An Examination of the Relationship Between Watershed Structure and Water Quality in the Valley Creek and Browns Creek Watersheds

by

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OTHER REPORTS

This TCQI project funded three separate reports, only the second of which is contained in this document:

1. **Watershed Hydrology of Valley Creek and Browns Creek: Trout streams influenced by agriculture and urbanization in eastern Washington County, Minnesota, 1998-99**
2. **An Examination of the Relationship Between Watershed Structure and Water Quality in the Valley Creek and Browns Creek Watersheds** *(this document)*
3. **An Atlas of Watershed Structure in the Browns Creek and Valley Creek Basins** *(available in both hard copy and as a searchable PDF document on CD-ROM)*

TABLE OF CONTENTS

LIST OF TABLES

An Examination of the Relationship Between Watershed Structure and Water Quality in the Valley Creek and Browns Creek Watersheds

By
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ABSTRACT

Regression analysis was used to examine the effects of the physiographic, hydrographic, and land cover structure of the Valley Creek and Browns Creek watersheds in Washington County, MN on several measures of water quality in streams (as measured in both high and low flow regimes), lakes, and groundwater sampled within the two watersheds. Findings suggested that interpretations of water quality within the two creeks must consider the mix of urbanization with other land uses, particularly forest cover and wetland area in the watershed. The influence of land cover patterns on water quality must also be considered relative to the topography on which they occur as well as the drainage properties of the soils and surficial geologic deposits that underlie the land cover pattern. Finally, interactions between the imperviousness of the watershed s surfaces and flow regime affect both the quantity and the quality of runoff flowing into the creeks.

INTRODUCTION

Water is an effective vector of both dissolved and suspended constituents. Surface water and groundwater flows within a watershed typically converge on streams as the ultimate point of discharge. The hydrology (both quality and quality) of stream water is a product of interactions between physiographic, hydrographic, and land cover attributes of the watershed through which and over which surface water and groundwater travel in their path toward stream discharge. Therefore, stream water hydrology provides an integrated measure of environmental quality within a watershed that is a direct product of interaction between physical, hydrologic, and land cover dimensions[1] of watershed structure. Trout streams are particularly sensitive indicators of the integrated, cumulative environmental quality in a watershed because trout and their invertebrate food base depend on high water quality.

Effects of Urbanization on Trout Stream Hydrology

The greatest perceived threat to trout stream water quality in the Twin Cities Metropolitan Area is urbanization related to a rapidly expanding population base. During the decade of the 1990 s, the percent of statewide population accounted for by residents living in the total metropolitan area increased from 58% to 60%. Within the metropolitan area, the urban core grew by three percent while the developing fringe expanded by 28%. Thus, much of the urban growth and development occurring in the state exists within the developing fringe of the metropolitan area. Of the 545,380 new residents in the state during the 1990 s, 68% found homes within the developing fringe[2]. Streams located within the developing fringe provide habitat for most of the remaining viable trout populations in the metropolitan area.

Urbanization can radically alter the hydrology of trout streams by providing new sources of suspended and dissolved materials (e.g., silt, nutrients, petrochemicals, heavy metals, etc.) that are detrimental to the trout stream ecosystem. Urbanization can also increase the impervious area in a watershed, thereby increasing runoff quantities and velocities, peak flows, and attendant erosion. The increased temperature of summer runoff from warm impervious surfaces is especially damaging to trout populations.

The adverse effects of urbanization on trout stream hydrology can be exacerbated depending upon the physiographic and hydrographic conditions present in the locale where development occurs. For example, the effects of urbanization on trout stream hydrology are likely to be accentuated in watersheds containing structural characteristics that promote runoff rather than infiltration of surface flows. Thus, examinations of the

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[1] Each quantifiable attribute of watershed structure may be represented as an independent axis in multivariate space, and each watershed can be plotted as a point in this multidimensional space. In this sense, the physiographic, hydrographic, and land cover attributes of the watershed may be viewed as dimensions of watershed structure.

[2] Peterson, D. The new Minnesota: More urban, more diverse. Star Tribune. Thursday, March 29, 2001. p.1.

relationships between land cover and hydrological performance of a stream must consider the physical and hydrological structure of the watershed in which the land cover exists.

Valley Creek and Browns Creek: Two Washington County Trout Streams

Valley Creek in southeastern Washington County, and Browns Creek in east-central Washington County are notable trout streams in the Twin Cities Metropolitan Area. Their hydrologies provide sensitive, integrative measures of watershed quality in a region where such measures are most needed. The eastern portion of Washington County is among the fastest growing regions of the Metropolitan Area. The watershed of Valley Creek is largely rural in nature, with 25% of the land area still devoted to agricultural uses and over 30% of the watershed area in forest cover. Lawn and impervious surfaces, two measures of urbanization, collectively cover approximately 12% of the Valley Creek watershed. Urban and agricultural land uses within the watershed are physically removed from the immediate valley of most of the creek s perennial reaches. The creek harbors naturally reproducing brook, brown, and rainbow trout populations.

The Browns Creek watershed, on the other hand, has already experienced intensive urbanization on its eastern and southern edges from the expansion of the city of Stillwater. Approximately 10% of the Browns Creek watershed remains in agriculture, while forest covers approximately 17% of the watershed. Over 20% of the Browns Creek watershed is covered by lawn and impervious surfaces. Parcel sizes are considerably smaller in Browns Creek, with parcels under one acre in size accounting for 8% of the watershed area. Such parcels account for less than 1% of the land area in the Valley Creek watershed. Over two-thirds of the Valley Creek watershed area is divided into parcels exceeding 10 acres in size, while such parcels account for less than half of the Browns Creek watershed area. Because the Browns Creek watershed has already experienced more intensive urbanization, the hydrologic regime of Browns Creek has been more severely disturbed than is true for the Valley Creek hydrologic regime. The differences in the development patterns between the two watersheds are attributable in part to the fact that the City of Stillwater provides a regional sewage treatment system that extends into adjacent hinterlands. The availability of this civic infrastructure has permitted higher densities of development to occur in the Browns Creek watershed than is true in the Valley Creek watershed.

The physical and hydrologic characteristics of the two watersheds have some important similarities and differences. Both watersheds contain similar patterns of bedrock geology, with St. Croixan sedimentary formations created during the later phases of the Cambrian and Ordovician Periods being the predominate formation. The two watersheds contrast with one another in terms of their surficial geology. The Browns Creek watershed is composed of two principal surficial geologic formations. The Twin Cities Formation is a series of glacial moraine formations deposited during the later phases of the Wisconsinan glaciation. These morainal deposits are associated with both the Superior lobe, which overspread central and northern Washington County approximately 35,000 years BP (before present), and the Grantsburg sublobe of the Des Moines lobe which overspread northwestern Washington County approximately 16,000 years BP. The Mississippi Valley Formation is a series of outwash plains deposited by the melting of the Superior and Des Moines ice lobes. The Valley Creek watershed also contains expansive areas of the Twin Cities and Mississippi Valley Formations. However, within this dominant matrix, the Browns Creek watershed contains more extensive deposits of glacial lake basins and organic deposits. In addition, the southern portion of the Valley Creek watershed contains portions of the Taopoli Plain, a morainal formation deposited during pre-Wisconsinan glaciations. The Taopoli Plain morainal deposits are at least 100,000 years older than the Superior lobe deposits. Because the Taopoli Plain landscape is considerably older than the Twin Cities Formation or the Mississippi Valley Formation, it has experienced considerably more erosion. Consequently, slopes are longer, and the drainage network of this portion of the watershed is better developed than is the drainage network in the Wisconsinan landscape. In addition, portions of the Valley creek watershed are covered with soils formed in wind-blown silt deposited immediately after the Wisconsinan glaciation. In contrast all of the soils in the Browns Creek watershed formed in either the Twin Cities or the Mississippi Valley Formations.

Opportunity to Examine Relationships Between Watershed Structure and Water Quality Performance

On the one hand, the two watersheds are quite similar to one another. They both exist in a common framework of bedrock geology, and they are situated on the eastern edge of a burgeoning metropolitan area. Similar types of development pressures exist in the two watersheds, but the two watersheds are at different points in time in the development process, and they contain varying levels of infrastructure to accommodate the pressures for growth and development. The two watersheds also possess both similarities and differences in their patterns of structural characteristics relating to surficial geology, surficial hydrology, and soils. The similarities and differences in land use, physical characteristics, and surficial hydrology between the two watersheds provide an opportunity to examine the interaction between land use and watershed structure on water quality performance.

Availability of Water Quality Data

The St. Croix Watershed Research Station of the Science Museum of Minnesota sampled about 60 locations in the two watersheds during 1998 and 1999 for a wide assortment of water quality parameters. Regular monthly or bimonthly monitoring of stream-water quality occurred at three main sites (mouth, north branch, and south branch) in both watersheds, plus three auxiliary sites in the Browns Creek watershed. The Station gathered additional surface-water grab samples on a limited basis at 15 additional stream sites and eight lakes in the Valley Creek area, and at one additional stream site and seven lakes in the Browns Creek area. All stream sites (including intermittent channels) and most lakes were within the surficial watersheds of the creeks; a few lakes outside the surficial watersheds were included because of being within the inferred groundwatersheds. Finally, the Station collected groundwater samples from four stream-bed piezometers, six bedrock wells, and seven spring sites in the Valley Creek groundwatershed, and from three stream-bed piezometers, two Quaternary-deposit wells, and four bedrock wells in the Browns Creek groundwatershed. Three other piezometers along Browns Creek were not included in data analysis because downward gradients made them potentially unrepresentative of groundwater. Nine of the piezometers were co-located at stream-sampling sites. A more complete discussion of these data and the procedures used in sampling can be found in a companion report to this report entitled Watershed hydrology of Valley Creek and Browns Creek: Trout streams influenced by agriculture and urbanization in eastern Washington County, Minnesota, 1998-99. Table 1 summarizes the sites used in sampling water quality in each watershed.

Availability of Watershed Structure Data

With funding provided from 1997 to 1999 by the Legislative Commission on Minnesota Resources, the Science Museum of Minnesota completed a project entitled "Watershed Science: Integrated Research and Education Program." As part of this project the Department of Landscape Architecture at the University of Minnesota prepared "An Atlas of Physiography, Hydrology and Land Use in the Valley Branch Watershed." This atlas documented the physiographic, hydrologic, and land use structure of the Valley Creek watershed as of 1994, and it contained the geographic information needed to characterize watershed structure for Valley Creek. This document served as a prototype for compilation of similar information in the Browns Creek watershed. Having completed development of the Browns Creek geographic and water quality databases, we could then focus on the subject of this report an examination of the relationships between watershed structure (as characterized by geology, hydrology, and land cover) in the Valley Creek and Browns Creek watersheds and various parameters of water quality in the two creeks.

Partnership Between the St. Croix Watershed Research Station and the Dept. of Landscape Architecture

The work reported in this paper represents a partnership between the St. Croix Watershed Research Station of the Science Museum of Minnesota and the University of Minnesota Department of Landscape Architecture. Compilation of the geographic information for the Valley Creek watershed was completed under a contractual relationship between the Station and the Department under auspices of the Legislative Commission on Minnesota Resources. Compilation of geographic information for the Browns Creek watershed, completion of "An Atlas of Watershed Structure in the Browns Creek and Valley Creek Basins," and the analysis of relationships between watershed structure and water quality parameters was completed under auspices of a grant to the Station from the Metropolitan Council s Twin Cities Water Quality Initiative.

PROJECT OBJECTIVES

The contribution of the Department of Landscape Architecture toward fulfillment of the Research Station s obligations to the Metropolitan Council include:

1. Compilation of a geographic information database to describe the structure of the Browns Creek watershed in terms of its bedrock and surficial geology, soils, surficial hydrology, and land cover.
2. Preparation of an atlas presenting the geographic themes used in examining the relationship between watershed structure and water quality in the two watersheds.
3. Examination of correlations between various dimensions of watershed structure as represented in the atlas and various parameters of water quality as contained in the Research Station s water-quality database. Specifically, this objective seeks to:
    a. Identify key relationships between selected parameters of surface and groundwater quality and key dimensions of watershed structure related to physiography, hydrography, and land cover; and
    b. Estimate predictive models for surface and groundwater quality in the two creeks as functions of structural dimensions related to physiography, hydrography, and land cover.

Procedures and findings of the first two objectives are discussed in An Atlas of Watershed Structure in the Browns Creek and Valley Creek Basins, a companion document to this report. This report focuses on discussions related to objective three.

METHODS

Four sets of methodological issues were critical to examining relationships between dimensions of watershed structure and parameters of water quality. These include:

1. Measurement of watershed structure variables;
2. Selection of watershed structure variables for inclusion in the analysis;
3. Selection of water quality variables for inclusion in analysis; and
4. Design of analysis procedures to examine relationships between watershed structure and water quality.

Measurement of Watershed Structure Variables

Identification of Structural Variables

The report titled "An Atlas of Watershed Structure in the Browns Creek and Valley Creek Basins" presents maps of various geographic themes relating to watershed structure in the two basins. Table 2 presents the watershed structure dimensions included in the atlas, the values delineated within the atlas for each watershed structure theme, and the sources of the information.

Some of the watershed structural class values presented in Table 2 contain inconsistencies in their dimensional classes. For example, the soil permeability dimension contains class values that are not mutually exclusive. Other structural dimensions in Table 2 contain class values that are present in one of the watersheds but not in the other. Resolution of these inconsistencies is presented in the column of Table 2 labeled Revised structural class values included in data analyses. The watershed structural analyses reported in this report are based on the data as categorized by the revised structural class values.

The compilation, processing, and analysis of the themes, as well as the preparation of the maps, used geographic information system (GIS) software produced by the Earth Systems Research Institute (ESRI) of Redlands, California. The ESRI product know as Arc-Info™ Version 7.2 provided the technology for compiling, processing, and analyzing spatial information, while ESRI s ArcView™ provided the technology for the map displays contained in the atlas. Both systems operated on a Dell Dimension XPS T850™ using a Windows NT™ operating system, and maps were produced on a Hewlett Packard DeskJet 1220c™ color inkjet printer.

Measurement of Structural Dimensions Within Sampling Basins[3]

The location of each of the 60 surface-water and groundwater sampling sites was plotted on a 7.5 minute USGS topographic quadrangle. The surficial drainage basins contributing water to the stream and lake sites were plotted and digitized for subsequent analysis. Because the six piezometers included in the data analysis were driven into the stream bed at the same locations as regularly sampled stream sites, the basins digitized for the stream sites were also presumed appropriate for the piezometer sites. Finally, the groundwater flow traces leading to each of the other 19 groundwater sites (bedrock wells, Quaternary wells, and springs) sampled were drawn on a 7.5 minute USGS Topographic Quadrangle. The alignments of the traces were estimated on the basis of groundwater levels available through the Minnesota Geological Survey's County Well Index. For the Valley Creek watershed, these levels were mapped for each aquifer by S.E. Grubb (Emmons and Olivier Resources, Lake Elmo, MN, written communication, 1999, as documented in Almendinger and Grubb, 1999); groundwater levels in the Prairie du Chien and Jordan aquifers were chosen to determine the traces used in this report, because these were the aquifers most likely to contribute groundwater to Valley Creek. For the Browns Creek watershed, groundwater levels in the Quaternary aquifer as mapped by the Minnesota Geological Survey (Kanivetsky and Cleland, 1990) were used to determine the ground water traces, because the creek apparently receives most of its groundwater from this aquifer (Almendinger, 2003). The traces were expanded by 100 meters on each side to identify a 200 meter wide strip of landscape that could be contributing water to a specified well or spring.

The stream-water sampling basins, lake-water sampling basins, piezometer sampling basins, and groundwater traces were plotted over each of the themes mapped in "An Atlas of Watershed Structure in the Browns Creek and Valley Creek Basins." The

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[3] A sampling basin is that area of the landscape that may contribute water to a sampling point.

landscape area contributing to each of the 66 included sampling sites was examined in terms of the revised structural class values for each of the watershed structural dimensions described in Table 2. The percentage of the plotted basins containing various categories of the structural dimension represented on the map was calculated. Four examples help illustrate application of this process to various dimensions of watershed structure:

1. The stream-water sampling basins were overlaid on the hydric soils map. The percentage of each basin containing hydric soils was then recorded.
2. The lake-water sampling basins were overlaid on the soil slopes map. The percentage of each basin containing soils with slopes in each of the following classes was recorded: (a) 0-3%; (b) 3-6%; (c) 6-12%; (d) 12-18%; (e) 18-25%; and (f) >25%.
3. The piezometer sampling basins were overlaid on the surficial geology map. The percentage of each basin containing surficial geologic formations in each of the following classes was recorded: (a) glacial till; (b) outwash deposits; (c) floodplain; (d) glacial lake deposits; and (e) organic deposits.
4. The bedrock-well and spring-flow trace areas were overlaid on the bedrock geology map. The percentage of each trace area containing bedrock geologic formations in each of the following classes was recorded: (a) Platteville-Glenwood Formation; (b) St. Peter Sandstone; (c) Prairie du Chien Group; (d) Jordan Sandstone; and (e) St. Lawrence and Franconia Formation.

Selection of Watershed Structure Variables for Inclusion in the Analysis

Table 3 presents the 46 variables that were used to initially characterize and measure the physiographic, hydrologic, and land cover structure for the 66 sampling basins and traces.

This study was designed to relate water-quality variables with key dimensions of watershed structure pertaining to physiography, hydrology, and land cover. Use of all 46 variables presented in Table 3 was neither practical nor necessary in this analysis. Identification of key variables to represent each dimension of watershed structure presented in Table 3 was required. The identified key variables would then serve as representatives for that dimension of watershed structure in examining relationships between watershed structure and water quality.

Identification of key representative variables for the watershed structure dimensions was conducted separately for four types of sample station basins (i.e., the 25 stream sample basins, the 15 lake sample basins, the 7 piezometer station basins, and the 19 well and spring station trace areas). The analyses conducted to identify these key variables pursued two strategies. Among the structural dimensions where only two variables are identified in Table 3 (i.e., surficial geology, depth to bedrock, depth to soil saturation, soil permeability, soil flooding, and hydric soils), the variable whose frequency distribution best approximated a normal distribution was selected to represent that structural dimension. In addition to yielding higher quality of data, such a procedure also makes sense conceptually. All of these dimensions contain two variables, and measurements on one of these variables are mutually exclusive with measurements on the other. For example, soils are classified as either hydric or non-hydric. A measurement of the percent of a drainage basin containing hydric soils would have as its inverse the percent of the basin containing non-hydric soils. Similarly, the inverse of the percent of soils in a drainage basin that never flood is the percent of the soils that do flood on a rare, occasional, or regular basis.

The collection of variables contained within each of the remaining structural dimensions on Table 3 were examined separately using factor analysis with varimax rotation, kaiser normalization, and an eigenvalue = 1.0. This statistical analysis procedure is a form of principal components analysis, and it identifies the simplest mathematical structure that can be used to describe all of the variability that exists among variables within a particular watershed structural dimension. The analysis creates factors or groups of related variables that contribute to the overall variability in a similar manner. The analysis also identifies how strongly each variable loads onto the extracted factors. These loading coefficients can be interpreted as correlation coefficients that describe the degree of association between an extracted factor and a particular variable. Variables possessing a high loading coefficient with a particular factor can be selected as representatives for that factor. For example, factor analysis of the land cover variables in Table 3 produced three factors. Collectively, the three factors explained 89% of the variance among all ten of the land cover variables. Each factor individually accounted for approximately 30% of the total variance. The variable identified as % of basin occupied by wetlands as interpreted from aerial photography had the strongest loading coefficient (i.e., correlation) with the first factor (0.97), and it was selected to represent that factor. In a similar manner, the variable identified as % of basin occupied by impervious surfaces had the strongest correlation with the second factor (>0.83), and it was selected to represent that factor. The variable % of basin occupied by forest had the strongest correlation with the third factor (-0.91), and it was selected represent this factor. Factor analyses of the variables in the slope and soil infiltration capacity watershed structure dimensions each produced two factors. In addition, factor analysis of the land cover dimension produced three factors. Thus, two variables were selected to represent both the slope and soil infiltration capacity dimensions, and land cover was represented by three variables.

For the stream and lake sample station basins, these analyses reduced the 46 variables described in Table 3 to 15 variables. As noted above, the slope and soil infiltration capacity dimension each contained two variables, and the land cover dimension contained three variables. The skewness of these 15 variables was subsequently examined for each type of sample station basin. Variables having skewness values exceeding 1.0 or less than -1.0 were transformed into their logarithmic (base 10) form. The final forms of the 15 variables that were used to measure watershed structure for the stream sample stations are presented in Table 4. Tables 5, 6 and 7 present the variables used to measure watershed structure for lake sample basins, the piezometer station basins and the bedrock well and spring sample traces (15, 13 and 13 variables respectively. The identification of key variables for the piezometer and bedrock well and spring sample basins deviated slightly from the procedures outlined above in a desire to examine specific relationships between land use and groundwater quality.

Selection of Water Quality Variables for Inclusion in Analysis

As noted earlier, the St. Croix Watershed Research Station of the Science Museum of Minnesota gathered both periodic and grab samples from about 66 sampling stations located in the Valley Creek and Browns Creek watersheds during the 1998 and 1999 calendar years. As many as 31 physical or chemical parameters were measured for each sample. These parameters are identified in Table 8. As noted earlier, the procedures used in gathering and analyzing these samples and a discussion of the data are presented in a companion paper by Almendinger (2003) entitled Watershed Hydrology of Valley Creek and Browns Creek.

As was true for the watershed structure variables, the use of all 31 water quality variables is neither practical nor necessary for accomplishment of the objectives of this investigation. Identification of key variables to be included in the analysis was required. Analyses were conducted separately to identify key water quality variables for the stream water samples, the lake samples, and groundwater samples (i.e., samples from the in-stream piezometers, bedrock wells, Quaternary wells, and springs were aggregated together).

The identification of key variables followed two strategies. Some of the variables in Table 8 such as dissolved oxygen, total suspended solids, total nitrogen and total phosphorous are prototypical indicators of water quality. These prototypical indicator variables were selected for inclusion in the study because of their standard use in water quality investigations.

In addition to hand-selecting specific variables for inclusion in the analysis, factor analysis was conducted on the 31 water quality parameters. As noted earlier, this statistical analysis identifies the simplest mathematical structure that can be used to describe all of the variability that exists among a set of variables. The analysis creates factors or groups of related variables that contribute to the overall variability in a similar manner. The analysis also identifies a loading coefficient that can be interpreted as describing the correlation between each variable and each factor. Based on the magnitude of the loading coefficients, a variable can be selected as a representative for each of the various factors that are extracted. In addition, the amount of total variability that is accounted for by all factors is defined. This measures the overall combined strength of all factors in explaining variability among all of the variables entered into the analysis. The relative strength of each factor in explaining total variability is indicated by a statistic known as eigenvalue.

Factor analysis was conducted separately on the stream water samples, lake samples and groundwater samples. For purposes of conducting the factor analyses, missing values for a particular variable in each of these analyses were replaced by mean values for the respective variable. After selecting variables to serve as representatives for the factor structures that emerged from the three factor analyses, the distributions of selected variables were examined. This analysis was conducted for only those samples containing actual (as opposed to missing) values. Variables having skewness values exceeding 1.0 or less than -1.0 were transformed into their logarithmic (base 10) values. The results of these analyses are presented in Tables 8, 9 and 10, respectively, and they are discussed below.

The factor analyses performed on the variables describing the watershed structure dimensions were driven by a desire to find the most parsimonious combination of variables to describe a set of a priori determined dimensions. For watershed structure dimensions in Table 3 that contained more than two variables, the factor analyses were conducted to determine which combination of variables best described the total variance among all variables associated within a particular dimension. The factor analyses performed on the water quality variables, on the other hand, were conducted in an attempt to define the most logical mathematical structure of variance among 31 parameters of water quality. Furthermore, the factor analyses were conducted on three different types of water (i.e., flowing surface water, lake water, and groundwater). Thus, a more detailed presentation of the water quality parameter factor analysis is presented.

Stream Water Quality Variables

Table 8 presents the results of the factor analysis conducted on the water quality variables for the 612 stream water quality samples. The analysis extracted nine factors, which collectively accounted for 81% of the total variability in the 31 variables.

The strongest factor accounted for 30.3% of the total variance, and variables loading strongly on this factor include calcium (0.92), magnesium (0.91) and strontium (0.94). Calcium and magnesium are often indicators of the presence of groundwater. Calcium was selected as a representative for this factor because it is a major cation (as opposed to strontium) and because its loading coefficient was slightly larger than that of magnesium. The second factor accounted for 13.4% of the total variance. Variables loading most strongly on this factor include dissolved inorganic carbon (0.86) and total phosphorous (-0.77). These coefficients suggest that this factor is also a groundwater signal, and the dissolved inorganic carbon variable was selected as the representative variable for this factor. The third factor accounted for 9.9% of the total variance with sodium (0.91) and chloride (0.94) having the strongest loading coefficients. These loading coefficients suggest this factor may be an indicator of surface runoff events containing quantities of road salt. Chloride was selected as the indicator variable for this factor.

The fourth factor accounted for 7.0% of the total variance. Total nitrogen, with a loading coefficient of 0.86, was the only variable to load substantially on this factor. The fifth factor accounted for 5.4% of the total variance. Iron (-0.79) and manganese (-0.74) loaded most strongly on this factor, and iron was selected as the representative for factor five. The sixth factor appeared to be an indicator of surface runoff activity, and the two variables possessing the strongest loading coefficients were total suspended solids (0.90) and volatile suspended solids (0.88). Total suspended solids was selected as a representative for this factor which accounted for 4.6% of the total variance.

Factor seven accounted for 3.7% of the total variance. Variables loading most strongly on this factor include heavy oxygen (0.82) and deuterium (0.82). Heavy oxygen was selected as the indicator for this factor, which appears to a signal for the evolution of groundwater into surface water as evaporation occurs. One variable, percent dissolved oxygen, loaded onto the eighth factor (0.79), and this factor accounted for 3.3% of the total variance. Finally, the ninth factor also accounted for 3.3% of the total variance. The variable possessing the strongest loading coefficient (pH at 0.89) was selected as a representative for this factor. In addition to the nine variables selected as representatives for the nine factors that emerged from the factor analysis, total phosphorous was also selected because of its well-known importance in aquatic ecology.

In summary, ten variables were selected for inclusion in the analysis of stream water quality and watershed structure. After transforming some variables to their logarithmic (base 10) forms, as appropriate, these variables included calcium, dissolved inorganic carbon, log (base 10) chloride, total nitrogen, log (base 10) iron, log (base 10) total suspended solids, heavy oxygen, % dissolved oxygen, pH, and log (base 10) total phosphorous.

Lake Water Quality Variables

Table 9 presents the results of the factor analysis conducted on the water quality variables for the 47 lake water quality samples. The analysis extracted seven factors, which collectively accounted for 88% of the total variability in the 31 variables.

The factor structure of the lake water sample analysis is similar to that from the stream water sample analysis. While there is variability in terms of when a variable emerged in the factor structure, the list of representative variables emerging from the lake water analysis is identical to the list of representative variables emerging from the stream water analysis. The first factor to emerge from the lake water analysis accounted for 27.4% of the total variance, and calcium had the strongest loading coefficient on this factor (0.95). Factor two accounted for 24.1% of the total variance. While aluminum, barium, manganese and bromide all loaded more strongly than iron on this factor, iron was selected as a representative variable for this factor because of its relatively high loading coefficient (0.91) and because of a desire to maintain consistency in methods with the stream water analysis. The third factor accounted for 9.7% of the total variance, and total suspended solids had the strongest loading coefficient with this factor (0.90).

Percent dissolved oxygen loaded most strongly on the fourth factor (0.90), and this factor accounted for 9.2% of the total variance. Total nitrogen loaded most strongly on the fifth factor (0.89), and this factor accounted for 7.1% of the total variance. Factor six accounted for 6.9% of the total variance, and chloride loaded most strongly (0.95) on this factor. Finally, pH was selected as a surrogate for the seventh factor. In addition to selecting these seven variables as surrogates for the factor structure that emerged from the lake water analysis, total phosphorous was also selected for inclusion.

In summary, eight variables were selected for inclusion in the analysis of lake water quality and watershed structure. After transforming variables to their logarithmic (base 10) forms, as appropriate, these variables included calcium, log (base 10) iron, log (base 10) total suspended solids, % dissolved oxygen, log (base 10) total nitrogen, chloride, log (base 10) pH, and log (base 10) total phosphorous.

Groundwater Quality Variables

Table 10 presents the results of the factor analysis conducted on the water quality variables for the 48 groundwater quality samples. The analysis extracted ten factors, which collectively accounted for 86% of the total variability in the 31 variables. The factor structure of the groundwater sample analysis is similar to that from the stream water and lake water sample analyses, and the list of representative variables emerging from the groundwater analysis is identical.

Three additional considerations affected selection of the groundwater variables. Some of the variables (i.e., pH and % dissolved oxygen) had a low number of actual measurements, and they were removed from further analysis. Because this analysis was being conducted exclusively on groundwater samples, only the dissolved forms of nutrient variables were selected (i.e., dissolved nitrogen and dissolved phosphorous as opposed to total phosphorous or total nitrogen). Finally, the distribution of selected variables varied slightly between the 20 piezometer samples and the 24 well and spring samples.

Seven variables were selected for inclusion in the analysis of groundwater quality and watershed structure. After transforming variables to their logarithmic (base 10) forms, as appropriate, these variables included calcium, dissolved inorganic carbon, iron, log (base 10) heavy oxygen, log (base 10) dissolved nitrogen (for piezometer samples), dissolved nitrogen (for bedrock well samples), chloride, and log (base 10) dissolved phosphorous.

Design of Analysis Procedures to Examine Relationships Between Watershed Structure and Water Quality[4]

Design of procedures to analyze relationships between watershed structure variables and water quality variables proceeded in three phases. Since the stream water samples were gathered under three different flow regimes, the first phase examined relationships between the water quality variables and the flow regime in which they were collected. Bivariate relationships were then examined between water quality variables selected for the stream, lake, piezometer and bedrock well samples and watershed structure variables selected for the basins draining into the respective sampling stations. Finally, multivariate relationships between watershed structure variables and each of the selected water quality variables were examined.

Effects of Flow Regime on Stream Water Quality

The stream water samples were gathered at varying flow regimes. For Valley Creek, where hourly flow values were available, low flows were defined as those at or below the 10th percentile, medium flows from the 10th to the 90th percentile, and high flows above the 90th percentile, for all flows measured for the calendar year. For Browns Creek, not enough hourly flows were available to calculate percentiles. Flow regimes were estimated from those at Valley Creek, except where field evidence indicated otherwise. Of the 612 total stream samples gathered, 57 were collected under low flow conditions, 384 were sampled under medium flow conditions, and 171 were gathered under high flow conditions. Before examining the effect of watershed structure on water quality parameters, the effects of flow regime on water quality needed to be ascertained.

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[4] The authors are grateful to Dr. Sanford Weisberg, Professor of Applied Statistics in the School of Statistics at the University of Minnesota for his help in designing the data analyses.

This was accomplished by performing one-way analysis of variance on each of the stream water quality variables. In these analyses, flow regime was treated as a main effect. Each of the 31 water quality variables was examined as a dependent measure to determine whether obtained values were affected by flow regime. For those water quality variables wherein flow regime significantly ($p<0.05$) affected observed values, a Scheffe Multiple Comparison test was conducted to identify the effect of flow regime.

Bivariate Effects of Watershed Structure on Water Quality

Simple correlation was used to examine the effects of selected watershed structure variables on key water quality variables. Simple correlation is a statistical analysis procedure that examines the extent to which variance (i.e., variability) in measures on one variable is associated with variance on measures for another variable. The procedure produces a coefficient of correlation (r), which describes the association or correlation between the two variables. This coefficient varies between -1.0 and +1.0. As the value approaches one (either -1.0 or +1.0), the measure of association or correlation between the two variables increases. Correlation coefficients tending toward +1.0 indicate a direct relationship between the variables, while coefficients tending toward -1.0 indicate an inverse relationship.

The focus of the analysis was on examining relationships between water quality variables measured in the stream, lake, piezometer and bedrock well samples and variables used to characterize watershed structure of the topographic or flow trace basins contributing surface or groundwater flow to each sampling station. Specifically, the interest was in determining how variance in the watershed structure variables affected variance in the water quality variables. In this analysis, each of the water quality variables was considered a dependent variable. Pearson correlation coefficients were calculated to describe the association of each dependent water quality variable with pertinent independent measures of watershed structure for the basin contributing flow to the station from which the sample was collected. In the instance of the stream water samples, partial correlation coefficients were calculated to control for the effects of flow regime on the water quality variables.

The square of the correlation coefficient (r^2) is called the coefficient of determination. This coefficient describes the amount of variance in a dependent variable that can be attributed to variance in an independent variable. This coefficient varies between 0 and 1.0. Coefficients of 0.60 mean that 60% of the variance in the dependent variable can be explained by variance in the independent variable. Coefficients of 0.95 mean that 95% of the variance in dependent variable can be explained by variance in the independent variable.

The analysis also calculates the probability that values as large as those derived from the analysis for the correlation coefficient or the coefficient of determination could have been produced by random chance. Probabilities of less than 5 chances in 100 (p † 0.05) are often recognized as being statistically significant. In a sense, statistical significance means that the effects described by the coefficients are real i.e., they are not a product of random chance. It is important to point out that a coefficient of determination can be statistically significant without being very meaningful. For example, an r^2 value of 0.33 may be statistically significant (i.e., not a product of random chance), but it still means that only one-third of the variance in a dependent variable can be explained by variance in the independent variable. Two-thirds of the variance in the dependent variable is attributable to sources other than variance on the independent variable. There is also a relationship between the probability that a correlation coefficient of a given magnitude will prove to be statistically significant and the size of the sample from which the coefficient was calculated. As the sample size increases, the magnitude of the coefficient needed to obtain statistical significance decreases. Some of the correlation analyses conducted on the stream samples were based on sample sizes that exceeded 500 records. With samples of this size, correlation coefficients as low as $r = 0.10$ may be statistically significant. Thus, a logic that is based on other than statistical significance is often needed to interpret data from samples as large as those used in this study.

Multivariate Effects of Watershed Structure on Water Quality

Step-wise multiple regression was used to examine the combined multivariate effects of selected watershed structure variables on key water quality variables. Multiple regression is a statistical analysis procedure that examines the extent to which variance (i.e., variability) in a dependent variable can be explained by variance in a specific mathematical combination of a series of independent variables. The procedure produces a coefficient of multiple correlation (R), which describes the association or correlation between the dependent variable and a specified combination of independent variables. This coefficient varies between 0 and +1.0. As the value approaches 1.0, the measure of association or correlation between the dependent and the specified combination of independent variables increases.

The square of the multiple correlation coefficient (R^2) is called the coefficient of determination. This coefficient describes the amount of variance in the dependent variable that can be attributed to variance in the combined effects of the independent variables, as specified in the regression model. As is true for the coefficient of determination in simple regression, this coefficient varies between 0 and 1.0. Coefficients of 0.60 mean that 60% of the variance in the dependent variable can be explained by variance in the independent variables. Coefficients of 0.95 mean that 95% of the variance in the dependent variable can be explained by variance in the independent variables.

The analysis also calculates the probability that values as large as those derived from the analysis for the multiple correlation coefficient (R) or the coefficient of determination (R^2) could have been produced by random chance. Probabilities of less than 5 chances in 100 ($p < .05$) are often recognized as being statistically significant. As noted earlier, statistical significance does not necessarily imply important causal relationships. For example, an R^2 value of 0.33 may be statistically significant (i.e., not a product of random chance), but it still means that only one-third of the variance in a dependent variable can be explained by variance in the independent variables. Two-thirds of the variance in the dependent variable is attributable to sources other than the independent variables.

In these analyses, independent variables measuring dimensions of watershed structure were allowed to enter the regression model using a forward step-wise procedure. In forward step-wise entry, independent variables enter the model based on their ability to contribute uniquely to the explanation of variance in the dependent variable. Thus, the first independent variable entered into the regression model accounts for the greatest amount of variance in the dependent variable. The second variable entering the model accounts for the largest amount of the remaining unexplained variance. The entry procedure continues until all variables that are capable of contributing to the explanation of variance in the dependent variable have entered the model. The effects of an independent variable in explaining variance in a dependent variable within a multiple regression analysis may be different than the effects of the same independent variable in explaining variance in the dependent variable within a simple correlation analysis. This difference is attributable to the fact that multiple regression examines the unique contribution of each independent variable to explaining total variance in a dependent variable after the contributions of more powerful independent variables have been removed from the model. In contrast, simple correlation analysis examines relationships between total variance in the dependent variable and total variance in the independent variable.

Multiple regression analysis calculates a regression coefficient for each variable entering the model and it calculates the statistical significance of this coefficient. The regression coefficient defines the effect created on the dependent variable the independent variable is changed by one unit. For example, an independent variable having a regression coefficient of 1.0 will produce one unit of change in the dependent variable for every unit of change that occurs in the independent variable. The analysis also calculates a constant, which defines the starting point of the mathematical function described by the regression model.

The parameters that are estimated by regression analysis allow construction of models that can be used to predict future occurrences either within the two watersheds wherein the study was conducted or in other watersheds. The estimated constant value and the regression coefficients can be applied to other sets of data containing similar watershed structure measurements to predict water quality conditions in other locations. The coefficient of determination provides a measure of potential accuracy in such extensions of the model. As this coefficient approaches one (1.0), there is greater assurance that functions similar to those described by the regression model will exist elsewhere. The probability estimates for both the coefficient of determination and the regression coefficients describe that likelihood that these functions are occurring simply by virtue of random chance.

These analyses were conducted separately for each of the identified stream water quality variables, each of the lake water quality variables, each of the piezometer water quality variables and each of the bedrock well water quality variables. Thus, a step-wise forward regression analysis was conducted for each of the ten variables selected to describe stream water quality, each of the eight variables selected to describe lake water quality, and each of the variables selected to describe piezometer and bedrock water quality, respectively. The dependent variables included in these analyses are highlighted in Tables 8, 9 and 10, respectively. Independent variables in these analyses include those variables previously identified in Tables 4, 5, 6 and 7, respectively.

The analysis procedure was modified slightly in examining the effects of watershed structure on stream water quality. A dummy variable was constructed to describe the flow regime occurring when the samples were collected. The original variable used to define the flow regime at the time of sampling was redefined such that low and moderate flows were combined into one category and high flows were defined as a separate category. The low/moderate flow category was assigned a value of zero (0), while the high flow category was assigned a value of one (1). Interactions between the dummy flow regime variable and the 15 watershed structure variables were calculated by multiplying each of the watershed structure variables by the dummy flow regime variable. The interaction variables were added to the list of independent variables. In the regression analysis, the dummy flow regime variable was forced into the regression model and the remaining independent variables were then allowed to enter using a forward step-wise procedure. This procedure allowed removal of the effects of flow regime prior to examining the effects of each of the watershed structure variables on the dependent water quality variables. It also allowed estimation of how the presence of high flow events altered the predictive models of the selected water quality variables.

RESULTS AND DISCUSSION

The discussion of findings is presented in three parts:

a. A discussion of the effects of flow regime on the water quality variables;
b. A discussion of the bivariate effects of selected dimensions of watershed structure on selected water quality variables; and
c. A discussion of the multivariate effects of selected dimensions of watershed structure on selected water quality variables.

Effects of Flow Regime on Water Quality Variables

Table 11 presents findings from the one-way analyses of variance that were conducted to examine the effect of flow regime on each of the 32 water quality variables for the stream samples.

Many of the stream sample water quality variables were affected significantly by flow regime. Some of these effects appear to result from high runoff events moving material from the watersheds into the creeks, while others provide evidence of high flows diluting flows attributable to baseflow from groundwater discharge. High flow regimes produced significantly ($p<0.05$) higher levels of suspended solids, phosphorous, and dissolved organic carbon. These materials typically flush out of a watershed into streams during periods of high runoff. High flows also produced significant decreases in specific conductivity, dissolved inorganic carbon, alkalinity, silicon, calcium, and magnesium. High measures of these variables are often used as indicators for the contribution of groundwater to stream flows. The fact that they were reduced during high flow events provides evidence of a change in the relative composition of channel flow between surface runoff and groundwater discharge at periods of high flow. The increased contribution of surface water during high flow events appeared to have a diluting effect on these groundwater indicator variables.

Finally, the lower levels of heavy oxygen and deuterium in the samples during high flow events point to the source of surface runoff in altering the balance of surface and groundwater in channel flow. Snow and early spring rains are isotopically lighter (i.e., more negative) compared to non-spring precipitation. For both Valley Creek and Browns Creek, the highest flows tend to be during spring snowmelt. These flows reflect the input of this isotopically-light direct runoff.

Bivariate Effects of Watershed Structure on Water Quality Variables

Findings from the examination of the bivariate effects of watershed structure on water quality are discussed separately for the stream samples, lake samples, piezometer samples and bedrock well and spring samples. This discussion examines the relationships between watershed structure variables and each of the water quality variables. This analysis includes only those watershed structure variables identified through factor analysis as reported in Tables 4 through 7 and only those water quality parameters identified through factor analysis as reported in tables 8 through 10. The discussion is based on correlation coefficients that exceed r =0.30.

Stream Sample Analyses

Table 12 presents results from the partial correlation analyses conducted with ten[5] of the water quality variables from the stream water samples as dependent measures and selected watershed structure variables as independent measures. The individual dependent measures of stream water quality are listed across the top of Table 12 while the independent measures of watershed structure are listed down the left margin of the table. The table contains only significant (p<0.05) partial correlation coefficients that describe the association between independent measures of watershed structure and dependent measures of water quality as measured in the stream samples. The partial correlation coefficients describe these relationships while controlling for variance that is attributable to the effect of differences in flow regime on the day of sample collection.

Of the 150 associations examined between water quality variables and watershed structure variables for the stream samples, 94 or slightly less than two-thirds produced partial correlation coefficients were statistically significant. Slightly less than one-third (n= 47) of the correlation coefficients had a magnitude exceeding r = 0.30. Table 12 illustrates that two of the water quality measures (pH and log 10 of total suspended solids) exhibited no correlations with watershed structure variables whose coefficients exceeded r = 0.30. Two additional water quality variables (% dissolved oxygen and log 10 total phosphorous) exhibited only one correlation with watershed structure variables whose coefficient exceeded r = 0.30. The remaining 11 variables exhibited correlations with between 3 and 12 watershed structure variables having a magnitude exceeding r = 0.30.

The preponderance of relatively low correlation coefficients in Table 12 calls into question the validity and reliability of the measurement methods used as they relate to

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[5] Total phosphorous was included along with the nine variables listed in bold face on Table 9. Total phosphorous was also selected because of its well-known importance in aquatic ecology.

both the water quality and the watershed structure variables. Such challenges are mitigated by the fact that three of the water quality variables (total nitrogen, log 10 iron and log 10 chloride) exhibited correlations exceeding r = 0.30 with at least 10 or more watershed structure variables. Many of these associations, especially for total nitrogen, are characterized by correlation coefficients exceeding r = 0.60. The attainment of these larger correlation coefficients between water quality variables and watershed structure variables lends measures of both validity and reliability to the measurement procedures used in these analyses. The preponderance of low correlation coefficients in Table 12 may also be a result of the inability of bivariate analyses strategies to capture underlying associations among the data points. This suggestion lends credence to the multivariate analyses reported subsequently in this paper.

The effects of various dimensions of watershed structure exhibiting an association characterized by a partial correlation coefficient exceeding r = 0.30 will be described separately.

1. **Total Phosphorous.** Of the 15 watershed structure variables, only the percent of the sample station s drainage basin containing forest cover exhibited a correlation with total phosphorous that exceeded r = 0.30. The inverse nature of this relationship (r = -0.44) suggests that the forest cover released less phosphorous than other cover types, as one might expect in comparison with urban or agricultural cover types.

2. **Total Nitrogen.** While the correlation coefficients between total nitrogen and the watershed structure variables were among the highest that emerged from the correlation analyses, they were also among the more difficult to interpret in an integrated manner. Several pieces of evidence suggest that total nitrogen may be a product of both overland flow processes and subsurface flows within the watersheds. Increases in wetland area within a sample station s drainage basin were associated with decreases in total nitrogen in the stream samples. This finding implies that some denitrification of runoff may occur as runoff spends more time within a wetland. An increase in wetland area would also be associated with an increase in the percentage of a sampling station s drainage basin containing slopes of less than 3%. The inverse relationship between total nitrogen and slopes less than 3% supports this proposition. Areal increases for wetlands, impervious, and forest cover types result in decreases in total area for agricultural cover. To the extent that agricultural cover is more likely to be a source for total nitrogen in overland flow, reductions in agricultural area would also lead to reductions in total nitrogen.

   Subsurface flows also appeared to affect total nitrogen levels in the stream samples. Direct relationships exist between measures of total nitrogen in channel flow and the presence within a drainage basin of a larger proportion of non-hydric soils, soils that never flood, and soils containing deep zones of saturation. Inverse relationships existed between nitrogen levels in channel flow and basins containing extensive areas of steeper slopes. The inverse relationship between the extent of impervious cover in a basin and nitrogen levels in channel flow can also be interpreted as a sign of a decreased ability of nitrogen-laden water within a basin to infiltrate into soils and move through subsurface pathways into channel flow. Collectively, these conditions relate to more nitrogen infiltrating into sampling station basins and moving through substrate toward surface runoff channels. They link conditions that promote infiltration, deep percolation and movement of subsurface watershed flows with higher levels of nitrogen in surface streams. This interpretation is refuted by the finding that higher nitrogen levels in the stream samples were inversely associated with the extent of the basin containing soils with high infiltration capacities[6]. Perhaps the increased infiltration permitted greater uptake of nitrogen by plants in the vadose zone, resulting in the retention of nitrogen within the drainage basin.

In addition to the patterns described above, measures of total nitrogen in the stream channel samples were also directly correlated with the percent of the station s drainage basin containing highly erosive soils. Nitrogen levels were also inversely correlated with the percent of the basin containing Prairie du Chien or Jordan Sandstone as the first bedrock formation.

3. **Dissolved Inorganic Carbon and Calcium.** Relationships between the measures of watershed structure and dissolved inorganic carbon paralleled those between watershed structure and calcium. In addition, dissolved inorganic carbon and calcium are often used as indicators of the presence of groundwater within channel flow. Thus, these two water quality variables are discussed jointly.

   Measures of dissolved inorganic carbon (DIC) and calcium were inversely correlated with the percent of the basin containing impervious surfaces and the percent of the basin containing till surficial geologic formations. DIC and calcium were directly related to the percent of the watershed in forest cover, the percent of the basin containing soils with high infiltration capacity (i.e., Hydrologic Group A), the percent of the basin containing soil saturation zones deeper than 72 inches, and with the percent of the basins soils that are not hydric. These findings suggest that as the basin surface area becomes more impermeable, either because of increased glacial till or because of increased human settlement, DIC and calcium measures in channel flow decline. As conditions more favorable to infiltration and deep percolation occur, DIC and calcium levels in channel flow increase. Reduced infiltration capacity may alter the balance between surface water and groundwater in the stream channel, producing conditions more favorable to the presence of surface water. Such a balance could dilute signals of groundwater contribution to channel flow, such as dissolved inorganic carbon and calcium ions. These relationships may be reversed in situations more favorable to increased infiltration, deep percolation and movement of water through subsurface flows back into the stream channel. This pattern is refuted by the finding of decreased levels of DIC and calcium in stream samples from basins containing shallower depths to bedrock. Shallower depths to bedrock would be expected to bring groundwater flows closer

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[6] Soil infiltration rates were measured indirectly in Table 12 by variables describing the percent of a sampling point s watershed that contained soils in Hydrologic Soil Group A and the percent of a sampling point s watershed that contained soils in Hydrologic Soils Groups C and D.

to the surface and increase the likelihood of groundwater flow in the channel. However, this pattern seemed not to prevail in the data.

4. **Iron.** Correlations exceeding a magnitude of r = 0.30 were associated with measures of iron ions and 10 watershed structure variables. Iron measures were directly correlated with the percent of the sample station s drainage basin containing wetlands, the percent of the basin containing highly erosive soils, the percent of the basin containing soils with low infiltration capacity, the percent of the basin containing soils with bedrock depth exceeding 60 inches, and the percent of the basin contain slopes of less than three percent. Inverse correlations existed for iron measures in the stream samples and the percent of the drainage basin in forest cover, the percent of the basin containing soils that never flood, the percent of the basins containing soils with depths to saturation exceeding 72 inches, the percent of basin s area containing non-hydric soils and the percent of the basin containing slopes exceeding 6%. This pattern is qualitatively opposite that shown for percent dissolved oxygen. Flat, saturated landscapes, especially those with organic (peat) soils, tend to report lower levels of percent dissolved oxygen, and consequently allow higher concentrations of iron, which is soluble only under reducing (i.e., low dissolved oxygen) conditions.

5. **Chloride.** As was true with the iron, correlations exceeding a magnitude of r = 0.30 were associated with chloride concentration and 10 watershed structure variables. Direct correlations existed between chloride measures in the stream samples and the percent of the sampling station s drainage basin containing wetlands, the percent of the basin containing impervious cover, the percent of the basin containing soils with bedrock depths exceeding 60 inches, the percent of the basin containing till formations and the percent of the basin containing steeper slopes. Inverse correlations existed between chloride measures and the percent of the basin containing highly erosive soils, the percent of the basin that contains soils that never flood, the percent of the basin containing soils with saturation zones deeper that 72 inches, the percent of the basin containing soils with low permeability ratings and the percent of the basin containing soils that are not hydric. Interpretation of these findings is difficult. On the one hand, more impermeable surfaces on steeper slopes may provide a ready conduit for the transport of road salts into a stream channel. The correlation of chloride measures with greater percentages of wetlands, hydric soils and flooded soils and shallower depths to soil saturation suggests that a runoff hypothesis may be particularly useful in periods of high runoff. A runoff hypothesis is not supported, however, by the findings that higher measures of chloride are associated with the presence of soils having higher rates of permeability and greater depths to bedrock. Such conditions suggest subsurface movement of chloride. On the other hand, such bedrock and permeable soil conditions may be more likely to occur in situations where population and road density are higher.

6. **Heavy Oxygen.** In the Valley Creek and Browns Creek watersheds, as in other studies, the largest concentrations of heavy oxygen (^{18}O, measured as δ^{18}O, the per

mil difference between the $^{18}O/^{16}O$ ratio in the sample versus that in standard mean ocean water) occur in lakes where evaporation has selectively removed the lighter oxygen (as $H_2{}^{16}O$ vapor) (Almendinger, 2003). In the Browns Creek watershed, the chain of lakes that includes Long Lake allows considerable evaporative concentration of $H_2{}^{18}O$. Consequently, the south branch of Browns Creek bears this heavy oxygen signature. Because this basin has a high percentage of impervious cover, this variable correlates highly with heavy oxygen. Perhaps the summertime-hot impervious surfaces cause a greater evaporative concentration of ^{18}O per unit volume than would be expected from lake evaporation alone; or, perhaps simply the evaporation within the Long Lake chain itself may be enough to create this heavy-oxygen signal. In contrast, the lightest values of oxygen were found in the snowmelt runoff (Almendinger, 2003). Thus, concentrations of heavy oxygen should correlate negatively with factors promoting such runoff (e.g., percentage of basin containing low permeability soils). However, positive correlations with the percent coverage within a basin of steep slopes (>6%) and percent of impervious cover confound this interpretation and demonstrate the importance of local hydrologic conditions. In fact, impervious surfaces could be hypothesized to correlate with *both* heavy and light oxygen isotopes: heavy oxygen isotopes could result in summer from high evaporation rates per unit volume from hot impervious surfaces, and light oxygen isotopes could result during winter and spring from runoff of isotopically light snowmelt. Impervious surfaces may correlate with the *range* in isotopic content, whereas systems with more infiltration and less overland runoff may have more equable isotopic signals because of mixing along groundwater flow paths. Further work would need to be done to test this hypothesis.

Lake Sample Analyses

Table 13 presents results from the correlation analyses conducted with eight of the water quality variables from the lake water samples as dependent measures and selected watershed structure variables as independent measures. The individual dependent measures of lake water quality are listed across the top of Table 13 while the independent measures of watershed structure are listed down the left margin of the table. The table contains significant ($p<0.05$) correlation coefficients that describe the association between independent measures of watershed structure and dependent measures of water quality as measured at the lake samples.

Of the 120 associations examined between water quality variables and watershed structure variables for the stream samples, 23 or slightly more than one-sixth produced correlation coefficients that were statistically significant. All of the correlation coefficients had a magnitude exceeding $r = 0.30$. Table 13 illustrates that two of the water quality measures (pH and percent dissolved oxygen) exhibited no correlations with watershed structure variables. An additional water quality variable (total suspended solids) exhibited only one correlation with watershed structure variables with a magnitude exceeding $r = 0.30$, and two variables (total nitrogen and total phosphorous) exhibited two correlations with watershed structure variables with magnitudes exceeding r = 0.30. The remaining three variables exhibited correlations with between 5 and 7 watershed structure variables with a magnitude exceeding r = 0.30.

The effects of various dimensions of watershed structure exhibiting an association with each water quality variable characterized by a correlation coefficient exceeding r = 0.30 will be described separately.

1. **Total Suspended Solids.** Of the 15 watershed structure variables, only the percent of the sample station s drainage basin containing impervious surfaces exhibited a correlation with total suspended solids that exceeded r = 0.30. The direct nature of this relationship (r = 0.31) suggests that as impervious area within a sampling station s drainage basin increased, total suspended solids in the lake sample increased. As in most lakes, the particles composing the total suspended solids were largely organic matter, presumably algal particles. A few of the higher total suspended solids values had an organic matter content below 50%, suggesting input of inorganic particles from turbid runoff.

2. **Total nitrogen.** Measures of total nitrogen in the lake samples were directly correlated with the percent of the sampling station s drainage basin that contained non-hydric soils and inversely correlated with the percent of the basin containing slopes less than 3%. Whereas the interpretation of the stream sample correlation analyses seemed to suggest a subsurface association between watershed structure and stream water quality, the lake sample analyses suggest a surface runoff association. Higher levels of lake sample nitrogen appeared to be associated with basins containing non-hydric soils occurring on slopes that are steeper than 3%. Such conditions are more likely to create conditions favorable to the surface transport of nitrogen from basin to lake.

3. **Calcium.** Measures of calcium in the lake samples were directly correlated with the percent of the sampling station s basin covered by impervious surfaces, the percent of the basin in forest cover, the percent of the basin that contains soils which never flood, the percent of the basin containing soils with saturation depths exceeding 72 inches and the percent of the basin containing non-hydric soils. Calcium was inversely correlated with the percent of the basin containing soils with low infiltration capacity and with the percent of the basin containing till surficial geologic formations. As was true for the stream samples, calcium measures in the lake samples appear to be related to infiltration and deep percolation of surface water and subsurface movement of this water into lake discharge. Evidence for this hypothesis is provided by the facts that calcium was directly related to the presence of forest cover, the absence of flooded and hydric soils, the absence of soils with low infiltration capacities, the presence of soils having increased depths to saturation, and the absence of less permeable glacial till formations. All of these conditions relate to higher levels of infiltration, percolation, and subsurface flows. This hypothesis is not supported by the direct correlation of calcium in lake samples with impervious surface area within the sampling station drainage basin. Because calcium levels in epilimnetic lake water are sensitive to biological productivity,

which can vary from day to day, such data interpretations should be viewed with caution.

An additional hypothesis was put forth in Almendinger (2003), wherein the calcium (and magnesium and DIC) concentration was inversely related to the coverage by lakes and wetlands in the watershed. Because lakes commonly precipitate calcium carbonate in this ecoregion, watersheds with a greater coverage of lakes would sequester more calcium carbonate in lake sediments, leaving less available to occur in other lakes, groundwater, and stream water.

4. **Iron.** The presence of iron in the lake samples was directly correlated with the sampling station s drainage basin area that contained soils that were highly erosive, never flooded, and non-hydric. Higher measures of iron were also recorded in basins containing soils with larger extents of soils having deeper zones of saturation and larger extents of soils with lower levels of permeability. Finally, higher measures of iron were also associated with the absence of surficial geologic formations containing till. The association of higher measures of iron with the absence of till, the absence of hydric or flooded soils, and the presence of soils having deeper zones of saturation suggest that iron is moving from the watershed into the lakes via subsurface flow patterns. The association of higher iron measures with the presence of soils having lower permeability rates does not support this hypothesis. As with calcium, the sensitivity of iron to biological productivity and respiration (affecting redox conditions in the lake) makes data interpretation difficult.

5. **Chloride.** As with the stream sites, chloride was related to percent impervious cover, most likely because of the input of road salt from these surfaces. The relationship of chloride to other factors (e.g., an increased presence of highly erosive soils, an increased presence of soils having a depth to bedrock exceeding 60 inches, an increased presence of Prairie du Chien or Jordan Sandstone formations, and the absence of soils having low infiltration capacities) is more difficult to interpret.

6. **Total Phosphorous.** Higher measures of total phosphorous in the lake samples were associated with an increased presence of wetlands in the sampling station s drainage basin and an increased presence of non-hydric soils. The association of higher levels of phosphorous with an increased presence of wetlands suggests that the wetlands may be releasing phosphorous within the basins. However, more commonly wetlands are expected to sequester some phosphorus as accumulated biomass; they would have a net release of phosphorus under conditions of altered hydrology, e.g., dry climate cycles or anthropogenic drainage that allowed net decomposition of accumulated organic matter. However, Washington County does not appear to be experiencing a dry climate cycle, as groundwater levels have been at historic high levels during the past few decades. We do not know the status of wetland drainage in the study watershed, although we presume it has been minimized during the last 10 years because of regulatory changes. Furthermore, this phosphorus-wetland relationship is in near-opposition to the other relationship

found, that between phosphorous and the increased presence of non-hydric soils. Consequently, we can offer no convincing interpretations of these relationships found in our data set.

Piezometer Sample Analyses

Table 14 presents results from the correlation analyses conducted with seven of the water quality variables from the piezometer water samples as dependent measures and selected watershed structure variables as independent measures. The individual dependent measures of piezometer water quality are listed across the top of Table 14 while the independent measures of watershed structure are listed down the left margin of the table. The table contains significant ($p<0.05$) correlation coefficients that describe the association between independent measures of watershed structure and dependent measures of water quality as measured in the piezometer samples.

Of the 105 associations examined between water quality variables and watershed structure variables for the stream samples, 34 (about one-third) produced correlation coefficients that were statistically significant. All of the correlation coefficients had a magnitude exceeding $r = 0.53$. Table 14 illustrates that all of the variables exhibited correlations with between 3 and 7 watershed structure variables at a magnitude exceeding $r = 0.53$.

The effects of various dimensions of watershed structure exhibiting an association with each water quality variable will be described separately.

1. **Dissolved Phosphorous.** Dissolved phosphorous levels in the piezometer samples were inversely correlated with the percent of the sampling station s basin containing forest cover, the percent of the basin containing soils with high infiltration capacity, and the percent of the basins containing outwash surficial geologic deposits. These findings suggest that increased forest cover tends to retain its phosphorous and release only small amounts in dissolved form. The inverse correlation with an increased presence of soils possessing a high-infiltration rate and the increased presence of outwash soils also implies that conditions are not conducive for the mobilization of dissolved phosphorous, perhaps because of the oxidizing conditions that may be present in the soils.

2. **Dissolved Nitrogen.** Levels of dissolved nitrogen in the piezometer samples were directly correlated with the percent of a basin that contained outwash deposits. Dissolved nitrogen was inversely correlated with the percent of the sampling station s drainage basin that contained wetlands, impervious surfaces and lawn cover. Both watersheds contain a relatively high percent of area in agriculture (25% for Valley Branch and 10% for Browns Creek). As agricultural area increases within the watersheds, the percent of area devoted to other cover types decreases. Because nitrogen was likely associated with inputs from agricultural land use, higher agricultural area would simultaneously produce higher levels of nitrogen and lower areas of wetlands, impervious and lawn cover types. Wetlands can also treat and remove nitrate, through denitrification, producing perhaps another reason for the inverse correlation. Nitrogen may be correlated positively with the presence of

outwash soils because these soils promote rapid infiltration of water without significant treatment, delivering nitrate-rich water to the surficial aquifer.

3. **Dissolved Inorganic Carbon.** Higher levels of dissolved inorganic carbon (DIC) in the piezometer samples were directly correlated with greater percentages of cropland in the sampling station s basin. They were inversely correlated with the presence of lakes and wetlands as well as with the presence of impermeable surface area in the sampling station s basin. Lakes can precipitate calcium carbonate and therefore may reduce DIC in the aquifer tapped by the piezometer. Still, the correlations are difficult to interpret and may not be meaningful.

4. **Calcium.** Calcium levels in the piezometer samples were inversely correlated with the percent of the sampling station s basin in wetlands as well as with the percent of the basin in lawn cover. For the same reasons given above for DIC, these correlations are difficult to interpret and may not be meaningful.

5. **Iron.** Iron levels in the piezometer samples were directly correlated with the presence of lakes and wetlands in the sampling station s basin. Iron was also directly related to the percent of the sampling station s drainage basin that contained soils with low infiltration capacities as well as the percent of the basin containing Jordan Sandstone or Prairie du Chien Formations as the first bedrock formation. The saturated sediments of lakes and wetlands can contribute to low redox conditions in groundwater, and this promoted the solution and transport of iron in an aquifer.

6. **Chloride.** Chloride levels in the piezometer samples were directly correlated with the percent of the sampling station s drainage basin that contained forest cover, soils with high permeability and outwash deposits. Chloride was inversely related to the percentage of lawn cover in the sampling basins. The positive correlation of chloride in the piezometer samples with the presence of highly permeable soils and outwash soils is understandable, as these conditions permit passage of water and highly soluble chloride through the the aquifer. The correlations with forest cover (positive) and percent lawn cover (negative) appear spurious.

7. **Heavy Oxygen.** Higher levels of heavy oxygen isotopes in the piezometer samples were recorded from basins containing larger percentages of lakes and wetlands and from basins containing larger percentages of soils with low infiltration capacities. These findings suggest that the impermeable soils may be enhancing surface runoff flows. When impounded in wetlands or lakes, this increased runoff evaporates, a process that increases the concentration of heavy oxygen isotopes. The fact that this signal is being seen in piezometer samples suggests that lake water containing heavy oxygen isotopes may be seeping from these bodies and migrating by subsurface flow into the piezometer samples. Heavy oxygen isotopes measures were also inversely correlated with the percent of crop cover in the sampling station s drainage basin and directly correlated with the percent of the basin containing Jordan Sandstone or Prairie du Chien Formations as the first bedrock.

Bedrock Well, Quaternary Well, and Spring Sample Analyses

Table 15 presents results from the correlation analyses conducted with seven of the water quality variables from the bedrock wells, Quaternary wells, and springs as dependent measures and selected watershed structure variables as independent measures. The individual dependent measures of groundwater quality from these sources are listed across the top of Table 15 while the independent measures of watershed structure are listed down the left margin of the table. The table contains significant ($p<0.05$) correlation coefficients that describe the association between independent measures of watershed structure and dependent measures of water quality as measured in these groundwater samples.

Of the 105 associations examined between water quality variables and watershed structure variables, 14 or slightly more than one-sixth produced correlation coefficients that were statistically significant ($p<0.05$). All of the correlation coefficients had a magnitude exceeding $r = 0.53$. None of the watershed structure variables exhibited significant correlations with dissolved phosphorous or chloride. Table 15 illustrates that all of the variables exhibited correlations with between 3 and 7 watershed structure variables at a magnitude exceeding $r = 0.52$.

The effects of various dimensions of watershed structure exhibiting an association with each water quality variable will be described separately.

1. **Dissolved Nitrogen.** Dissolved nitrogen levels in the bedrock well, Quaternary well, and spring water samples were directly correlated with the percent of the well trace area that contained impervious cover, lawn, crops, and outwash deposits. Dissolved nitrogen levels were inversely correlated with the percent of the well trace area containing forest cover. Not surprisingly, the data suggest that cropland and urban land (lawn and impervious surfaces) are sources of nitrogen, the transmission of which into aquifers is promoted by the presence of outwash soils. In contrast, forests supply little nitrogen.

2. **Dissolved Inorganic Carbon.** Dissolved organic carbon (DIC) levels within these groundwater samples were inversely correlated with the percent of the well trace area that contained lakes and the percent of the well trace that contained soils with high infiltration capacities. DIC was directly correlated with the percent of the well trace area containing soils with low permeability and the percent of the trace area containing Prairie du Chien or Jordan Sandstone formations as first bedrock. As noted before, lakes can remove calcium carbonate from the hydrologic system, thereby also reducing DIC. The Prairie du Chien is a carbonate bedrock unit. It would be an obvious contributor to high DIC levels in aquifer waters.

3. **Calcium.** Measures of calcium ions in the bedrock well, Quaternary well, and spring water samples were directly correlated with the percent of the well trace area that contained extents of lawn, cropland, or impervious surfaces. These correlations are not easily interpretable, and they may be spurious. One would think that

calcium would have correlations with watershed structure variables that paralleled those of DIC.

4. **Iron.** Iron ion levels in these groundwater samples were directly correlated with the percent of the well trace area that contained Prairie du Chien or Jordan Sandstone formations as first bedrock. Iron levels were inversely correlated with the percent of the trace area that contained water or wetlands cover. Finally, iron was also inversely correlated with the percent of the trace area containing soils with high infiltration capacities as well as the percent of the trace area containing soils with low infiltration capacities. There is an obvious and unexplainable contradiction in the fact that iron in the groundwater samples appeared to be inversely correlated with the extent of the trace area that contained soils with both high and low infiltration capacities. However, the fact that iron increases with less surface water or wetland area in the well trace implies a relationship between higher levels of iron and higher rates of infiltration within the trace area. In addition, the inverse correlation with surface water (i.e., lakes and wetlands) is in contrast to the positive correlation found for the piezometers. These differences, if not contradictions, indicate that such correlations for may not be meaningful.

5. **Heavy Oxygen.** Measures of heavy oxygen isotopes in these groundwater samples were inversely correlated with the percent of the trace area that contained cropland. No explanation for this correlation is obvious. In contrast to groundwater in piezometers, no correlation was found between heavy oxygen in these groundwater samples and percent of trace area covered by lakes and wetlands. Perhaps the flow lines tapped by the bedrock and Quaternary wells, and some springs, are too deep to be influenced meaningfully by many of the surface features mapped above its flow trace.

Multivariate Effects of Watershed Structure on Water Quality Variables

Findings from the examination of the effects of watershed structure on water quality are discussed separately for the stream samples, lake samples, piezometer samples, and other groundwater (bedrock well, Quaternary well, and spring) samples.

Stream Sample Analyses

Table 16 presents results from the step-wise regression analyses conducted with ten of the water quality variables from the stream water samples as dependent measures and selected watershed structure variables as independent measures. The individual dependent measures of stream water quality are listed across the top of Table 16 while the independent measures of watershed structure are listed down the left margin of the table. The table contains regression coefficients that describe the effect of significant independent variables for each of the regression models as well as summary statistics (e.g., coefficients of determination) that describe the overall strength of the models. Each of the models will be briefly described.

1. **pH.** The regression model for pH was the weakest of the ten models generated for the stream samples, having an R^2 of 0.05. This value means that while statistically significant relationships exist between the watershed structure variables and pH, these relationships contribute almost nothing to explaining variance in the observed pH values.

2. **Percent Dissolved Oxygen.** The regression model generated for percent dissolved oxygen in the stream samples was also not a strong model, having an R^2 of 0.22. Once again, while statistically significant relationships exist between percent dissolved oxygen and three watershed structure variables, these relationships contribute little to explaining variance in the percent dissolved oxygen values.

3. **Total Suspended Solids.** The regression model for total suspended solids (measured in logarithmic form) generated an R^2 of 0.50. Measures of total suspended solids were directly related to (a) flow regime; and (b) the percentage of the sample station drainage basins that contained soils with permeability values less than 6.0 inches per hour. Levels of total suspended solids were inversely related to (a) the percent of the sample station drainage basin containing forest cover, (b) the percent of the basin containing non-hydric soils, and (c) the percent of the basin containing highly erosive soils. In high flow conditions, the logarithmic value of total suspended solids was also inversely related to the portion of the basin containing slopes exceeding six percent.

   Many of these relationships have intuitive appeal. The production of larger quantities of sediment would be expected during periods of high flow. Greater amounts of suspended solids were also more likely to be generated from basins where runoff rather than infiltration or retention is promoted, i.e., basins having low soil permeability, lower abundance of wetland soils, and lower abundance of forest area. Less explicable is the fact that basins containing larger amounts of highly erosive soils produced lower measures of total suspended solids. Similarly, the fact that basins containing larger geographic extents of steeper land produced lower measures of suspended solids under high flow conditions is not intuitively understandable.

   The predictive model for the logarithmic form of total suspended solids has two forms, depending upon whether or not flow conditions are at a high stage. During periods of low or moderate value, the predictive model for the logarithmic value of total suspended solids measured at the stream sampling stations is estimated as:

   $$Y = 11.66 + 7.73(X_1) - 0.81(X_2) - 5.12(X_3) + 0.03(X_4) - 0.03(X_5)$$

   During periods of high flow, this model becomes:

   $$Y = 11.66 + 7.73(X_1) - 0.81(X_2) - 5.12(X_3) + 0.03(X_4) - 0.03(X_5) - 4.46(X_6)$$

where: Y = predicted logarithmic form of total suspended solids measured at a stream sample station
X_1 = flow regime value (0 if low/moderate; 1 if high)
X_2 = logarithmic form of the percent of the sample station s drainage basin in forest cover
X_3 = logarithmic form of the percent of the sample station s drainage basin in highly erosive soils
X_4 = percent of the sample station s drainage basin that contain soils with permeability < 6 inches/hour
X_5 = percent of the sample station s drainage basin that contain non-hydric (wetlands) soils
X_6 = percent of the sample station s drainage basin that contain soils steeper than six percent

4. **Total Phosphorous.** Sixty-four percent of the variance in the logarithmic form of total phosphorous measured at the stream sample stations was attributable to variance in selected watershed structure variables (i.e., $R^2 = 0.64$). Direct relationships existed between total phosphorous and (a) flow regime and (b) the percent of the station s basin that is covered by impermeable surfaces. An inverse relationship existed between total phosphorous measured at a sample station and the percent of the station s basin that contained soils with a depth to saturation exceeding 72 inches. During periods of high flow, total phosphorous measured at a sampling station was also inversely related to the percent of the sampling station s basin that is in wetlands, contains wetland soil conditions or contains forest land cover.

Higher flow levels, more impervious surface area and soils with shallow depths to saturation were associated with generating increasing levels of runoff. These factors were likely to contribute to transporting phosphorous from the watershed into the streams. In high flow regimes, increased forest area and wetland conditions also seemed to establish increased watershed buffering capacity. These land covers created opportunities to retain phosphorous within the watershed before it reaches the stream.

Under low or moderate flow conditions, the predictive model for the logarithmic form of total phosphorous measured at the stream sampling stations is estimated as:

$$Y = 2.53 + 4.70(X_1) + 0.61(X_2) - 0.02(X_3)$$

During periods of high flow, this model becomes:

$$Y = 2.53 + 4.70(X_1) + 0.61(X_2) - 0.02(X_3) - 0.67(X_4) - 0.75(X_5) - 0.04(X_6)$$

where: Y = predicted logarithmic form of total phosphorous measured at a stream sample station
X_1 = flow regime value (0 if low/moderate; 1 if high)

X_2 = logarithmic form of the percent of the sample station s drainage basin in impervious surfaces

X_3 = the percent of the sample station s drainage basin containing soils with depth to saturation >72 inches

X_4 = logarithmic form of the percent of the sample station s drainage basin in wetlands

X_5 = logarithmic form of the percent of the sample station s drainage basin in forest cover

X_6 = percent of the sample station s drainage basin that contain non-hydric (wetlands) soils

5. **Total Nitrogen.** Of the ten regression models created to estimate water quality parameters for the stream samples, the total nitrogen model proved to be the strongest. The specified combination of watershed structure variables contained in the model accounted for 86% of variance in the measurements of total nitrogen at the stream sample stations (i.e., $R^2 = 0.86$) Total nitrogen was inversely related to flow, with higher measurements recorded during low and moderate flow events. Total nitrogen measurements were also inversely related to the percent of the sampling station s basin that was in wetlands as well as to the percent of the basin that contained soils with depth to bedrock of less than 60 inches. Nitrogen values at the sampling stations increased as the percent of the station s basin that contained soils with low infiltration capacity increased. During high flow events, total nitrogen values were further enhanced by the presence of forest cover and non-hydric soils in the sampling station basins. During high flow events, nitrogen levels were reduced with increases in the percentage of a sampling station s basin that contained till surface geology formations and soils having saturation zones deeper than 72 inches.

The fact that nitrogen levels were higher during periods of low or moderate flow suggests that this nutrient is contributed largely by groundwater discharge to the creeks baseflow. Nitrogen levels also decreased with a reduction in the percent of the sampling station basins that contain soils with depths to bedrock that exceed 60 inches. Thus, in a basin containing a greater percentage of shallow bedrock, nitrogen may be moving from surface sources into the groundwater regime and eventually discharging into the stream s baseflow. During periods of high runoff, when nitrogen discharge from baseflow is diluted, the presence of larger percentage of forest cover and wetlands in the sampling basins may retain some runoff and thereby reduce the dilution effect.

Under low or moderate flow conditions, the predictive model for nitrogen values measured at the stream sampling stations is estimated as:

$$Y = 25.44 - 11.20(X_1) - 1.68(X_2) + 0.03(X_3) - 11.52(X_4)$$

During periods of high flow, this model becomes:

$$Y = 25.44 - 11.20(X_1) - 0.53(X_2) + 0.08(X_3) - 11.52(X_4) + 2.32(X_5) - 0.11(X_6) + 0.18(X_7) - 0.03(X_8)$$

where: Y = predicted value of total nitrogen measured at a stream sample station
X_1 = flow regime value (0 if low/moderate; 1 if high)
X_2 = logarithmic form of the percent of the sample station s drainage basin in wetlands
X_3 = the percent of the sample station s drainage basin containing soils with low infiltration capacity
X_4 = logarithmic form of the percent of the sample station s drainage basin containing soils with depth to bedrock >60 inches
X_5 = logarithmic form of the percent of the sample station s drainage basin in forest cover
X_6 = percent of the sample station s drainage basin containing soils with depth to zone of saturation >72 inches
X_7 = percent of the sample station s drainage basin that contain non-hydric (wetlands) soils
X_8 = percent of the sample station s basin contain till surface geologic formations

6. **Dissolved Inorganic Carbon.** Seventy-two percent of the variance in the dissolved inorganic carbon (DIC) measures at the stream water sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.72$). Dissolved inorganic carbon is often an indicator of groundwater contribution to stream flow, and low to moderate flow events did experience higher levels of DIC. This pattern is further reinforced by the facts that DIC levels were directly related to the percent of a sampling station s basin that contained slopes of less than 3% and soils with saturation zones at depths of greater than 72 inches. DIC levels were inversely related to the presence of till surface geologic formations within the sampling station basins. All three of these watershed conditions are favorable to the infiltration of precipitation to recharge the groundwater regime. This pattern is not supported, however, by the facts that DIC levels increased with greater amounts of impervious surface area and with larger percentages in the sampling station basins of soils containing low infiltration capacities. Such conditions suggest an association of higher DIC levels and conditions favorable to the generation of surface runoff, which does not make apparent sense.

During high flow events, increased levels of DIC were associated with increasing areas of wetlands, forest cover, and soils that do not flood. As with nitrogen, DIC is diluted during high flow events, and land covers that reduce total runoff volume can reduce the degree of dilution.

Under low or moderate flow conditions, the predictive model for dissolved inorganic values measured at the stream sampling stations is estimated as:

$$Y = -103.14 - 125.29(X_1) + 26.02(X_2) + 1.01(X_3) + 1.31(X_4) - 0.31(X_5) + 0.30(X_6)$$

During periods of high flow, this model becomes:

$$Y = -103.14 - 125.29(X_1) + 26.02(X_2) + 1.01(X_3) + 1.31(X_4) - 0.31(X_5) + 0.30(X_6) + 17.03(X_7) + 27.79(X_8) + 0.89(X_9)$$

where: Y = predicted value of dissolved inorganic carbon measured at a stream sample station
X_1 = flow regime value (0 if low/moderate; 1 if high)
X_2 = logarithmic form of the percent of the sample station s drainage basin in impervious surface area
X_3 = the percent of the sample station s drainage basin containing soils with low infiltration capacity
X_4 = percent of the sample station s drainage basin containing soils with depth to zone of saturation >60 inches
X_5 = percent of the sample station s basin containing till surface geologic formations
X_6 = percent of the sample station s basin containing soils with slopes < 3%
X_7 = logarithmic form of the percent of the sample station s drainage basin in wetlands
X_8 = percent of the sample station s drainage basin in forest cover
X_9 = percent of the sample station s drainage basin containing soils that never flood

7. **Calcium.** Seventy-three percent of the variance in the calcium ion measures at the stream water sampling stations was attributable to variance in watershed structure variable (i.e., $R^2 = 0.73$). As is true for dissolved inorganic carbon, calcium is often an indicator of groundwater contribution to stream flow, and its concentration is inversely related to flow because of dilution during high runoff events. Under low to moderate flow conditions, calcium levels in the stream samples were also inversely related to the percent of the sampling station s drainage area that contained soils with depth to bedrock exceeding 60 inches or till surface geologic formations. The greater the area of shallow bedrock, the higher the calcium concentrations, suggesting that direct contact of infiltrating water with the bedrock enhances calcium content, at least during baseflow conditions. This is an especially likely possibility given the extensiveness of the Prairie du Chien bedrock, a unit containing large amounts of calcium carbonate, throughout both watersheds. During high flow events, calcium levels were also directly related to the percent of wetlands present in a sampling station s basin as well as the presence of soils within the basin having depths to saturation zone that exceeded 72 inches. As with nitrogen and DIC, these features encourage stormwater retention and infiltration, thereby reducing total runoff volume and limiting the dilution of calcium that could otherwise take place during high flows.

Under low or moderate flow conditions, the predictive model for the calcium ion values measured at the stream sampling stations is estimated as:

$$Y = 47.86 - 83.25(X_1) - 161.67(X_2) - 0.69(X_3)$$

During periods of high flow, this model becomes:

$$Y = 47.86 - 83.25(X_1) - 161.67(X_2) - 0.69(X_3) + 22.54(X_4) + 0.80(X_5)$$

where: Y = predicted value of calcium ions measured at a stream sample station
X_1 = flow regime value (0 if low/moderate; 1 if high)
X_2 = logarithmic form of the percent of the sample station s drainage basin containing soils with depth to bedrock >60 inches
X_3 = percent of the sample station s basin containing till surface geologic formations
X_4 = logarithmic form of the percent of the sample station s drainage basin in wetlands
X_5 = percent of the sample station s drainage basin containing soils with depth to zone of saturation >72 inches

8. **Iron.** Sixty-six percent of the variance in the logarithm of iron concentrations at the stream water sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.66$). Iron concentration varied directly with flow regime. High flows produced higher measures of iron than the medium or low flow stages. This direct relationship is somewhat surprising, as one would expect iron to be a signal of groundwater. When deoxygenated, groundwater can have high iron concentrations. Iron ion measures were inversely related to the percent of the stations basins containing forest. Under low/moderate flow conditions, iron measures were directly related with the percent of the sampling stations drainage basin that contained soils with slopes of less than 3%. Under high flow regimes, however, iron measures were inversely related with the presence of level slopes[7]. Most of these relations imply that iron concentrations in streams are enhanced by factors that promote runoff rather than infiltration. We have no clear explanation for these results and caution that they may not be meaningful.

Under low or moderate flow conditions, the predictive model for the logarithmic form of total iron ions measured at the stream sampling stations is estimated as:

$$Y = 0.11 + 0.99(X_1) - 1.88(X_2) + 0.04(X_3)$$

During periods of high flow, this model becomes:

$$Y = 0.11 + 0.99(X_1) - 1.88(X_2) + 0.01(X_3)$$

where: Y = predicted logarithmic form of iron ions measured at a stream sample station
X_1 = flow regime value (0 if low/moderate; 1 if high)

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[7] Under high flow conditions, the total effect of the variable relating to the percent of the basin containing soils with slopes less than 3% is $+0.04(X_3)$ (i.e., the effect under low/moderate flow conditions) - $0.03(X_3)$ (i.e., the effect generated by high flow conditions) = $+0.01(X_3)$.

X_2 = logarithmic form of the percent of the sample station s drainage basin in forest cover
X_3 = logarithmic value of the percent of the sample station s drainage basin containing soils with slopes less than 3%

9. **Chloride.** Among the ten stream water analyses, the chloride analysis produced the second strongest regression model. Eighty-three percent of the total amount of variance in the logarithmic form of measures of the chloride ion at the stream sampling stations was explained by watershed structure variables (i.e., $R^2 = 0.83$). Higher levels of chloride were associated with a larger percent of sampling station drainage basins containing impervious surfaces. This is likely a product of the increased ability of impervious surfaces to generate runoff that would transport residual chloride measures on road surfaces into the streams. At the same time, however, lower measurements of the chloride ion were obtained during periods of high flow. This may be attributable to the diluting effect of the higher levels of runoff generated during these periods. Note, however, that this dilution effect during high flows was evident only in the Valley Creek watershed, which dominated this sample set because of the number of samples collected there. In fact, Browns Creek showed the opposite pattern, where chloride concentrations increased during the few snowmelt runoff events sampled there.

Chloride measures were also inversely related to the percent of a sampling station drainage basin that contained highly erosive soils and directly related to the presence of non-hydric soils in the drainage basins. During periods of high flow, the increased presence of wetlands and forest cover in the sampling station drainage basins was also directly related to higher measures of chloride ions. As discussed earlier, we suggest that these land cover types enhance chloride concentrations during runoff events because they reduce runoff volume and thereby limit dilution of chloride not because these cover types are themselves sources of chloride.

Under low or moderate flow conditions, the predictive model for the logarithmic form of chloride ions measured at the stream sampling stations is estimated as:

$$Y = 1.63 - 0.36(X_1) + 0.84(X_2) - 0.74(X_3) + 0.004(X_4)$$

During periods of high flow, this model becomes:

$$Y = 1.63 - 0.36(X_1) + 0.84(X_2) - 0.74(X_3) + 0.004(X_4) + 0.12(X_5) + 0.23(X_6)$$

where: Y = predicted logarithmic form of chloride ions measured at a stream sample station
X_1 = flow regime value (0 if low/moderate; 1 if high)
X_2 = logarithmic form of the percent of the sample station s drainage basin in impervious surface area
X_3 = logarithmic form of the percent of the sample station s drainage basin containing highly erosive soils

X_4 = percent of the sample station s drainage basin containing non-hydric soils
X_5 = logarithmic form of the percent of the sample station s drainage basin in wetlands
X_6 = logarithmic form of the percent of the sample station s drainage basin in forest cover

10. **Heavy Oxygen.** Sixty-four percent of the variance in the heavy oxygen content (^{18}O, as in $H_2{}^{18}O$) was attributable to variance in watershed structure variables (i.e., $R^2 = 0.64$). Heavy oxygen was inversely related to flow, i.e., the higher the flow, the lower (more negative) the heavy oxygen content. Under baseflow conditions, heavy oxygen was apparently strongly related to impervious cover. However, under high flow conditions, the influence of impervious cover was much reduced, and heavy oxygen was more directly related to forest cover.

    The sources and modifications of heavy oxygen, as well as the specific hydrologic setting of the two creeks may explain these results. Most heavy oxygen values clustered near the median value ($\delta^{18}O$ ¯ -9 per mil). Heavier (less negative) values typically were measured in lakes, where evaporation had concentrated heavier oxygen values, and in stream reaches fed by outflow from these lakes. Lighter (more negative) values resulted from snowmelt runoff, because cold season precipitation is depleted in heavy oxygen relative to warm season precipitation.

    The inverse relation between flow and heavy oxygen is clearly related to the fact that snowmelt runoff is composed largely of isotopically light water, and snowmelt contributes to the largest annual runoff event in both creeks. In fact, water temperature, alone, is a good predictor of heavy oxygen ($r^2 = 0.71$ for a sample regression of $\delta^{18}O$ on temperature). The reason for the direct correlation of heavy oxygen and impervious cover under baseflow conditions is not clear and may be mostly spurious. The south branch of Browns Creek had a high impervious cover relative to other sites, and a high heavy oxygen content at baseflow but this site was fed by outflow from a chain of lakes, including Long Lake. The high heavy oxygen content was certainly related to lake evaporation. However, evaporation from runoff generated on summertime-warm pavements may in fact enhance the heavy-oxygen signal (see Almendinger, 2003). More work could be done to sample such runoff directly to test whether it has an enriched heavy-oxygen signal prior to reaching the lake. Note that during high flows, snowmelt runoff overwhelmed such lake outflow and the relation between heavy oxygen and impervious cover was effectively eliminated. The direct relation between heavy oxygen and forest cover under high flow conditions is again one of reduced dilution of channel water by runoff. That is, forest cover helps to reduce runoff volumes, thereby keeping heavy oxygen content of the stream greater than if mixed with the light snowmelt runoff.

    Under low or moderate flow conditions, the predictive model for the heavy oxygen isotopes measured at the stream sampling stations is estimated as:

$$Y = -15.01 - 10.06(X_1) + 9.01(X_2)$$

During periods of high flow, this model becomes:

$$Y = -15.01 - 10.06(X_1) + 0.88(X_2) + 9.87(X_3)$$

where: Y = predicted value of heavy oxygen isotopes measured at a stream sample station
X_1 = flow regime value (0 if low/moderate; 1 if high)
X_2 = logarithmic form of the percent of the sample station s drainage basin in impervious surface area
X_3 = logarithmic form of the percent of the sample station s drainage basin in forest cover

Lake Sample Analyses

Table 17 presents results from the step-wise regression analyses conducted with eight of the water quality variables from the lake water samples as dependent measures and selected watershed structure variables as independent measures. The individual dependent measures of lake water quality are listed across the top of Table 17 while the independent measures of watershed structure are listed down the left margin of the table. The table contains regression coefficients that describe the effect of significant independent variables for each of the regression models as well as summary statistics (e.g., coefficients of determination) that describe the overall strength of the models. Only one of the models (i.e., the model for the chloride ion) achieved a coefficient of determination exceeding 0.50. For the remaining seven models, other undetermined factors exerted greater influence than did the independent variables. The identities and effects of these undetermined factors cannot be determined from our data set. Note that most of the lakes were sampled only twice, once in the summer and once in the winter through the ice. Seasonal variations in many of the measured parameters dominated the variance structure and probably masked the potential influence of some watershed structure variables. Only those variables that were conservative and persistent enough to transcend seasonal variability were identified in our analysis. Each of the models will be briefly described.

1. **pH.** Multiple regression analysis failed to generate a significant regression model to describe relationships between the logarithmic value of pH in the lake samples and the independent measures of watershed structure.

2. **Percent Dissolved Oxygen.** Multiple regression analysis failed to generate a significant regression model to describe relationships between percent dissolved oxygen in the lake samples and the independent measures of watershed structure.

3. **Total Suspended Solids.** The variance in the logarithmic values of total suspended solids in the lake samples that was explained by the watershed structure variables is only 7% (i.e., $R^2 = 0.07$). This value means that while statistically significant relationships exist between the watershed structure variables and the logarithmic values of total suspended solids, these relationships contribute almost nothing to

explaining variance in the observed total suspended solids values in the lake samples. The only watershed structure variable to have a significant relationship with the logarithmic value of total suspended solids is the logarithmic value of the percent of the sampling station drainage basin that contains impervious surfaces. This relationship, though small, could be real. Runoff from impervious surfaces could deliver fines to a lake, depending upon the source of these fine particles in the lake s watershed. Or, perhaps more likely, runoff that causes significant lake level change (i.e., bounce) could cause shoreline erosion and consequently contribute to the suspension of fines in the lake.

4. **Total Nitrogen.** The variance in the logarithmic values of total nitrogen in the lake samples that were explained by the watershed structure variables is 19% (i.e., $R^2 = 0.19$). This value means that while statistically significant relationships exist between the watershed structure variables and the logarithmic values of total nitrogen, these relationships contribute little to explaining variance in the observed total nitrogen values in the lake samples. The logarithmic value of total nitrogen was inversely related to the amount of forest cover in a sampling station drainage basin and directly related to the amount of non-hydric soils present in the basin. These relationships do make qualitative sense in that forests (as opposed to urban or agricultural lands) would not contribute much nitrogen. Hydric soils (as opposed to non-hydric soils) could reduce nitrates via denitrification.

5. **Calcium.** Fifty percent of the variance in the calcium ion measures at the lake sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.50$). Calcium ion measures in the lake samples were directly related to the percent of the sampling station s drainage basin that contained impervious surfaces and inversely related to the amount of till geologic formations present in the basins. We see no obvious reason for the relation between calcium and impervious cover. Calcium content should be enhanced by input of calcium-rich groundwater into lakes, which can be related to the permeability of the surface aquifer. The relatively low permeability of till aquifers (as opposed to outwash aquifers) could account for the inverse relationship between calcium and the presence of till in the lake basins.

   The predictive model for calcium ions in the lake samples is estimated as:

$$Y = 20.58 + 29.20(X_1) - 0.48(X_2)$$

where: Y = predicted value of calcium ions measured at a lake sample station
X_1 = logarithmic form of the percent of the lake sample station basin area covered by impervious surfaces
X_2 = percent of the lake sample station basin area containing till geologic formations

6. **Iron.** Forty-five percent of the variance in the logarithmic form of the iron ion measures at the lake sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.45$). Watershed structure variables contributing directly to the regression model included the percent of the lake station basin area in

forest cover. Inverse relationships existed between the measures of iron ions and: a) the percent of the lake sample drainage basins that contained soils with high infiltration capacity; and b) the percent of the basin occupied by till surface geologic formations. We find no obvious explanations for these relationships.

The predictive model for the logarithmic form of the iron ions measured in the lake samples is estimated as:

$$Y = 5313.88 + 161.41(X_1) - 229.39(X_2) - 108.69(X_3)$$

where: Y = predicted logarithmic form of the value of iron ions measured at a lake sample station
X_1 = percent of the lake sample station basin area containing forest cover
X_2 = percent of the lake sample station basin containing soils with high infiltration capacity
X_3 = percent of the lake sample station basin area containing till geologic formations

7. **Chloride.** Among the eight lake sample analyses conducted, the chloride analysis produced the strongest regression model. Fifty-six percent of the variance in the chloride ion measures at the lake sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.56$). Measures of chloride ions were directly correlated with the logarithmic form of the percent of impervious surfaces within the lake sample station drainage basins as well as with the percent of the basins containing Jordan Sandstone or Prairie du Chien formations as the first bedrock formation. The relation between chloride and impervious cover is clear, as these surfaces deliver road salt to receiving waters. The relationship between chloride and the occurrence of Prairie du Chien and Jordan Sandstone bedrock units seems spurious.

The predictive model for chloride ions in the lake samples is estimated as:

$$Y = -6.07 + 22.17(X_1) + 0.18(X_2)$$

where: Y = predicted value of chloride ions measured at a lake sample station
X_1 = logarithmic form of the percent of the lake sample station basin area covered by impervious surfaces
X_2 = percent of the lake sample station basin containing Jordan Sandstone or Prairie du Chien formations as the first bedrock formation

8. **Total Phosphorous.** Forty-seven percent of the variance in total phosphorous measures at the lake sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.47$). Watershed variables directly associated with phosphorous include (a) percent of the lake sample station drainage basin containing non-hydric soils and (b) percent of the basin containing soils with slopes steeper than 6%. These factors may be associated with greater runoff, and therefore with greater delivery of particle-bound phosphorous to lakes. Total phosphorous measurements were inversely associated with the percent of the lake sample station basin containing highly erosive soils and with the percent of the basin

containing soils with a depth to saturation zone exceeding 72 inches. We have no good explanation for these inverse relations.

The predictive model for the logarithmic value of the total phosphorous values measured in the lake samples is estimated as:

$$Y = 0.24 - 0.01(X_1) - 0.02(X_2) + 0.04(X_3) + 0.01(X_4)$$

where: Y = predicted value of the logarithmic form of total phosphorous measured at a lake sample station
X_1 = percent of the lake sample station basin area containing forest cover
X_2 = percent of the lake sample station basin containing soils with a depth to saturation that exceeds 72 inches
X_3 = percent of the lake sample station basin containing non-hydric soils
X_4 = percent of the lake sample station basin containing soils with slopes greater than 6%

Piezometer Sample Analyses

Table 18 presents results from the step-wise regression analyses conducted with seven of the water quality variables from the piezometer water samples as dependent measures and selected watershed structure variables as independent measures. The individual dependent measures of piezometer water quality are listed across the top of Table 18 while the independent measures of watershed structure are listed down the left margin of the table. The table contains regression coefficients that describe the effect of significant independent variables for each of the regression models as well as summary statistics (e.g., coefficients of determination) that describe the overall strength of the models. Many of the models described in Table 18 have relatively high coefficients of determination (i.e., greater than 0.70). The validity of these coefficients must be interpreted with care, as none of these analyses was conducted on a data set that contained more than 17 complete records. Each of the models will be briefly described.

1. **Dissolved Phosphorous.** Among the seven piezometer sample analyses conducted, the analysis of the logarithmic form of dissolved phosphorous measures produced the strongest regression model. Eighty-eight percent of the variance in the logarithmic form of the dissolved phosphorous measures at the piezometer sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.88$). Direct relationships occurred between measures of dissolved phosphorous and the percent of the piezometer sampling station drainage basin that contained wetlands or forest cover. Dissolved phosphorous measures were inversely related to the percent of the drainage basin containing Jordan Sandstone or Prairie du Chien Formations as the first bedrock formation. We have no satisfactory explanation for any of these relations.

   The predictive model for the logarithmic form of the dissolved phosphorous values measured in the piezometer samples is estimated as:

$$Y = 1.30 + 1.76(X_1) + 5.68(X_2) - 0.12(X_3)$$

where: Y = predicted value of the logarithmic form of dissolved phosphorous measured at a piezometer sample station
X_1 = logarithmic form of the percent of the piezometer sample station basin area containing wetlands
X_2 = logarithmic form of the percent of the piezometer sample station basin area covered by forest
X_3 = percent of the piezometer sample station basin containing Jordan Sandstone or Prairie du Chien Formation as the first bedrock formation

2. **Dissolved Nitrogen.** Seventy-four percent of the variance in the logarithmic form of the dissolved nitrogen measures at the piezometer sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.74$). The only watershed structure variable exhibiting a significant relationship with dissolved nitrogen was the percent of the piezometer sample station basin containing lawn cover, which was inversely related to dissolved nitrogen. The reasons for this inverse relationship are unclear.

   The predictive model for the logarithmic form of the dissolved nitrogen values measured in the piezometer samples is estimated as:

$$Y = 1.37 - 0.13(X_1)$$

where: Y = predicted value of the logarithmic form of dissolved nitrogen measured at a piezometer sample station
X_1 = percent of the piezometer sample station basin area containing lawn cover

3. **Dissolved Inorganic Carbon.** Fifty-three percent of the variance in the logarithmic form of the dissolved nitrogen measures at the piezometer sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.53$). The only watershed structure variable exhibiting a significant relationship with dissolved nitrogen was the logarithmic form of the percent of the piezometer sample station basin containing surface water cover, which was inversely related to dissolved inorganic carbon. Lakes may remove DIC via photosynthetic use of dissolved carbon dioxide and precipitation of calcium carbonate. However, calcium would be expected to follow the same pattern, but apparently does not.

   The predictive model for the dissolved inorganic carbon values measured in the piezometer samples is estimated as:

$$Y = 1.37 - 7.36(X_1)$$

where: Y = predicted value of the dissolved inorganic carbon measured at a piezometer sample station
X_1 = logarithmic form of the percent of the piezometer sample station basin area containing surface water cover

4. **Calcium.** Seventy-seven percent of the variance in the calcium ion measures at the piezometer sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.77$). The calcium measures were inversely related to both the logarithmic form of the percent of the piezometer sample station basins containing wetlands and the percent of the basins containing agricultural crop cover. Neither relationship is easily interpreted.

   The predictive model for calcium ions in the piezometer samples is estimated as:

$$Y = 89.91 - 22.35(X_1) - 1.89(X_2)$$

where: Y = predicted value of the calcium ions measured at a piezometer sample station
X_1 = logarithmic form of the percent of the piezometer sample station basin area containing wetlands.
X_2 = percent of the piezometer sample station basin area containing agricultural crop cover

5. **Iron.** Eighty-three percent of the variance in the iron ion measures at the piezometer sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.83$). The iron ion measures were directly related to the percent of the piezometer sample station drainage basin containing surface water or wetland cover and to the logarithmic form of the percent of the basin containing soils having low infiltration capacity. All of these factors could lead to lower redox conditions in the groundwater, which could enhance iron mobilization.

   The predictive model for iron ions in the piezometer samples is estimated as:

$$Y = -5.76 + 0.23(X_1) + 5.43(X_2)$$

where: Y = predicted value of the iron ions measured at a piezometer sample station
X_1 = percent of the piezometer sample station basin area containing surface water or wetlands
X_2 = logarithmic form of the percent of the piezometer sample station basin area containing soils with low infiltration capacity

6. **Chloride.** Seventy-one percent of the variance in the chloride ion measures at the piezometer sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.71$). Measures of chloride ions were directly related to the logarithmic form of the percent of the piezometer sample station drainage basin area that contained outwash surficial geologic formations. This pattern suggests a link between the infiltration of chloride into outwash formations within the watershed and the reappearance of chloride as discharge to stream baseflow.

   The predictive model for chloride ions in the piezometer samples is estimated as:

$Y = -60.31 + 44.21(X_1)$

where: Y = predicted value of the chloride ions measured at a piezometer sample station
X_1 = logarithmic form of the percent of the piezometer sample station basin area containing outwash surficial geologic deposits

7. **Heavy Oxygen.** Eighty-three percent of the variance in the logarithmic form of heavy oxygen isotope measures at the piezometer sampling stations was attributable to variance in watershed structure variables (i.e., $R^2 = 0.83$). Heavy oxygen was directly related to the percent of the station s drainage basin that contained surface water cover or wetlands. As noted previously, evaporation from lakes can concentrate heavy oxygen, perhaps thereby influencing groundwater conditions that are down gradient from these water bodies.

   The predictive model for heavy oxygen isotopes in the piezometer samples is estimated as:

   $Y = 0.05 + 0.02(X_1)$

   where: Y = predicted value of the logarithmic form of the heavy ions measured at a piezometer sample station
   X_1 = percent of the piezometer sample station basin area containing surface water or wetlands

Bedrock Well, Quaternary Well, and Spring Sample Analyses.

Table 19 presents results from the step-wise regression analyses conducted with seven of the groundwater quality variables from the bedrock well, Quaternary well, and spring water samples as dependent measures and selected watershed structure variables within the flow traces of these groundwater sources as independent measures. The individual dependent measures of groundwater quality are listed across the top of Table 19 while the independent measures of watershed structure within the groundwater-flow traces are listed down the left margin of the table. The table contains regression coefficients that describe the effect of significant independent variables for each of the regression models as well as summary statistics (e.g., coefficients of determination) that describe the overall strength of the models. Only two of the regression models produced coefficients of determination above 0.50. Each of these models will be briefly described.

1. **Dissolved Nitrogen.** Fifty-four percent of the variance in the dissolved nitrogen measures at the bedrock well, Quaternary well, and spring sampling stations was attributable to variance in watershed structure variables within the groundwater-flow traces (i.e., $R^2 = 0.54$). The values of dissolved nitrogen in these groundwater samples was directly related to the logarithmic form of the percent of the flow-trace area that was covered by impervious surfaces. We are skeptical of this relationship. The highest nitrogen values were found in groundwater from the Valley Creek watershed. They are likely the result of years of agriculture in the basin. The

relationship to impervious cover, much of which has originated only within the past few years is very likely spurious and misleading.

Nonetheless, the predictive model for dissolved nitrogen in the bedrock well, Quaternary well, and spring samples is estimated as:

$$Y = -1.73 + 5.29(X_1)$$

where: Y = predicted value of dissolved nitrogen measured at a bedrock well sample station
X_1 = logarithmic form of the percent of the well sample station flow trace area that contains impervious surfaces

2. **Dissolved Inorganic Carbon.** Sixty percent of the variance in the dissolved inorganic carbon measures at the bedrock well sampling stations was attributable to variance in watershed structure variables within the well traces (i.e., $R^2 = 0.60$). The dissolved inorganic carbon measures were inversely related to the logarithmic form of the percent of the well traces that contained soils having a high infiltration capacity. We see no obvious explanation for this relationship.

   The predictive model for dissolved inorganic carbon in the bedrock well samples is estimated as:

$$Y = 53.50 - 12.43(X_1)$$

where: Y = predicted value of dissolved inorganic carbon measured at a bedrock well sample station
X_1 = logarithmic form of the percent of the well sample station flow trace area containing soils with high infiltration capacity

CONCLUSIONS

Several generalized patterns emerge from the analyses of variance, the simple correlation analyses, and the multiple regression analyses.

Influence of Flow Regime on Stream Water Quality

Bivariate Effects of Flow Regime on Water Quality

As illustrated in Table 11, flow regime exhibited significant bivariate relationships with several of the stream water quality variables. Total suspended solids, phosphorous, and dissolved organic carbon increased in channel flow during periods of high runoff. High flows also produced significant decreases in specific conductivity, dissolved inorganic carbon, alkalinity, silicon, calcium, and magnesium. The reduction of these typical indicators of groundwater contribution to channel flow suggests the diluting effects of increased surface runoff during periods of high flow. This pattern was reinforced by the finding that higher quantities of isotopically lighter snowmelt and early spring precipitation produced isotopically-light direct runoff.

Multivariate Effects of Flow Regime on Water Quality

As illustrated in Table 16, flow regime influenced six of the ten water quality variables examined using multivariate regression analysis. These six variables included total suspended solids, total phosphorous, total nitrogen, dissolved inorganic carbon, calcium, and heavy oxygen. The effect of flow regime on dissolved oxygen and pH was insignificant, while the effect on iron and chloride was inconclusive.

In most instances, the significant effects of flow regime on the water quality variables in the stream samples were conceptually understandable. These effects provided evidence of hydrologic processes known to exist in watersheds. For example, the presence of dissolved inorganic carbon and calcium ions are often used as indicators for the presence of groundwater. Both of these indicators were inversely related to flow regime, meaning that measurements of the dissolved inorganic carbon and calcium variables were higher for samples gathered during low and moderate flow events than they were for samples collected during high flows. Increased precipitation and runoff during the high flow events alter the balance between surface water and groundwater in channel flow by contributing increased amounts of surface water. With higher quantities of surface water, the groundwater signals were diluted.

This dilution effect can lead to counter-intuitive results regarding the effect of certain land cover types. For example, total nitrogen content was inversely related to flow, i.e., high levels of nitrogen carried in baseflow were simply diluted by surficial runoff during snowmelt events. Yet, at high flows, total nitrogen was directly related to areal coverages of forest and wetlands. Does this mean that forests and wetlands were being flushed of accumulated nitrogen that was then carried to the stream? We believe this is unlikely, and that a better explanation is that forest and wetland cover reduced total runoff volume. During runoff events, nitrogen concentrations were still more dilute than during baseflow just less dilute with the presence of forest and wetlands than they would have been without.

The inverse relationship between heavy oxygen isotopes and flow regime is also conceptually understandable. Values of heavy oxygen isotopes recorded during periods of high flow were lower than were values recorded during low or moderate flow. This pattern is attributable to the greater influx of isotopically light water from snowmelt runoff. The presence of impervious surface area within a basin further enhanced delivery of this snowmelt to the stream.

Finally, total dissolved solids and phosphorous are often indicators of overland runoff, as these materials are transported from a watershed into a stream during periods of high flow. Measures of both of these variables were higher during high flow events.

Influence of Impervious Surface Area

The amount of impervious area present in a sampling station s drainage basin had some important and consistent consequences on water quality. Impervious area was directly related to increases in phosphorous and chloride ions in the stream samples and an increase in chloride and total dissolved solids in the lake samples. Phosphorous transport within a watershed is primarily associated with adsorption to soil particles and movement of these particles from watershed to stream. To the extent that pavement facilitates the flow of phosphorous-laden sediment, increasing impervious area could lead to an increase in phosphorous. Impervious area is also an indicator of development within a watershed. To the extent that increased development results in increased use of phosphorous-based fertilizers and delivery of yard waste to gutters and storm sewers within the watershed, increases in impermeable surface area could result in increases in phosphorous. Increased impervious area also often means increased use of road salt to melt snow and ice in the winter. Such a pattern could explain the direct association between chloride ions and impervious area.

The simple correlation analyses revealed that an increase in impervious surface area within a basin was also associated with a decrease in dissolved inorganic carbon (DIC) and calcium in the stream samples and with a decrease in DIC in the piezometer samples. These findings further suggest that in addition to affecting qualitative dimensions of surface runoff, impervious surface area may also have affected the hydrologic balance within a basin. As indicated earlier, DIC and calcium are indicators of the presence of groundwater. A decrease in DIC and calcium in channel flow in association with an increase in impermeable surface area suggests that the groundwater signals may have been diluted by an increase in surface runoff. A decline in DIC and calcium in piezometer water in association with an increase in impervious surfaces suggests that less infiltration and percolation of precipitation may have occurred because of an increased impervious area in a basin, although the net effect of urban imperviousness on groundwater recharge is complex and variable. Imperviousness was also related to heavy oxygen isotope content of runoff. While this relation may be spurious and site-specific to the southern part of the Browns Creek watershed, where runoff passes though a large evaporative basin (Long Lake) prior to entering the creek, we conjecture that runoff from warm pavements in summer may become isotopically heavy prior to entering the lake, and that heavy oxygen may in fact be a summertime urban signal. This conjecture needs to be tested, however. Paradoxically, some of the isotopically lightest water was delivered to Browns Creek during snowmelt runoff, where runoff from impervious surfaces was less mixed with heavier pre-existing water (see Almendinger, 2003). Hence we further conjecture that the annual range in heavy oxygen isotope content (heavy in summer, light in winter and spring) could be related to the impervious cover in a watershed.

Nutrient Buffering Capacity of Watersheds

Some evidence exists to suggest that certain conditions in the drainage basins of the sampling points were helping to buffer nutrient movement from the watersheds into the stream, lake, piezometer, well, or spring sampling stations.

Buffering Nitrogen Movement.

Two sets of patterns are discernable in an examination of relationships between movement of total nitrogen levels and watershed characteristics. The first pattern is characterized by conditions that retard nitrogen movement from the watershed into the stream channel. In the stream samples, lower levels of total nitrogen were associated with the increased presence in the watershed of forest cover, soils having high infiltration capacities and soils having gentle slopes. Increasing amounts of basin forest cover were also associated with decreasing measures of dissolved nitrogen in the well water samples. Furthermore, the increased presence within a basin of wetlands and hydric or flooded soil conditions were associated with decreased levels of total nitrogen in the stream samples. Total nitrogen levels in the lake samples was also correlated with increased amounts of non-hydric soils in the lake sample s basins. Collectively, these conditions suggest lower levels of nitrogen in the stream samples may be associated with increased infiltration within the watershed as long as there is sufficient vegetative cover or other forms of biologic activity to absorb or denitrify dissolved nitrogen in the infiltrated runoff. In addition, these land cover types are all non-agricultural, and they do not add artificially high levels of nitrogen to the landscape.

In basins that do not possess the nitrogen retention potential associated with forest cover or wetlands, there is evidence that the infiltrated nitrogen may move directly into subsurface pathways that eventually lead to discharge into stream or piezometer samples. Nitrogen levels in stream samples were directly correlated with basins that contained greater extents of soils with deeper saturation zones. Increasing depth to saturation zone would allow greater amounts of infiltration to percolate below the root zone. Once below the root zone, nitrogen can more readily move through subsurface flow into stream and piezometer samples, especially if geologic materials in this zone are highly permeable. The presence of outwash deposits in a basin was associated with increased measures of nitrogen in both the piezometer and the well water samples.

These two sets of inferences reinforce the importance of maintaining nitrogen-buffering capacity with the cover pattern of the two watersheds. Existing wetlands and forest cover appear to play significant roles in the retention of nitrogen in the basins. Their protection and expansion should be encouraged as a means of preventing the leakage of nitrogen from the watersheds into the streams. Also, agricultural best management practices should be implemented to reduce the input of nitrogen to groundwater, as this subsurface pathway is the primary mover of nitrogen to the creeks.

Buffering Phosphorous Movement

Higher measures of total phosphorous in the stream samples were associated with decreasing amounts of forest in the sampling station s basin, the presence of soils having low infiltration capacities, the presence of highly erosive soils, increasing amounts of till surficial geologic deposits, and increasing amounts of impervious surface area. Under low and moderate flow conditions, phosphorous levels were moderated by the presence of soils having deeper depths to saturation. Under high flow conditions, phosphorous levels were also moderated by the presence of wetlands and forest cover within the sampling station s drainage basin. Dissolved phosphorous measures in the piezometer samples increased with a decline in forest cover and declining amounts of both soils having high infiltration capacities and outwash surficial geologic deposits. Collectively, these findings suggest that phosphorous levels in stream and piezometer samples were sensitive to the buffering capacity afforded by forested areas and permeable surfaces. Greater amounts of erosive soils provided a source from which phosphorous-laden soil particles can move. Decreased infiltration capacity due to soil and surficial geologic conditions generates larger volumes and velocities of runoff to move these particles into stream channels. Increased infiltration capacity and the presence of forest cover, on the other hand, retards the volume of runoff, resulting in less sediment and phosphorous delivery to stream channels. These findings stress the importance of proper management of forest cover and permeable soils as agents for buffering the movement of phosphorous from the basins into stream channels.

Influence of Surficial Geologic Deposits

Within the two watersheds, the most prevalent surficial geologic formations are till and outwash. Till generally has a lower capacity for infiltration of surface water and lower internal permeability. These properties of till manifest themselves in association with the dissolved inorganic carbon (DIC) and the calcium ion regression models. Higher percentages of till within the stream sampling station drainage basins were associated with lower levels of both DIC and calcium. The lower infiltration capacities and permeability of these till deposits may influence the balance of surface runoff to baseflow within the streams. Increased surface runoff may be diluting the values of DIC and calcium. Increasing extents of till in the surficial geologic formations also resulted in increased chloride and phosphorous levels in the stream samples. This pattern likewise reflects the lower infiltration capacities associated with till deposits, which promotes increased overland runoff during snowmelt or storm events.

An alternative hypothesis is that the till deposits were more common in the morainal and ice-contact landforms, more prevalent in the Browns Creek watershed than in the Valley Creek watershed, and that these pocked landforms had a greater areal coverage of lakes than other landforms. Lower concentrations of DIC and calcium (and magnesium) may be related to mineral precipitation and sequestering of these components in lake sediment. These two hypotheses to explain lower DIC and calcium concentrations (dilution by runoff and sequestration in lake sediment) are not mutually exclusive, and the latter does nothing to explain the increased chloride and phosphorus concentrations.

Integrated Understanding of the Creeks' Hydrology

Collectively, these patterns suggest that interpretation of water quality performance in the Valley Creek and Browns Creek watersheds is complex. As measured by impermeable surface area, urbanization occurring in the watersheds is not the sole determinant of water quality in the streams. This study suggests that interpretations of water quality within the two creeks must consider the mix of urbanization with other land uses, particularly forest cover and wetland area in the drainage basin. The findings also suggest that the influence of land cover patterns on water quality must be considered relative to the topography on which they occur as well as the drainage properties of the soils and surficial geologic deposits that underlie the land cover pattern. Finally, it is also apparent that the dynamics of water quality in the two creeks changes dramatically during periods of high flow. Interactions between the imperviousness of the watershed s surfaces and flow conditions affect both the quantity and the quality of runoff flowing into the creeks.

The findings of this study suggest that increased reliance on infiltration may be a successful strategy for moderating the flow of larger quantities of runoff into the creeks. The infiltration facilities must, however, be designed to have sufficient capacity to store the large volumes of runoff associated with high flow conditions. Infiltration may also be able to mitigate adverse water quality in the creeks that is associated with overland runoff flowing from the watersheds into the creeks. But the findings of this study imply that increased infiltration strategies will only provide these water quality benefits if they are combined with careful design of land cover patterns that retain, or at least minimize, soluble materials moving through the hydrologic cycle within the watershed. In the absence within the watershed of sufficient areas of forest and wetlands to absorb the soluble substances, the infiltrated materials are likely to travel via subsurface pathways and find their way into groundwater, and eventually surface-water, flows.

REFERENCES CITED

Almendinger, J.E., 2003, Watershed hydrology of Valley Creek and Browns Creek: Trout streams influence by agriculture and urbanization in eastern Washington County, Minnesota, 1998-99. Report to the Metropolitan Council Environmental Services: St. Croix Watershed Research Station, Science Museum of Minnesota. 80 p.

Almendinger, J.E., and Grubb, S.E., 1999, Monitoring and Modeling Valley Creek Watershed: 5. Groundwater Hydrology and Flow Model. Report to the Legislative Commission on Minnesota Resources: St. Croix Watershed Research Station, Science Museum of Minnesota.

Kanivetsky, R. and Cleland, J.M., 1990, Hydrogeology. Plate 5. Geologic Atlas, Washington County, Minnesota. County Atlas Series, Atlas C-5. Swanson, L., and Meyer, G.N. (eds.). St. Paul, MN: University of Minnesota, Minnesota Geological Survey.

Table 1. Summary of water-quality sampling sites in the Valley Creek and Browns Creek watersheds

Type of Site	Number of Sites Valley Creek	 Browns Creek
Stream sites:		
Regular sampling	3	6
Grab sampling	15	1
Lake sites	8	7
Groundwater sites:		
Piezometers	4	3 + 3 not included
Springs	7	
Quaternary wells		2
Bedrock wells	6	4
Totals	43	26

NOTES: 60 site locations, plus piezometers co-located at nine stream sites, for a total of 69 sites. Three piezometer sites were rejected for analysis because downward head gradients indicated that samples would not be representative of groundwater entering the creek. Consequently, a total of 66 sites were included in the data analysis.

Table 2. Watershed structure characteristics included in An Atlas of Watershed Structure in the Browns Creek and Valley Creek Basins.

Characteristic of watershed structure	**Structural class values included in atlas**	**Revised structural class values included in data analysis**	**Source**
Bedrock geology (i.e. first formation encountered beneath land surface)	Platteville-Glenwood Formation St. Peter Sandstone Prairie du Chien Group Jordan Sandstone St. Lawrence and Franconia Formation Franconia-Ironton-Galesville Formation Eau Claire Formation Mt. Simon Sandstone (Note: Formations are listed in order of increasing depth from land surface)	Platteville-Glenwood Formation St. Peter Sandstone Prairie du Chien Group Jordan Sandstone St. Lawrence and Franconia Formation (Note: Formations are listed in order of increasing depth from land surface)	Minnesota Geological Survey
Surficial geology	Areas with bedrock within five feet of land surface Glacial till Outwash deposits Ice contact deposits Floodplain Glacial lake deposits Organic deposits	Glacial till Outwash deposits	Minnesota Geological Survey (MGS)
Surficial hydrology	Wetlands	Wetlands	Aerial photographic reconnaissance
	Water bodies	Water bodies	Aerial photographic reconnaissance
	Floodplain soils	Floodplain soils	Soil Survey Manual for Ramsey and Washington Counties
	National Wetlands Inventory sites	National Wetlands Inventory sites	US Fish and Wildlife Survey
	Drainage basins of stream sampling stations	Drainage basins of stream sampling stations	Inspection of USGS Topographic Quadrangles
	Drainage basins of lake sampling stations	Drainage basins of lake sampling stations	Inspection of USGS Topographic Quadrangles
	Drainage network	Drainage network	Inspection of USGS Topographic Quadrangles
	Drainage order	Drainage order	Inspection of USGS Topographic Quadrangles
Sub-surface hydrology	Approximate drainage area of Piezometer sampling stations	Approximate drainage area of Piezometer sampling stations	Inspection of USGS Topographic Quadrangles
	Groundwater traces	Groundwater traces	Inferred from groundwater level maps in MGS Washington County Geologic Atlas
Topographic elevation	50 foot topographic contours	50 foot topographic contours	USGS digital elevation model data
Topographic slope	0-3% slope 3-6% slope 6-12% slope 12-18% slope 18-25% slope > 25% slope	0-3% slope 3-6% slope 6-12% slope 12-18% slope 18-25% slope > 25% slope	Soil Survey Manual for Ramsey and Washington Counties
Soil parent material	16 classes of geomorphic material from which soils evolved	16 classes of geomorphic material from which soils evolved	Soil Survey Manual for Ramsey and Washington Counties
Depth of soil to bedrock	< 20 inches depth to bedrock 20-40 inches 40-60 inches > 60 inches	< 20 inches depth to bedrock 20-40 inches 40-60 inches > 60 inches	Soil Survey Manual for Ramsey and Washington Counties

Table 2. (continued)

Characteristic of watershed structure	**Structural class values included in atlas**	**Revised structural class values included in data analysis**	**Source**
Depth to zone of saturation in soils	<12 inches 12-24 inches <24 inches 12-36 inches 18-36 inches 24-36inches 24-42inches 24-48 inches 36-60 inches 48-72 inches > 72 inches	<12 inches 12-36 inches 36-72 inches > 72 inches	Soil Survey Manual for Ramsey and Washington Counties
Soil infiltration capacity (Based on soil hydrologic group rating)	High High to moderate Moderate to low Low	High High to moderate Moderate to low Low	Soil Survey Manual for Ramsey and Washington Counties
Soil permeability	< 0.2 inches per hour 0.2-6.0 inches per hour 0.6-2.0 inches per hour 2.0-20.0 inches per hour 2.0-6.0 inches per hour 6.0-20.0 inches per hour >20.0 inches per hour	< 6.0 inches per hour 6.0-20.0 inches per hour >20.0 inches per hour	Soil Survey Manual for Ramsey and Washington Counties
Frequency of soil flooding	None Rare Common Frequent	None Rare Common Frequent	Soil Survey Manual for Ramsey and Washington Counties
Hydric soils	Presence/absence of hydric soils (i.e. soils formed in a wetland hydrologic regime)	Presence/absence of hydric soils	Soil Survey Manual for Ramsey and Washington Counties
Soil erodibility	Highly erosive soil Possibly erosive soil Not highly erosive soil	Highly erosive soil Possibly erosive soil Not highly erosive soil	Soil Survey Manual for Ramsey and Washington Counties
Land cover	Water body Wetland Crop land Impervious Lawn (e.g. turfgrass around residences) Forest Shrub and grassland complex	Water body Wetland Crop land Impervious Lawn (e.g. turfgrass around residences) Forest Shrub and grassland complex	Aerial photo and field reconnaissance
Land parcels	Parcel boundaries	Parcel boundaries	Washington County Surveyor s Office

Table 3. Variables used to measure watershed structural characteristics for the stream and lake sample stations.

Watershed Structure Characteristic	**Variables Used to Measure Structural Characteristic**
Bedrock geology*	% basin occupied by St. Peter Sandstone deposits* % basin occupied by Prairie du Chien Group deposits* % basin occupied by Jordan Sandstone deposits* % basin occupied by Prairie du Chien Group or Jordan Sandstone deposits* % basin occupied by St. Lawrence-Franconia Formation deposits*
Surficial geology*	% basin occupied by outwash deposits* % basin occupied by till deposits*
Slope	% basin occupied by slopes less than 3% % basin occupied by slopes 3-6% % basin occupied by slopes > 6% % basin occupied by slopes 6-12% % basin occupied by slopes 12-18% % basin occupied by slopes 18-25% % basin occupied by slopes > 25%
Depth to bedrock	% basin occupied by soils with depth to bedrock < 60 inches % basin occupied by soils with depth to bedrock > 60 inches
Depth to soil saturation	% basin occupied by soils with depth to saturation < 72 inches % basin occupied by soils with depth to saturation > 72 inches
Soil infiltration capacity*	% basin occupied by soils with high infiltration capacity* % basin occupied by soils with moderately high infiltration capacity* % basin occupied by soils with high or moderately high infiltration capacity* % basin occupied by soils with moderately low infiltration capacity* % basin occupied by soils with low infiltration capacity* % basin occupied by soils with moderately low or low infiltration capacity*
Soil permeability*	% basin occupied by soils with permeability < 6 inches per hour* % basin occupied by soils with permeability > 6 inches per hour*
Soil flooding	% basin occupied by soils that are commonly or frequently flooded % basin occupied by soils that are never flooded
Hydric soils	% basin occupied by hydric soils % basin occupied by non-hydric soils
Soil erodibility	% basin occupied by highly erosive soils % basin occupied by potentially highly erosive soils % basin occupied by highly erosive or potentially highly erosive soils % basin occupied by not highly erosive soils
Land cover*	% basin occupied by National Wetland Inventory Site* % basin occupied by surface water* % basin occupied by wetlands as interpreted from aerial photography* % basin occupied by surface water or by wetland as interpreted from aerial photography* % basin occupied by lawn* % basin occupied by impervious surfaces* % basin occupied by crop land* % basin occupied by lawn, impervious surfaces or crop land* % basin occupied by forest* % basin occupied by grassland complex*

NOTES: Variables identified with and asterisk (*) were also used to measure structural dimensions for the piezometer and bedrock well stations.

Table 4. Key variables used to represent characteristics of watershed structure for stream sample basins

Watershed Structure Characteristic	**Variables Used to Measure Structural Characteristic**
Bedrock geology	% basin occupied by Prairie du Chien Group or Jordan Sandstone deposits
Surficial geology	% basin occupied by till deposits
Slope	% basin occupied by slopes less than 3% Log (base 10) of % basin occupied by slopes > 6%
Depth to bedrock	Log (base 10) % basin occupied by soils with depth to bedrock > 60 inches
Depth to soil saturation	% basin occupied by soils with depth to saturation > 72 inches
Soil infiltration capacity	% basin occupied by soils with high infiltration capacity % basin occupied by soils with moderately low or low infiltration capacity
Soil permeability	% basin occupied by soils with permeability < 6 inches per hour
Soil flooding	% basin occupied by soils that are never flooded
Hydric soils	% basin occupied by non-hydric soils
Soil erodibility	Log (base 10) % basin occupied by highly erosive soils
Land cover	Log (base 10) % basin occupied by wetlands as interpreted from aerial photography Log (base 10) % basin occupied by impervious surfaces Log (base 10) % basin occupied by forest

Table 5. Key variables used to represent characteristics of watershed structure for lake sample basins

Watershed Structure Characteristic	**Variables Used to Measure Structural Characteristic**
Bedrock geology	% basin occupied by Prairie du Chien Group or Jordan Sandstone deposits
Surficial geology	% basin occupied by till deposits
Slope	% basin occupied by slopes less than 3% % basin occupied by slopes > 6%
Depth to bedrock	% basin occupied by soils with depth to bedrock > 60 inches
Depth to soil saturation	% basin occupied by soils with depth to saturation > 72 inches
Soil infiltration capacity	% basin occupied by soils with high infiltration capacity % basin occupied by soils with moderately low or low infiltration capacity
Soil permeability	% basin occupied by soils with permeability < 6 inches per hour
Soil flooding	% basin occupied by soils that are never flooded
Hydric soils	% basin occupied by non-hydric soils
Soil erodibility	Log (base 10) % basin occupied by highly erosive soils
Land cover	% basin occupied by wetlands as interpreted from aerial photography Log (base 10) % basin occupied by impervious surfaces % basin occupied by forest

Table 6. Key variables used to represent characteristics of watershed structure for piezometer sample basins

Watershed Structure Characteristic	**Variables Used to Measure Structural Characteristic**
Bedrock geology	% basin occupied by Prairie du Chien Group or Jordan Sandstone deposits
Surficial geology	Log (base 10) % basin occupied by outwash deposits
Soil infiltration capacity	Log (base 10) % basin occupied by soils with high infiltration capacity Log (base 10) % basin occupied by soils with moderately low or low infiltration capacity
Soil permeability	% basin occupied by soils with permeability < 6 inches per hour
Land cover	Log (base 10) % basin occupied by surface water Log (base 10) % basin occupied by wetlands as interpreted from aerial photography Log (base 10) % basin occupied by surface water or by wetland as interpreted from aerial photography % basin occupied by lawn Log (base 10) % basin occupied by impervious surfaces % basin occupied by crop land % basin occupied by lawn, impervious surfaces or crop land Log (base 10) % basin occupied by forest

Table 7. Key variables used to represent characteristics of watershed structure for bedrock well trace sample basins

Watershed Structure Characteristic	**Variables Used to Measure Structural Characteristic**
Bedrock geology	% basin occupied by Prairie du Chien Group or Jordan Sandstone deposits
Surficial geology	% basin occupied by outwash deposits
Soil infiltration capacity	Log (base 10) % basin occupied by soils with high infiltration capacity % basin occupied by soils with moderately low or low infiltration capacity
Soil permeability	% basin occupied by soils with permeability < 6 inches per hour
Land cover	Log (base 10) % basin occupied by surface water Log (base 10) % basin occupied by wetlands as interpreted from aerial photography % basin occupied by surface water or by wetland as interpreted from aerial photography % basin occupied by lawn Log (base 10) % basin occupied by impervious surfaces % basin occupied by crop land % basin occupied by lawn, impervious surfaces or crop land Log (base 10) % basin occupied by forest

Table 8. Rotated factor structure of water quality variables for stream samples in Valley Creek and Browns Creek.

	Factor								
Water Quality Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Temperature	.05	.31	.04	-.54	.13	-.12	.15	-.34	.14
Specific Conductivity	.03	.66	-.09	.25	.08	-.104	.04	-.29	-.16
pH*	-.05	-.02	-.01	-.04	.03	-.04	.03	-.04	**.89***
Dissolved oxygen	-.007	.01	-.002	.04	-.007	.03	-.04	.72	-.34
% dissolved oxygen	-.01	-.006	.02	.12	.14	-.08	-.02	**.79***	.24
Total suspended solids*	-.14	-.26	-.06	.07	-.02	**.90***	-.08	-.01	-.02
Volatile suspended solids	-.16	-.22	-.04	.04	-.05	.88	-.11	-.02	-.01
% volatile suspended solids	.16	.19	.27	.35	.06	-.36	.02	.04	.30
Total phosphorous	-.25	-.77	-.21	.12	.03	.35	.0009	-.04	-.08
Dissolved phosphorous	-.22	-.83	-.22	.16	.08	.03	.01	.0009	-.08
Total nitrogen*	.02	.14	-.10	**.86***	.14	.12	-.04	.02	-.03
Dissolved nitrogen	.08	.23	-.02	.83	.13	-.06	-.04	.04	.02
Dissolved organic carbon	-.08	-.53	.30	-.25	-.30	.15	-.04	-.28	-.08
Dissolved inorganic carbon*	.31	**.86***	-.10	.22	.06	-.15	.06	.04	-.03
Alkalinity	.30	.86	-.10	.21	.06	-.15	.06	.04	-.03
Silicon	.87	.16	-.28	-.01	-.15	-.10	.11	-.009	-.03
Calcium*	**.92***	.18	-.12	.11	.23	-.09	.002	-.002	-.01
Magnesium	.91	.18	-.10	.10	.29	-.10	-.03	-.00001	-.01
Sodium	-.18	-.03	.91	-.06	-.13	-.11	.21	-.02	-.02
Potassium	-.80	-.18	-.30	.06	-.05	.12	-.32	.005	-.02
Iron*	-.25	-.03	-.10	-.13	**-.79***	.09	-.15	-.07	-.01
Sulfate	.74	.17	-.16	.18	.45	.04	-.28	.02	-.01
Chloride*	.006	.01	**.94***	-.05	-.09	-.11	.14	-.02	-.03
Aluminum	-.77	-.12	-.35	.005	.10	.14	-.22	-.007	.003
Barium	-.29	.01	.44	-.02	.14	.16	.22	.10	.14
Manganese	.02	-.02	.36	-.06	-.74	-.08	-.21	-.07	-.06
Strontium	.94	.18	-.04	.02	.05	-.13	.18	-.008	-.01
Fluoride	.84	.18	-.21	.02	.05	.005	.22	.02	.03
Bromide	.58	.11	.07	0.06	.61	-.12	-.23	-.01	-.03
Heavy oxygen*	0.30	.06	.36	-.11	.12	-.14	**.82***	-.06	.03
Deuterium	.38	.08	.27	-.09	.15	-.14	.82	-.06	.04
% total variance explained	**30.3%**	**13.4%**	**9.9%**	**7.0%**	**5.4%**	**4.6%**	**3.7%**	**3.3%**	**3.3%**

NOTES: 1. Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.
2. **Bold face*** indicates variable selected as surrogate for each factor.

Table 9. Rotated factor structure of water quality variables for lake samples in Valley Creek and Browns Creek.

	Factor						
Water Quality Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Temperature	-.10	.001	-.07	.69	-.45	.004	-.42
Specific Conductivity	.82	.01	-.08	-.08	.18	.29	.04
pH*	-.34	-.02	.04	.73	-.32	.14	**-.37**
Dissolved oxygen	-.14	-.03	-.37	.70	.27	-.16	.24
% dissolved oxygen*	-.17	-.02	-.27	**.90**	.005	-.08	.01
Total suspended solids*	.005	.02	**.90**	-.10	.14	-.06	-.06
Volatile suspended solids	-.08	.02	.84	-.25	.19	-.005	-.05
% volatile suspended solids	-.12	-.02	-.28	-.64	-.01	.02	-.14
Total phosphorous	-.23	.05	.77	.24	.17	.004	.37
Dissolved phosphorous	-.39	.04	.55	.09	-.002	-.13	.47
Total nitrogen*	.08	.03	.30	.02	**.89**	.09	-.06
Dissolved nitrogen	.19	.02	.13	-.11	.89	-.11	-.13
Dissolved organic carbon	-.64	-.14	.30	-.12	.29	.26	.08
Dissolved inorganic carbon	.94	.05	-.09	-.06	.01	-.03	.04
Alkalinity	.94	.05	-.09	-.06	.01	-.03	.04
Silicon	.63	.73	-.03	-.02	-.06	-.02	.02
Calcium*	**.95***	-.19	-.03	-.09	.06	.01	-.04
Magnesium	.95	-.17	-.08	-.02	.04	-.01	-.07
Sodium	-.07	-.05	-.04	-.07	-.04	.96	.05
Potassium	-.27	.90	.15	.003	.11	.01	.17
Iron*	-.20	**.91**	.14	.06	-.04	-.05	.15
Sulfate	.89	.11	-.13	-.02	0.10	.06	.05
Chloride*	.16	.12	-.06	-.01	.01	**.95**	.12
Aluminum	-.02	.99	-.04	.002	-.02	.02	-.0005
Barium	-.02	.99	-.04	.002	-.01	.02	.001
Manganese	.04	.96	.05	-.06	.04	.02	-.05
Strontium	.77	.53	-.07	-.10	.04	.14	.05
Fluoride	.04	.99	-.05	-.005	.01	.04	.08
Bromide	-.01	.99	-.04	-.0001	-.02	.02	-.002
Heavy oxygen	-.90	.24	-.16	.12	-.09	.02	.12
Deuterium	-.84	.41	-.19	.08	-.07	.03	.12
% total variance explained	**26.7%**	**24.1%**	**9.7%**	**9.2%**	**7.1%**	**6.9%**	**4.6%**

NOTES: 1. Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.
2. **Bold face*** indicates variable selected as surrogate for each factor.

Table 10. Rotated factor structure of water quality variables for groundwater samples in Valley Creek and Browns Creek.

	Factor									
Water Quality Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Temperature	-.02	-.10	-.91	.15	-.06	-.10	.14	.08	.02	.04
Specific Conductivity	.26	-.12	.19	.31	-.07	-.23	.20	-.74	.01	.12
pH*	-.09	-.24	.18	-.17	.06	.20	-.08	**.56***	.04	.53
Dissolved oxygen	.10	-.14	.25	.92	.06	.02	-.15	-.09	.05	.01
% dissolved oxygen*	.12	-.15	.10	**.94***	.04	.002	-.16	.01	.06	.01
Total suspended solids*	.09	.002	**.93***	.21	.09	.27	.02	-.22	-.03	-.03
Volatile suspended solids	.06	.01	.90	.33	.08	-.02	.04	.06	.0007	.04
% volatile suspended solids	.13	.02	-.23	.23	-.03	-.14	.04	.80	.10	.20
Total phosphorous	.38	.10	-.08	.08	.0006	.04	.04	.10	-.07	.83
Dissolved phosphorous	.30	.31	.06	-.44	-.18	.12	.02	.33	.08	-.02
Total nitrogen*	.16	-.17	.06	-.05	-.03	-.22	-.09	.26	**.72***	-.26
Dissolved nitrogen	-.13	-.13	-.05	.08	.03	.13	.02	-.09	.80	.12
Dissolved organic carbon	-.02	-.004	.001	-.12	.47	.71	-.008	.27	-.07	-.20
Dissolved inorganic carbon*	**.90***	-.05	.14	.06	.01	-.007	.19	.08	.08	.06
Alkalinity	.90	-.05	.14	.06	.01	-.007	.19	.08	.08	.06
Silicon	-.33	.70	-.11	-.08	.04	-.48	-.09	-.05	.14	.16
Calcium*	.02	-.25	-.13	.09	.07	-.57	.18	.09	**.62***	-.04
Magnesium	.72	-.47	-.21	.02	.20	-.15	-.09	-.22	.15	.03
Sodium	.14	-.16	.15	.08	.83	.25	.08	.13	-.13	.02
Potassium	.75	-.29	-.13	.11	.19	-.03	-.02	-.08	-.36	.15
Iron*	.17	**.74***	-.006	-.24	-.12	.28	.34	-.10	.02	.16
Sulfate	.10	-.62	-.11	.11	.35	-.30	-.24	-.04	.19	.09
Chloride*	.02	.06	.13	.04	**.91***	-.05	.25	-.03	.17	-.04
Aluminum	-.10	.30	.05	.07	.02	.83	-.004	-.01	.03	.26
Barium	.41	.10	-.08	-.19	-.04	.05	.78	-.08	-.14	-.01
Manganese	.62	.27	-.06	-.16	.11	.15	.47	-.23	-.27	18
Strontium	-.30	0.4	-09	-.008	.17	-.42	.61	.34	.10	-.04
Fluoride	-.56	-.12	.02	-.17	-.61	.07	.28	.31	.007	-.09
Bromide	.15	.004	.004	-.13	.16	-.01	.78	-.10	.10	.02
Heavy oxygen*	-.10	**.92***	.05	-.06	.09	.08	-.05	.03	-.21	-.01
Deuterium	-.09	.93	.04	-.12	.06	.08	-.03	.02	-.17	-.05
% total variance explained	**13.8%**	**13.0%**	**9.5%**	**8.2%**	**8.0%**	**7.9%**	**7.8%**	**7.2%**	**6.6%**	**4.4%**

NOTES: 1. Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.
2. **Bold face*** indicates variable selected as surrogate for each factor.

Table 11. Mean values of 31 water quality variables measured in Valley Creek and Browns Creek stream samples under different flow regimes.

	Flow Regime			
Water Quality Variable	**Low**	**Medium**	**High**	**Overall**
Temperature (°Celsius)	8.89a	11.94b	9.35a	10.94
Specific Conductivity (_ S)	454.98a	457.48a	386.57b	437.43
pH	**7.67a**	**7.45b**	**7.42b**	**7.46**
Dissolved oxygen (mg/l)	**12.21a**	**11.69a**	**11.65a**	**11.73**
% dissolved oxygen	107.15a	102.46b	102.42b	102.89
Total suspended solids (mg/l)	**9.10a**	**13.38a**	**108.98b**	**39.69**
Volatile suspended solids	3.66a	5.15a	22.15b	9.76
% volatile suspended solids	70.24a	59.60b	41.40c	55.51
Total phosphorous (_ g/l)	**64.28a**	**68.56a**	**350.31b**	**146.89**
Dissolved phosphorous (_ g/l)	32.74a	42.43a	207.47b	87.64
Total nitrogen (mg/l)	**4.74a**	**4.15b**	**4.27ab**	**4.24**
Dissolved nitrogen (mg/l)	4.38a	4.08a	3.98a	4.08
Dissolved organic carbon (mg/l)	1.80a	2.57b	4.03c	2.91
Dissolved inorganic carbon (mg/l)	**42.14a**	**41.71a**	**30.46b**	**38.60**
Alkalinity (meq/l)	3.53a	3.50a	2.59b	3.25
Silicon (mg/l)	5.89a	5.99a	5.44b	5.83
Calcium (mg/l)	**39.21a**	**39.27a**	**35.50b**	**38.21**
Magnesium (mg/l)	16.25a	16.29a	14.67b	15.83
Sodium (mg/l)	8.48a	8.68b	8.38c	8.57
Potassium (mg/l)	3.25a	3.11a	3.87b	3.33
Iron (mg/l)	**0.11a**	**0.11a**	**0.12a**	**0.11**
Sulfate (mg/l as S)	3.29a,b	3.25b	3.07a	3.20
Chloride (mg/l)	**17.36a**	**17.70a**	**16.99a**	**17.47**
Aluminum (mg/l)	0.04a	0.04a	0.05b	0.04
Barium (mg/l)	0.04a	0.04a	0.04a	0.04
Manganese (mg/l)	0.04a	0.04a	0.04a	0.04
Strontium (mg/l)	0.05a	0.05a	0.05b	0.05
Fluoride (mg/l)	0.11a	0.11a	0.10b	0.11
Bromide (mg/l)	0.007a,b	0.007a	0.006b	-.007
Heavy oxygen _ ^{18}O	**-9.86a**	**-9.72a**	**-10.18b**	**-9.86**
Deuterium _D	-70.22a	-69.20a	-72.50b	-70.22

NOTES: 1. Values followed by identical letters (a,b,c) are not significantly different at $p<.05$ using the Scheffe Multiple Comparison test.

2. Values in **bold face** represent water quality variables examined in the stream sample analysis.

Table 12. Coefficients of partial correlation between water quality variables and watershed structure variables controlling for effects of flow regime in stream water samples.

Watershed Structure Variable (independent variables)	**Water Quality Variables** (dependent variables)									
	pH	**% dissolved oxygen**	**Log 10 total suspended solids**	**Log 10 total phosphorous**	**Total nitrogen**	**Dissolved inorganic carbon**	**Calcium ion**	**Log 10 iron ion**	**Log 10 chloride ion**	**Heavy oxygen**
Log % watershed area in wetland cover		-.15**			-.82**	-.10*		.39**	.54**	.25*
Log % watershed area in impervious cover		-.26**	.18**	.17**	-.73**	-.38**	-.50**		.77**	.38**
Log % watershed area in forest cover	.13*	.15**	-.16**	-.44**	-.10*	.45**	.42**	-.62**		
Log % watershed area containing highly erosive soils	-.14*			.22**	.40**			.51**	-.50**	-.28*
% watershed area containing soils in Hydrologic Group A				-.25**	-.47**	.26**	.36**			
% watershed area area containing soils in Hydrologic Groups C/D				.17**				.48**		
% watershed area containing soils that never flood		.23**	-.19**	-.20**	.80**	.26**	.25**	-.48**	-.35**	
% watershed area containing soils with saturation zone deeper than 72 inches		.24**	-.20**	-.27**	.76**	.35**	.34**	-.52**	-.44**	-.24*
% watershed area containing soils with permeability < 6 in./hr.					.78**	.12*			-.63**	-.40**
Log % watershed area containing soils with bedrock deeper than 60 inches		-.31**	.20**	.21**	-.88**	-.31**	-.26*	.48**	.47**	.27*
% watershed area containing soils that are not hydric		.23**	-.21**	-.22**	.81**	.29**	.26*	-.49**	-.34**	
% watershed area containing till surface geologic formation		.13*		.19**	.25**	-.35**	-.53**		.43**	
% watershed area containing soils with slopes < 3%		-.26**	.17**	.18**	-.69**	-.15**		.54**		
Log of % watershed area containing soils with slopes > 6%	.14*			-.21**	-.53**			-.32**	.58**	.34**
% watershed area containing Jordan or Prairie du Chien bedrock geologic formation		-.27**	.12**		-.58**					.28*

NOTES: Only significant ($p < 0.05$) partial correlation coefficients are shown.
** $p < 0.01$
* $p < 0.05$

Table 13. Coefficients of correlation between water quality variables and watershed structure variables in lake samples.

Watershed Structure Variable (independent variables)	**Water Quality Variables** (dependent variables)							
	Log 10 pH[a]	**% dissolved oxygen**[a]	**Log 10 total suspended solids**	**Log 10 total nitrogen**	**Calcium ion**	**Log 10 iron ion**	**Chloride ion**	**Log 10 total phosphorous**
% Watershed in wetland cover								.34*
Log % watershed in impervious cover			.31*		.33*		.54**	
% watershed in forest cover					.42**			
Log % watershed containing highly erosive soils						.33*	.53**	
% watershed containing soils in Hydrologic Group A								
% watershed containing soils in Hydrologic Groups C/D					-.36*		-.39*	
% watershed containing soils that never flood					.43**	.32*		
% watershed containing soils with saturation zone deeper than 72 inches					.59**	.45**		
% watershed containing soils with permeability < 6 in./hr.						.32*		
% watershed containing soils with bedrock deeper than 60 inches							.35*	
% watershed containing soils that are not hydric				.37*	.45**	.35*		.38*
% watershed containing till surface geologic formation					-.63**	-.48		
% watershed containing soils with slopes < 3%				-.34*				
% watershed containing soils with slopes > 6%								
% watershed containing Jordan or Prairie du Chien bedrock geologic formation							.59**	

NOTES: Only significant ($p<0.05$) correlation coefficients are shown.

** $p < 0.01$

* $p < 0.05$

[a] None of the watershed structure variables exhibited significant relationships with this water quality variable.

Table 14. Coefficients of correlation between water quality variables and watershed structure variables in piezometer samples.

Watershed Structure Variable (independent variables)	**Water Quality Variables** (dependent variables)						
	Log 10 Dissolved phosphorous	**Log 10 dissolved nitrogen**	**Dissolved inorganic carbon**	**Calcium ion**	**Iron ion**	**Chloride ion**	**Log10 heavy oxygen**
Log 10 % watershed in lakes			-.74**		.57*		.80**
Log 10 % watershed in wetland cover		-.70*	-.60**	-.67**	.69**		.83**
% watershed in water or wetland			-.70**	-.53*	.70**		.87**
Log 10 % watershed in impervious cover		-.72*	-.61**				
% watershed in lawn cover		-.88**		-.62*		-.70**	
% watershed in lawn, impervious or crops (i.e. total disturbed area)			.54*		-.78**		-.91**
% watershed in crop cover			.65**		-.78**		-.89**
Log 10 % watershed in forest cover	-.76*					.58*	
Log 10 % watershed containing soils in Hydrologic Group A	-.66*					.71**	
Log 10 % watershed containing soils in Hydrologic Groups C/D					.80**		.57*
% watershed containing soils with permeability < 6 in./hr.							
Log 10 % watershed containing outwash surface geologic formation	-.75*	.78**				.85**	
% watershed containing Jordan or Prairie du Chien bedrock geologic formation					.53*		.70**

NOTES: Only significant ($p < 0.05$) correlation coefficients are shown.
** denotes $p < 0.01$
* denotes $p < 0.05$

Table 15. Coefficients of correlation between water quality variables and trace area structure variables in bedrock well samples.

Trace Area Structure Variable (independent variables)	**Water Quality Variables** (dependent variables)						
	Log10 Dissolved phosphorous [a]	**Dissolved nitrogen**	**Dissolved inorganic carbon**	**Calcium ion**	**Iron ion**	**Chloride ion** [a]	**Log10 heavy oxygen**
Log % trace area in lakes			-.52*		-.61**		
Log % trace area in wetland cover							
% trace area in water or wetland					-.65**		
Log % trace area in impervious cover		.75**					
% trace area in lawn cover							
% trace area in lawn, impervious or crops (i.e. total disturbed area)		.64**		.55*			
% trace area in crop cover							-.63*
Log % trace area in forest cover		-.60**					
Log % trace area containing soils in Hydrologic Group A			-.79**		-.69**		
% trace area containing soils in Hydrologic Groups C/D					-.62**		
% trace area containing soils with permeability < 6 in./hr.			.62**				
% trace area containing outwash surface geologic formation		.60*					
% trace area containing Jordan or Prairie du Chien bedrock geologic formation			.56**		.71**		

NOTES: Only significant ($p < 0.05$) correlation coefficients are shown.

** denotes $p < 0.01$

* denotes $p < 0.05$

[a] None of the trace area structure variables exhibited significant relationships with this water quality variable.

Table 16. Regression coefficients and coefficients of determination derived from regression of water quality variables on watershed structure variables for stream water samples.

Watershed Structure Variable (independent variables)	**Water Quality Variables** (dependent variables)				
	pH	**% dissolved oxygen**	**Log 10 total suspended solids**	**Log 10 total phosphorous**	**Total nitrogen**
Constant	5.91**	585.06**	11.66**	2.53**	25.44**
Flow Regime (Flow)	-0.08	-1.15	7.73**	4.70**	-11.20**
Log % Watershed in wetland cover (Wetland)		8.84**			-1.68**
Log % watershed in impervious cover (Impervious)				0.61**	
Log % watershed in forest cover (Forest)			-0.81**		
Log % watershed containing highly erosive soils (Erosive)			-5.12**		
% watershed containing soils in Hydrologic Group A (HydroA)					
% watershed containing soils in Hydrologic Groups C/D (HydroC/D)					0.03**
% watershed containing soils that never flood (NoFlood)					
% watershed containing soils with saturation zone deeper than 72 inches (Water Table)				-.02**	
% watershed containing soils with permeability < 6 in./hr. (Perm)		-0.74**	0.03**		
Log % watershed containing soils with bedrock deeper than 60 inches (Deep Bedrock)	-1.16*	-220.46**			-11.52**
% watershed containing soils that are not hydric (No Hydric)			-0.03**		
% watershed containing till surface geologic formation (Till)	0.007**				
% watershed containing soils with slopes < 3% (Flat)					
Log of % watershed containing soils with slopes > 6% (Steep)	2.27**				
% watershed containing Jordan or Prairie du Chien bedrock geologic formation (Jordan-PdC)					
Interaction of Flow x Wetland				-0.67**	1.15**
Interaction of Flow x Impervious					
Interaction of Flow x Forest				-0.75**	2.32**
Interaction of Flow x Erosive					
Interaction of Flow x HydroA					
Interaction of Flow x HydroC/D					0.05**
Interaction of Flow x NoFlood					
Interaction of Flow x Water Table					-0.11**
Interaction of Flow x Perm					
Interaction of Flow x Deep Bedrock					
Interaction of Flow x No Hydric				-.04**	0.18**
Interaction of Flow x Till					-.03**
Interaction of Flow x Flat					
Interaction of Flow x Steep			-4.46**		
Interaction of Flow x Jordan-PdC					
Coefficient of determination (Adjusted R^2)	0.05	0.22	0.50	0.64	0.86
F-value of regression model	4.74**	19.93**	90.12**	137.31**	254.22**
Degrees of freedom	4,293	4,271	6,529	6,451	10,411

NOTES: Only significant ($p < 0.05$) are shown.
** $p < 0.01$
* $p < 0.05$

Table 16. Regression coefficients and coefficients of determination derived from regression of water quality variables on watershed structure variables for stream water samples (continued).

Watershed Structure Variable (independent variables)	**Water Quality Variables** (dependent variables)				
	Dissolved inorganic carbon	**Calcium ion**	**Log 10 iron ion**	**Log 10 chloride ion**	**Heavy oxygen**
Constant	-103.14**	47.86**	.11	1.63**	-15.01**
Flow Regime (Flow)	-125.29**	-83.25**	.99**	-0.36*	-10.06**
Log % Watershed in wetland cover (Wetland)					
Log % watershed in impervious cover (Impervious)	26.02*			0.84**	9.01**
Log % watershed in forest cover (Forest)			-1.88**		
Log % watershed containing highly erosive soils (Erosive)				-0.74**	
% watershed containing soils in Hydrologic Group A (HydroA)					
% watershed containing soils in Hydrologic Groups C/D (HydroC/D)	1.01**				
% watershed containing soils that never flood (NoFlood)					
% watershed containing soils with saturation zone deeper than 72 inches (Water Table)	1.31**				
% watershed containing soils with permeability < 6 in./hr. (Perm)					
Log % watershed containing soils with bedrock deeper than 60 inches (Deep Bedrock)		-161.67**			
% watershed containing soils that are not hydric (No Hydric)				0.004**	
% watershed containing till surface geologic formation (Till)	-0.31**	-0.69**			
% watershed containing soils with slopes < 3% (Flat)	0.30**		0.04**		
Log of % watershed containing soils with slopes > 6% (Steep)					
% watershed containing Jordan or Prairie du Chien bedrock geologic formation (Jordan-PdC)					
Interaction of Flow x Wetland	17.03**	22.54**		.12**	
Interaction of Flow x Impervious					-8.13**
Interaction of Flow x Forest	27.79**			.23*	9.87**
Interaction of Flow x Erosive					
Interaction of Flow x HydroA					
Interaction of Flow x HydroC/D					
Interaction of Flow x NoFlood	0.89**				
Interaction of Flow x Water Table		0.80*			
Interaction of Flow x Perm					
Interaction of Flow x Deep Bedrock					
Interaction of Flow x No Hydric					
Interaction of Flow x Till					
Interaction of Flow x Flat			-0.03**		
Interaction of Flow x Steep					
Interaction of Flow x Jordan-PdC					
Coefficient of determination (Adjusted R^2)	0.72	0.73	0.66	0.83	0.64**
F-value of regression model	126.91**	46.06**	35.24**	69.02**	29.99
Degrees of freedom	9,424	5,80	4,65	6,78	4,62

NOTES: Only significant ($p < 0.05$) are shown.
** $p < 0.01$; * $p < 0.05$

Table 17. Regression coefficients and coefficients of determination derived from regression of water quality variables on watershed structure variables for lake water samples.

Watershed Structure Variable (independent variables)	**Water Quality Variables** (dependent variables)							
	Log 10 pH[a]	**% dissolved oxygen**[a]	**Log 10 total suspended solids**	**Log 10 total nitrogen**	**Calcium ion**	**Log 10 iron ion**	**Chloride ion**	**Log 10 total phosphorous**
Constant			0.28	-.043	20.58**	5313.88**	-6.07	0.24
% Watershed in wetland cover								
Log % watershed in impervious cover			0.63*		29.20**		22.17**	
% watershed in forest cover				-0.005*		161.41**		-0.01**
Log % watershed containing highly erosive soils								
% watershed containing soils in Hydrologic Group A						-229.39**		
% watershed containing soils in Hydrologic Groups C/D								
% watershed containing soils that never flood								
% watershed containing soils with saturation zone deeper than 72 inches								-0.02**
% watershed containing soils with permeability < 6 in./hr.								
% watershed containing soils with bedrock deeper than 60 inches								
% watershed containing soils that are not hydric				0.01**				0.04**
% watershed containing till surface geologic formation					-.048**	-108.69**		
% watershed containing soils with slopes < 3%								
% watershed containing soils with slopes > 6%								0.01**
% watershed containing Jordan or Prairie du Chien bedrock geologic formation							0.18**	
Coefficient of determination (Adjusted R^2)			0.07	0.19	0.50	0.45	0.56	0.47
F-value of regression model			4.48*	5.40*	17.7**	13.56**	22.65**	9.14**
Degrees of freedom			1,43	2,35	2,32	3,43	2,32	4,33

NOTES: Only significant ($p < 0.05$) coefficients are shown.

** $p < 0.01$

* $p < 0.05$

[a] Regression analysis failed to generate a significant ($p < 0.05$) model.

Table 18. Regression coefficients and coefficients of determination derived from regression of water quality variables on watershed structure variables for piezometer samples.

Watershed Structure Variable (independent variables)	**Water Quality Variables** (dependent variables) **Log 10 Dissolved phosphorous**	**Log 10 Dissolved nitrogen**	**Dissolved inorganic carbon**	**Calcium ion**	**Iron ion**	**Chloride ion**	**Log10 heavy oxygen**
Constant	1.30	1.37**	48.88**	89.91**	-5.76**	-60.31**	.05
Log 10 % watershed in lakes			-7.36**				
Log 10 % watershed in wetland cover	1.76**			-22.35**			
% watershed in water or wetland					.23**		.02**
Log 10 % watershed in impervious cover							
% watershed in lawn cover		-.13**					
% watershed in lawn, impervious or crops (i.e. total disturbed area)							
% watershed in crop cover				-1.89**			
Log 10 % watershed in forest cover	5.68*						
Log 10 % watershed containing soils in Hydrologic Group A							
Log 10 % watershed containing soils in Hydrologic Groups C/D					5.43*		
% watershed containing soils with permeability < 6 in./hr.							
Log 10 % watershed containing outwash surface geologic formation						44.21**	
% watershed containing Jordan or Prairie du Chien bedrock geologic formation	-.12*						
Coefficient of determination (Adjusted R^2)	.88	.74	.53	.77	.83	.71	.83
F-value of regression model	22.84**	26.04**	20.01**	24.42**	34.63**	35.14**	69.08**
Degrees of freedom	(3,6)	(1,8)	(1,16)	(2,12)	(2,12)	(1,13)	(1,13)

NOTES: Only significant ($p < 0.05$) coefficients are shown.

** denotes $p < 0.01$

* denotes $p < 0.05$

Table 19. Regression coefficients and coefficients of determination derived from regression of water quality variables on trace area structure variables for bedrock well samples.

Trace Area Structure Variable (independent variables)	**Water Quality Variables** (dependent variables)						
	Log10 Dissolved Phosphorous[a]	**Dissolved nitrogen**	**Dissolved inorganic carbon**	**Calcium ion**	**Iron ion**	**Chloride ion**[a]	**Log10 heavy oxygen**
Constant		-1.73	53.50**	44.92**	-.51		.44**
Log % trace area in lakes							
Log % trace area in wetland cover							
% trace area in water or wetland							
Log % trace area in impervious cover		5.29**					
% trace area in lawn cover							-.009*
% trace area in lawn, impervious or crops (i.e. total impervious area)				.30*			
% trace area in crop cover							
Log % trace area in forest cover							
Log % trace area containing soils in Hydrologic Group A			-12.43**				
% trace area containing soils in Hydrologic Groups C/D							
% trace area containing soils with permeability < 6 in./hr.							
% trace area containing outwash surface geologic formation							
% trace area containing Jordan or Prairie du Chien bedrock geologic formation					.04**		
Coefficient of determination (Adjusted R^2)		.54	.60	.26	.47		.33
F-value of regression model		19.55**	29.91**	6.52*	15.31**		6.46*
Degrees of freedom		(1,15)	(1,18)	(1,15)	(1,15)		(1,10)

NOTES: Only significant ($p < 0.05$) coefficients are shown.
** $p < 0.01$
* $p < 0.05$
[a] Regression analysis failed to generate a significant ($p < 0.05$) model.