

Optimizing a Monitoring Network Using Water Quality and Environmental Factors in the Glacial Aquifer System, United States

By Terri L. Arnold and Kelly L. Warner, U.S. Geological Survey National Water-Quality Assessment Program, Illinois Water Science Center

Introduction

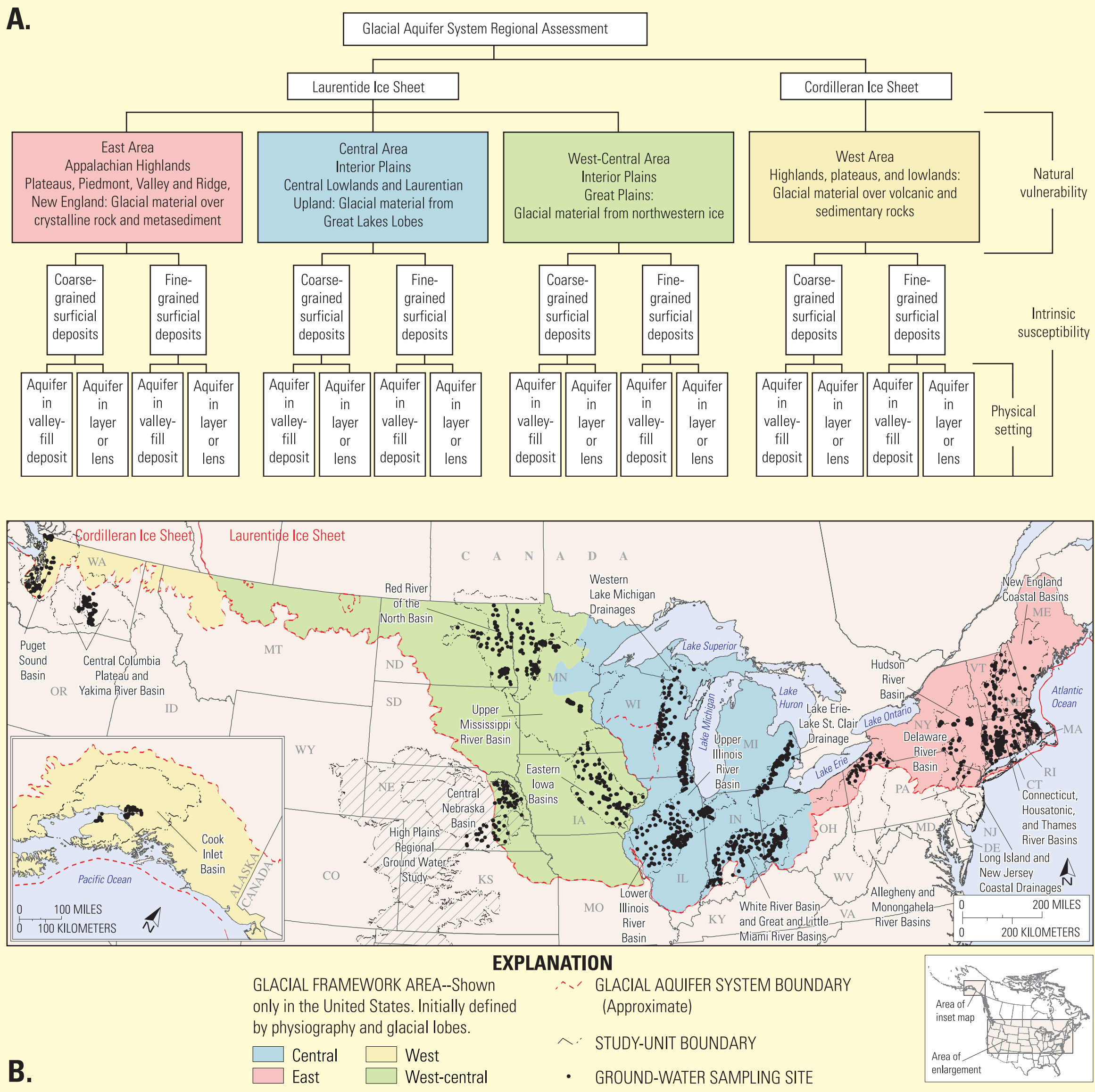
The glacial aquifer system (fig. 1) is a large (953,148 square miles in the United States) regional aquifer of heterogeneous and varied composition. Many water-chemistry reactions are studied on a local scale; however, regional scale studies can give a broad understanding of general differences in water quality across an aquifer. Examining variations in water quality on a regional scale reveals that the variations in major ion and some trace-element concentrations are most likely the result of natural variations in the geologic and physical environment.

Concentrations of major ions are typically used to describe broad types of water because they can be indicative of the geological sources of the water along a flow path. Additionally, anions and cations are important in how they chemically react with other constituents. By looking at combined variations in concentrations of various major ions and by finding related variables to aid in explaining those variations, extrapolations can be used to map hydrochemical regions which show areas where water quality is likely to be similar (figure 2 in Results section). The hydrochemical regions presented here specifically describe water quality in the glacial aquifer system because they were formed based on actual ground-water quality data collected from the aquifer system. Knowing where there are hydrochemical regions of varying ground-water quality will help researchers calibrate the monitoring well network as new sites are added to study the glacial aquifer system.

Regional Framework

Study of the glacial aquifer system was designed around a regional framework (fig. 1) that hypothesizes two primary characteristics can affect water quality: (1) intrinsic susceptibility, which indicates how easily water moves through the aquifer system, and (2) natural vulnerability, which refers to the tendency or likelihood of contaminants to reach the ground-water system.

Figure 1 (right). (A) Hypothesized framework for designing a study of the glacial aquifer system and (B) locations of monitoring wells in the glacial aquifer system.

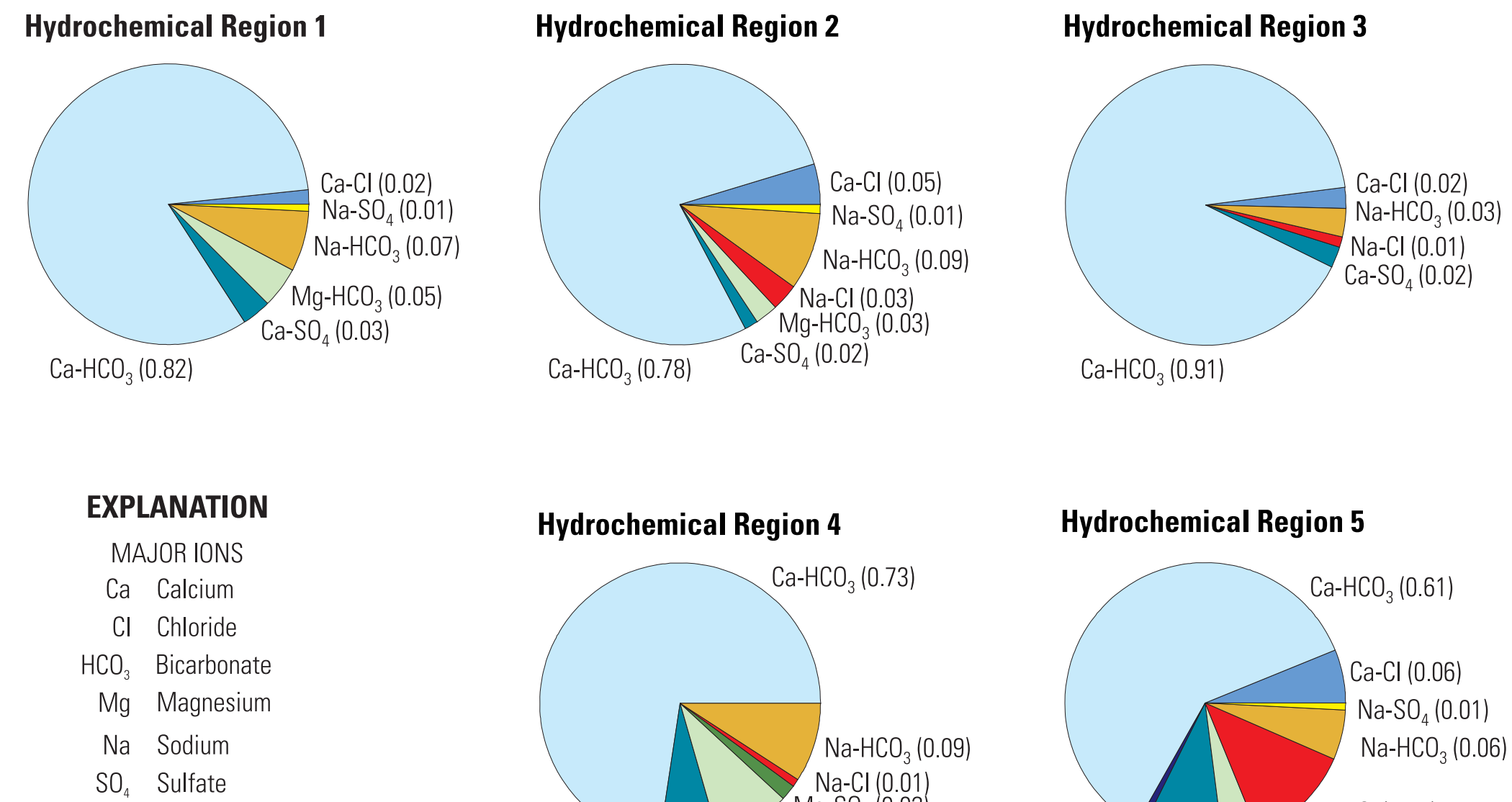


Results

Figure 2 (right): Hydrochemical regions in the glacial aquifer system are based on environmental variables that fit into the two primary components of the hypothesized framework used to design the glacial aquifer study: intrinsic susceptibility and natural vulnerability. The hydrochemical regions reflect the importance of the two basic components and closely resemble the hypothesized framework areas that were based on physiography and approximate locations of glacial lobes. Major ions and some trace elements (some of which are graphed below in figure 3) show statistically significant differences between the hydrochemical regions, which supports the hypothesized framework design. Although not used as a variable in the Maximum Likelihood Classification, bedrock appears to have an influence on the spatial distribution of the hydrochemical regions. Areas under hydrochemical regions 3 and 5 are generally igneous and metamorphic rocks; whereas, areas under hydrochemical regions 1, 2, and 4 are generally sedimentary rocks of varying textures which results in the differentiation between region 1 and 4.



Figure 4 (right): Ground water in the hydrochemical regions is predominantly hard and alkaline except for hydrochemical region 5, which has more acidic and softer water than the other regions. Water type is mostly calcium-bicarbonate; however, there are significant variations in other major ions.



Methods

Data analyzed for this study was collected at 1,719 ground-water sampling sites from 19 National Water-Quality Assessment Program study units across the glacial aquifer system over the period 1991-2003.

Steps to analysis	Purpose and results of analysis
Step 1. Unsupervised classification using cluster analysis. Unsupervised classification guarantees that the clusters are as distinct as possible.	- Form 5 groups of sites with similar concentrations of calcium, chloride, fluoride, magnesium, potassium, sodium, sulfate, and bicarbonate. Clustering the sites into 5 groups is like dividing the data set into five quantiles in 8-dimensional space. Most sites (89%) fit into distinct groups, 11% of the sites could not be distinctly grouped. Groups 2 and 3 had the most distinct sites (97% and 100%, respectively) and groups 1, 4, and 5 had the least distinct sites (79%, 88%, and 83%, respectively). - The likely reason some sites (11%) could not be distinctly grouped is that the basic water types of the glacial aquifer system are overwhelmingly calcium-bicarbonate with variations in the other major ions (fig. 4 in Results section).
Step 2. Identify environmental characteristics relating to the framework components (fig. 1) that vary significantly among clusters. These characteristics are mapped for the entire glacial aquifer system and can be used to extrapolate areas where water quality may be similar to the water quality in the sites that were sampled and analyzed.	- Seventeen environmental variables varied the most among clusters. Highly correlated variables were eliminated. - Logistic regression analysis showed that some variables were important for predicting some clusters but not others (table 1 below). Cumulatively, these variables describe how much water can enter the ground water system and provide opportunities for the water to remain in contact with the rock and soil material from which many of the major ions originate.
Step 3. Supervised classification using Maximum likelihood classification (MLC) spatial analysis. To perform the classification, a signature/index file was used to define the range of possible environmental variables for each cluster group.	- The MLC made an extrapolation of the water-quality groups defined by points into areas based on the related environmental variables. - Each environmental variable was a layer in a Geographic Information System (GIS). The layers (table 1) were then combined and classified following the characteristics identified in the index/signature file. - The result is a map showing hydrochemical regions in the glacial aquifer system (fig. 2 in Results section).

Table 1. Environmental variables used in classification and their significance.

Framework component	Environmental variable (Layer used in GIS)	Significant linear predictor indicated by logistic regression (95% confidence)				
		Group 1	Group 2	Group 3	Group 4	Group 5
Vulnerability from natural sources	Normalized (1980-1997) average annual precipitation (centimeters)	no	no	no	yes	yes
Vulnerability from natural sources	Normalized (1980-1997) average annual temperature (degrees F)	yes	no	yes	yes	yes
Vulnerability from natural sources	Land surface slope (percent)	yes	no	yes	yes	no
Vulnerability from human sources	1990's land cover from the National Land Cover Data set	yes (urban, ag, and forest)	yes (urban and ag)	yes (urban and forest)	yes (ag and forest)	yes (ag)
Intrinsic susceptibility	Vertical soil permeability (inches per hour)	yes	yes	yes	yes	yes
Intrinsic susceptibility	Soil clay content (percent of material less than 2mm in size)	no	no	no	yes	yes
Intrinsic susceptibility	Texture of surficial deposits	yes	no	yes	yes	no
Intrinsic susceptibility—physical setting	Type of surficial deposit (only used as a layer in the GIS not used to test significance as linear predictor)	NA	NA	NA	NA	NA
Intrinsic susceptibility	Estimated annual natural ground-water recharge (inches per year)	yes	yes	yes	no	yes

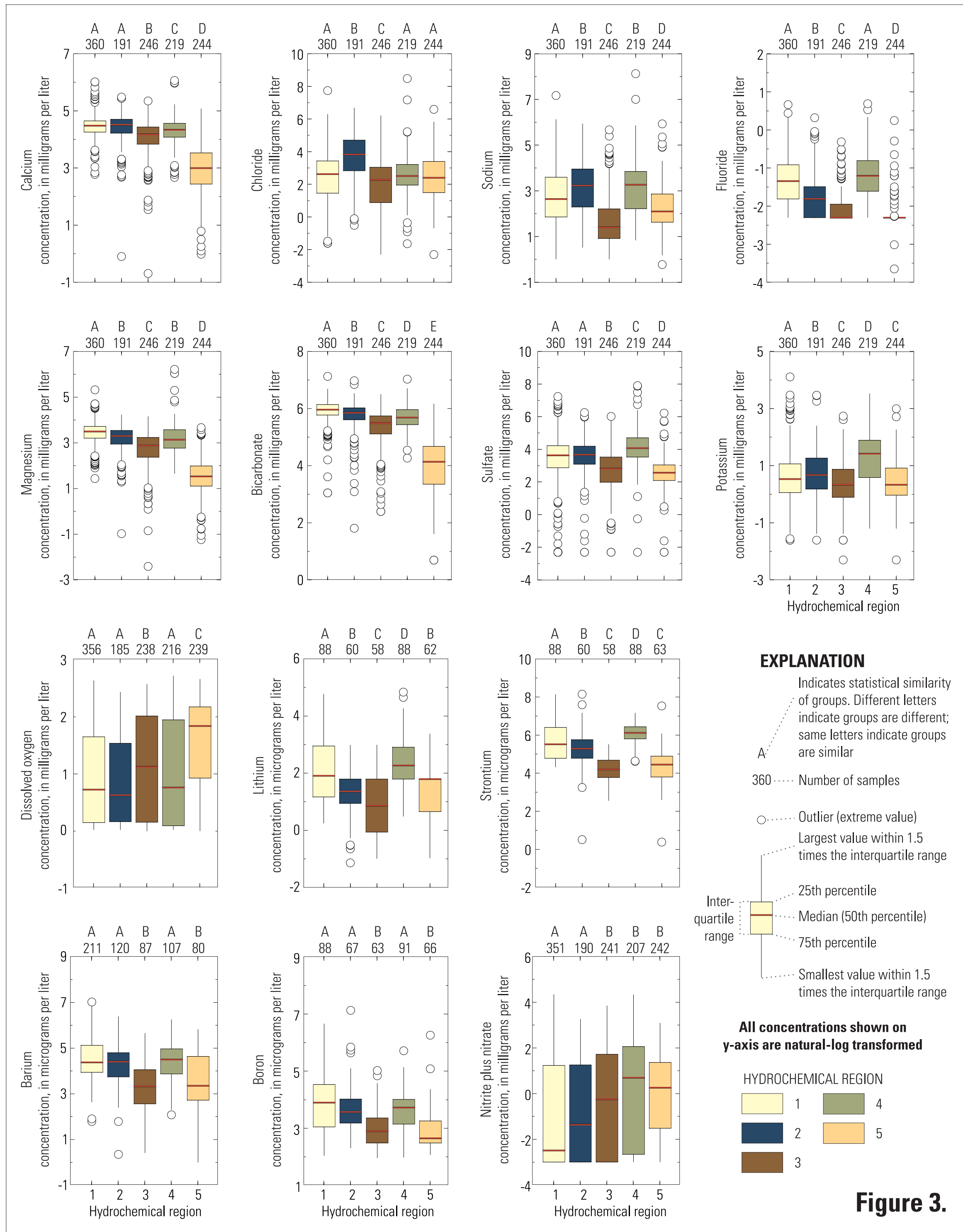


Figure 3.

Figure 3 (left) and table 2 (right): Ion exchange sites are commonly found on clays, organic matter, and metal oxides in soil and surficial materials. Hydrochemical regions 3 and 5 (fig. 2, table 2) have the lowest percent clay in soil and generally have the lowest major ion concentrations (fig. 3). In addition, both of these hydrochemical regions have environmental characteristics that facilitate movement of water through the system (high natural ground water recharge, low percentage of fine-grained surficial and soil material, and high vertical permeability) as well as relatively high dissolved oxygen concentrations (table 2 and fig. 3). Because water can move quickly through the system, there are lower major ion concentrations in the water (fig. 3). As a comparison, hydrochemical regions 1, 2, and 4 (fig. 2) generally have higher major ion concentrations across the board and have environmental characteristics that retard the flow of water through the system: high percentage of clay and mixed-texture or fine-grained surficial deposits, low natural ground-water recharge potential, and low vertical permeability (table 2 and fig. 3).

Table 2. Environmental characteristics of each hydrochemical region:

Environmental characteristic estimated from GIS layer	Region 1	Region 2	Region 3	Region 4	Region 5
Land cover (5 percent or more of region)	agriculture (83%), forest (9%)	forest (35%), agriculture (27%), urban (26%)	forest (49%), agriculture (27%), wetlands (16%)	agriculture (61%), grasslands (24%), forest (10%)	forest (66%), agriculture (12%), water (6%), urban (5%), wetlands (5%)
Surficial deposits and bedrock	surficial deposits are fine grained silty till over sedimentary rocks	thin, fine-grained clayey or silty surficial deposits, or exposed bedrock	sandy or silty till over igneous and metamorphic bedrock	clayey till over sedimentary bedrock	coarse-grained sandy till over metamorphic, igneous, or sedimentary rock
Soil texture	silty and clayey	silty and sandy	sandy and clayey; rich in organic material	silty and clayey	sandy and silty
Average vertical permeability (inches/hour)	1	2	4	1	3
Normalized average annual precipitation (inches/year)	36	38	35	21	45
Normalized average annual temperature (degrees F)	48	46	43	45	45
Average estimated ground-water recharge (inches/year)	3	6	7	1	13
Average slope (percent)	1	2	2	1	8

Conclusions

When optimizing a monitoring well network, a framework design hypothesizes what characteristics and environmental settings of the aquifer may affect water quality. The framework hypothesis for the glacial aquifer system, based on intrinsic susceptibility and natural vulnerability, was tested by using actual ground-water quality data to examine variability in major ion concentrations across the framework components. Statistical analysis grouped sites with similar water-quality characteristics (unsupervised classification) and identified environmental variables that were related to the variations in water quality (graphical, correlation, and logistic regression analysis). Spatial analysis (supervised classification) combined information about the water-quality groups and the environmental variables to extrapolate hydrochemical regions of similar water-quality. This extrapolation into hydrochemical regions further refined the hypothesized framework.

The hydrochemical regions define the most common water-quality conditions that can be expected across the glacial aquifer system. In addition to major ions, constituents such as iron, manganese, nitrate plus nitrite, dissolved oxygen, lithium, selenium, molybdenum, strontium, barium, and boron also vary significantly among the hydrochemical regions (fig. 3). Because the hydrochemical regions show researchers where water-quality parameters are likely to vary, these regions can be used to identify areas where new sites should be added to the monitoring well network for the glacial aquifer system.

For additional information, contact:

Terri Arnold
tlarnold@usgs.gov
217-344-0037 ext 3039

Kelly Warner
klwarner@usgs.gov
217-344-0037 ext 3010

For online information, reports, and data from the National Water-Quality Assessment program:
<http://water.usgs.gov/nawqa/>