TP were nearly twice as high in urban watersheds as in rural and agricultural watersheds near Rochester, NY [6]. Mean concentrations of suspended solids in runoff were at least >24 times larger than those in low-flow samples for a watershed containing construction sites in Fort Leavenworth, KS [7]. Urban stormwater runoff thus significantly increases sediment and nutrient loadings to surface waters. The effects of urban runoff on receiving water quality are highly site-specific [2], however, making it difficult to predict impacts and design appropriate management and control practices without site-specific data.

Geographic and physical factors—type and intensity of land use, degree of imperviousness, tree cover, soil type, slope, and drainage density—are important determining factors in the generation of nonpoint pollution. Climatic factors such as rainfall intensity and duration, storm frequency, and time since antecedent rainfall are also important [5]. Rain itself is a significant source of some pollutants; nitrate and ammonium in rainfall samples were up to half the concentrations found in roadway runoff in eastern Minnesota [8].

The type of urban land use also plays an important role. Commercial and industrial land uses contribute more pollutants than urban open space, parks, and low density residential land uses [9]. Construction sites are the most detrimental activity in terms of sediment runoff [5]; septic systems and construction erosion were identified as the most common sources of pollution in suburban areas [1]. Streets are important pollutant sources in all land-use types [10]. Although many loading estimates have been reported for various land uses, high variability and inconsistencies exist among reported values. These differences may represent real variations or differences in sampling and analytical methods [9].

Stormwater runoff monitoring in the TCMA has focused on mixed land-use watersheds. The TCMA often experiences severe winters that contribute to high snowmelt runoff, but most past studies have focused on rainfall runoff. The most extensive runoff monitoring in the TCMA was conducted in 1980 (e.g., [4,11,12]). Precipitation, runoff and water quality data were collected at 17 rural and urban sites of differing land use. Results show that total pollution load was primarily a function of total runoff volume [12]. Snowmelt contributed significantly to annual loads and dominated total loads in rural areas; 75–95% of pollutant loading occurred during snowmelt or spring rain on frozen ground (before vegetative cover was established). Pollutant loading in urban areas occurred year round, but highest loadings were in summer. Watersheds with even a few construction sites were especially large sources of solids and nutrients.

In a study of a northern TCMA watershed, Arntson and Tornes [13] found that the most urbanized site had the highest concentrations of metals, chloride, dissolved solids, and suspended sediment. Rural sites had low concentrations of metals but the highest concentrations of many nutrients. TP concentrations were comparable at rural and urban sites. Mitton and Payne [8] found higher median suspended solid levels in runoff from guttered than unguttered roadways in the northeastern TCMA, but TP was higher at unguttered sites. Vegetated road ditches were thought to trap suspended solids but contribute organic matter to runoff.

The source of runoff water—precipitation or snowmelt—also may affect the quality of urban runoff. During thawing and freezing cycles, soluble pollutants are flushed through the snowpack and concentrated at the bottom where they are available for transport in snowmelt [14], but particulate pollutants, such as suspended solids and particulate P, are filtered by the snowpack during melt events and eventually deposited on the ground [1]. Pollutants accumulated in snowpack during winter and those washed off land surfaces by melt water can affect runoff water quality during snowmelt [14]. Runoff behavior during snowmelt also differs from rainfall events in that water is generally flowing over frozen or saturated soils.

Walker et al. [15] found lower median concentrations and loads of TSS and TP in snowmelt than in rainfall runoff in urban Wisconsin watersheds, and Oberts [14] reported that TSS and volatile suspended solids (VSS) in snowmelt from the TCMA were much lower than in runoff from rainfall. Dissolved P (DP) and TP concentrations were similar in snowmelt and rainfall runoff, but chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), Pb, chloride and nitrate were higher in snowmelt runoff. Oberts [14,16] attributed high concentrations of solids, P, Pb, and Zn in urban snowmelt to the use of sand and salt on roadways in winter.

In addition to differences between snowmelt and rainfall runoff, seasonal differences in urban runoff have been noted. According to Kappel et al. [6], the period of snowmelt and spring runoff (late January to early March) accounted for $>50\%$ of the annual suspended sediment load, $\sim 50\%$ of the TP load, 40% of the TKN load, and $\sim 70\%$ of the annual Pb load in a creek near Rochester, NY. Wilson [17] found that concentrations of Pb, TP, soluble reactive P (SRP) and TN (but not NH_4^+ and NO_3^+) were higher in snowmelt and fall runoff than in summer runoff in Minneapolis. Fall runoff had much higher TP than snowmelt and summer runoff. Nitrate was significantly higher in snowmelt than in summer and fall runoff. SRP and TN were similar and significantly higher in snowmelt and fall than in summer runoff.

Site-specific models have been developed to predict runoff volumes, loads and concentrations across the United States [18–20], but predictive models applicable across regions are rare. Donigian and Huber [21] reviewed modeling options, including unit loads, spreadsheets, statistical models, rating curves and buildup/washoff methods. Driver and Tasker [3] developed regional regression models to estimate volumes, loads, and EMCs from physical, land-use, and climatic characteristics of urban US watersheds. Models were developed for three regions defined by mean annual rainfall. Total rainfall and drainage area were the most significant explanatory variables in all models, but impervious area, land-use, and annual climatic conditions were significant in some. Runoff volume generally was modeled more accurately than loads or concentrations. The most accurate load models for the region that includes the TCMA were for COD, TN, and TKN. Load models for TSS and Pb were the least accurate. EMCs generally were inversely related to total rainfall and drainage area, but a few constituents (e.g., TSS) were positively related to rainfall or drainage area. Land use was not useful in explaining differences in EMCs between sites or predicting EMCs of unmonitored sites. Ayers et al. [11] developed event and daily load models for common pollutants from the 1980 TCMA data. In storm-sewered urban watersheds, total precipitation was the most important predictor for runoff and loads. Antecedent soil moisture and rainfall intensity were important factors for estimating runoff in some watersheds.

3. Study area, database and methods

The TCMA (population of 2.8 million in 2000) encompasses 7800 km^2 and consists of seven counties surrounding Minneapolis and Saint Paul, MN. Stormwater data from 15 studies were assembled for 68 watersheds in the TCMA. Many of the recent studies are unpublished; further information on the data sources and database is found in Anderle [22]. Monitored events occurred between June 1980 and October 1998. EMCs and total loads were available for TSS, VSS, TP, DP, SRP, COD, TKN, TN, nitrate plus nitrite–nitrogen (NN), and lead (Pb). Event-mean concentrations were obtained for 562 events at 65 sites. Event loads were obtained for 360 events at 43 sites. The most commonly monitored variables were TSS (15 studies), TP (15), SRP (9) and TN (7). Watershed size was available for 58 sites, and land-use information was available for 49 sites. Catchment sizes ranged from 6.9 to 215 ha. Land uses included residential, public and open space, commercial/industrial, grassland, woods, and wetlands.

3.1. Data manipulation

Since the data were from various sources, preprocessing was needed. Concentrations were converted to mg/L; loads to kg/event, and total runoff (when provided) to m^3/event. Runoff depth (cm) was calculated as runoff volume divided by drainage area for sites where both data were available. For many sites, either concentration or load data, but not both, were provided. When only loads and runoff volume were available, EMCs were calculated by dividing total load by runoff volume. When EMCs and runoff volume were available, loads were calculated by multiplying the EMC by total runoff. TN was calculated as NN + TKN.

3.2. Precipitation

On-site precipitation data (including total precipitation, duration, intensity, and days since last event) were used when available. For sites/events lacking such data, we calculated total precipitation (CP_k) based on daily total precipitation (P_j) measured at 16 TCMA stations [23] by a distance weighting method:

$$CP_k = \frac{\sum(P_j W_{jk})}{\sum W_{jk}},$$

where $W_{jk} = 1/(\text{distance between site } k \text{ and station } j)^2$. Hourly precipitation from the Minneapolis–St. Paul Airport [24] was used to determine rainfall duration in hour increments and days since the last event. Rainfall intensity was calculated as total precipitation divided by rainfall duration. Days since the last event were based on the days since at least 2.5 mm of precipitation.

3.3. Statistical methods

SYSTAT 8.0 was used to compute descriptive statistics, generate histograms and box plots of variables, and compute the Pearson correlation matrices and stepwise multiple linear regressions. The Mann–Whitney *U* test was used to determine whether differences existed at $p<0.05$ between snowmelt- and rain-induced runoff loadings and concentrations for sites where both types of events had been monitored at least three times. The Kruskal–Wallis test (a nonparametric analog of one-way ANOVA) was used to determine whether differences existed at $p<0.05$ between seasonal groupings of load and concentration data. Since the data were skewed, variables were log transformed before correlations and regressions were calculated. Variables having zero values were expressed as log(variable + 1). Log transforms improved the symmetry of the distributions, but the results were not always normal. The Lilliefors test [25] was used to evaluate the fit of transformed data to a normal distribution.

Correlation matrices were computed between log-transformed stormwater constituents and physical, land-use, and climatic variables. Only correlations significant at $p<0.01$ are reported here. Forward stepwise multiple regression was used to relate runoff volumes, loads and EMCs to storm characteristics, antecedent conditions, drainage area, and land use. Highly correlated variables were not combined in the same model. Standard errors of the estimate (SEE, %) were converted from log units to percent by: $\mathrm{SEE} = 100[e^{(\sigma^2\times 5.302)} - 1]^{0.5}$, where σ^2 = mean square error in log units [3]. Sites were divided into six groups based on land-use and watershed size. EMC statistics by group were compared using box plots, and regression models were developed for each group to predict runoff volumes and EMCs using log-transformed data.

4. Results and discussion

4.1. Characterization of stormwater runoff

Runoff events were monitored throughout the year, with most in spring and summer. Load and concentration data were obtained for 341 and 499 rainfall events, respectively, and 19 and 63 snowmelt or combined snowmelt/rain runoff events, respectively. Precipitation data were available for 511 rainfall events. Duration and average rainfall intensity were available for most events. Precipitation amounts ranged from 0.25 to 74 mm, and average rainfall intensity ranged from 0.25 to 44 mm/h. Time to antecendent rainfall (> 2.5 mm) ranged from 9 h to 30 days. All precipitation data were positively skewed with a long right tail. Snowmelt was measured for 20 events at six sites that in some cases included combined snowmelt and precipitation. Melt depths ranged from 2.5 to 14 mm. Time since the last event extended up to 17 days. Runoff volumes for 343 events ranged from <24 to 28,300 m^3, and runoff depths for 317 events at sites where drainage area was available ranged from 0.03 to 23 mm. After log transformation, runoff volume was normally distributed. The symmetry of runoff depth was improved but the data still were not normal. Runoff volumes for 20 snowmelt events ranged from 13 to 77,000 m^3. The data were positively skewed, and the Lilliefors test indicated that the data were log-normally distributed.

Loads ranged over two or more orders of magnitude for all constituents (Table 1). All data were positively skewed, and log transformations yielded normal distributions except TP, DP and TN. Loads expressed as yields (load per area) for sites reporting drainage area (Table 2) ranged over several orders of magnitude. Event mean concentrations (Table 3) ranged over two or more orders of magnitude for all constituents. Log-transformation yielded normal distributions for TSS, TP and TN, and symmetry was improved for the rest

Table 1
Summary of monitored event load data[a]

	TSS	VSS	TP	DP	SRP	COD	TKN	NN	TN	Pb
n	351	148	360	147	85	149	222	213	294	166
Minimum	0.51	0.45	0.005	0.01	0.001	2.73	0.043	0.015	0.06	0.0005
Maximum	40,877	4770	30.1	24.8	23.7	4636	125	85	210	4.03
Median	76	36	0.36	0.17	0.06	119	2.27	0.53	2.17	0.05
Mean	519	171	1.06	0.74	0.66	245	6.6	1.80	6.7	0.20
Standard deviation	2650	595	2.85	2.50	2.85	475	15.5	6.5	18.2	0.46

[a] All values except *n* in kg/event.

Table 2
Summary of stormwater yields[a]

	TSS	VSS	TP	DP	SRP	COD	TKN	NN	TN	Pb
n	325	148	334	147	82	149	222	213	270	166
Minimum	0.006	0.010	8.8E-5	1.2E-4	1.3E-5	0.076	4.4E-4	3.8E-4	9.6E-4	4.3E-6
Maximum	192	57.9	0.436	0.360	0.344	77.2	1.50	0.393	1.85	3.2E-2
Median	1.50	0.662	6.5E-3	3.1E-3	1.6E-3	2.31	4.0E-2	9.1E-3	4.4E-2	1.0E-3
Mean	7.43	2.25	1.9E-2	9.9E-3	9.1E-3	5.16	9.6E-2	2.0E-2	0.103	3.0E-3
Standard deviation	20.8	6.25	0.034	0.034	0.045	9.80	0.19	0.044	0.19	0.011

[a] All values except *n* in kg/ha.

Table 3
Summary of monitored event-mean concentration data[a]

	TSS	VSS	TP	DP	SRP	COD	TKN	NN	TN	Pb
n	520	170	561	147	213	149	221	317	466	284
Minimum	2	2	0.03	0.01	0.003	22	0.21	0.00	0.43	0.00
Maximum	3577	1690	9.40	1.40	1.40	2030	18.5	2.10	19.4	0.91
Median	88	21	0.41	0.15	0.10	90	1.85	0.44	2.50	0.01
Mean	184	66	0.58	0.20	0.20	169	2.62	0.53	3.08	0.06
Standard deviation	322	157	0.69	0.17	0.23	240	2.59	0.36	2.44	0.10

[a] All values except *n* in mg/L.

although several remained skewed. The National Urban Runoff Program (NURP) also found that EMCs for most variables were log-normally distributed [1]. EMCs in the TCMA are comparable with those for the median site in NURP [2] except for Pb (13 μg/L for TCMA; 144 μg/L for NURP). The latter data are much older than most TCMA data, and decreased use of leaded gasoline explains the difference. Coefficients of variation ranged from 0.68 to 2.38 for TCMA data, and were above or near the upper end of the range for NURP data. Runoff concentrations generally are high compared with typical ranges of summer lake water quality in the TCMA [26].

4.2. Comparison of snowmelt and rainfall runoff

The effect of runoff type on event loads was compared at six sites where loads were monitored for both snowmelt and rainfall runoff. Snowmelt events and combined snowmelt–rainfall runoff were lumped together. Large differences in snowmelt runoff volumes occurred among the sites, reflecting differing amounts of snowfall in the years when the sites were monitored. Median loads were higher in snowmelt runoff at sites having larger snowmelt runoff volumes, and the converse was true for precipitation runoff. Median runoff volumes at site 19 were similar for both types of events, and loads were similar for the two types of runoff. Loadings thus appear to be more a function of runoff volume than source of runoff water.

Snowmelt and rainfall runoff concentrations were compared at 21 sites, where both types of runoff were monitored. Snowmelt events and combined snowmelt–rainfall events again were lumped into one group. EMCs for TP and TN were higher for snowmelt events at most sites (Fig. 1). In contrast, Walker et al. [15] reported that TP EMCs tended to be lower in snowmelt. Runoff volume was measured at only a few sites; thus runoff concentrations and volumes could not be compared. Statistical comparisons of snowmelt and rainfall EMCs were done for 17 sites, where both types had been monitored at least three times. When significant differences were detected ($p < 0.05$, Mann–Whitney U test), snowmelt EMCs were higher. Differences were detected for TP at three sites, SRP at seven sites, TN at six sites, NN at eight sites, and Pb at five sites. Mitton and Payne [8] similarly found that mean concentrations of Pb and other metals were 2–4 × greater in snowmelt than in rainfall runoff from TCMA roads.

Significant differences ($p < 0.05$) also were found for TSS, VSS, and DP at site 13, a 61 ha suburban residential watershed. TSS and VSS were higher in rainfall runoff, but DP was higher in snowmelt. Two spring rainfall events especially high in TSS concentration contributed largely to the differences. The high TSS possibly was caused by wash-off of accumulated solids from the earlier snowmelt period and loose soil available for transport before vegetative cover had been established. It is interesting to note that the TP in snowmelt events was nearly all DP.

In years with large amounts of winter snowfall (thus large amounts of snowmelt runoff), high nutrient and Pb levels in snowmelt runoff may have important impacts on the quality of TCMA surface waters. Large loads of nutrients washed into lakes and streams in early spring are available for uptake during the subsequent growing season and may cause eutrophication problems. Large inputs of toxic metals, such as Pb, may have harmful effects on biota.

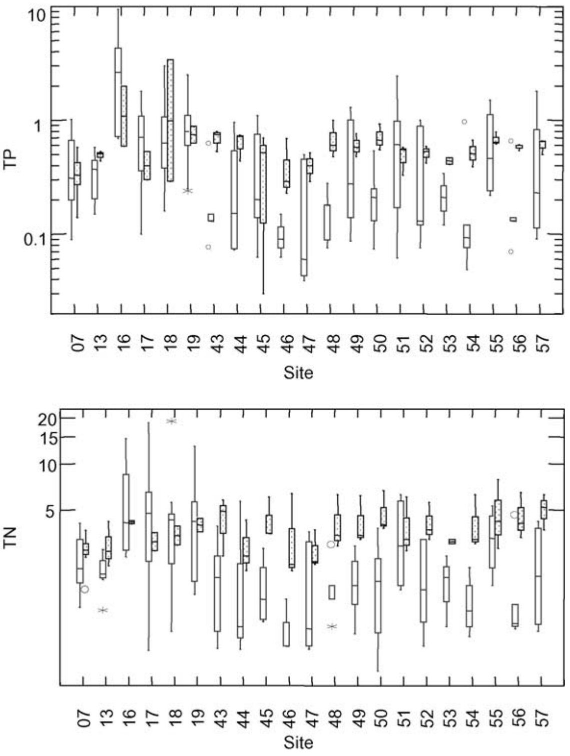

Fig. 1. Comparison of event-mean concentrations of TP and TN in snowmelt runoff (stipled bars) and rainfall-induced runoff (open bars) for sites having both runoff types.

4.3. Seasonal analysis of stormwater runoff

Seasonal differences in loadings (Fig. 2) and concentrations (Fig. 3) were examined for each constituent. Loads were expressed in yields (kg/ha) to eliminate differences due to watershed size. The largest range in event yields for TSS, VSS, and Pb was in summer; the largest range for all other variables was in spring. Significant seasonal differences were found ($p<0.05$, the Kruskal–Wallis test) for all variables except SRP. Median yields (Table 4(A)) were highest in spring for TSS, VSS, COD, and Pb. Median yields for TN, TKN, and NN were lowest in fall.

Ranges of EMCs were largest in spring for VSS, TP, COD, TKN, and TN but in fall for DP, SRP and Pb. Seasonal differences ($p<0.05$ the Kruskal–Wallis test) were found for all variables except VSS. Median EMCs for TP and SRP were much higher in fall and winter than in spring and summer (Table 4(B)), as Wilson [17] found for Minneapolis sites. The largest median EMCs for TN and NN were in winter; the largest median EMC of TKN occurred in spring.

4.4. Relationships between runoff data and explanatory variables

Factors contributing to nonpoint source pollution in the TCMA were identified as a step in developing models to predict runoff volumes and pollutant loads and concentrations. Correlation coefficients were calculated between stormwater variables and physical, land-

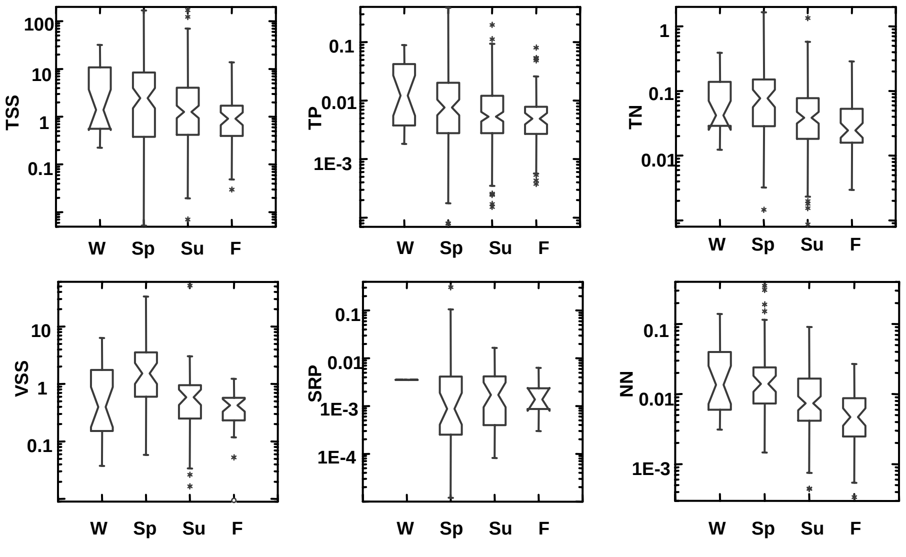

Fig. 2. Box plots of runoff yields (kg/ha) grouped by season for six water quality constituents.

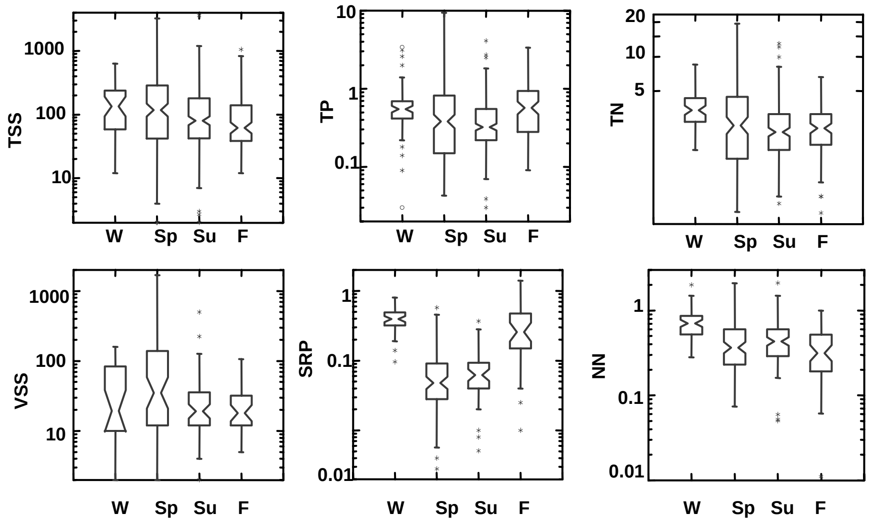

Fig. 3. Box plots of event-mean concentrations (EMCs, mg/L) grouped by season for six water quality constituents.

Table 4
Median seasonal values for (A) yields (kg/km^2) and (B) event-mean concentrations (mg/L)

Constituent	Winter	Spring	Summer	Fall
(A)				
TSS	156	274	141	102
VSS	45	170	66	47
TP	1.37	0.85	0.59	0.55
DP	0.37	0.53	0.21	0.21
SRP	—	0.10	0.19	0.16
COD	198	342	208	165
TKN	3.25	8.70	3.72	2.04
NN	1.51	1.57	0.83	0.53
TN	4.69	8.59	4.32	2.74
Pb	0.07	0.17	0.12	0.04
(B)				
TSS	134	118	80	62
VSS	20	35	19	18
TP	0.55	0.38	0.32	0.57
DP	0.23	0.19	0.14	0.14
SRP	0.40	0.05	0.06	0.26
COD	196	129	82	70
TKN	2.01	2.40	1.80	1.50
NN	0.71	0.37	0.43	0.32
TN	3.40	2.50	2.20	2.37
Pb	0.011	0.003	0.062	0.013

use, and climatic characteristics of the watersheds to determine whether these parameters could be used to create predictive models using readily obtainable storm and watershed information. The following explanatory variables were considered. *Storm characteristics*: precipitation amount (mm), storm duration (h), average storm intensity (mm/h), and days since last event >2.5 mm; *watershed characteristics*: total drainage area (ha), residential land use (%), commercial and industrial land use (%), public and open space (%), and impervious area (%). Variables were selected based on the frequency of collection in TCMA stormwater studies and data availability. In the 15 TCMA stormwater studies, the most commonly collected watershed characteristics were drainage area (13 studies), residential land use (9 studies), commercial and industrial land use (8 studies) and public and open space (8 studies). The easiest storm variable to acquire is total precipitation, but other storm variables usually can be obtained or estimated from nearby sites.

Before comparing explanatory variables with runoff variables, we evaluated correlations among the log-transformed variables in each group. Precipitation amount was correlated with rainfall duration ($r = 0.50$) and intensity ($r = 0.47$), but duration was inversely correlated with intensity ($r = -0.53$). No storm characteristic was correlated with days since the last event. Drainage area and residential land use were negatively correlated ($r = -0.44$). No other significant ($p<0.01$) correlations were found between log-transformed watershed and land-use characteristics.

Runoff volume was correlated with several storm and watershed characteristics: total precipitation ($r = 0.60$), rainfall duration ($r = 0.35$) and intensity ($r = 0.18$), and drainage area ($r = 0.46$). These are expected; all four variables lead to the generation of more runoff. In contrast, runoff was negatively correlated albeit weakly with days since last rainfall ($r = -0.18$). This makes sense because more infiltration and less runoff would be expected after a long dry period. Runoff has a weak negative correlation with residential land ($r = -0.28$) and a weak positive correlation with commercial/industrial land ($r = 0.18$). This may reflect the imperviousness associated with these land uses, but no significant correlation was found between runoff and percent imperviousness. However, data on imperviousness were available for only 16 sites.

Correlation coefficients were calculated between storm variables and runoff loads (Table 5). Most loads were correlated with at least two storm variables; SRP was correlated only with rainfall intensity, but TKN was correlated with all four storm variables. All runoff loads except for SRP were positively correlated with precipitation amount, but coefficients were low. The strongest relationships were for COD ($r = 0.53$) and TKN ($r = 0.50$). Five pollutant loads, all forms of N and P, were correlated with rainfall duration. All constituents except DP and NN were correlated with rainfall intensity. DP, TKN and NN were negatively correlated with days since the last event, which is counter-intuitive to the idea of a buildup/washoff process for pollutants. Precipitation amount seems to be the main factor determining pollutant loading in the TCMA.

Correlations between runoff loads and watershed characteristics (Table 5) showed positive correlations with drainage area for all loads except Pb; r values ranged from 0.28 (TSS) to 0.50 (NN). Six variables, including TSS, TP, TN and NN, were negatively correlated with residential land use. All variables except SRP and TKN were positively correlated with commercial and industrial land use, but coefficients were low (0.2–0.3). Five variables were correlated with open space, again with low coefficients (0.19–0.28). No loads were significantly correlated with percent impervious area, but as noted above, such data were available for only 16 sites.

Table 5
Pearson correlation coefficients (r) between stormwater loads and storm variables and watershed variables (log-transformed data)

	Storm variables[a]				Watershed variables[a]			
	PRE	DUR	INT	LAS + 1	DA	RES + 1	CI + 1	OP + 1
TSS	0.411	—	0.365	—	0.283	−0.298	0.289	0.263
VSS	0.359	—	0.317	—	0.382	−0.324	0.343	0.276
TP	0.443	0.160	0.297	—	0.317	−0.202	0.187	—
DP	0.271	0.249	—	−0.265	0.419	—	0.249	—
SRP	—	—	0.378	—	0.426	—	—	—
COD	0.530	—	0.229	—	0.461	−0.282	0.328	0.281
TKN	0.503	0.201	0.245	−0.204	0.404	—	—	—
NN	0.397	0.241	—	−0.212	0.503	−0.241	0.222	0.192
TN	0.433	0.232	0.186	—	0.432	−0.285	0.302	0.197
Pb	0.450	—	0.397	—	—	—	0.231	—

[a] PRE = precipitation (cm); DUR = duration (h); INT = intensity (cm/h); LAS = days since last event >25 mm; DA = total drainage area (ac); RES = residential area (%); CI = commercial and industrial land-use area (%); OP = public and open area (%). Note: no correlations significant at $p < 0.01$ were found for % impervious area (IMP).

Table 6
Pearson correlation coefficients between event-mean concentrations in stormwater and storm and watershed variables (log-transformed data)

	Storm variables[a]				Watershed variables[a]				
	PRE	DUR	INT	LAS + 1	DA	RES + 1	CI + 1	OP + 1	IMP + 1
TSS	—	−0.256	0.279	0.122	−0.107	—	—	0.144	—
VSS	—	−0.387	0.423	0.204	—	—	—	—	−0.293
TP	—	−0.198	—	0.354	−0.177	0.134	−0.246	—	—
DP	−0.348	−0.375	0.233	0.326	−0.411	0.252	−0.406	−0.305	—
SRP	—	—	—	0.193	—	—	—	—	—
COD	−0.366	−0.401	0.238	0.543	−0.250	—	—	—	−0.305
TKN	−0.180	−0.381	0.317	0.360	−0.212	—	—	—	—
NN	−0.265	−0.237	—	0.338	—	—	—	—	—
TN	−0.183	−0.243	—	0.371	—	—	—	—	−0.200
Pb	—	—	—	0.514	—	—	—	—	0.229

[a] See Table 5 for key to symbols.

All EMCs except for SRP and Pb were correlated with at least two storm variables (Table 6). EMCs of DP, COD, TKN, NN, and TN were negatively correlated with precipitation amount. The strongest relationships were for DP ($r = -0.35$) and COD ($r = -0.37$). In contrast, only 22% of the >500 correlations between EMCs and runoff volume examined in NURP were found to be statistically significant [1], and both positive and negative correlations were found. Overall, NURP concluded that there is no significant linear correlation between EMCs and runoff volume.

All variables except SRP and Pb were negatively correlated with rainfall duration, which suggests that long storms generate more dilute runoff. Five constituents (TSS, VSS, DP, COD and TKN) were weakly correlated with rainfall intensity; r values ranged from 0.23 to 0.42. All concentrations were correlated with time since the last event, supporting the idea that pollutants build up during dry periods. Correlation coefficients ranged from 0.12 for TSS to 0.54 for COD.

Significant correlations were less common between EMCs and watershed characteristics (Table 6). Most correlations were negative (decreasing concentration with increasing value of the watershed characteristic). Most of the constituents had significant correlations with one or two watershed characteristics, but DP was correlated with four watershed characteristics, and SRP and NN were not correlated with any. Concentrations of five constituents were negatively correlated with drainage area (r ranging from -0.11 for TSS to -0.41 for DP). EMCs for TP and DP were positively correlated with residential land use and negatively correlated with commercial and industrial land use. TSS was positively correlated with public and open space ($r = 0.14$), but DP was negatively correlated ($r = -0.31$). VSS, COD, and TN were negatively correlated with percent impervious area, but Pb was positively correlated with imperviousness ($r = 0.23$).

4.5. Estimating runoff volume

Runoff volumes were estimated by multiple linear regression using only rain-induced runoff events. Both two- and three-variable regression models were used (Table 7). Models 1 and 2 were based on the complete data set. Models 3 and 4 excluded five far outliers that generated very low runoff ($< \sim 70\,\mathrm{m}^3$) compared with the rest of the events, even though two had >50 mm of rain. The best predictive equation (model 4, $R^2 = 0.78$) estimates runoff based on total precipitation, watershed drainage area, and percent impervious area. A two-variable model that made use of more events (by not including impervious area) (model 3) had an R^2 of 0.66.

Simple runoff coefficients, calculated as total runoff divided by total precipitation (both in mm), were determined for each event with precipitation >2.5 mm. Coefficients spanned a wide range (0.001–0.761), which is not surprising given the range in storm and basin characteristics in the data. The mean coefficient was 0.157, and the median was 0.133. Ayers et al. [11] reported that annual runoff from storm-sewered watersheds in the TCMA ranged from 13% to 57% and averaged ~27% of annual precipitation. Coefficients were not correlated with storm variables but were correlated with several log-transformed land-use variables: commercial and industrial land use ($r = 0.23$) impervious area ($r = 0.35$), and residential land use ($r = -0.30$). No seasonal differences in coefficients were found. Mean coefficients for the 37 sites, where runoff was measured ranged from 0.017 to 0.587 (average over all sites = 0.153; median = 0.120).

4.6. Multiple regression estimates of loads and EMCs for pooled data set

As noted earlier, linear correlations between explanatory variables and stormwater loads and concentrations were not strong. This reflects the fact that many factors contribute to the observed runoff concentrations and loads. In an effort to take these factors into account, multiple linear regression models were computed using the whole data set to predict stormwater loads and EMCs (Table 8) for rain-induced runoff events. Standard errors were large for all equations, however, and the equations are not useful for predicting stormwater variables for future events.

Table 7
Multiple linear regression equations for estimating runoff volume (m^3)[a]

Model[a]	Constant	PRE (cm)	DA (ha)	IMP + 1 (%)	n	R^2	SEE (Log)	SEE (%)
1	1.486	0.970	0.763	—	317	0.58	0.395	113
2	0.652	1.149	0.834	0.525	178	0.74	0.276	71
3	1.443	1.035	0.793	—	314	0.66	0.349	95
4	0.553	1.121	0.839	0.600	176	0.78	0.244	61

[a] All equations have form: log (runoff volume) = Constant + $\sum a_i$ log(predictor variable); e.g. for model 1: log (runoff volume) = 1.486 + 0.97 log (PRE) + 0.763 log (DA).

Table 8
Multiple linear regression equations for estimating (A) constituent loads and (B) constituent concentrations[a]

	Const	PRE[b]	DUR	INT	LAS + 1	DA	RES + 1	CI + 1	n	R^2	SEE
(A)											
TSS	1.998	0.888	—	0.556	—	0.568	−0.446	—	263	0.45	226
VSS	3.609	0.929	—	0.622	—	—	−1.043	—	127	0.42	160
TP	−1.205	0.801	—	0.244	—	0.461	—	—	304	0.40	161
DP	−1.423	0.949	−0.183	—	—	0.621	—	−0.248	126	0.43	104
SRP	−2.142	—	—	0.676	—	0.772	—	—	68	0.33	245
COD	1.642	0.731	—	0.271	—	0.595	−0.338	—	141	0.48	112
TKN	−1.004[c]	1.044	—	0.328	0.257	0.654	—	—	200	0.57	107
NN	−1.781	1.109	−0.208	—	0.253	0.701	—	—	191	0.53	102
TN	−1.058	0.927	—	0.223	0.302	0.684	—	—	247	0.51	118
Pb	−1.319	0.883	—	0.541	—	—	—	0.315	145	0.36	281
(B)											
TSS	2.421	−0.173	0.392	0.363	−0.229	—	0.152	—	319	0.24	147
VSS	1.539	—	0.632	0.373	—	—	—	—	149	0.23	160
TP	−0.525	−0.213	—	0.514	—	−0.162	—	—	364	0.30	89
DP	−0.460[c]	−0.222	—	0.348	−0.230	—	−0.250	—	127	0.38	84
SRP	−1.402	—	—	0.807	—	—	−0.246	—	104	0.29	135
COD	2.623	−0.228	—	0.518	—	—	—	−0.629	116	0.41	88
TKN	0.187	−0.199	—	0.303	—	—	—	—	201	0.24	71
NN	−0.569	−0.158	—	0.347	—	—	—	—	251	0.20	73
TN	0.694	−0.179	—	0.271	—	—	—	−0.278	172	0.28	59
Pb	−3.072	—	—	0.638	—	—	—	0.852	135	0.14	264

[a] All equations have form: log (runoff volume) = Constant + $\sum a_i$ log(predictor variable); e.g. for TSS: log (TSS) = 1.998 + 0.888 log (PRE) + 0.556 log (INT) + 0.568(DA)–0.446 log (RES + 1).

[b] See Table 5 for key to symbols.

[c] Not significantly different from zero.

The most useful variables to predict loads were drainage area, total precipitation, and rainfall intensity, all of which are associated with runoff volume (apparently the main factor determining loads). Still, only 33–57% of the variance in load was explained by the models, and the range in SEE for estimated loads was 102–281%. Dividing the load data into seasonal groups improved some regressions, but SEEs remained high. The most useful variables to predict runoff EMCs were rainfall duration and days since last event. The coefficient for duration always was negative, suggesting dilution during long storms. The coefficient for days since last event was always positive, reflecting a buildup/washoff mechanism. The models explained only 14–41% of the variance in each EMC, and the SEEs ranged from 59% to 264%. Dividing the EMC data into seasonal groups improved some regressions slightly, but SEEs remained high.

4.7. *Analysis of sites grouped by land use and size*

Since regression models using the entire data set had large uncertainties, the sites were divided into groups with similar land-use characteristics. The working hypothesis was that such sites would behave similarly and yield more accurate models. Six groups were defined based on dominant land use and watershed size: (1) urban residential, ⩽40 ha; (2) urban residential, > 40 ha; (3) suburban residential, ⩽40 ha; (4) suburban residential, > 40 ha; (5) commercial/industrial; (6) mixed land use. Sites in Groups 1–4 had at least 50% residential land use. Sites in Group 5 had at least 50% commercial and industrial land. Group 6 sites had no single land use representing > 50% of the watershed. Due to the lack of information, 15 sites were not categorized. Urban versus suburban distinctions were based on geographic location and density of residential housing [22]. Using these classifications, we calculated runoff and EMC regression equations and runoff coefficients for each group to determine whether better estimates could be obtained for each group than for the data set as a whole.

Linear regressions to estimate runoff volumes for each group (Table 9) were computed using two or three log-transformed variables, one of which was total precipitation. Except for Groups 1 and 2 (urban sites), each group regression explained more variance in runoff volume and fit the data better than Model 3, the two-variable model using the pooled data. The regressions for Groups 3–5 had smaller SEEs than Model 4, the three-variable model using pooled data.

Mean and median runoff coefficients for events with precipitation >2.5 mm were in the range 0.1–0.2 for all groups except commercial/industrial sites (mean = 0.35), which may reflect high imperviousness for commercial/ land uses. However, coefficients at these sites varied greatly and spanned the full range of values.

In most cases, ranges of the EMCs in each land-use group were less than the ranges for each constituent in the whole data set (Table 10). Grouping sites by land use and size thus provides better estimates of expected EMCs at unmonitored sites for which watershed characteristics are known. Box plots of EMCs (Fig. 4) for the water quality variables in the land-use groups were examined for overlap of 95% confidence intervals for median values. Significant differences in EMCs among land use groups were found for all constituents. EMCs of TSS, TP, SRP and TN were higher for urban residential sites than for large suburban residential sites. Urban residential and small suburban residential sites had higher EMCs for SRP than the commercial/ industrial sites and higher EMCs for TP than the mixed land-use sites. EMCs for the small suburban residential sites were significantly higher than those for large suburban residential sites for all constituents except NN and Pb, possibly because the greater storage in larger watersheds traps constituents and decreases runoff volumes and concentrations. In contrast, no significant differences in EMCs were found between the two sizes of urban residential sites. Commercial/industrial and small suburban sites had higher EMCs for TSS than urban residential sites, and commercial/industrial sites had higher EMCs for TSS, COD, and Pb than large suburban residential sites. Our results thus differ from those reported for NURP [2], which found no statistically significant differences in EMCs among three land-use types (residential, mixed, commercial) for a set of variables similar to those studied here.

Since differences in EMCs were found among the land-use groups, we hypothesized that the separate regression equations for each group would provide better estimates of pollutant EMCs. Table 11 lists the regressions for each group that are better than the regressions for the pooled data set. These equations had smaller SEEs (and usually larger R^2 values than regressions that used the whole data set. As before, all models were computed using log-transformed data.

Regression equations for both urban residential groups had smaller SEEs for TSS, TP and TKN than

Table 9
Multiple linear regression equations for estimating log runoff volume (m^3)[a]

Group	Const	PRE[b] (cm)	INT (cm/h)	DA (ha)	LAS + 1 (d)	RES + 1 (%)	IMP + 1 (%)	n	R^2	SEE (log)	SEE (%)
1	2.553	0.864	—	—	—	—	—	24	0.56	0.358	99
2	0.896	0.896	—	1.074	—	—	—	96	0.44	0.421	125
3	1.232	1.208	0.184	0.920	—	—	—	52	0.89	0.154	37
4	2.314	0.908	—	—	−0.190	—	0.653	58	0.77	0.174	42
5	3.222	1.294	—	—	—	−0.257	—	12	0.99	0.052	12
6	2.907	1.293	—	—	—	—	—	49	0.68	0.270	69

[a] All equations have form: log(runoff volume) = Constant + $\sum a_i$ log(predictor variable); e.g. for group 1: log(runoff volume) = 2.553 + 0.864log(PRE).

[b] See Table 5 for key to symbols.

Table 10
Range of event-mean concentrations by site grouping (mg/L)

Group	1	2	3	4	5	6	All
TSS	16–636	3–1570	7–3577	6–2400	42–418	12–3240	2–3577
VSS	—	—	4–416	3–416	—	2–1690	2–1690
TP	0.05–1.84	0.03–3.81	0.11–9.40	0.08–3.40	0.22–0.77	0.04–1.80	0.03–9.40
DP	—	—	0.05–1.40	0.01–0.53	—	0.02–0.33	0.01–1.40
SRP	0.004–1.40	0.01–1.10	0.05–0.58	0.02–0.18	0.02–0.04	0.01–0.31	0.003–1.40
COD	70–330	39–190	23–814	22–1060	54–319	28–2030	22–2030
TKN	1.20–5.40	1.12–6.99	0.61–13.5	0.42–18.5	1.38–7.39	0.21–18.0	0.21–18.5
NN	0.01–1.20	0.07–1.90	0.08–2.10	0.05–2.10	0.18–0.86	0.15–2.05	0.00–2.10
TN	0.44–8.79	0.52–19.4	0.82–14.7	0.60–19.1	1.80–8.18	0.43–18.6	0.43–19.4
Pb	0.00–0.20	0.00–0.40	0.007–0.91	0.001–0.41	0.028–0.27	0.00–0.53	0.00–0.91

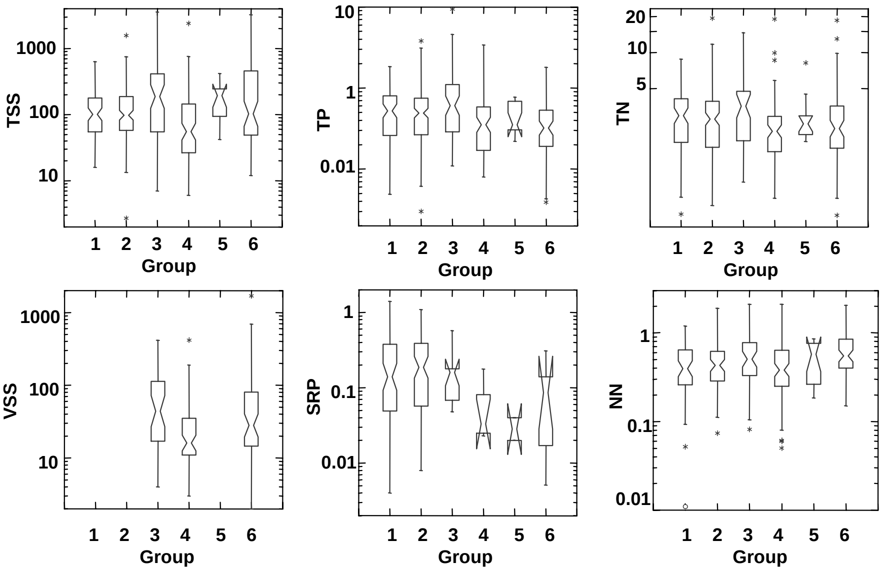

Fig. 4. Box plots of event-mean concentrations (EMCs, mg/L) by land-use group for six water quality constituents.

equations using the pooled data. The group equations for TKN also explained more of the variance than the pooled-data equation. As in the pooled data models, days since the last event was an important variable in estimating EMCs. Regression equations to estimate DP, COD, TKN and Pb for small suburban residential sites, had smaller SEEs than equations for the pooled data. Days since last event also was an important variable in these equations. The large suburban residential category had the most equations (9) with better predictive capability than the models using pooled data. Equations for all constituents but SRP had smaller SEEs than those using all the data. The equations also explained more of the variance in this group for all constituents except COD and TKN. Five models in this group had a negative term for rainfall duration; six models had a positive term for days since the last event; five models had a positive term for commercial and industrial area; and seven models had a negative term for impervious area.

Group 5 regression equations for TSS, TP, COD, TKN, TN and Pb had the greatest reduction in SEE from the equations using the pooled data. However, data were collected for only 14 events in these predominantly commercial/industrial sites. In contrast to the other EMC models, total precipitation was important in three equations; for TSS, the coefficient was positive, but for TKN and TN it was negative. Residential land use was important for the TSS, TP and Pb models. Group 6 equations for VSS, DP, NN, and Pb had smaller SEEs than the equations for the pooled data. No single explanatory variable was used in all the models for this group.

5. Summary and conclusions

Event loads and mean concentrations (EMCs) in 343 events included in this study ranged over several orders of magnitude, and the distributions were skewed with long right tails. EMCs of nutrients and TSS in stormwater were high compared with TCMA lake waters. Although pollutant loads depended primarily on runoff volume and not source of runoff (snowmelt versus rainfall), median EMCs for TP, SRP, TN, NN, and Pb were higher in snowmelt than in rainfall at most sites. Significant differences in seasonal yields and EMCs were found for most constituents. Median TP and SRP were much higher in fall and winter than in spring and summer.

Runoff volume was correlated most highly with total precipitation and drainage area. The best regression equation to estimate runoff for rain events was based on rainfall amount, watershed area, and percent impervious area ($R^2 = 0.78$).

In general, correlations between explanatory variables and stormwater loads and EMCs were weak. All loads except SRP were positively correlated with total precipitation; all except DP and NN were correlated with rainfall intensity; and all except Pb were correlated with drainage area. Pollutant EMCs were positively correlated with days since the last event, which supports the idea that pollutants build up during dry periods. Most constituents were negatively correlated with rainfall duration, which suggests that long duration storms generate more dilute runoff. Significant correlations were not common between EMCs and watershed characteristics. Precipitation amount, rainfall intensity,

Table 11
Group regression equations for estimating constituent concentrations[a]

Group 1	Const	INT[b]	LAS + 1	n	R^2	SEE	SEE
TSS	1.911	0.261	0.296	66	0.14	0.363	101
TP	−0.971		0.810	68	0.39	0.330	88
TKN	−0.428[a]		0.885	12	0.39	0.182	44

2	Const	DUR	INT	LAS + 1	RES + 1	n	R^2	SEE	SEE
TSS	2.160		0.336			113	0.12	0.400	116
TP	−7.770			0.443	3.640	122	0.28	0.315	83
SRP	−1.288			0.614		64	0.17	0.428	128
TKN	0.100[a]	−0.161		0.322		16	0.52	0.140	33

3	Const	DUR	INT	LAS + 1	RES + 1	n	R^2	SEE	SEE
DP	−1.020			0.524		33	0.33	0.258	65
COD	1.669	−0.288		0.718		37	0.53	0.319	85
TKN	0.112		0.316	0.541		42	0.42	0.264	67
Pb	32.58				−17.06	27	0.26	0.467	148

4	Const	DUR	INT	LAS + 1	RES + 1	CI + 1	OP + 1	IMP + 1	n	R^2	SEE	SEE
TSS	3.989	−0.365				0.775		−1.139	72	0.42	0.39	111
VSS	4.789	−0.306				−0.753		−2.065	49	0.55	0.31	82
TP	−1.742[a]		0.239	0.352	1.665	−0.351		−1.250	72	0.54	0.23	57
DP	−9.800		0.230	0.321	5.802	−0.770		−1.171	49	0.70	0.24	61
COD	3.357			0.529				−1.356	48	0.38	0.31	83
TKN	1.925	−0.139						−1.122	72	0.19	0.26	67
NN	−3.115	−0.150		0.389	1.323				71	0.36	0.26	66
TN	1.358	−0.144		0.272			−0.17	−0.750	72	0.32	0.22	54
Pb	−3.110			0.900		1.439	1.52		50	0.40	0.50	168

5	Const	PRE	INT	LAS + 1	RES + 1	n	R^2	SEE	SEE
TSS	1.681	0.396			0.626	14	0.72	0.179	43
TP	−0.633				0.305	14	0.44	0.159	38
COD	1.036		0.319	1.116		7	0.94	0.075	17
TKN	0.341	−0.261				14	0.32	0.167	40
TN	0.435	−0.243				14	0.34	0.148	35
Pb	−1.553				0.635	12	0.40	0.245	61

6	Const	DUR	INT	LAS + 1	RES + 1	CI + 1	IMP + 1	n	R^2	SEE	SEE
VSS	4.791		0.657			−2.675		45	0.45	0.461	144
DP	1.317	−0.158					−1.531	45	0.44	0.223	55
NN	0.426			0.208	2.432		−3.202	46	0.41	0.186	45
Pb	0.775		0.499			−2.930		38	0.63	0.525	182

[a] All equations have form: log (concentration, mg/L) = Constant + $\sum a_i$ log(predictor variable); e.g. for group 1 TSS, log (TSS) = 1.911 + 0.261 log (INT) + 0.296 log (LAS + 1).

[b] See Table 5 for key to predictor variables.

and drainage area were the most important variables to predict event loads. Rainfall duration and days since the last event were the most important variables in EMC models. Uncertainty was high for both load and EMC models using the pooled data set.

Regression models for runoff volume and EMCs for six groups of sites with similar size and dominant land use had better predictive ability in some but not all cases. Equations for three of the six groups explained more variance in runoff volume and had smaller SEEs than the best model for the entire data set. Within-group EMC ranges usually were smaller than overall ranges for constituents, and regression models for EMCs had improved predictions for some constituents in each group. Improved TKN models were found for five groups, and improved TSS, TP, and Pb models were found for four groups. However, all but one TSS model had SEE > 100%, and VSS and SRP were not modeled accurately in any case.

Based on these findings, we conclude that the group regression equations are the best method to estimate EMCs for small unmonitored TCMA watersheds. If loads are needed, estimated EMCs can be combined with runoff volume estimates. If land-use information is not available, the pooled regression equations, which typically had higher uncertainty, can be used, and results can be compared with the ranges and EMCs of similar types of watersheds.

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References

[1] Novotny V, Olem H. Water quality: prevention, identification, and management of diffuse pollution. New York: Van Nostrand Reinhold, 1994.

[2] US Environmental Protection Agency, 1983. Results of the nationwide urban runoff program, vol. I. Final Report, Water Planning Division, US EPA, Washington, DC.

[3] Driver NE, Tasker GD. Techniques for estimation of storm-runoff loads, volumes, and selected constituent concentrations in urban watersheds in the United States. US Geological Survey of Water-Supply Paper 2363, 1990.

[4] Payne GA, Ayers MA, Brown RG. Quality of runoff from small watersheds in the Twin Cities metropolitan area, Minnesota—hydrologic data for 1980. US Geological Survey of Open-File Report 82-504, 1982.

[5] Sonzogni WC, Chesters G, Coote DR, Jeffs DN, Konrad JC, Ostry RC, Robinson JB. Pollution from land runoff. Environ Sci Technol 1980;14(2):148–53.

[6] Kappel WM, Yager RM, Zarriello PJ. Quantity and quality of urban storm runoff in the Irondequoit Creek basin near Rochester, New York. Part 2: quality of storm runoff and atmospheric deposition, rainfall-runoff-quality modeling, and potential of wetlands for sediment and nutrient retention. US Geological Survey of Water Resources Investigation Report 85-4113, 1986.

[7] Rasmussen PP. Concentrations, loads, and yields of selected water-quality constituents during low flow and storm runoff from three watersheds at Fort Leavenworth, Kansas, May 1994 through September 1996. US Geological Survey of Water Resources Investigation Report 98-4001, 1998.

[8] Mitton GB, Payne GA. Quantity and quality of runoff from selected guttered and unguttered roadways in northeastern Ramsey County, Minnesota. US Geological Survey of Water Resources Investigation Report 96-4284, 1997.

[9] Mulcahy JP. Phosphorus export in the Twin Cities metropolitan area. Technical Report Metropolitan Council, St. Paul, MN, 1990.

[10] Bannerman RT, Owens DW, Dodds RB, Hornewer NJ. Sources of pollutants in Wisconsin stormwater. Water Sci Technol 1993;28(3-5):241–59.

[11] Ayers MA, Brown RG, Oberts GL. Runoff and chemical loading in small watersheds in the TCMA, Minnesota. US Geological Survey of Water Resources Investigation Report 85-4122, 1985.

[12] Oberts GL. Water resources management: nonpoint source pollution. Publication no. 10-82-016, Metropolitan Council, St. Paul, MN, 1982.

[13] Arntson AD, Tornes LH. Rainfall-runoff relationships and water-quality assessment of Coon Creek watershed, Anoka County, Minnesota. US Geological Survey of Water Resources Investigation Report 84-4013, 1985.

[14] Oberts GL. Design considerations for management of urban runoff in wintry conditions. Proceedings of the International Conference on Urban Hydrology under Wintry Conditions. Narvik, Norway, 1990.

[15] Walker JF, Graczyk DJ, Corsi SR, Owens DW, Wierl JA. Evaluation of nonpoint-source contamination, Wisconsin: land-use and best-management-practices inventory, selected streamwater-quality data, urban-watershed quality assurance and quality control, constituent loads in rural streams, and snowmelt-runoff analysis, water year 1994. US Geological Survey of Open-File Report 95-320, 1995.

[16] Oberts GL. Pollutants associated with sand and salt applied to roads in Minnesota. Water Resour Bull 1986;22(3):479–83.

[17] Wilson G. Analysis of urban stormwater quality from the Minneapolis chain of lakes watershed. MS thesis. University of Minnesota, Minneapolis, MN, 1993.

[18] Fisher GT, Katz BG. Analysis of urban storm-water runoff characteristics of four basins in the Baltimore metropolitan area, Maryland. US Geological Survey of Water Resources Investigation Report 84-4099, 1984.

[19] Niehus CA. Characterization of stormwater runoff in Sioux Falls, South Dakota, 1995–96. US Geological Survey of Water Resources Investigation Report 97-4070, 1997.

[20] Prych EA, Ebbert JC. Quantity and quality of storm runoff from three urban catchments in Bellevue, Washington. US Geological Survey of Water Resources Investigation Report 86-4000, 1986.

[21] Donigian AS, Huber WC. Modeling of nonpoint source water quality in urban and non-urban areas. Environ

Research Lab, Off Res Develop, US Environmental Protection Agency, Washington, DC, 1991.

[22] Anderle T. Analysis of stormwater runoff, lake water quality for the Twin Cities metropolitan area. MS thesis, University of Minnesota, Minneapolis, MN, 1999.

[23] National Oceanic and Atmospheric Administration. Climatological data—Minnesota. Monthly Summaries, 1980–98.

[24] National Oceanic and Atmospheric Administration. Hourly precipitation data—Minnesota. Monthly Summaries, 1987–98.

[25] Wilkinson L. SYSTAT 8.0 statistics. Chicago, IL: SPSS Inc., 1998.

[26] Monson BA. A primer on limnology. 2nd Edition. Public Report. Series #6, Water Resources Center, University of Minnesota, St. Paul, MN, 1992.