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# Framework for Regional Synthesis of Water-Quality Data for the Glacial Aquifer System in the United States

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## Introduction

The glacial aquifer system is the largest principal aquifer in aerial extent and ground-water use for public supply in the United States. A principal aquifer is defined as a regionally extensive aquifer or aquifer system that has the potential to be used as a source of potable water (U.S. Geological Survey, 2003). Multiple aquifers often are grouped into large, extensive aquifer systems such as the glacial aquifer system.

The glacial aquifer system is considered here to include all unconsolidated aquifers above bedrock north of the line of continental glaciation throughout the country (fig. 1). Total withdrawals from the glacial aquifer system were 3,560 million gallons per day in 2000, which constitutes almost 5 percent of total withdrawals from all aquifers in the United States (Maupin and Barber, 2005). Approximately 41 million people relied on the glacial aquifer for public supply and domestic use in 2000.

The U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program began assessing the glacial aquifer system in 1991. The assessment of water-quality data on a regional scale, such as the glacial aquifer system, is coincident with the regional framework established by the Regional Aquifer-System Analysis Program (RASA) (Sun and others, 1997). From 1978 to 1995, the RASA Program systematically evaluated 25 of the Nation's most important ground-water systems including studies in the glacial aquifer system in the northeast, Midwest, and northern Midwest United States. The NAWQA Program is building on the work of the RASA Program to study the water quality of 16 of the most important ground-water systems (Lapham and others, 2005). Over 1,700 water-quality samples have been collected by the NAWQA Program from 1991 to 2004 to assess the glacial aquifer system. This large data set is unique in that the samples have been collected using a consistent sampling protocol, and multiple nested samples. The nested samples address the recently recharged shallow ground water, deeper water from principal aquifers often used for domestic supply, and source water used for public supplies within the glacial aquifer system. Information concerning the NAWQA Program including study unit boundaries is shown in figure 1 (Lapham and others, 2005).

A framework for comparison of water quality across the glacial aquifer system has been developed based on two primary characteristics: intrinsic susceptibility and vulnerability. Intrinsic susceptibility, which is a measure of the ease at which water enters and moves through aquifer material, is a characteristic of the aquifer and overlying material and of the hydrologic conditions. Intrinsic susceptibility is independent of the chemical characteristics of the contaminant and its sources. In this way, intrinsic susceptibility assessments do not target specific natural or anthropogenic sources of contamination but instead consider only the physical factors affecting the flow of water to, and through the ground-water resource (Focazio and others, 2002). On a regional scale, intrinsic susceptibility is represented by the spatial distribution of fine- or coarse-grained material at the land surface, and the physical setting of the aquifer system. Vulnerability, which is a function of both intrinsic susceptibility and the proximity and characteristics of contaminant sources, includes consideration of features related to anthropogenic sources of contaminants, such as the character of the upgradient land use (for example, urban, agricultural, undeveloped, and others); as well as features related to natural sources of contaminants, such as the mineralogy of the aquifer material or the geochemical conditions within the aquifer system. The framework helps categorize this large region into areas of similar hydrogeologic characteristics for which water quality can be compared. The purpose of this report is to describe this framework and how it will be used for regional synthesis of water-quality data for the glacial aquifer system.

## Regional Framework

The regional framework (fig. 1b) consists of two primary characteristics: (1) intrinsic susceptibility that is an indication of how easily water moves through the aquifer system, and (2) vulnerability that refers to the tendency or likelihood of contaminants to reach the ground-water system (Focazio and others, 2002). The regional framework for the glacial aquifer system focuses on the vulnerability from contaminants of natural sources. Land use can be overlain on this regional framework as an indication of vulnerability from anthropogenic sources. Likewise, many other indicators of natural and anthropogenic sources can be overlain on this framework for making a comparative assessment of ground-water quality.

### Intrinsic Susceptibility

The glaciated area was divided for analysis of water quality into two types of surficial deposits—coarse- or fine-grained (fig. 1b). The purpose of dividing the glacial aquifer system based on surficial deposits is to incorporate intrinsic susceptibility into the framework. Numerous studies have been done on glacial sediments to determine differences in susceptibility based on matrix composition and texture (Hitt and Nolan, 2005; Arnold and Friedel, 2000; Berg and others, 1984). Varying horizontal and vertical hydraulic conductivities may be present for a range of textures. Information on the three-dimensional texture of materials is not available on a regional scale, so the coarse- or fine-grained sediment texture at the land surface is a surrogate for intrinsic susceptibility. The spatial distribution of fine- and coarse-grained deposits is derived from the digital data set by Soller and Packard (1998). Coarse-grained deposits, defined by Soller and Packard (1998) for the glacial materials, consist of layered sand and gravel, with less common silt and clay beds, deposited in fluvial, glaciofluvial, deltaic, and outwash-plain settings. Fine-grained deposits within the regional glacial aquifer system framework include fine-grained stratified sediments and till. The fine-grained stratified sediments are generally clay, silt, and very fine sand, but include lesser amounts of coarser material, commonly as interbeds. Till consists of poorly sorted sediments that are unstratified and composed of particles ranging in size from clay to large boulders. Although there is a wide range of till hydraulic conductivity, till is grouped with fine-grained deposits in this study. Intrinsic susceptibility considers physical factors affecting the flow of water to and through the ground-water resource. One of these factors is the physical setting of the aquifer system.

#### Physical Setting

The glaciated area was classified into two general patterns of aquifer geometry—valley-fill deposits, and layers or lenses (fig. 1b). The purpose of classifying the glacial aquifer system by aquifer geometry is to incorporate the physical setting of the aquifer into the regional framework. The valley-fill deposits are glacial deposits that fill a bedrock valley (although some deep valleys in glacial till are present in the western part of the study area), and may be in hydraulic connection to the land surface or buried. The layers or lenses are lenticular or continuous sand deposits that may be in physical connection to the land surface or buried. The aquifer geometry is an indication of the distribution and connectivity of aquifer material (potential lateral and vertical hydraulic connection). An understanding of the three-dimensional configuration of the aquifer and the aquifer boundaries is a prerequisite to development and protection of the aquifers. Randall (2001) summarizes the need to know aquifer geometry in conjunction with surficial material because the distribution of the glacial aquifer system is not coincident with the surficial distribution of coarse-grained deposits. For example, some coarse deposits constitute productive aquifers but are buried beneath fine-grained deposits and, thus, are not depicted on surficial geology or soils maps; other deposits are surficial but can not be considered aquifers because they rest on shallow bedrock and are thinly or variably saturated. The interpretation of site-specific information depends as much on the patterns of aquifer geometry the investigator expects or recognizes, as it does on the site-specific information.

Aquifer geometry is difficult to determine in layers and lenses, but the boundaries of an aquifer within a bedrock valley are more easily defined. Aquifers in a bedrock valley may be buried, in which case there is no surface topographic relief associated with this bedrock valley. Alternatively, a bedrock valley with surface topographic relief may have a thick sequence of glacial deposits in the bottom of the valley. Most of the glacial aquifer system located in bedrock valleys in the northeastern United States (East area, fig. 1a) is composed of deposits (called stratified drift in the northeastern United States) that are present to the land surface and bounded by bedrock with topographic relief. Although not common, some of the glacial aquifer system in bedrock valleys in the northeastern United States contains surficial confining units. The glacial aquifer system in valleys in the Central area (fig. 1a) often contains a thick sequence of fine-grained till and is bounded by carbonate bedrock (for example, the Mahomet aquifer in Illinois and buried valley aquifer near Dayton, Ohio (Rowe and others, 1999)), but there are many aquifers in valleys near rivers that have some topographic relief and are present to the land surface. A map of the spatial distribution of buried valleys is not available. For this study, the glacial aquifer system near river valleys was determined by buffering a digital data set of streams by approximately 3 miles and overlaying the resulting buffered areas on the surficial materials data set (Soller and Packard, 1998). The glacial aquifer system in valleys was defined where the buffered stream and coarse-grained sediments intersected. This process identified the aquifer geometry in the East area and adequately represented the aquifer geometry in the West, West-Central, and Central areas with some modification. These areas are described in the following section on "Vulnerability". Thickness of deposits was not appropriate for developing a map of buried valleys because the glacial deposits in Michigan are extremely thick (up to 1,000 feet thick in some areas). Information about locations of buried valleys was included where regional maps of the buried valleys were available.

## Vulnerability

The vulnerability of the glacial aquifer system is difficult to determine because many factors determine the composition of the aquifer matrix and geochemical conditions needed to mobilize constituents. Physiography and direction of travel of the glacial lobes are large-scale features (tens to hundreds of miles) used to group areas that may have similar glacial source materials. The glaciated area in the United States was divided into four major glacial areas based on differing glacial source material—East, Central, West-Central, and West areas (figs. 1a, b). Numerous studies have been done on glacial sediments that show distinct geochemical differences in the sediment based on geologic source of glacial sediment and sediment size (Randall, 2001; Shilts, 1995; Shilts, 1993; Shacklette and Boerngen, 1984). Weathering and leaching can dissolve and mobilize many constituents from the sediments that will affect the natural

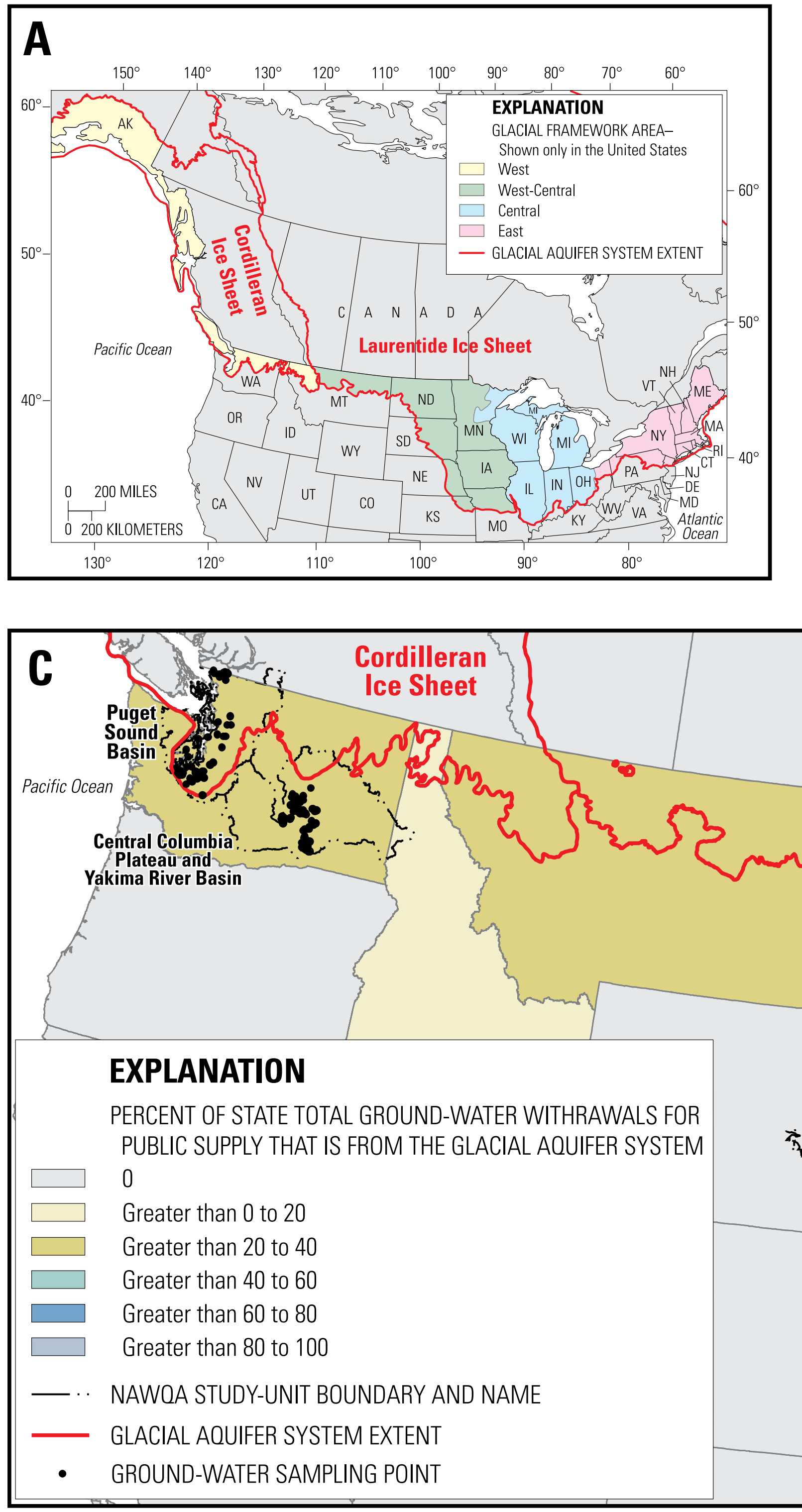
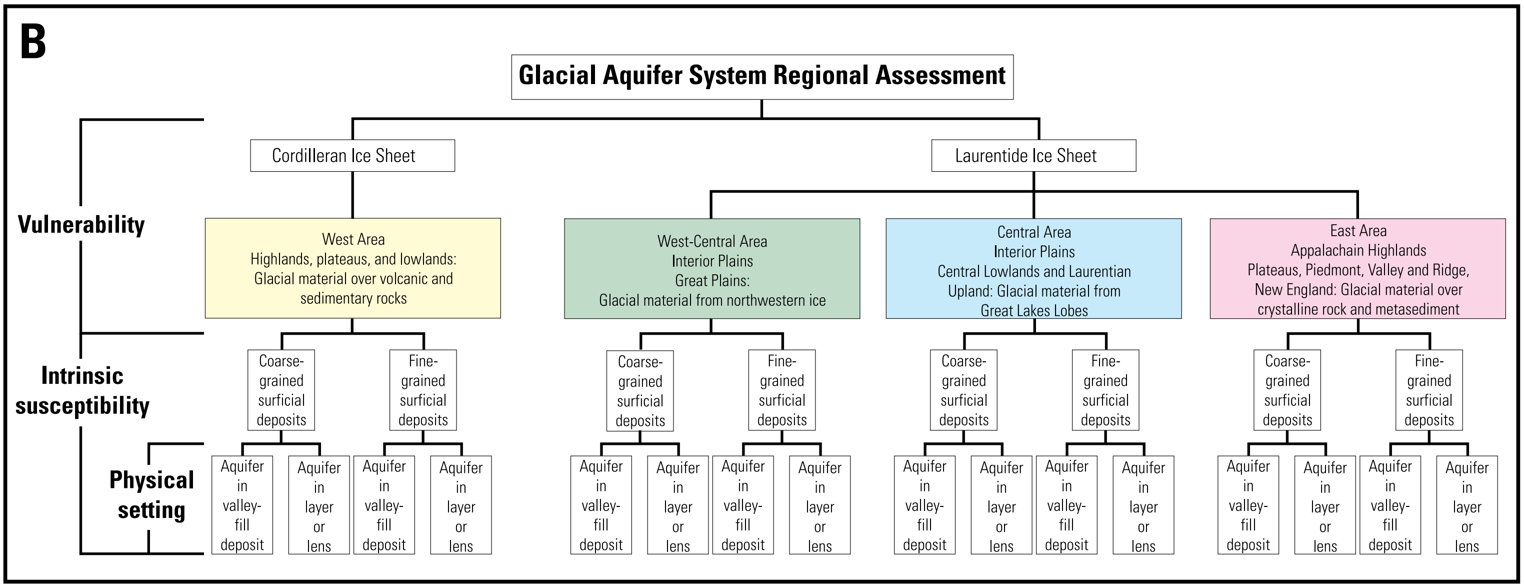
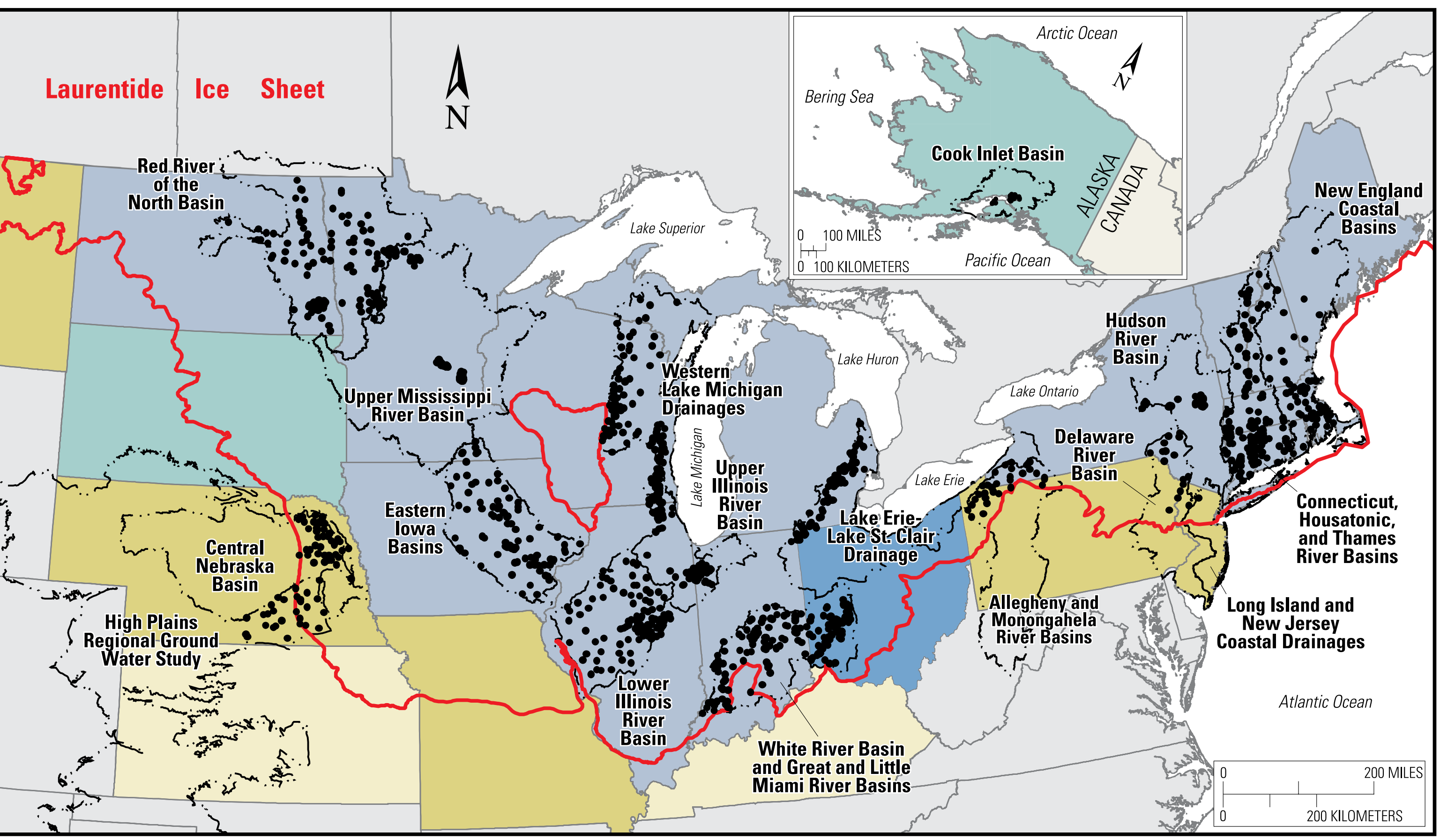



**Figure 1.** (A) Framework areas, (B) flowchart of framework layers, and (C) grou
system, United States.

ground-water chemistry, but the presence of a chemical constituent in the aquifer matrix is not directly related to its presence in ground water. Changes in aquifer conditions, such as oxidation-reduction potential (redox), may begin to mobilize chemical compounds within or adsorbed to the glacial source materials, and, thus, continue to alter the natural ground-water chemistry. Regional variations in the source of glacial sediments might be used to predict the reactivity of redox-sensitive contaminants in the glacial aquifer system. Combining




nd-water sampling points and percent of ground-water withdrawals for public supply (modified from Maupin and Barber, 2005) within the glacial aquifer the physiography map of Fenneman and Johnson (1946) with the boundaries of glacial lobes and sublobes as defined by Mickelson and others (1983) is the basis for the classification of glacial source material into East, Central, West-Central and West areas. These boundaries are a general guide for defining the areas (fig. 1a) in which to compare water quality across the glaciated area, but local detail on source of glacial material and geochemical conditions may further refine the boundaries of these areas.

## Water Quality

The framework for the glacial aquifer system classifies the entire study area into smaller areas of similar intrinsic susceptibility and vulnerability from natural sources. In addition, water-quality data collected by NAWQA are being used to delineate groundwater areas of similar chemistry. Comparing the areas of similar chemistry to the regional framework will help corroborate the framework design that is based on physical characteristics of the aquifer system.

Areas of similar intrinsic susceptibility in the glacial aquifer framework may have differing vulnerability depending on distribution of the natural or anthropogenic contaminant source. For example, in the East, the coarse-grained deposits in a bedrock valley may have high intrinsic susceptibility, but the vulnerability may vary because there is not a uniform distribution of natural contaminant or glacial source material. Even in areas where the source of the glacial materials is similar, such as the East, Central, West-Central, and West areas (fig. 1a), the natural contaminant source materials may not be uniform in distribution so the vulnerability may not be uniform. The unconsolidated nature of the glacial materials also makes these deposits vulnerable to anthropogenic contamination.

The glacial aquifer system is used extensively as a source of drinking water for public and domestic supply; therefore, water quality is an issue for water managers, health officials, and private well owners. Many natural contaminants are present in the glacial aquifer system because the geologic source of the aquifer material is from rock types containing a wide variety of minerals that contain arsenic, uranium, radon, and other potential contaminants.

Comparison of water quality within and among areas of the regional framework will provide insight on source, distribution, fate, and transport of possible contaminants. Some common water-quality issues across the glacial aquifer system include high nitrate, arsenic, radionuclide, and chloride concentrations, and multiple pesticide detections. Statistical analysis of contaminant concentrations and pesticide detections in ground water from the glacial aquifer system by framework area is shown in figure 2. Some variability in contaminant concentration among the framework areas helped identify the issues for further investigation. In addition to delineating areas of similar water chemistry for corroboration of the glacial

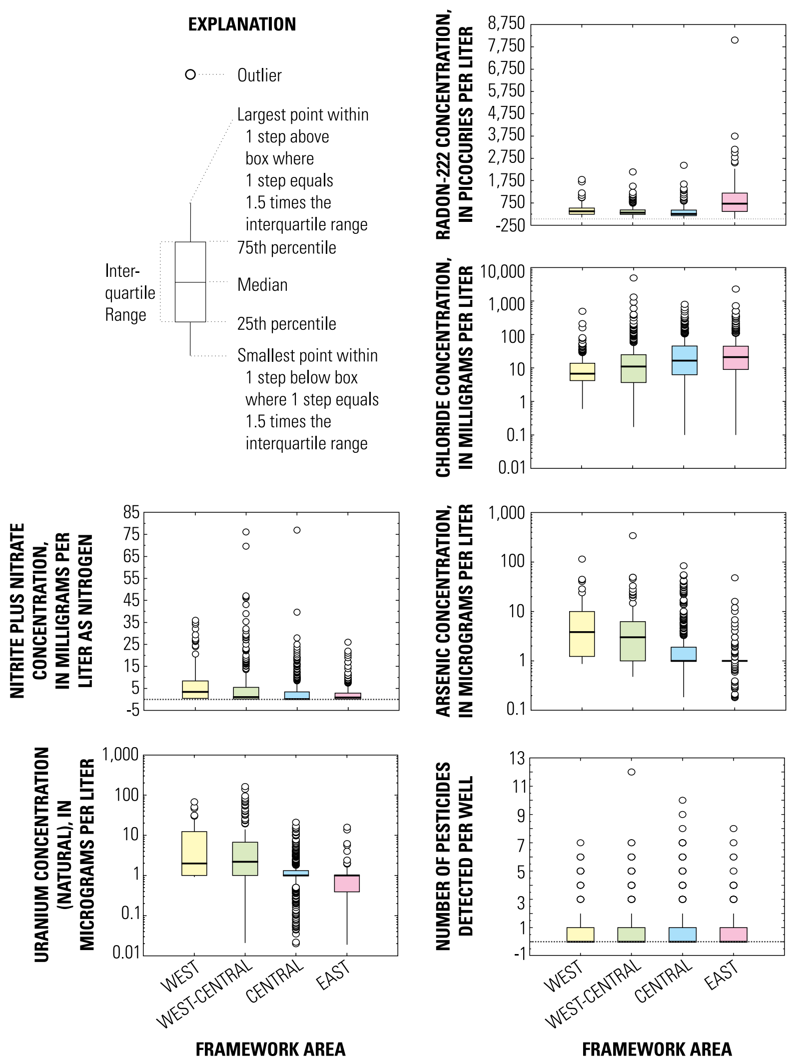



**Figure 2.** Boxplots showing contaminant concentrations and pesticide detections in ground water from the glacial aquifer system.

aquifer system framework, analyses of five regional water-quality issues are planned:

(1) Nutrients and pesticides in ground water supplying domestic wells;

(2) The association of arsenic in ground water with depth, redox conditions, and ground-water age in varied framework areas;

(3) Radon and uranium in ground water from the glacial aquifer system and underlying bedrock aquifers;

(4) Geochemical comparison of trace elements in the glacial aquifer system;

(5) Effects of deicing chemicals on ground- and surface-water quality.

The analyses of these five regional water-quality issues will begin the process of understanding regional differences in water quality in similar framework areas and the issues affecting the source and transport of contaminants on a regional scale.

## References Cited


Arnold, T.L., and Friedel, M.J., 2000, Effects of land use on recharge potential of surficial and shallow bedrock aquifers in the Upper Illinois River Basin: U.S. Geological Survey Water-Resources Investigations Report 00-4027, 18 p.

Berg, R.C., Kempton, J.P., and Cartwright, Keros, 1984, Potential for contamination of shallow aquifers in Illinois: Illinois State Geological Survey Circular 532, 30 p.

Fenneman, N.M., and Johnson, D.W., 1946, Physical divisions of the United States: U.S. Geological Survey Special USGS map, scale 1:7,000,000, accessed on June 15, 2005, at URL: http://aa179.cr.usgs.gov/metadata/wrdmeta/physio.htm/

Focazio, M.J., Reilly, T.E., Rupert, M.G., and Helsel, D.R., 2002, Assessing the ground-water vulnerability to contamination—providing scientifically defensible information for decision makers: U.S. Geological Survey Circular 1224, 33 p.

Hitt, K.J., and Nolan, B.T., 2005, Nitrate in ground water—using a model to simulate the probability of nitrate contamination of shallow ground water in the conterminous United States: U.S. Geological Survey Scientific Investigations Map 2881, 2 p.

Lapham, W.W., Hamilton, P.A., and Myers, D.N., 2005, National Water-Quality Assessment Program—Cycle II Regional Assessments of Aquifers: U.S. Geological Survey Fact Sheet 2005-3013, 4 p.

Maupin, M.A., and Barber, N.L., 2005, Estimated withdrawals from principal aquifers in the United States—2000: U.S. Geological Survey Circular 1279, 46 p.

Mickelson, D.M., Clayton, L., Fullerton, D.S., and Borns, H.W., Jr., 1983, The Late Wisconsin glacial record of the Laurentide Ice Sheet in the United States: Late-Quaternary environments of the United States, Volume 1, the late Pleistocene, S.C. Porter (ed.) University of Minnesota Press, Minneapolis, p. 3-37.

Randall, A.D., 2001, Hydrogeologic framework of stratified-drift aquifers in the glaciated northeastern United States: U.S. Geological Survey Professional Paper 1415-B, 179 p.

Rowe, G.L., Shapiro, S.D., and Schlosser, P., 1999, Use of environmental tracers to evaluate groundwater age and water-quality trends in a buried-valley aquifer, Dayton area, southwestern Ohio: U.S. Geological Survey Water-Resources Investigations Report 99-4113, 81 p.

Shacklette, H.T., and Boerngen, J.G., 1984, Element concentrations in soils and other surficial materials of the conterminous United States: U.S. Geological Survey Professional Paper 1270, 105 p.

Shilts, W.W., 1995, Geochemical partitioning in till: Ministry of Energy, Mines, and Petroleum Resources, British Columbia: Geological Survey of Canada publication, Paper 1995-2, p. 149-163.

Shilts, W.W., 1993, Geological survey of Canada's contributions to understanding the composition of glacial sediments: Canadian Journal of Earth Science, v. 30, p. 333-353.

Soller, D.R., and Packard, P.H., 1998, Digital representation of a map showing the thickness and character of Quaternary sediments in the glaciated Untied States east of the Rocky Mountains: U.S. Geological Survey Digital Data Series DDS-38.

Sun, R.J., Weeks, J.B., and Grubb, H.F., 1997, Bibliography of Regional Aquifer-System Analysis Program of the U.S. Geological Survey, 1978-96: U.S. Geological Survey Water-Resources Investigations Report 97-4074, 63 p.

U.S. Geological Survey, 2003, Principal Aquifers: National Atlas of the United States of America, map scale 1:5,000,000.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