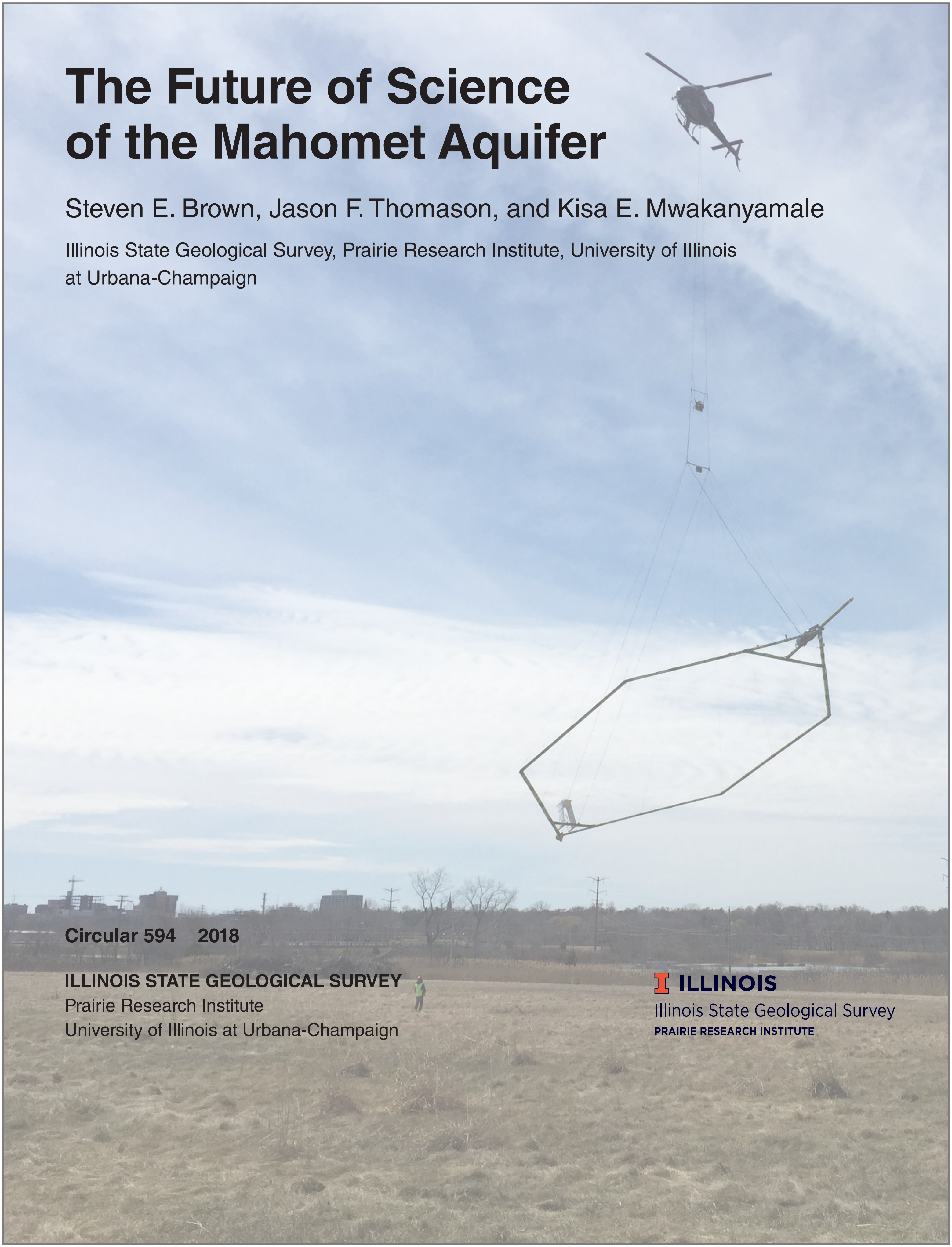


The Future of Science of the Mahomet Aquifer

Steven E. Brown, Jason F. Thomason, and Kisa E. Mwakanyamale

Illinois State Geological Survey, Prairie Research Institute, University of Illinois
at Urbana-Champaign

Circular 594 2018

ILLINOIS STATE GEOLOGICAL SURVEY
Prairie Research Institute
University of Illinois at Urbana-Champaign

ILLINOIS
Illinois State Geological Survey
PRAIRIE RESEARCH INSTITUTE

Front cover: *Helicopter takeoff for a geophysical survey of the Illinois Lake Michigan coast, April 2017. Project funded by the National Oceanic and Atmospheric Administration, Office for Coastal Management, Projects of Special Merit program, and the Illinois Department of Natural Resources Coastal Management Program. Photograph by Kisa Edson Mwakanyamale.*

The Future of Science of the Mahomet Aquifer

Steven E. Brown, Jason F. Thomason, and Kisa E. Mwakanyamale

Illinois State Geological Survey, Prairie Research Institute, University of Illinois
at Urbana-Champaign

Circular 594 2018

ILLINOIS STATE GEOLOGICAL SURVEY
Prairie Research Institute
University of Illinois at Urbana-Champaign
615 E. Peabody Drive
Champaign, Illinois 61820-6918
http://www.isgs.illinois.edu

ILLINOIS
Illinois State Geological Survey
PRAIRIE RESEARCH INSTITUTE

For more information about helicopter-based time-domain electromagnetics (HTEM) and other geophysical techniques, contact

Kisa E. Mwakanyamale (kemwaks@illinois.edu)
Jason F. Thomason (jthomaso@illinois.edu)
Timothy H. Larson (thlarson@illinois.edu)

Suggested citation:
Brown, S.E., J.F. Thomason, and K.E. Mwakanyamale, 2018, The future of science of the Mahomet aquifer: Champaign, Illinois State Geological Survey, Circular 594, 25 p.

CONTENTS

Table

Figures

FOREWORD

While searching for groundwater supplies to support World War II industrial efforts, Dr. C. Leland Horberg, hydrogeologist at the Illinois State Geological Survey and professor at the University of Chicago, discovered the significance of a regionally widespread and thick sand deposit that he named the "Mahomet sand." This deposit would later become known as the "Mahomet aquifer" for its significance to groundwater supply. He identified this deposit based on evidence noted on water-well driller reports for only *three* water wells drilled near the village of Mahomet in western Champaign County, Illinois. Those three water wells had the unique feature of penetrating the entire thickness of the sand—several hundred feet of it. In his paper "A Major Buried Valley in East-Central Illinois and Its Regional Relationships," published in the *Journal of Geolog*y in 1945, he recalled a conversation with a local water-well driller who, during his 25 years of drilling experience, had never drilled through the sand to bedrock because of the *abundance of water* in the sand.

Horberg's *Bedrock Topography Map of Illinois*, published in 1950, inked a statewide network of bedrock valleys, showing evidence of a midcontinental pre-Ice Age river system that must have existed for millennia. The bedrock valleys were created by these rivers, much as you might imagine how the Grand Canyon was formed through the power of flowing water. Through these millennia, the ancestral Mississippi River flowed through central Illinois along a route partly parallel to the course of the modern-day Illinois River. The ancestral Mississippi was also the destination for other midcontinental pre-Ice Age rivers that crossed parts of West Virginia, Ohio, Indiana, and Illinois through a complex network of bedrock valleys later named the Teays-Mahomet Bedrock Valley System. Most of the evidence for these ancient bedrock valleys that once channeled great rivers cannot be seen. They are buried by layers of clay, silt, and other sediment, a legacy of the Ice Age. However, during the Ice Age, the bedrock valleys functioned just as they had for thousands of years prior. They drained meltwater flowing from the expansive glaciers, and that meltwater carried tons of sediment, sorting it and cleaning it on its southward path to the Gulf of Mexico. These kinds of events happened repeatedly and are the reason east-central Illinois has such a unique and incredibly valuable groundwater resource: The Mahomet sand fills part of the Mahomet Bedrock Valley and is the primary geologic unit that forms the Mahomet aquifer, the container for our local groundwater in east-central Illinois. Nearly 70 years after Dr. Horberg's epiphany, the United States Environmental Protection Agency designated the Mahomet aquifer, *as described in the petition*, a Sole Source Aquifer. That federal designation, and the implications for groundwater protection that justify it, was possible only because of the geologic and hydrogeologic investigations, interpretations, mapping, and modeling provided by the Illinois State Geological Survey and the Illinois State Water Survey.

Since the time of Horberg's discovery and description, much has been revealed about the geological characteristics of the aquifer. For example, *thousands* of publicly available water-well driller reports provide evidence of the thickness, distribution, and extent of the Mahomet aquifer, in addition to documenting rates of water withdrawal and the ability of particular water wells to do so. Much is understood about the chemistry of water that moves into, through, and out of the aquifer. Considerable public and private investment has made this knowledge possible, which has primed the development of a public water supply infrastructure, allowed agricultural irrigation to nourish fertile land, and given rise to grassroots entities such as the Mahomet Aquifer Consortium and the Mahomet Aquifer Advocacy Alliance. These organizations advocate long-term sustainability of the region's vital water supply, good stewardship, and aquifer protection, and they are a driving force that focuses our attention on important water resource and protection issues. State legislation that protects groundwater resources is in place because of the knowledge gained since Horberg's discovery. In addition, community members have participated with government agencies, planning organizations, private businesses, and water authorities in water supply planning endeavors; convened conferences and workshops; and formed special task force committees. The name "Mahomet aquifer" is so well known that it is not uncommon to read an article about it in the local newspaper or hear a reference to it on local radio broadcasts. Nowhere else in the Midwest have I witnessed such widespread use of an apparently well-known hydrogeologic term in the public domain.

To a great extent, we still do not know about large parts of the Mahomet aquifer, particularly its boundaries. The point is, we are at our limit of knowledge about the physical characteristics of the Mahomet aquifer, and a bigger, broader strategic vision is needed for how to overcome that limit. We need leaps forward, not just incremental steps. Solving complex and difficult natural resource challenges is what the Prairie Research Institute does. The Institute is a powerhouse of brilliant minds, and like other scientific organizations, passion and curiosity drive Institute staff to produce rigorous, valuable, and unique information that is on par with that of our peers at other leading research universities.

What is different is that we focus on, and solve, local problems. We develop long-term relationships with people and organizations at the local community level. And our passion is amplified because we are also stakeholders: We drink the same water from the same aquifer. The problems we solve are just as important to us as to you—not just as curiosities, but as relevant societal issues. We are in this *together.*

This document is intended to kick-start the next era of knowledge creation and make the argument that *The Future of Science of the Mahomet Aquifer* is a serious issue of public concern and thus more relevant than ever. After reading the Sole Source Aquifer petition and related documents, you might conclude that we have sufficiently mapped and modeled the aquifer, its geology, and the groundwater flow within it. In this circular, Part 1 makes the argument that our knowledge about the aquifer has made groundwater management more challenging because we have not been able to adequately explain the complexity of the aquifer's geology and hydrogeology. This is not unique to the Mahomet aquifer, but the numerous names and definitions assigned to the aquifer attest to the scientific challenge of characterizing something that is so complex. The simple fact is that we cannot see it and have "sampled" or had opportunities to observe its characteristics in relatively few places compared to its vast regional extent.

In addition, from time to time, high-profile events or issues flash before us, calling attention and bringing focus to possible threats to the quality of our drinking water source. As they should. But even with as much knowledge as we have gained about the aquifer, we still cannot answer the questions that are asked at a level of detail that actually prioritizes the greatest threats, provides guidance on places that can produce greater volumes of water to support high-capacity industrial and municipal needs, and gives us comfort that we have done our best to protect the areas that need it most.

That is why the Prairie Research Institute gathered community stakeholders together on June 28, 2017, to discuss, list, and consider the most relevant topics regarding groundwater in the Mahomet aquifer. The title of the workshop and this publication, *The Future of Science of the Mahomet Aquifer*, is about that bigger, broader strategic vision. This workshop sought to engage stakeholders so that the future of science of the Mahomet aquifer would proceed and be driven by the most important, highest priority issues. Part 2 of this Circular describes the results of that workshop and summarizes key strategies to ensure consistent, productive, and valuable knowledge exchange between scientists and stakeholders.

Yet even with this grassroots advocacy and broad awareness, and the large body of information about the aquifer collected and analyzed since Horberg's time, we are still asking questions about recharge areas and many other features and operational aspects of the aquifer and how it responds to both natural and human interactions. Indeed, the conclusion of Part 2 demonstrates that ambiguity. If we do not act now, then we will still be asking the same questions about recharge areas and other issues in 5 years, and in 10 years, and in 25 years.

The path for action in Part 3 describes the means by which we can overcome our current limit of scientific knowledge about the Mahomet aquifer. Part 3 addresses the need to apply state-of-the-art technology to map the geologic framework of the aquifer in high resolution and three dimensions, and it explains the technology that can help us do that. Part 3 is written as a white paper and presents the case that we need to use the best technologies to overcome what seem to be insurmountable scientific challenges. Nowhere is there such geographic-wide advocacy, planning, and interest in a particular scientific topic. Nowhere is there a scientific organization like the Prairie Research Institute that is capable of answering the questions discussed in Part 2 with the science described in Part 3. To borrow from the title of a book by the founders of the Mayo Clinic Center for Innovation, it is time to "Think Big, Start Small, and Move Fast." We are thinking big. We have started small. Now it is time to move fast, with the financial resources required to understand, in high resolution, the three-dimensional characteristics of the Mahomet aquifer. That is the path to understanding our water resource. This is not an endeavor that whittles away the challenges one small project at a time. We must draw on all our resources. We much use the intellect of the Prairie Research Institute scientists, with stakeholders at the table, and we must finish the job according to policy and management guidelines that ensure protection, use, and long-term sustainability. Otherwise, we will have to accept more decades of slow, incremental progress toward an objective that is attainable and solvable now.

Steven E. Brown
Chief Scientist
Illinois State Geological Survey
Prairie Research Institute
University of Illinois at Urbana-Champaign
February 2, 2018

Part 1—The Challenge to Effective Groundwater Decision Making

Steven E. Brown and Jason F. Thomason

Scientific understanding of any natural resource requires researchers to provide clear explanations of often obscure scientific ideas in ways that benefit fellow scientists while also empowering stakeholders, including the public, with usable knowledge. The concept of an aquifer is certainly no exception, and it may arguably compare in obscurity to such concepts as gravity, photosynthesis, or genetics. Fortunately, over years of conducting controlled experiments and gathering observations, aquifer scientists have established solid principles for how water moves through soil and rock. These principles are consistently upheld over time in groundwater research, and they have helped build a firm foundation for knowledge growth and research productivity. However, the concept of aquifers as dynamic entities within a larger water-cycle system remains rather elusive to much of the public, and despite aquifer scientists' attempts to make sense of the complexities of an aquifer, they may be contributing to this obscurity by using esoteric terms and formulas and hesitantly concluding that more studies are needed. Such disparities may muddle communication between scientists and the public.

The United States Environmental Protection Agency (US EPA) broadly defines an *aquifer* as "a geological 'formation,' group of formations, or part of a formation that is capable of yielding a significant amount of water to a well or spring" (US EPA 2011, p. 704). Similarly, the Illinois Groundwater Protection Act defines *aquifer* as "saturated (with groundwater) soils and geologic materials which are sufficiently permeable to readily yield economically useful quantities of water to wells, springs, or streams under ordinary hydraulic gradients" (Illinois Environmental Protection Agency 1996, p. 1). These definitions help constrain our idea of the remote, unseen geologic entity that is an aquifer, but they also contain a broadly standardized human element, which complicates the applicability of the word *aquifer*. Nonetheless, these definitions are critical for framing our understanding of aquifers, how they work, and how to manage them. Therefore, it is universally important to use consistent, accepted terminology when communicating about aquifers.

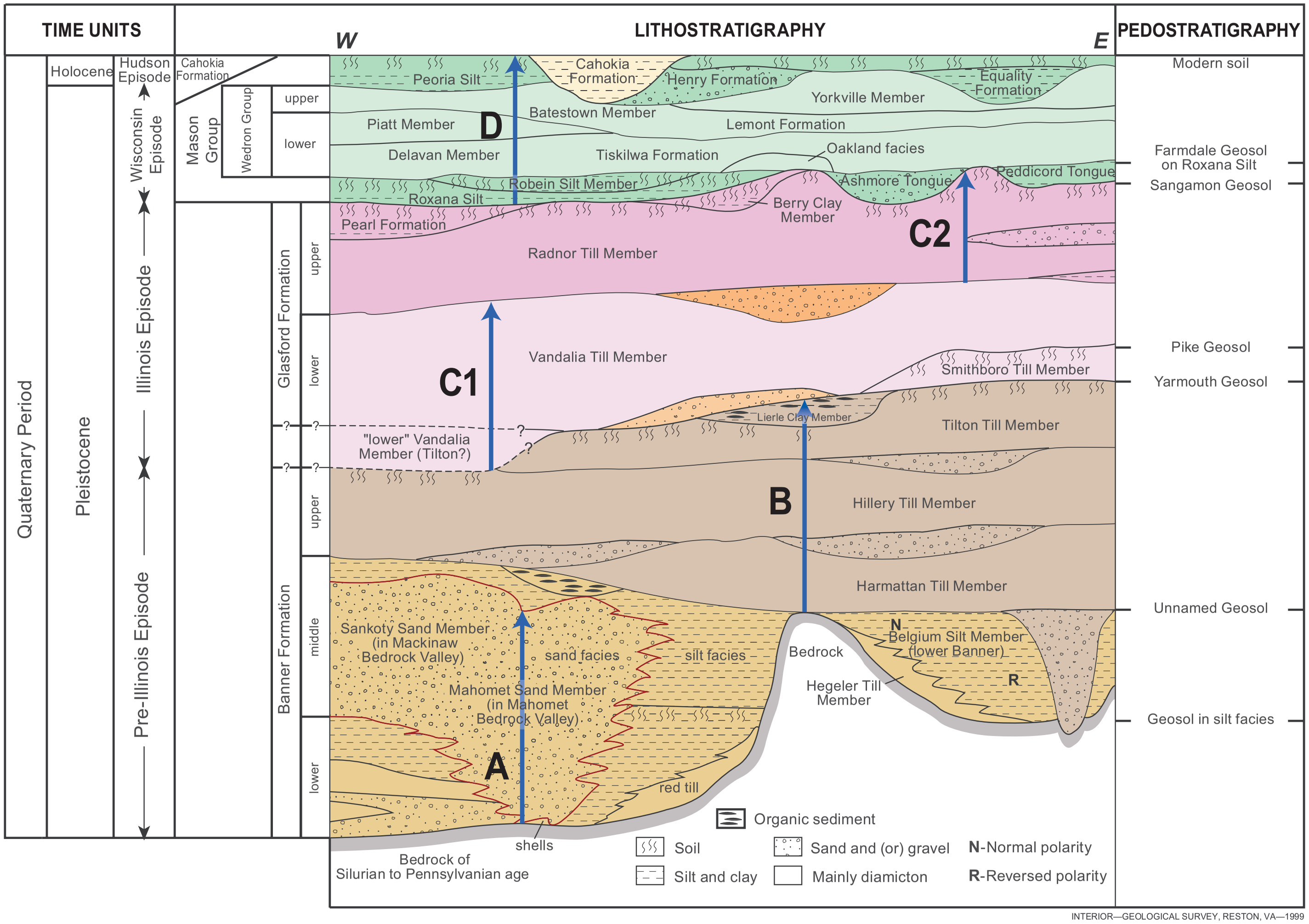
For more than 70 years, the concept of the *Mahomet aquifer* (Figures 1 and 2) has been defined and described repeatedly in the contexts of scientific research, land-use planning, and public policy. Generally speaking, these efforts have resulted in a broad spectrum of identities for the Mahomet aquifer. Despite this multiplicity of terms, it is key to remember the holistic relationships among the physical characteristics of aquifer material (as defined above), the complexity of its distribution, the balance and processes of water movement through it, and its value as a natural resource to humans and the natural ecosystem. Explaining these relationships in consistent, standard ways will guarantee an improved knowledge exchange between scientists and stakeholders and ensure successful management of the resource.

At some localities within the area of the Mahomet aquifer, hydraulic and geochemical observations indicate possible vertical or circuitous connections between the Mahomet aquifer and overlying aquifers. Conversely, ample evidence exists that "over much of the *Mahomet system* [italics ours] there are additional confined aquifers in the shallower deposits, each having a different potentiometric head" (Roadcap et al. 2011, p. 29). Geologic evidence for connectedness is sparse because data from subsurface borehole records document very few connections. Yet the Sole Source Aquifer petition (SSAP) states that "numerous connections to the surface via complex pathways composed of relatively coarse-grained materials have been documented" (US EPA 2012, p. 4). This earlier suggestion of aquifer connectedness has evidently now led to considering the Mahomet aquifer a "Mahomet Aquifer System." This, in part, could be why the SSAP "intended to designate the Mahomet Aquifer System as a Sole Source Aquifer including overlying aquifers and geologic units as one hydrogeologic system" (US EPA 2012, p. 45). The SSAP essentially created a new definition of the aquifer for the purpose of the Sole Source Aquifer designation. The vertical extent of the aquifer includes all geologic units from the land surface to the bedrock surface within an area of the Mahomet Bedrock Valley (Figures 1 and 2; see sidebar "What's in a Name"). The horizontal, or geographic, extent is defined by the shape of the Mahomet Bedrock Valley, outlined by the location of the 500-foot bedrock surface elevation contour. As a matter of enabling effective public policy, this may be the most practical definition of the aquifer because of the documented geologic and hydrogeologic complexity of the entire region, a large part of which still cannot be explained. Perhaps the inability to adequately explain the complexity revealed by scientific observations did not allow an alternative. However, it also adds yet another definition of *aquifer* to an already confusing mix of concepts, and it perpetuates the inconsistent and overlapping use of the name "Mahomet" interchangeably with an aquifer or aquifer system, geologic unit, and bedrock valley. It is logical for scientists to create names or terms, some defined and some not, as a part of the process of making sense of their observations. Clearly, however, the myriad terms, definitions, and unexplainable observations demonstrate the need for further research to understand the region's complex geology and the implications of that geology for scientifically informed, long-term, groundwater-focused policy formulation and decision making.

The Sole Source definition creates a dilemma for both scientists and policy makers. Including all the various geologic units (and aquifers) noted above to accommodate management of this complex and obscure resource creates a great challenge to understanding the flow of water through *all* the

Part 1 continues on page 6

Figure 1 Location and extent of the Mahomet aquifer (green) in east-central Illinois. From Roadcap et al. (2011). Figure used courtesy of the Illinois State Water Survey.



aquifers defined in Roadcap et al. (2011)

Mahomet Aquifer System defined in US EPA (2015)

- A — Mahomet aquifer
- B — aquifers in the Banner Formation
- C1 — aquifers in the lower Glasford Formation
- C2 — aquifers in the upper Glasford Formation
- D — shallow and surficial aquifers

Figure 2 Diagrammatic stratigraphic column and correlation of glacial deposits (lithostratigraphic units) as shown in Soller et al. (1999). The hydrogeologic framework is depicted as the Mahomet aquifer (A), aquifers in the Banner Formation (B), aquifers in the lower Glasford Formation (C1), aquifers in the upper Glasford Formation (C2), and shallow and surficial aquifers (D) recreated from Roadcap et al. (2011). The Sole Source Aquifer designation of the Mahomet aquifer, the Mahomet Aquifer System (US EPA 2015), includes all of the hydrogeologic units shown in Roadcap et al. (2011). The Mahomet Sand Member and the Sankoty Sand Member of the Banner Formation (lithostratigraphic units) are outlined in red. Figure used courtesy of the U.S. Geological Survey.

What's in a Name: The Mahomet Bedrock Valley, the Mahomet Sand, and the Mahomet Aquifer

An ancient midcontinental river and its tributaries (a river system) once flowed through the Midwest before the Ice Age, serving the same purpose as the Ohio River and its tributaries today (Figure 3)—it captured surface water for a significant part of the north-central United States. This ancient river system was carved into solid bedrock. Hence, the term *bedrock valley* is used to describe the rock that once formed the valleys that contained flow-through rivers.

The headwaters of the former large midcontinental river, named the Teays River, possibly extended to North Carolina (Hansen 1995). This ancient Teays River flowed northward into Ohio, then routed westward through central Indiana and central Illinois, where it joined an ancestral Mississippi River. Vestiges of the Teays River valley are revealed as segments of big valleys without big rivers, such as at Teays Valley, West Virginia, the place name of the river. The ancient river was destroyed when glaciers covered parts of Ohio, Indiana, and Illinois. The resulting diversion of surface water flow across the midcontinental U.S. watershed created the route of the modern Ohio River, linking segments of old river valleys with newly created ones. Because the valley of the ancient Teays River was an existing low area on the landscape, it served to carry glacial meltwater toward the Gulf of Mexico and, in the process, to fill parts or segments of the valley with sand and gravel. The spaces between the grains of sand and gravel hold groundwater. When used to supply water, the geologic deposit that holds groundwater is called an *aquifer*. More than one geologic deposit can make up a single aquifer.

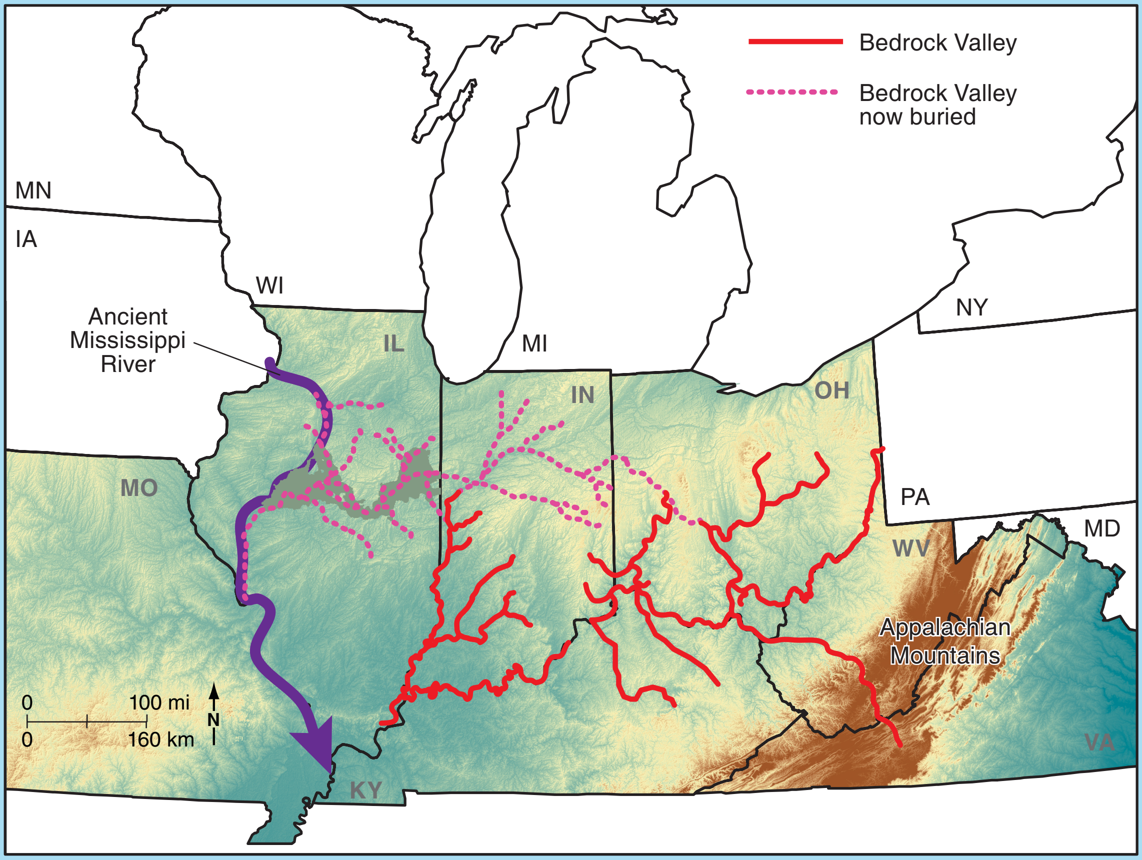


Figure 3 Midcontinent of the United States showing segments of bedrock valleys and generalized land surface elevation (brown is high; blue-green is low). The dotted line indicates bedrock valley segments buried by glacial deposits. These bedrock valleys connected a network of rivers that flowed to the ancient Mississippi River, shown by the thick purple line. Solid red lines indicate bedrock valleys that can be seen today. A gap in the red line for the Ohio River along the southern border of Indiana near the tristate area of Indiana, Ohio, and Kentucky indicates the pre-Ice Age configuration of the Ohio River. Parts of these bedrock valleys form the Teays-Mahomet Bedrock Valley System. Base map used courtesy of the U.S. Geological Survey.

The term *Mahomet aquifer* is derived from its place name, the Illinois city of Mahomet. The name Mahomet has been applied to a wide spectrum of features and materials that are entities originating from a complicated ancient river system that extended across the midcontinental United States in geologic history. The diverse scientific literature about this ancient river system and its routes demonstrates the complexity of its geologic evolution. This complexity (and its obscurity) has led to a number of names for the bedrock valley or valleys that contained the old river system. Some refer to the bedrock gorge made by the rivers, and some add to that definition by including remnants of sediment deposited in them. Some names refer to parts of the larger network of bedrock valleys shown in Figure 3. Some parts are buried by glacial deposits; others are not. It is important to note that these all describe the shape of a feature, not the geology of that feature—a valley is a geometric shape. The following are some names for the bedrock valley:

> Teays Valley • Teays Bedrock Valley • Teays-Mahomet Bedrock Valley • Teays-Mahomet Bedrock Valley System • Mahomet Bedrock Valley (specific to Illinois) • Mahomet Valley (specific to Illinois) • Mahomet Bedrock Valley System (specific to Illinois) • Mahomet Valley Section, Lafayette Bedrock Valley System (specific to Indiana) • Mahomet-Teays

The concept of the bedrock valley described above, collectively with its tributaries, is a *bedrock valley system*. The word *system* simply means more than one part, and the term is technically used to describe the whole of something that lacks certainty about the extent of the whole or that has many obscure, complex, vaguely defined, or unknown parts.

The Sankoty Sand Member and the Mahomet Sand Member of the Banner Formation are two named deposits that fill part of the Mahomet Bedrock Valley and the downstream adjoining Mackinaw Bedrock Valley (see Melhorn and Kempton 1991; Soller et al. 1999). Both Members are permeable, porous, and widespread glacial deposits in the bottom of the bedrock valleys that contain them. They differ in some mineralogical properties and have some textural differences. The Sankoty Sand Member occurs in a segment of a north–south bedrock valley, the Mackinaw Bedrock Valley of the ancient Mississippi Valley, and the Mahomet Sand Member occurs in the Mahomet Bedrock Valley.

The Sankoty Sand Member and the Mahomet Sand Member adjoin one another in the subsurface where the Mackinaw Bedrock Valley and Mahomet Bedrock Valley meet one another (a place referred to in some literature as "the confluence"), so hydrogeologically, they have been referenced collectively as the "Sankoty-Mahomet aquifer," "Mahomet-Sankoty aquifer," and "Mahomet-Sankoty Aquifer System" (e.g., see Wilson et al. 1994). The Sankoty aquifer, also included in the concept of the Sankoty-Mahomet aquifer, has been included in the singular definition of the Mahomet aquifer (Roadcap et al. 2011).

Within the area of the Mahomet Bedrock Valley, other similar coarse, water-bearing deposits are not physically connected directly to the Mahomet Sand Member but reside stratigraphically above it. In this context, reference has been made to "aquifers," suggesting more than one aquifer. Terms such as "Mahomet Bedrock Valley aquifer" and "Mahomet Valley aquifers" are used in both the singular and plural. One definition of the Sankoty-Mahomet aquifer excludes fine deposits of the Mahomet Sand Member but also includes overlying "confining units that separate it from other aquifers" (Wilson et al. 1994, p. 25). One report describes the Mahomet Bedrock Valley aquifer and the Mahomet Valley aquifer as the equivalent of the Mahomet Sand Member of the Banner Formation (Panno et al. 1994). Other literature describes the Mahomet aquifer without defining what geologic units are included (Holm 1995).

Other sources of groundwater within the area of the Mahomet aquifer, which extend beyond its geographic boundary at some localities, have been recognized as geologically and hydrologically distinct and separate from the Mahomet aquifer. For this reason, groundwater flow in the "Mahomet Aquifer System" has been numerically modeled with "three aquifers and three confining layers" (Figure 2; Roadcap et al. 2011, p. 1). Names of these, for example, include the "upper Banner aquifers" and "lower and upper Glasford aquifers" (Roadcap et al. 2011), the latter also noted for supporting high-capacity water wells at some localities. The differentiation of the upper Glasford also includes "upper Glasford aquifers," with more than one upper (Roadcap et al. 2011). Hence, sources of water not directly derived from the Mahomet aquifer are considered a valued resource, especially in areas where the Mahomet aquifer is absent. Even though they may not sustain the production of water for public water supply utilities, private uses of these sources help sustain the health and economy of east-central Illinois.

For further reading about the Ice Age, bedrock valleys, and aquifers in Illinois, see *Illinois' Ice Age Legacy* by Myrna M. Killey, Illinois State Geological Survey, Geoscience Education Series 14, and *Illinois Groundwater: A Vital Geologic Resource* by Myrna M. Killey and David R. Larson, Illinois State Geological Survey, Geoscience Education Series 17.

geology. Implementing the guidelines that must follow the legal designation may be impractical because doing so requires knowledge of more than just the Mahomet Sand Member (Figure 2; see sidebar “What’s in a Name”). It requires understanding the spatial relationships of the totality of geologic units that underlie the entire area of the Mahomet aquifer and those beyond its boundaries. Perhaps the alternative is to apply all management decisions uniformly across the region in its entirety. However, such a decision would have immeasurable long-term costs and probably would not address the sense of community urgency to understand this groundwater resource. That could likely be accomplished even without the Sole Source designation. In addition to the numerous scientific definitions of the Mahomet aquifer and the SSAP definition noted above, the State of Illinois has set clear definitions of the terms *aquifer* and *groundwater* in general and has designated classes of groundwater under the Illinois Environmental Protection Act [415 ILCS 5] and the Illinois Groundwater Protection Act [415 ILCS 55]. Although the state statutes apply broadly to all groundwater resources in the state, the science of the Mahomet aquifer must, at some juncture, have sufficient clarity to be functionally applied to state law.

The Prairie Research Institute (PRI) of the University of Illinois at Urbana-Champaign has responded to the urgent need to answer questions about the Mahomet aquifer groundwater resource through a planned effort called The Future of Science of the Mahomet Aquifer. This effort was initiated on June 28, 2017, through a workshop in which stakeholders and scientists could discuss and understand issues of science, policy, and groundwater management related to the Mahomet aquifer. In addition to including a broad assessment of the regional issues and their stakeholder-defined importance, this effort involved promoting an ambitious plan to provide the science needed to see through the complex and obscure geology and hydrogeology of the Mahomet aquifer.

Part 2—Scientist–Stakeholder Relationships

Jason F. Thomason and Kisa E. Mwakanyamale

INTRODUCTION

Natural resource management and conservation are essential for the public health, ecological sustainability, and economic development of future generations. Water resources in east-central Illinois are no exception. The Mahomet aquifer supplies water for dozens of communities across east-central Illinois, hundreds of irrigating farms, and thousands of private-use landowners across the region (Figure 1). In addition, parts of the aquifer have been federally designated by the US EPA as a Sole Source Aquifer (US EPA 2015). Thus, safe, sustainable management of this resource is important and requires continual engagement and collaboration among scientists, industry leaders, and public decision makers. These entities have engaged for decades to support effective management of the Mahomet aquifer, but as new issues, information resources, and research strategies evolve, the need for innovative engagement becomes even more critical.

The development and utilization of natural resources depends on knowing the scientific framework that controls the quantity and distribution of those resources. One way for stakeholders to make more effective, efficient, and economical decisions associated with their water resources is to prioritize innovative, science-based research as a knowledge base for both land- and water-use planning. Conversely, scientists need to communicate scientific strategies and findings effectively in ways that empower community leaders and planners with discernible, usable results and concise information. This type of information exchange is especially important with groundwater resources, where stakeholders may make long-term, wide-ranging decisions about a resource that is underground and conceptually obscure.

On June 28, 2017, the PRI hosted a one-day workshop for Mahomet aquifer stakeholders aimed at exchanging new information, critically evaluating societal aquifer issues, and developing new ideas associated with the future of scientific research on the Mahomet aquifer. This was the first such workshop initiated by scientists to address the present level of scientific understanding of the aquifer and discuss the future of scientific research in the region. The workshop included plenary presentations and breakout sessions about research and policy strategies focused on the Mahomet aquifer. Attendees represented a broad spectrum of interest groups, including public policy makers, scientists and leaders from government and academia, industry leaders, organized advocacy groups, and private aquifer users (Figure 4). Subject matter experts provided perspectives related to groundwater science and geology, environmental consulting, public health, agriculture, land-use planning, economics, law, and public policy.

A primary goal of the workshop was to facilitate direct communication between scientists and a wide spectrum of stakeholders. New studies have shown that the effectiveness of scientific information can be improved by moving away from a one-way exchange of scientific knowledge toward an integrated practice of iterative, scientist–stakeholder communication and research development strategies (Reed et al. 2014; Cvitanovic et al. 2016). Often, scientific research is driven by research-career incentives that may not be relevant to decision makers, and those decision makers are often engulfed in short-term operations or needs that may not benefit from long-term scientific research programs (Cvitanovic 2015). If decision makers are to devise and implement policy based on scientific knowledge, the scientist–stakeholder relationship must be built on personal and professional trust, effective knowledge transfer, and a focus on increasing science literacy. Productive exchanges of information can improve the timing and coordination of research and decisions, help remove barriers associated with limited scientific expertise or long-standing practices devoid of scientific merit, and add clarity to different research outcomes.

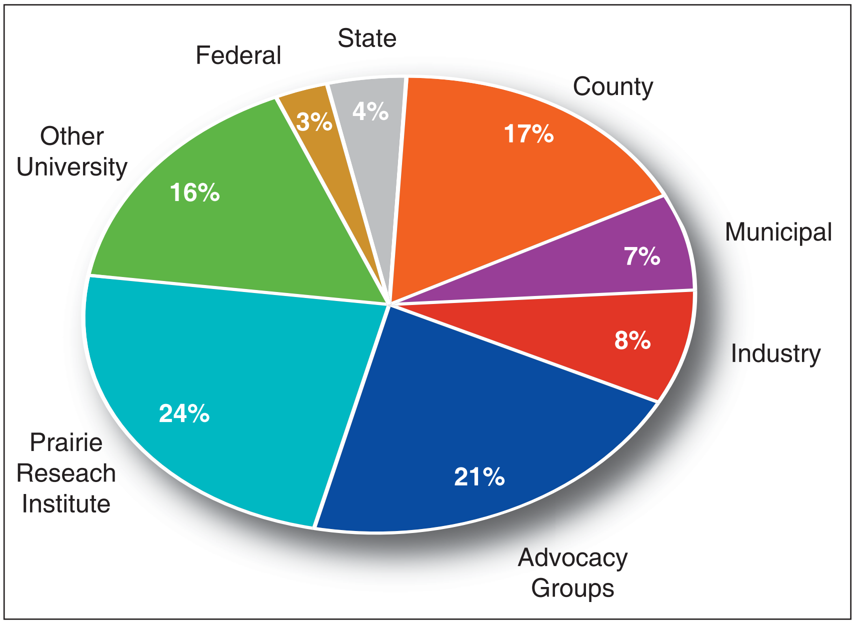


Figure 4 Affiliations of the 71 attendees at the The Future of Science of the Mahomet Aquifer workshop held June 18, 2017.

HISTORY OF MAHOMET AQUIFER RESEARCH

Although water has been withdrawn from the Mahomet aquifer regularly for more than 100 years, scientific research associated with the geologic framework of this natural resource was not formalized until the 1940s (Horberg 1945), when Illinois State Geological Survey (ISGS) scientists first identified and mapped the extent of the Mahomet Bedrock Valley, which contains the Mahomet aquifer (see sidebar "What's in a Name"; Melhorn and Kempton 1991). Since then, dozens of studies have been conducted to further delineate the boundaries and character of the aquifer. Understanding the extent and character of the aquifer is the first step to answering questions associated with water quantity, quality, and sustainability. Lithologic descriptions of the various sediments as sand, gravel, silt, clay, and diamicton (mixture of sand, gravel, silt, and clay deposited directly by glaciers) from water-well records and stratigraphic borings made up the primary data set for many of the initial studies of the geologic framework and properties of the Mahomet aquifer (e.g., Horberg 1953; Visocky and Schicht 1969; Kempton et al. 1982). These studies were vital to developing the multiscale geologic framework and stratigraphic relationships (i.e., the layering of deposits from oldest to youngest) of the Mahomet aquifer. As more geologic and hydrogeologic data were collected and field or database technologies improved, more robust studies further delineated complex geologic relationships within the aquifer at both local and regional scales (Wilson et al. 1994; Herzog et al. 1995; Kempton and Herzog 1996; Soller et al. 1999). Since the early 2000s, geophysical technologies developed for oil and gas exploration that image the subsurface and are deployed across the land surface have been adapted and implemented to unravel site-specific-scale stratigraphic relationships and characteristics of the Mahomet aquifer. These studies have provided detailed virtual views into the complexities of the Mahomet aquifer framework (Larson et al. 2003; Pugin et al. 2004; Stumpf and Dey 2012; Stumpf

Groundwater: The Single Most Important Critical Renewable Resource for the Everyday Livelihood and Health of Humans and Natural Ecosystems

Global water availability and security are becoming increasingly stressed because of a changing climate and an increasingly populated planet. By 2040, water shortages are expected to increase the risk to global food markets, national and global security, and global human health. Along with water shortages, challenges include water quality and protecting water from contamination, water security, and the ecological sustainability of water systems (Figure 5).

In Illinois, more than 1 billion gallons of groundwater are used every day (Illinois State Water Survey [ISWS] 2016) to meet drinking water, agricultural, industrial, and power generation needs. The future of water supply and demand is critical for Illinois, with projected increases in demand primarily arising from population growth and redistribution and increased agricultural use. One challenge for stakeholders is to increase awareness of the need for a conservational approach to groundwater resources to preserve sustainable levels of access to groundwater for all user groups.

Regional water supply plans are being developed and used to manage water resources because these plans provide an integrated understanding of the diversity of environmental, social, and economic conditions as they relate to available water resources (Regional Water Supply Planning Committee [RWSPC] 2009). The duration and intensity of rainfall and snowfall events, overall seasonal weather situations, and evaporation are all conditions that are likely to change under an evolving global climate, and these changes will have major implications for aquifer recharge and the long-term water supply. Having high-resolution depictions of the geology under the ground that better defines the composition, thickness, and boundaries of aquifers and their water-yielding capabilities will help in the process of planning to adjust to those changing climatic conditions.

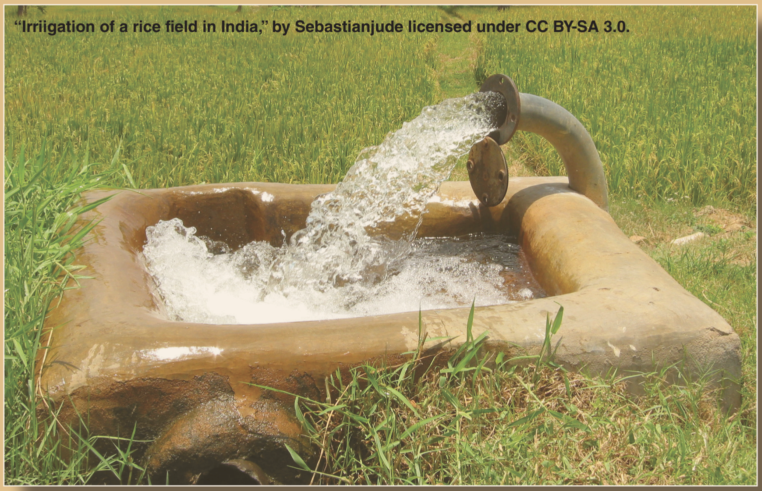

"Irriigation of a rice field in India," by Sebastianjude licensed under CC BY-SA 3.0.

Figure 5 A changing climate and growing population will affect the availability of clean, plentiful water and will greatly affect public health, food supplies, and the economy. It will alter regional drinking water availability and cause the redistribution of agricultural production. Projections shows that global water demand will reach 40% above current sustainable water supplies by 2040.

and Ismail 2013; Ismail et al. 2014). All these studies and technologies form the basis for the most recent and most detailed regional interpretations of the geology and stratigraphy of deposits that inset the Mahomet Bedrock Valley in east-central Illinois (Stumpf and Atkinson 2015).

As scientists gained a better understanding of the geologic framework, so followed a long history of water supply studies to understand the flow, quantity, and quality of water within the Mahomet aquifer. A comprehensive study conducted in the 1960s (Visocky and Schicht 1969) included a regional geologic framework of the deposits within the Mahomet Bedrock Valley, a rigorous summary of municipal withdrawals and associated water levels, an assessment of aquifer recharge, and an analog predictive model of suppressed water levels associated with water withdrawal from the Champaign water-well field. This study became the foundation for subsequent projects aimed at regional assessments of the Mahomet aquifer, which included evaluating the aquifer in McLean and Tazewell Counties (Wilson et al. 1998), identifying interconnections with neighboring aquifer systems (Wilson et al. 1994), and tracing water quality and patterns throughout the aquifer (Panno et al. 1994, 2005). Most recently, Roadcap et al. (2011) evaluated the water supply needs of east-central Illinois until 2050. For their comprehensive study, the authors compiled and analyzed long-term observations of groundwater levels and other information measured in a large number of groundwater wells and derived a predictive groundwater flow model to assess various regional groundwater demand scenarios, the surface water availability, and the risk to local withdrawal systems.

WORKSHOP GOALS AND OUTCOMES

Regional assessments of aquifer properties and water supply predictions, coupled with dramatic technological advances, have greatly improved scientific understanding of the Mahomet aquifer and provided decision makers with valuable resources. However, decision makers are increasingly charged with managing more urgent and complex issues at spatial scales and time frames that our current science cannot fully address (Cvitanovic et al. 2016). In any individual case, stakeholders are still often left asking questions such as, How much water is available? How long will the aquifer last? and How and where do we protect the aquifer? The answers to these questions are not clearcut. Rather, they depend on the location, demand, acceptable impact, and economic feasibility of extracting water from any location in the aquifer (Roadcap et al. 2011). Thus, even at the present level of understanding of the Mahomet aquifer, innovative technologies, scientific techniques, and communication strategies are needed to drive research and optimize the effectiveness of information exchange between scientists and stakeholders.

At the workshop, stakeholders and scientists outlined key issues related to the future management of the Mahomet aquifer. Presentations by scientists and policy experts facilitated discussion of these issues, as did breakout sessions on the following topics:

- Regional Coordination among Stakeholder Groups
- Illinois Water-Use and Water-Quality Statutes
- The Vision for Scientific Research of the Mahomet Aquifer
- Agricultural Use, Economic Impacts,and the Environment
- Innovative Water Supply Strategies
- Strategies for Scientist–Stakeholder Communication

Stakeholders and scientists were generally able to converge on research questions about the Mahomet aquifer that remain unanswered, and they identified communication barriers and proposed strategies associated with effective knowledge transfer. A summary of workshop discussions and recommendations follows.

Scientific Research

• **Water quantity.** Although the average use of the Mahomet aquifer is more than 200 million gallons per day, the quantity of water in the Mahomet aquifer is not fixed. Defining the sustainable use or localized depletion of the Mahomet aquifer depends on a variety of factors, which include

  - ○ water withdrawals that change in time and space;
  - ○ variable distribution, spatial extent, and properties of the aquifer;
  - ○ aquifer interactions with surface water; and
  - ○ seasonal weather and climate variability.

For example, high-capacity municipal pumping centers in the cities of Champaign, Normal, and East Peoria have decreased local water levels, but the withdrawals have not resulted in enough desaturation to affect aquifer productivity. Alternatively, seasonal pumping by irrigators and emergency pumping by the City of Decatur have resulted in significant seasonal water-level declines in the eastern portion of the aquifer. Although the Mahomet aquifer is generally unaffected by variations in seasonal precipitation, observations suggest that variable events, such as flooding, sustained drought, or increased irrigation pumping, may locally affect water pressure in the aquifer (as measured by water levels in wells). Scientists still have very little or no data on vast areas throughout the aquifer, so to address long-term, multiscale water quantity issues, scientists ultimately need more information to

  - ○ define the boundaries of the Mahomet aquifer,
  - ○ identify water interactions with other aquifers,
  - ○ assess regional and local patterns of groundwater flow paths, and
  - ○ address domestic and agricultural withdrawal rates.

• **Recharge.** Understanding aquifer recharge processes, locations, and rates is critical to addressing long-term aquifer management. Aquifer recharge depends on some of the same factors as water quality: weather and climate variability, the geologic framework of the aquifer, and groundwater–surface water interactions. Scientists need a better understanding of the geologic controls on aquifer recharge to define recharge processes more fully. Keys steps include

- defining recharge areas and processes,
- studying transitional areas of the confined versus unconfined aquifer, and
- addressing recharge in terms of managing withdrawal.

For example, recharge over the area of Mason County is very high because of the shallow, unconfined conditions. However, the mechanisms and rates of recharge are much different in counties where the aquifer is confined, such as Champaign, Ford, and Vermilion. Furthermore, the concept of aquifer recharge must include a function of balancing withdrawal rates with aquifer recovery from pumping. Thus, local recharge and aquifer sustainability may be controlled in part by adjusting the withdrawal rates and placement (geographic locations) of new water wells to accommodate variations in other recharge factors.

- **Water quality issues.** Protecting the Mahomet aquifer from contamination is one of the highest stakeholder priorities. For example, many active and closed landfills are sited above the Mahomet aquifer. Scientists need more information to address the risk of contamination by landfills and other potential sources, but that risk often depends largely on local factors such as waste type, facility construction type, and geologic setting, all of which depend on an understanding of the local hydrogeologic system.

Common human-derived contaminants in the Mahomet aquifer include nitrate and chloride, which have multiple sources, including agricultural and road deicing practices. Arsenic is also a common contaminant in parts of the Mahomet aquifer, but it occurs naturally. Understanding the chemical and physical processes that control the fate and transport of contaminants to and within the aquifer can help guide land-use practices that protect the aquifer quality.

High-priority water quality issues associated with the Mahomet aquifer include

- landfill leachate monitoring,
- nitrate and chloride runoff,
- naturally occurring arsenic, and
- industrial solvent storage, transportation, and handling.

Communication

A major outcome of the workshop was identifying communication barriers, communication successes, and new strategies for effective knowledge exchange between scientists and stakeholders. A summary follows.

- **Direct public engagement.** A key component to effective planning and applying scientific research to decision making is iterative participant input and feedback in public forums. The participation of scientists in stakeholder, government agency, and special-interest association meetings is an effective strategy for the clear exchange of knowledge. Scientists routinely participate in meetings hosted by the Mahomet Aquifer Consortium, the East-Central Illinois Regional Water Supply Planning Committee, the Illinois Association of Groundwater Professionals, and other public events and forums. Part of this strategy involves allowing stakeholders to help develop research questions and to be involved throughout the research process, which helps increase their understanding of the research results. At the same time, it provides researchers with immediate feedback on research priorities and possibly new research directions. These tactics help build an effective level of trust between scientists and stakeholders, which is critical to progressive, efficient, and adaptable research-based decision-making processes.
- **Accessibility to information.** As data and interpretations from scientific research become available, they need to be communicated to stakeholders. Users find web-based map servers, online data portals, and mobile applications of the most value, as opposed to hard-copy reports or isolated presentations. Furthermore, stakeholders need up-to-date information, preferably online, to develop effective planning tools and strategies, including emergency response tactics. These services can also be used to deliver interpretive information or derivative products and data.
- **Effective formats and tools.** For scientific information to be useful to stakeholders, it must be delivered in effective, understandable formats. Scientific data and interpretations need to be compiled and presented in ways that are easy to understand and simple to engage with. Examples include narrated animations, visualizations, and videos. Similarly, information must be versatile for a diverse audience, including a range of products or data formats and innovative decision-support tools. Examples related to the Mahomet aquifer include the ISGS ILWATER web service and the ISWS Illinois Groundwater Resources Interactive Map(s).
- **Information exchange community.** In addition to public engagement in meetings, stakeholders and scientists can effectively engage via online community networks. These tools and strategies allow versatile and efficient communication among and between scientists and stakeholders.

FUTURE RESEARCH DIRECTIONS

The state of scientific understanding of the Mahomet aquifer is at a crossroads and is limited by human resources, funding, and technology. At present, our ability to address stakeholder concerns at a regional level is relatively robust, but scientists are exploring more automated strategies to gather, process, and interpret data at various resolutions and deliver results at time scales relevant to urgent stakeholder needs. Data of higher quality and density are necessary to drive our understanding of the Mahomet aquifer geologic framework to a new level of research productivity and impact. Geophysical tools can be used to acquire detailed subsurface data at resolutions and efficiencies beyond traditional methods of drilling, sampling, and laboratory analysis. Innovations in groundwater modeling methods that automate data inputs and processing can also push scientific understanding to new levels.

Experts at the PRI are using new airborne geophysical technologies to map geologic systems deep in the subsurface. One such technology, which is discussed more fully in Part 3, is helicopter-based time-domain electromagnetics (HTEM), which has been described as a “game changer for hydrogeology” (Singha 2017). HTEM methods are used to measure the electrical properties of subsurface geologic materials, which can be interpreted to map and characterize aquifer systems to depths of more than 1,500 feet. The HTEM technology gathers a much higher density of data than ground-based geophysics or invasive research methods such as drilling, and the airborne method allows for rapid, continuous collection of data. For example, PRI scientists deployed this technology in 2017 to map sand distribution along the Illinois part of the Lake Michigan coast. The entire shoreline and near-offshore area were surveyed by use of the HTEM method in a matter of days. This technology has also been deployed extensively in Denmark to map and characterize shallow sand and gravel aquifer systems within buried bedrock valleys at high resolutions and regional scales (Høyer et al. 2015), and the geologic frameworks of those aquifers are closely analogous to that of the Mahomet aquifer. When coupled with other geophysical or sampling methods, HTEM could be the most effective and efficient method for characterizing the Mahomet aquifer that has yet to be conducted.

Groundwater experts at the PRI are also developing strategies to optimize the efficiency of groundwater modeling studies by integrating multiscale modeling frameworks into a singular modeling domain (ENIGMA [Evolving New Illinois Groundwater Architecture]; Daniel Abrams, ISWS, personal communication). This process merges many subregional groundwater flow models, but it also incorporates methods of integrating new information and interpretations more efficiently. Model inputs include geologic frameworks, surface water bodies, aquifer properties, and groundwater levels. These inputs change as new time-dependent data are collected and interpreted. ENIGMA will incorporate new data-management methods to integrate those changes efficiently and will ultimately allow nearly real-time updates to groundwater modeling frameworks. Thus, ENIGMA will dramatically increase the rate and quality of information transfer between scientists and stakeholders.

FUTURE COMMUNICATION STRATEGIES

Scientists and stakeholders with an interest in the Mahomet aquifer must continue to engage at all levels of research development and implementation. Implementation of new communication strategies includes

- regular scientist-led stakeholder meetings and workshops,
- integrated program development with scientists and stakeholders,
- an online, collaborative network of Mahomet aquifer constituents, and
- online data or information exchange portals.

These strategies will help identify and manage links among the data, scientific resources, and tools; the diversity of stakeholder objectives; and the anticipated outcomes. They will also facilitate knowledge exchange within time frames that are collectively relevant to scientific researcher and stakeholder needs. Ultimately, systematic and periodic collective knowledge exchange is the key to successful long-term management of the Mahomet aquifer.

SCIENCE AND POLICY

A primary mission of the PRI is to bridge the worlds of science and policy. Groundwater science is aimed at explaining aquifer systems by implementing objective, standardized scientific tools and methods. The policy of managing groundwater resources often depends on subjective interests. Thus, integrating new scientific methods and clear communication strategies is key to the positive progression of science-based policy. Implementing scientifically informed policy associated with the Mahomet aquifer will have positive impacts on the quality of life, water security, sustainability, and risk. Furthermore, successful science-based policy can greatly advance the progression of fundamental science.

A recent effort to integrate scientific research into policy and decision making is Illinois Senate Bill 611 (The Mahomet Aquifer Protection Task Force Act), which has charged a collective of constituents from government, science, industry, and other stakeholder groups with "address[ing] the issue of maintaining the clean drinking water of the Mahomet Aquifer, the principal aquifer in east-central Illinois" (Illinois General Assembly 2017, p. 1). The task force will develop strategies for prioritizing, communicating, researching, and implementing future management of the Mahomet aquifer.

Part 3—Innovative Technology for Aquifer Mapping

Kisa E. Mwakanyamale and Steven E. Brown

INTRODUCTION

Are you concerned about the sustainability and quality of underground drinking water resources? Does your business or community rely on consistent, reliable, and nearby sources of construction aggregate? Are you concerned about living in an area with an earthquake history? Will the Lake Michigan shoreline continue to host sandy beaches for your recreation and enjoyment?

As citizens and stakeholders of our future, we ask these questions repeatedly—through public policy debate and implementation, economic development and forecasting, water supply planning, energy resource exploration, and natural disaster emergency response. Information provided on high-resolution geologic maps guides the answers to these questions. Geologic mapping is a process that describes and determines the extent of geologic materials at the land surface and under the ground, what geologists refer to as the *subsurface*. Specialized state and federal scientists are part of dedicated programs to map and document the geology beneath our feet in three dimensions (3-D). However, the financial resources to do so have not met the demand for information, particularly at the detailed resolution required to address local stakeholder questions and make reliable predictions.

A number of steps are necessary to determine the physical distribution, thickness, and properties of geologic deposits, all of which constitute the "containers" and sources of drinking water, energy resources, and construction materials. Traditionally, subsurface mapping in any given area has focused on drilling many exploratory boreholes, often hundreds of feet deep, to retrieve geologic samples. Drilling methods are often coupled with on-the-ground sensing methods, such as geophysical surveys, to image the subsurface.

Mapping subsurface rocks, minerals, and soils by these traditional on-the-ground methods (e.g., drilling and geophysical surveying) is valuable but also time consuming. Individual exploration sites are typically spread out over large areas, in some cases miles apart, creating knowledge or data gaps between boreholes or geophysical surveys. Geologists certainly use these data and scientific principles to create geologic maps that fill in the gaps, but knowledge gaps remain because we simply cannot see everything under the ground.

Technologies that can rapidly sample and sense large tracts of land and the geologic materials beneath the ground are required to answers the questions posed above. Clearly, technological advances made during the last few decades have driven unprecedented progress in the fields of communication, medicine, science, and engineering. Similarly, new and proven technologies are now available to help us understand and map the relationships among our natural resources in the subsurface, and we can do this in 3-D.

A FOCUS ON WATER

The continued development and implementation of technologies is key to developing strategies that help us use and manage groundwater resources effectively. For example, agricultural irrigation is by far the most nonsustainable consumptive use of water on the planet. Can we improve irrigation efficiency and still grow the food we need? We can expedite subsurface geologic mapping of aquifers by deploying transformative technologies, which in turn will provide a basis for realistically estimating groundwater supplies. Experts at the ISGS are ready to apply a number of transformative technologies and methods at local (e.g., small areas of interest with a specific question or problem to solve) to regional (e.g., counties or larger planning areas) to statewide scales to assess the current status of groundwater supplies for all uses, to predict the impacts of increased water demand, and potentially to discover new sources of water from unmapped aquifers.

Part 3 describes a key component of an exploration strategy that invests in our water future by using an innovative technology to map geologic formations beneath the ground that hold our drinking water. Significant increases in the resolution of the geologic framework are expected to transform decision making by allowing us to see into the subsurface like never before. The outcome will catalyze collaboration among scientists, engineers, planners, and economists to meet long-term societal challenges associated with our most vital natural resources. Together we can develop and implement innovative scientific, technological, and management strategies to conserve our known water supply, discover new water resources, and better understand the earth's capacity to provide the water we need to sustain our health, safety, and economic security.

THE TECHNOLOGY

A wide range of new technological methods are available that enable us to identify and map the details of aquifers and, consequently, to determine and describe the availability of groundwater supplies. Many of these technologies use well-established principles of physics and engineering in new ways to map water resources effectively and efficiently. Some include ground-based surveys, fiber-optic systems, and specialized geotechnical subsurface probes. All these methods measure physical characteristics of the earth that relate directly to identifying and delineating water resources.

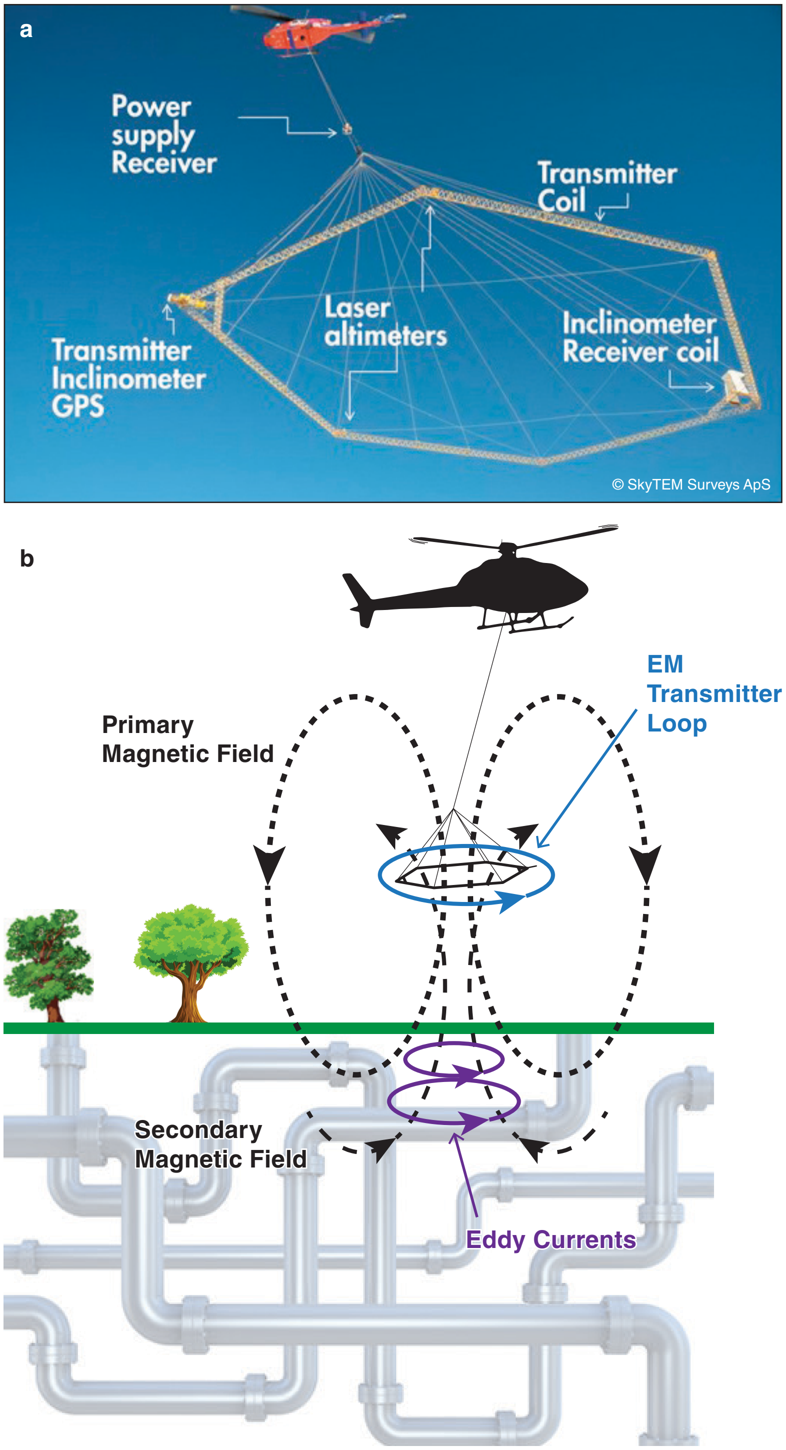
Aircraft deployed with sensors that directly and indirectly detect properties or physical parameters such as elevation, mineral content, water chemistry, light reflectance, density, and electrical conductivity can cover a wide area quickly and efficiently. Although the use of aircraft is a significant cost, the speed of data acquisition and uninterrupted wide coverage extent quickly reduce overall costs for mapping compared with ground-based methods, and subsurface mapping can be accomplished at a rapidly accelerated pace.

A recent innovation of particular interest is the use of airborne geophysical surveys, as introduced above, which can remotely collect high-resolution data below land surface to depths of more than 1,500 feet (Figure 6). These data can reveal in detail the subsurface network of groundwater resources. To date, these methods have been implemented in only a few areas around the world, and they have proved to be cost-effective compared with typical ground-based methods of geologic and geophysical data collection.

HOW IT WORKS

The HTEM system is a geophysical technology towed through the air (Figure 6a). Unlike on land, there are theoretically no spatial limits to where data collection can take place, although the Federal Aviation Administration and, in some cases, local rules or laws constrain some flight conditions. A helicopter can therefore track almost anywhere over land and adjust flight patterns to collect data and best accommodate the required resolutions. Large spatial coverage, rapid data collection, continuous data streams, and resolution adjustment provide a considerable financial incentive compared with traditional mapping methods. Data gaps are filled; geologic variability is determined; and critical resource, environmental, and economic development questions are answered.

The HTEM system consists of a transmitter and a receiver (similar to a TV or radio broadcast system) suspended from a helicopter and flown over a mapping area. The transmitter generates a magnetic field that repeatedly turns on and off. By measuring the magnetic field many times during the on–off cycle, an electrical conductivity profile, or sounding, is obtained (Figure 6b). The results are similar to reading an electronic fish finder, which operates on sonar or sound technology. Just as a fish finder shows fish under water, HTEM shows geologic details under the land surface. HTEM data can be processed into a 3-D format



© SkyTEM Surveys ApS

Figure 6 (a) Helicopter carrying geophysical equipment in the field. The lightweight technology allows these instruments to be towed from the helicopter to conduct a helicopter-based time-domain electromagnetic (HTEM) geophysical survey. Image used courtesy of SkyTEM Surveys ApS. (b) Basic principles of the HTEM method and how it works. Electric current and primary magnetic field in the transmitter loop. Induced eddy currents and secondary magnetic field in the ground. The resulting secondary magnetic field is measured by the receiver coil. The network of pipes is used to illustrate complex subsurface geology.

to generate 3-D images and depth slices of the subsurface electrical conductivity, which is an indicator of the geologic material (e.g., clay, sand, or gravel). Electrical conductivity correlates well with several physical and chemical properties of subsurface materials, including sediment particle size, texture, and salinity. Materials that have very different electrical properties show a higher visual contrast in the slices or images created from the data. For example, the boundary between clay and sand is typically very clear. However, the HTEM technology not only provides a detailed picture of subsurface materials, but also can detect contrasting water chemistries. In coastal areas, this technology is used to show saltwater intrusion into freshwater aquifers.

FILLING IN THE GAPS

The HTEM technology is crucial for geologic mapping because it fills in data gaps that are not observed by typical land-based technologies such as geologic test hole drilling. The spacing between exploratory drill holes may be miles apart (Figure 7a and 7b); thus, the character of the geologic materials or layers present between them must be interpolated. In areas of sparse data, geologists must predict or interpret what exists between data points by using their knowledge of how various materials were deposited. The complexity of subsurface geology can make this process very challenging, especially in areas with few drill holes. The ability of HTEM to fill in the gaps with actual data greatly reduces the geologist's uncertainty, resulting in more accurate and useful map products.

Figure 8 demonstrates conceptually how HTEM improves our ability to visualize the subsurface geology in all its complexity. Consider a complex network of pipes in the subsurface. Suppose you were able to drill only three boreholes to map this network (Figure 8a). If the data you have are derived from only three boreholes (Figure 8b), you could come to the wrong conclusion about the connectivity of the pipes. In contrast, HTEM data give us a much more complete glimpse into the subsurface (Figure 8c and 8d).

Figure 7 (a) Drilling, core sampling, and geophysical logging in the field, and (b) drilling and core sampling in the field. Photographs by Timothy C. Young.

GROUND TRUTH—LEVERAGE KNOWLEDGE

Geophysics is most powerful when used in combination with other traditional geological measurements. Existing data derived from water-well logs and geologic test holes, other ground-based geophysical surveys, and even written ground observations supplement and guide the way we determine what the HTEM data reveal. HTEM data are not a substitute for actual physical samples of geologic material, so it is desirable to discover existing geologic data and integrate these data with additional new

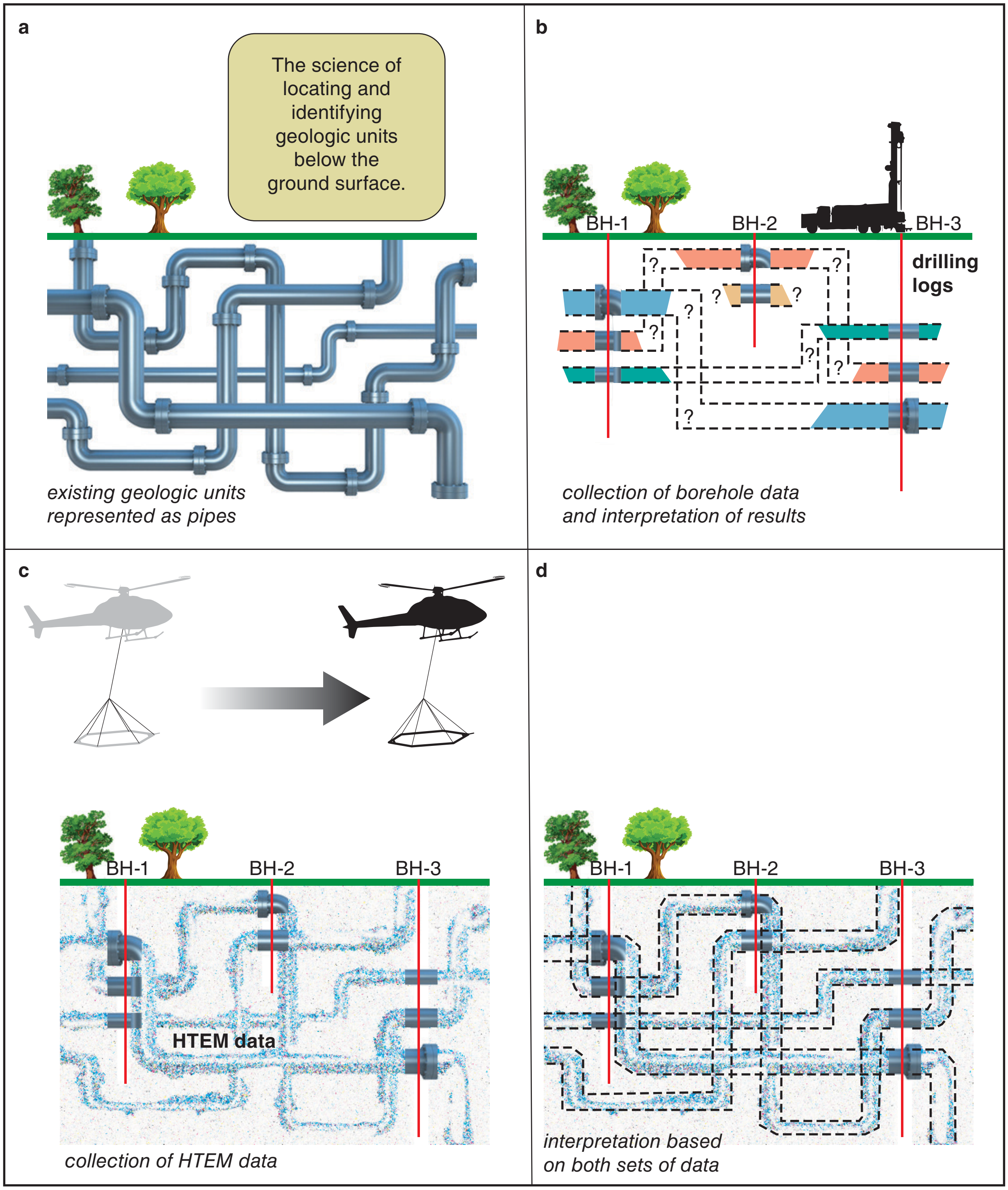


Figure 8 Illustration showing the benefit of combining the airborne geophysical method with traditional measurements to improve understanding of the subsurface and efficiency in mapping. (a) The network of pipes is used to illustrate complex subsurface geology. (b) Borehole information is too sparse to derive detailed subsurface information. (c) Use of the HTEM method provides data between boreholes and fills in data gaps. (d) Borehole data are used to calibrate the HTEM data, providing a more complete understanding of the subsurface.

targeted ground-based data obtained through exploration of drill holes or by using the WalkTEM technology (a land-based time-domain electromagnetic [TEM] system; Figure 9). The WalkTEM system can be used on a local scale in areas inaccessible by helicopter or to supplement or compare ground-based data with HTEM data. The WalkTEM system operates similarly to the HTEM system, using a transmitter and receiver. However, the equipment in a WalkTEM survey is smaller, remains stationary on the ground during data collection, and is moved manually from place to place. The WalkTEM provides results similar to the HTEM but is obviously more time consuming and has a shallower depth of investigation.

Geologic test holes provide a detailed log and actual geologic samples from specific sites, which are used to calibrate the geophysical data, so any HTEM project should include exploration test holes. This information is necessary to translate HTEM data into information that corresponds to the various geologic materials. The number of test holes, depths drilled, and cost for collecting additional geologic information depends on the size of the area being investigated and the existing knowledge and complexity of the geology. Collectively, these data guide a fully integrated and implemented 3-D geologic mapping endeavor. The ISGS is fully equipped with the drilling and land-based geophysical equipment necessary for a full HTEM exploration and discovery project.

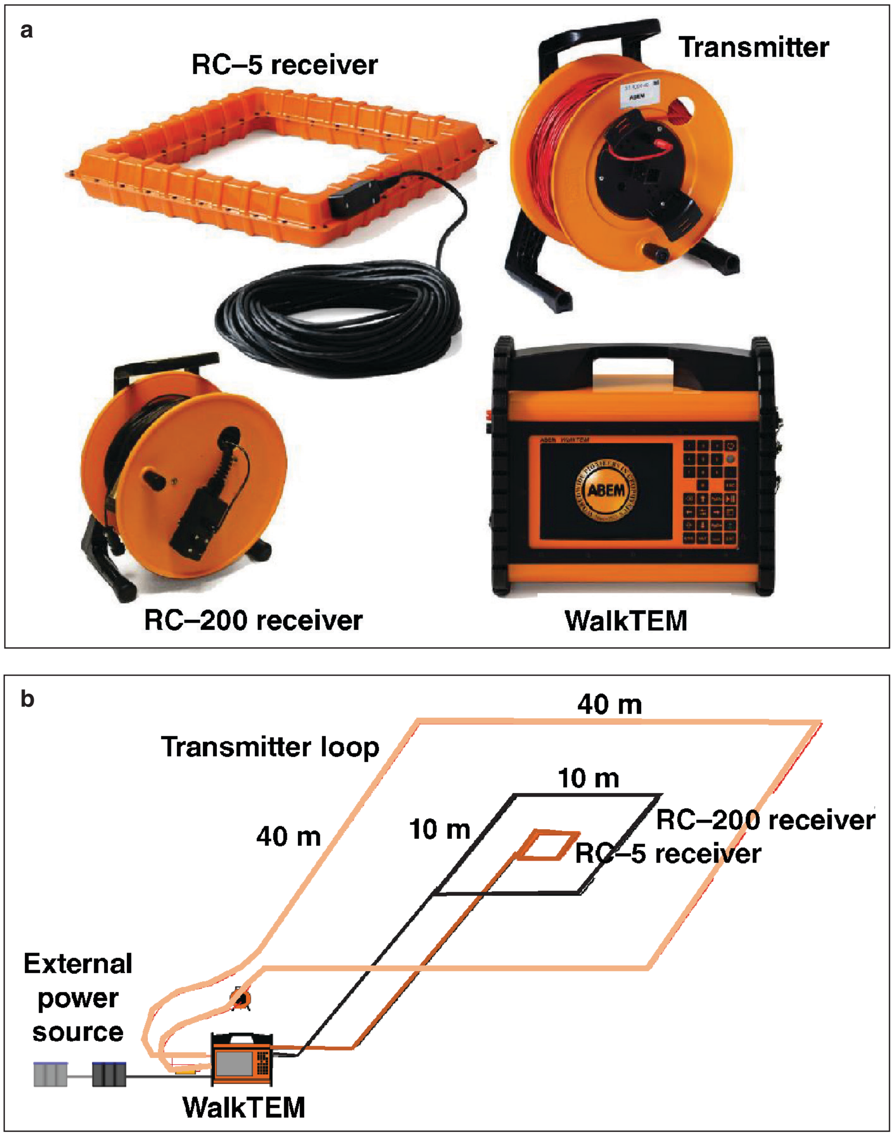


Figure 9 (a) WalkTEM system components used to supplement HTEM surveys. (b) WalkTEM system layout in the field using a 40 x 40 meter (m) transmitter loop and dual receiver antennas. Images courtesy of MALÅ Geoscience/Guideline Geo.

QUESTIONS ANSWERED

Airborne geophysical surveys will change the way scientists evaluate water resources and revolutionize the ways society manages its global water issues. Geologic mapping with HTEM technology benefits stakeholders by providing information on the characteristics of the subsurface geology at an enhanced resolution. How we map and describe geologic features has a significant impact on policy decisions, which ultimately become a matter of cost, safety, and health. The mapped locations or descriptions of geologic features guide our water management, land-use policies, landscape stewardship, natural hazard mitigation, and even awareness of the source of our drinking water. Detailed information on subsurface water resources provides local, regional, and statewide decision makers with unbiased and scientifically defensible information to balance critical economic development considerations with proper water use and environmental protection strategies. In particular, the danger of overusing water resources or contaminating those resources is greatly reduced through more effective land-use and water-resource planning.

Several geologic features that are important for making water supply planning and use decisions are described below. The HTEM technology can be applied to identify or characterize each feature, demonstrating its value and benefit to stakeholders.

Aquifer Boundaries, Thicknesses, and Properties. Current methods rely on making assumptions about the thickness, properties, or continuity of a boundary or edge of an aquifer by interpolating the geology between two or more widely spaced points on the ground. HTEM eliminates much of the guesswork by providing a continuous image of the subsurface geologic materials, including their boundaries, thicknesses, and geologic properties (e.g., grain size, inferred porosity, hydraulic conductivity). Use of the HTEM method is expected to reveal sand and gravel deposits that may change our knowledge of the extent of the Mahomet aquifer, the detailed shape of bedrock valleys, and the extent of connections among different geologic units suggested by interpretations of water-level observations in groundwater monitoring wells.

Recharge Areas and Contamination Pathways. Groundwater flow models use assumptions about flow rates and directions. The HTEM technology can provide a resolution that may show actual pathways that water might follow as it moves through the ground.

Aquifer Protection and Water Security. Aquifers are vulnerable to contamination, yet information about the integrity of protective natural barriers above sources of drinking water can be unclear. To properly assess this risk, detailed mapping of the depth to aquifers, assessment of their thicknesses and properties, and modeling of groundwater flow are needed. Although mapping and modeling cannot prevent contamination, outcomes of these efforts help decision makers and emergency responders evaluate risks.

POTENTIAL APPLICATIONS

Characterizing the Mahomet Aquifer

The Mahomet aquifer provides more than 200 million gallons of groundwater per day (RWSPC 2009; Roadcap et al. 2011; Wehrmann et al. 2011). Sustainable long-term management of this groundwater resource is critical for maintaining and expanding the economy of central Illinois. The water within the aquifer is of such importance to the health and economy of Illinois that the US EPA has designated it a Sole Source Aquifer (US EPA 2015). We know much about the aquifer through data provided by water-well drillers and exploratory drilling for geologic mapping projects, but many questions remain:

- What are the long-term effects of pumping water?
- Can our knowledge of the boundary of the aquifer be improved? In fact, the boundary can be characterized in a number of ways, so which ones best serve our needs?
- Does the aquifer extend into presently unknown buried bedrock valleys that are tributaries to the main valley containing the Mahomet aquifer? We know that the aquifer resides in an old bedrock river valley that existed before glaciers entered Illinois, and like most river valleys, tributary valleys exist, but how long and wide are these buried tributary bedrock valleys, and do they contain the geologic material and quantities of groundwater to make viable aquifers?
- How interconnected are different geologic layers?
- How effectively do the geologic layers overlying the aquifer protect it from contamination?
- What happens to contaminants that are spilled on the ground or stored in the subsurface above the aquifer? Can they seep into the aquifer?
- Do any surface lakes or streams connect directly to the aquifer?
- Can we identify areas where rain and snow recharge the aquifer faster than other areas?

The use of HTEM technology to map the geology in the Mahomet aquifer region would help answer these questions. The land area over the aquifer is large, so flying a helicopter over the entire area would require considerable financial resources. However, the deployment of a helicopter can be divided into units or smaller areas (Figure 10), which can be prioritized so that the most important areas are investigated first. In addition, some areas may require a finer resolution, depending on the known geologic complexity or a particular groundwater question. This can be achieved by spacing the flight lines closer together.

Table 1 provides estimated costs for deploying the HTEM technology for each of the hypothetical survey areas shown in Figure 10. Collecting data for more than one area concurrently would also achieve some cost savings (Figure 11). Survey areas are delineated only for demonstration purposes and are not intended to indicate planned or targeted locations. Survey area units of alternative dimensions could be planned to reduce costs or to survey the highest priority locations. An actual HTEM project would include additional costs related to the scope of the project, administration fees, and other variables as determined on a case-by-case basis.

Mapping Other High-Priority Regions in Illinois

In addition to mapping the Mahomet aquifer region in central Illinois, the ISGS is mapping other high-priority areas throughout Illinois in 3-D (Illinois Geologic Mapping Advisory Committee 2018), with a focus on northeastern Illinois and the greater metropolitan Chicago region. The ISGS has meticulously and judiciously evaluated regions with high population growth, transportation corridors, natural resources, recreational areas, and environmentally sensitive areas. Guided by Special Report 1 (ISGS 1992), the ISGS Geologic Mapping Advisory Committee regularly evaluates priority regions for 3-D geologic mapping to address myriad land- and water-use issues. Geologic mapping is typically time consuming, but these high-priority efforts require mappers to stay ahead of economic development and the associated planning decisions to minimize environmental problems while optimizing the growth potential of those parts of Illinois.

The bulleted questions pertaining to studying, mapping, and addressing issues in the Mahomet aquifer region also apply to the rest of the state. Buried bedrock valleys (e.g., see Figure 3) are known to hold aquifer material. In a few cases, traditional mapping using surface geophysics has led to the discovery of buried aquifers that inset buried bedrock valleys. For example, the Newark Bedrock Valley containing the water-rich St. Charles aquifer was discovered in Kane County, and this aquifer now serves several municipalities. In Champaign County near Homer, a true hit-or-miss, “needle in a haystack” investigation yielded a very narrow 300-foot-wide and 100-foot-thick aquifer. However, the use of HTEM to discover aquifers in

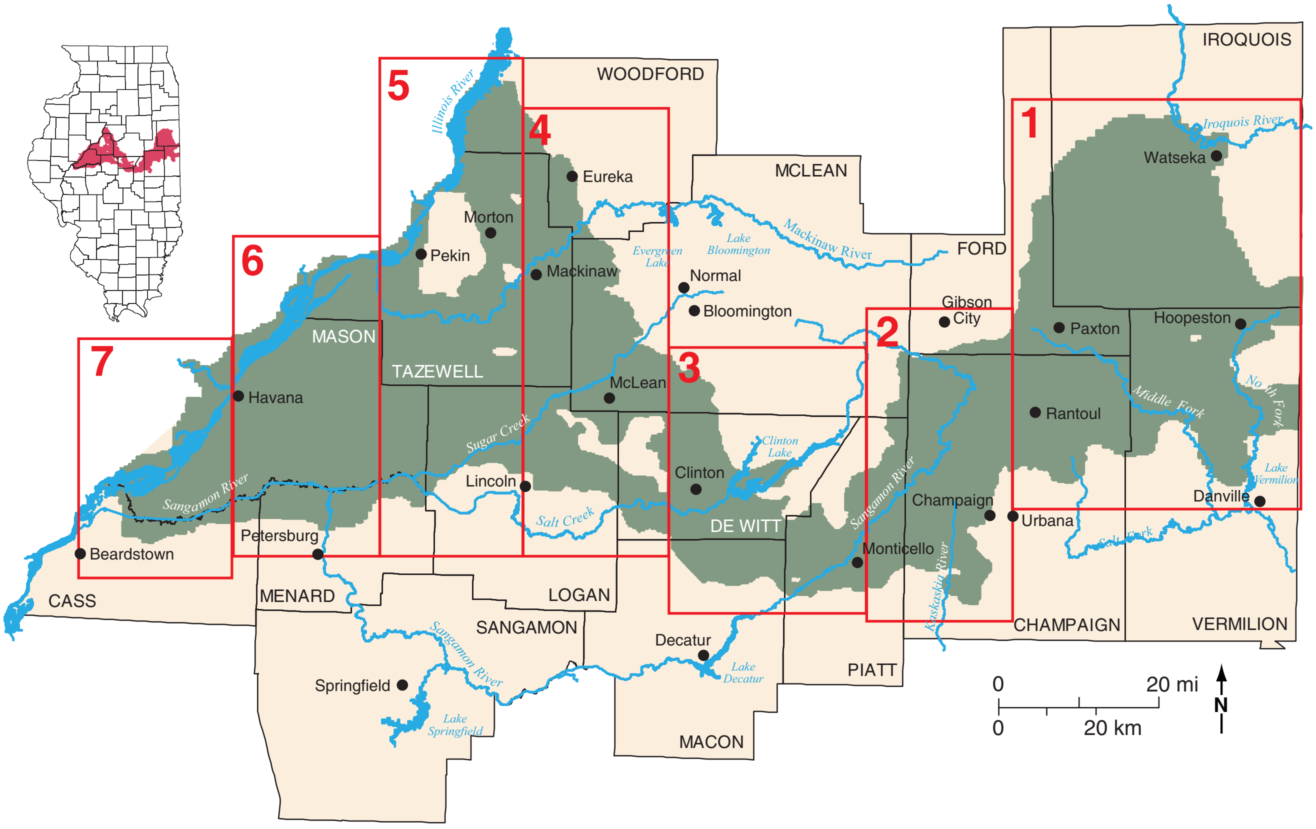


Figure 10 Hypothetical delineation of Mahomet aquifer HTEM data collection into phases for cost comparison. Base figure courtesy of the Illinois State Water Survey.

Table 1 Estimated cost to deploy the HTEM technology for the Mahomet aquifer region[1]

	Survey area						
Parameter	1	2	3	4	5	6	7
Size (mi²)	1,540	1,080	900	1,200	1,300	945	400
Flight line length (mi)	18,647	7,337	6,785	8,784	9,539	6,383	4,792
Total cost ($)	3,239,247	1,291,676	1,196,660	1,540,772	1,670,884	1,127,324	853,404

[1] Cost based on 2017 rates. Hypothetical survey areas are shown geographically in Figure 10.

presently buried bedrock valleys and obtain fill-in-the-gap coverage of large regions would make such intensive, luck-driven discoveries of aquifers a thing of the past. Discovery of aquifers in similar geologic settings has been a cornerstone of the HTEM subsurface mapping program in Denmark (Høyer et al. 2015; The Rethink Water Network 2016; Sandersen and Jørgensen 2010–2015). Figure 12 from Jørgensen et al. (2012) demonstrates some of the results from an HTEM survey that was used to map buried valleys, sand aquifers, and other structures that control groundwater flow in the western part of the border between Denmark and Germany.

Outside the areas of bedrock valleys and their associated aquifers are vast regions of Illinois that also contain sand and gravel aquifers within and between the various layers of deposits laid down by the many advances and retreats of glaciers. Many of these aquifers serve as local groundwater sources for municipalities and private residences. For example, detailed 3-D mapping in McHenry and Lake Counties (e.g., see Thomason and Keefer 2013) revealed multiple aquifers separated by till and lake sediment (clay deposits). However, these efforts took several years to complete when using traditional subsurface mapping techniques. HTEM is regarded as a technique that can greatly supplement the traditional methods, reduce the time commitment for mapping, considerably reduce the long-term costs, increase efficiency, and most important, complete desperately needed subsurface mapping throughout the state of Illinois, beginning with the high-priority regions.

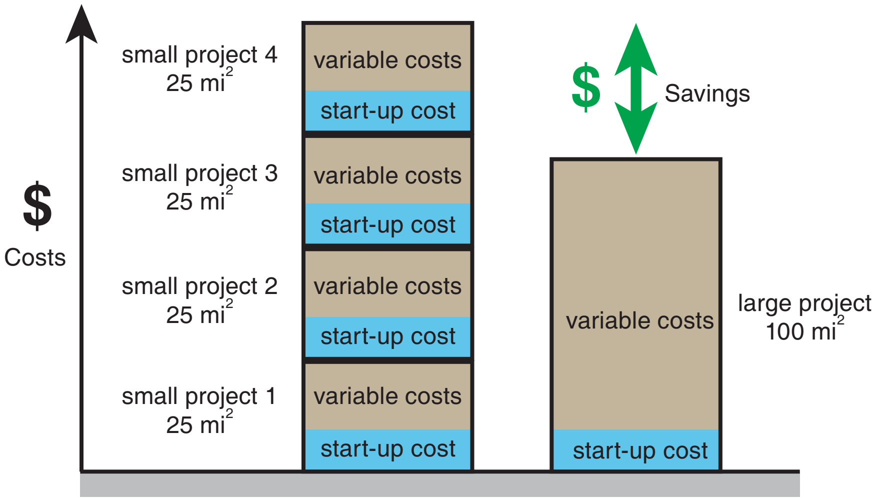


Figure 11 Deploying HTEM technology over a larger area can be more cost effective than deploying it in multiple phases over a small area.

Mapping the Sandwich Fault Zone

The area of the Sandwich Fault Zone (SFZ; Figure 13) in northern Illinois has significant environmental and economic importance to the continued viability of the greater Chicago metropolitan area. The southern and western suburbs of Chicago, an area of substantial projected population growth, are presently facing a water crisis resulting from unsustainable water withdrawals from bedrock aquifers. The SFZ is of great interest because it appears to be impeding groundwater flow in the aquifers, yet the subsurface geology of the SFZ is poorly understood and its lateral extent is not known with any degree of certainty. To manage these bedrock aquifers sustainably, an understanding of the SFZ is critical.

Given the importance of having accurate, high-resolution subsurface 3-D geologic maps, it is crucial to use shallow and deep geophysical surveys, conventional and angled-exploration drilling, geochemical assays, and other methods to characterize local to regional fault zone features and stratigraphic relationships. Shallow and deep geophysical techniques are needed to map and characterize the overall fault zone geometry, as well as details of the subsurface faults, fault displacement, fractures and fracture networks, rock unit lithologic variations, and stratigraphy. Advanced geophysical methods, such as high-resolution seismic reflection and the HTEM technology, would provide both shallow (<1,000-foot-deep) and deep (>1,600-foot-deep) information, as well as spatially dense data at a very high resolution and with the large spatial coverage required for detailed subsurface mapping.

CASE EXAMPLES

Characterizing Illinois' Lake Michigan Shoreline

The Illinois Lake Michigan coast is a very dynamic system, with complex coastal processes occurring along the shore. Beach sand is a vital coastal resource because it helps alleviate shoreline erosion when present. When sand is reduced, beaches erode and a general loss of shoreline occurs, including heightened recession of the heavily developed bluffs along a significant portion of the Illinois coast, oftentimes endangering sensitive ecosystems and habitats. In addition, when sand is removed from the shallow offshore, the underlying clay lake bottom is left unprotected and can erode as well, thereby deepening the water and allowing larger waves to impact the shore. This ultimately increases additional beach and bluff erosion and threatens the infrastructure. The beach and bottom sand along the Lake Michigan coast are in a constant state of flux, moving on-, off-, and alongshore in response to changing waves, currents, and ice. As sand moves along the shore, it becomes diverted and trapped by harbors and other structures, depleting the supply that moves along the coast. When the amount of sand removed from an area exceeds the amount transported in, beach erosion results. Erosion has significant economic and recreational value impacts for municipalities trying

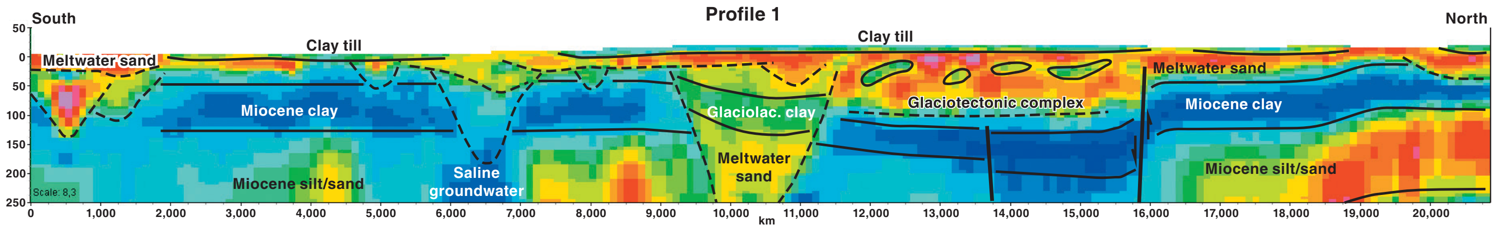


Figure 12 Cross section showing HTEM results in Denmark mapping buried valleys, clay, and structures, all of which control groundwater flow. From Jørgensen et al. (2012), Hydrology and Earth System Sciences, v. 16, p. 1845–1862 (www.hydrol-earth-syst-sci.net/16/1845/2012/). Licensed under CC BY 3.0.

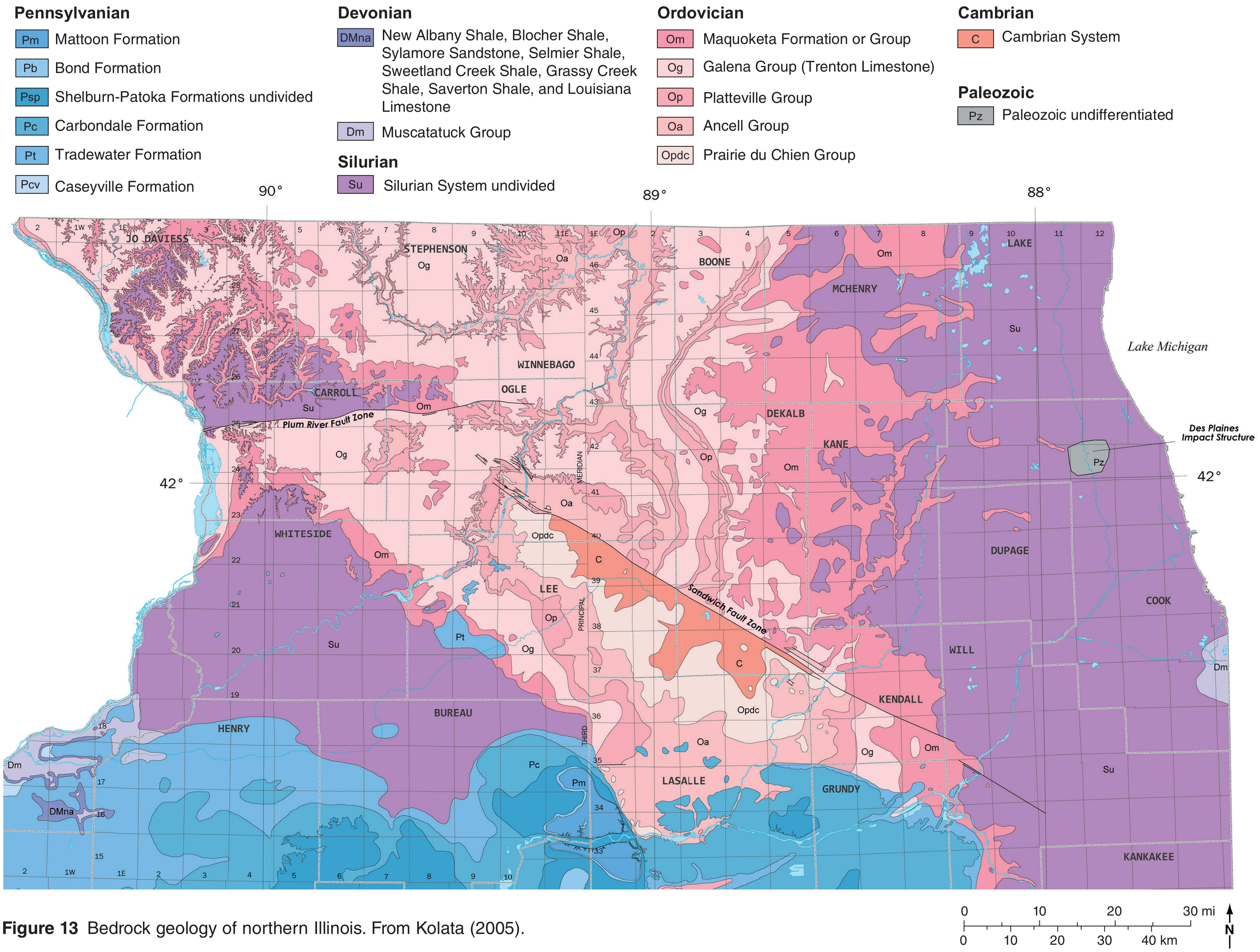


Figure 13 Bedrock geology of northern Illinois. From Kolata (2005).

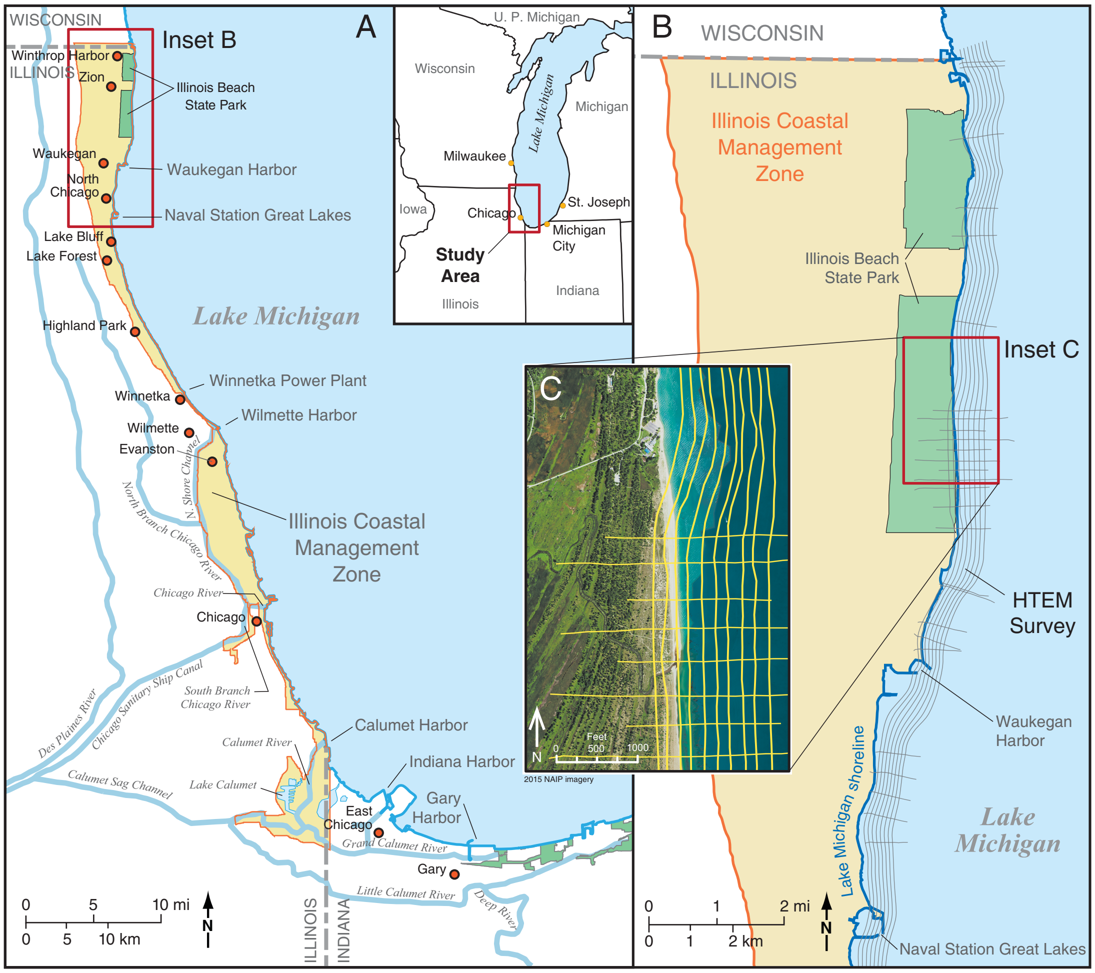


Figure 14 (A) Map showing the HTEM-surveyed area along the southwestern Lake Michigan shore between Kenosha, Wisconsin, and the Illinois–Indiana state line. This National Oceanic and Atmospheric Administration project included more than 640 miles flown in a half-mile-wide zone. (B) Close-up of the area shown by the red rectangle in A. (C) Close-up of a part of Illinois Beach State Park showing flight lines parallel and perpendicular to the shore, spaced approximately 200 to 400 feet apart.

to maintain their beaches and coastal infrastructure. At the same time, accretion along harbors results in substantial dredging costs, as well as impacts to recreational and commercial boating.

In response to this situation, HTEM was used in April 2017 to map the sediment distribution on the beach and nearshore bottom of the Illinois Lake Michigan coast. The helicopter surveyed the southwestern shore of the Lake Michigan coast from the Illinois–Indiana state line to Kenosha, Wisconsin (Figure 14). The resulting data will provide a map of the distribution and thickness of beach and lake-bottom sand, which will be used to develop strategies and action plans to address shoreline erosion effectively, reduce the cost of harbor maintenance, and target habitat restoration. (For news coverage of the project, see http://www.chicagotribune.com/news/local/breaking/ct-lake-michigan-shoreline-helicopter-research-met-20170319-story.html.)

Yellowstone National Park, November 2016

A team of scientists from the U.S. Geological Survey, the University of Wyoming, and Aarhus University in Denmark applied the HTEM method at Yellowstone National Park to gain a better understanding of Yellowstone's hydrothermal systems. The HTEM data will help researchers map lithological variations and structural controls on groundwater flow within the park, delineating zones of fresh water versus saline water and mapping clay and unaltered rock (http://skytem.com/airborne-geophysical-survey-yellowstone/).

Water Survey in California, September 2016

Through a joint effort between U.S. Geological Survey scientists and the California Water Resources Control

Board, the HTEM method was applied in the Southern San Joaquin Valley to help address California's drought and drinking water shortage. The main objective of the survey was to monitor groundwater levels in aquifers and to characterize and monitor risk zones (http://skytem.com/water-survey-california/).

Groundwater Mapping in Antarctica, April 2015

The HTEM method was used in the Taylor Valley in Antarctica to help improve understanding of the occurrence of groundwater, particularly in the ice-free regions and along the coastal margins. A groundwater system with a high solute (brine) content was inferred from the HTEM results. It was shown to be widespread within permafrost and to extend below the glaciers and lakes. Furthermore, hydrological connectivity between water bodies was observed, which had significant implications for the subsurface ecosystem (Mikucki et al. 2015).

Mineral Exploration

Economic geological applications of the HTEM system include explorations for gold, uranium, and graphite, as well as direct detection of massive sulfides. HTEM can resolve the localization of these ore deposits and minerals associated with the ore deposits. Examples of such applications are mapping of uranium mineralization in Saskatchewan, Canada, and Australia, graphite exploration in Alaska, and exploration of massive sulfide deposits in Québec, Canada.

Geotechnical Engineering

Rock sliding and other geotechnical hazards are a result of weak zones and sliding planes embedded within strong, hard rocks. The contrast in physical properties between the two rock formations can be accurately mapped by HTEM at very high resolutions. Furthermore, HTEM can be used to detect near-surface coarse-grained material (e.g., gravel) for engineering applications such as road construction. HTEM has been successfully used to map rock slides in Norway.

SUMMARY

The HTEM technology has had domestic and international success in regions with geology analogous to the Mahomet aquifer. Given the inherent complexity of Illinois' shallow geologic systems, the growing expertise of the ISGS in HTEM technology, and the critical role of high-resolution, shallow geologic models in the sustainable management of groundwater resources, this circular outlines a proposal for a cost-effective, multiyear program to collect HTEM data and model the geologic deposits of the Mahomet aquifer. This program would greatly enhance the ISGS' efforts since the 1940s to provide information on the Mahomet aquifer, particularly during these times of population growth and stresses on water usage.

ACKNOWLEDGMENTS

The authors thank the scientists who have provided insights into the Mahomet aquifer. These insights have enhanced our understanding of the aquifer and form the basis for thinking about the future of Mahomet aquifer science. We also thank the people of east-central Illinois for advocating for the sustainability of the Mahomet aquifer as a groundwater resource. Participants in The Future of the Science of the Mahomet Aquifer workshop on June 28, 2017, provided the information presented in Part 2. Richard Winkel and Trish Barker diligently provided support in planning for and conducting the workshop. Richard C. Berg, Walton R. Kelly, Randall A. Locke, and Mark A. Yacucci provided critical review of the manuscript. The authors express their sincere thanks to Deette Lund, Susan Krusemark, and Michael Knapp for preparing the figures, editing the text, and compiling the publication.

REFERENCES

Cvitanovic, C., A.J. Hobday, L. van Kerkhoff, S.K. Wilson, K. Dobbs, and N.A. Marshall, 2015, Improving knowledge exchange among scientists and decision-makers to facilitate the adaptive governance of marine resources: A review of knowledge and research needs: Ocean and Coastal Management, v. 112, p. 25–35.

Cvitanovic, C., J. McDonald and A.J. Hobday, 2016, From science to action, Principles for undertaking environmental research that enables knowledge exchange and evidence-based decision-making: Journal of Environmental Management, v. 183, p. 864–874.

Hansen, M.C., 1995, The Teays River: Ohio Department of Natural Resources, Division of Geological Survey, GeoFacts No. 10, 2 p.

Herzog, B.L., S.D. Wilson, D.R. Larson, E.C. Smith, T.H. Larson, and M.L. Greenslate, 1995, Hydrogeology and groundwater availability in southwest McLean and southeast Tazewell Counties, Part 1: Aquifer characterization: Champaign, Illinois State Geological Survey and Illinois State Water Survey, Cooperative Ground-Water Report 17, 70 p.

Holm, T.R., 1995, Ground-water quality in the Mahomet aquifer, McLean, Logan, and Tazewell Counties: Champaign, Illinois State Water Survey, Contract Report 579, 42 p.

Horberg, L., 1945, A major buried valley in east-central Illinois and its regional relationships: The Journal of Geology, v. 53, no. 5, p. 349–359.

Horberg, L., 1950, Bedrock topography of Illinois: Champaign, Illinois State Geological Survey, Bulletin 73, 111 p., 2 plates with 3 sheets.

Horberg, L., 1953, Pleistocene deposits below the Wisconsin drift in northeastern Illinois: Champaign, Illinois State Geological Survey, Report of Investigations 165, 61 p.

Høyer, A.S., F. Jørgensen, P.B.E. Sandersena, A. Viezzoli, I. Møller, 2015, 3D geological modelling of a complex buried-valley network delineated from borehole and AEM data: Journal of Applied Geophysics, v. 122, p. 94–102.

Illinois General Assembly, 1996, Environmental Safety, Illinois Groundwater Protection Act, Illinois Compiled Statute (ICS) 415, Part 55, Sec. 3: Illinois General Assembly, http://

www.ilga.gov/legislation/ilcs/ilcs3.sp?ActID=1595&ChapterID=36 (accessed February 19, 2018).

Illinois General Assembly, 2017, Mahomet Aquifer Protection Task Force Act, Public Act 100-0403, Illinois Senate Bill 611: Illinois General Assembly, http://www.ilga.gov/legislation/publicacts/100/PDF/100-0403.pdf (accessed February 20, 2018).

Illinois Geologic Mapping Advisory Committee, 2018, About the committee: Champaign, Illinois State Geological Survey, http://www.isgs.illinois.edu/illinois-geologic-mapping-advisory-committee (accessed February 19, 2018).

Illinois State Geological Survey, 1992, Geologic mapping for the future of Illinois: Champaign, Illinois State Geological Survey, Special Report 1, 49 p., http://hdl.handle.net/2142/44595. (Prepared in cooperation with the Senate Working Committee on Geologic Mapping, assisted by the Senate Geologic Map Task Force.)

Illinois State Water Survey, 2016, How is water used in Illinois?, https://www.isws.illinois.edu/docs/wsfaq/wsmore.asp?id=q2 (accessed February 18, 2018).

Ismail, A., A.J. Stumpf, and R. Bauer, 2014, Seismic characterization of glacial sediments in central Illinois: Journal of Applied Geophysics, v. 101, p. 1–10.

Jørgensen, F., W. Scheer, S. Thomsen, T.O. Sonnenborg, K. Hinsby, H. Wiederhold, C. Schamper, T. Burschil, B. Roth, R. Kirsch, and E. Auken, 2012, Transboundary geophysical mapping of geological elements and salinity distribution critical for the assessment of future sea water intrusion in response to sea level rise: Hydrology and Earth System Sciences, v. 16, p. 1845–1862, https://doi.org/10.5194/hess-16-1845-2012.

Kempton, J.P. and B.L. Herzog, 1996, Mapping the Mahomet sand and other aquifers of DeWitt and Piatt Counties: Champaign, Illinois State Geological Survey, Open File Series 1996-9, 13 p.

Kempton, J.P., W.J. Morse and A.P. Visocky, 1982, Hydrogeologic evaluation of sand and gravel aquifers for municipal groundwater supplies in east-central Illinois: Champaign, Illinois State Geological Survey and Illinois State Water Survey, Cooperative Groundwater Report 8, 60 p.

Killey, M.M., 2007, Illinois' Ice Age legacy: Champaign, Illinois State Geological Survey, Geoscience Education Series 14, 74 p.

Killey, M.M., and D.R. Larson, 2004, Illinois groundwater: A vital geologic resource: Champaign, Illinois State Geological Survey, Geoscience Education Series 17, 61 p.

Kolata, D.R., compiler, 2005, Bedrock geology of Illinois: Champaign, Illinois State Geological Survey, Illinois Map 14, 1:500,000.

Larson, D.R., E. Mehnert, and B.L. Herzog, 2003, The Mahomet aquifer, A transboundary resource in east-central Illinois: Water International, v. 28, no. 2, p. 170–180.

Melhorn, W.H. and J.P. Kempton, eds., 1991, Geology and hydrogeology of the Teays-Mahomet Bedrock Valley system: Boulder, Colorado, Geological Society of America, Special Paper 258, 128 p.

Mikucki, J.A., E. Auken, S. Tulaczyk, R.A. Virginia, C. Schamper, K.I. Sørensen, P.T. Doran, H. Dugan, and N. Foley, 2015, Deep groundwater and potential subsurface habitats beneath an Antarctic dry valley: Nature Communications, v. 6, p. 6831, doi:10.1038/ncomms7831.

Panno, S.V., K.C. Hackley, K. Cartwright, and C.L. Liu, 1994, Hydrochemistry of the Mahomet Bedrock Valley aquifer, east-central Illinois: Indicators of recharge and ground-water flow: Ground Water, v. 32, p. 591–604.

Panno, S.V., K.C. Hackley, E. Mehnert, D.R. Larson, D. Canavan, and T.C. Young, 2005, Declining specific capacity of high-capacity wells in the Mahomet aquifer, mineralogical and biological factors: Champaign, Illinois State Geological Survey, Circular 566, 51 p.

Pugin, A.J.M., T.H. Larson, S.L. Sargent, J.H. McBride, and C.E. Bexfield, 2004, Near-surface mapping using SH-wave and P-wave seismic land-streamer data acquisition in Illinois, U.S.: Leading Edge, v. 23, p. 677–682.

Reed, M.S., L.C. Stringer, I. Fazey, A.C. Evely, and J.H.J. Kruijsen, 2014, Five principles for the practice of knowledge exchange in environmental management: Journal of Environmental Management, v. 146, p. 337–345.

Regional Water Supply Planning Committee (RWSPC), 2009, A plan to improve the planning and management of water supplies in east-central Illinois: Champaign, Regional Water Supply Planning Committee, 92 p., http://www.rwspc.org/documents/ECI-WaterPlan_062909.pdf (accessed February 20, 2018).

The Rethink Water Network, Danish Water Forum & State of Green, 2016, Greater water security with groundwater: Groundwater mapping and sustainable groundwater management: Copenhagen, State of Green, White Paper, Version 2.1, 24 p., https://stateofgreen.com/en/infocus/publications/greater-water-security-with-groundwater (accessed February 20, 2018).

Roadcap, G.S., H.V. Knapp, H.A. Wehrmann, and D.R. Larson, 2011, Meeting east-central Illinois water needs to 2050: Potential impacts on the Mahomet aquifer and surface reservoirs: Champaign, Illinois State Water Survey, Contract Report 2011-08, 188 p.

Sandersen, P.B.E., and F. Jørgensen, 2010–2015, Mapping buried valleys in Denmark: Copenhagen, Geological Survey of Denmark and Greenland (GEUS), http://begravede-dale.dk/english_version.htm (accessed February 19, 2018).

Singha, K., 2017, Geophysics is not a silver bullet, but worth a shot: Groundwater, v. 55, p. 149.

Soller, D.R., S.D. Price, J.P. Kempton, and R.C. Berg, 1999, Three-dimensional geologic maps of Quaternary sediments in east-central Illinois: Reston, Virginia, U.S. Geological Survey, Geologic Investigations Series Map I-2669, 3 sheets.

Stumpf, A.J., and L.A. Atkinson, 2015, Geologic cross sections across the Mahomet Bedrock Valley, Champaign, Ford, McLean, Piatt, and Vermilion Counties, Illinois: Champaign, Illinois State Geological Survey, Illinois Map 19, 1:48,000.

Stumpf, A.J., and W.S. Dey, eds., 2012, Understanding the Mahomet aquifer: Geological, geophysical, and hydrogeological studies in Champaign County and adjacent areas: Champaign, Illinois State Geological Survey, report under contract to Illinois-American Water Company, Contract No. IL Amer Water 2007-02899, 350 p., http://hdl.handle.net/2142/95787 (accessed February 20, 2018).

Stumpf, A.J. and A. Ismail, 2013, High-resolution seismic reflection profiling, an aid for resolving the Pleistocene stratigraphy of a buried valley in central Illinois, USA: Annals of Glaciology, v. 54, p. 10–20.

Thomason, J.F., and D.A. Keefer, 2013, Three-dimensional geologic mapping for McHenry County: Champaign, Illinois State Geological Survey, unpublished contract report.

United States Environmental Protection Agency (US EPA), 2011, Code of Federal Regulations, Title 40—Protection of Environment, Part 144, Section 144.3–Definitions: Washington, DC, U.S. Government Publishing Office, https://www.gpo.gov/fdsys/pkg/CFR-2011-title40-vol23/pdf/CFR-2011-title40-vol23-sec144-3.pdf (accessed February 20, 2018).

United States Environmental Protection Agency (US EPA), 2012, Petition to Designate the Mahomet Aquifer as a Sole Source Aquifer: Technical Preparation by Layne Hydro, Bloomington, Indiana, for the City of Champaign, the Town of Normal, City of Urbana, University of Illinois-Champaign/Urbana, Village of Savoy, City of Delavan, Village of Mahomet, Village of Mansfield, and City of Gilman, December 10, 2012, 108 p.

United States Environmental Protection Agency (US EPA), 2014, Support Document for Proposed Designation of the Mahomet Aquifer System as a Sole Source with Errata Sheet—March 2015: Chicago, US EPA Region 5, 15 p., https://www.epa.gov/il/mahomet-sole-source-aquifer (accessed February 19, 2018).

United States Environmental Protection Agency (US EPA), 2015, Sole Source Aquifer designation of the Mahomet Aquifer System in east-central Illinois; FRL-9923-75-Region 5; Notice of final determination; FR Doc No: 2015-06365: Washington, DC, Federal Register, v. 80, no. 53, p. 14370–14371, https://federalregister.gov/a/2015-06365 (accessed February 19, 2018).

Visocky, A.P. and R.J. Schicht, 1969, Groundwater resources of the buried Mahomet Bedrock Valley: Champaign, Illinois State Water Survey, Report of Investigation 62, 52 p.

Wehrmann, A., J. Unterreiner, G. Roadcap, J. Sullivan, R. Cobb, D. Larson, G. Rogers, and R. Schmidt, 2011, Results of the Illinois–Indiana pilot study for the National Ground-Water Monitoring Network: Reston, Virginia, U.S. Geological Survey, Advisory Committee on Water Information, 90 p., http://acwi.gov/sogw/pubs/tr/pilot_results/IL-IN.pdf (accessed February 19, 2018). (Prepared for the Advisory Committee on Water Information Subcommittee on Ground Water.)

Wilson, S. D., J.P. Kempton, and R.B. Lott, 1994, The Sankoty-Mahomet aquifer in the confluence area of the Mackinaw and Mahomet Bedrock Valleys, central Illinois: A reassessment of aquifer characteristics: Champaign, Illinois State Water Survey and Illinois State Geological Survey, Cooperative Ground-Water Report 16, 64 p.

Wilson, S.D., G.S. Roadcap, B.L. Herzog, D.R. Larson, and D. Winstanley, 1998, Hydrogeology and ground-water availability in southwest McLean and Southeast Tazewell Counties, Part 2: Aquifer modeling and final report: Champaign, Illinois State Water Survey and Illinois State Geological Survey, Cooperative Ground-Water Report 19, 138 p.