A multiagency and multijurisdictional approach to mapping the glacial deposits of the Great Lakes region in three dimensions

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INTRODUCTION—PROBLEM WITH MAPPING GLACIAL SEDIMENTS

William Smith’s *A Geological Map of England and Wales and Part of Scotland* (Smith, 1815) is one of the oldest geologic maps, and perhaps the most celebrated one, and on that map, the first geologic cross sections depicting a two-dimensional (2-D) view of the subsurface were published. Since the publication of Smith’s map, there has been a continual need for subsurface mapping, not just to satisfy scientific curiosity, but also to conceptualize and improve understanding of Earth’s history and processes, so that lithological descriptions can be placed within a stratigraphic and paleogeographic context (Berg and Leetaru, 2011). The primary driver of such mapping has been economic development by governments and private industry, which have prospered from the numerous discoveries of minerals, coal, oil, and natural gas that mapping has revealed.

Geologic mapping to delineate and predict the occurrence of minerals and often-deep energy resources remains a central theme within the discipline of geology (Berg and Leetaru, 2011). However, during the twentieth century, the need arose for geologic maps also to depict the shallow subsurface. Serious efforts were made in the early 1900s to map the upper 1–2 m at a large scale (1:100,000 or larger), particularly in The Netherlands and Germany, both of which were dealing with land- and water-use issues associated with urbanization and industrialization. However, it was not until the mid-1960s that major strides were made in “modern” three-dimensional (3-D) geologic mapping of surficial deposits to depths of several, and later to hundreds, of meters in areas once glaciated in the Midwestern United States (Frye, 1967). Here, the identification and delineation of aquifers, environmental protection of land and water resources in a sustainable fashion, and assessment of hazards all became (and remain today) very prominent societal issues. There are several challenges to mapping in this area, including the following:

1. The Great Lakes region was glaciated multiple times during the Wisconsin, Illinois, and pre-Illinois glacial episodes, and these episodes were separated by two primary
interglacial episodes (Sangamon and Yarmouth). Each major successive glacial advance and retreat (including multiple smaller advances and retreats within each episode) eroded some of the existing landscape and preserved other portions. Therefore, the region is characterized by multiple successive and very complex landscapes, with resultant deposits of diamicton, sand and gravel, lacustrine silts and clays, loess, and organic materials.

(2) Because of glaciation, the topography of the region is relatively flat, and exposures of geologic materials are rare, particularly to the depths required for 3-D mapping. Therefore, subsurface information must be obtained via test drilling and geophysical techniques, and then supplemented with lower-quality data from validated water-well drilling logs to ascertain the geometries of the subsurface units and predict their distributions in areas of sparse data. The latter is achieved by understanding the sedimentology of units and their environments of deposition. This process is indeed challenging.

(3) Considering the complexity of glacial deposition and mapping subsurface distributions of deposits (particularly sand and gravel as an aquifer resource), questions arise as to how 3-D geologic information, often to depths of several hundred meters, can be
(a) provided at a scale usable to local jurisdictions for land- and water-use planning, particularly in urban or rapidly expanding suburban settings, and
(b) accomplished within a reasonable period and address local water- and land-use issues before they become serious problems.

Recognizing that no single agency had the financial, intellectual, or physical resources necessary to conduct a massive geologic mapping effort at a detailed scale over a wide jurisdiction, the directors of the state geological surveys of Illinois, Indiana, and Ohio approached the U.S. Geological Survey (USGS) in 1997 with a strategy for generating support to conduct 3-D geologic mapping of the glacial sediments and shallow bedrock that cover their states. The strategy involved establishing a mapping coalition of geological surveys that would seek federal funds, pool physical and personnel resources, and share mapping expertise to characterize the thick cover of glacial sediments and shallow bedrock in three dimensions, particularly in areas of greatest societal need. These leaders felt that the combined resources of multiple agencies, in concert with increased targeted federal funding for the coalition, would allow 3-D geologic mapping to be conducted in a cost-efficient and cost-effective manner.

DEVELOPING THE SOLUTION—FORMATION OF THE CENTRAL GREAT LAKES GEOLOGIC MAPPING COALITION

Growing out of this initial meeting, the Central Great Lakes Geologic Mapping Coalition (CGLGMC) was formed in 1997, consisting of the state geological surveys from Illinois, Indiana, Michigan, and Ohio, and the USGS. Its common mission was to “(1) develop, in partnership with map users, a dynamic data base of comprehensive geologic information and to create updatable three-dimensional geologic maps and map products that delineate in detail the surficial deposits down to the bedrock surface of the region, and (2) produce, with partner groups, derivative map folios, assessments, and economic analyses that directly support critical decisions concerning natural resources, hazards, and environmental management in the region” (Berg et al., 1999, p. 5). For this mission to be realized, a planning document (Berg et al., 1999) and a promotional CGLGMC (1999) circular were developed. In addition, regional mapping forums with stakeholders were conducted, documenting the need for mapping among various public and private user groups.

This planning document, Mapping the Glacial Geology of the Central Great Lakes Region in Three Dimensions—A Model of State-Federal Cooperation (Berg et al., 1999), was written to analyze the cost-benefit ratio and justify the viability of the program to the USGS and U.S. Congress, and it discusses the purposes of the coalition, including the following:

(1) Accomplish the goals of the program (p. 6), which are:
(a) to conduct a comprehensive, detailed surficial geologic mapping program in high-priority areas that provides accurate geologic information for solutions to societal problems pertaining to resources, hazards, and the environment;
(b) to increase the understanding of geologic processes, history, and framework in the interest of solving societal problems in the four states (i.e., providing unbiased and scientifically defensible information);
(c) to deliver scientific information that is in formats readily usable by public policymakers and that supports the sustainable development of resources and an understanding of environmental and hazards issues;
(d) to attract and train new scientists in new mapping techniques and emerging technologies; and
(e) to develop a new model of state and federal collaboration and cooperation focused on geologic mapping.

(2) Provide educational and economic benefits, including the results of economic cost-benefit analyses (Bhagwat and Berg, 1991; Bernknopf et al., 1993).

(3) Supply background information on mapping glacial sediments and techniques available for obtaining subsurface data.

(4) Develop program concepts and approaches, including local issues, existing data, database management, information delivery systems, the production of basic and derivative maps (CGLGMC, 1999, their tables 2 and 3), the establishment of outreach programs, the continuous reassessment of mapping priority areas, and the rapid response to natural disaster events.

(5) Design a program involving program coordination via a technical team composed of scientists from each survey, and project planning and protocols with a particular...
emphasis on assessing each survey’s in-house capabilities and needs for field sampling and description, laboratory analysis, and mapping support (Table 1).

(6) Design a pilot-study mapping region in each state.

(7) Develop a systematic long-term mapping approach, including time lines for completion of mapping in 1 to 1.5 yr cycles over a 14 yr period, specifying the number of staff required to facilitate the effort and a program that balances geologists and support staff in each survey team at a ratio of 2:3.

(8) Attain program outcomes, including obtaining geologic information for the region, enhancing the public service missions of the geological surveys, providing science-based decision-support systems, enhancing public awareness of earth science issues in public policy, improving communication between earth scientists and public policymakers, and extending the CGLGMC’s program to other regions (including international).

The planning document also includes nine two-page articles on regional societal issues requiring earth science information, and each ends with a specific outcome resulting from the mapping effort. They are (1) competition for the land, (2) water resources, (3) construction materials, (4) coastal erosion, (5) floods, (6) earthquakes, (7) contamination of land and water, (8) ecosystem change, and (9) education as part of the program.

To assist the newly formed coalition to establish mapping priorities, four full-day forums were conducted between 1997 and 2002 in Indianapolis, Indiana; Columbus, Ohio; Chicago, Illinois; and Peoria, Illinois. More than 300 participants, representing ~100 state, local, and federal agencies; educational institutions; and private industries, repeatedly stated their need for sound 3-D geologic information, and preferably at a scale of 1:24,000. In particular, they requested geologic maps and data in understandable formats to be used as a basis for evaluating their options in public policy, and for environmental and economic decision making. The critical issues identified by the universally enthusiastic participants in these forums, predominantly nongeologists, included quality and quantity of groundwater; aggregate resources and land-use conflicts; energy- and mineral-resource management; mitigation of land and water contamination; the acceleration of permitting processes; infrastructure siting and construction; agricultural land loss and agrichemicals; waste-disposal planning and

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**TABLE 1. PORTION OF TABLE 4 FROM U.S. GEOLOGICAL SURVEY OPEN-FILE REPORT 99-349 SHOWING IN-HOUSE CAPABILITIES AND ADDITIONAL FUNDS REQUIRED FOR GEOLOGICAL SURVEYS TO CONDUCT THREE-DIMENSIONAL (3-D) GEOLOGICAL MAPPING PROGRAMS**

<table>
<thead>
<tr>
<th>Method/procedure</th>
<th>Type</th>
<th>In-house capabilities/needs*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surficial geology field sampling and description</td>
<td></td>
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<tr>
<td>Sediment coring to 1500 ft (457 m) depth</td>
<td>Sampling</td>
<td>USGS Y IGS Y20 ISGS Y20 ODGS Y20 MGS Y20 US$ 60</td>
</tr>
<tr>
<td>Rotary cuttings to 1000 ft (305 m) depth</td>
<td>Sampling</td>
<td>USGS Y IGS Y20 ISGS Y20 ODGS Y20 MGS Y20 US$ 80</td>
</tr>
<tr>
<td>Hollow stem auger</td>
<td>Sampling</td>
<td>Y40 Y</td>
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<tr>
<td>Split spoon, Shelby tube, 75–150 ft (23–46 m)</td>
<td>Sampling</td>
<td>USGS Y Y5 IGS Y5 ISGS Y5 ODGS Y5 MGS Y5 US$ 15</td>
</tr>
<tr>
<td>Continuous sampler, 75–180 ft (23–55 m)</td>
<td>Sampling</td>
<td>USGS Y Y5 IGS Y5 ISGS Y5 ODGS Y5 MGS Y5 US$ 20</td>
</tr>
<tr>
<td>Probing</td>
<td></td>
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<tr>
<td>Geoprobe, PowerProbe 80 ft (24 m)</td>
<td>Sampling</td>
<td>USGS Y IGS Y</td>
</tr>
<tr>
<td>Giddings 45 ft (14 m)</td>
<td>Sampling</td>
<td>ODGS 20 Y Y10</td>
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<td>Hoverprobe</td>
<td>Sampling</td>
<td>USGS Y</td>
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<tr>
<td>Vibracore</td>
<td>Sampling</td>
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<tr>
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<td>Description</td>
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<td>Logging</td>
<td>USGS Y Y</td>
</tr>
<tr>
<td>Downhole logging</td>
<td>Logging</td>
<td>USGS Y</td>
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<tr>
<td>P-wave velocity</td>
<td>Logging</td>
<td>USGS Y</td>
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<td>Resistivity</td>
<td>Logging</td>
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<td>Gamma</td>
<td>Logging</td>
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<td>Logging</td>
<td>USGS Y Y</td>
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<td>Logging</td>
<td>USGS Y</td>
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<tr>
<td>Vane shear</td>
<td>Logging</td>
<td>USGS Y</td>
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<tr>
<td>Acoustic televiewer</td>
<td>Logging</td>
<td>USGS Y</td>
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<tr>
<td>Magnetic susceptibility</td>
<td>Logging</td>
<td>USGS Y</td>
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<tr>
<td>Spectral gamma</td>
<td>Logging</td>
<td>USGS Y</td>
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<tr>
<td>Core splitting and sensitive subsampling (bulk density, moisture content, ...)</td>
<td>Description</td>
<td>USGS Y Y Y Y Y</td>
</tr>
<tr>
<td>Photography</td>
<td>Description</td>
<td>USGS Y Y Y Y Y</td>
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<tr>
<td>Visual descriptions (Munsell color, lithology, bedding, texture, fractures, contacts, horizon, structure, cutans/silans, reaction, depth, thickness, %recovery...)</td>
<td>Description</td>
<td>USGS Y Y Y Y Y</td>
</tr>
</tbody>
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**Notes:** This table presents the top portion of Table 4 in U.S. Geological Survey Open-File Report 99-349 (Berg et al., 1999, p. 26). Abbreviations: USGS—U.S. Geological Survey; IGS—Indiana Geological Survey; ISGS—Illinois State Geological Survey; ODGS—Ohio Division of Geological Survey; MGS—Michigan Geological Survey. Capabilities and needs are indicated as follows: Y—yes, capability exists; Y10—some capability exists, additional needs in thousands of dollars; 10—new capability needed in thousands of dollars.
Multiagency, multijurisdictional approach to mapping glacial deposits of the Great Lakes region

mitigation; habitat alteration and biodiversity; and coastal erosion, landslides, radon, flooding, and earthquakes.

On the basis of input from these forums, as well as from statewide advisory panels, the CGLGMC prioritized mapping in urban and suburban areas, transportation corridors, regions with known environmental and homeland security risks, and areas of high water demand (Fig. 1). In addition, resulting from these forums and the plan, a direct congressional appropriation of US$500,000 in 2001 was obtained to support initiation of the program. (Funds were increased in 2009 to US$750,000, where they remain.) Then USGS Director Charles Groat wrote in the Foreword of USGS Circular 1190:

[T]he Coalition represents several important new directions for the U.S. Geological Survey. The plans developed by the Coalition provide a new model for state-federal collaboration in research, information delivery, and outreach, as well as a most welcome opportunity to work more closely with the various information-user communities....The scope of this activity is such that no single agency can go it alone. Only by actively sharing and combining our resources can we hope to achieve the worthy goals set forth by the Coalition. Although this Circular deals primarily with the geologic foundation for sustainable growth, the program it describes will also serve as the cornerstone in a new integrated science effort that will focus all of the capabilities of the USGS (biology, geography, geology, and hydrology) to address societal needs in the Central Great Lakes region (CGLGMC, 1999, p. iii).

As a partner in the CGLGMC, the USGS recognized the value in mapping the surficial geology of the Great Lakes states and the economic dependence of the region on these deposits. This regional similarity of deposits establishes a commonality of interests among the geological surveys and citizens of these states. The geological surveys agreed that working toward an understanding of the 3-D framework of the glacial sediment is essential to provide policymakers with the earth science information required to make wise decisions regarding the use of natural resources and environmental protection for the citizens of this geologically unique region.

Figure 1. Central Great Lakes States Geologic Mapping Coalition original priority mapping areas (from Berg et al., 1999, p. 2). Map courtesy of the U.S. Geological Survey.
EXPANSION OF THE COALITION

The coalition remained as a five-member organization until 2008, when it expanded to include the state geological surveys of Minnesota, Wisconsin, Pennsylvania, and New York, thereby including all the Great Lakes states. Subsequently, the name changed to the Great Lakes Geologic Mapping Coalition (GLGMC). It expanded again in 2012 by adding the Ontario Geological Survey (OGS) as a nonfunded partner. As a regional entity extending east-west from New York to Illinois and northward into Ontario, the GLGMC states and province are unique because they share (1) multiple continuous, thick, complex layers of glacial deposits containing groundwater resources used by ~50% of their residents, (2) similar geomorphology, (3) high populations, (4) a long-standing tradition of developing light and heavy industry, (5) serious brownfield redevelopment issues, (6) high agricultural productivity, and (7) similar weather and climate. Most important, only a very small percentage (<10%) of the surficial deposits of the region had been mapped (and particularly in the subsurface) to adequately address the critical land- and water-use decisions that state/provincial and local officials would be required to make in order to cope with the complexities of the glacial geology and interrelated regional characteristics.

To meet its goals, the GLGMC has specifically undertaken mapping of the glacial geology of the region and providing 3-D geologic maps to depths of several hundred meters that provide scientific interpretations to decision makers. Such decisions constitute cost-effective economic development; enhanced groundwater availability assessments for residential, municipal, industrial, and energy consumption; avoidance of areas where groundwater is susceptible to contamination; identification of terrain susceptible to natural hazards; delineation of erosion, flooding, and subsidence areas; accurate inventories of sand and gravel resources for infrastructure development; the preservation and restoration of wetlands; safe redevelopment of abandoned industrial lands; siting of manufacturing enterprises; impacts of urban expansion on agricultural lands; and evaluation of impacts from new or expanded waste-disposal facilities. Figure 2 shows a revised map of short- and long-range mapping plans in priority areas with the addition of four states and the province of Ontario.

It was estimated, based on Berg et al. (1999), that 3-D geologic mapping, on average, costs about US$250,000 per 1:24,000 scale quadrangle (~56 mi² or 145 km²) in the often-complex geological environment of the region, as shown in several figures in this chapter. Although the cost to map the Great Lakes region appears formidable, it can be compared with the tens of millions of dollars required to mitigate a single Superfund site or with dollars lost because geologic information was lacking, and economic development opportunities were located elsewhere.

At present funding levels, it will take well over 100 yr to produce the needed 3-D geologic maps of the high-priority areas of the Great Lakes region. Unfortunately, by that time, countless land- and water-use decisions will have been made in ignorance of critically important geologic interpretations, decisions that may have negative impacts on the region’s long-term economic development and environmental security.

OVERALL PROGRAMMATIC SUCCESS

Even though adequate levels of funding have not been obtained, and mapping has not been as extensive as originally planned, the “spirit of the coalition” has been a tremendous success:

(1) Using state and other federal dollars to supplement congressional funds, the GLGMC has completed mapping in pilot mapping areas in Illinois, Indiana, Michigan, and Ohio, and it has modestly expanded mapping to surrounding regions. Additionally, detailed mapping programs have been undertaken in Minnesota, Pennsylvania, New York, and Wisconsin. In Ontario, the recognition of a looming groundwater yield and contamination crisis led to the establishment of a small groundwater research group within the OGS in the early 1990s, but it was not until the 2000s that the Ontario political, social, and technical perspectives on groundwater needs were in alignment. The result has been an ongoing commitment by Ontario to apply geoscience to enhance the understanding of groundwater resources.

(2) Each year since 1999, GLGMC geologists have visited congressional offices in Washington, D.C., and locally to discuss the merits of the 3-D mapping program and to request a programmatic increase. To date, more than 800 meetings have been held, and 22 congressional delegation letters have been sent to appropriations committees, the Department of the Interior, and the USGS requesting support for the GLGMC. These efforts have been successful in maintaining the budget and gaining an increase in funding from US$500,000 to US$750,000 (split among eight states and the USGS) during a time of considerable federal funding cuts.

(3) The success of the program also rests with the hundreds of support letters sent to multiple congressional offices from constituents representing economic development agencies, the environmental community, secondary educational institutions, geotechnical consulting firms, the aggregate industry, the oil industry, county government agencies and boards, municipal government agencies, and state and local politicians.

(4) County officials have been using, and plan on using, the information from the GLGMC. For example, in Lake County, Illinois (northeastern corner of the state), a regional framework plan has been written such that new geologic information can be quickly incorporated into planning and zoning decisions (Lake County, 2004). Specific language refers to the various communities and agencies being prepared to utilize the GLGMC database and map products to assist in decision making. It is important to note that the plan recognizes the
significance of having detailed geologic information. The plan specifically emphasizes the relationships among rivers, lakes, wetlands, and shallow aquifers and the need to understand the distribution and characteristics of aquifers. The plan (p. 4–18) states that “municipalities must be prepared to act when the [geologic] maps become available showing the priority recharge areas. Lake County and the municipalities may need to revise their comprehensive plans, zoning maps, and land development regulations.”

Moreover, through collaboration, geologists within the 10 participating GLGMC agencies have overcome a former lack of communication, resulting in unprecedented sharing, not only of equipment and people, but also of ideas and technologies focused on unraveling the complex glacial geology of the Great Lakes region. Quaternary geologists from the eight states, Ontario, and the USGS assemble for a 2-day meeting each year to discuss issues involving interpretation of their science, new technological developments for obtaining subsurface information (e.g., new drilling procedures and new geophysical tools), and new concepts for subsurface mapping and viewing, managing data (including best practices for evaluating logs from water-well drilling), and Web-based delivery of information. Particular emphasis is given to discussing lessons learned and avoiding having to “reinvent the wheel.” In addition, geological surveys from the UK, The Netherlands, and Denmark and Greenland have been guests at the annual meeting, and based on the GLGMC’s mode of operation and focus on 3-D mapping, European geological surveys are following this same template and are, for the first time, meeting regularly and conducting various workshops on 3-D mapping and modeling.

A GLGMC Web site (www.greatlakesgeology.org) was established and is maintained by the Indiana Geological Survey (IGS). The site prominently displays publications...
relationships that have developed, all of which address specific state and local issues tackled, technological achievements, outlined by Berg et al. (1999). The examples include scientific issues that have been addressed, mapping that has been accomplished, and goals of the GLGMC apply to all 10 partners, variability in fiscal and personnel resources among GLGMC partners results in considerable differences in the stage of the 3-D mapping program that has been feasible, the speed at which mapping can progress, and the programmatic goals that can be realized. In addition, light detection and ranging (LiDAR), which greatly aids in mapping of surficial deposits and their associated landforms, is not uniformly available throughout the region. The following examples from Illinois and Ohio in particular relied on these newly acquired data to enhance their mapping efforts and products.

Illinois

The Illinois State Geological Survey (ISGS) embarked on three countywide 3-D geologic mapping projects beginning in the early 2000s, all located in the northeastern part of the state as part of the Chicago metropolitan area (Fig. 3). As the third most populated area in the United States (U.S. Census Bureau Metropolitan Statistical Area, http://www.census.gov/population/metro/), and as the most populous area of the Great Lakes region (more than 9 million people, including parts of southeast Wisconsin and northwest Indiana, with 7.2 million in Illinois alone), this area faces critical decisions regarding the long-term availability of water for consumptive, industrial, and agricultural use. In an area where surface water and groundwater are apparently abundant, water availability issues related to limitations of Lake Michigan withdrawals as well as groundwater-resource potential have created an environment in which communities are competing with one another for water supplies. As a border state to Lake Michigan, Illinois has access to this large surface-water resource. However, because of the volume of water withdrawn for such uses as public water supply, diversions of water for the maintenance of navigable waterways, and watershed removal through the reversal of rivers, the allocation for Illinois (as well as all the Great Lakes states) is limited by a 1967 U.S. Supreme Court ruling (Wisconsin v. Illinois, 388 U.S. 426 [1967]; http://www.dnr.illinois.gov/WaterResources/Pages/LakeMichiganWaterAllocation.aspx).

Lake County encompasses 55 municipalities, and with its population of more than 700,000 and mix of urban, suburban, rural, agricultural, and unique natural areas, planning for the long-term management and supply of water to the county’s residents has presented a challenge. In part, geologic mapping has been driven by the need to determine the viability of developing the groundwater resource further, as opposed to the cost of building infrastructure to withdraw, treat, and transport additional quantities of surface water from Lake Michigan to more distant communities.

McHenry County, bordering Lake County to the west, is on the fringe of the Chicago metropolitan area, where the contrasting suburban and rural cultures present differing land- and water-use issues. Irrigated agriculture dominates land use in the western portion of the county, whereas dense urbanization prevails in the eastern portion. Implementation of 3-D geologic mapping was driven largely by elected county officials and specialized water-resource staff. This county has been aggressively funding and implementing science-based research to best understand its long-term water supply needs. Thus, the 3-D geologic maps produced by the ISGS have been used as the primary framework for long-term predictive water supply modeling.

Will County adjoins the southern fringe of the Chicago metropolitan area along the southern Lake Michigan rim industrial complex and the midcontinental transportation corridors. It has planned primary expressways, growing intermodal transportation facilities, and the possible development of a third Chicago airport. Geologic mapping has only begun, but a number of process steps have been optimized based on the experiences with 3-D mapping in Lake and McHenry Counties.

The most costly aspect of mapping subsurface glacial deposits in Illinois and elsewhere has been drilling deep exploratory test holes, adequately sampling the variety of deposits, and determining the lithologic characteristics, thicknesses, and continuity.
of sediment bodies. The ISGS built a robust drilling program focused around geologic mapping, and it operates several drills that can accommodate different objectives (shallow vs. deep drilling; varying access and site conditions). To complement drilling, the ISGS uses several surface and subsurface geophysical techniques, including 1-D and 2-D data acquisition, that provide further insight into the subsurface distribution and character of geologic materials. The combination of drilling and geophysics (particularly P- and Sh-wave and resistivity) has proved vital to efficient and reliable 3-D geologic mapping.

Characterization of geologic deposits is essential not only for the mapping process, but also for the development of an informational database that can be accessed, queried, and applied to answer a variety of earth-resource questions. Paramount to this process is laboratory analysis of sediment. Therefore, the ISGS maintains laboratories dedicated to providing consistent measurement of the physical properties of materials, including a particle-size and clay-mineralogy laboratory.

Detailed countywide 3-D geologic mapping, based on subsurface exploration, sampling, and laboratory support, presents numerous challenges revolving around (1) the discovery of geologic information and placement into a framework, (2) the classification of mappable geologic entities from that framework, and (3) the implementation of technological steps and use of software to conduct the mapping. By far, the most significant challenge in undertaking 3-D geologic mapping has been the implementation of technology and the management of large data sets of subsurface information. Because of the large metropolitan Chicago population, vast numbers of subsurface geologic records exist in the form of water-well and engineering borehole records, which have, in part, enabled detailed, 3-D geologic mapping. However, this information exists in a variety of formats, with a range in
trusted quality. Thus, to utilize these data effectively, great effort has been made to standardize and optimize the data quality.

**Pennsylvania**

The problems inherent in developing, evaluating, and utilizing water-well logs as a part of a mapping program are best exemplified in the recent initiation by the Pennsylvania Geological Survey (PGS) of its 3-D mapping program, and the realization that the program must begin with a useful water-well database. It has been estimated that Pennsylvania has more than 1,000,000 domestic water wells, yet its water-well database, called the Pennsylvania GroundWater Information System (PaGWIS), contains only ~420,000 records. Bringing this database up to acceptable standards has been problematic because it has been largely neglected and not maintained for decades, resulting in a chaotic collection of records varying in quality and completeness, with few containing adequate locational or driller’s log data. Furthermore, because all records were submitted on paper forms, conversion of the data to digital format has been slow (Fig. 4).

Using various online tools (e.g., Google Maps, White Pages, tax maps, historical county road maps, etc.), two people at the PGS independently determine locations from the written location descriptions and sketch maps on the paper forms (Fig. 4). Those two locations are then compared, and if they are close, the location is accepted and transferred to the PaGWIS. The definition of “close” is based on the (1) average separation of the dual well locations in the area, (2) geologic setting of the two specific locations, and (3) data density in the area. The locations accepted for the PaGWIS provide a starting point for field location of wells when more accurate locations are needed, and they are adequate for regional bedrock topographic and drift thickness mapping, which are the two most basic maps needed to initiate a 3-D mapping program. The production of bedrock topographic maps is a particular mapping priority because of its value not only in building the base of 3-D glacial maps, but also in developing bedrock geologic maps (for assessment of mineral resources and radon potential), supporting groundwater studies, and understanding the glacial and drainage history.
of the area. This work has provided recognition of the value of accurately located, detailed well logs and a method and strategy for improving the entire PaGWIS database.

The long-range goal of the PGS is to develop 3-D geologic maps, beginning in the glaciated northwestern portion of the state, where glacial sediments as much as 150 m deep characterize the region. However, before digital contouring of the bedrock topography and drift thickness can be performed, data entry and interpretation of driller’s logs must be completed for ~40,000 water wells in the region.

**Michigan**

The geologic mapping program of the Michigan Geological Survey (MGS) has produced maps in Berrien, Barry, Calhoun, and Livingston Counties to address specific scientific issues in all four counties. Berrien County was part of a joint USGS/MGS pilot mapping study, whereas Barry, Calhoun, and Livingston Counties were mapped using combined resources of the Coalition and STATEMAP programs. Both Barry and Calhoun Counties are located along the east to west I-94 growth and development corridor in southern Michigan, one of Michigan’s priority mapping areas. Full implementation of a 3-D mapping program similar to that in Illinois has not been possible because internal funding and personnel have been lacking. Therefore, the strategy has been to map the surficial geology in detail, relate sediments to landforms (called “land systems”), and construct a preliminary stratigraphic framework of the glacial deposits by using a small number of continuously cored Roto-sonic and Geoprobe borings. These data are then compared with lower-quality, validated information in the state’s digital water-well database (WELLOGIC). These projects constitute the first detailed, 1:24,000 scale mapping in Berrien County revealed three regional recessional moraines that cross the county from north to south. Lake Border moraine deposits are till-ridge moraines (composed chiefly of till at the surface), and the Kalamazoo and Valparaiso morainic systems are stratified moraines composed primarily of glacial-deltaic deposits. The mapping demonstrated the stratigraphic relationships among regional morainic systems, deposits of large glacial lakes, distal meltwater terrace deposits, and postglacial effects of base-level lake changes in the Lake Michigan basin. Mapping this county was accomplished through an unprecedented research effort by the USGS, MGS, and other GLGMC partners. Aerial geophysics, seismic profiles, time-domain electromagnetics, vibracoring, hollow- and solid-stem auger drilling, and split-spoon coring were all used to better define the stratigraphy.

Land-system concepts (Kehew et al., 2012, 2013), used for mapping in Barry, Livingston, and Calhoun Counties, revealed four regional sediment-landform assemblages related to glacial dynamics within the Saginaw lobe (Fig. 5). In particular, the land system shown in Figure 5 has subtle stagnation topography, with tunnel valleys that are deeply incised but lack thick sand and gravel fills. For the land system shown in Figure 6, uplands underlain by diamicton/glaciolacustrine successions are cut by tunnel valleys with thick glaciofluvial units. These valleys should be the focus of future groundwater exploration.

Composite county maps for Barry and Calhoun Counties are being prepared by stitching individual quadrangle maps together. These maps will be valuable for aquifer delineation, aggregate exploration, and aquifer vulnerability assessment. Irrigation, particularly for agriculture, is increasing rapidly in Michigan, and all new large-quantity water withdrawals must be evaluated by the Michigan Department of Environmental Quality Water Withdrawal Assessment Tool to predict the effects of withdrawal on surface-water flows. This example of GLGMC mapping illustrates an important step toward 3-D delineation of aquifer and aquitard characteristics of glacial deposits.

The USGS is presently mapping the surficial geology of the Manistee National Forest in Manistee and Wexford Counties (Fig. 5), as well as Sleeping Bear Dunes National Lakeshore under the aegis of the GLGMC. The focus is on the stratigraphy of the three moraines that dominate the landscape. In many places, the moraines were discovered to be composed of well-sorted outwash fans and ice-contact deltas. This new GLGMC information in Michigan has substantially improved knowledge of the types and distribution of sediments that can be expected in the glacial stratigraphy compared with previous work. The result of new geologic mapping will be an accurate depiction of the surficial geology and the consequent ability to predict the volume and type of earth materials at any particular location. Predictions can then be assigned particular values to best assess erosion potential, aquifer vulnerability, and aggregate reserves.

**Minnesota**

In Minnesota, the GLGMC program builds on an existing statewide County Geologic Atlas Program, with particular emphasis on enhancing subsurface mapping of Quaternary sediments (Fig. 7). The atlases, produced cooperatively by the Minnesota Geological Survey (MNGS) and the Minnesota Department of Natural Resources, provide information for sustainable management of groundwater resources, mineral-resource assessment, and engineering applications. Atlas maps are published at 1:100,000 scale, which is sufficiently detailed to depict features that significantly influence groundwater flow, yet they do not require a data density that would be too costly to be practically obtained (Setterholm, 2012). A database map shows the distribution of data used in the construction of the atlas products, including water wells, geophysical surveys, exposures, technical drilling, cores, cuttings, and analyses. The water-well
database—known as the County Well Index and operated cooperatively by the MNGS and the Minnesota Department of Health—contains almost 500,000 wells. Another database, the Quaternary Data Index, contains information on sediments in the upper 15 m, including engineering test results, textural and lithological analyses, outcrop descriptions, and other data. Seismic reflection and refraction are regularly applied to investigate the depth to bedrock and other surfaces, whereas much effort is now being applied to a broadened application of passive seismic techniques (Chandler and Lively, 2014) to evaluate the thickness of Quaternary sediments. Downhole geophysical surveys mainly involve a natural gamma tool that has been used in more than 6000 wells, with ~200 being done each year.

The GLGMC efforts in Minnesota have concentrated on Quaternary stratigraphy, 3-D modeling, and sand bodies. The Quaternary stratigraphy atlas plate depicts three to five cross sections, whereas the sand body thickness and extent models are based on cross sections at 1 km spacing. Bedrock topography and depth to bedrock maps are important elements of each atlas, whereas the bedrock surface and its elevation are mapped mostly with data from the records of wells and geotechnical drill holes, with some support from seismic surveys (Setterholm, 2012).

Ohio

The Ohio Division of Geological Survey (ODGS) has focused on several 3-D mapping programs. A GLGMC pilot
Figure 6. Tunnel valleys and profiles in land-system 3 north of the Thornapple Valley in Barry County, Michigan, and adjacent counties.
project developed methods for constructing 3-D models using the Milan 7.5-minute quadrangle (Pavey, 2014a; Fig. 8) as a test area. This is a high-priority mapping area because it is next to Lake Erie, and it contains major transportation corridors and a National Estuarine Research Reserve. Because of the geological complexity of the area, the quadrangle also provided a scientifically and technically challenging area for developing 3-D surficial geologic modeling methods. Because groundwater issues were important, the Milan quadrangle model became the basis for developing a highly detailed groundwater-flow simulation, which is described in more detail later herein.

In addition, the ODGS initiated precision mapping of karst features, such as sinkholes, caverns, and springs, by using 3-D methods. An understanding of the complex surficial geology of karst terrain is important in the protection of groundwater resources, as well as for public safety where ground collapse may occur. Three high-priority karst areas are mapped, and a fourth is in progress.

Other significant GLGMC projects include 3-D mapping of the Powell quadrangle (Pavey and Martin, 2012a, 2012b, 2012c, 2012d), one of the most rapidly developing areas in Ohio, and mapping of the Rainsboro (Pavey, 2014b, 2014c, 2014d, 2014e) and Bainbridge (Pavey and Martin, 2015a, 2015b, 2015c, 2015d) quadrangles in an area of scientifically challenging surficial mapping at the edge of glaciation. The use of 3-D methodology allows for the detailed mapping of previously undocumented Pleistocene processes.

**Ontario**

The OGS maintains a well-established 3-D geologic mapping program of glacial sediments (Fig. 9), and it interacts collaboratively with GLGMC members and shares scientific, societal, technological, and mapping outcomes. In 2002, a pilot 3-D mapping project was initiated in the regional municipality of Waterloo (Bajc and Shirot, 2007) because this area is one of the leading municipal users of groundwater in Canada and is within an area of intense population growth. Here, pressures on groundwater resources are expected to increase significantly over the next two to three decades. Protocols for 3-D mapping were established, guided by experience from national, state, and provincial geological surveys doing similar work across the globe, including those of the GLGMC.

The 3-D mapping projects include four important stages:

1. Compilation of existing subsurface information and identification of data gaps.
2. Acquisition of new geophysical and geological information to infill data gaps. Regional gravity, seismic, ground-penetrating radar, and airborne electromagnetic surveys coupled with continuous coring to bedrock and downhole geophysics are part of the OGS toolkit for 3-D mapping.

![Figure 7. Status of the Minnesota County Geologic Atlas Program, showing shaded counties that have an atlas or that are in progress, and counties for which an atlas has not yet been initiated.](image-url)
Figure 8. Milan quadrangle, Ohio, three-dimensional view, as an ArcScene model. Colors represent Quaternary and Paleozoic sediments at land surface. Copyright © 2014 State of Ohio, Department of Natural Resources. Used with permission of the Ohio Division of Geological Survey.

Figure 9. Location of published and ongoing three-dimensional (3-D) mapping projects in southern Ontario. ORM—Oak Ridges moraine, which is within a large open-space preserve in Ontario known as the Greenbelt (m asl—m above sea level). Copyright © Queen's Printer for Ontario, 2015. Used by permission of the Ontario Geological Survey.
and assist with the development of conceptual geologic models (e.g., Bajc and Hunter, 2006; Endres et al., 2006; OGS, 2012, 2014). Groundwater monitoring wells are also installed in partnership with local conservation authorities to provide long-term pump test, static water level, and geochemical/isotopic information that contributes additional inputs to regional groundwater-flow models. This information can also enhance conceptualizations of geology and aid in verifying geologic models produced as part of the interpretive process.

(3) Data interpretation and the construction of fully attributed 3-D block models using the scriptable commercial software Datamine Studio (Bajc and Newton, 2005).

(4) Preparation of Groundwater Resources Studies (described later in the Delivering Information section).

**New York**

The New York State Geological Survey (NYSGS) initiated a 3-D mapping project in collaboration with the U.S. Fish and Wildlife Service and the New York Department of Environmental Conservation in 2009 to map the geologic framework of a nine-quadrangle area that covers the Montezuma Wetlands Complex of northern Cayuga and Wayne Counties in central New York (Fig. 10). The Montezuma Wetlands Complex is an assemblage of private, state, and federal lands that encompasses more than 14,569 ha and is one of the largest wetland systems in the Great Lakes states.

Water resources and ecological importance are the driving factors that led to prioritizing this mapping project. The Montezuma Wetlands Complex occupies a low-relief (<30 m), undulating topography that extends from the north end of the Finger Lakes almost to the southern Lake Ontario shoreline. The southern half of the Montezuma Wetlands Complex is bisected by the I-90 New York Thruway traffic corridor between Rochester and Syracuse, which serves ~40,000 vehicles daily. Despite its size and central location, very little was known about the geologic framework, water-resource potential, and paleoenvironmental history of this important ecological area. As a wetland system, understanding the geologic framework and water resources is critical. A complicating factor in management strategies is the broad-distribution, yet poorly understood, presence of saline-hypersaline groundwater (from Silurian bedrock), some of which discharges as springs (Kappel and Goodman, 2014).

The process used to begin development of 3-D modeling was an aggressive exploratory drilling program, which to date has resulted in more than 60 exploration boreholes (Kozlowski et al., 2014; Fig. 11). In addition to the drilling program, the NYSGS utilized near-surface geophysical methods (such as ground-penetrating radar) and LiDAR terrain models to reevaluate glacial landforms (Kozlowski et al., 2010, 2011; Kozlowski and Bird, 2013) and accurately delineate former glacial lake basins (Bird and Kozlowski, 2014). Mapping in the Montezuma Wetlands Complex focused on characterizing the complex interaction between extensive and thick proglacial lake sediments that blanket the topography and the large ice-marginal meltwater channels that routed copious volumes of water during deglaciation. The 3-D data indicate a wide array of lithologies, including a great abundance of low-permeability tills that occur within drumlins on bedrock highs (Gentoso et al., 2012; Hopkins et al., 2014) and stratified aquifers of fine sand, silt, and clay greater than 65 m in thickness that infilled large and extensive bedrock channels. Despite the thickness of these aquifers, their saline water quality diminishes their utility in the deep channel deposits. However, the 3-D drilling program located alternate coarse gravels associated with meltwater deposits that contain abundant volumes of freshwater.

An unforeseen outcome of the drilling program was the discovery and recognition of chronologic and paleoenvironmental data previously undocumented in central New York. Detailed analysis of sediments recovered in drill cores routinely yielded plant macrofossils and botanical remains. Radiocarbon dating of plant macrofossils provided important chronologic and paleoenvironmental data that documented well-preserved deposits associated with periods of abrupt climate change known as the Younger Dryas and a much more detailed history of glacial events in central New York.

**Wisconsin**

Similar to mapping in Minnesota, the Wisconsin Geological and Natural History Survey (WGNHS) has long conducted mapping primarily at the 1:100,000 scale. Historically, mapping and research conducted by the WGNHS have focused on the glaciated portion of the state. However, shifts in personnel and evolving mapping priorities elevated the level of attention given to the Driftless Area, a region with a conspicuous lack of glacial “drift” in southwest Wisconsin, northeast Iowa, and northwest Illinois that was never covered by Quaternary ice. It consists of almost flat-lying Paleozoic strata that are deeply incised by fluvial processes, particularly along the Mississippi and lower Wisconsin Rivers. The range of issues driving mapping included (1) flooding susceptibility, particularly groundwater-derived flooding, such as that which inundated the town of Spring Green, Wisconsin, during the summer of 2008; (2) county-level land management decisions, such as the siting of landfills and large confined-animal feeding operations; (3) economic development along the Highway 151 corridor (which connects Madison, Wisconsin, to Iowa), including the effects of continued expansion of Madison and the more distant effects of expansion from the Chicago metropolitan area; (4) groundwater vulnerability associated with karst; and (5) groundwater vulnerability associated with the progressive conversion of agricultural land to suburban residential development. As part of this newer emphasis in mapping, two major mapping initiatives, both partially funded by the GLGMC, were initiated in this southwesternmost portion of the state (Fig. 12).

The WGNHS mapping strategy highlights a central premise of the GLGMC that emphasizes the inherent synergy between research and mapping, and that by combining the two, both efforts are optimized for maximum impact. High-quality
Figure 10. Location of the Montezuma Wetland Complex north of the Finger Lakes, New York.
Figure 11. Example of a three-dimensional (3-D) geologic framework being developed in New York showing a shaded relief surface topography and borings into the subsurface. The vertical exaggeration is greatly enhanced.
Multiagency, multijurisdictional approach to mapping glacial deposits of the Great Lakes region

mapping also provides the foundation to conduct affiliated high-quality research.

Two prominent research and mapping efforts cover Grant County and the lower Wisconsin River valley region. Grant County is the southwesternmost county in Wisconsin. From 2009 to 2012, the WGNHS completed a countywide mapping project that resulted in the release of a 1:100,000 scale surficial geologic map (Carson, 2012; Fig. 12). The WGNHS is currently involved in a 6 to 8 yr project to map the surficial geology for the entire lower Wisconsin River valley drainage. This includes Richland, Crawford, Vernon, and southern Monroe Counties as well as northeastern Iowa. The results of this mapping, which will be produced as a series of

1:100,000 scale county surficial geology maps with an accompanying WGNHS Bulletin, will assist with (1) flood-mitigation planning along the lower Wisconsin River; (2) rural land management issues, including the siting of planned confined-animal feeding operations; (3) siting of future landfills and management of current and retired landfills; and (4) groundwater vulnerability associated with residential expansion on the bluffs above the Mississippi River. Major scientific issues addressed in conjunction with the mapping include (1) the extent of pre–Illinois episode glaciations that mark the western boundary of the Driftless Area (Carson and Knox, 2011); (2) the precise chronology for the terminal advance and retreat of the Green Bay lobe that marks the eastern boundary of the Driftless

Figure 12. Project mapping areas of the Wisconsin Geological and Natural History Survey in southwestern Wisconsin. GLGMC—Great Lakes Geologic Mapping Coalition.
Area (Carson et al., 2012; Carson and Attig, 2013); and (3) the long-term landscape evolution of the lower Wisconsin River valley, and related questions of continental-scale drainage evolution (Carson et al., 2013a, 2013b).

Delivering Information (Goal b)

Coalition Goal

Another GLGMC goal is to deliver scientific information that is in formats readily usable by public policymakers and that supports sustainable development of resources and understanding of environmental and hazards issues.

It is challenging to apply geologic map information to help users shape public policy and infrastructure development, particularly in understandable “user-ready” formats. The 3-D geologic mapping process is often complex. It generates a mass of data and information that render complex geologic information as 3-D representations that conform to 3-D (depth or height) values, and it incorporates assumptions, interpretations, and the merging of a multitude of geologic concepts. In turn, the concepts are typically bundled into geographic information system (GIS) layers and described in long and often prose-filled jargon within accompanying legends or reports that can be overwhelming to a user. Nevertheless, geologic mapping and the knowledge that is exported from the mapping process have been packaged by GLGMC partners to serve as meaningful aids to decision makers for sustained planning of long-term water supplies. The following examples describe how this issue has been addressed.

Illinois

The 3-D geologic information has enabled the ISGS to provide counsel to local Lake County officials, and their hydrogeologic consultants, about the feasibility of continuing to develop groundwater resources versus building infrastructure to withdraw, treat, and move water from Lake Michigan to communities inland from the lake at an estimated cost of more than US$200 million (Fig. 13). The cost is substantial, but because of the large population, it can be distributed widely. In McHenry County, ISGS staff have worked closely with elected county officials, water-resources staff, and consultants to communicate the mapping results effectively. Consistent communication, often through meetings and field trips, has directly benefited numerous municipalities, consultants, and residents as they have considered the future of their local water supply needs (e.g., in the cities...
of Marengo and Fox River Grove and among private landowners). Furthermore, a fully interactive, digital version of the 3-D geologic map and model of McHenry County (Fig. 14), with an explanatory report, has been made publicly available through county resources. Thus, at a minimum, the 3-D geologic information is readily accessible to the public, and the ISGS encourages continued communication and collaboration to ensure that those map products are used efficiently, reliably, and as intended.

Indiana

IGS education and outreach efforts have focused on creating Web sites that support the sustainable development of water and mineral resources and understanding of environmental and hazards issues in formats readily usable by public policymakers. To date, two Web sites have been completed, one for Allen County, located in northeastern Indiana and the home of Fort Wayne (Indiana’s second largest city), and one for Marion County in central Indiana (which includes Indianapolis, Indiana’s largest city). Increasing population and economic growth in both Allen and Marion Counties have resulted in increased demands on groundwater and the availability of aggregate for construction and road building (GLGMC, 2012).

For Allen County, earlier IGS publications were augmented (Bleuer and Moore, 1978; Fleming, 1994), and a Web site was created to disseminate much-needed geologic information about accessing and protecting resources to a broad audience (GLGMC, 2012). The site includes an Internet map server (IMS) for constructing customized thematic maps, illustrations, educational summaries, and discussions of geologic maps, geomorphic (terrain) images, and databases (Hasenmueller et al., 2007; Rupp et al., 2008; Fig. 15). Water- and mineral-resource agencies; environmental, planning, and public health professionals; and the public can all access the data.

This Web site provides widespread distribution of geologic information that can be updated quickly and economically. A recent GLGMC project here focused on the characteristics (e.g., thickness, extent, and composition) of the Lagro Formation (Wisconsin glacial episode) and the influence of these characteristics on aquifer sensitivity to contamination from surface sources. To display this sensitivity, four zones of aquifer sensitivity were delineated, which were individually defined according to material properties. Upon completion of the study, new content that clearly addressed aquifer sensitivity in Allen County was prepared and added to the Web site (Prentice and Letsinger, 2013).

In Marion County, from 1989 to 1993, the IGS conducted a study in cooperation with the Marion County Health Department, Bureau of Environmental Health, to identify and map the 3-D distribution of major aquifer systems and their hydrogeologic settings (Fleming et al., 1993). Its purpose was to prepare interpretable maps of geologic and hydrogeologic characteristics known to influence the occurrence, movement, and relative sensitivity to contamination of groundwater within varying county hydrogeologic settings. Drawn from this earlier study, as well as other projects (Brown and Laudick, 2003), an IMS component was developed whereby anyone having an Internet connection could produce and print custom maps of all or part of the county. Map layers pertaining to bedrock geology, surficial geology, hydrology, infrastructure, and imagery are included (Indiana Geologic Survey, 2010; Rupp et al., 2010). Illustrations, educational summaries, and discussions of geologic maps, terrain images, and databases that complement the IMS were incorporated into the Web site in 2011.

The IGS reached a significant milestone when the geologic maps of Marion County were made available on the Internet to facilitate Web-based environmental planning. Recently, the Marion County interactive Web site maps were used to determine whether the residents of a neighborhood that relies on private drinking-water wells would be at risk from an expanding nearby sanitary landfill (Great Lakes Geologic Mapping Coalition, 2012).

Wisconsin

Wisconsin focuses on significantly advancing knowledge of both the surficial glacial geology and the stratigraphy of glacial and bedrock deposits within mapped areas. In Wisconsin, the publication of the Grant County map (available on the Web for free download) complemented the release of a new Flood Insurance Rate Map and has assisted with development along the Highway 151 corridor between Dubuque, Iowa, and Platteville, Wisconsin.

Michigan

New interpretations of the glacial geology have been disseminated on maps that are available at the MGS, as well as in guidebooks and journal articles. Numerous stakeholders involved with aggregate, groundwater, and planning issues are using completed maps. Specifically, the Berrien County products include a 1:100,000 scale geologic map (Stone, 2001), a map of land cover and calculated groundwater recharge and discharge areas (Stone, 2001; Stone et al., 2006; Olyphant et al., 2006; Fig. 16), a field-conference guidebook (Stone et al., 2003), and a planned 1:50,000 scale Quaternary map. In addition, recharge and discharge areas were determined by analyzing output from a numerical model that calculated groundwater flow through a 3-D geologic-framework model (Letsinger and Olyphant, 2008).

Project 3-D mapping results directly benefited municipalities, businesses, and residents of Berrien County (GLGMC, 2012): (1) The village of Coloma saved more than US$50,000 when an elementary school discovered contamination in its groundwater supply well and was immediately able to begin construction of a pipeline to the affected area, rather than wait for the completion of additional studies; (2) the availability of groundwater supplies for cooling in a “peaker” power plant (i.e., one operating only during peak demand) was assessed; (3) consultants used MGS geologic data to enhance remediation of a Superfund site in Benton Harbor; (4) real estate developers better understood land-use and development potential; (5) consultants used MGS advice on the location of a buried valley to successfully drill an
Figure 14. Graphical-user interface for a three-dimensional (3-D) geologic map of McHenry County, Illinois. The publicly available software package SubsurfaceViewer allows interaction with the 3-D map and data through map, cross-section, and perspective views, and it allows dissection of the map and data at any location. Copyright © University of Illinois Board of Trustees. Used with permission of the Illinois State Geological Survey.
irrigation well for a planned golf course in Benton Harbor; and (6) a gravel-pit owner was able to predict the direction a gravel bed would trend in the area.

**Minnesota**

In Minnesota, the County Geologic Atlas Program provides information essential for sustainable management of groundwater resources, mineral-resource assessments, and engineering applications. The atlases outline aquifer properties and boundaries, as well as the connection of aquifers to the land surface and to surface-water resources, and they provide a broad range of information on county geology, mineral resources (such as construction materials), and natural history. An atlas consists of a part A, which is prepared by the MNGS and includes the water-well database and 1:100,000 scale geologic maps showing the properties and distribution of sediments and rocks in the subsurface, and a part B, which is constructed by the Department of Natural Resources Division of Waters and includes maps of water levels in aquifers, the direction of groundwater flow, water chemistry, and sensitivity to contamination.

Each atlas typically requires more than 7000 person-hours of work (Setterholm, 2012). The first atlas, produced in 1982, was for Scott County, and this county was the first to be updated. Although the selection of counties has been based on population and groundwater sensitivity, the willingness of local county decision makers to collaborate and co-fund the mapping projects has been a key consideration. The MNGS is committed to the expeditious completion and periodic updating of atlases, and a plan is in place for statewide completion in less than 15 yr. The Minnesota legislature strongly supports the County Geologic Atlas Program through funding, and the atlases are highly valued by counties, consultants, state agencies, federal agencies, educators, researchers, well contractors, and citizens.

**New York**

The success of mapping efforts in the Montezuma Wetlands Complex in New York has yielded field conferences with stakeholders and public educational programming (Kozlowski and Graham, 2014) and has led to an overall broader interest in 3-D geologic mapping. Presently, the mapping effort has expanded to encompass all of Cayuga County after the NYSGS recognized the critical need and added benefit of such a program for the citizens of New York. By supplementing surficial mapping with high-resolution LiDAR terrain models, the NYSGS also has simultaneously mapped the distribution of crucial societal resources such as aggregates and water resources, and it is rewriting the narrative of natural history, thus expanding the breadth of stakeholders and beneficiaries.

**Ohio**

In Ohio, multiple methods have been used to deliver geologic information, including new map formats, 3-D models, and public outreach. Ohio’s GLGMC products are readily available on the ODGS Web site (http://ohiogeology.com/) and the GLGMC
Web site (http://greatlakesgeology.org). The availability of 3-D geologic information improved planning for a major combined sewer–deep storage tunnel to prevent high-flow releases of polluted water into major streams in Columbus, Ohio. This 7.24-km-long, 6.7-m-diameter tunnel is now under construction.

The four-county karst region around Bellevue, Ohio, experienced major groundwater flooding in 2008 that inundated homes and roads and resulted in closure of a state highway. Using 3-D methods, the ODGS mapped the flood-prone sinkhole basins and provided local policymakers with tools to help mitigate future risks (Fig. 17). In addition, through ongoing “Project Underground” field meetings, the ODGS presented karst mapping results and information to several sizable groups of teachers, who helped spread the importance of this work.

To avoid random costly test drilling for a better groundwater supply, a public water utility in Highland County, Ohio, sought the assistance of the ODGS. A deep, narrow, high-yielding glacial aquifer was located in an area of shallow, low-yielding bedrock by using GLGMC-developed 3-D mapping and seismic surveys.

Finally for Ohio, products from the Milan quadrangle 3-D mapping effort can be used to address a wide variety of water management, land-use, environmental, and resource issues that are crucial to local, state, and federal agencies; private industry; and the public (Pavey et al., 2008). The 3-D geologic model and companion groundwater-modeling results have been used to produce a range of derivative products, such as maps of recharge areas (Pavey et al., 2008; Pavey, 2014a).

Ontario

The delivery of 3-D geologic information in Ontario has been a concerted effort (Fig. 9) after the events of May 2000 in the town of Walkerton, a rural community of ~5000 people in southwestern Ontario. Here, seven people died and nearly half of the town’s population became ill from drinking municipal water contaminated with Escherichia coli bacteria. Since this incident, the OGS model for information delivery protocols and products has been highly refined and is based on the needs of the province. The provincial government invested deeply to ensure that sources of drinking water will be safe for provincial residents, and legislation was enacted calling for conservation authorities to develop Source Water Protection Plans at a watershed scale. These plans focus on identifying risks to local drinking-water sources and developing strategies to help reduce or eliminate those risks. They contain sections on (1) watershed characterization, which includes a summary of the local geology and geologic controls on surface and groundwater flow; (2) a water budget, which is generated by creating regional 3-D geologic models and derived groundwater-flow models; (3) aquifer recharge and aquifer vulnerability assessments; and (4) the identification of wellhead protection areas. The OGS develops geoscience products that help

![Figure 17. Portion of a karst-induced groundwater flooding map near Bellevue, Ohio. Groundwater flooding areas are shown in green (from Pavey et al., 2012). Pink area designates the municipality of Bellevue. Copyright © 2014 State of Ohio, Department of Natural Resources. Used with permission of the Ohio Division of Geological Survey.](specialpapers.gsapubs.org)
fulfill these requirements. Updates or revisions to Source Water Protection Plans will be undertaken every 10 yr, thereby including new geoscience information as it is collected, interpreted, and synthesized by the OGS.

An initial response to the Source Water Protection Plan initiative was the OGS release of a series of detailed, fully attributed, seamless maps (mainly 1:50,000 scale), including bedrock geology, physiography, surficial geology, drift thickness, and bedrock topography (Gao et al., 2006; Chapman and Putnam, 2007; OGS, 2010, 2011). These data sets form an integral part of the watershed characterization portion of the Source Water Protection Plans. After the release of these data sets, the OGS initiated several subsurface mapping programs, including an ambient groundwater geochemistry project. This project involved sampling and analysis of bedrock- and overburden-derived groundwater for a wide suite of parameters, to establish natural background levels of metals in the environment (Hamilton, 2011). A karst-potential map of southern Ontario was published, which has important implications for groundwater flow and public safety (Brunton and Dodge, 2008). Work is also underway on defining the stratigraphic and geologic controls on groundwater flow through Silurian and Devonian, carbonate-hosted bedrock aquifers in southern Ontario (Brunton and Brintnell, 2011).

The OGS program of 3-D mapping of Quaternary deposits has been ongoing in southern Ontario since 2002, with the primary objective of developing interactive models that aid (1) groundwater extraction, protection, and remediation studies; (2) the development of policies surrounding land use and nutrient management; and (3) increased understanding of groundwater and surface-water interactions. Priority areas were identified and guided by the Places to Grow Act (Ontario Ministry of Municipal Affairs and Housing, 2005a) and were established in collaboration with local Conservation Authorities who are knowledgeable about local water issues and long-term pressures facing groundwater resources. These priority areas lie just beyond the Greenbelt, an area of roughly 728,000 ha along the northern and western perimeter of Lake Ontario that is protected from further development by the Greenbelt Act of 2005 (Ontario Ministry of Municipal Affairs and Housing, 2005b). The Greenbelt includes the Niagara Escarpment, the Oak Ridges moraine, and selected areas adjacent to these referred to as “protected countryside” (Fig. 9). The population is projected to leapfrog beyond the Greenbelt and into cities and communities lying along the outer perimeter, many of which rely on groundwater for their municipal water supply.

A critical factor to the success of the program is ensuring that geologic and hydrogeologic information is delivered in an understandable manner to both technical experts and nontechnical users. Derivative maps (e.g., aquifer recharge and vulnerability) are particularly useful in this endeavor. An attempt has been made to produce standardized products that merge models and facilitate creation of a provincial-scale 3-D model of Quaternary geology. This effort is balanced with the development of new products, such as interactive utilities for viewing newly acquired subsurface information that take advantage of advancements in visualization technology (Burt and Webb, 2013; Burt and Chartrand, 2014).

Groundwater Resources Studies are another component of the OGS’s information delivery. They describe the geologic setting, outline protocols for constructing 3-D models, and contain descriptions of the distribution and properties of modeled geologic units. Discussions of important recharge areas as well as aquifer vulnerability are also included. Other deliverables include structure-contour and isopach maps of all modeled units, west-east and south-north cross sections at 2.5 km intervals, and depth-to-aquifer maps for assessing aquifer vulnerability and recharge areas (Fig. 18). To date, the OGS has released three Groundwater Resources Studies as part of its 3-D mapping program (Fig. 9), with two studies nearing completion and another two in progress (Bajc and Shirota, 2007; Bajc and Dodge, 2011; Burt, 2011, 2013, 2014; Burt and Dodge, 2011; Bajc et al., 2012; Burt and Webb, 2013; Mulligan, 2014). In addition, the Geological Survey of Canada has published a 3-D study of the Oak Ridges Moraine Planning Area (Sharpe et al., 2007). The total area covered by all these surveys exceeds 26,000 km², which is slightly more than 20% of the populated area of southern Ontario. Future studies are planned for both the extreme southwestern corner of the province and the Ottawa–St. Lawrence lowlands, where municipal, agricultural, and industrial pressures on both the surface and groundwater resources are mounting.

Digital data also accompany the Groundwater Resources Studies. These data consist of (1) portable document format (.pdf) versions of the contained plates; (2) comma-delimited text (.csv) files of both continuous and discontinuous surfaces on a 100 m grid; (3) 100 m ESRI ArcInfo structural contour grids of discontinuous surfaces; (4) a stripped-down version of the subsurface database (.mdb) containing borehole location and stratigraphic information, stratigraphic “picks” data, and static water level and screen depth information; (5) new borehole information, including graphic and written logs, grain-size and carbonate data, geophysical and heavy mineral profiles, and photographs of the core; (6) a cross-section viewer (.exe) capable of drawing sections along user-defined lines drawn on a Microsoft Windows Virtual Earth base map (Fig. 19); and (7) a hypertext mark-up language (.kml) file portraying transparent overlays of structure-contour and isopach maps as well as borehole locations and lithologic logs in a Web-based (Google Earth mapping service) environment. This functionality allows for enhanced user interaction with the spatial data.

Training New Scientists (Goal d)

Coalition Goal

A goal of GLGMC is to attract and train new scientists in new mapping techniques and emerging technologies.

A challenge for 3-D geologic mapping has been the lack of trained geologists capable not only of conceptualizing the 3-D nature of geology, but also of having the skills for making correlations, mapping buried surfaces, portraying and visualizing their
three-dimensionality, and then effectively explaining scientific and societal outcomes to decision makers and funders. A market has yet to be developed that is attracting large numbers of students to 3-D mapping programs within colleges and universities. However, the need exists for such trained students in the Great Lakes region; therefore, the GLGMC has undertaken to train and deeply involve students in its 3-D mapping programs, and thereby help GLGMC partners accelerate their mapping projects.

In Pennsylvania, Allegheny College has been a partner with the PGS in developing topographic maps of the bedrock surface for northwestern Pennsylvania. Several students have been involved in this partnership, all of whom have gained valuable experience with geologic mapping.

In New York, the GLGMC program of 3-D mapping and modeling has provided 12 undergraduate interns, two graduate students, and two postdoctoral positions with educational training in mapping. Considering the small size of the NYSGS, this student help has greatly accelerated its mapping program.

In Illinois, graduate students have played an integral part in 3-D mapping in McHenry County by helping the ISGS gain new insights into the surficial and subsurface geology (Carlock et al., 2009b; Flaherty et al., 2012a). They have learned key concepts in field and laboratory investigations, data management and processing, and map production. In turn, these surficial geologic studies have (1) been used as a framework for regional and local 3-D geological mapping and geostatistical modeling with Petrel commercial software; (2) contributed greatly to the overall goals of better understanding shallow aquifer distribution and character (Carlock et al., 2009a; Lau, 2011; Flaherty et al., 2012b); and (3) utilized the completed 3-D maps as a detailed geologic framework for a local groundwater-flow modeling study, including capture zone analyses of shallow irrigation wells (Seipel et al., 2014).

In Indiana, graduate and undergraduate student interns have worked with the IGS to learn field and laboratory techniques that have prepared them for geologic mapping careers.
Figure 19. Example of a cross section produced using a viewer developed by the Ontario Geological Survey for viewing three-dimensional block model information along user-defined lines. Example is from the Kitchener-Waterloo region. Copyright © Queen's Printer for Ontario, 2007. Used with permission of the Ontario Geological Survey.
Other students have learned and developed techniques for data analysis, numerical modeling, and advanced visualization that have furthered their ability to assimilate multiple data sources to gain a greater understanding of the subsurface. Along the way, they have forged their own mark, typically contributing to the professional literature by collaborating with their mentors and publishing theses documenting their research. Examples in Indiana include students who have learned drilling, core description, geophysical techniques, grain-size analysis, and other laboratory analyses to reconstruct the glacial stratigraphy in northeastern Indiana (Ducey, 2013; Prentice et al., 2013). Other students have explored numerical modeling and visualization techniques to advance understanding of the role of the subsurface geologic framework on hydrogeologic processes. These areas of inquiry include modeling groundwater flow in heterogeneous geologic materials in Berrien County, Michigan (Letsinger et al., 2006; Medina et al., 2006; Olyphant et al., 2006; Medina, 2007), and relating the role of groundwater recharge to near-surface aquifer sensitivity to contamination in Allen County, Indiana (Letsinger et al., 2011; Riddle, 2014).

**Collaboration (Goal e)**

**Coalition Goal**

The last GLGMC goal is to develop a new model of state and federal collaboration and cooperation focused on geologic mapping.

When the GLGMC was formed, it was clear that no one geological survey had the personnel, monetary resources, technology, or equipment to conduct detailed 3-D geologic mapping of its jurisdiction. It was only through collaboration and the sharing of resources that the goals of the GLGMC could be realized. Collaborative efforts are prominently portrayed on the GLGMC Web site (http://www.greatlakesgeology.org), and several GLGMC projects have been highlighted in a series of international 3-D geologic mapping workshops illustrating the value of the GLGMC as a model for state and federal cooperation (http://www.isgs.illinois.edu/three-dimensional-geological-mapping). Collaborative scientific discussions at annual meetings of the GLGMC regarding geologic history, provenance, environments of deposition, lithology, and stratigraphy within individual states and Ontario have provided all GLGMC partners with valuable insights. The GLGMC partners also have benefited immensely from discussing their experiences with technology and sharing their insights on its use. This sharing translates into a considerable cost savings in appropriated tax dollars for geologic mapping because GLGMC partners do not have to duplicate efforts. For example, the ISGS invented scripts (DeMeritt, 2012; Carrell, 2014) for the commercial software ArcGIS that have enabled scientists to conduct geologic mapping within 3-D computer space (ArcScene). ArcGIS tools create 3-D representations of the data, provide efficient attribution of the data, facilitate on-the-fly generation of structure surfaces as raster data, and enable slicing of multiple structure surfaces into 2-D and 3-D cross-section profiles.

The development of various digital mapping technologies to address 3-D mapping and map-portrayal issues is a shared interest of all GLGMC partners. Several software applications have evolved that have facilitated the 3-D geologic mapping process, although data structures, purchase and maintenance costs, proprietary formats, and training all have impacts on the viability of using any particular application. Another shared concern has been output file format because end users (e.g., county governments or geotechnical and hydrogeologic consulting companies) are also bound to particular software platforms dependent on particular file formats. Illinois’ Lake County and McHenry County projects serve as examples of different geologic mapping staff using different computer technology workflows to achieve mapping goals despite the projects having overlapping completion time frames. The Lake County project relied solely on the ArcGIS set of software tools, coupled with the MAPublisher plug-in for Adobe Illustrator. The McHenry County project relied heavily on Java-based software called SubsurfaceViewer MX, which allows for geologic interpretation, visualization, and model construction all within a single interface. However, similar to the Lake County project, ArcGIS and other 3-D visualization software were used in conjunction with SubsurfaceViewer MX to optimize mapping efficiency. The selection of mapping approaches depended on the degree of familiarity and usability of software by the geologists who developed the information, in addition to rapid changes in technology that have been made available to geologists, GIS specialists, or both. These technological changes have made it virtually impossible to standardize any one approach, even within single organizations of the GLGMC.

An example of a multistate and federal 3-D mapping collaboration was the study conducted in Berrien County, Michigan, mentioned previously, which utilized geological expertise, technology, and equipment from the Illinois, Indiana, Michigan, Ohio, and U.S. Geological Surveys. This project demonstrated the central premise of the GLGMC—that pooling resources would be a cost-effective way to deliver scientific results to the public (GLGMC, 2012). The project was designed as a feasibility study to determine best practices for mapping surficial geology in glacial terrain by using a variety of techniques (Campbell, 2001; Stone, 2001; Duval et al., 2002; McKinney et al., 2003; Stone et al., 2003).

Another collaborative GLGMC project was the geologic and hydrogeologic modeling of the Milan 1:24,000 scale quadrangle in north-central Ohio (discussed earlier). Geologists from the ODGS, working with hydrogeologists from the IGS, used a detailed 3-D geologic-framework model and merged it with an equally detailed groundwater-flow model to produce a realistic depiction of the controls exerted by glacial geology and geomorphology on shallow groundwater-flow systems (Pavey et al., 2008). The top of the geologic model is the surface topography, which was also used to derive the drainage network, an important boundary condition for the groundwater-flow model. The bottom of the geologic model is the top surface of the Devonian Ohio Shale. Flow in the shallow saturated zone
reflects strong control by the surface topography and assumes hydraulic properties of the mapped sedimentary units. In contrast, the flow at depth is not strongly influenced by the topography of the Ohio lobe and adjacent Saginaw lobe. The prominent end moraine in northeastern Indiana composed of Erie lobe tills fades out 20 km north of the Wabash-Erie Channel and is replaced by a composite land system that covers the extensive northern margin of Erie lobe deposits (Prentice et al., 2013). The principal data consist of geomorphic observations, microstratigraphic studies of several high-quality cores, and 12 km of high-resolution shear-wave seismic-reflection profiles.

Finally, the ODGS (1) worked with the IGS to learn GIS methodologies for creating improved digital elevation models of the land surface from digital contour data where the two surveys share common border areas to produce seamless elevation coverage for both states; (2) collaborated with Allegheny College partners of the PGS to share bedrock topography data in the common boundary area of the two states, and, with a long history of bedrock topographic mapping, helped focus student efforts to refine and produce similar maps for Pennsylvania; and (3) collaborated with the IGS, MGS, and USGS on the nature and extent of Saginaw lobe glacial deposits in the northwestern corner of Ohio, thereby providing a basis for producing more accurate subsurface mapping.

CONCLUSIONS

The GLGMC’s geologic mapping program was conceived from a societal need for unbiased and scientifically defensible information on the shallow subsurface. Driven by basic scientific research to best understand subsurface complexities of the region’s glacial geology, it has been nurtured by a desire to best explain and portray geologic complexities to decision makers and the lay public. The program was and continues to be an unprecedented and long-term successful experiment of 10 geologic survey organizations working together to address common issues, including field and subsurface mapping techniques; regionally common science issues pertinent to dealing with uncertainties of climate change and mitigation options; water and mineral resource issues; technological advancements in data procurement and management; GIS and 3-D visualization; and product delivery. The “spirit of the coalition” has been a tremendous success. However, success is measured not only in terms of the funding that has been secured, but also by the commitment of geologists to act unselfishly toward common goals that ultimately serve both the discipline of geology and society as a whole. Consequently, this commitment has produced, and will continue to produce, new scientific discoveries that have been and will be the foundation for societally relevant and timely derivative products. Therefore, the greatest measure of success is geologic informa-

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A multiagency and multijurisdictional approach to mapping the glacial deposits of the Great Lakes region in three dimensions

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