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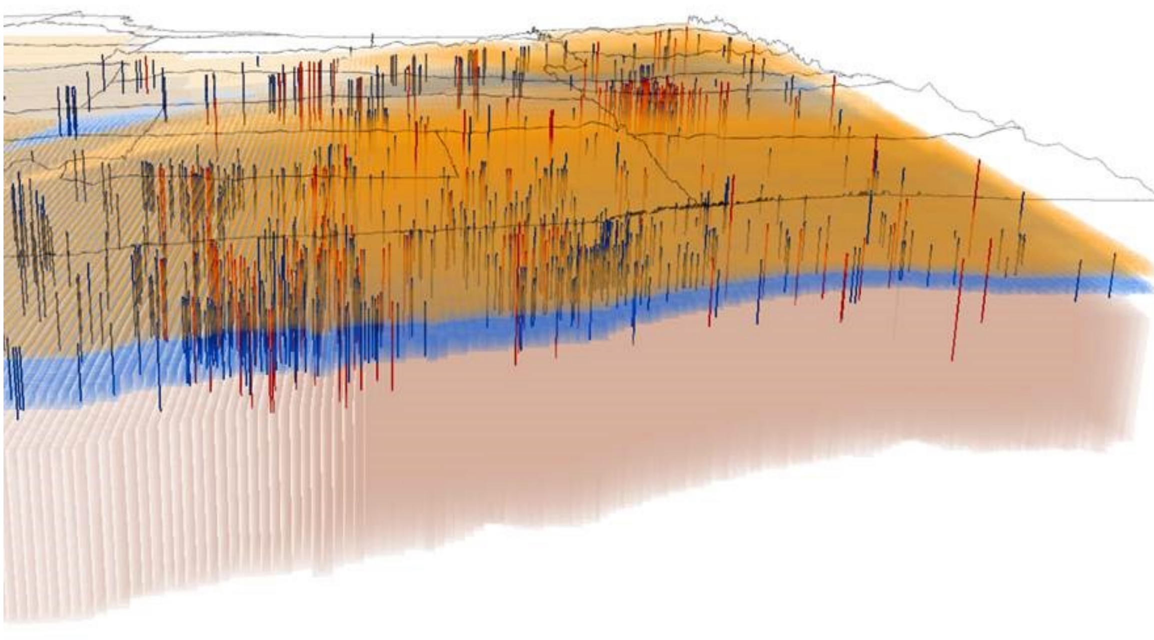
December 2018



ILLINOIS

Illinois State Water Survey

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Contents

Table of Figures

Table of Tables

Abstract

The Illinois State Water Survey (ISWS) has a long history of developing groundwater flow models to simulate water supply and groundwater contamination issues in the state of Illinois. However, past local- and regional-scale models developed by the ISWS have traditionally been project based; thus models are archived when the project is completed and may not be updated for many years. This report presents the first version of the Evolving Network of Illinois Groundwater Monitoring and Modeling Analyses (ENIGMMA), which is the framework of data, procedures, protocols, and scripts that facilitate the development of a single, continuously updated groundwater flow model and other outputs (hydrographs, maps, animations of groundwater potentiometric surfaces). This report focuses on five aspects of ENIGMMA:

1. The archived models and high-resolution datasets that serve as inputs to ENIGMMA
2. The procedures for developing model-ready datasets from these inputs
3. The Illinois Groundwater Flow Model (IGWFM), which serves as the single model that will be continuously updated by ENIGMMA
4. The ISWS Calibration Toolbox, used to facilitate a transient calibration of the IGWFM
5. Animations of groundwater potentiometric surfaces using head-specified models

This report is a living document that will be updated periodically. Future updates to this report will focus on additional aspects of ENIGMMA, including the automated development of model-ready inputs and display of model outputs. Updates to this report will also chronicle any additional geologic data added to ENIGMMA, and subsequently, to the Illinois Groundwater Flow Model. Updates will also highlight both local- and regional-scale advancements made with the model, including any key results from these models.

The current version of the IGWFM combines and expands on two existing groundwater flow models: 1) the Northeastern Illinois Cambrian-Ordovician Sandstone Aquifer model and 2) the East-Central Illinois Mahomet Aquifer model. In addition, the model incorporates new geologic information developed by the Illinois State Geological Survey in the Middle Illinois Water Supply Planning region. The current model domain covers large portions of Illinois, Wisconsin, Indiana, and Michigan. This large spatial extent is necessary to capture the far-reaching regional head declines in the deep Cambrian-Ordovician sandstone aquifer system, which can extend beyond state boundaries. Depicting some shallow, unconsolidated aquifers also requires a simultaneous simulation of the deep sandstone to account for flow exchange between units. This is because the low-permeable stratigraphic units (aquitards) overlying the sandstone aquifers are absent over large areas of northern Illinois or are locally punctured by wells with long, open intervals. To capture these complex flow pathways, the three-dimensional IGWFM explicitly simulates all geologic materials from the land surface to the impermeable Pre-Cambrian crystalline bedrock. The IGWFM does not currently include a groundwater flow simulation of the southern portion of the state where the deep basin sandstones are highly saline and not used for water supply. Incorporating the shallow aquifers in the southern portion of the state into the IGWFM is a long-term goal.

The primary datasets currently incorporated into IGWFM include surface water elevations, annual groundwater withdrawals, well information such as open intervals, geologic

surfaces, measured water levels, and aquifer properties inferred from previous modeling studies. These datasets are input at their best available spatial and temporal resolutions, allowing for the development of refined local-scale models. Such local-scale models are essential for simulating groundwater-surface water interactions, well interference, and contaminant transport. Major local-scale models already exist for the Mahomet Aquifer, Kane County, and McHenry County.

The IGWFM can address a number of water supply planning questions, particularly the impacts of historic, modern, and future high-capacity groundwater withdrawals on heads and groundwater discharging to surface waters. In addition, where detailed geologic information of the shallow aquifers is available, the IGWFM can also simulate the subsurface migration of point (e.g., volatile organic compounds) and nonpoint (e.g., chloride and nitrate) contaminants.

1 Introduction

1.1 Groundwater issues in Illinois

Illinois is considered a groundwater-rich state. Groundwater generally has a good water quality because the porous subsurface provides a filtering mechanism that removes many unwanted constituents. Groundwater also has a relatively long residence time that allows some contaminants to degrade naturally. However, in some portions of Illinois, diminished quality or quantity of groundwater are a concern, requiring additional investigations into the subsurface flow. There are a number of facets of groundwater levels and flow that the Illinois State Water Survey (ISWS) uses models to investigate, including 1) drawdown, 2) reductions in natural groundwater discharge, and 3) groundwater contamination.

Local and regional drawdown

Most large communities and industries that use groundwater rely on an aquifer that is capable of providing economically feasible withdrawals. Aquifer yield is variable in Illinois, but as a general rule, the shallow, unconsolidated sand and gravel aquifers are high yielding, but the deep sandstone aquifers have a significantly lower yield. This low aquifer yield is one of the main reasons that drawdown from the sandstone aquifers is more severe for a given pumping rate than is typically observed in sand and gravel.

Many of the first wells drilled into the deep sandstone aquifers of northern Illinois were flowing artesian; that is, water flowed above the land surface without the need for a pump. However, due to the low permeability of the sandstone, water withdrawals from the sandstone have led to large head declines. This decline is exacerbated by shale overlying the sandstone that severely limits the ability of precipitation to infiltrate into the sandstone to replace withdrawn water. Currently, heads in the sandstone have fallen by hundreds of feet throughout the northern part of the state, with the largest drawdowns of over 900 feet in northeastern Illinois. The uppermost sandstone within the Cambrian-Ordovician, the St. Peter, is partially desaturated at the current center of the cone of depression (Abrams et al., 2015). The deeper Ironton-Galesville Sandstone is also at risk of desaturation in the coming decades.

The deepest sandstone withdrawals in Illinois often have regional impacts that extend beyond counties and even state boundaries. As a result, an assessment of the long-term viability of these deep aquifers requires analysis on both a regional and local scale. The deep sandstone aquifers are also subject to a host of water quality issues, including elevated radium, barium, and chloride (Gilkeson et al., 1984; Balding, 1991; Kay, 1999), that can require expensive treatment to meet drinking water standards.

Many shallow aquifers can also experience impacts related to drawdown from pumping wells, particularly where covered by clay-rich glacial till aquitards that inhibit recharge. These impacts are generally more localized than in the sandstone, largely because of the higher permeability of sand and gravel, greater leakage from overlying units (even in the presence of aquitards), and the presence of natural hydrologic boundaries such as surface water features. Where aquitard materials do not overlie the shallow aquifers, recharge rates are generally higher and drawdown is less of an issue. Understanding the impacts of shallow withdrawals on nearby wells requires a model that captures the local geology and stressors of the aquifer.

Reductions in natural groundwater discharge

Large withdrawals from an aquifer can result in reductions in groundwater discharging to a hydrologically connected stream, lake, or wetland, either by capturing water that would have otherwise discharged at a natural water body or by inducing flow from that water body into the aquifer (Heath, 1983). Reductions in natural groundwater discharge reduce the amount of water discharging to a surface water or wetland at a relatively consistent temperature regulated by groundwater, potentially degrading the habitat of sensitive species (Zorn et al., 2008). This could create detrimental ecologic changes in non-urbanized watersheds, although the comparative impact on the highly urbanized watersheds in Illinois (particularly the northeastern region) requires further investigation. The watershed scale is appropriate for most studies of reductions in natural groundwater discharge, although certain areas may require a regional-scale analysis where linkages exist between the shallow aquifers and deeper sandstone. Future research into the impacts of groundwater withdrawals on low flows may also require finer time scales to capture variability in streamflow, which in turn may require direct coupling of transient groundwater flow models to surface water models.

Groundwater contamination

Although drawdown is often not as much of a concern in shallow aquifers without aquitards, solutes can easily enter the aquifer via recharge. This leads to an increased risk of contamination in shallow aquifer systems. For example, a continuously worsening contamination issue in suburban areas of Illinois that rely on shallow aquifers is the steadily increasing chloride concentration in groundwater, originating from road salt applications (Kelly, 2008; Kelly et al., 2015). Nitrate is another non-point source contaminant observed in agricultural settings throughout the Midwest due to fertilizer applications (Spalding and Exner, 1993). Volatile organic compounds are point source contaminants that originate from chemical leaks or spills, and are often associated with industrial activity (Wehrmann et al., 1988). The fate and transport of these contaminants will determine how far-reaching the contamination issue will become. Township-scale analyses are generally required to assess point-source contaminants, while non-point source analyses often require a regional watershed-scale analysis. These factors are critical when determining the necessary spatial domain and detail within that domain when developing a groundwater flow model to investigate contamination.

Domestic well issues

Domestic well issues generally fall outside of the regional-scale analyses considered in this report. One reason is the highly variable density of domestic wells, which can exceed 100 wells per square mile in some areas, for example, central Kane County (Campton Township). In contrast, the Illinois Groundwater Flow Model (IGWFM) is composed of 0.22 square mile cells, so simulation of such a densely clustered network of domestic wells is not feasible in the IGWFM if the desired result is to understand local well interference. Furthermore, withdrawals from domestic wells are generally considered insignificant compared with regional model results (Meyer et al., 2009), although some alternative methods (such as lowering recharge rates) can accommodate unsimulated, shallow domestic withdrawals in densely clustered areas.

Although the model developed in this report does not explicitly consider impacts to individual residential wells, it does assess the impact of dense clusters of residential wells on the regional simulation. In particular, the presence of long-open interval residential wells open to multiple geologic units changes the natural-flow pathways by short-circuiting aquitards, and is an important consideration in the current generation of groundwater flow models considered in this report.

1.2 Groundwater flow models at the Illinois State Water Survey

Applied modeling

As outlined in the previous section, groundwater issues facing Illinois occur on multiple scales, requiring analyses ranging from detailed local-scale studies to broader, regional investigations. Most issues involving high-capacity wells require a numerical analysis. To that end, scientists at the ISWS develop groundwater flow models that conceptualize the geology of the study area and use the fundamental laws governing groundwater flow to simulate water levels (heads) and flow. The ISWS has a long history of using groundwater flow models to understand the processes defining flow in an aquifer (recharge, aquifer properties, pumpage, boundary conditions). Furthermore, the models are deterministic, allowing for the assessment of changes in future pumping conditions to determine different water supply planning strategies, as shown in Abrams et al. (2015). A flow model coupled with reactive transport equations can also simulate the migration of contaminants through an aquifer, allowing for the simulation of different remediation approaches, as shown in Meyer et al. (2009).

Model development

In addition to applied groundwater flow modeling, the ISWS has been a leader in the innovative development of modeling approaches and technologies. Before the advent of computers, researchers at the ISWS took advantage of the similarity between the fundamental equations of groundwater flow and electrical current to develop electric analog models of groundwater flow (Prickett, 1967), as shown in Figure 1. A few years later, PLASM (Prickett and Lonnquist, 1971), developed by Tom Prickett and Carl Lonnquist, was one of the first numerical groundwater flow modeling codes, preceding MODFLOW by over a decade. The ISWS has since adopted the United States Geological Survey's finite-difference code MODFLOW (McDonald and Harbaugh, 1988), the current industry standard backed by a large user community that continues to advance the capabilities of the code. MODFLOW allows ISWS scientists to continue high-level, innovative research that is relevant to a large community of groundwater scientists.

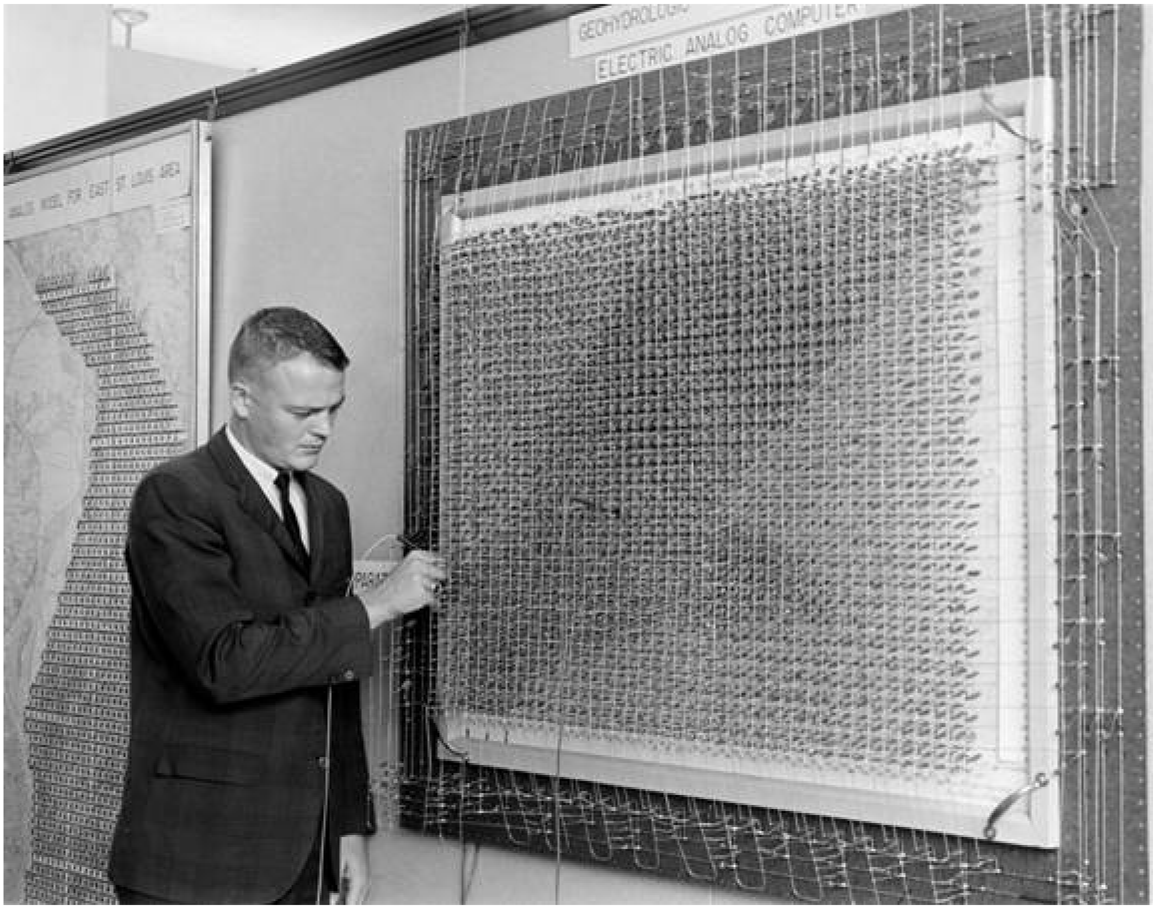

Figure 1: Tom Prickett operating a multi-layer electric analog model of the Mahomet Aquifer, circa 1964. A second, single-layer model of East St. Louis is in the background.

1.3 Contents of this report

The purpose of this report is to detail the current generation of groundwater flow model developed by the ISWS, as well as the data underlying these models. The primary model discussed is the IGWFM, which is a regional model constructed to assess the far-reaching impacts of withdrawals from the deep sandstone aquifers of northern Illinois. Since the model and the underlying data continually evolve, this report is a living document that will undergo periodic updates to reflect any changes and advances achieved through data collection and model development that increase our understanding of Illinois aquifers.

In this report we discuss the technical development and performance of the IGWFM. Chapter 2 introduces the Evolving Network of Illinois Groundwater Monitoring and Modeling Analyses (ENIGMMA), which currently houses all underlying data and archived groundwater flow models relevant to Illinois, and will in the future be expanded to automate the linkages of the models to certain datasets such as annually updated groundwater withdrawals. Chapter 3 outlines the conceptual model that defines the current understanding of groundwater flow and water demands in Illinois. Chapters 4–6 detail the preparation of model-ready data. Chapter 7 discusses the ISWS Calibration Toolbox, used to compare model results to observed data. Chapter 8 discusses the current status of the Illinois Groundwater Flow Model. Chapter 9 discusses the complementary head-specified models, which rely on collected head data from

ISWS observation networks. Chapter 10 discusses future development needs for the IGWFM and ENIGMMA.

This report provides a few key results from the IGWFM, but is not a means to communicate all model simulations conducted throughout the state. Specific model results will be included in reports pertaining to a particular region or on the ISWS website.

1.4 Acknowledgments

The sponsor of this report is the Prairie Research Institute, with additional support provided by the Illinois Department of Natural Resources Office of Water Resources. This report was greatly improved by the technical review provided by Steve Wilson of the ISWS and Rick Cobb, Bill Buscher, and Amy Zimmer of the Illinois Environmental Protection Agency. Lisa Sheppard provided editorial review of the content of this report. Conor Healy, ISWS Illinois Water Inventory Program coordinator, provided pumping data for Illinois. Greg Rogers helped design and improve the database used to store data pertinent to this study. Walt Kelly provided advice regarding the content of this report.

2 The Modeling Process

2.1 Complications with project-specific models

Historically, ISWS scientists developed groundwater flow models for specific projects, archiving the final version of the model along with a written analysis. A model update only occurred if a new project required its use, leading to two issues. First, an archived model will likely require many updates to address a current water supply or contamination concern, including modifications to the conceptual model, new reported withdrawals from the aquifer, and the incorporation of improved geologic surfaces. Second, the software and hardware used to create the original model are often obsolete. For example, the early ISWS digital models developed with PLASM are not easily compatible with the current numerical code of MODFLOW.

Another major issue regarding long-term model upkeep is that modelers must use imperfect sets of data when developing a geologic framework, pumping dataset, stream network, and other important components of a groundwater flow model. These datasets require some level of modification (filling in incomplete data, removing outliers, etc.) before they are ready for analysis. Although the report accompanying a model will typically list these modifications in general terms, replicating the precise and complete steps often takes considerable time and effort. Further complicating the matter, different modelers will potentially interpret an imperfect dataset in different ways, based on their own experiences and expertise. This is particularly problematic for raw datasets with frequent updates, such as pumping. To incorporate the new information in the raw dataset, the imperfections in the rest of the dataset must be resolved each time. Finally, the modification of a raw dataset is generally conducted only on a subset of the data, based on the time frame and local area being modeled.

2.2 ENIGMMA

The issues listed in the previous section highlight the need for two things: 1) analysis-ready datasets that are statewide and current, and 2) a system to incorporate these datasets into existing groundwater flow models. To overcome these challenges, we initiated and continue to develop the *Evolving Network of Illinois Groundwater Monitoring and Modeling Analyses (ENIGMMA)* for linking active groundwater flow models to the underlying data. ENIGMMA consists of three major components (see also Figure 2):

1. Data inputs used in model development;
2. The procedures and protocols for converting raw data into model-ready data; and
3. The models and analyses that are updated by ENIGMMA.

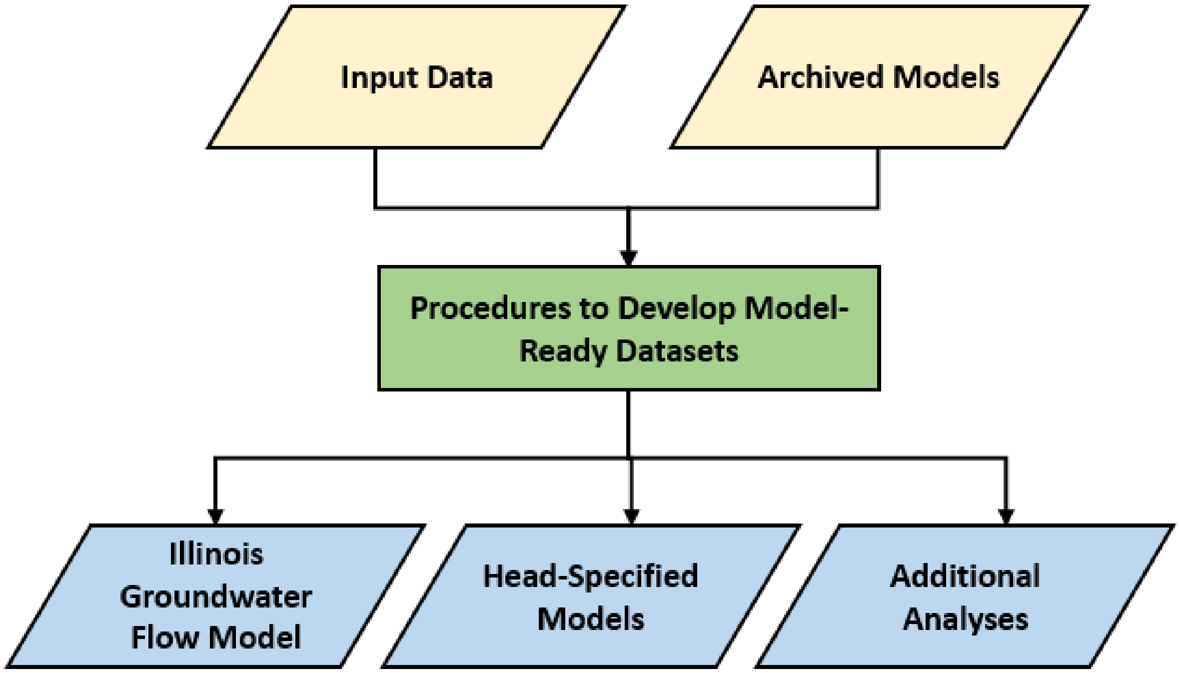

Figure 2: Diagram of ENIGMMA depicting the data used to create analysis-ready datasets

2.2.1 *Inputs used in model development*

The primary goal of the future development of ENIGMMA is to ensure that the IGWFM will be based on the most up-to-date datasets available. These datasets include geologic layers and features, surface waters, well withdrawals and open intervals, aquifer properties, and observed head values. These raw data are stored at their highest spatial and temporal resolution, in either a database, file geodatabase, or shapefile. Chapters 4–6 detail these data.

2.2.2 *Procedures and protocols*

ENIGMMA includes all of the procedures and protocols for creating model-ready datasets and adding these to the continuously updated groundwater flow model. These steps are discussed in more detail in Chapters 4–6. Furthermore, ENIGMMA defines methodologies for evaluating the calibration of a groundwater flow model, as discussed in Chapter 7.

Future versions of ENIGMMA will work toward automating the process of updating all models with current groundwater withdrawals and geology using the coding language Python. Currently, this work is in a very early state, with a completed script that develops model-ready datasets from withdrawals reported to the Illinois Water Inventory Program (IWIP) (Illinois State Water Survey, 2018). Automatically migrating this model-ready data into the existing groundwater flow models is the next priority.

Still, automation within ENIGMMA will not preclude a manual check of the data to investigate specific issues; not all data checks can be 100 percent automated. However, any manual change to the data will be stored within the ENIGMMA framework to ensure that it is fully captured. For example, consider a single well that pumps half the amount of water that it did in the previous or subsequent year. This may not be flagged as an outlier, since it is a realistic water supply scenario that would involve a temporary purchase of water from an outside source. In this hypothetical case, however, it is determined that the value is indeed erroneous after talking to the water operator. This might not be reflected in the raw data table, but an "interpreted" data table would be populated to remove this data point and replace it with the more realistic value.

2.2.3 Models updated by ENIGMMA

IGWFM

Groundwater flow models in Illinois traditionally simulate some anthropogenic impact on a groundwater flow system, be it aquifer withdrawals or migration of a contaminant plume. Water supply planners often rely on these models to investigate different best management practices or changing water demands. Such "scenario" models use groundwater withdrawal rates as a model input, allowing the transient simulation of historical, current, and future aquifer heads and flows. To improve confidence in model results, model parameters and conceptualizations are modified until the simulated heads match observed heads; this process is known as calibration.

The Illinois Groundwater Flow Model (IGWFM) that serves as the single regional model updated by ENIGMMA is a scenario model. The IGWFM covers the northern half of Illinois, southern Wisconsin, eastern Iowa, and northwestern Indiana (Figure 3). The regional area of this model is critical to studies of the Cambrian-Ordovician sandstone aquifer system, where the impacts of withdrawals are far-reaching. Iowa, Wisconsin, and Illinois all compete for water from the sandstone aquifers, necessitating the need for this regional-scale analysis. This model has evolved from previous ISWS studies of the sandstone in northeastern Illinois (Prickett and Lonnquist, 1971; Visocky, 1982; Burch, 1991; Meyer et al., 2009; Meyer et al., 2012; Meyer et al., 2013; Roadcap et al., 2013).

The IGWFM as currently developed is primarily used for regional-scale analyses of sandstone withdrawals. The IGWFM is a large regional model, meaning that it is not appropriate for most local-scale studies because of its 2500-foot grid. However, developing a stand-alone local-scale model may also miss important regional influences, particularly for shallow aquifers that are connected to deeper sandstones where pumping has far-reaching impacts. Hence, capturing both local details of unconsolidated geology and the regional influences of stressors on an aquifer is critical. To overcome this requirement, regional models are often used to pass boundary conditions to local-scale models, via either constant heads or fluxes placed along the edges of the local-scale models. Another alternative is to use the MODFLOW-USG nested grid option with the IGWFM to achieve this local grid refinement and investigate groundwater issues in the shallow aquifers. The two shallow aquifer systems considered in this report, the Middle Illinois region and the Mahomet Aquifer, are still simulated at the 2500-foot grid.

Chapter 8 provides the technical details and key results of the Illinois Groundwater Flow Model and highlights early efforts to migrate the Mahomet Aquifer model into the IGWFM.

Head-specified models

ISWS scientists have created potentiometric head contours for different aquifers of Illinois since the early 1900s. These contours typically result from a detailed study of measured water levels (henceforth referred to as *heads*) in a region over a relatively short period to capture a snapshot in time of aquifer conditions. The traditional approach to develop contours is by hand, which leads to varied and inconsistent interpretations of how to draw contours. Consequently, a comparison of heads in an aquifer through time can be difficult to interpret with hand-drawn contours. To counter this, Roadcap et al. (2011) generated contours for the Mahomet Aquifer with MODFLOW by assigning observed heads at dedicated monitoring wells as constant head cells. This approach provides a consistent methodology that strictly abides to the two fundamental groundwater laws, mass balance and Darcy's Law. Furthermore, by using MODFLOW, the potentiometric surface can account for either steady-state or transient conditions, which is not possible with traditional contouring methods. Abrams et al. (2015) followed this approach to make potentiometric surfaces for years when synoptic measurements of static heads in wells open to the sandstone aquifers were made.

In contrast to a scenario model, a head-specified model has limited predictive capabilities. However, the models are not subject to head calibration errors since observations are assigned as constant head cells; in other words, MODFLOW cannot deviate from the assigned head at an observation well. Constant heads also serve as a source and sink of groundwater in the model, allowing for simple mass balance calculations that can provide insight into sources of water in an aquifer. Furthermore, the simulated heads from a transient contouring model allow for animations of changing water levels through time that are not subject to calibration errors. Chapter 9 details the status and ongoing research related to these head-specified models.

2.2.4 A note on archived models within ENIGMMA

Many models exist that were not fully considered or incorporated during development of the IGWFM, largely because of time constraints or being located in areas not currently investigated for water supply planning. However, these models often provide valuable insight into the local area that may not be reflected in the base data; indeed, the base data used to make many of these models are not available. To ensure that the information in these models is not lost, we also store archived models within ENIGMMA (Figure 2), allowing future updates of either the input data or conceptual model assumptions used to develop the Illinois Groundwater Flow Model.

A number of regional models from other organizations provide valuable insight into interstate flow in the Cambrian-Ordovician sandstone aquifer system, often stretching beyond the boundaries of the IGWFM.

- The Great Lakes Basin Model (Feinstein et al., 2010) simulates regional flow over a larger area, using a coarser discretization than the IGWFM. ENIGMMA includes an archived version of this numerical model.
- Two other modeling reports on regional flow in the Cambrian-Ordovician sandstone aquifers, an Iowa study (Gannon et al., 2009) and a multistate study (Mandle and Kontis, 1992), are also available, although the models are not currently archived in ENIGMMA.

Although these models do not simulate many details pertinent to Illinois, they still provide valuable insight into the interstate flow of groundwater through the sandstone.

The remaining scenario models archived in ENIGMMA depict local shallow aquifers of Illinois (Figure 3).

- The Kane County (Meyer et al., 2009) and McHenry County (Meyer et al., 2013) models simulate the impacts of urban withdrawals in their respective counties. Subset models created from these county-scale models allow the investigation of local contamination plumes (the Marengo and Montgomery models) or groundwater-surface water interactions (the Crystal Lake model).
- Areas with older groundwater flow models developed by the ISWS and archived within ENIGMMA include Winnebago County (Wehrmann, 1984), Woodstock (unpublished), Shelbyville (Anliker and Roadcap, 1997), American Bottoms (Ritchey et al., 1984), Kankakee Watershed (Cravens et al., 1990), and Pekin (Varljen and Shafer, 1993).
- Scientists outside of the ISWS have also developed local-scale models, including for DeKalb County (Greer, 2017), Boone County (Mills et al., 2002), and the American Bottoms (Clark, 1997).

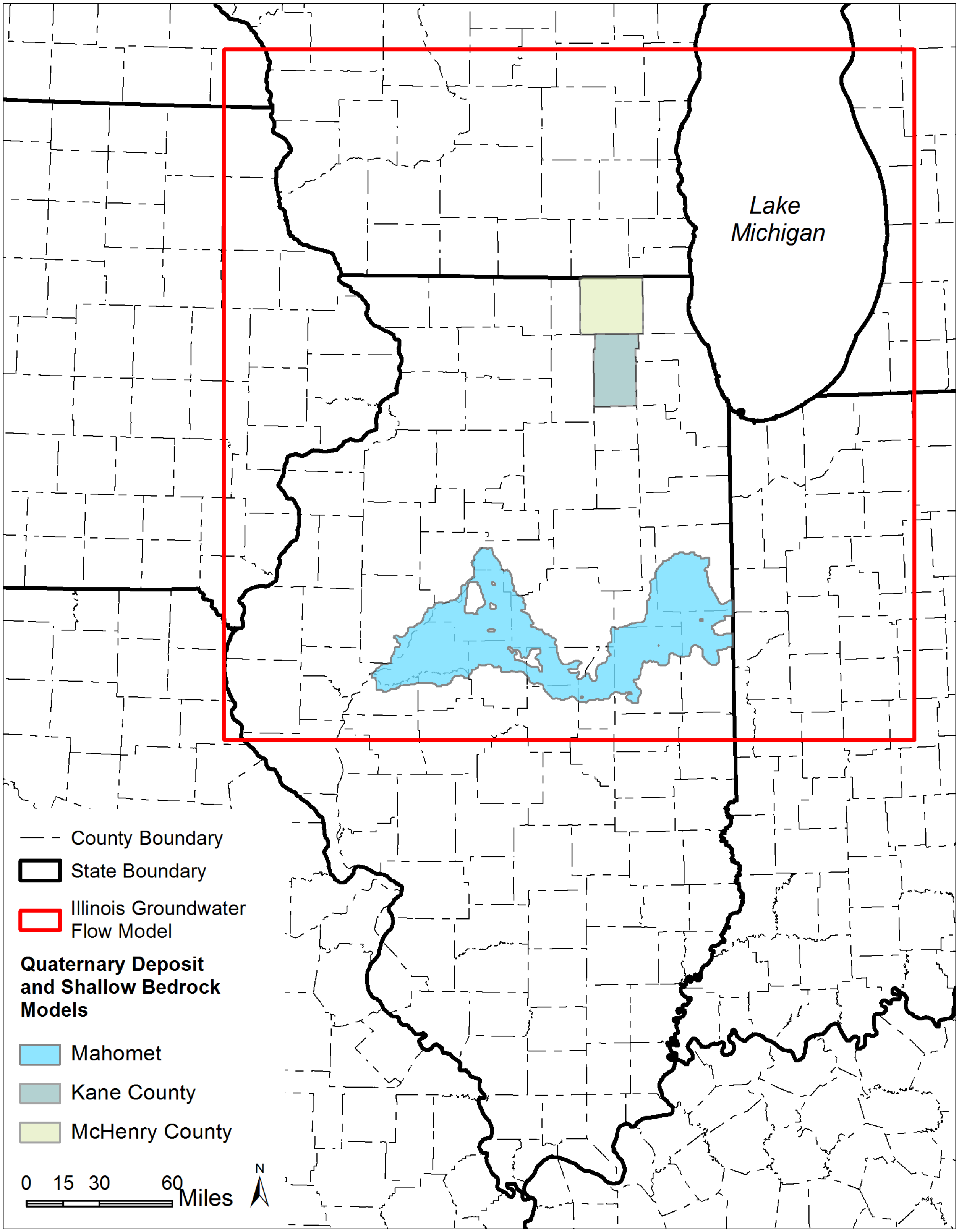

Figure 3: Spatial extent of the IGWFM and local-scale models developed by the ISWS since 2000

2.3 Long-term goals of ENIGMMA

ENIGMMA is currently still in an early stage and will be under continuous development. ENIGMMA is ultimately intended to provide periodic updates to the groundwater flow models using the most up-to-date model-ready datasets by incorporating the methodologies outlined in this report. This will ensure that all simulations use consistent, up-to-date data. All of these processes are time-consuming without automation. Hence, the immediate goal in developing ENIGMMA is to automate the creating and uploading of model-ready data into the groundwater flow models (particularly the Illinois Groundwater Flow Model). Since an update could have a detrimental effect on model calibration, a similar automation process will be required to assess the performance of each model within ENIGMMA before and after the update. An automated tool is already under development for withdrawal data (Chapter 6) and the comparison of calibration results (Chapter 7). We are developing these tools with FloPy (Bakker et al., 2016), a Python scripting package that facilitates updating MODFLOW packages and analysis of results without using a Graphical User Interface, which would entail additional manual steps.

3 Conceptualization of groundwater in Illinois

3.1 Major aquifer types

For most groundwater investigations, the most important hydrologic characteristic of a geologic material is permeability, which refers to the ability of a medium to transmit a liquid through its open spaces. Aquifers are layers or lenses of geologic material with a high permeability and sufficient porosity that can provide an economically feasible withdrawal of groundwater from a well. Illinois has three types of major aquifers (Figure 4): 1) coarse-grained unconsolidated (sand and gravel), 2) weathered carbonates, and 3) Cambrian-Ordovician sandstone.

Unconsolidated materials overlie the bedrock, primarily a result of Quaternary-aged glacial activities or modern river outwash. Coarse-grained unconsolidated aquifers generally composed of sand and gravel, with gravel-dominated aquifers having the highest permeability. Even sand and gravel aquifers mixed with fine-grained materials generally have a higher permeability than the other major aquifer types found in Illinois. However, these aquifers are often more susceptible to contamination, particularly if the sand and gravel is at or near the land surface. The most extensive sand and gravel aquifer in Illinois is the Mahomet Aquifer, located in east-central Illinois. Regional sand and gravel deposits are also present in portions of northern Illinois (the Green River lowlands, Kane and McHenry Counties, the Rock River Bedrock Valley). In the southern portion of the state, sand and gravel aquifers are much more localized.

The second major aquifer type found in Illinois is weathered carbonate (Figure 4). Lithified, carbonate rocks (limestone and dolomite) can serve as aquifer material in Illinois, particularly where they are within 25 to 125 feet of the bedrock surface (Willman et al., 1975). Carbonates are more susceptible to chemical weathering than the other lithologies (e.g., sandstone and shale). This weathering causes dissolution and removal of carbonates and consequent development of secondary porosity in the form of solution-enlarged fractures, cracks, and crevices. Secondary porosity can also form in carbonates that are deeper than 125 feet, but this is generally a local phenomenon based on weathering prior to the Quaternary glaciation and on karst development during the Paleozoic Era.

The third aquifer type, sandstone, is a sedimentary rock composed of sand-sized grains with significant primary intergranular porosity, at least in Illinois (Willman et al., 1975). Preferential flow in the sandstone can also occur along bedding planes; this is readily observable in sandstone outcrops (Figure 6), although the importance of bedding planes on groundwater flow is more speculative in the subsurface. The two major sandstone aquifers in Illinois, the St. Peter and Ironton-Galesville, are relatively old, Cambrian or Ordovician in age. Younger lithified material overlies these aquifers throughout most of Illinois, except in north-central Illinois where a bedrock valley has incised into the St. Peter, and in LaSalle County (Figure 5).

The conceptual model of the subsurface in Illinois consists of alternating layers of similar geologic materials, as shown for the bedrock in Figure 7, and shallow materials in the inset images. Each layer represents a hydrostratigraphic unit, defined as a sequence of geologic strata with a similar composition, allowing for a generalized lithology of coarse-grained, fine-grained, crystalline, shale, carbonate, or sandstone. Laterally continuous layers of fine-grained formations, such as shale or crystalline and unweathered carbonate materials, often act as aquitards by limiting aquifer recharge and groundwater movement between layers.

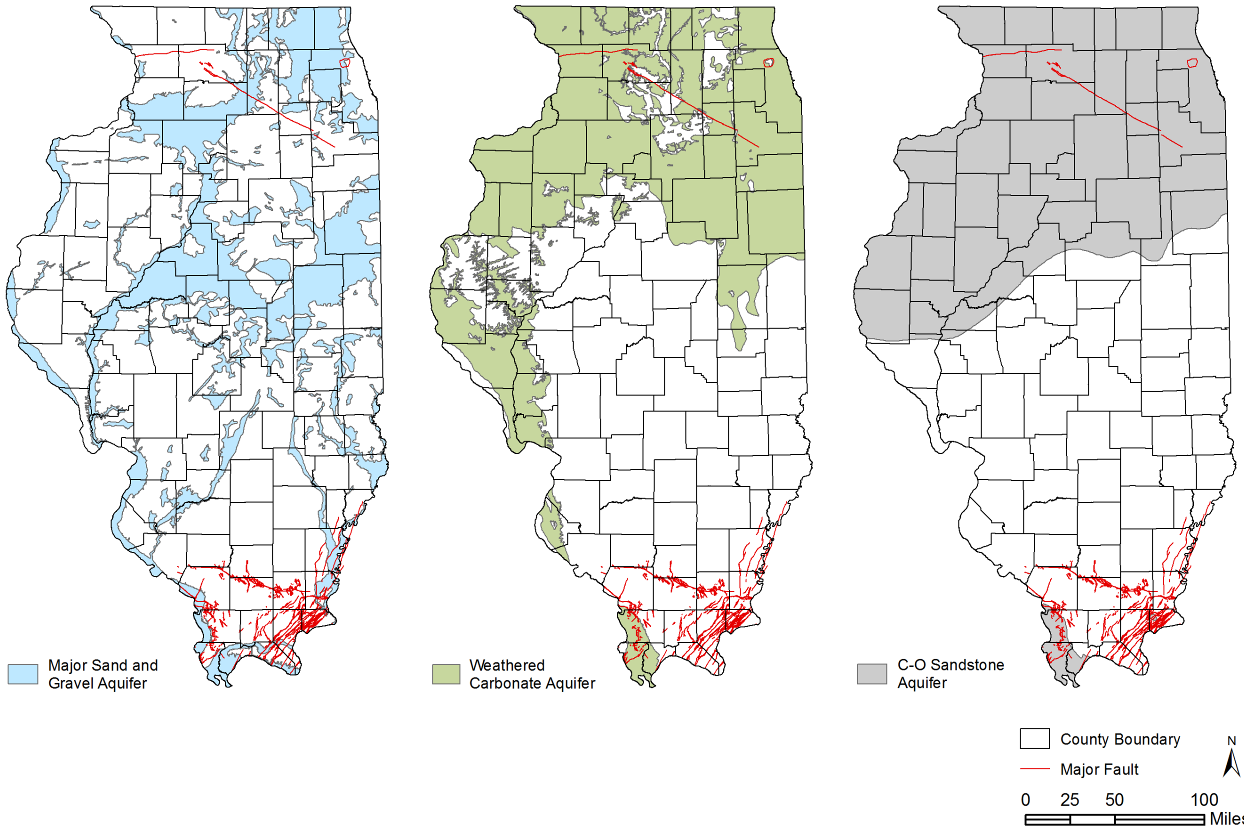

Figure 4: Depiction of the major aquifers in Illinois, including unconsolidated (sand and gravel) aquifers, weathered carbonate bedrock aquifers, and Cambrian-Ordovician (C-O) sandstone aquifers

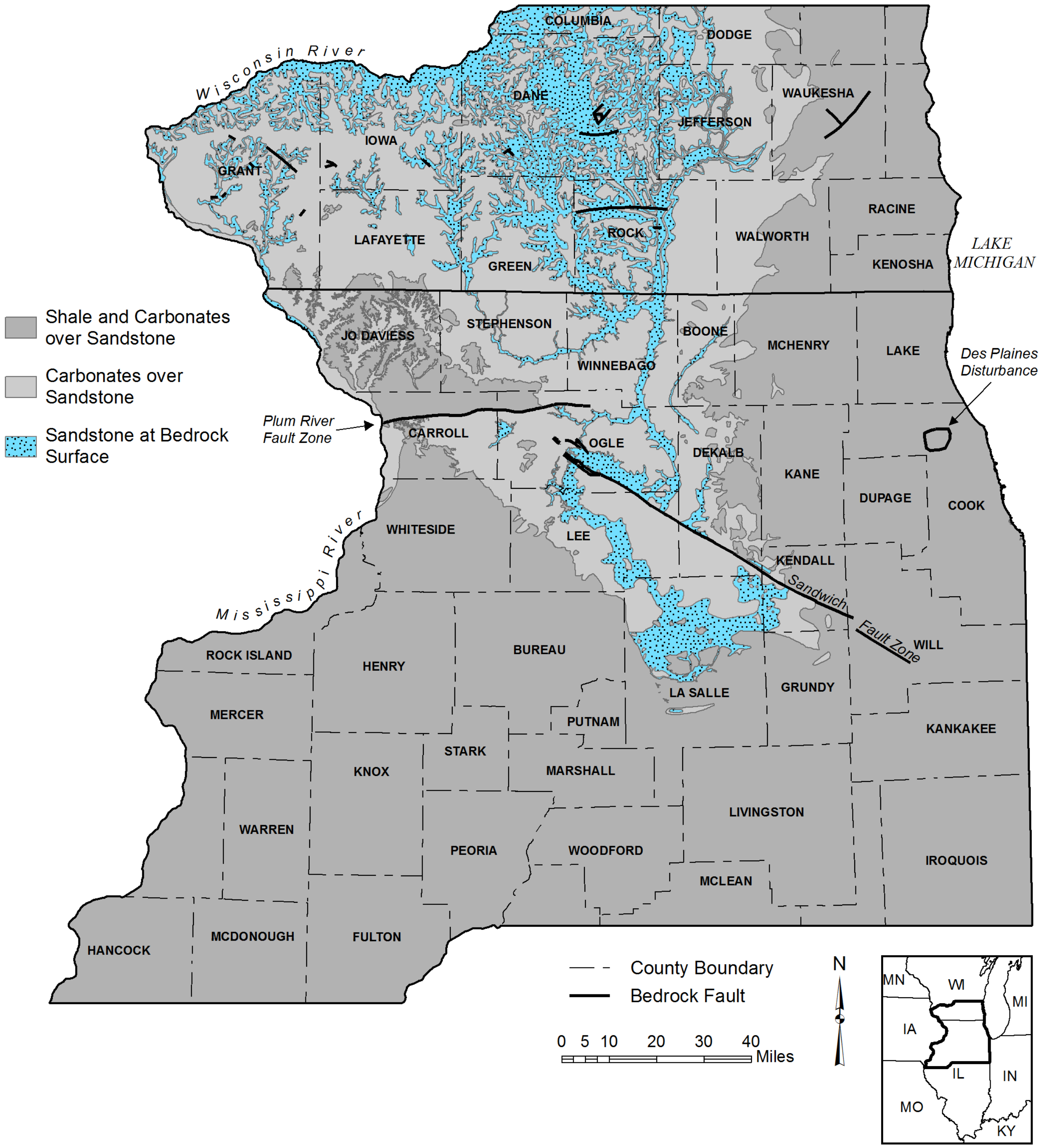

Figure 5: Lithology of bedrock materials overlying the Cambrian-Ordovician sandstone aquifers. Figure originally from Abrams et al. (2015).

Figure 6: Photograph of the bedding planes in the St. Peter Sandstone at Starved Rock State Park, IL. Image taken by Daniel R. Hadley on 4/26/2015.

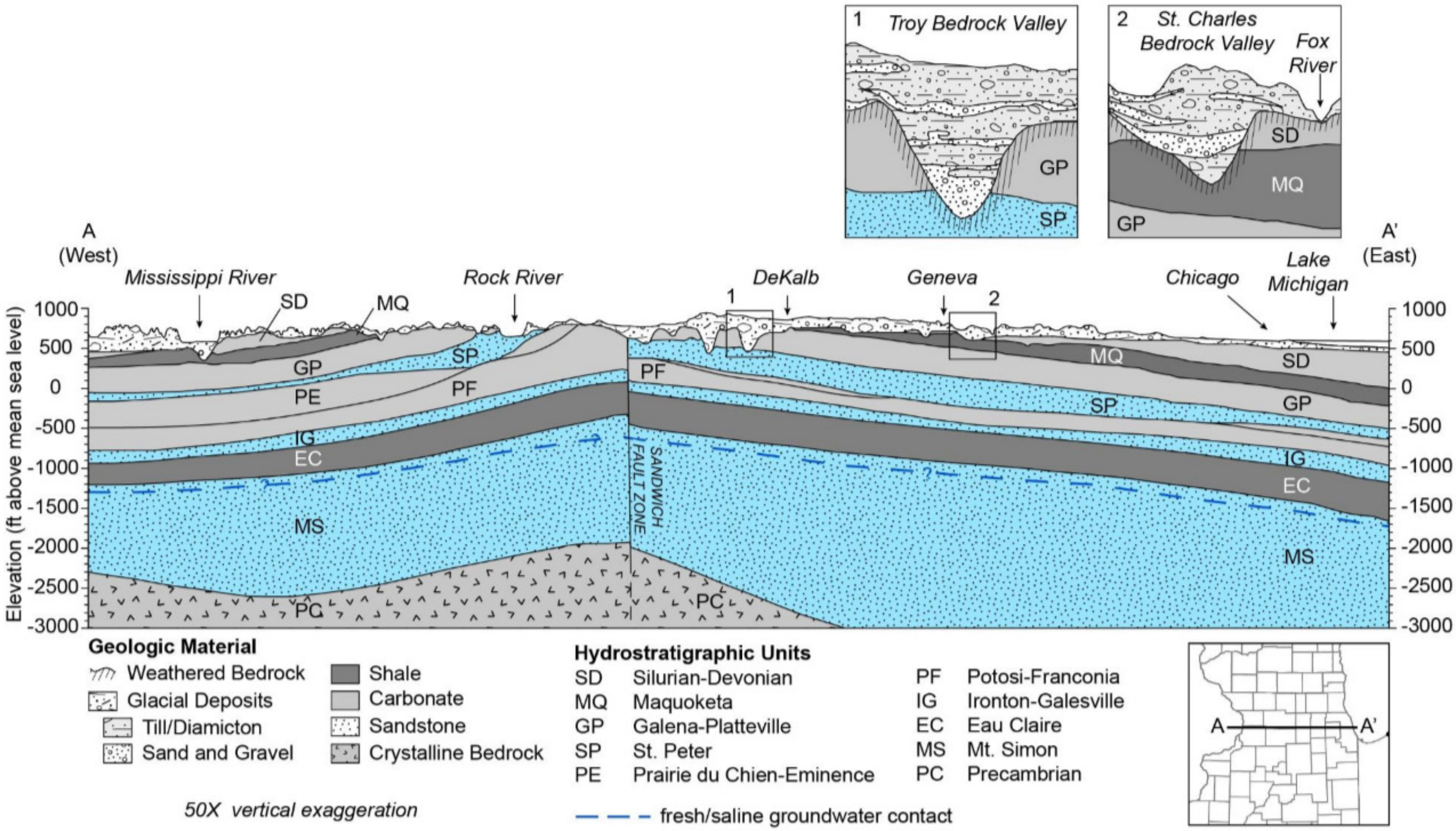

Figure 7: West-to-east cross section across northern Illinois showing the hydrostratigraphic units of the study area. The Troy Bedrock Valley and St. Charles Bedrock Valley incise the bedrock, decreasing the resistance to flow between glacial sands and deeper bedrock aquifers, thus forming potential hydrologic connections. The Troy Bedrock Valley inset modified from Vaiden et al. (2004) and the St. Charles Bedrock Valley inset modified from Dey et al. (2007b). Figure originally from Abrams et al. (2015).

3.2 Leaky aquitards

A major challenge in conceptualizing the role of aquitards is to understand how laterally continuous they are. Even where fine-grained aquitards mostly overly an aquifer, local coarse-grained materials may provide pathways for vertical flow exchange (Figure 8). The geologic origin of these natural pathways ranges from complex patterns of glacial advances and retreats (as discussed in Meyer et al. (2013) for McHenry County), ancient clastic volcanoes (as discussed in Roadcap et al. (2011) for the Mahomet Aquifer), or incisions of ancient rivers into bedrock (as discussed in Abrams et al. (2015) for northern Illinois). The latter is of particular importance where bedrock valleys incise through shale, thereby reducing the resistance to vertical flow between the shallow unconsolidated coarse-grained materials to deeper, permeable bedrock layers (see the insets in Figure 7).

Multi-aquifer wells can also bypass the natural resistance to flow that is normally associated with aquitards by providing a direct hydraulic connection between aquifers separated by aquitards. ISWS records indicate that many of the earliest wells penetrated multiple units, including shallow aquifers and the deeper Mt. Simon sandstone (Anderson, 1919), the latter of which is too saline for water supply purposes in Illinois except for along the Wisconsin border. Until recently, most deep wells were also open to both sandstone aquifers (Abrams et al., 2015), the St. Peter and Ironton-Galesville. These wells provide pathways for groundwater movement between aquifers that would not otherwise be present (Figure 9). Without the additional sources of water introduced by multi-aquifer wells, the sandstone aquifers would not have supported withdrawals for as long as they have. However, the sealing of multi-aquifer wells was prevalent in the past two decades as communities switched to Lake Michigan water, reducing the potential for groundwater movement between hydrostratigraphic units. Hence, the conceptual model of the sandstone in Illinois includes transient depictions of both withdrawals and multi-aquifer well connections. This report discusses new techniques to simulate and calibrate a changing multi-aquifer well network, with new research focused on further improving these techniques.

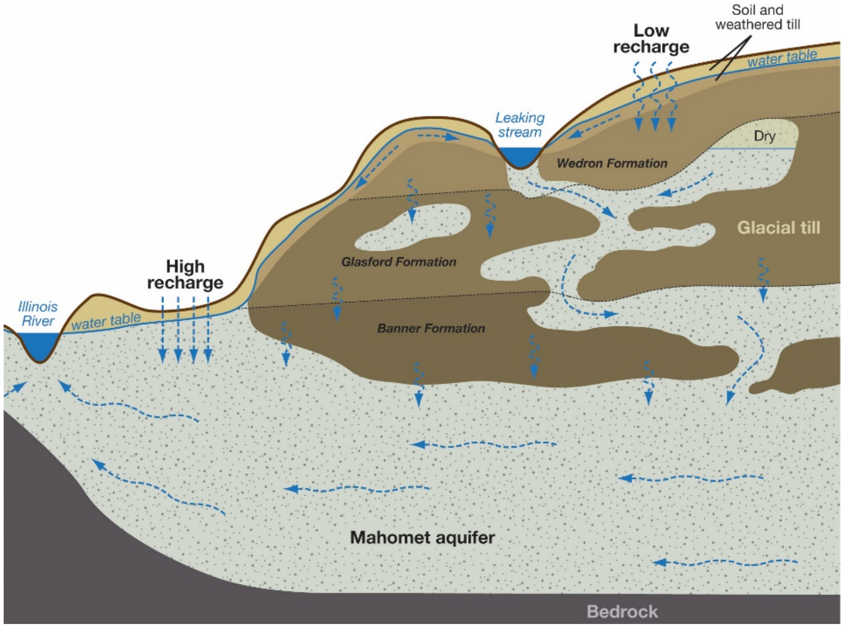

Figure 8: Conceptual model of recharge pathways and groundwater movement between aquifers in the Mahomet Aquifer. Figure originally from Roadcap et al. (2011).

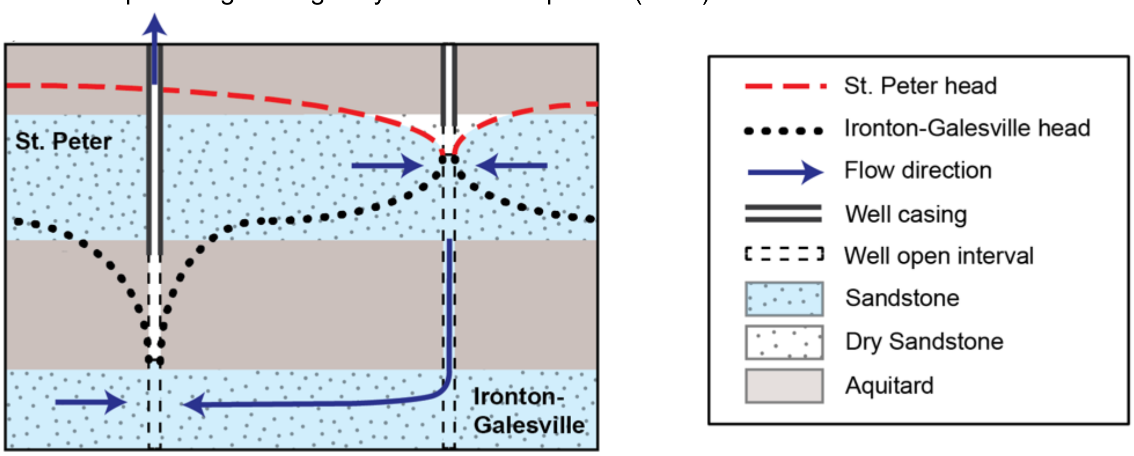

Figure 9: Groundwater movement induced by a multi-aquifer well connection between the St. Peter and Ironton-Galesville. Figure modified from Abrams et al. (2015).

3.3 Fault zones

Many fault zones in Illinois consist of a series of parallel faults defined by a series of up and down thrown blocks that offset hydrostratigraphic units and disrupt flow in a bedrock aquifer. This is particularly critical for the Sandwich Fault Zone (Kolata et al., 1978), which appears to disrupt flow within the sandstone aquifers near the current center of the cone of depression in Will and Kendall Counties. An analysis of well test records indicates that specific capacities within a 2.5-mile buffer of the delineated Sandwich Fault Zone are lower than the regional values (Figure 10), indicating a lower local permeability compared to regional values. However, these low specific capacities are not ubiquitous; other wells within the zone often do not have an exceedingly large drawdown. As a result, treatment of the Sandwich Fault Zone in a numerical model is contingent on the scale of the problem. For large regional groundwater flow models, we conceptualize the area within 2.5 miles of the delineated Sandwich Fault Zone as a slightly lower hydraulic conductivity than the regional value. Local-scale modeling will be a topic for future research.

Vertical fracturing within the Sandwich Fault Zone is also an uncertainty in the current conceptual model. Some degree of vertical flow moving between units is likely based on studies of other faults (Bense et al., 2013), but the magnitude of flow is unknown. Groundwater chemistry investigations within the Sandwich Fault Zone may improve this conceptualization by identifying the mixing (or lack thereof) of water of different sources. The current regional model does not have an enhanced vertical hydraulic conductivity within the Sandwich Fault Zone, but this assumption will be tested in future model simulations.

Four other major fault zones may influence groundwater flow in northern Illinois: 1) the LaSalle Anticlinal Belt, 2) the Plum River Fault Zone, 3) the Des Plaines Disturbance, and 4) a series of shelf structures in the western portion of the state (Figure 11). The LaSalle Anticlinal Belt may influence the impact of withdrawals from the city of Bloomington that are expected to begin in 2019. The Plum River Fault Zone, which extends from northwest Illinois into Iowa, may influence flow exchange in the sandstone aquifer between the two states. The Des Plaines Disturbance has historical significance as a complex flow regime that influenced well productivity in northern Cook County, although most communities have switched to Lake Michigan water in this area. The western shelf is a relatively flat-lying area with a series of shallow anticlines and synclines that have an unknown impact on regional groundwater flow (Nelson, 2010). All four areas are currently treated as undisturbed sandstone in the model, but the individual behavior of each faulted area will be subject to further research.

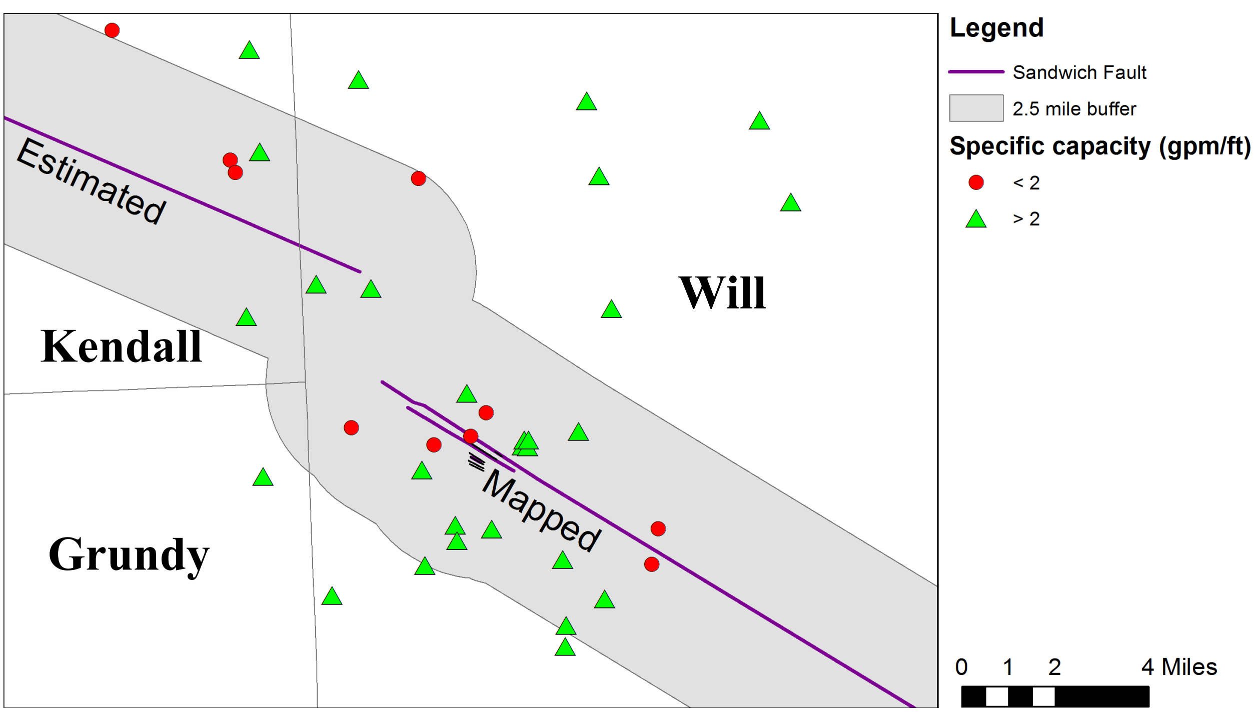

Figure 10: Specific capacities within the Sandwich Fault Zone near Joliet

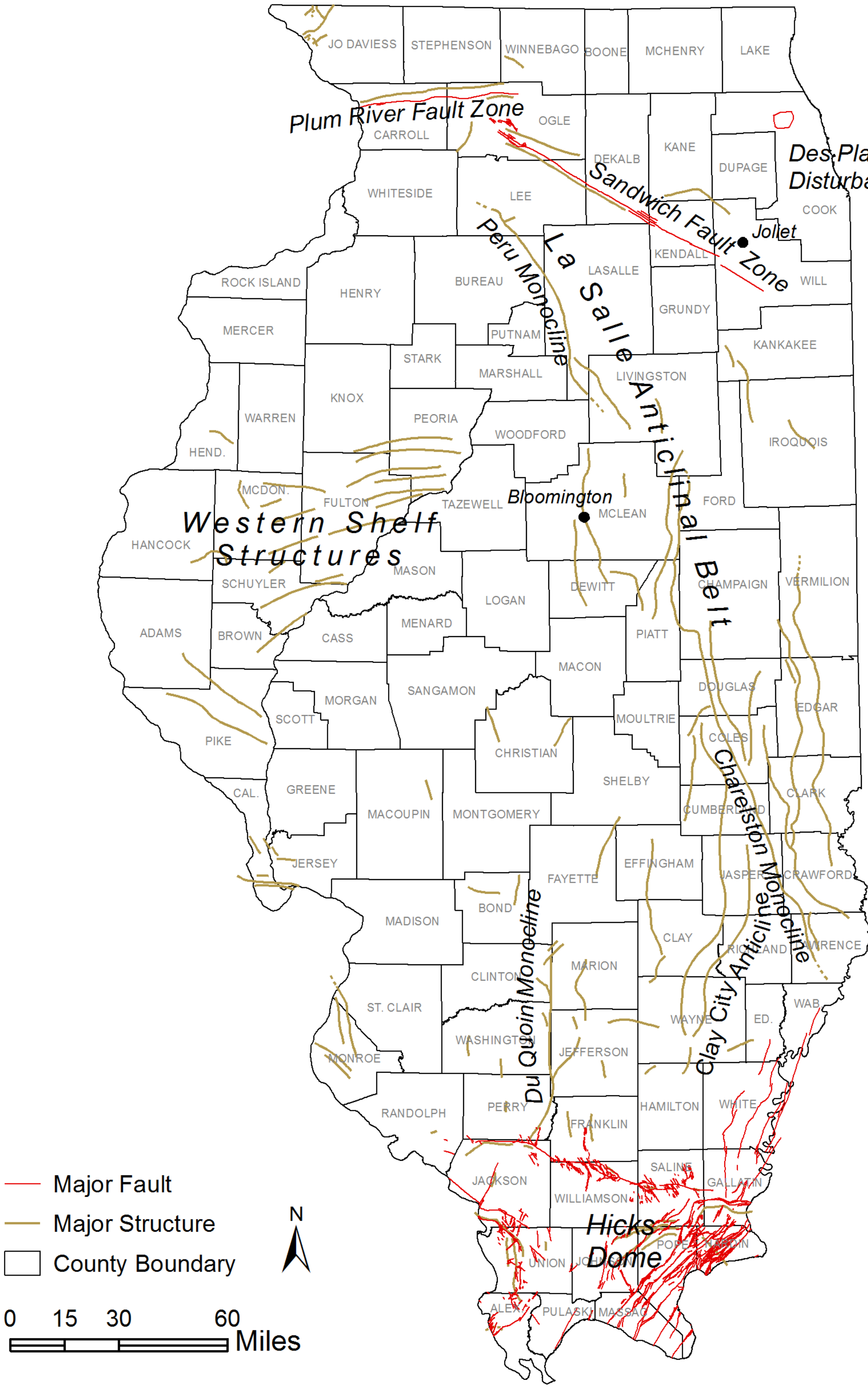

Figure 11: Location of faults, anticlinal belts, and other bedrock structures that may influence flow in the Cambrian-Ordovician sandstone aquifer system

3.4 Groundwater flow as a four-dimensional problem

The need for three-dimensional model simulations is evident: the natural state of aquitards has been disrupted such that local connections between shallow and deeper aquifers can have major impacts on the sources of water used to satisfy demands. However, it is also worth exploring whether the IGWFM must be transient to capture the impacts of changing withdrawals from the sandstone aquifers. Because the sandstone is overlain by confining materials (limiting vertical leakage) and has a relatively low transmissivity, we would expect it to be relatively responsive to changes in pumping. Haitjema (2006) developed a criterion to assess whether aquifers truly require a transient model or if a steady-state model might suffice. The metric used to determine this criterion is calculated by equation (1):

$$\tau = \frac{SL^2}{4kbP} \qquad (1)$$

Where τ is a characteristic dimensionless parameter, S is aquifer storativity (-), L is the distance between boundary conditions (ft), k is the hydraulic conductivity (ft/day), b is the saturated thickness (ft), and P is the length of time in which boundary (in this case, pumping) fluctuations are periodic (days). According to Haitjema (2006), if $\tau < 0.1$, then a transient model is not needed, but rather pumping could be depicted with a series of successive steady-state simulations. Before the sandstone aquifers in northeastern Illinois were dewatered, $S = 2.6 \times 10^{-7}$, L = 50 miles, k = 5 ft/day, b = 400 ft (combined thickness of St. Peter and Ironton-Galesville), and P = 365.25 days. Note that L is estimated as twice the distance from the center of the cone of depression to the nearest stream. The resulting $\tau = 0.006$, indicating that indeed a single model using the annually averaged pumpage for a single year might yield an accurate result for periods when the sandstone aquifers remained truly confined.

The validity of the steady-state simulation breaks down after the early 1940s, when the Galena-Platteville began to dewater. As a result, S of the Galena-Platteville is 0.0075, and the resulting $\tau = 178.9$ far exceeds the 0.1 threshold presented by Haitjema (2006). Practically, this large τ indicates that the aquifer responds rather slowly to changes in pumpage on the regional scale because of the dewatering of pore spaces in the limestone overlying the sandstone. Because the annually averaged pumping rate can change dramatically from year to year, the impact of pumping cannot be captured with a series of successive steady-state groundwater flow models. Dewatering of the St. Peter, where S = 0.075, only exacerbates this issue.

Hence, the IGWFM must capture not only the three-dimensionality of a system, but also the transient changes to properly simulate the potentiometric surface of the sandstone. The timing of desaturation is critical, as a newly desaturated unit introduces a new source of water. A delay in desaturation of a unit will ultimately propagate into modern or future simulations. As a result, to understand the flow dynamics of a system, the models of these units must simulate groundwater flow spatially and temporally. To ensure that a model performs over the entire history of withdrawals, a transient calibration is necessary. Although thousands of conceptualizations might be calibrated to a single set of heads from one specific point in time, there should be far fewer that will allow calibration to heads at multiple points through time.

3.5 Conceptual uncertainties

ISWS scientists have long recognized the basic components of the conceptual model of groundwater flow in Illinois as outlined above (Suter et al., 1959; Wehrmann et al., 1988; Burch, 1991; Visocky, 1997; Meyer et al., 2013). However, details of the conceptual model have often not been quantified, but the model can provide estimates that fit model results to the observed data, thereby increasing confidence in the conceptual model. Furthermore, the model solution is rarely unique, so a model can be used to test many different conceptual or parameter uncertainties, both on a regional and local scale, including:

- The value of aquifer parameters (hydraulic conductivity, recharge, storage, etc.) and how they are spatially and temporally distributed;
- Sources of water that satisfy demands;
- Groundwater flow rates through faulted zones, both horizontally and vertically;
- The rate and impact of groundwater flowing through a borehole open to both shallow and deeper aquifers;
- The lateral continuity of fine-grained, unconsolidated materials that serve as aquitards or aquicludes, both locally and regionally;
- Alternative conceptualizations of weathered carbonates (ranging from continuous isotropic to discrete conduit flow); and
- Factors controlling the migration of contaminants (porosity, dispersion, diffusion).

Conceptual uncertainty will always exist for a subsurface groundwater system. However, groundwater flow models can help elucidate the viability of different conceptual models by comparing the model results with observed data, a process known as calibration. Although the calibration process eliminates some conceptual models, multiple conceptualizations of a system may still lead to a reasonable calibration. However, using modeling to narrow down those possibilities will allow more focused and appropriate field investigations.

3.6 Conceptual model of shallow aquifers

The early development of the IGWFM that is reflected in this report primarily focused on conceptualization and simulation of the sandstone aquifers in Illinois and surrounding states. Future iterations of this report will expand this section to include more conceptual discussion of the sand and gravel and weathered carbonate aquifers as they are more intensively modeled.

4 Hydrogeologic units and properties

4.1 Hydrostratigraphic units

Groundwater researchers commonly combine an adjacent geologic strata with similar hydrologic characteristics into individual hydrostratigraphic units. The Illinois Groundwater Flow Model employs 24 hydrostratigraphic units (Table 1). Each unit is assigned a generalized lithology (coarse-grained, fine-grained, carbonate, sandstone, shale, or crystalline) based on the available geologic information and insights from previously calibrated groundwater flow models. The generalized lithology of each hydrostratigraphic unit reflects its regional effect on groundwater flow. However, local geology is usually more complicated and can be poorly understood; as a result, other lithologies are frequently present within a hydrostratigraphic unit and may affect groundwater flow on a local scale.

4.1.1 Bedrock hydrostratigraphic units

Twelve hydrostratigraphic units compose the bedrock of the IGWFM domain. The hydrostratigraphic units in northern Illinois dip gently northeastward and southwestward from the axis of a broad, northwest-to-southeast-trending structural arch known as the Kankakee Arch, which separates the Illinois Basin to the south from the Michigan Basin to the northeast. The west-to-east cross section shown in Figure 7 shows the axis of this feature to be located between DeKalb and the Rock River.

Most hydrostratigraphic units are located at the bedrock surface area somewhere within the IGWFM domain, allowing for weathering and dissolution that can enhance horizontal and vertical permeability. Where a hydrostratigraphic unit exists at the bedrock surface depends on a number of factors, including structural geology (the deformational history of the region and the resulting three-dimensional orientation of bedrock units) and erosion of the bedrock surface. In Illinois, the hydrostratigraphic units present at the bedrock surface include the Pennsylvanian-Mississippian, Silurian-Devonian, Maquoketa, Galena-Platteville, St. Peter, Prairie du Chien-Eminence, and Potosi-Franconia Units. In Wisconsin, the older hydrostratigraphic units, including the Ironton-Galesville, Eau Claire, Mt. Simon, and Precambrian Units, are also present at the bedrock surface.

Each hydrostratigraphic unit has a corresponding raster depicting top and bottom elevations. Appendix C of Meyer et al. (2009) details the source and methodology used to create surfaces at a 2500-foot grid for the original northeastern Illinois model and later at a 625-foot grid to accommodate the local-scale McHenry County model (Meyer et al., 2013). If a hydrostratigraphic unit was not present, the assigned bottom elevation is 1 foot lower than the bottom elevation of the overlying hydrostratigraphic unit. Model layers with a thickness of 1 foot or less are removed from the simulation, as discussed in Chapter 7.

The IGWFM incorporates all bedrock hydrostratigraphic units in Table 1. In the conceptual model, the upper 100 feet of the bedrock represents a weathered zone comprising many hydrostratigraphic units. Layer 10 of the IGWFM depicts this weathered zone. We adjusted the layer elevations of the remaining bedrock hydrostratigraphic units to ensure that they were below the bottom of layer 10 and had a 1 foot thickness if absent. Hence, all layers below Layer 10 represent unweathered bedrock material.

Table 1: Geologic composition of the hydrostratigraphic units present in the IGWFM domain, along with an associated generalized geology

AGE (SYSTEM OR SERIES)		**STRATIGRAPHY**		**HYDROSTRATIGRAPHIC UNIT**	**GENERALIZED GEOLOGY**
QUATERNARY	Wisconsin Episode	Wadsworth		Fine-grained	Silt, clay
		Haeger-Beverly		Coarse-grained	Sand, gravel
		Yorkville-Batestown		Coarse-grained	Sand, gravel
		Tiskilwa		Fine-grained	Silt, clay
		Ashmore		Coarse-grained	Sand, gravel
	Illinois Episode	Winnebago-Upper Glasford		Fine-grained	Silt, clay
		Upper Glasford Sand		Coarse-grained	Sand, gravel
		Lower Glasford		Fine-grained	Silt, clay
		Lower Glasford Sand		Coarse-grained	Sand, gravel
	Pre-Illinois Episode	Banner Formation		Coarse-grained	Sand, gravel
	Unspecified Episode	Unnamed coarse-grained		Unnamed coarse-grained	Sand, gravel
		Unnamed fine-grained		Unnamed fine-grained	Silt, clay
CRETACEOUS		*Stratigraphic units not detailed*		Pennsylvanian-Mississippian	Shale
PENNSYLVANIAN					
MISSISSIPPIAN					
UPPER DEVONIAN					
MIDDLE DEVONIAN		*Stratigraphic units not detailed*		Silurian-Devonian	Carbonate
LOWER DEVONIAN					
SILURIAN					
ORDOVICIAN		Maquoketa Group		Maquoketa	Shale
		Galena Group		Galena-Platteville	Carbonate
		Platteville Group			
		Ancell Group	Glenwood Formation	St. Peter	Sandstone
			St. Peter Sandstone		
		Prairie du Chien Group		Prairie du Chien-Eminence	Carbonate
CAMBRIAN		Jordan Formation			
		Eminence Formation			
		Potosi Dolomite		Potosi-Franconia	Carbonate
		Franconia Formation			
		Ironton Formation		Ironton-Galesville	Sandstone
		Galesville Formation			
		Eau Claire Formation	Proviso Member	Eau Claire	Shale and Carbonate
			Lombard Member		
			Elmhurst Member	Mt. Simon (Freshwater)	Sandstone
		Mt. Simon Formation-Freshwater			
		Mt. Simon Formation-Saline		Mt. Simon (Saline)	Sandstone
PRECAMBRIAN		*Stratigraphic units not detailed*		Precambrian	Crystalline

4.1.2 Quaternary hydrostratigraphic units

The hydrostratigraphy of the unconsolidated materials in the IGWFM domain are determined using three approaches, as outlined in the following sections: 1) a simple generalized Quaternary depiction using statewide datasets, 2) complex three-dimensional, local-scale models of the unconsolidated materials, and 3) an intermediate database analysis of well bore information.

4.1.2.1 Generalized Quaternary deposits

For much of the state, extensive mapping of the Quaternary deposits is not available. However, an approximation of the composition of the unconsolidated materials was necessary for the IGWFM. To populate the Quaternary deposits in this model, we developed a methodology that does not differentiate between the named Quaternary deposits, but rather lumps materials into two classifications: "unnamed coarse-grained" and "unnamed fine-grained." The sources of data used to approximate the Quaternary deposits in the unmapped areas are the Major Sand and Gravel Aquifer coverage of Illinois (Illinois Department of Natural Resources, 1996) and a statewide Geological Stack Map (Berg and Kempton, 1988). The major sand and gravel aquifer map (Figure 4) is a polygon shapefile that indicates where the predominant coarse-grained unconsolidated aquifers of the state are located, but does not provide information regarding the exact depth or thickness of these aquifers. The Stack Map is a polygon shapefile that provides information regarding the glacial composition of the upper 50 feet of the subsurface. Each polygon includes all named geologic units within the upper 50 feet of the land surface, which we generalized as either coarse- or fine-grained (Table 2). The Stack Map does not provide top and bottom elevations for each unit; rather, each unit has a flag indicating whether it is greater or less than 17 feet thick. The flag also indicates whether the unit is continuous over the extent of the polygon.

Figure 12 details the process of developing a 9-layer generalized depiction of the Quaternary geology for use in the IGWFM (hence this dataset is developed at a 2500-foot grid consistent with this regional model). The bottom elevation of the first layer is assigned as the interpolated surface of all stream elevations minus 10 feet. The resulting thickness of the first layer has two advantages. First, any till present in the upper layer likely falls within a weathered zone influenced by recharge and stream fluctuations; hence a higher vertical hydraulic conductivity can be assigned to the till in layer 1 than in the lower layers. Second, the water table is often a subdued replica of the topography; hence it normally falls above the interpolated surface between streams, minimizing dry areas that could slow the model simulation and reduce model stability. The resulting zonation matches the upper layer of the Stack Map, except in the presence of third-order or greater streams, in which case a zonation representing coarse-grained materials was assigned to the intersecting 2500-foot grid cell. This assumption was necessary to obtain numerical convergence but would not be appropriate for local-scale analyses and will be revisited in future versions of the IGWFM.

The next step is to divide layers 2 to 9 into equal thicknesses to depict the remaining unconsolidated materials above the bedrock surface. If the layers fall within the upper 50 feet of the land surface, we used the Stack Map to determine first if aquifer material is present, then if continuous aquitards are present that separate one or more aquifers. For areas where the Quaternary thickness ranges from 50 to 100 feet, layers less than 50 feet from the land surface are zoned based on the Stack Maps, and layers greater than 50 feet deep are zoned based on the major sand and gravel aquifer map. This ensures that a major sand and gravel aquifer will always be depicted in the model, just not necessarily at the correct depth. We modified this approach for areas where the Quaternary aquifer is greater than 100 feet deep. Layers less than 50 feet deep are still zoned based on the Stack Maps, and layers within 50 feet of the bedrock surface represent the major sand and gravel aquifer map. Intermediate layers represent fine-grained material. This procedure acknowledges that few aquifers in Illinois are entirely sand over a thickness of greater than 100 feet, thus preventing the over-representation of a single sand layer.

The approach used to develop the generalized Quaternary geology for the IGWFM captures the spatial distribution of all the known major coarse-grained aquifers in the state, as well as minor aquifers present in the upper 50 feet. However, the vertical distribution of these layers is likely not correct. This is less essential for a regional-scale analysis of the sandstone aquifers, but becomes critical for a local-scale study of the glacial deposits. Hence, more detailed geologic mapping and locally refined models are essential for investigations of local drawdown, groundwater-surface water interactions, and contaminant transport.

Table 2: Named geologic Quaternary units within the Stack Map

Named Quaternary material	**Generalized Unconsolidated Geology**
Cahokia Alluvium	Coarse
Peyton Colluvium	Fine
Richland Loess	Fine
Peoria and Roxana Loess	Fine
Parkland Sand	Coarse
Grayslake Peat	Fine
Equality Formation, Carmi Member	Fine
Equality Formation, Dolton Member	Coarse
Henry Formation	Coarse
Wedron Formation, silty and clayey diamictons	Fine
Wedron Formation, loamy and sandy diamictons	Fine
Sand and gravel within Wedron Formation:	Coarse
Winnebago Formation, mainly sandy diamictons	Fine
Sand and gravel within Winnebago Formation:	Coarse
Teneriffe Silt	Fine
Pearl Formation (includes Hagarstown Member)	Coarse
Glasford Formation, silty and clayey diamictons	Fine
Glasford Formation, loamy and sandy diamictons surface	Fine
Glasford Formation, sand and gravel	Coarse
Wolf Creek Formation (mainly diamictons)	Fine
Mounds gravel and related units	Coarse
Cretaceous sediments, silts, sands, etc.	Fine

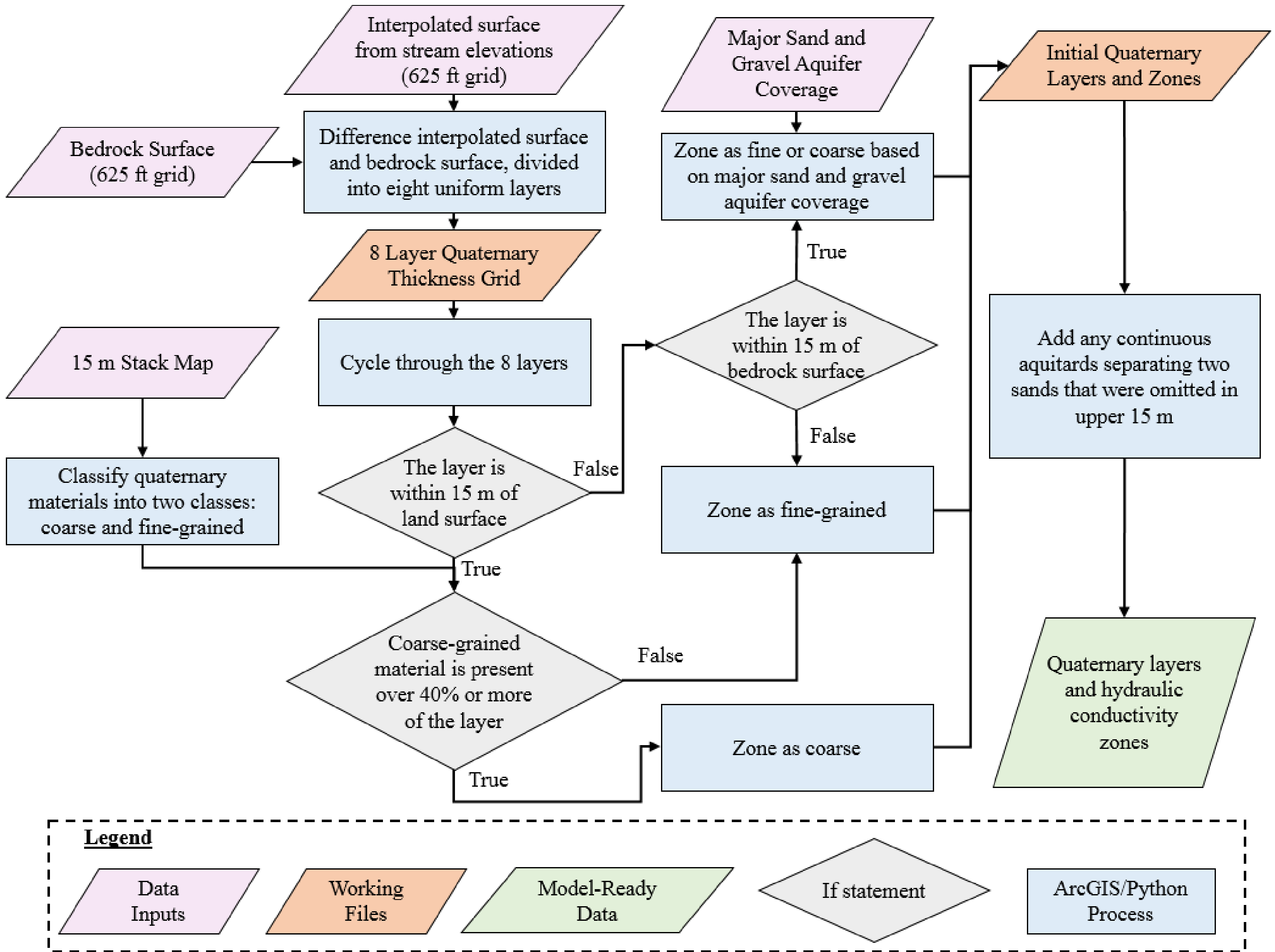

Figure 12: Procedural diagram depicting the development of the Quaternary geology for unmapped areas using Stack Maps and major sand and gravel aquifer coverages

4.1.2.2 Detailed Quaternary hydrostratigraphic units

Only a few areas of Illinois have had intensive geologic mapping of Quaternary-aged materials with the purpose of constructing groundwater flow models, most notably Kane County, McHenry County, and the Mahomet Aquifer. Hydrostratigraphic units in these areas represent the named Quaternary deposits (Table 1).

The glacial deposits of east-central Illinois comprise four major sands that form aquifers that are often (but not always) separated by fine-grained unconsolidated materials that serve as aquitards (Roadcap et al., 2011; Stumpf and Dey, 2012). The first, associated with the Mason Group, includes sand and gravel deposits that are typically at or near the land surface, mostly filling the valleys that contain major streams. The Mason Group is generally discontinuous, but can serve as an important local aquifer or as a pathway for water to penetrate into deeper aquifers. The second major sand unit is the upper Glasford, and the third is the lower Glasford-upper Banner. The aquifers associated with the Glasford are relatively thin and discontinuous with a variable thickness. Finally, the Banner Formation, which includes the Sankoty and Mahomet Formations, has the thickest sand deposits. The Glasford and Banner Formations in east-central Illinois are collectively referred to by their more common name: the Mahomet Aquifer System. Top elevation maps of each hydrostratigraphic unit are at a resolution of 1320 feet.

The hydrostratigraphic units defined in Kane and McHenry Counties are different from those defined in east-central Illinois (Dey et al., 2007a; Dey et al., 2007b; Dey et al., 2007c; Meyer et al., 2009; Meyer et al., 2013; Thomason and Keefer, 2013). The Banner Formation is not present in this portion of the state. However, the Upper and Lower Glasford Units are present, with the Lower Glasford in particular exceeding 100 feet of thickness in the bedrock valleys of this area. The Ashmore Tongue of the Mason Group is also an important sand and gravel aquifer. Finally, the Haeger-Beverly contains important surficial sands that are commonly used as aquifers where saturated, and is a particularly important aquifer in valley-filled deposits. Top elevation maps of each hydrostratigraphic unit are at a resolution of 625 feet in McHenry County and 660 feet in Kane County.

Detailed mapping of the Mahomet model is integrated into the IGWFM, overriding the generalized Quaternary geology discussed in the previous section. Future iterations of the IGWFM will also incorporate the detailed Quaternary geology developed for Kane and McHenry Counties.

4.1.2.3 Quaternary geology determined from a database analysis

One long-term goal of the model is to assess groundwater flow conditions throughout the state, including in the unconsolidated deposits, at both regional and local scales. However, the generalized Quaternary geology often lacks sufficient detail to understand the local complexities of a system. Complicating this, funding is often not available for detailed geologic mapping, particularly outside of northeastern Illinois or east-central Illinois (Mahomet Aquifer). As an alternative method, the Illinois State Geological Survey (ISGS) recently developed a simplified database approach that assesses all well logs in a region and, accessing a library of common terms, converts that information into a binary classification of fine- or coarse-grained materials.

The resulting interpolation, which is conducted for each of the nine equal thickness layers, yields a relative thickness of coarse-grained materials in an aquifer. For modeling purposes, this is further simplified into three categories: > 50% coarse, 25–50% coarse, and < 25% coarse (predominantly till).

This approach was applied to the unconsolidated deposits of the Middle Illinois Water Supply Planning region, and the Quaternary geology in the IGWFM of this region is depicted using this approach. An analysis of the performance of this database method to depict Quaternary geology is ongoing, but initial assessments of regional model calibration appeared reasonable. Preliminary results from the Middle Illinois Water Supply Planning region are presented in Chapter 8. The ISGS continues to expand and refine the approach with the ultimate goal of generating a statewide depiction of the unconsolidated materials of Illinois.

4.2 IGWFM hydraulic conductivity zonations

Table 3 depicts all zones used to represent hydraulic conductivity in the IGWFM. Zone groups represent different hydrogeologic and anthropogenic features:

- Zones 1–9 are working zones for purposes of experimentation during model development.
- Zones 10–59 depict the basic geology of each bedrock hydrostratigraphic unit, which generally includes at least two zones defining a generalized weathered and unweathered hydraulic conductivity.
- Zones 60–79 depict hydraulic conductivity zonations for simulating multi-aquifer wells.
- Zones 80–99 are reserved for future zonation of faulted zones in sandstones, shales, and carbonates.
- Zones 100–119 depict hydraulic conductivity zonations for the Mahomet Aquifer, following Roadcap et al. (2011).
- Zones 120–139 depict hydraulic conductivity zonations for Kane and McHenry Counties, which will be incorporated into future iterations of the IGWFM.
- Zones 140–149 depict hydraulic conductivity zonations for the generalized geologic conceptualization of the unconsolidated materials in Illinois.

The hydraulic conductivity values assigned to the zones shown in Table 4 are a result of the model calibration process, either during the current IGWFM work or previous modeling exercises. The ISWS also has an aquifer property database with values determined from various aquifer tests conducted over the history of the ISWS. These ranges establish realistic limits for values assigned to the groundwater flow model. Property values assigned to the groundwater flow model that fall outside the realistic range in the aquifer property database require closer investigation of the numerical simulation and the underlying conceptual model.

Examples of the spatial distributions of these zones are shown in Figure 13 for unconsolidated materials at the land surface (soil zone), Figure 14 for unconsolidated materials directly above the bedrock surface, and Figure 15 for the bedrock surface itself.

Table 3: Property zones in the IGWFM that correspond to the base hydrogeologic framework and anthropogenic influences on that framework

Layer		Hydrostratigraphic units	Zone	Description
Generalized	1-9	Unconsolidated	140	Sand (>50 %)
			141	Sand (25-50%)
			145	Soil developed on till (layer 1 only)
			146	Till
Mahomet	1	Soil Zone	101	Surficial Mahomet sand
			111	Soil developed on Wisconsinan till
			112	Soil developed on Illinois till
			116	Sandy soils on Glasford sands
	2	Wedron till/Surficial Glasford till	103	Wedron till
			108	Surficial Glasford till
	3	Upper Glasford sand	106	Upper Glasford sand
			107	Local till
			109	Local till
	4	Glasford till	102	Glasford till
			115	Dirty sands within the Glasford
	5	Lower Glasford sand	105	Lower Glasford sand
			114	Local till
	6	Banner till	104	Banner till
	7	Mahomet sand	101	Mahomet sand
			110	Dirty sands within the Mahomet
			113	Coarse sand within the Mahomet
10		Weathered bedrock units	11	Weathered Mt. Simon
			16	Weathered Eau Claire
			21	Weathered Ironton-Galesville
			26	Weathered Potosi-Franconia
			31	Weathered Prairie du Chien-Eminence

		36	Weathered St. Peter
		41	Weathered Galena-Platteville
		42	Weathered Galena-Platteville (Driftless)
		46	Weathered Maquoketa
		47	Weathered Maquoketa (Driftless)
		51	Weathered Silurian-Devonian
		52	Weathered Silurian-Devonian (Driftless)
		53	Silurian-Devonian (At bedrock surface but covered by shale prior to glaciation; minimal weathering)
		56	Weathered Pennsylvanian-Mississippian
		72	Discrete, modern long-open interval wells
11	Pennsylvanian-Mississippian	55	Unweathered Pennsylvanian-Mississippian
12	Silurian-Devonian	50	Unweathered Silurian-Devonian
13	Maquoketa	45	Unweathered Maquoketa
		48	Unweathered Maquoketa heavily influenced by dense clusters of long-open interval wells
		71	Discrete, historic long-open interval wells
		72	Discrete, modern long-open interval wells
14	Galena-Platteville	40	Unweathered Galena-Platteville
		43	Unweathered Galena-Platteville heavily influenced by dense clusters of long-open interval wells
		65	Discrete, historic long-open interval wells
		66	Discrete, modern long-open interval wells
15	St. Peter	35	Unweathered St. Peter

		90	Sandwich Fault Zone
16	Prairie du Chien-Eminence	30	Unweathered Prairie du Chien-Eminence
		60	Discrete long-open interval wells connecting the St. Peter to Ironton-Galesville
17	Potosi-Franconia	25	Unweathered Potosi Franconia
		27	Unweathered Potosi Franconia heavily influenced by dense clusters of long-open interval wells
		61	Discrete long-open interval wells connecting the St. Peter to Ironton-Galesville
18	Ironton-Galesville	20	Unweathered Ironton-Galesville
		90	Sandwich Fault Zone
19	Eau Claire	15	Unweathered Eau Claire
		62	Discrete long-open interval wells connecting the Ironton-Galesville to Mt. Simon
20	Mt. Simon (Freshwater)	10	Unweathered Mt. Simon (Freshwater)
21	Mt. Simon (Saline)	13	Mt. Simon (Saline), northern Illinois/Wisconsin
		14	Mt. Simon (Saline), deep basin

Table 4: Property values assigned to zones in the current model and changes from the previous iteration

Hydrostratigraphic Unit	Zone	K_x (ft/d)	K_z (ft/d)	Change from previous version
Mt. Simon	10	5.00	0.1	Zone 45, k_x increased from 4.2 and k_z increased from 0.028
	11	8.00	0.1	Not in previous version
	13	1.0	0.00283	Not in previous version, saline Mt. Simon (northern Illinois/Wisconsin)
	14	0.1	0.00283	Not in previous version, saline Mt. Simon (Deep basin)
Eau Claire	15	0.00684	0.00000684	Zone 42, unchanged
	16	0.00684	0.00684	Not in previous version
	-	0.72	0.014	Zone 47, removed in the new model
Ironton-Galesville	20	5.00	0.1	Zone 40, k_x increased from 4.0 and k_z lowered from 0.11
	21	5.00	0.1	Zone 40, k_x increased from 4.0 and k_z lowered from 0.11
Potosi-Franconia	25	0.00684	0.00000684	Zone 42, unchanged
	26	2.00	0.1	Not in previous version
	27	0.3	5.50E-03	Not in previous version, new zone used beneath Zone 26
Prairie du Chien-Eminence	30	0.00684	0.00000684	Zone 28, k_x lowered from 0.79 and k_z lowered from 0.00053
	31	2.00	0.1	Not in previous version, new zone used where Prairie du Chien-Eminence is at bedrock surface (weathered)
St. Peter	35	5.00	0.6	Zone 29, k_x lowered from 6.2 and k_z lowered from 0.6
	36	5.00	0.6	Zone 29, k_x lowered from 6.2 and k_z lowered from 0.6
Galena-Platteville	40	0.05	0.000275	Zone 26, k_z increased from 0.000055
	41	0.3	0.0055	Zone 23, k_z increased by an order of magnitude
	42	0.3	0.3	Not in previous version
	43	0.05	0.001	Not in previous version
Maquoketa	45	0.0004	0.0000014	Zone 16, k_z lowered from 0.000014
	46	0.006	0.000275	Zone 15, k_x rounded up to 0.006, k_z lowered from 0.00055
	47	0.006	0.006	Not in previous version
	48	0.006	0.000275	Not in previous version
Silurian-Devonian	50	4.00	0.1	Not in previous version
	51	20.00	2.00	Zone 14, unchanged
	52	20.00	20.00	Not in previous version
	53	4.00	0.1	Not in previous version

Pennsylvanian-Mississippian	55	0.00015	0.0000022	Zone 11, unchanged
	56	0.00015	0.0000022	Zone 11, unchanged
Long-open interval wells	60	0.00684	0.22	Zone 3, k_z lowered from 10 (used from 1900 to 2015)
	61	0.00684	0.22	Zone 3, k_z lowered from 10 (used from 1900 to 2015)
	62	0.00684	0.22	Zone 3, k_z lowered from 10 (used from 1900 to 2015)
	65	0.05	0.003	Not in previous version (used from 1900 to 1963)
	66	0.05	0.0015	Not in previous version (used from 1964 to 2015)
	70	0.0004	0.0015	Not in previous version (used from 1900 to 1963)
	71	0.006	0.003	Not in previous version (used from 1900 to 1963)
	72	0.006	0.003	Not in previous version (used from 1964 to 2015)
Fault Zones	90	2.50	0.1	Zone 4, k_x increased from 0.0004, zone much wider
Mahomet Aquifer	101	275	35	Zone 1, unchanged
	102	0.00036	0.0001	Zone 2, unchanged
	103	0.00036	0.0001	Zone 3, unchanged
	104	0.00036	0.00004	Zone 4, unchanged
	105	150	35	Zone 5, unchanged
	106	150	20	Zone 6, unchanged
	107	1	1	Zone 7, unchanged
	108	0.0008	0.0008	Zone 8, unchanged
	109	0.01	0.01	Zone 9, unchanged
	110	10	1	Zone 10, unchanged
	111	0.01	0.0006	Zone 11, unchanged
	112	0.005	0.0008	Zone 12, unchanged
	113	430	35	Zone 13, unchanged
	114	0.01	0.001	Zone 14, unchanged
	115	0.1	0.1	Zone 15, unchanged
	116	0.05	0.05	Zone 16, unchanged
Generalized Unconsolidated	140	150	150	Not in previous version
	141	50	10	Not in previous version
	145	0.1	0.001	Not in previous version
	146	0.00036	0.0001	Not in previous version

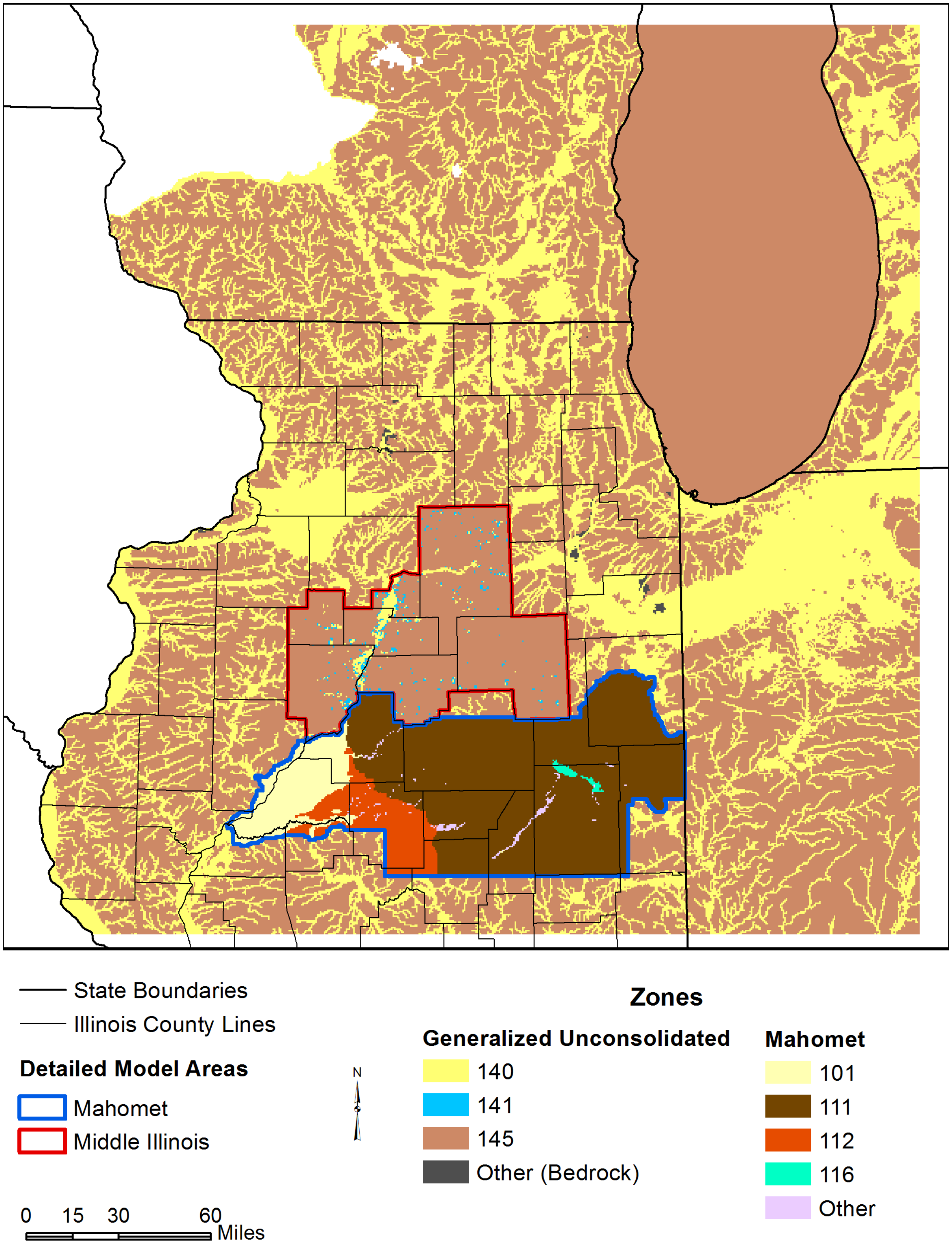

Figure 13: Material at land surface in the IGWFM, as categorized by hydraulic conductivity zones. Yellow and blue colors represent sands, while browns and oranges represent tills.

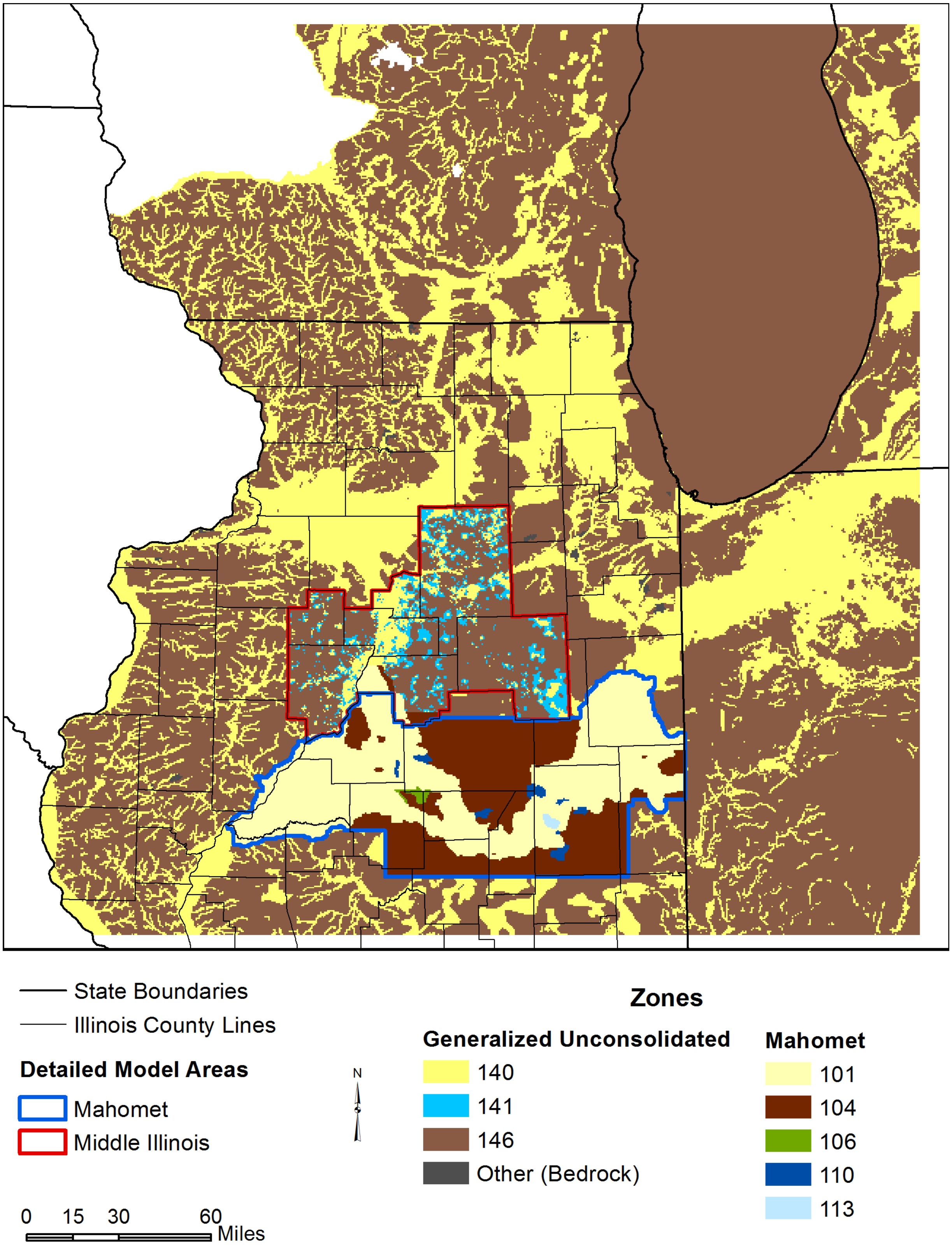

Figure 14: Material above the bedrock surface in the IGWFM, as categorized by hydraulic conductivity zones. Yellow and blue colors represent sands, while browns and oranges represent tills.

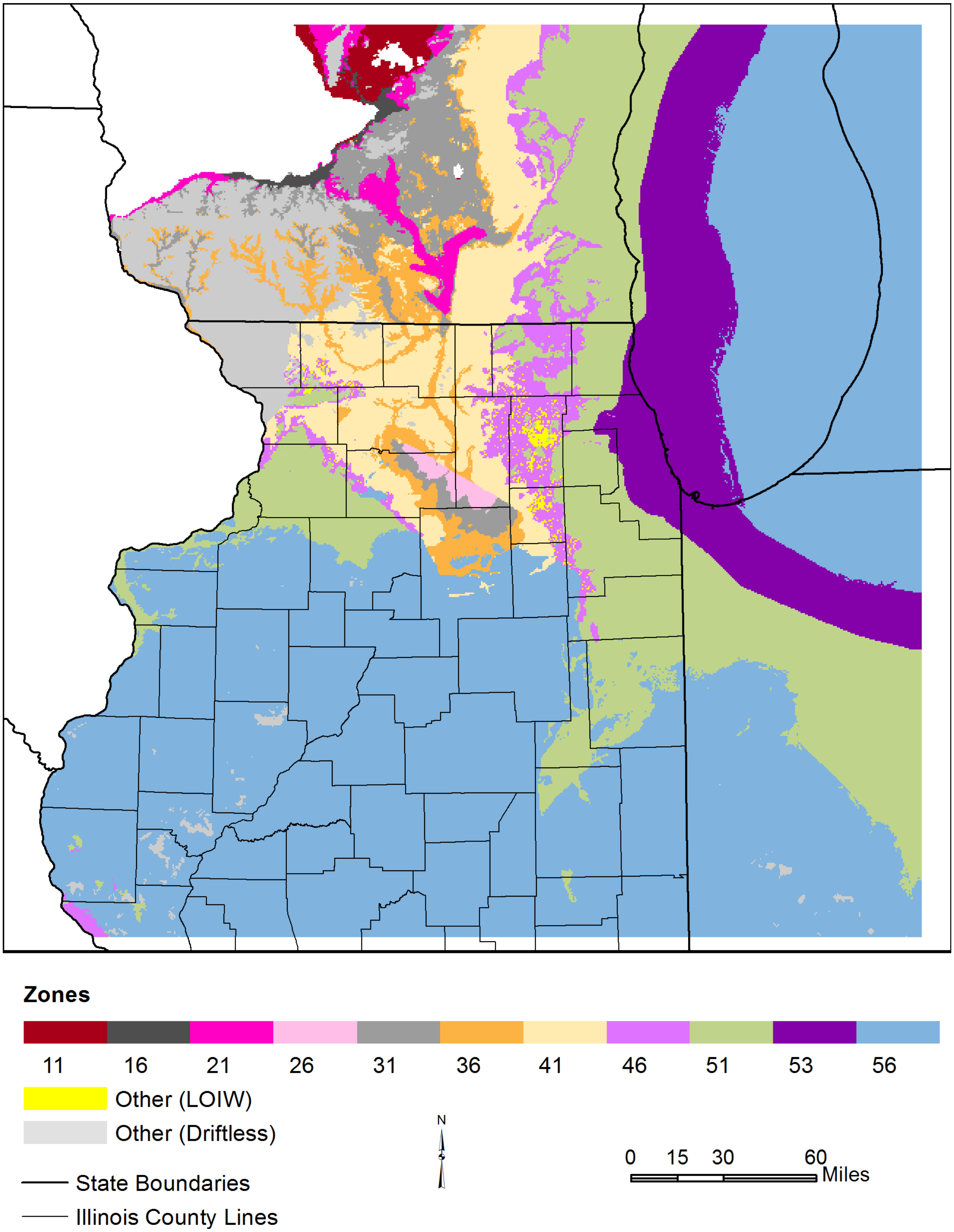

Figure 15: Hydrostratigraphic units present at the bedrock surface in the model domain

4.3 Zones based on faulting

Fault zones are important geologic features that dictate flow in portions of the model domain. One of the most prominent, the Sandwich Fault Zone, vertically displaces the Cambrian-Ordovician sandstone aquifers, either partially or completely (Figure 7). We hypothesize that the net effect of the Sandwich Fault Zone is a decrease in horizontal permeability due to the potential development of deformation bands, increased cementation, and offset of high permeability zones (Kolata et al., 1978; Antonellini and Aydin, 1994; Gutmanis et al., 1998; Jourde et al., 2002). Heads in the Cambrian-Ordovician sandstone aquifers differ on opposing sides of the Sandwich Fault Zone, often by more than 100 feet (Roadcap et al., 2013), supporting this hypothesis.

The ISGS has delineated the most prominent fault zones in Illinois with an ArcGIS polyline file (Figure 11). While depicted as lines, fault zones generally include a series of up- and down-thrown blocks that cause extreme local flow barriers with a more subdued regional impact. To determine the width of the fault zone, we examined specific capacity tests associated with sandstone wells in Will and Kendall Counties (Figure 10). This area is of particular importance due to its proximity to the center of the cone of depression in the Cambrian-Ordovician sandstone aquifer system. The lowest specific capacities generally fell within a 2-mile buffer around the line depicting the Sandwich Fault Zone. This buffer area corresponds to the zone depicting the Sandwich Fault Zone in the IGWFM (Figure 16).

The Sandwich Fault Zone is currently included only in the sandstone aquifer layers (St. Peter and Ironton-Galesville) of the IGWFM to act as a regional horizontal flow barrier (Figure 16). Only Zone 90 (Table 3) defines the fault zone at this time. Future research will investigate alternative conceptualizations with the use of multiple zones to depict the impedance to horizontal flow along the Sandwich Fault Zone. Furthermore, fault zones may enhance vertical flow in addition to restricting horizontal flow, so future conceptualizations will explore adding zones of increased vertical hydraulic conductivity in the materials overlying and underlying the sandstones to determine the conceptualization that best matches the data on a local and regional scale.

Future model conceptualizations will consider the influence of other fault zones found throughout the state. Three in particular will be part of future studies. First, the LaSalle Anticlinorium consists of a number of up- and down-thrown blocks and likely behaves similarly to the Sandwich Fault Zone. Although it is not adjacent to a large cone of depression, this fault zone may play a role in dictating flow from the recharge zone in LaSalle County (Figure 5) to the western part of the state. Second, the Plum River Fault Zone may affect groundwater flow in the northwestern part of the state, although a large head offset on either side of the fault is not present. Finally, the Des Plaines disturbance in Cook County has complicated local geology and groundwater flow patterns. Although this area only sparingly uses the sandstone aquifers in the present day, this fault zone likely played a major role in groundwater movement up to the late 1980s when a major cone of depression was formed. It will remain an important area of investigation to improve historical model calibration.

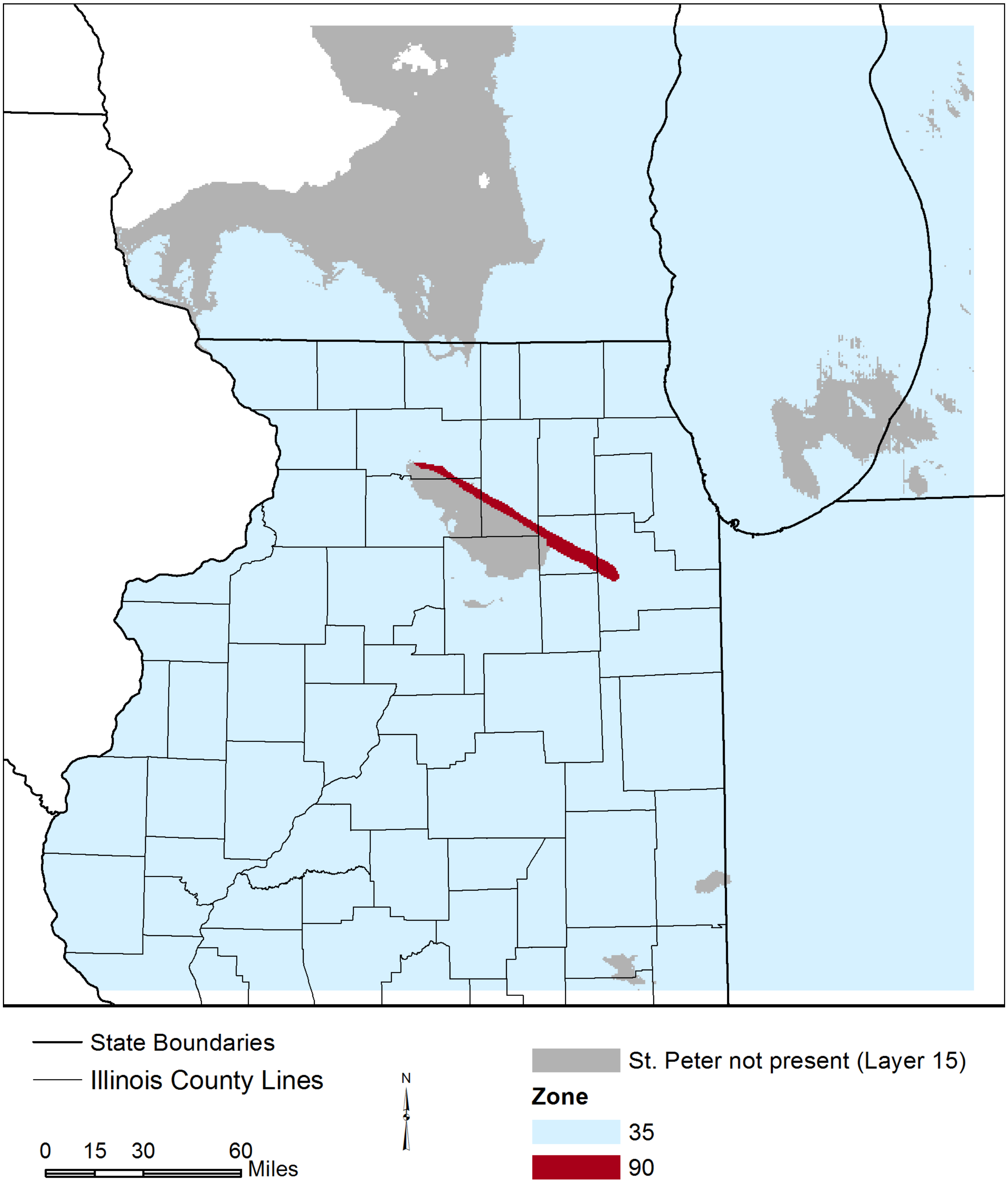

Figure 16: Location of zonation depicting the Sandwich Fault Zone (zone 90), shown for the St. Peter Sandstone model Layer 15

4.4 Zones based on multi-aquifer wells

Multi-aquifer wells that penetrate shale or unweathered carbonates create a pathway for groundwater movement that is absent under natural conditions. Since multi-aquifer wells are so prevalent in the Cambrian-Ordovician sandstone aquifer system (and to a lesser extent in shallow aquifer systems), natural groundwater flow pathways have been altered. It appears that through model calibration, these anthropogenic flow pathways must be considered to facilitate proper flow between aquifers. To this end, the model has property zones depicting these connections, allowing for decreased vertical resistance (increased vertical hydraulic conductivity) through aquitards. Hydraulic conductivity zones are included for multi-aquifer wells fully bypassing the following hydrostratigraphic units: Maquoketa (Figure 17), Galena-Platteville (Figure 18), Prairie du Chien-Eminence and Potosi-Franconia (Figure 19), and Eau Claire (Figure 20).

A single vertical hydraulic conductivity value throughout the entire history of northeastern Illinois is not sufficient to represent multi-aquifer wells in a regional simulation of the entire history of pumping. In pre-development times (prior to 1863), no multi-aquifer wells were present. The earliest wells constructed in Cook and DuPage Counties were left open through multiple units, often including the shallow bedrock (Silurian-Devonian) and deep saline Mt. Simon Sandstone. However, many of those wells were sealed by the 1960s. Conversely, many newer domestic wells in the western counties (Kane, Kendall, Will, and McHenry) are open to the St. Peter Sandstone, often bypassing either the Maquoketa shale or minor shales within the Galena-Platteville Dolomite. As a result, these wells should only provide a decreased resistance to vertical flow for only the period of the model simulation. However, due to the long memory of both pumping and changes in aquifer construction, a model calibrated to modern heads may not be calibrated to previous years, which in turn raises questions regarding the validity of future simulations.

To address the transient nature of multi-aquifer wells in Illinois, we developed three different versions of the Illinois Groundwater Flow Model to depict discrete time ranges, each depicting the different drilling practices of the period. The models were chained together by passing the heads from the final stress period from the previous model as initial heads into the next model. This is based on our initial assessment of well information and water level data and may be modified as part of the continuing calibration effort for the IGWFM. More details on the temporal discretization of the model can be found in Section 6.1.

1. The first model runs with annual stress periods from 1863 to 1900 and includes the earliest pumping in northern Illinois from the sandstone aquifers. However, zones 60–72 are not present in this model simulation, meaning that pumping proceeds without the influence of multi-aquifer wells. This run maintains the integrity of pre-development (1863) groundwater conditions where the sandstone aquifers were generally separated by impermeable aquitards. The year 1900 was used as a cutoff point to ensure that the influence of multi-aquifer wells was not removed from the simulation for too long of a period.

2. The second model depicts a period of time when public supply and industrial wells were open to most or all bedrock layers, particularly common in wells constructed prior to the 1929 stock market collapse. This model runs from 1901 to 1963, using annual stress periods.

The 1963 cutoff was determined by assuming that newly drilled wells in 1928 had a life span of 35 years, the median life span of deep sandstone wells as determined from ISWS records and also corroborated by a study on municipal well mortality (Hudson Jr. and Geils, 1952). All cells containing multi-aquifer wells connecting the sandstone to shallower aquifers were assumed to revert back to natural aquitard conditions in 1963, which would only be possible if all old wells were plugged. This plugging could have been a result of well sealing practices or from the natural precipitation of barite (barium sulfate mineral), observed in the records for multiple wells connecting shallower to deeper hydrostratigraphic units in Cook and DuPage Counties.

From 1901 to 1963, the following zones are used in the model:

- Zone 70: high-capacity wells open through the unweathered Maquoketa (Figure 17)
- Zone 71: high-capacity wells open through the weathered Maquoketa (Figure 17)
- Zone 65: high-capacity wells open through the Galena-Platteville (Figure 18)
- Zones 60 and 61: high-capacity wells connecting the St. Peter to Ironton-Galesville (Figure 19)
- Zone 62: high-capacity wells connecting the Ironton-Galesville to the Mt. Simon (Figure 20)

3. The third model depicts modern times where residential wells are routinely left open to multiple units. Public supply and industrial wells constructed after 1963, on the other hand, were generally cased through the Maquoketa shale, though many are still drilled through multiple sandstones. This model runs from 1964 to 2015 using annual stress periods. During this period, the following zones are active:

- Zone 72: predominantly low-capacity wells open through the Maquoketa (Figure 17)
- Zone 66: predominantly low-capacity wells open through the Galena-Platteville (Figure 18)
- Zones 60 and 61: predominantly high-capacity wells connecting the St. Peter to Ironton-Galesville (Figure 19)
- Zone 62: predominantly high-capacity wells connecting the Ironton-Galesville to the Mt. Simon (Figure 20)

The vertical hydraulic conductivity used when a zone is active for a model simulation adds another degree of freedom and complexity to the calibration process. As a result, chaining model runs in sequence greatly improves the calibration of transient targets through time. However, the precise timing of wells being constructed and sealed are still not simulated using this approach; this very likely will never be possible. Multiple modeling approaches need to be investigated to simulate multi-aquifer well construction on a finer temporal resolution to better capture this complexity, which will be more probable as we continue to collect new, reliable data.

Not all wells are open over the entirety of an aquitard's thickness, but rather some portion. For example, many high-capacity sandstone wells are also open to a considerable portion of the overlying Galena-Platteville. Similarly, many domestic wells are open to a considerable portion of the uppermost bedrock unit but not into the sandstone. These wells provide conduits that effectively eliminate some of the natural resistance to vertical flow in an aquifer. This is particularly influential to the flow domain where a subset of wells is open to the upper portion of an aquitard, and a second subset is open to the lower portion. In this case, groundwater can "short-circuit" through the upper portion of the aquitard, and again through the lower portion. The vertical distance that groundwater needs to travel to pass through the aquitard is reduced. In some cases, water may only need to travel horizontally from the first subset of wells open to the upper portion of the aquitard to the second subset open to the lower portion of the aquitard. Consequently, horizontal, not vertical, resistance will be the major impediment to groundwater flow in this case. However, horizontal hydraulic conductivity (the inverse of resistance) is generally orders of magnitude larger than vertical hydraulic conductivity. Consequently, on a regional scale, we effectively increase the vertical flow where complex networks of long open interval wells may be present. To simplify this assumption, we currently assume that this occurs where a hydrostratigraphic unit is at the bedrock surface, and we effectively extend the weathered properties of that material down to the next hydrostratigraphic unit. This is currently done for the Maquoketa Shale (zone 48), Galena-Platteville (zone 43), and Potosi-Franconia (zone 27) in areas where an evaluation of the well logs has shown this is likely the case. These regional zones are depicted in Figure 17 and Figure 18. These zones were necessary to obtain enough vertical infiltration to the sandstone to satisfy historic and modern demands.

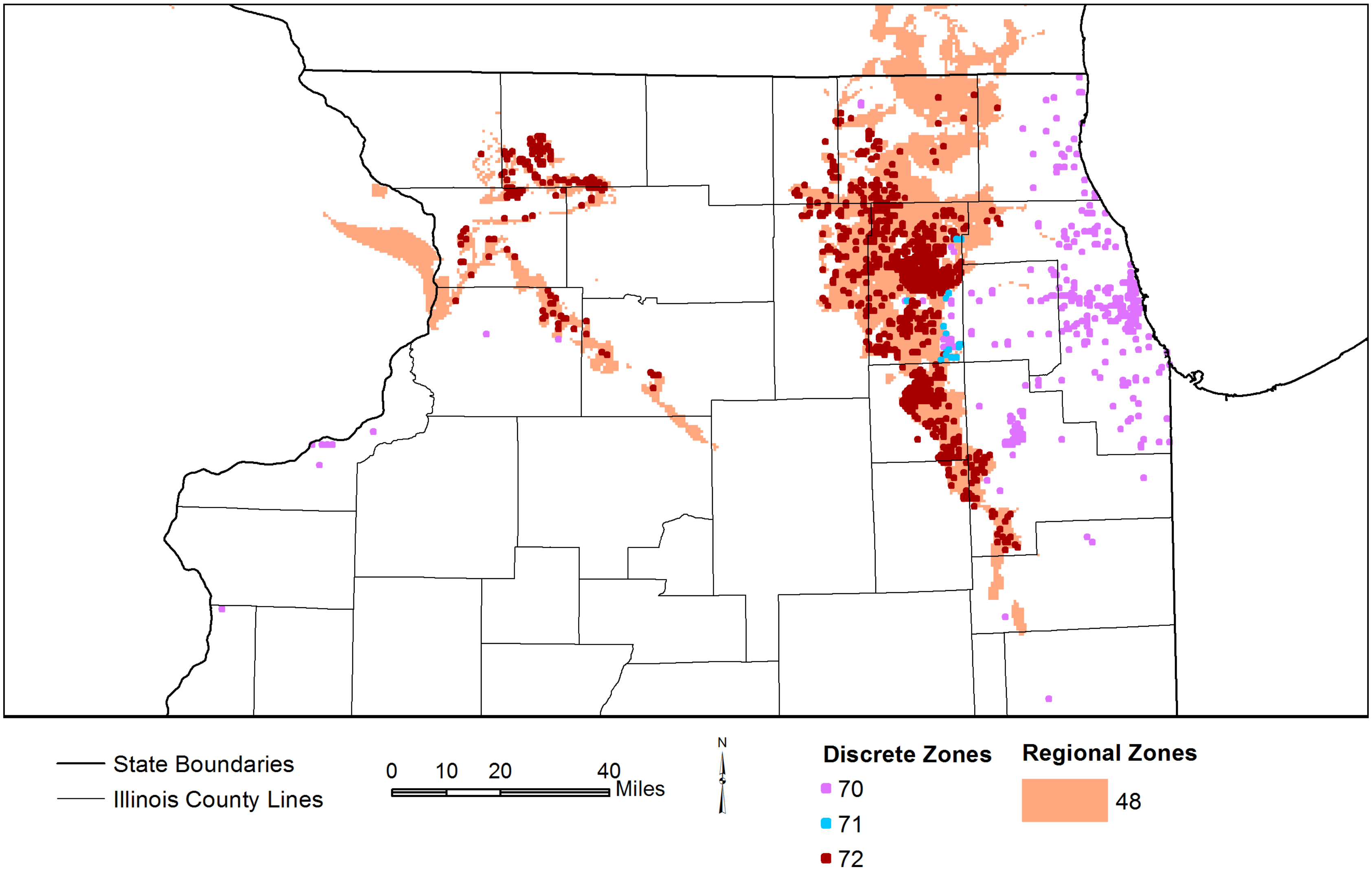

Figure 17: Discrete high k_z zones used in the IGWFM for northeastern Illinois for depiction of wells bypassing the Maquoketa shale (zones 70-72). The cell size of these discrete zones are exaggerated for display purposes. Zone 48 depicts a regional area where dense clusters of long open interval wells reduce resistance to vertical flow through the Maquoketa.

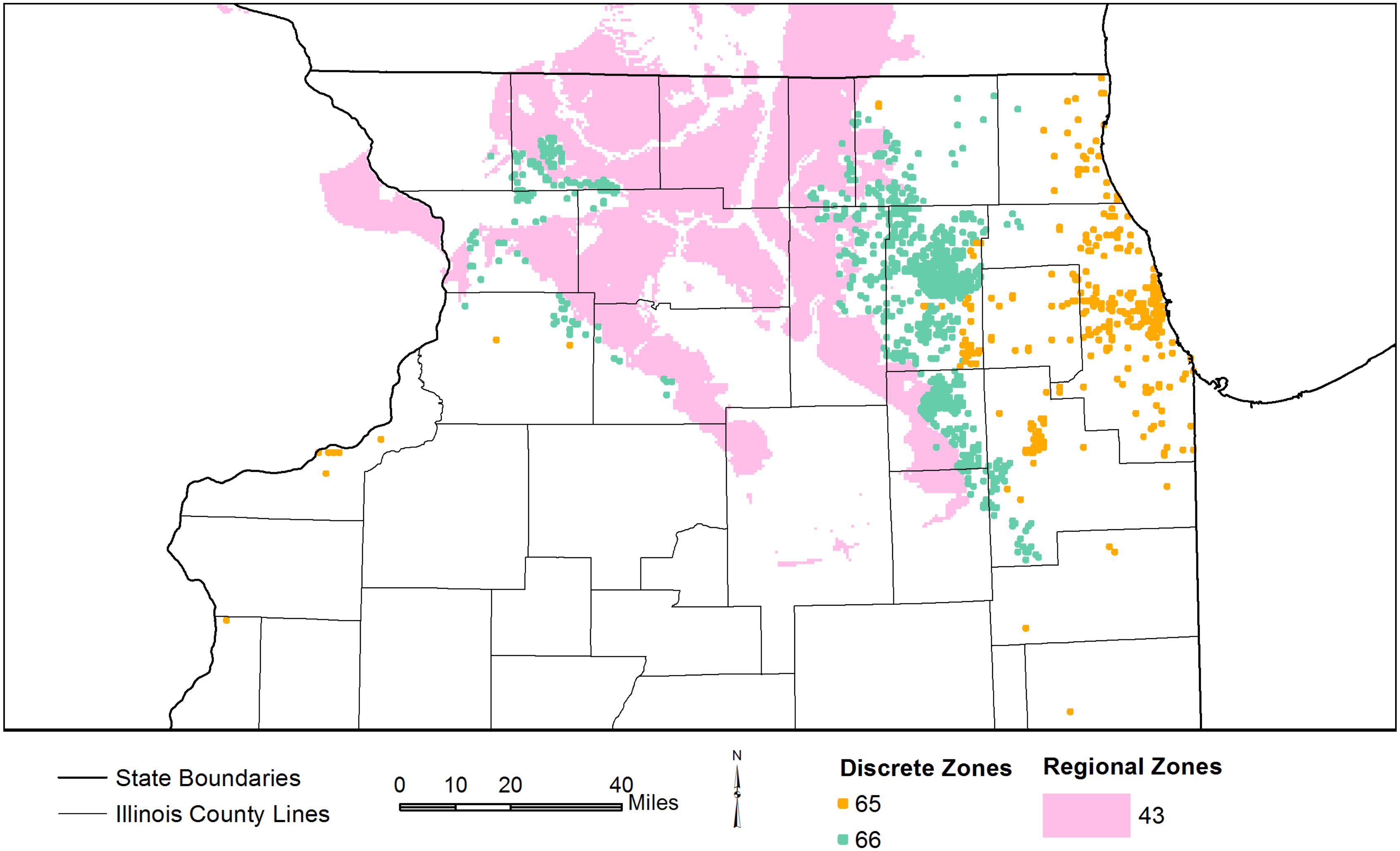

Figure 18: Discrete high vertical k-zones used in the IGWFM for northeastern Illinois for wells bypassing the Galena-Platteville (zones 65 and 66). The cell size of these discrete zones are exaggerated for display purposes. Zone 43 depicts a regional area where dense clusters of long open interval wells reduce resistance to vertical flow through the Galena-Platteville.

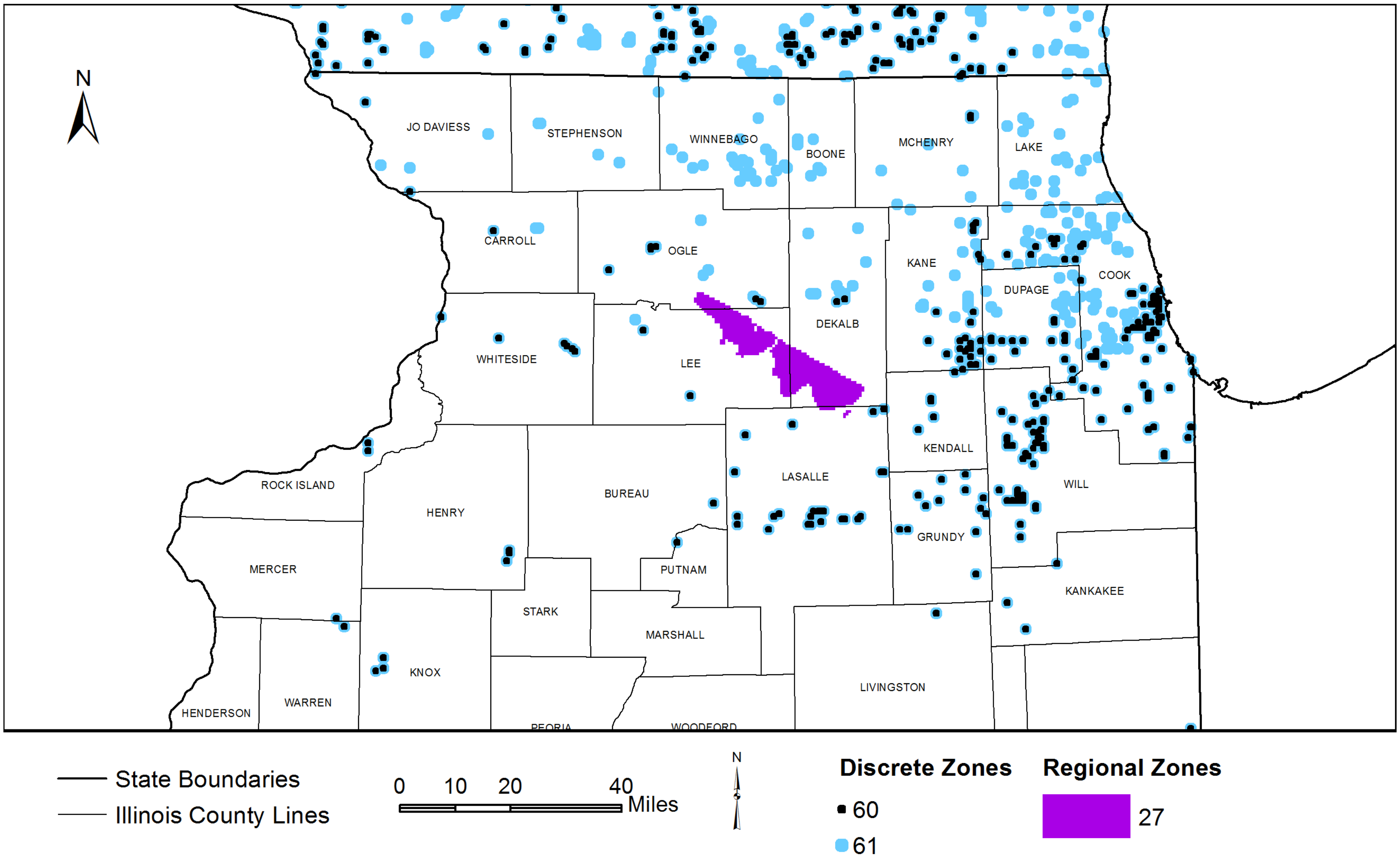

Figure 19: Discrete high vertical k-zones used in the IGWFM for northeastern Illinois for wells connecting the St. Peter and Ironton-Galesville through the Prairie du Chien- Eminence (zone 60) and Potosi-Franconia (zone 61). The cell size of these discrete zones are exaggerated for display purposes. Zone 27 depicts a regional area where long open interval wells reduce resistance to vertical flow through the Potosi-Eminence (potentially also related to enhanced vertical flow along the Sandwich Fault Zone).

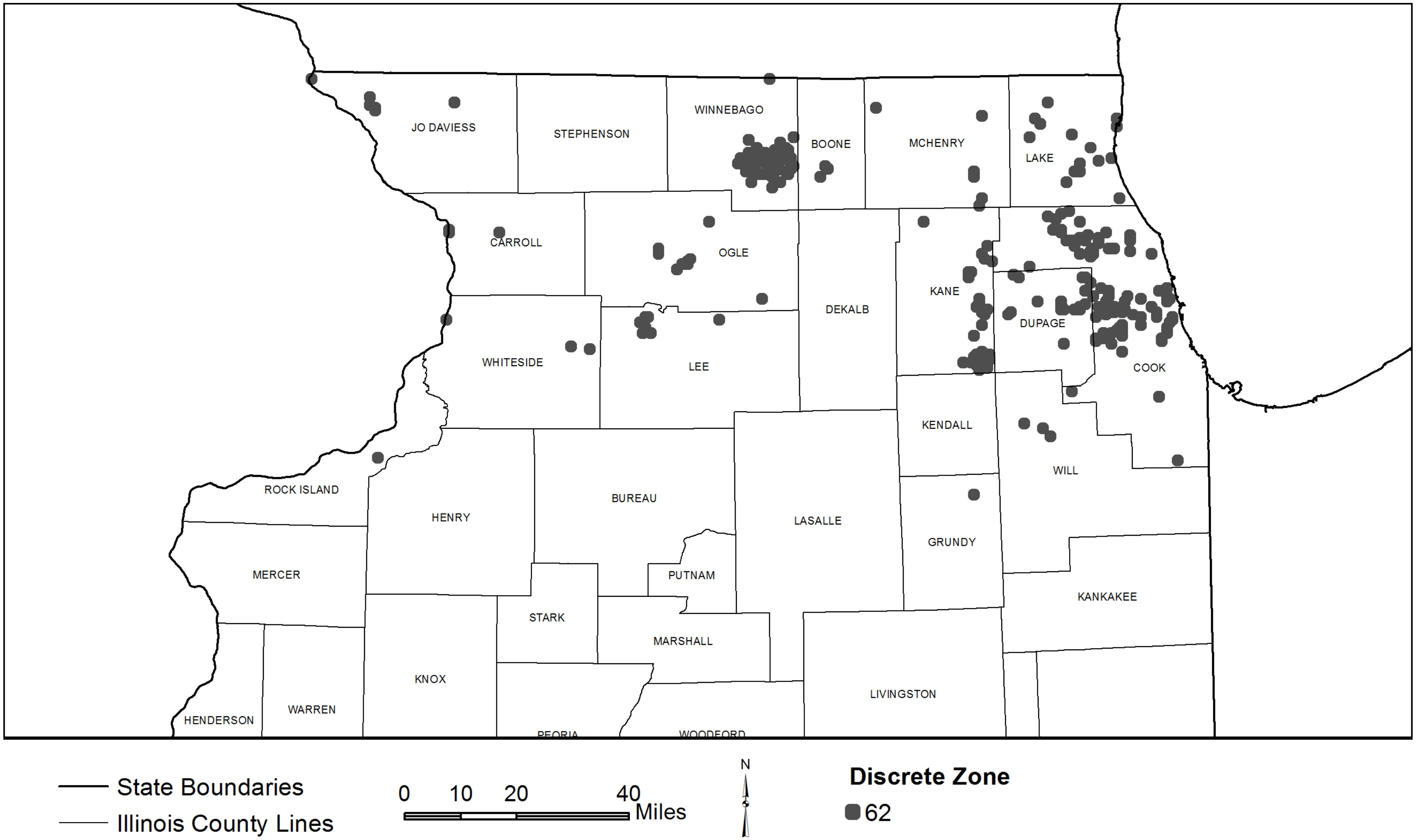

Figure 20: High vertical k-zones used in the IGWFM for northeastern Illinois for wells connecting the Ironton-Galesville and Mt. Simon through the Eau Claire (zone 62)

4.5 Storage values

The transient removal of water from storage plays an important role in the simulation of groundwater flow. The addition or removal of water in a transient groundwater flow model is determined by the storativity, S. Storativity is a unitless parameter that is equivalent to the volume of water that an aquifer releases or takes into storage per unit surface area per unit change in head. How storativity is parameterized depends on whether an aquifer is unconfined or confined.

In an unconfined aquifer, storativity is defined by the aquifer's specific yield, S_y. Specific yield is the ratio of the volume of water that can be extracted from a material's pore spaces to the volume of porous material. It is often similar to an aquifer material's porosity, which is the ratio of the volume of voids in a material to the volume of porous material. However, porosity and specific yield generally differ, at least slightly, because some water will adhere to the surface of material, preventing complete desaturation of pore spaces.

Unlike an unconfined aquifer where changes in storage are a result of desaturation or resaturation of pore spaces, storage changes in a confined aquifer are a result of removing or adding pressure within the pore spaces of an already saturated aquifer. Specifically, storativity in a confined aquifer is calculated as the product of the specific storage coefficient, S_s, and aquifer thickness, b. Specific storage is equivalent to the volume of water released or taken into storage per unit volume of a porous material per unit change in head. As a result, it has units of 1/ft, resulting in a unitless storativity.

For this study, specific yield and specific storage zones were the same as those assigned for hydraulic conductivity in Table 3. Values assigned to the model were adjusted for individual hydrostratigraphic units (Table 5), which is necessary to achieve a transient calibration. This is in contrast to the three specific yield values used for the entire model in previous simulations (Meyer et al., 2009; Meyer et al., 2013; Roadcap et al., 2013). Most notably, both the Maquoketa and Galena-Platteville specific yield values had to be lowered, sandstone specific yield values (St. Peter, Ironton-Galesville, and Mt. Simon) had to be increased, and specific yield values of the aquitards below the St. Peter had to be decreased. These changes were critical to achieving calibration after the introduction of the transient multi-aquifer well network discussed in Section 4.4.

Table 5: Specific yield and specific storage values used in the groundwater flow model

Hydrostratigraphic Unit	Zone	Specific Yield (-)	Specific Storage (1/ft)	Change from previous
Mt. Simon	10-14	0.075	2.6e-7	Specific Yield: 0.05 Specific Storage: 2.6e-7
Eau Claire	15-19	0.01	2.6e-7	
Ironton-Galesville	20-24	0.075	2.6e-7	
Potosi-Franconia, Prairie du Chien-Eminence	25-34	0.01	2.6e-7	
St. Peter	35-39	0.075	2.6e-7	
Galena-Platteville	40-44	0.0075	2.6e-7	
Maquoketa	45-49	0.001	2.6e-7	Specific Yield: 0.01 Specific Storage: 2.6e-7
Silurian-Devonian, Pennsylvanian-Mississippian	50-59	.01	2.6e-7	
Unconsolidated	101-146	0.15	5.7e-6	Unchanged

5 Surface water and geologic boundary conditions

5.1 High-resolution stream network

Surface waters are an important source or sink to the shallow aquifers of the state. As a result, groundwater flow models require a depiction of these surface waters to serve as boundary conditions where appropriate. To ensure consistency between the regional IGWFM (2500-foot grid) and any higher resolution inset models, we have developed a single high-resolution stream network, with the methodology outlined in Figure 21 and in the text below.

The primary data sources for the high-resolution stream network are the National Hydrography Dataset Plus (NHDPlus) (Horizon Systems Corporation, 2012) and a 33-foot Digital Elevation Model (DEM) from the National Elevation Dataset (United States Geological Survey, 2015). NHDPlus is a hydrologic framework dataset developed by the U.S. EPA and the U.S. Geological Survey. The outputs from the hydrologic framework include a 98-foot (30 meter) resolution National Hydrography Dataset (NHD) flowline feature (Figure 22) that contains stream order, watershed unit, and flow parameter attributes assigned to and between stream segments (McKay et al., 2016). We combined the NHDPlus flowlines for the Mississippi and Great Lakes watersheds in a Geographic Information System (GIS) using ArcGIS 10.3 (Environmental Systems Research Institute, 2017) and clipped the flowlines to the regional model domain. Stream segments disconnected from other stream segments (isolated flow paths) within the NHDPlus flowline coverage were not included in this process.

The drainage pathways in the 33-foot DEM do not always correspond to the NHDPlus flowlines. A spatial join between the two would not yield a monotonically decreasing stream network, which is desirable in a groundwater flow model. To obtain such a stream network while still leveraging the power of the attributed NHDPlus flowlines, we used the NHDPlus coverage to "hydrologically condition" the 33-foot DEM throughout the state. Hydrologically conditioning a DEM ensures that the lowest elevations of stream and river valleys match the locations of the NHDPlus flowlines, as demonstrated for the Rock River Valley in Figure 23. Furthermore, this process removes anomalous pits from the DEM. To perform the hydrologic conditioning, we used ArcHydro Terrain Processing tools to fill in pits that were less than 10 feet deep in the 33-foot DEM and then "burned" the NHDPlus flowlines into the DEM. We used drop values of less than 1 foot (i.e., the stream network could not be burned deeper than 1 foot into the 33-foot DEM over any given length) and applied a stream buffer of two cells (i.e., the width of the burning could not exceed 66 feet). These parameters were selected to ensure that there were no drastic changes to the original 33-foot DEM. A spatial join of the hydrologically conditioned DEM to the NHDPlus flowlines resulted in a high-resolution, near-monotonically decreasing stream network.

The resulting polygon file depicts the stream network at a 33-foot resolution, with every cell attributed with the original NHDPlus flowline properties. Each polygon has a flag designating whether it is a river cell, drain cell, or neither (Figure 22). These flags, based on stream order, control how an individual polygon is imported into MODFLOW.

- Third-order streams or greater have river cell flags. MODFLOW river cells simulate permanent streams with perennial streamflow and can either receive water from the subsurface or discharge water to the subsurface. The aquifer head, river stage, and resistance to flow through the river's sediment control the rate of exchange.

- Second-order streams have drain cell flags. MODFLOW drain cells simulate intermittent streams with ephemeral streamflow and can only receive water from the subsurface.
- First-order streams are local drainages that have minimal or no interaction with the aquifer. The regional-scale IGWFM omits first-order streams as boundary conditions, but they may be important for a local-scale model.

5.2 Other boundary conditions

In addition to the stream network, other boundary conditions can influence groundwater flow. Lakes serve as a local sink or source of groundwater, and groundwater withdrawals can potentially lower lake levels. We spatially joined a lake file from the NHDPlus to the hydrologically conditioned DEM to create a high-resolution lake polygon shapefile with attributed features (lake names, elevations, etc.). In the regional model, lakes are imported as constant head cells (which do not account for vertical resistance to flow with groundwater), but in local-scale models, lakes can be represented by constant head cells, river cells, or lake cells. The latter allows for explicit simulation of transient lake stages and can assess the combined impact of groundwater stresses and precipitation/runoff/evapotranspiration conditions.

Agricultural drainages are also possible discharge points for groundwater that requires a simulation of drain cells in the model. To account for this, we spatially joined the hydrologically conditioned DEM with a polygon depicting low-permeable surficial geology in the groundwater flow model (areas shaded brown and orange in Figure 13). The elevation assigned to the modeled drain cells is 3 feet lower than land surface, consistent with common burial depths of tile drainages. These drain cells ensure that the water table does not exceed land surface in areas with low-permeable soils.

Urban drainages are another possible discharge point for groundwater and, in systems with an old infrastructure, a possible recharge point as well. In the regional IGWFM, we do not currently include drain cells to represent urban areas. Future iterations of the model may include a spatial join of an urban land use coverage and the hydrologically conditioned DEM where appropriate to ensure that the water table does not exceed the land surface.

5.3 Importing boundary conditions into the model

The high-resolution dataset developed for the boundary conditions in northern Illinois will serve as the base data for regional IGWFM and all future local-scale modeling efforts. Multiple types of boundary conditions (lakes, rivers, drains) may fall within a single model cell, particularly true for the IGWFM in which cells are 2500 feet on a side. To ensure consistency, the following order dictates how boundary conditions are imported into the model cell: 1) lake, 2) river, 3) drain from NHD, and 4) drain from another coverage. Furthermore, the model cell will honor the minimum elevation of all boundary conditions falling in the cell during the import process, ensuring that surface waters have a continuously decreasing (or at least stable) elevation in one direction. While not essential for regional-scale modeling, a monotonically decreasing surface water network is important for local-scale analyses or for application of more advanced packages, such as the Streamflow Routing Package (SFR).

All boundary conditions require a conductance. The conductance controls the exchange of flow between surface water and groundwater. Physical parameters needed to calculate the conductance are the width of the stream, the thickness of the stream sediment, the vertical hydraulic conductivity of the stream sediment, and the length of the stream within the cell. Spatially variable conductances are difficult to calculate on a regional scale. Consequently, we assigned a single conductance for all river cells (400,000 ft^2/d) and drain cells (1600 ft^2/d).

Local studies, particularly those related to groundwater-surface water interactions, will likely require modifications to the high-resolution stream network developed using the procedure in Figure 21. The blanket assumptions on the conductance of river and drain cells may not be applicable on a local scale, requiring modification to ensure that model simulations match local observations. Furthermore, the use of the junction of second- and third-order streams as the transition point from drain to river cells is arbitrary. A more accurate criterion for this transition point is the location where a stream continues to flow during a drought, obtainable through field verification. The Kane County modeling study employed this approach (Meyer et al., 2009). Future versions will investigate methodologies to incorporate such field verifications into the established methodology for creating a high-resolution dataset from only the NHDPlus and a 33-foot DEM.

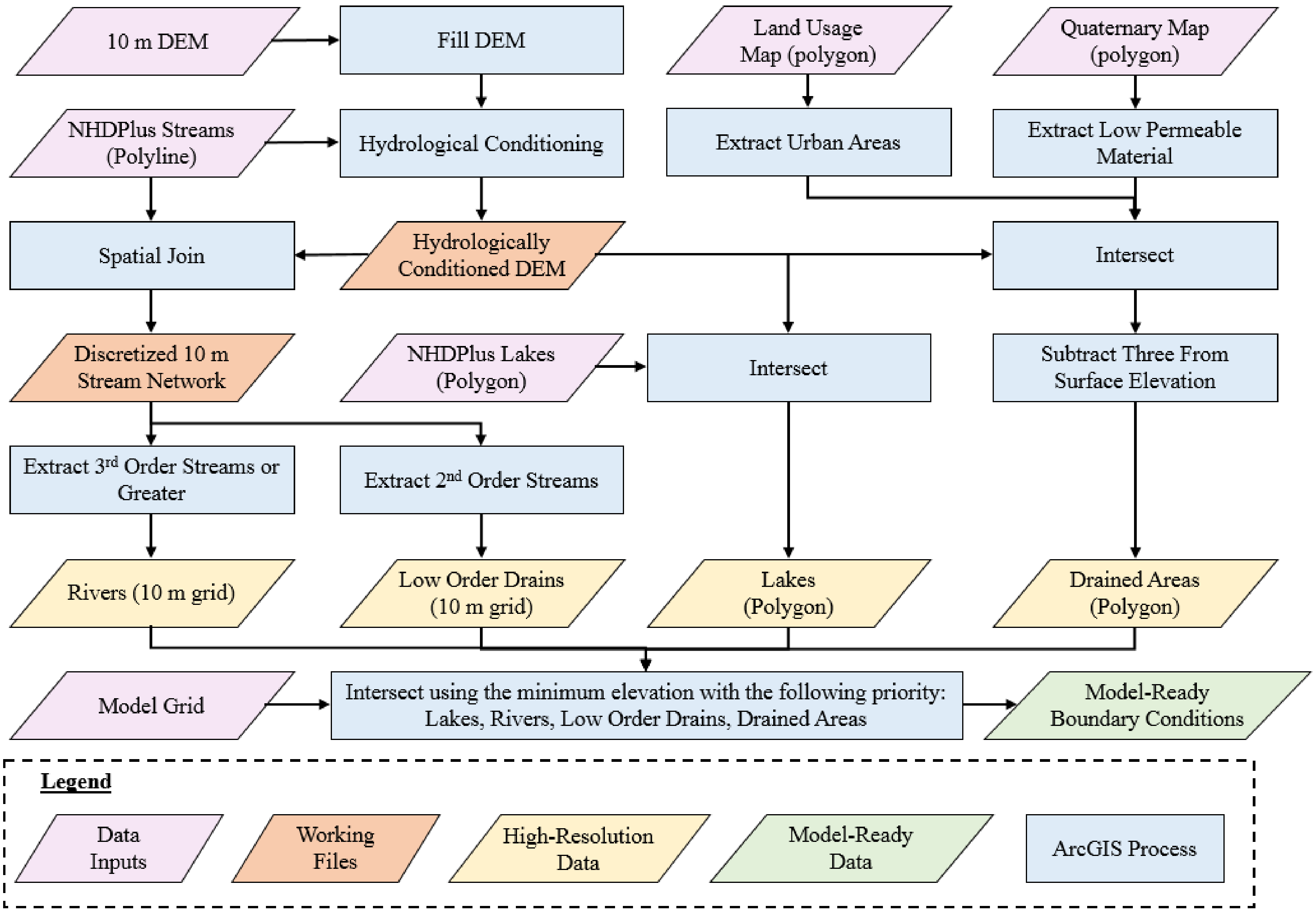

Figure 21: Workflow depicting the creation of a high-resolution stream network and its import into a model grid

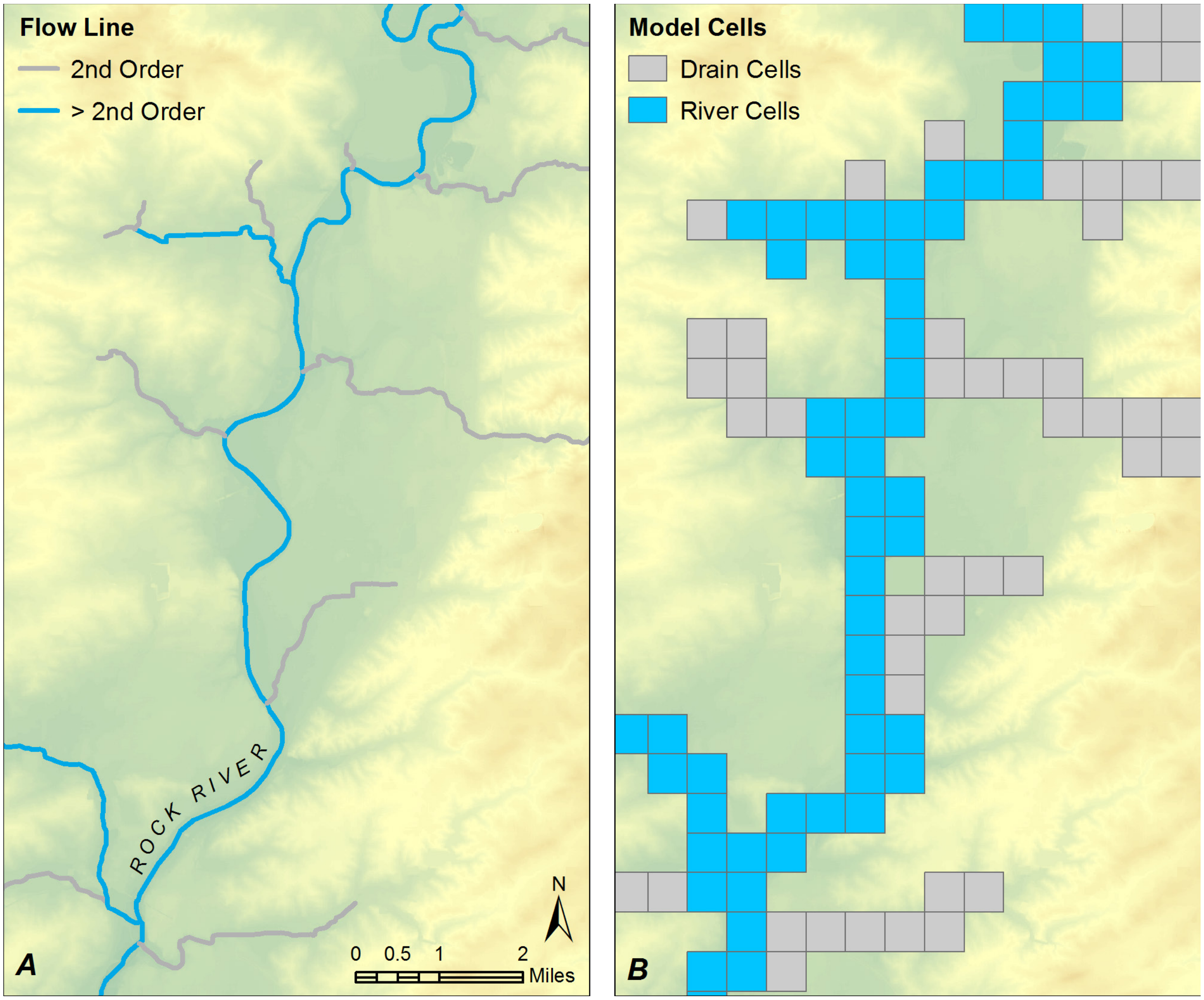

Figure 22: (A) Example of the NHDPlus flowline coverage in Ogle County showing the Rock River and second-order tributaries. (B) Model cells classified as drain or river, based on the NHDPlus flowline coverage.

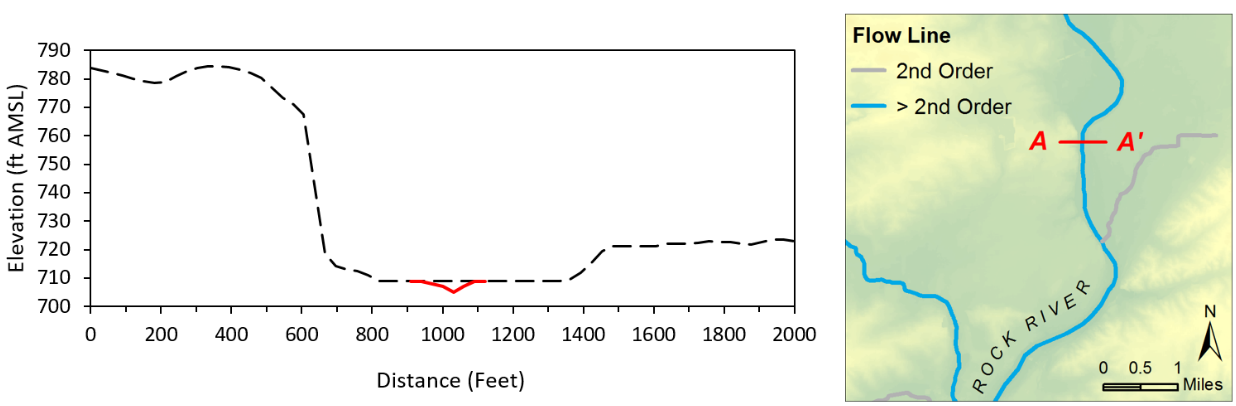

Figure 23: Cross section of the Rock River channel depicting the profile of the original 33-foot DEM and the profile after flowlines were burned in (in red) to hydrologically condition the DEM

6 Wells: withdrawals, open intervals, and head observations

6.1 Temporal discretization of the model domain

The groundwater flow model is divided temporally into 198 stress periods, within which a unique model solution is calculated. The initial stress period is run at a steady state, with no pumping, and represents predevelopment conditions in 1863. Each subsequent stress period has a length of 365.25 days. Stress period 153 represents the year 2014, which is an important milestone as it coincides with the 2014 synoptic measurement of heads that were used as a calibration target for the sandstone (Abrams et al., 2015). The remaining years are populated by pumping values derived from future demand scenarios, if available, or are just held constant from their most recent reported year to IWIP.

6.2 Model-ready withdrawals

Groundwater withdrawals in Illinois have varied greatly with time; capturing the impacts of this varied pumping is one of the major goals of the IGWFM. The ISWS has either estimated or collected withdrawal data in some form since high-capacity withdrawals began in the early 1860s. Until 1963 for northeastern Illinois and 1980 for some portions of the rest of the state, pumping estimates are available at a county level for the sand and gravel, weathered bedrock, and sandstone aquifers. Historical withdrawals aggregated by facility are available from 1964 to 1979. Since 1980, the Illinois Water Inventory Program (IWIP) has collected withdrawal data for high-capacity wells throughout the state, not just in northeastern Illinois (Illinois State Water Survey, 2018).

Data from 1964 onward has three major complicating factors. First, gaps in facility reporting are common, and often do not represent a period of zero water demand. Second, the pumping database often includes consecutive years with the exact same reported demand, likely indicating that a water operator or ISWS data-entry staff carried the previous year's value forward. Third, some years have markedly high or low withdrawals compared to the intervening years. Although this may make sense for some facilities, this could also be the result of a recording error. Historically, such issues have been resolved on a model-by-model basis, resulting in different methodologies and assumptions about actual usage when data are suspect.

We have developed a withdrawal script (Figure 24) that processes the post-1980 IWIP statewide data to account for data gaps and remove suspect records, particularly when facilities report the same total withdrawals for consecutive years or an anomalously high/low withdrawal. The script also removes any manually flagged records, which are stored in a separate table within the database so as not to override the raw reported data. With the remaining records, the script linearly interpolates annual withdrawals by well for a continuous model output. If the facility reported within the past seven years, the script carries the last known withdrawals forward to the current year or a manually assigned facility stop year, whichever is less. The procedure offers a significant improvement in the 1990s, when a few major public water supplies in the region failed to report to the IWIP program, leaving large data gaps (Figure 25). Wisconsin's withdrawals, provided by the U.S. Geological Survey (USGS) on a per-well basis for the entire history of pumping (Buchwald, 2015), receive a similar treatment, interpolating between gaps in the data record and carrying withdrawals forward to the current year for recently active wells.

The withdrawal script also conducts an interpolation on the northeastern Illinois specific 1964–1979 data. Procedurally, this portion of the script is the same as the IWIP portion, except it also disaggregates withdrawals to individual wells. For pre-1963 data in northeastern Illinois and pre-1980 data in the rest of the state, the script disaggregates regional withdrawal trends to individual wells, distributed by their last reported year of pumpage.

Another complication in developing model-ready pumping files is the assignment of the model layer or layers to a well. To this end, the script gives precedence to existing model files, as previous iterations of models have likely involved the manual assignment of layers to individual wells based on well log information, particularly for Quaternary aquifers that involve complicated geology. If a well was not present in previous models, the script uses the aquifer code from the ISWS well point database to determine the open interval model layers, if populated. Any manual adjustment to the aquifer code is reflected in the ISWS well point database. Failing that, the script will estimate an aquifer code from the casing and bottom elevations compared against the geologic surface elevations at the well's location, or assign an aquifer code based on nearby wells of a similar depth. The script translates this aquifer code into a model layer top and bottom. The script moves wells to the nearest aquifer if they start or finish in a confining unit; for example, most Ironton-Galesville wells terminate in the underlying Eau Claire shale, but the shale provides a negligible amount of water so the simulation terminates the open interval in the Ironton-Galesville. This results in an increase in computational efficiency, particularly when applying MODFLOW's more advanced well packages.

Withdrawal rates for public supplies and industries in most areas in the state exhibit increasing or stable trends. In contrast, northeastern Illinois withdrawals have followed distinct periods of increasing and decreasing trends (Figure 26). Groundwater withdrawals from high-capacity production wells in northeastern Illinois started around 1863 and continued to increase until the late 1920s, when many wells in and around the city of Chicago and adjacent suburbs switched from groundwater to Lake Michigan water, resulting in a short period of decline in demands, particularly from the deep sandstone aquifers of the region. This period of decline corresponded with the Great Depression. From 1940 to 1980, demands for groundwater again increased. Due in part to rapidly declining water levels in the sandstone aquifers and increasing water quality concerns in the shallow aquifers, most communities in Cook and DuPage Counties switched to Lake Michigan water in the 1980s and early 1990s. Two large communities in Kane County, Aurora and Elgin, also switched to the Fox River as a partial source of water during this timeframe. Since the mid-1990s, groundwater demands have stayed relatively constant in the shallow aquifers and have been steadily increasing in the sandstone aquifers. Figure 27 shows the 2013 withdrawals from the sandstone aquifers of Illinois, and Figure 28 and Figure 29 show the 2013 withdrawals from the shallow aquifers. Currently, a number of communities in Will, Kendall, and Grundy Counties are investigating alternative sources of water because of various threats to their water supplies, which could result in drastic changes in groundwater demands for these counties in the coming decades.

Withdrawals reported by facilities to IWIP have historically taken two to four years to become available for use in a groundwater flow model. The delay results from the use of paper forms to submit IWIP data, requiring transcription by ISWS staff for every facility. In 2015, IWIP began to switch to electronic reporting, a process that will take a few years to fully implement, but when complete will make the turn-around time for having model-ready data much quicker. Once IWIP staff have completed the QA-QC for a particular year, the data are added to the groundwater flow model.

6.3 Irrigation demands

The reported and estimated withdrawals discussed above and shown in Figure 25 and Figure 26 primarily depict demands from public supplies and self-supplied commercial and industrial facilities. Many small irrigators, such as sod farms and golf courses, also report to IWIP. However, most large agricultural facilities did not report to the IWIP program until 2015, when reporting became a legal requirement. Even with this requirement, there will be a number of complications to overcome before reliable numbers across the state are available, including the accuracy of the reported values and the need to disaggregate values originally reported over a large area.

Irrigation generally has its greatest impact on the shallow aquifers of the state. The groundwater flow model of the Mahomet Aquifer required estimated historical irrigation demands (Roadcap et al., 2013). In 2005, 139.4 mgd was the estimated annual demand for irrigated water by the Imperial Valley Water Authority. This value was then disaggregated using a map of irrigation systems. The transient pumping network was then estimated by using a linear interpolation at each well from 1940 (the start of irrigation) to their 2005 value.

Using GIS, The Illinois State Water Survey has updated the location of some new center-pivot wells by locating circular irrigated acreage areas from aerial photographs (Figure 30) (Bridges et al., 2015). This methodology will allow periodic updates of well coverages, particularly during drought years when irrigated acreage is most prevalent. This approach will be particularly valuable as large irrigators start reporting aggregated withdrawals, but the technique is still under development. Irrigation will be explored at length in the upcoming water supply planning work for the Kankakee and Iroquois County region (Figure 31).

6.4 Projected demands

Groundwater flow models facilitate the assessment of the impacts of future withdrawals. To this end, demand projections for three different water supply planning regions are included in the current iteration of the model. First, three demand scenarios for northeastern Illinois (least resource intensive, current trends, and most resource intensive) project water demands out to 2050 (Dziegielewski and Chowdhury, 2008). Second, the same three demand scenarios project out to 2050 for the Mahomet Aquifer (Dziegielewski, 2008). Third, the same three demand scenarios (currently in draft form) project out to 2060 for Middle Illinois (Meyer et al., 2018). For the rest of the state where projections have not been developed, we hold modern demands constant out to 2060. Future demands from 2050 to 2060 are also set at 2050 levels.

Projected demands will be addressed in more detail in future iterations of this report. At the time of this report (summer 2018), northeastern Illinois demands are being reassessed under the purview of water supply planning sponsored by the Illinois Department of Natural Resources Office of Water Resources, and Middle Illinois demands are undergoing review.

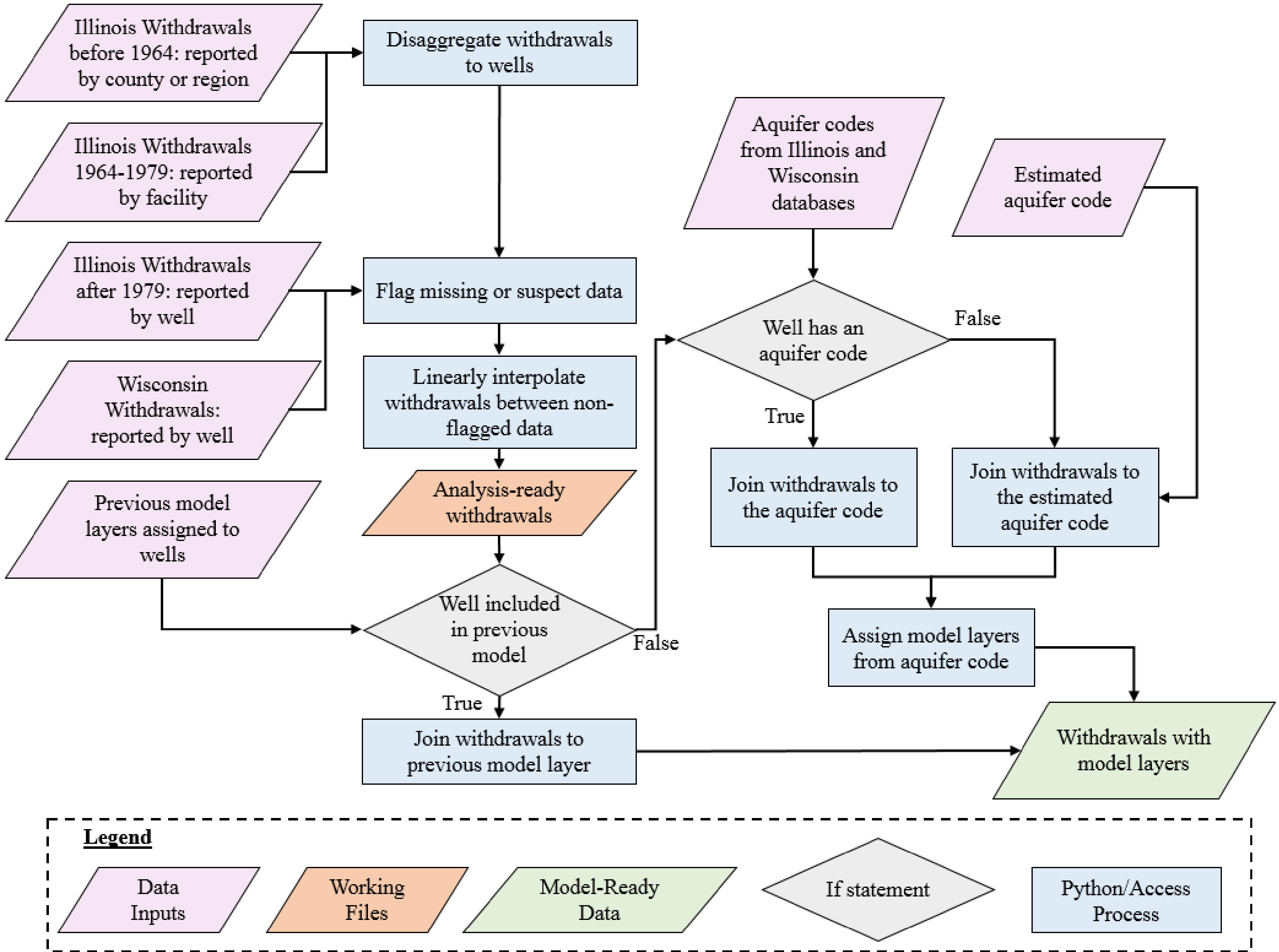

Figure 24: Process diagram depicting the development of model-ready withdrawal data

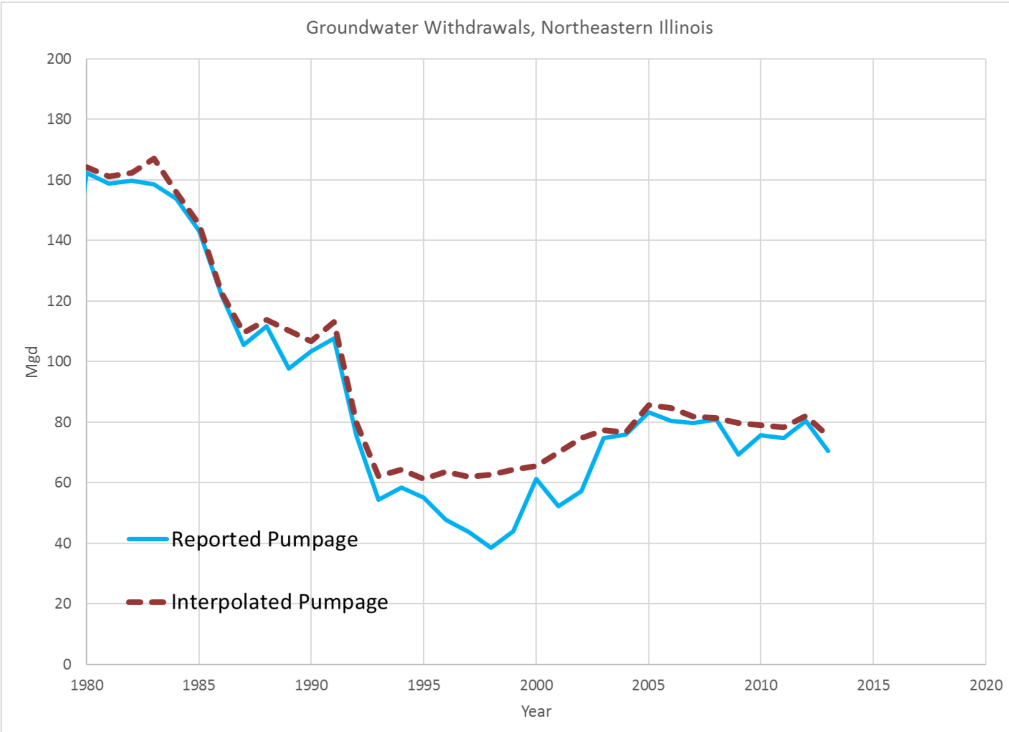

Figure 25: Reported and interpolated pumpage for the sandstone aquifers since the advent of IWIP in 1980

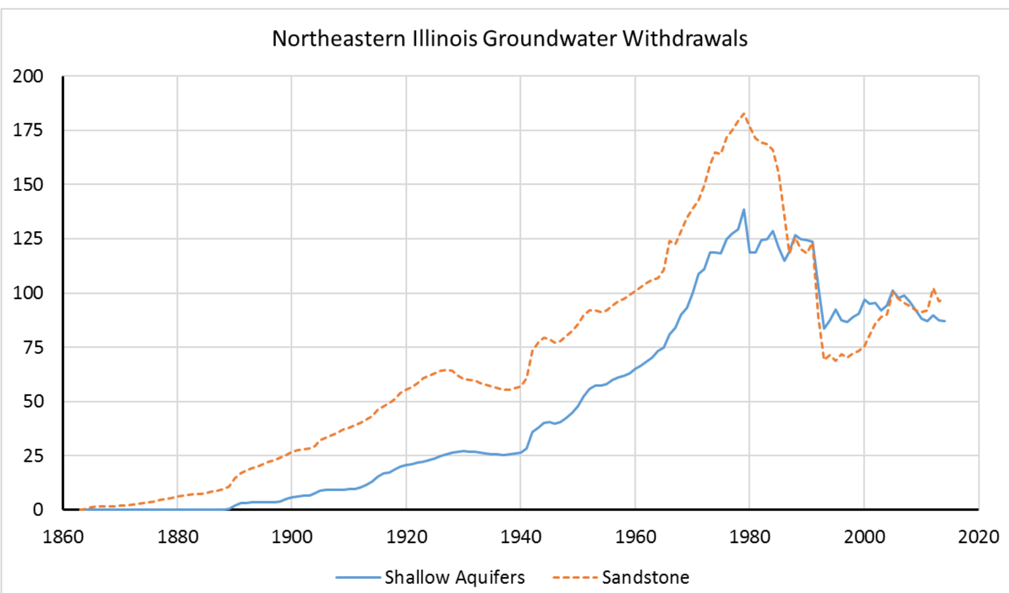

Figure 26: Northeastern Illinois withdrawals from the Cambrian-Ordovician sandstone aquifer system and the combined unconsolidated/weathered bedrock aquifers

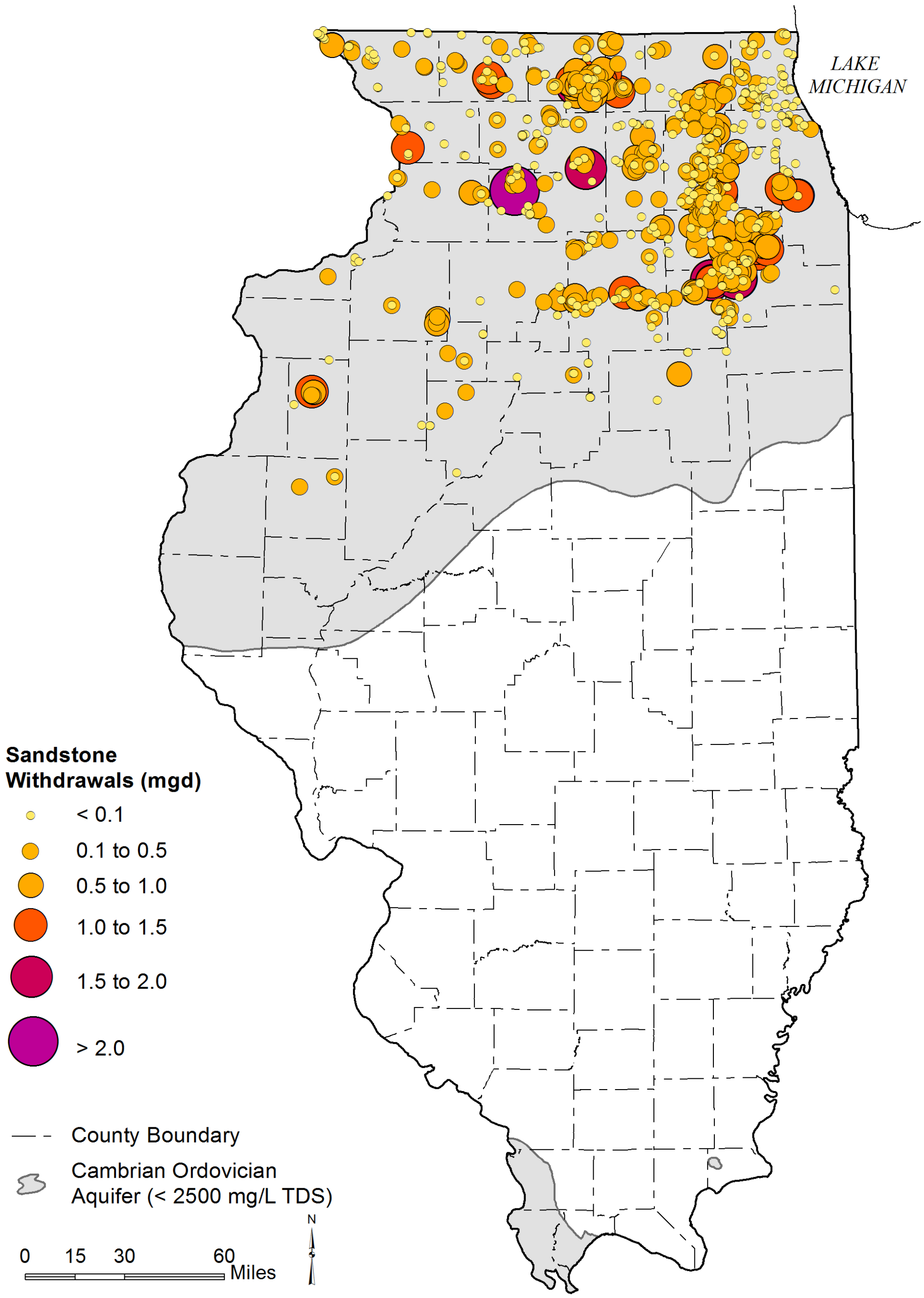

Figure 27: 2013 withdrawals from the Cambrian-Ordovician sandstone aquifers

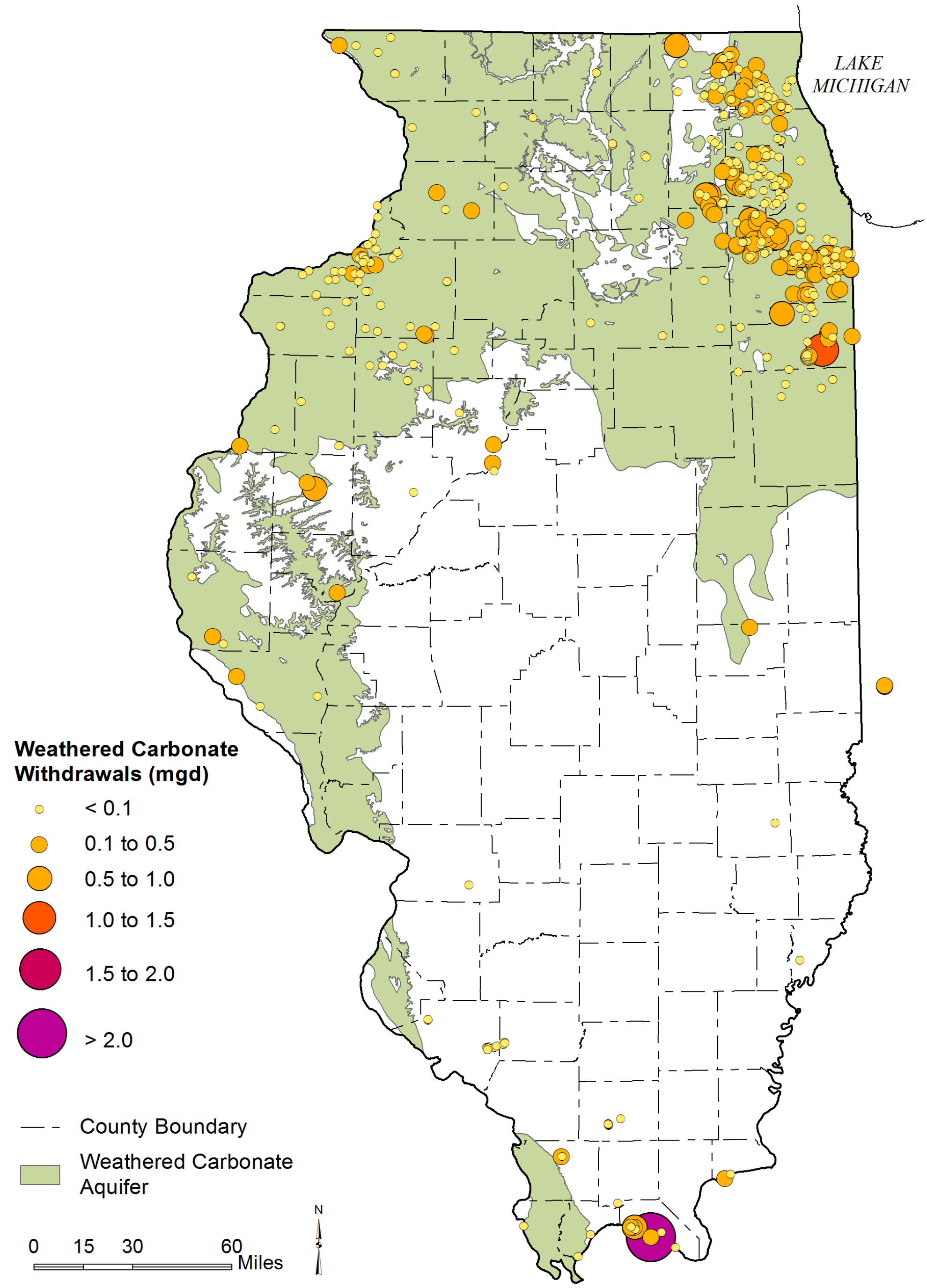

Figure 28: 2013 withdrawals from weathered carbonate bedrock aquifers in Illinois

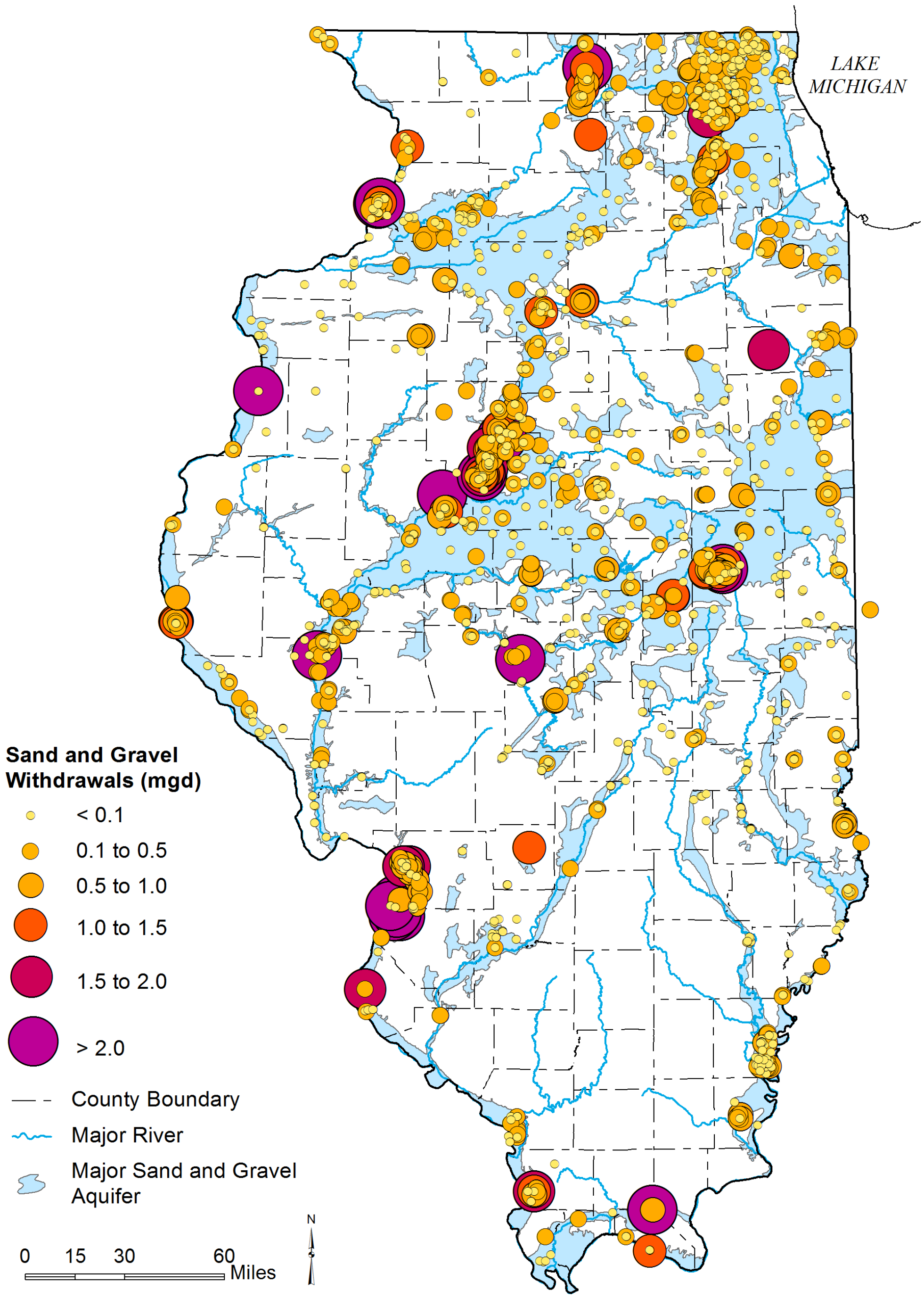

Figure 29: 2013 withdrawals from sand and gravel aquifers in Illinois

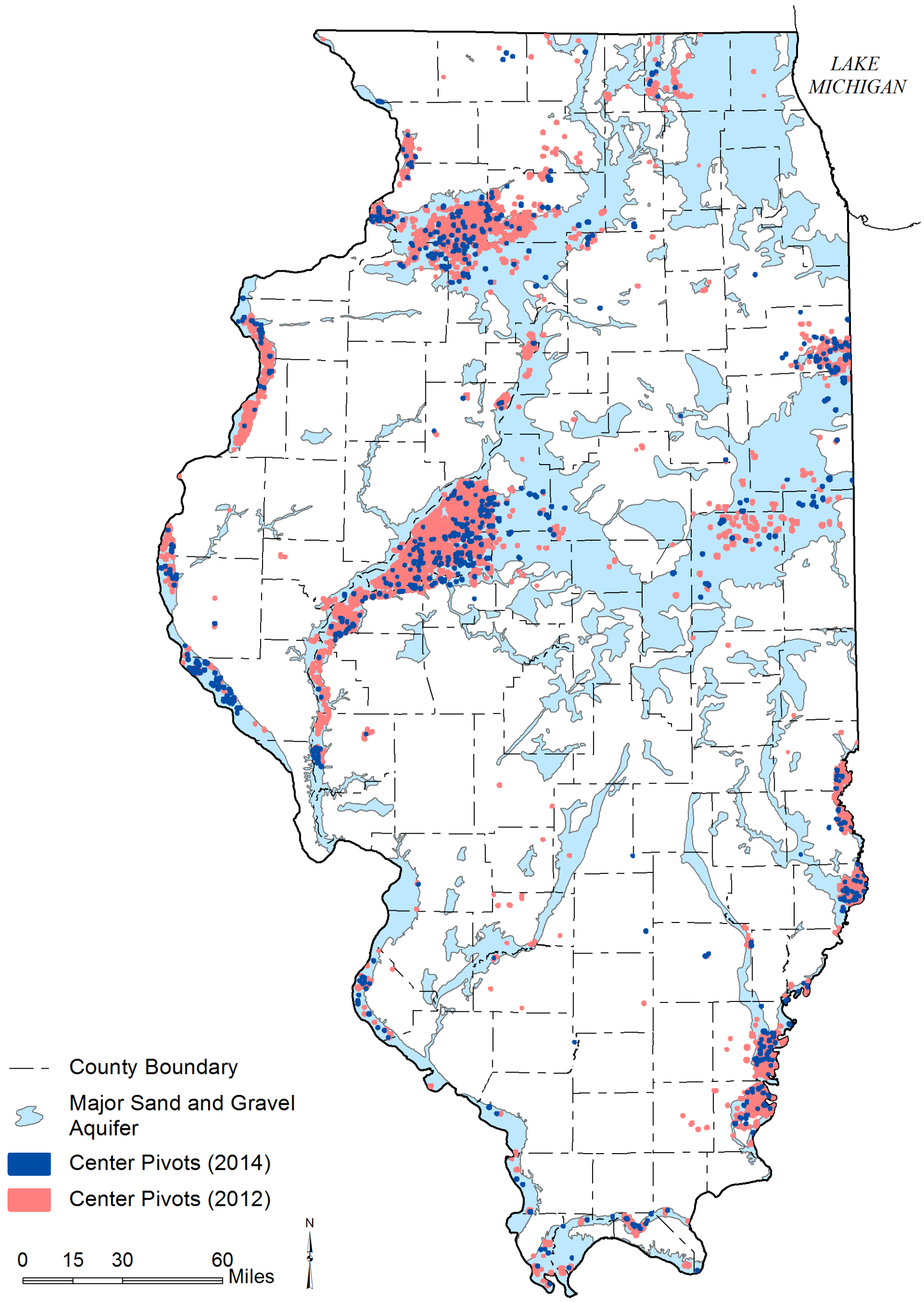

Figure 30: Location of irrigated acreage attributed to center pivots in 2012 and 2014 in Illinois. Size of irrigated acreages is slightly exaggerated for purposes of display (from Bridges et al. (2015)).

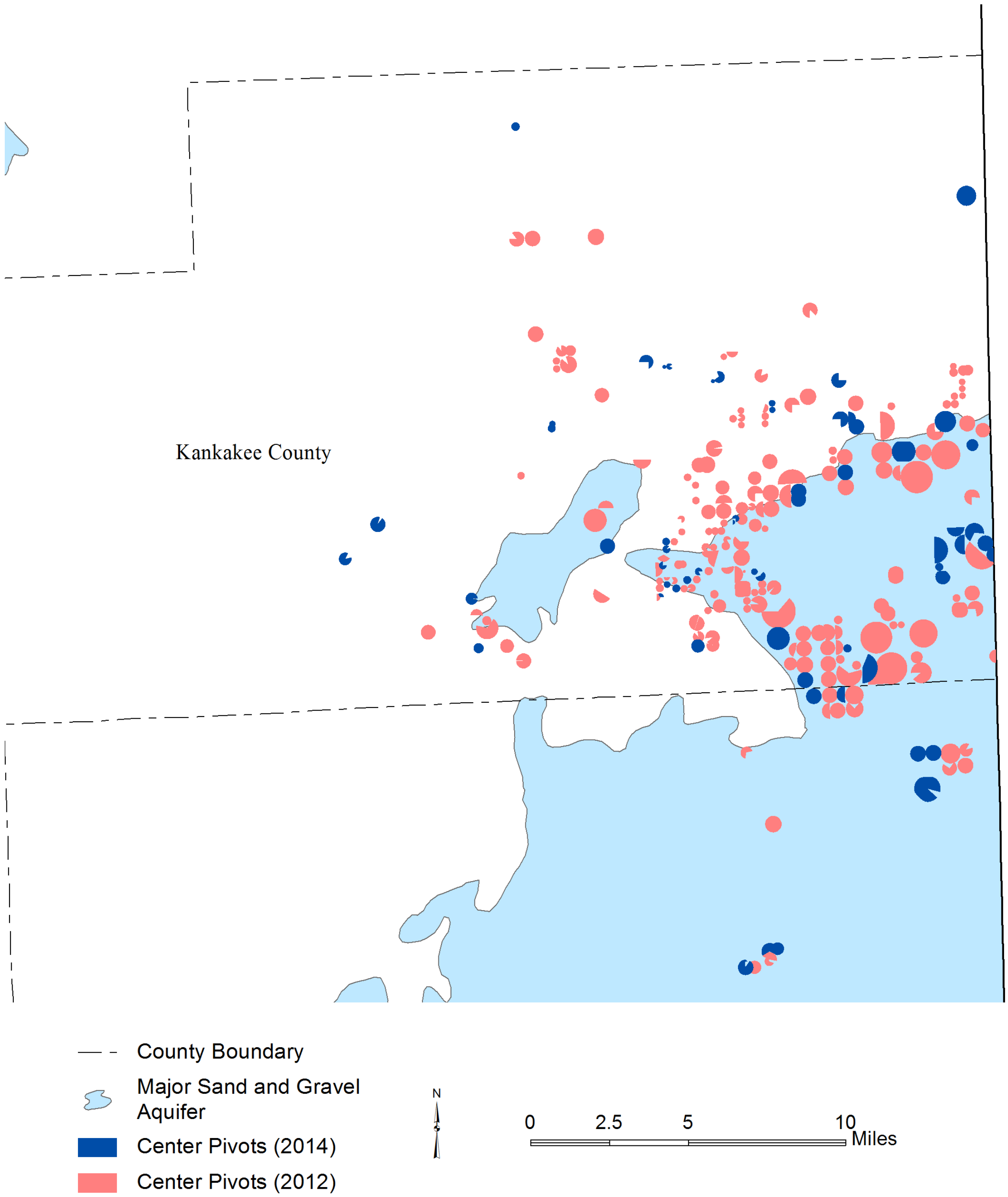

Figure 31: Location of irrigated acreage attributed to center pivots in 2012 and 2014 in Kankakee and Iroquois Counties (from Bridges et al. (2015))

7 ISWS calibration toolbox

7.1 Water level data

The ISWS has a long history of collecting water level data from both dedicated observation and active production wells. Hard copy files in the records room at the ISWS contain water level data from before 1900. The ISWS water level database includes measurements from multiple synoptic studies of the sandstone aquifers in northeastern Illinois conducted by ISWS staff over the years (Suter et al., 1959; Visocky, 1997; Burch, 2008; Abrams et al., 2015), with the most recent conducted in 2014. Although not repeated with the same frequency, the database also includes multiple county or city-scale measurements of shallow bedrock and sand and gravel aquifers in the northeastern Illinois region (Roadcap et al., 1993; Meyer, 1998; Locke and Meyer, 2005). Furthermore, drillers sometimes provide the static and pumping level from new residential and public supply wells, which can be used as targets in otherwise unstudied areas. In addition, some facilities report water levels through IWIP, which can provide valuable information in the years intervening a synoptic measurement.

The ISWS has a growing monitoring network of shallow aquifer and sandstone wells by collaborating with partners throughout the state. These wells, which are often equipped with pressure transducers that can record near continuous water levels, can facilitate data analysis on a more refined time scale, particularly valuable for the contouring models developed in highly irrigated regions. Proper analysis of observed water level data is contingent on accurate knowledge of the well's open interval. The procedure for identifying the open interval of a monitoring well is the same as that for a pumping well, though for those installed by the ISWS, complete data are available.

7.2 Calibration

The common modeling practice has been to calibrate groundwater flow models to observed data from a single year. This calibration is generally conducted for predevelopment conditions in a steady-state simulation. In addition, the model is also generally calibrated in a transient simulation to the most recent observed head dataset available (provided pumping for that year is also available). This process of calibration ensures that the simulated heads are a reasonable match to observed heads, both spatially and vertically for specific snapshots in time. However, there are multiple ways to converge onto a well-calibrated solution for a single year in a transient simulation, which means that both historic and future simulations may be in error, even if the model is calibrated to both predevelopment and a single year. Hence, there is often a need to at least consider all available data during calibration.

Achieving calibration to multiple points in time is much more difficult than to a single dataset from one point in time. Many factors can change over the timeframe captured by a model simulation. For example, additional pumpage will place new stresses on an aquifer, resulting in well interference and perhaps even interference with observed heads used as calibration targets. Furthermore, long-open interval wells may introduce new sources of water to an aquifer by connecting it to a second aquifer. Lacking a discrete way to simulate these connections, model properties will have to change transiently, as discussed in Section 4.4. These transiently changing factors may reveal important insights into aquifer conceptualization and parameterization that were not obvious from calibration to data from a single time.

Transient calibration in a regional model is cumbersome, even when using commercially available software. For the IGWFM in particular, we needed to evaluate model statistics through time, simulation error maps at specific points in time, differences between layers, and differences between previous simulations. Such analyses, however, allow the modeler to make improved decisions about potential conceptual models or parameterizations that could improve the calibration. To this end, we developed the ISWS Calibration Toolbox to aid in the development of the IGWFM presented in this report. This toolbox is one of the scripted tools within ENIGMMA to help in the evaluation of new model results after new data (pumping, geologic surfaces, etc.) are updated in the IGWFM.

The ISWS Calibration Toolbox imports the simulated heads from a MODFLOW simulation and a point shapefile containing the observed heads. Attributes for these heads include location, layer, and time information to facilitate matching to the simulated, transient head grid. Furthermore, the attributes include three user-defined parameters that allow for quick analyses of the performance of a subset of the observations. The graphical user interface developed for the calibration toolbox allows users to perform a number of analyses on all observations or a subset based on selected layers, stress periods, and user-defined parameters.

The interface currently offers four main features to assess a current model's calibration performance, listed below. Figure 32 through Figure 35 demonstrate these capabilities using an early iteration of the IGWFM. Chapter 8 discusses the calibration statistics for the current version of this model.

1) Calibration plot. Capabilities provided by this feature are the development of an observed vs. simulated plot, as well as five error statistics (mean, absolute mean, root mean square, minimum, and maximum). The "Group by" option in the "Calibration plot" menu allows users to classify points by stress period, layer, or any of the three user-defined parameters. Figure 32 shows an observed vs. simulated plot of heads for all times and layers from an early version of the IGWFM.
2) Calibration statistics. This feature allows users to view the change in calibration statistics by layer, stress period, or one of the three user-defined parameters. Options for calibration statistics include mean error plots (mean error, root mean square error, and absolute mean error) and quantile plots. Figure 33 shows the change in calibration statistics from stress period 118 (1980) to stress period 152 (2014) for wells open to the sandstone.
3) Spatial plot. This feature allows users to view a spatial map of errors, interpolated from the point differences between observed and simulated heads. This option allows users to map only a single layer and stress period at a time. Figure 34, which is based on an early version of the IGWFM, shows the spatially interpolated error in heads from observations taken during the last synoptic measurement in 2014 (stress period 152) and that are open to the Ironton-Galesville (layer 18).

4) Comparison. This feature allows users to view an observed vs. simulated plot for two model runs or to map the difference in heads in two model runs for a single stress period and layer. Figure 35 depicts a simulated Ironton-Galesville head comparison taken in stress period 118 (1980) for two model runs with different conceptualizations of multi-aquifer wells.

The ISWS Calibration Toolbox can accommodate any model grid and properly formatted shapefile. As a result, the same toolbox will be able to assess the impacts of any future conceptual model or parameterization changes in the IGWFM and to analyze any local-scale models derived from the IGWFM. A future goal of ENIGMMA is to use this toolbox to generate an automated comparative analysis of model performance compared to the previous version. This will be particularly important as we move to near real-time updates of datasets that are automatically linked to the groundwater flow models.

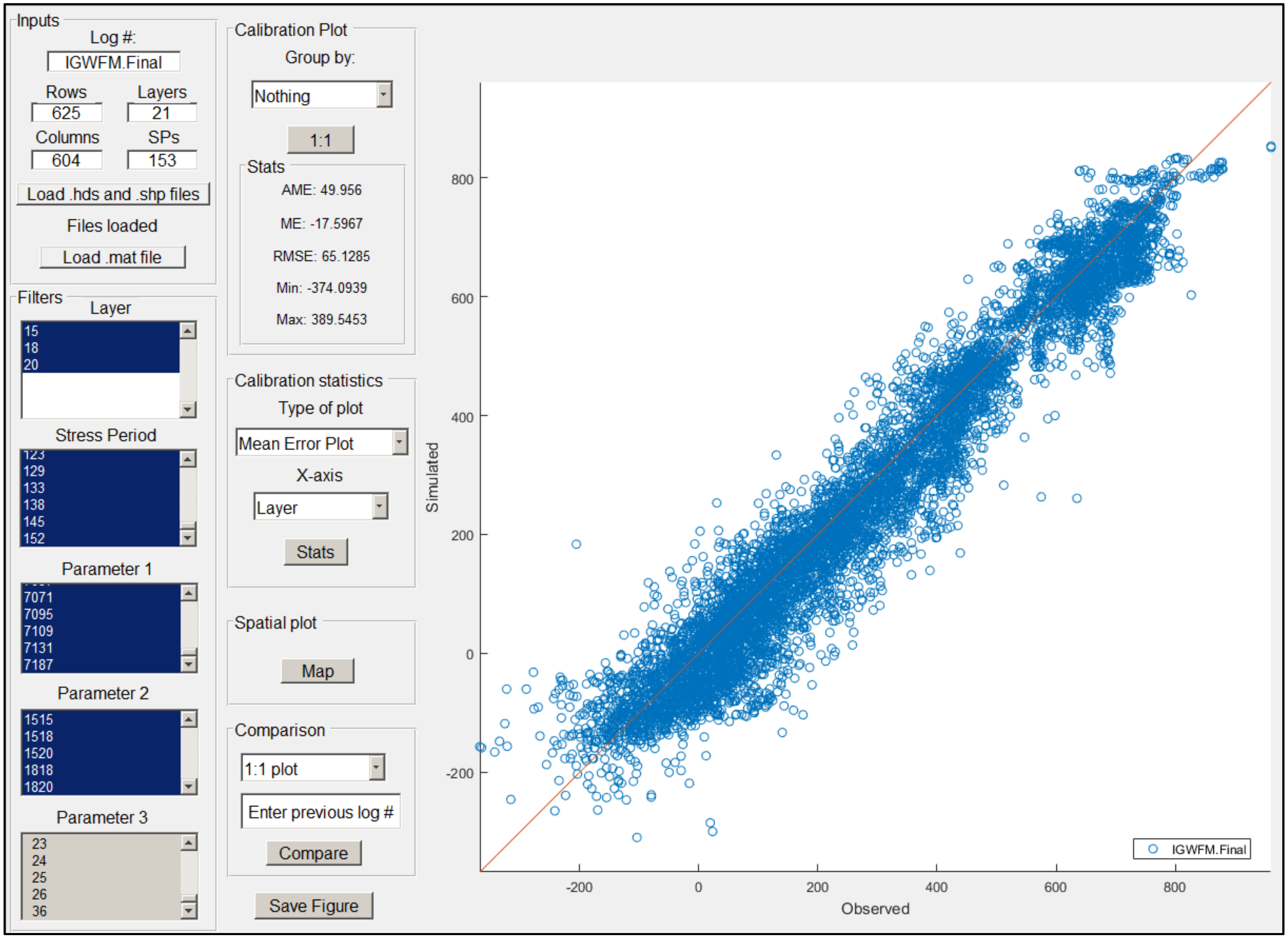

Figure 32: Graphical user interface of the calibration toolbox depicting a 1:1 plot of observed vs. simulated heads and calibration statistics: Absolute Mean Error (AME), Mean Error (ME), Residual Mean Square Error (RMSE), Minimum, and Maximum

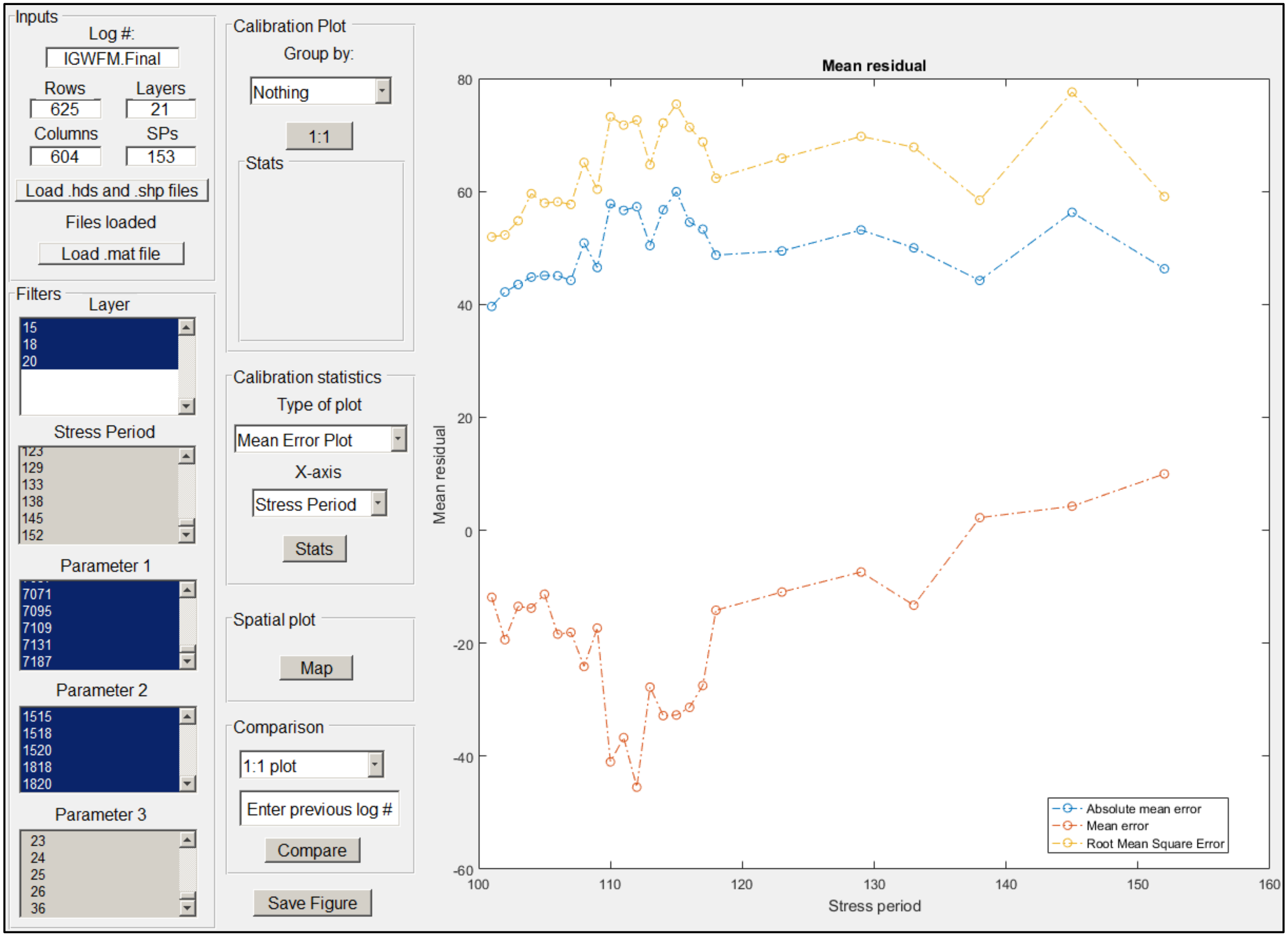

Figure 33: Graphical user interface of the calibration toolbox depicting the change in calibration statistics through time

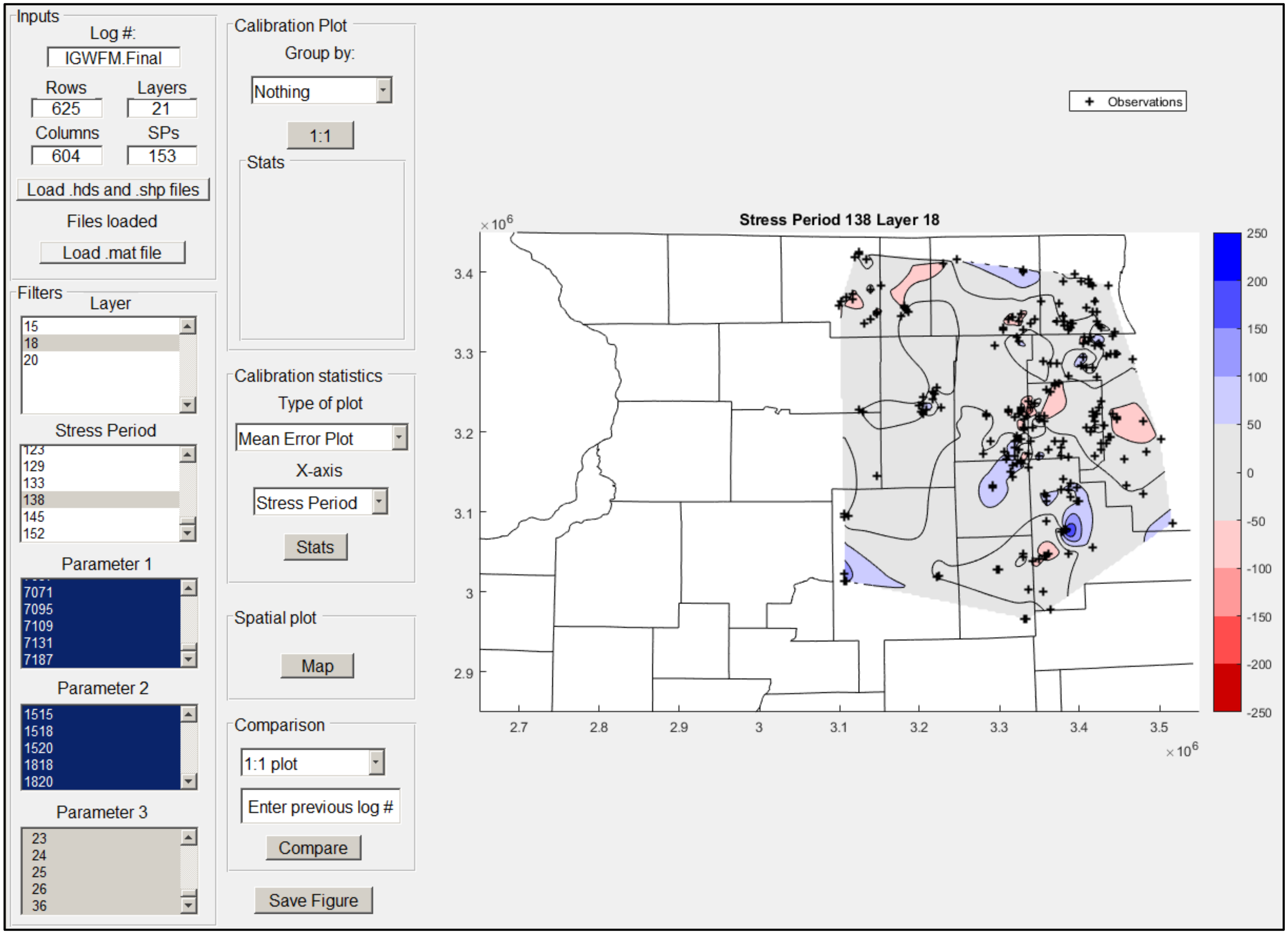

Figure 34: Graphical user interface of the calibration toolbox depicting an error map comparing simulated to observed heads. Red indicates that simulated heads are too low and blue indicates that simulated heads are too high.

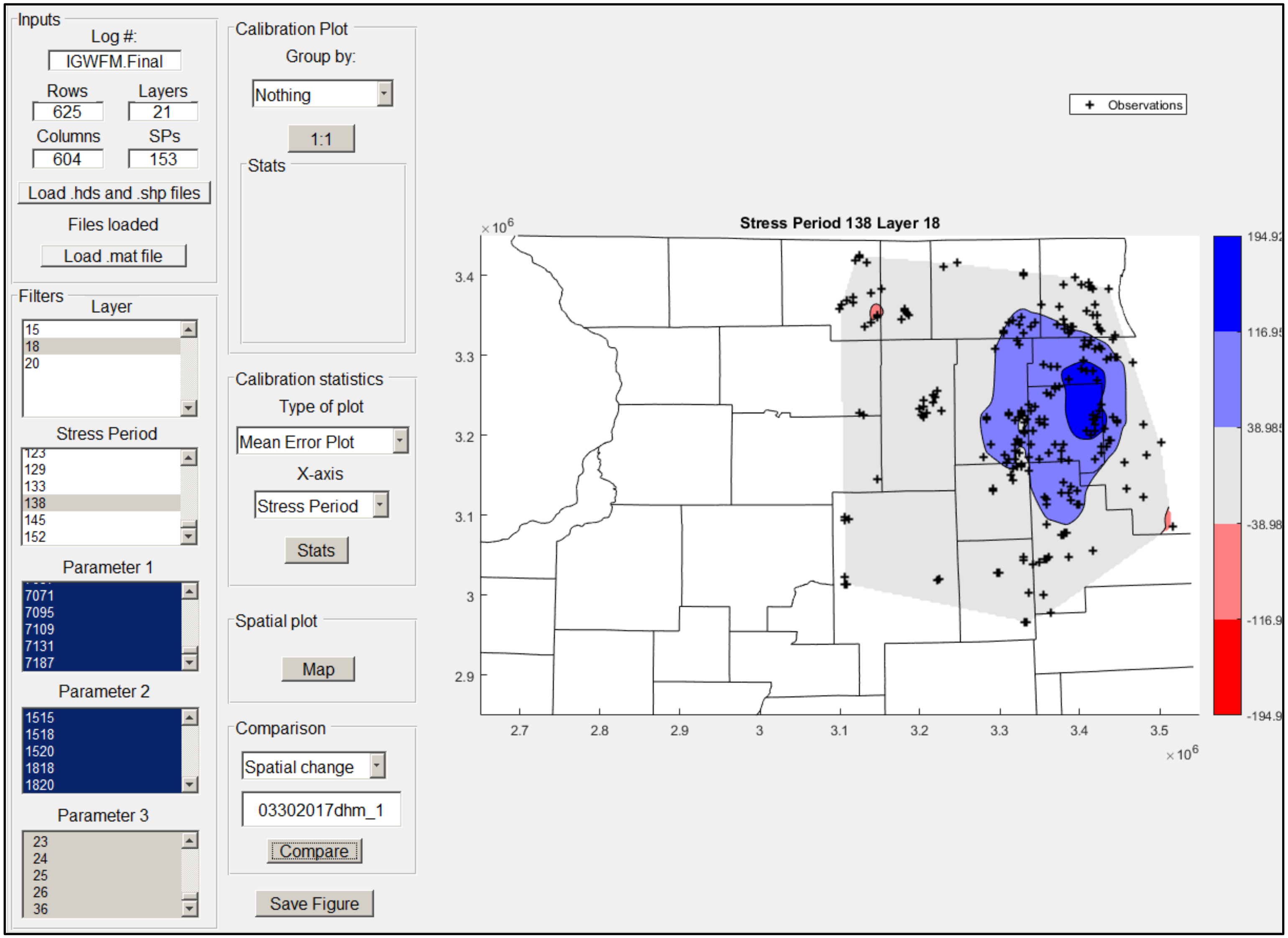

Figure 35: Graphical user interface of the calibration toolbox depicting the change in heads between two model simulations. Blue indicates that the current model simulation (IGWFM.Final) has higher heads than a previous, uncalibrated model simulation (03302017dhm_1).

8 The Illinois Groundwater Flow Model (IGWFM)

The IGWFM is the primary regional model for ENIGMMA and the emphasis of this report. This chapter focuses on the current version of the regional model and initial efforts to develop local-scale models for the Middle Illinois Water Supply Planning region and the Mahomet Aquifer.

8.1 Model settings

The IGWFM uses MODFLOW-USG, the last official release of the USGS finite-difference code (Panday et al., 2013). MODFLOW-USG is an unstructured grid solver that provides a number of advantages over the traditional MODFLOW-2000 solver. First, MODFLOW-USG offers a robust handling of dry cells. The IGWFM is particularly sensitive to cells where the head falls below the bottom of a cell, indicating that the cell is dry. This is most problematic in the driftless area of northwestern Illinois, where multiple units may be dry in reality and in the model simulation. Traditional MODFLOW solvers (PCG, SIP) struggled or failed to converge. Furthermore, these solutions resulted in local spikes in the potentiometric surface that were created by excessive recharge bypassing dry cells and mounding onto low permeable material. MODFLOW-USG, however, was able to create a suitable solution with a minimal mass balance error that eliminated these spikes.

A second major advantage of MODFLOW-USG is the ability to pinch out layers where a hydrostratigraphic unit is less than 1 foot thick, which was the thickness assigned to layers where they are not present. Since these cells are removed entirely from the matrix, the model has fewer nodes to solve for during the finite difference solution. Model runtimes decreased by a factor of four when enabling the pinch-out option.

A third advantage of MODFLOW-USG is that it allows for the simulation of nested grids within the regional model, as is demonstrated in this chapter for the Mahomet Aquifer. A drawback of doing this, however, is the inability to pinch out layers when using a nested grid, which increases computation time and decreases the numerical stability considerably. Nested grids vs. more traditional TMR approaches will be a topic of future research.

The SMS solver used for MODFLOW-USG has more settings than the traditional MODFLOW solver. We have not experimented from the default settings, which could ultimately improve model runtimes. Table 6 details these settings, and will be updated in future versions of this report as settings are optimized for model runtimes and solution quality. An alternative solver approach for MODFLOW-USG, SAMG, allows for parallel processing and has the potential to accelerate the model solution even more, but in the initial tests this solver also appears to be more unstable than SMS and will require further evaluation.

Table 6: Solver settings used in the IGWFM

SMS Setting	Value
HCLOSE	0.001
HICLOSE	1e-5
MXITER	250
ITERI	600
IPRSMS	1
NONLINMETH	1
LINMETH	1
THETA	0.7
AMOMENTUM	0
NUMTRACK	200
BTOL	1.1
BREDUC	0.2
RESLIM	1

xMD Solver Options	Value
IACL	1
NOORDER	0
LEVEL	7
NORTH	14
IREDSYS	0
RRCTOL	0
IDROPTOL	1
EPSRN	0.001

8.1.1 Model performance

One of the contributing factors to slow model runtimes and unstable solutions is the presence of dry cells. The original version of MODFLOW removes all withdrawals in cells that are dry, creating numerical instabilities and large dry well flow losses (Harbaugh et al., 2000). To improve the computational stability of the solution and eliminate excessive dry well flow loss throughout the model domain, newer versions of MODFLOW, including MODFLOW-USG, have options that reduce withdrawals as the groundwater head falls within a user-defined threshold above the bottom of a well cell. In other words, wells do not go dry instantaneously in the simulation, which creates a more stable solution (Niswonger et al., 2011; Panday et al., 2013). Although other factors can slow model convergence, the elimination of dry cells is the most important factor in speeding up model simulation time (at least in the experience of all modelers involved in developing this report).

By taking advantage of MODFLOW-USG, the current model successfully convergences on the criteria listed in Table 6 for all 153 historic stress periods (the remaining 45 stress periods are for simulation of future pumping conditions out to 2060). The mass balance error, defined as the percent difference between total simulated inflow and outflow, was less than 1e-6 ft^3/day for all stress periods. The current model runtime on all machines at the ISWS is approximately 19 hours. It should be noted that a comparison to model runtimes with standard MODFLOW is not available, as the older solvers could not achieve convergence because of the prevalence of dry cells in northwestern Illinois's Driftless Region, an area that was not simulated before this study.

In addition to adversely impacting the model runtime, any simulated flow reduction from assigned model inputs diverges from the pumpage distribution in reality. We seek to minimize simulated total flow reductions (Figure 36). The peak of the flow reduction occurred in the mid-1990s, with a maximum of 3.5 mgd removed from the simulation. Most of this was due to pumping that was removed from the model simulation but did not result in dry cells (partial flow reductions). Flow reductions associated with dry cells never exceeded 1 mgd. Both values are within the margin of uncertainty in actual pumpage, with most of the flow reduction occurring in central Wisconsin; as a result, this eliminated pumpage is not likely to have a major impact on the model results. However, continued reduction of these values will provide better overall model performance.

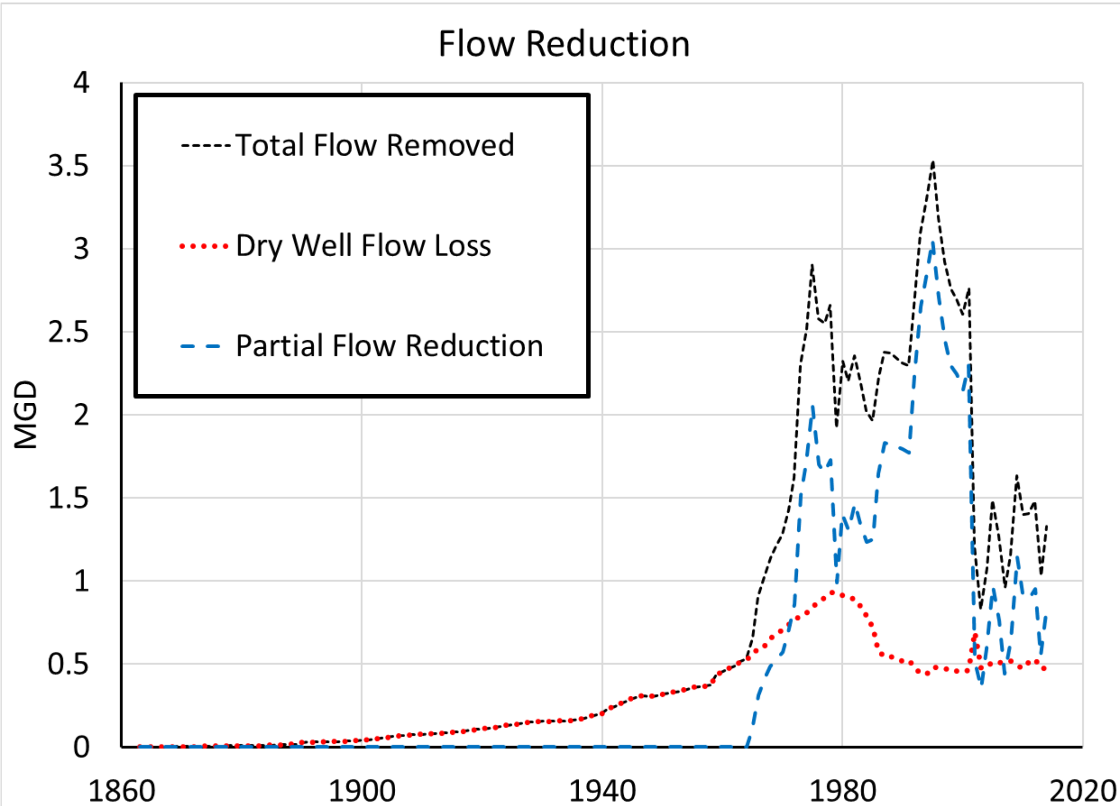

Figure 36: Simulated flow reduction (both partial and complete due to dry cells)

8.2 Regional sandstone aquifer simulation

The IGWFM is the first model developed at the ISWS with the purpose of evaluating flow in the sandstone aquifers throughout *all* of northern Illinois and portions of neighboring states. This section highlights changes made to the IGWFM to facilitate this regional calibration and features key results related to the sandstone aquifer.

8.2.1 Changes to the regional IGWFM

Previous studies of the regional impact of sandstone withdrawals have focused on northeastern Illinois (Meyer et al., 2009; Roadcap et al., 2011; Meyer et al., 2012; Meyer et al., 2013). These regional sandstone models were relatively refined (2500-foot grid spacing) in northeastern Illinois, but coarse (up to 25,000-foot grid spacing) in other areas of the state. Although this spacing was sufficient for studies of the northeastern Illinois cone of depression, the model was too coarse to simulate flow properly in the rest of the state, including the natural recharge zones to the sandstone aquifer (blue areas in Figure 5). However, due to advances in computing capabilities, we were able to apply a uniform 2500-foot grid over the entire domain of the IGWFM (Figure 3), using surfaces originally developed for (Meyer et al., 2009).

The previous models both exaggerated the extent of the recharge zone due to coarse cells and assigned constant head cells to the upper layer of this region, providing a source of water to recharge the sandstone with minimal resistance. The amount of water entering through the recharge zone in the previous models, however, was sufficient to achieve calibration in the areas of interest within northeastern Illinois (Roadcap et al., 2013). Since the IGWFM has a well-defined, smaller recharge zone and uses river cells in the upper layer, less recharge reached the sandstone in this region. Consequently, using the same properties and conceptualization as the previous models, the IGWFM lacked enough flow into the sandstone to achieve calibration. To overcome this, we made multiple modifications to the conceptual and numerical models to reflect this improved resolution:

1. The weathered Galena-Platteville and weathered Maquoketa comprise the entire thickness of those units where they are at the bedrock surface. Consequently, the weathered Galana-Platteville zone was included in the weathered bedrock zone, layer 10 through layer 14. Similarly, the weathered Maquoketa zone was included in layer 10 through layer 13. Although these units have likely not formed secondary porosity below 100 feet, ISWS records indicate that wells are often open to a significant portion of the Galena-Platteville and Maquoketa Units. Such wells would not be included explicitly as multi-aquifer wells in the model simulation, but still may provide pathways for water to move vertically to the St. Peter Sandstone, effectively increasing the vertical hydraulic conductivity.
2. Similar to the Galena-Platteville and Maquoketa, the Potosi-Franconia was weathered over its entire thickness where it was present at the bedrock surface. However, the values assigned to weathered Potosi-Franconia were too high to extend over the entire thickness of the unit. As a result, a slightly less weathered zone is also included in layer 17 in this area, providing an additional source of water to the Ironton-Galesville.

3. Previous models did not explicitly simulate multi-aquifer wells connecting shallow aquifers to deeper sandstones, bypassing the Maquoketa Shale. This iteration of the model explicitly includes those connections (Figure 17). Most of the shallow aquifers connecting to sandstones are not very transmissive, and each individual multi-aquifer well contributes only a small amount of water from the shallow to the sandstone in the model simulation. However, the net total of water entering from these multi-aquifer well connections is significant. Since the network of multi-aquifer wells change throughout the simulation, we chained together three model runs using different hydraulic conductivity zonations for each time period.
4. Previous models treated the Sandwich Fault Zone as a discrete feature, consistent with its shapefile coverage. However, data indicates that the zone is much wider than a single 2500-foot cell, so the width of the zone (90) was increased to reflect these data (Figure 16) and hydraulic conductivity was increased to achieve calibration. Calibration was not possible within the fault zone at this regional scale due to unmodeled local complexities.
5. Previous models used a large zonation to simulate a high vertical hydraulic conductivity in areas with dense multi-aquifer wells that separated sandstone. After an extensive database analysis of point-level information, the IGWFM now depicts multi-aquifer wells as single cells rather than a large zone (Figure 17-20). This modification improved the model's capability to capture observed head separation between sandstone layers in western Joliet, while maintaining the observed equilibration of heads between the sandstones throughout most of northeastern Illinois.
6. The IGWFM has some modifications to zonations compared to previous iterations. First, the unweathered Prairie du Chien-Eminence has the same zonation as the unweathered Potosi-Franconia. This change was made since the Prairie du Chien-Eminence is generally not an aquifer in Illinois except where weathered. Although these two units are currently both in the model's geologic framework, a single zonation will allow a combination of the two layers in future iterations of the model.
7. Another major zonation change was in the Eau Claire. Previous models included a facies change in the Eau Claire that ran through northeastern Illinois, shifting from shale near Lake Michigan to carbonate near the recharge zone. However, well logs indicate shale in the Eau Claire throughout northern Illinois and into Wisconsin. The layer depicting the Eau Claire pinches out near the Wisconsin River where the Eau Claire grades into sandstone. Consequently, the carbonate zone of the Eau Claire was removed and we treated the layer everywhere it had thickness as shale.
8. The Driftless area in the northwestern portion of Illinois introduced a number of complications, particularly related to model stability. Temporary zones within the weathered bedrock layer 10 have been assigned specifically to improve the simulation in this area (Table 3), with minimal influence on the regional solution. However, local simulation of the Driftless area will require more detailed investigation.
9. The Quaternary layers as derived from the stack maps defined the zonation of layers 1–9, replacing the five-layer unconsolidated material in the previous models. This allowed for an improved (albeit still approximate) simulation of flow through bedrock valleys in the central portion of the state.

10. The above modifications required changes to the zone numbers found in specific model layers and the values assigned to those zones. Table 3 compiles the current zonations and their associated layers.

8.2.2 Calibration results for sandstone aquifers

The IGWFM is reasonably well calibrated for targets from all times and the most recent synoptic measurement in 2014 (Table 7). The simulated heads in the model are, on average, too low before 1997 and too high afterward (Figure 37). However, the mean error does not range by more than 50 feet through time, as opposed to over 200 feet for previous simulations that used a single hydraulic conductivity zonation throughout the entire history of pumping and did not chain models together. The absolute mean error is always near 50 feet, while the root mean square error is always near 60 feet. This likely represents the inherent noise in the static water levels from production wells used as targets in this study. This calibration is a significant improvement over the entire history of pumping compared to previous simulations.

There do not appear to be any major biases by layer in the 2014 calibration (Figure 38). Simulated St. Peter and Mt. Simon heads do appear to be slightly biased too high, while Ironton-Galesville targets do not appear to be biased in any direction. Spatial plots of heads in the St. Peter and Ironton-Galesville provide an additional means to evaluate calibration (Figure 39 to Figure 44). The simulated heads tend to be too low in Cook and DuPage Counties in 1980 for both sandstones (Figure 41 and Figure 42) during the peak of pumping in that area. This bias is not present in 1964 (Figure 39 and Figure 40) or 2014 (Figure 43 and Figure 44).

Simulated heads are also too high in the northwestern portion of the state in both sandstones for 1980 and 2014 (Figure 41 to Figure 44). The most likely explanation is the influence of unsimulated withdrawals in Iowa, which the model currently represents as a no-flow zone. Future model iterations will incorporate geology and withdrawals from Iowa into the groundwater flow model.

Table 7: Calibration statistics for the sandstone aquifers within the model domain of the IGWFM

Statistic	**Error (ft)- All Targets**	**Error (ft) – 2014 Targets**
Mean Error	-9.4	13.1
Absolute Mean Error	48.8	46.6
Root Mean Square Error	63.5	59.4
Minimum Error	-357.1	-224.5
Maximum Error	393.1	168.9
# of Observations	8470	512

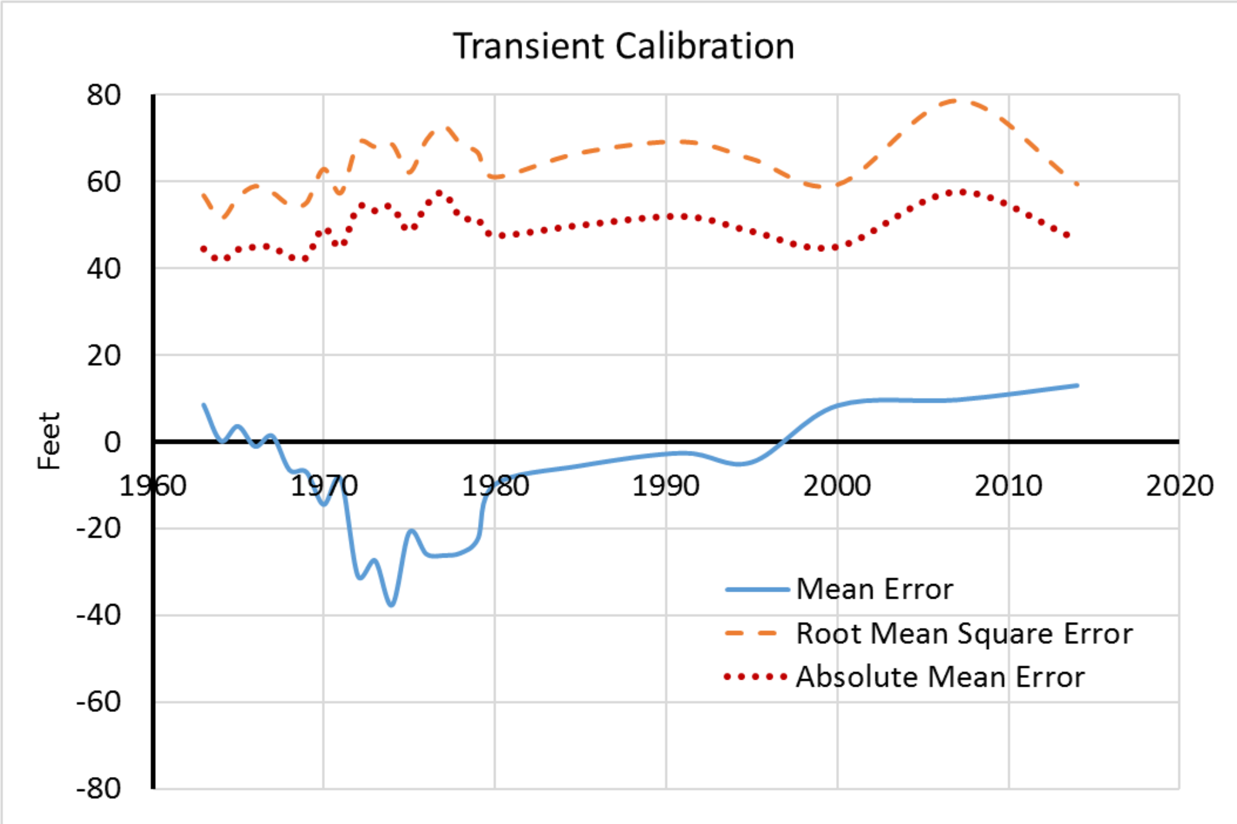

Figure 37: Change in mean, absolute mean, and root mean square error through time for the IGWFM

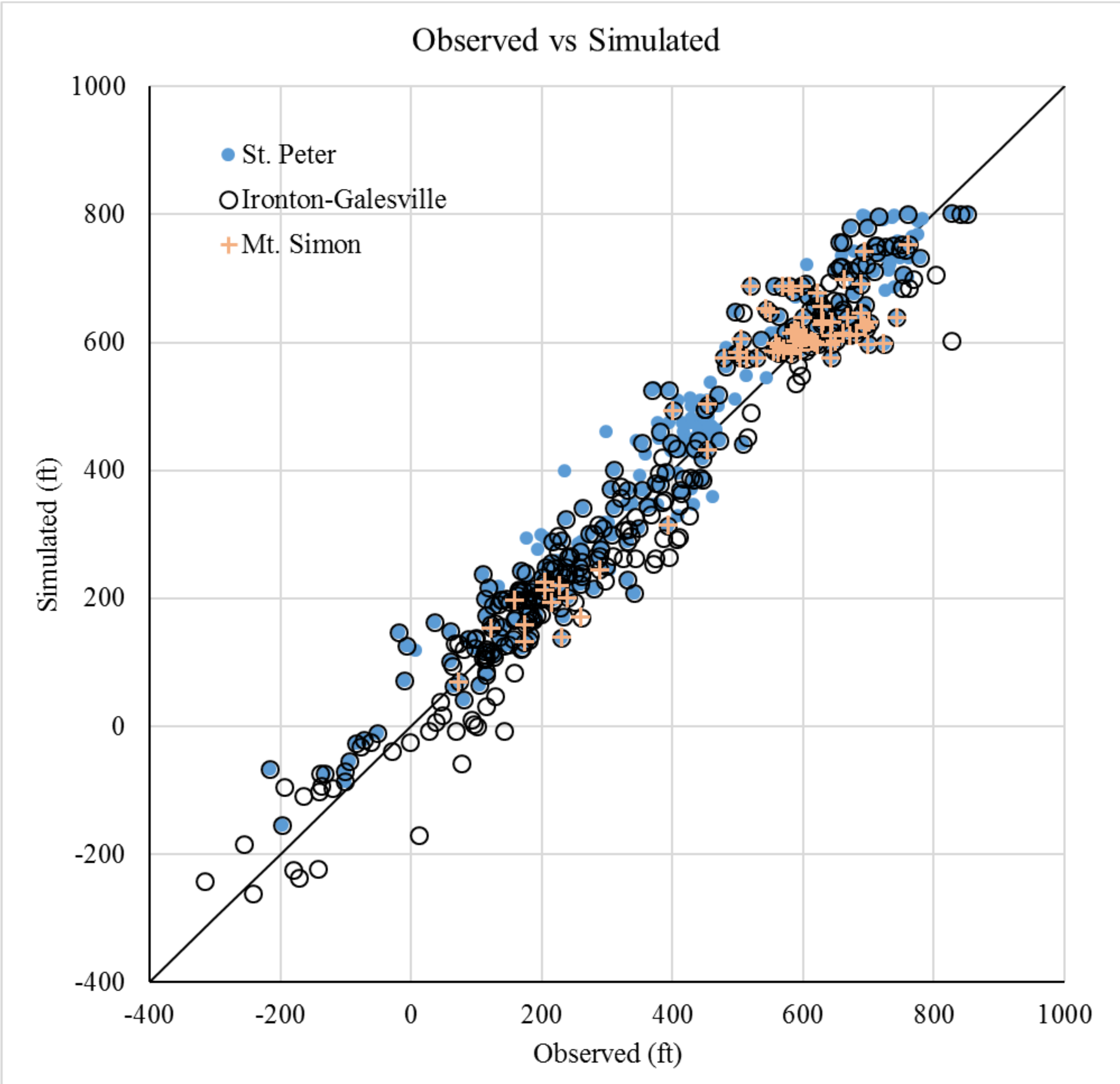

Figure 38: Observed vs. simulated plot for 2014 observations classified by sandstone

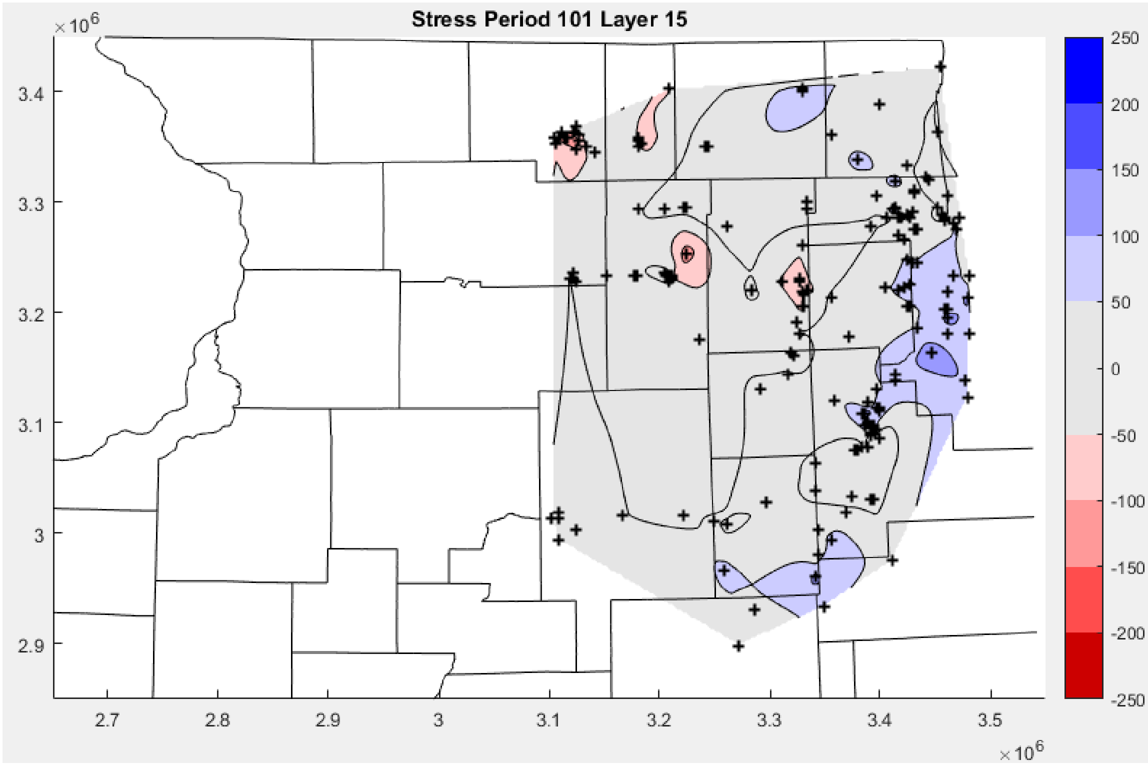

Figure 39: 1964 model calibration to observed St. Peter heads. Image captured from the ISWS Calibration Toolbox.

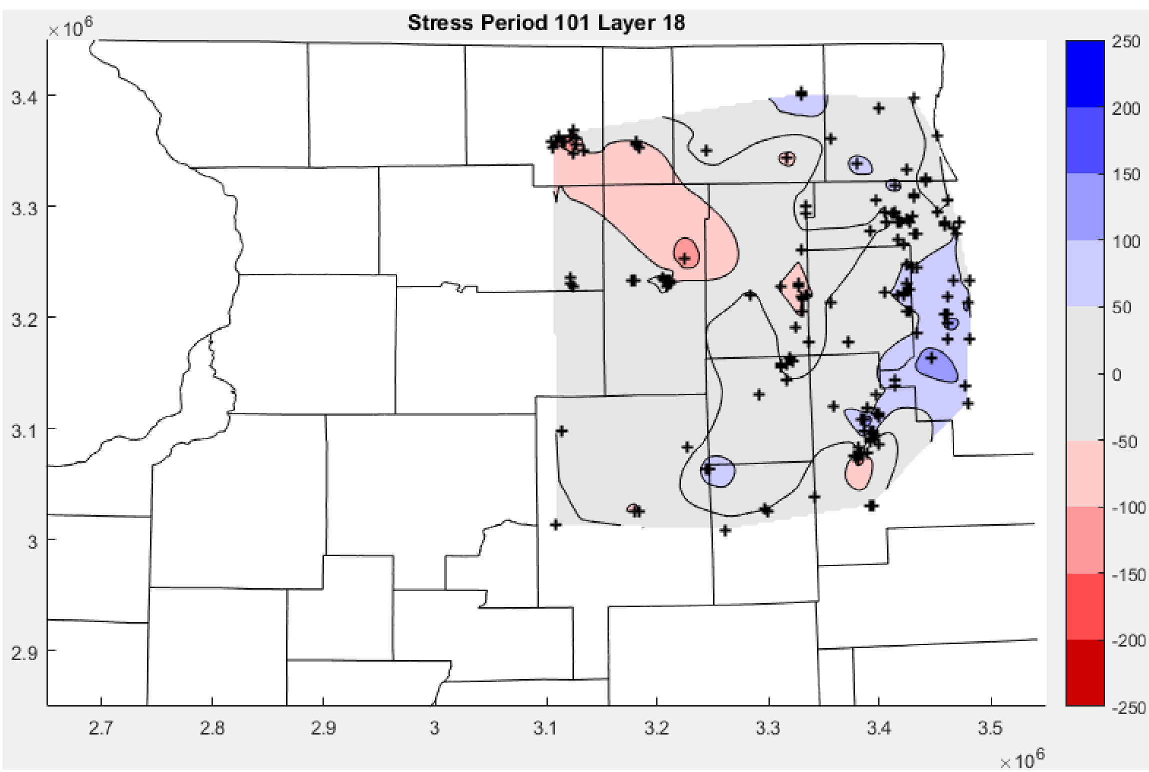

Figure 40: 1964 model calibration to observed Ironton-Galesville heads. Image captured from the ISWS Calibration Toolbox.

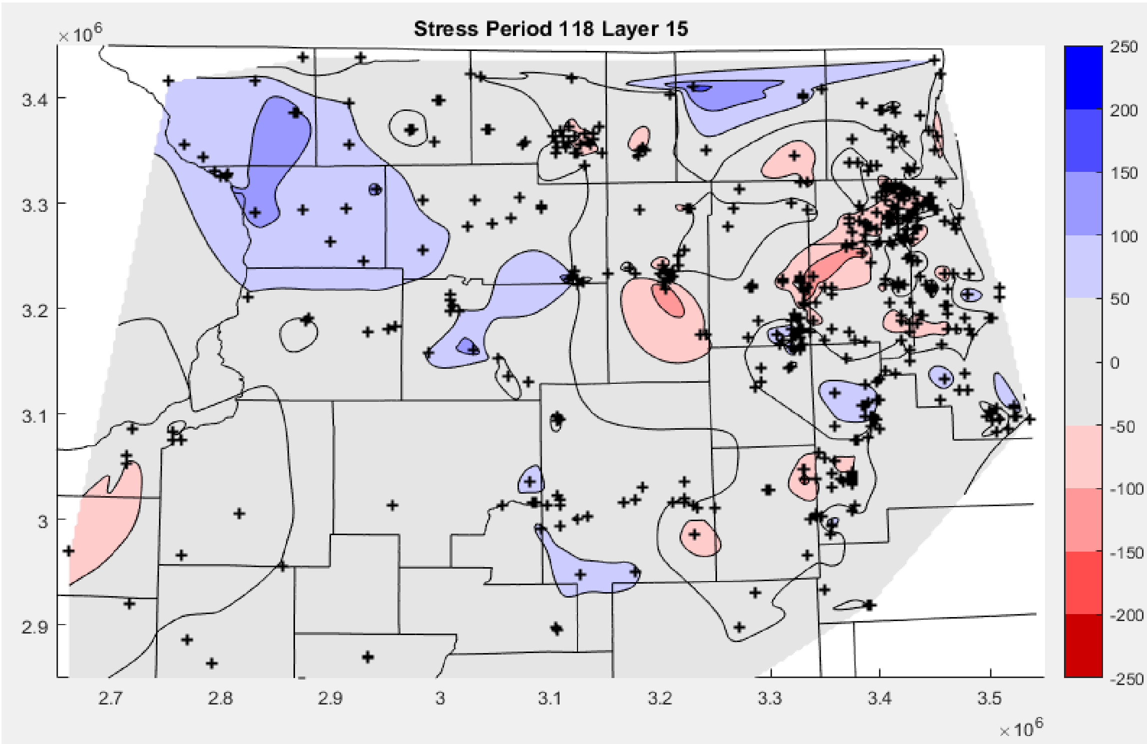

Figure 41: 1980 model calibration to observed St. Peter heads. Image captured from the ISWS Calibration Toolbox.

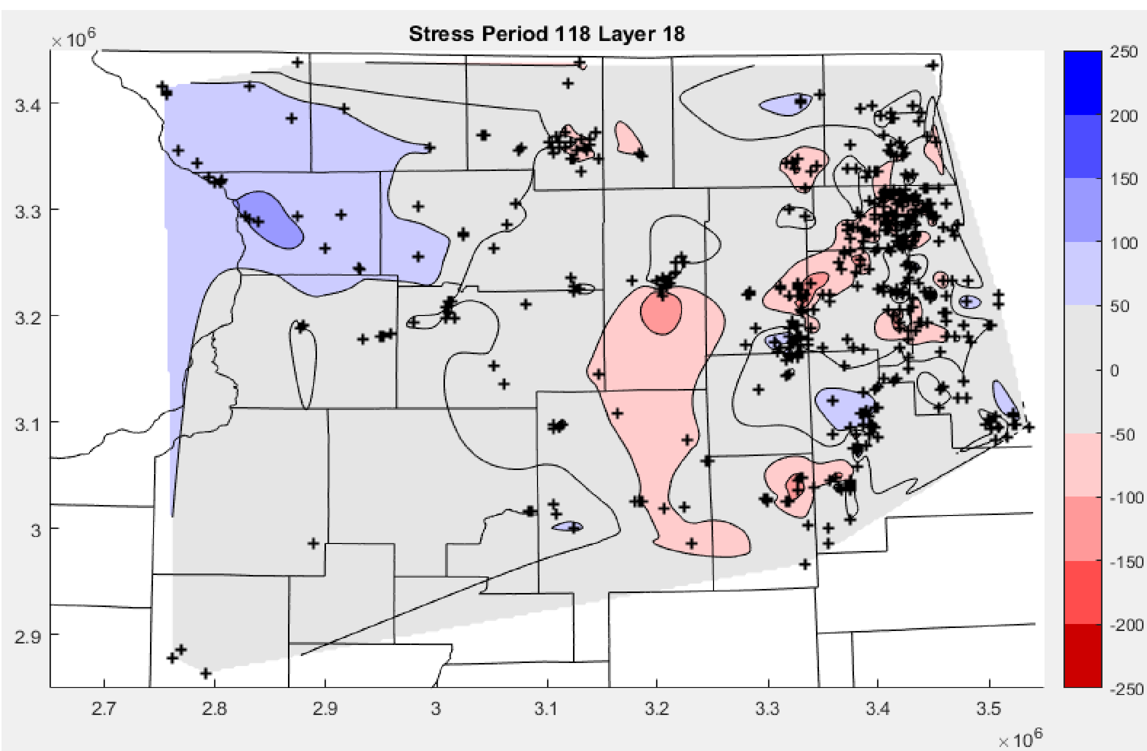

Figure 42: 1980 model calibration to observed Ironton-Galesville heads. Image captured from the ISWS Calibration Toolbox.

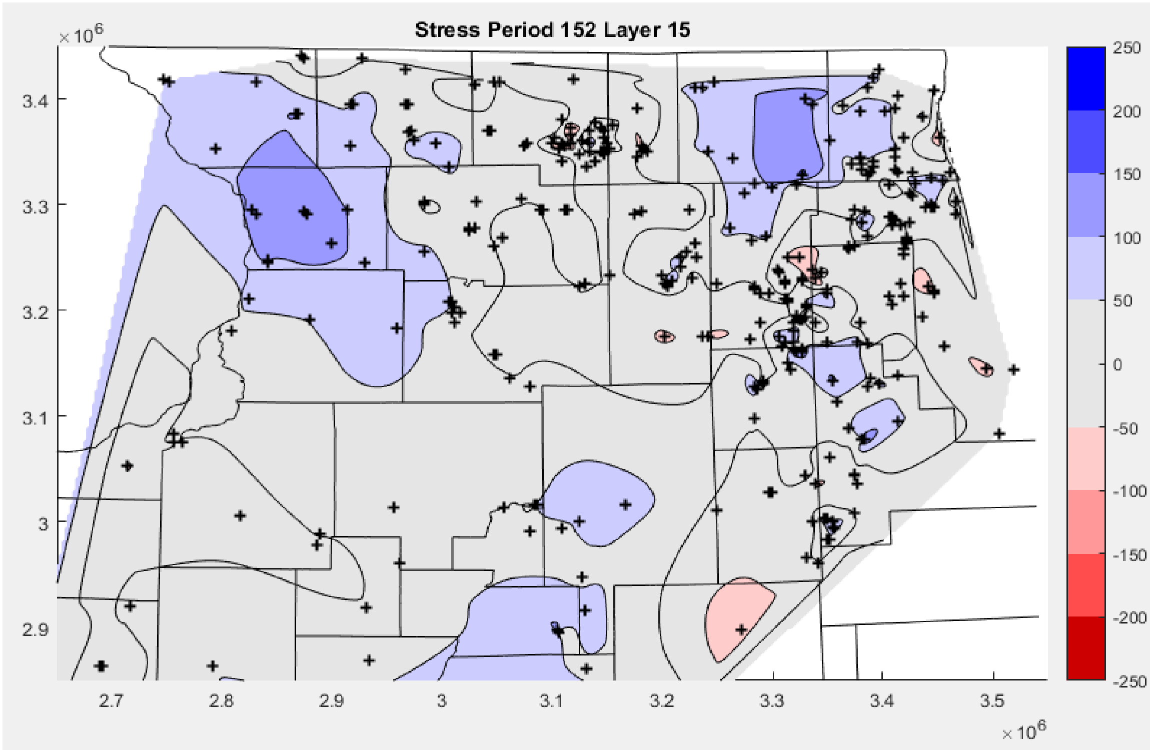

Figure 43: 2014 model calibration to observed St. Peter heads. Image captured from the ISWS Calibration Toolbox.

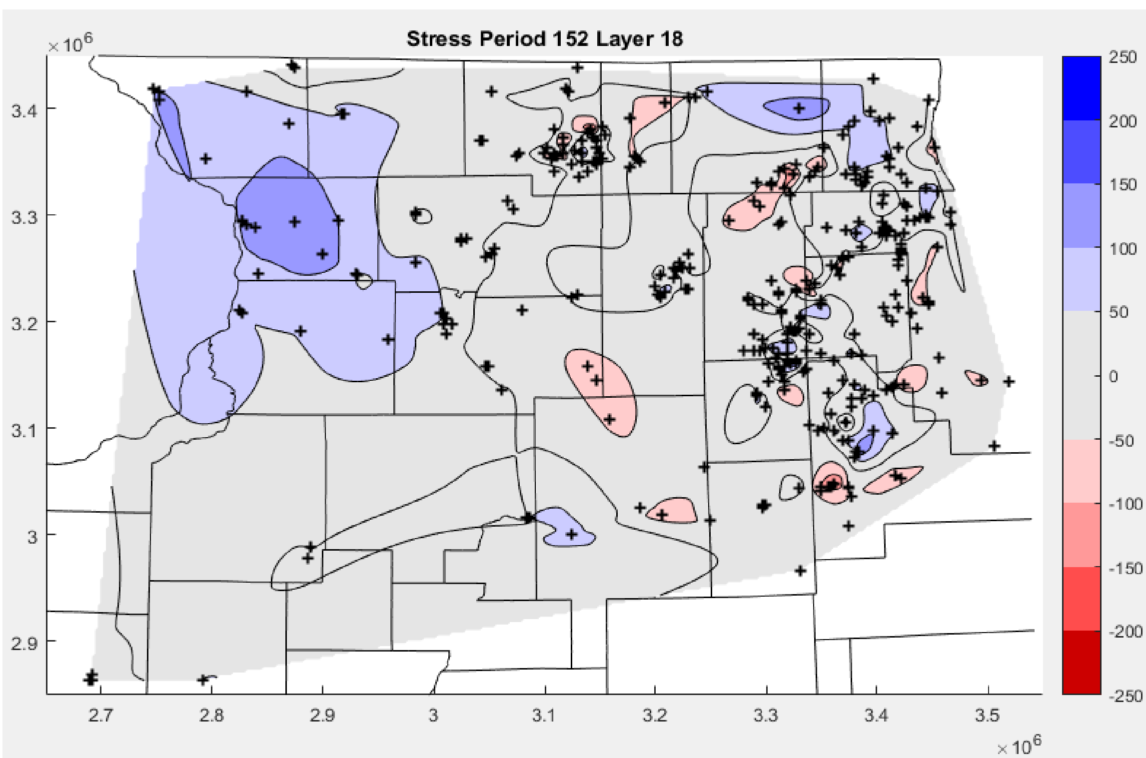

Figure 44: 2014 model calibration to observed Ironton-Galesville heads. Image captured from the ISWS Calibration Toolbox.

8.2.3 Key sandstone results

The IGWFM is calibrated to heads in four dimensions (three-dimensional space and time), which is a key improvement over earlier models of the region, increasing confidence in the simulations of future conditions. We used the Current Trend (CT) scenario developed for northeastern Illinois (Dziegielewski and Chowdhury, 2008), Middle Illinois (Meyer et al., 2018), and northwestern Illinois (unpublished) regions to simulate groundwater conditions out to 2060. Since the demands in northeastern Illinois only went to 2050, we held pumping constant out to 2060. Furthermore, since industrial demands had grown much slower than projected for the groundwater systems in the region, we also held all industrial demands at their current level out to 2060. Note that these results are subject to change, as northeastern Illinois demands are being updated at the time of this report (summer 2018).

We simulated head changes from 2014 to 2060 in both the St. Peter Sandstone (Figure 45) and Ironton-Galesville Sandstone (Figure 46). Future drawdown in the Ironton-Galesville Sandstone is simulated to be much more severe, at least locally in Kendall, western Will, and southern Kane Counties. There are two reasons for this: 1) newly constructed wells in these counties are increasingly open to only the Ironton-Galesville Sandstone, and 2) the Ironton-Galesville Sandstone is deeper than the St. Peter Sandstone and receives less leakage from overlying units. Head change outside of northeastern Illinois is less severe in both aquifers, but still present. Until statewide demands are available for the sandstone, it is difficult to assess future changes in heads in this part of the state. Furthermore, demands from Iowa, which are currently unsimulated, will also play an important role as the sandstone is increasingly used for public supply and industrial demands (Gannon et al., 2009).

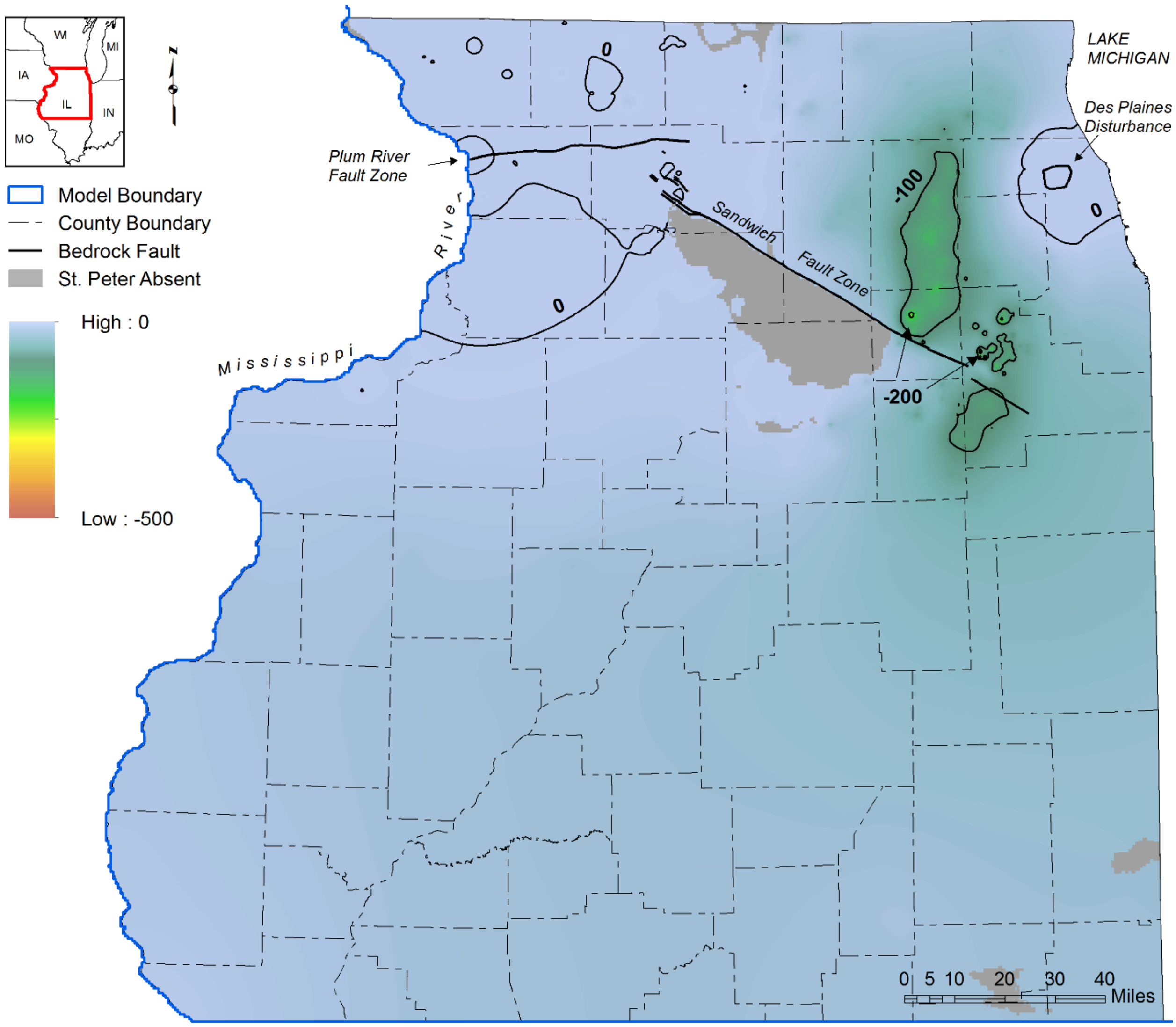

Figure 45: Simulated drawdown from 2014 to 2060 in the St. Peter Sandstone

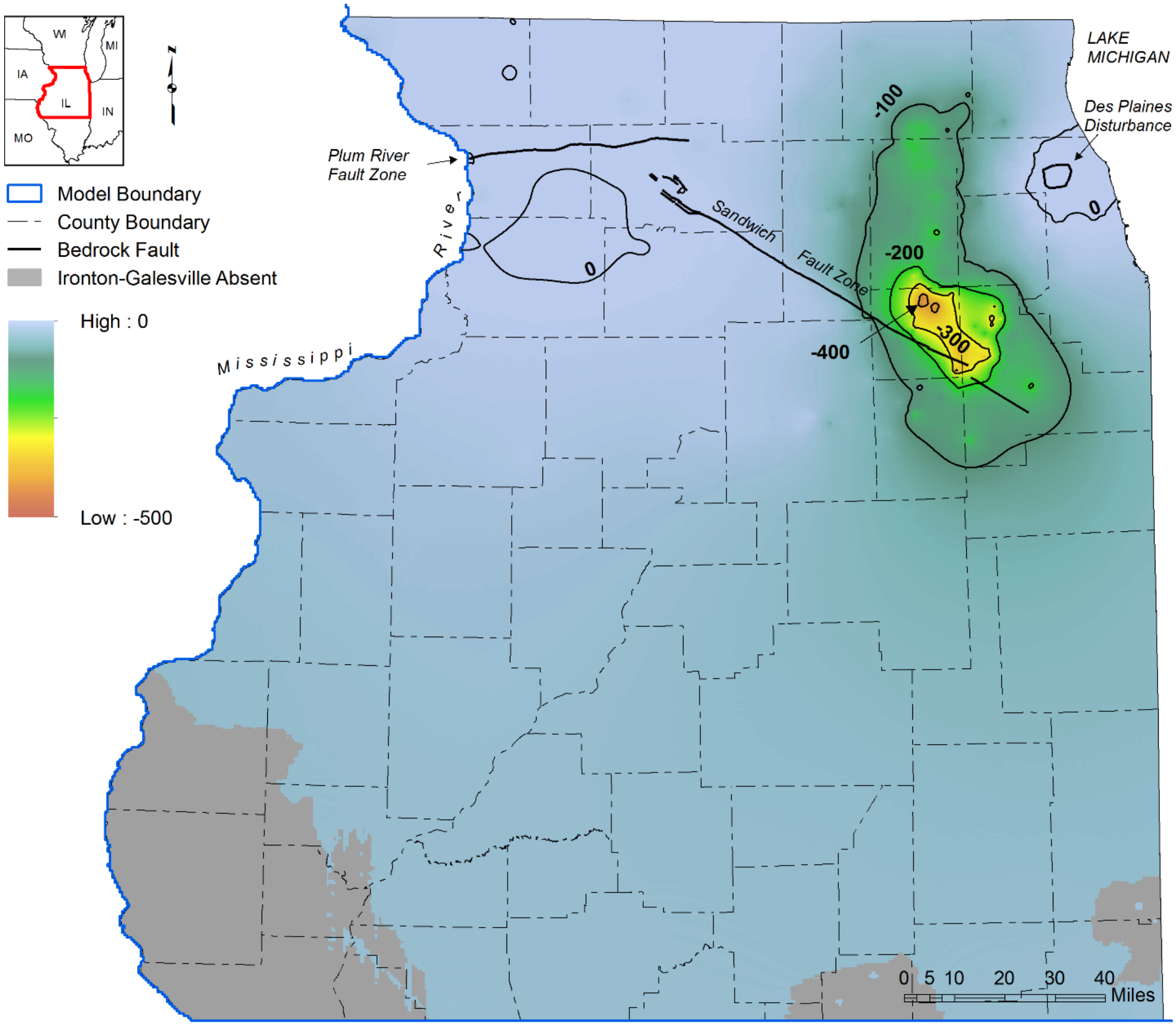

Figure 46: Simulated drawdown from 2014 to 2060 in the Ironton-Galesville Sandstone

Large declines in sandstone heads do not necessarily correspond to at-risk areas, at least not immediately. What truly matters is the available head above the top of each sandstone. When a sandstone aquifer desaturates, a number of water supply issues can manifest, including loss in well production, dry wells, entraining of sand during pumping, and geochemical ramifications.

Risk to the sandstone aquifers was determined for both current and future conditions using simulated drawdown for 2060 based on the CT Scenario. The risk threshold for the two aquifers differs based on well construction trends and expected impacts. Risk is defined as:

1. Available head above the St. Peter Sandstone is less than 200 feet.
2. Available head above the Ironton-Galesville Sandstone is less than 550 feet.
3. In both cases, risk is assigned only if the available head is less than 50 percent of the predevelopment available head, indicating the aquifer has been affected by pumping.

A detailed justification of how risk zones are calculated is beyond the scope of this model report, but will be published in a future water supply planning report on the Kankakee Watershed Sub-region.

Risk zones for the year 2014 are shown for the St. Peter (Figure 47) and Ironton-Galesville (Figure 48) Sandstones. These risk zones are based on a three-dimensional head-specified model (discussed in Chapter 9) of the region, which is a data-driven approach that is not subject to calibration errors in the head. The heads from the head-specified model were compared to the top of the St. Peter and Ironton-Galesville Sandstones to determine the risk as described above.

To calculate future risk, the simulated drawdown from 2014 to 2060 was subtracted from the head-specified model potentiometric surface for each sandstone unit to create a 2060 potentiometric surface. This was done to prevent modern calibration errors in heads from propagating into the future. The subsequent future risk zone covers a greater extent than the current risk zone in both the St. Peter and the Ironton-Galesville Sandstones. The risk in the Ironton-Galesville in particular extends into new areas, including Kendall, Kane, and McHenry Counties, emphasizing the need to evaluate potential alternatives in the coming years. The increased risk in Kendall and Kane Counties has been long recognized (Meyer et al., 2009; Roadcap et al., 2013), but the potential risk in McHenry County is a new observation emanating from detailed investigation of the disparate open interval of wells and trend to wells completed only in the Ironton-Galesville. These results need to be re-evaluated upon completion of the updated northeastern Illinois demands.

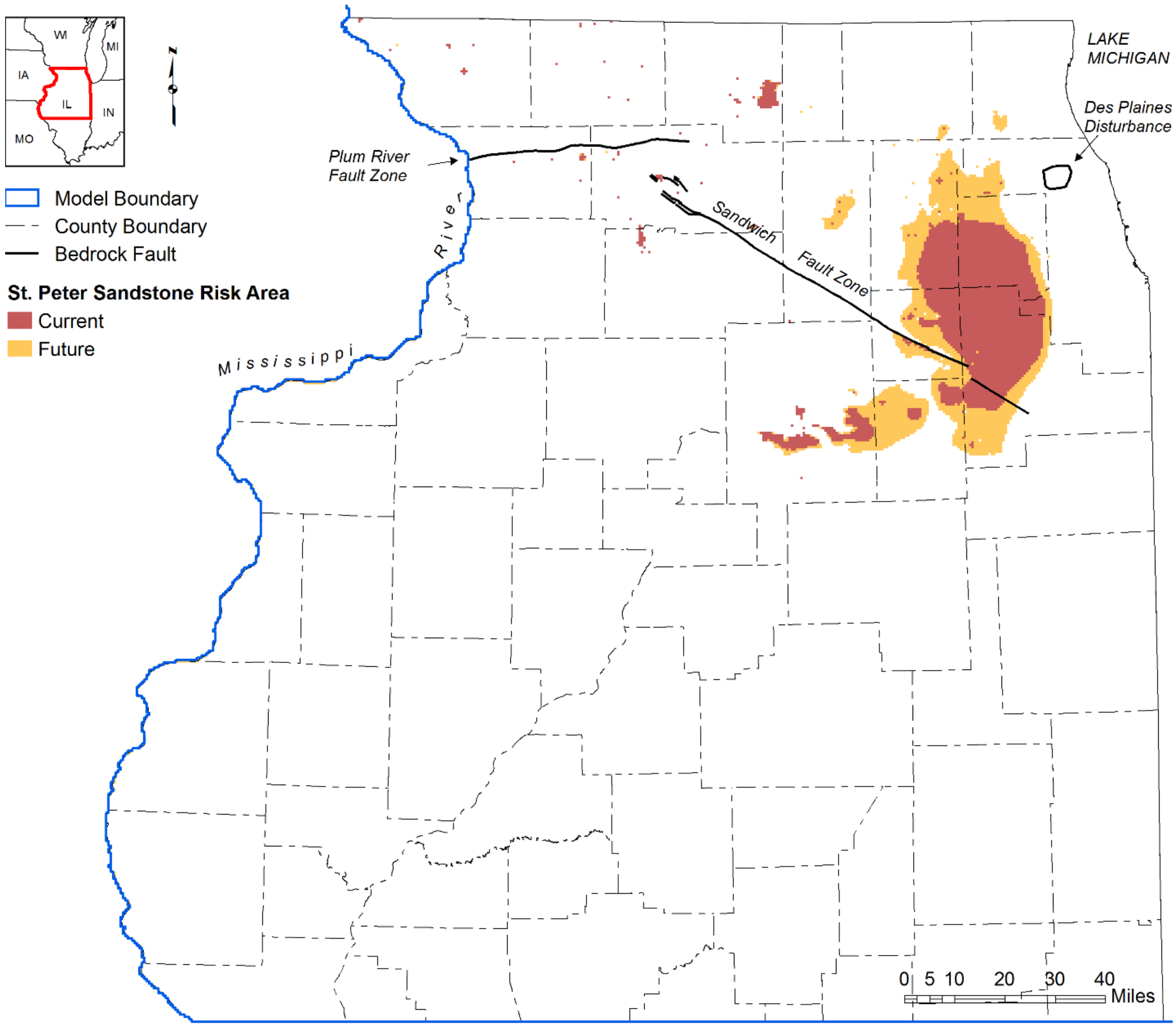

Figure 47: 2014 (current) and 2060 (future) risk zones for wells in the St. Peter Sandstone

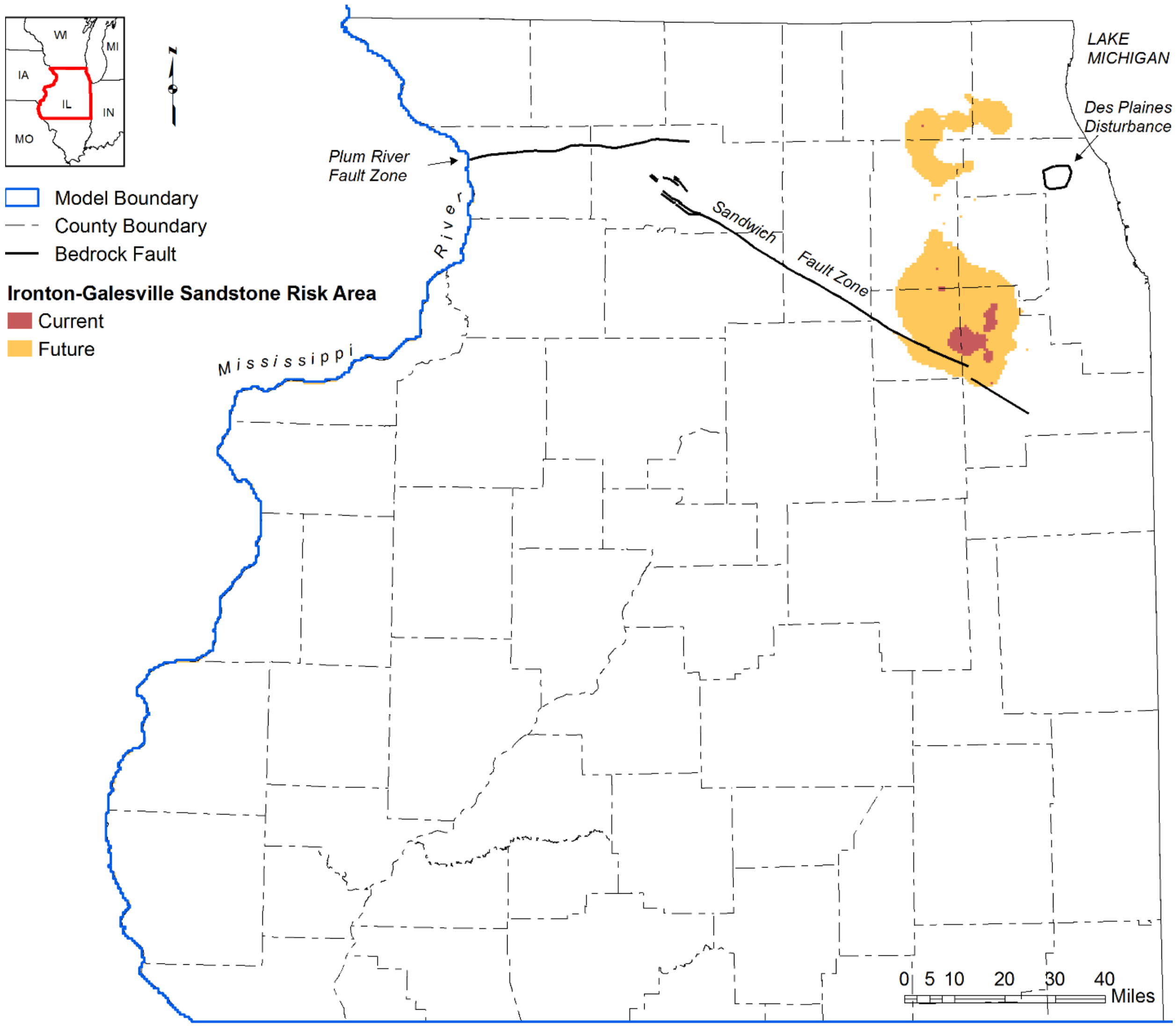

Figure 48: 2014 (current) and 2060 (future) risk zones for wells in the Ironton-Galesville Sandstone

8.3 Middle Illinois shallow aquifer simulation

8.3.1 Development of the Shallow Middle Illinois model within the IGWFM

The Middle Illinois Water Supply Planning Region, outlined in Figure 49, is the trial region for the methodology defined in Section 4.1.2.3 to depict the Hydrostratigraphic units of the Quaternary geology through a database method, depicting zones for coarse and fine-grained materials. Figure 50 depicts the fine- and coarse-grained materials of the Middle Illinois Water Supply Planning Region is north-south and east-west cross sections. While most of the sand is near the Illinois River, various sand pockets that serve as aquifers for communities exist sporadically across the region. The same patterns can be observed in a plan view transmissivity map of the shallow aquifer materials in the Middle Illinois region (Figure 51).

Many wells in the shallow aquifers of the Middle Illinois shallow model domain were located in cells with no sand. If the open interval of these wells was uncertain, then the wells were moved vertically to the nearest sand lens. If a sand lens was not present above or below the cell, then the cell containing the well was assigned the hydraulic conductivity zone for sand (zone 140).

After all high-capacity production wells were assigned to a cell depicting sand, there were still numerical issues owing to the presence of isolated sands (generally single cells) that were not connected to a larger sand or recharge source. These cells generally went dry during the simulation. The model was modified to provide enough water to these isolated sands, generally by connecting to more considerable nearby sandy areas, to ensure that these cells did not go dry (or that pumpage was not eliminated) in areas of known active production wells.

For purposes of this investigation, the model resolution of the Middle Illinois domain is the same as that of the regional model, 2500 feet. Future work, particularly in the Peoria region, will require refinement of this region to better capture well interference and groundwater-surface water interactions. As such, the current simulation of the Middle Illinois region remains approximate.

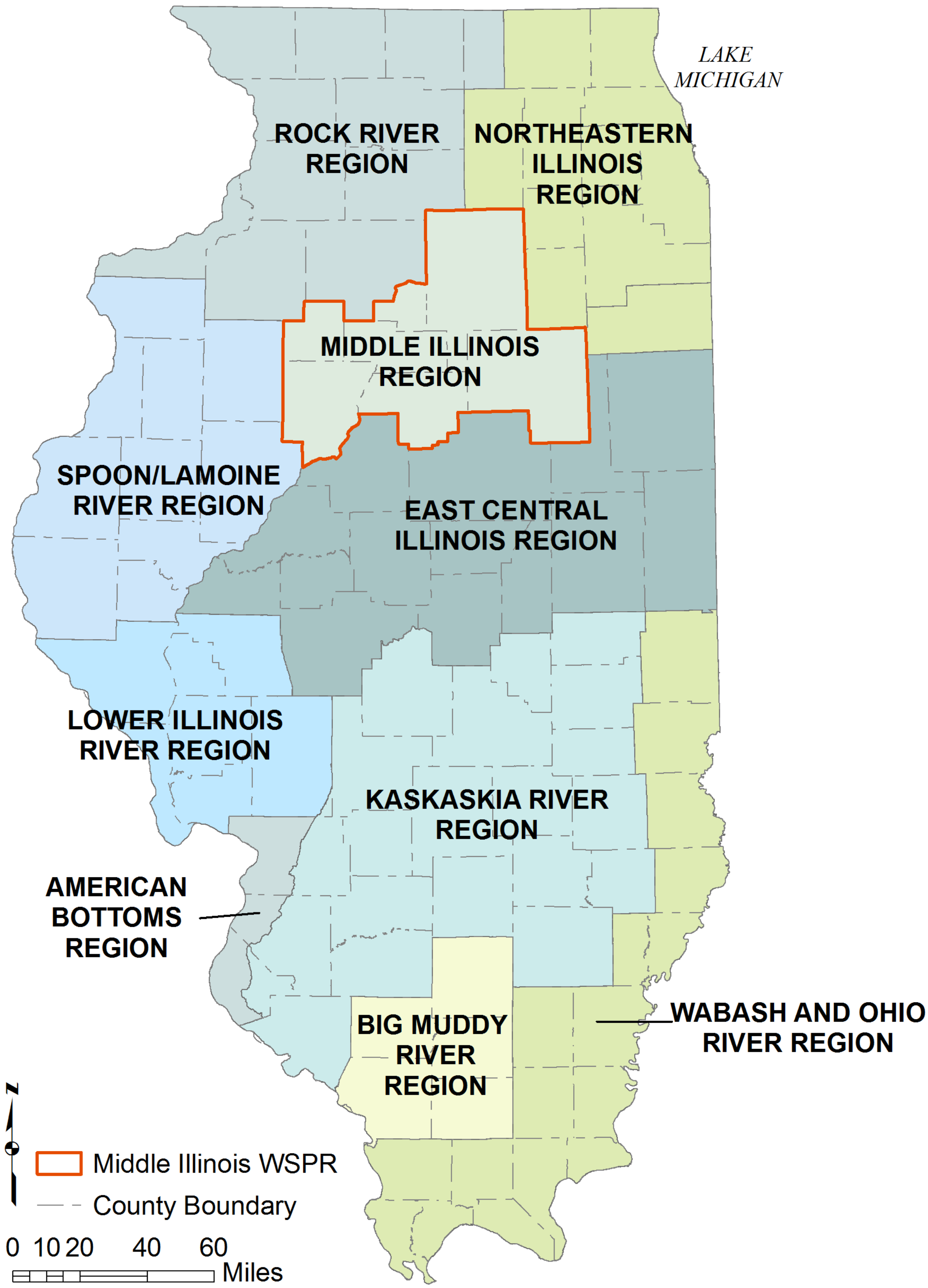

Figure 49: Water supply planning regions in Illinois

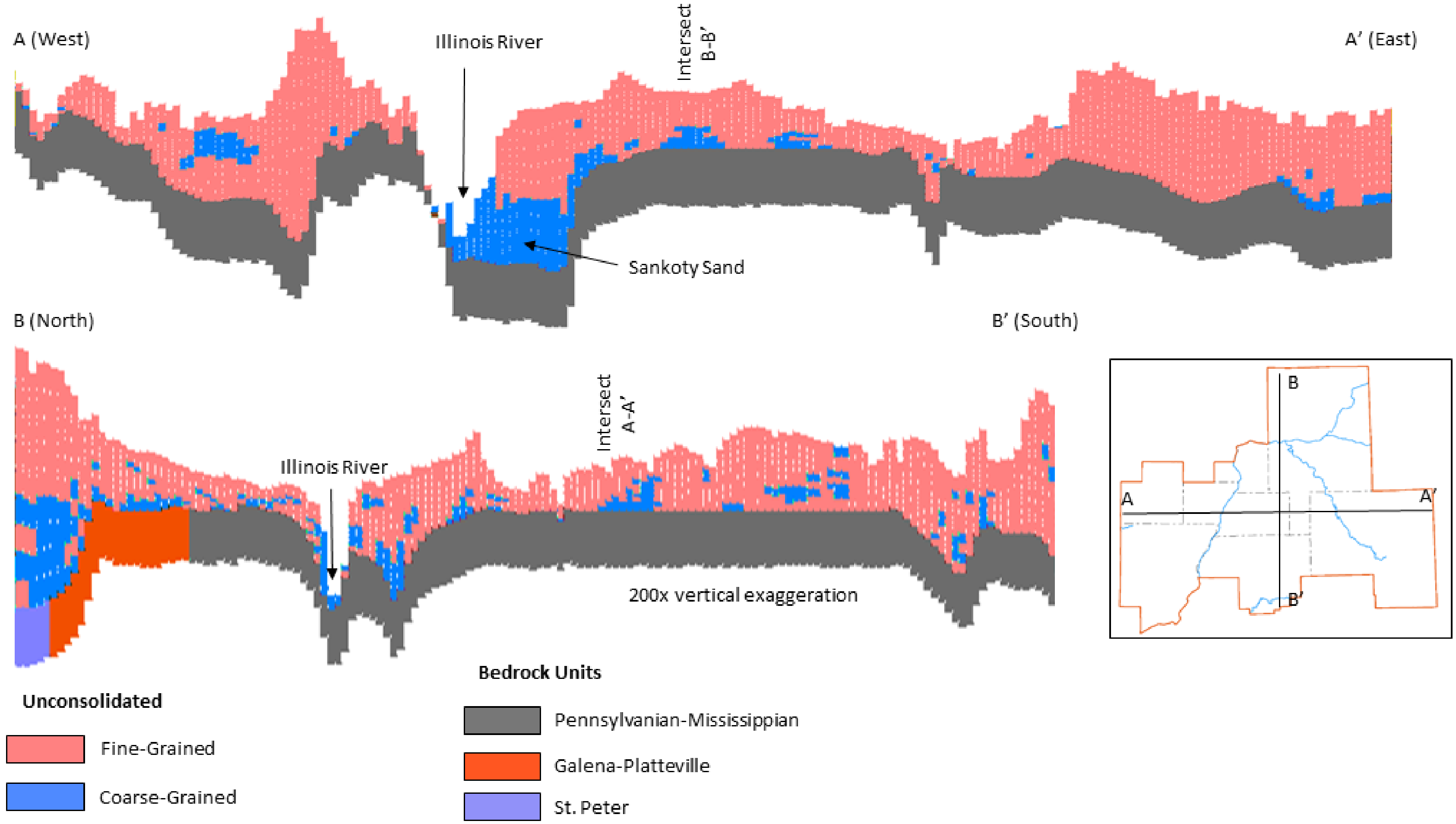

Figure 50: East-west (A–A') and north-south (B–B') cross sections depicting the conceptualization of unconsolidated materials throughout the Middle Illinois WSPR used in the groundwater flow model. Inset map shows location of cross-sections in region. Figure replicated from Kelly et al. (2018)

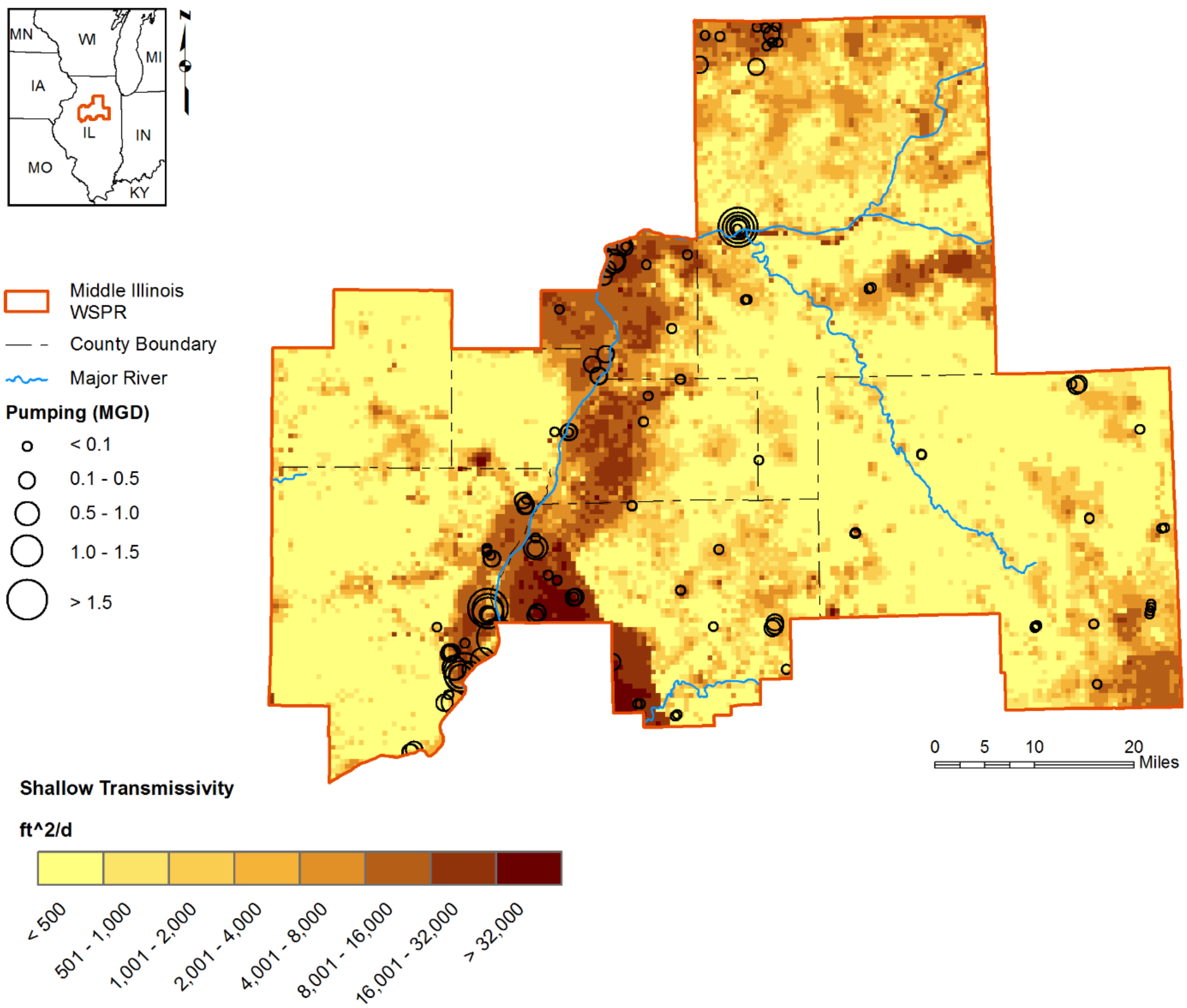

Figure 51: Combined transmissivity map of the sand and gravel and shallow bedrock aquifers in the Middle Illinois Water Supply Planning Region, along with pumping in the region. Reproduced from Kelly et al. (2018)

8.3.2 Calibration results for Shallow Middle Illinois

For purposes of calibration, we gathered the observed heads during the time of drilling of all wells in the Middle Illinois Water Supply Planning region for the ISWS wells database. Each observation was compared to its respective stress period. The mean error for the shallow aquifers in the Middle Illinois Water Supply Planning region is -4.96 feet, while the absolute mean error is 26.93 feet. The absolute mean error is much higher than preferable for a shallow aquifer, which is evident by the considerable scatter when comparing observed with simulated heads (Figure 52).

It should be noted that the data used for calibration are from a database pull of all wells in the region, including location data. However, these location data are often approximated to occur at the center of a section or plot and do not depict the accurate coordinates. Along the Illinois River in the Middle Illinois Water Supply Planning Region, this discrepancy in the stored and actual locations can lead to considerable differences in actual vs. estimated land surface elevation. For example, in the Peoria area of the Middle Illinois Water Supply Planning Region, land surface can vary by more than 200 feet over distances of less than a mile. This potentially inaccurate land surface elevation is then combined with the reported depth to water to calculate the head above mean sea level, which is the calibration target used in the groundwater flow model. Consequently, considerable error may be present in the observed heads used as calibration targets. As such, it is difficult to judge the quality of the calibration in Middle Illinois without using monitoring wells with accurate location data. This is compounded by the uncertainties associated with using observations taken during or soon after the drilling process, as well as natural fluctuations in the shallow aquifers that stem from variable recharge or stream elevations that are lost in the simulated annual stress periods.

Future calibration of the Middle Illinois model domain will focus only on those targets with verified location information.

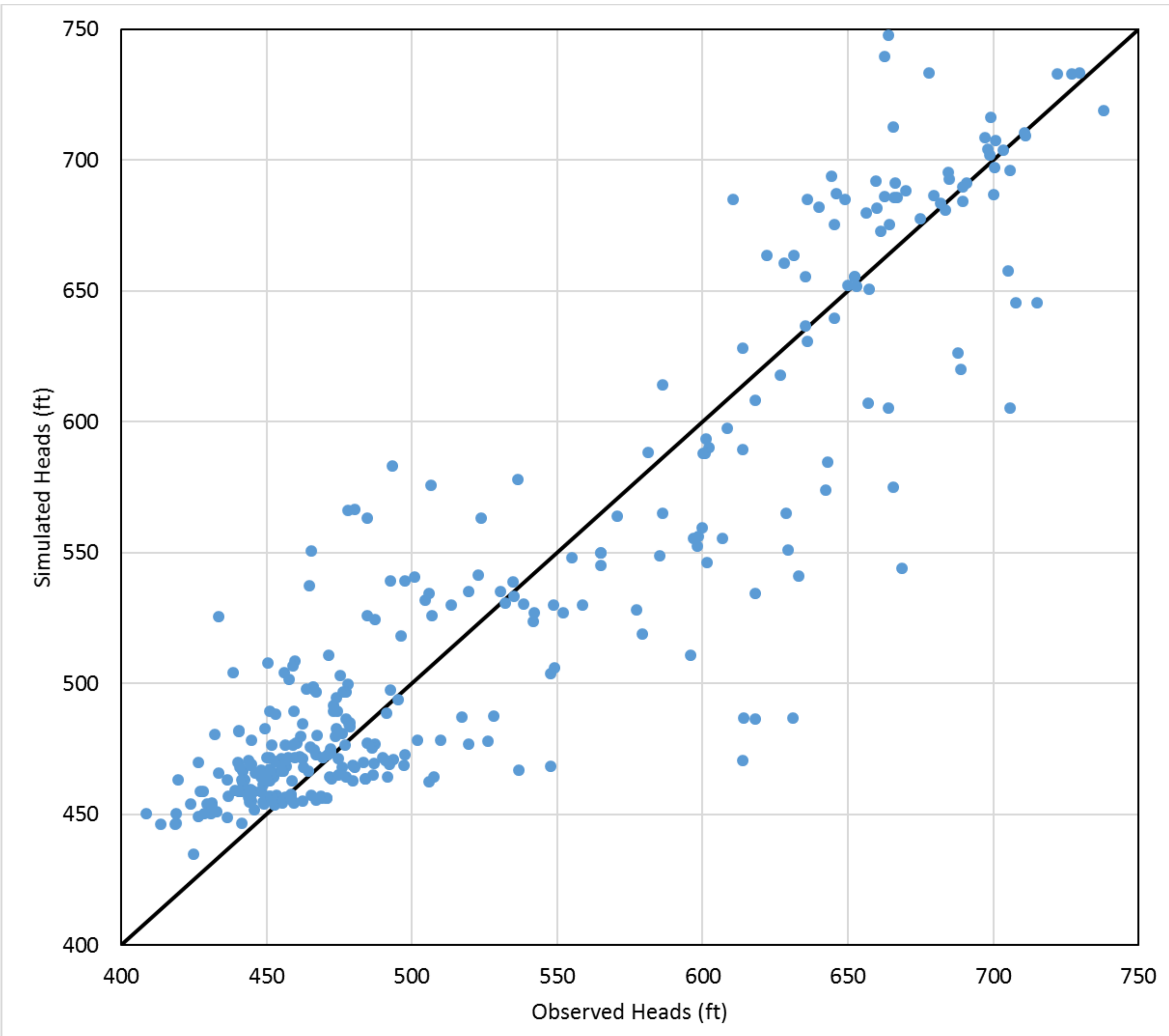

Figure 52: Calibration plot for the shallow Middle Illinois domain

8.3.3 Key Shallow Middle Illinois results

The simulated results in stress period 153 (which represents year 2015) in the basal sand and gravels of the Middle Illinois Water Supply Planning Region are shown in Figure 53. The lowest points in the potentiometric surface occur along the Illinois River, which has a strong hydrologic connection to the sand and gravels in most areas. Even still, a localized cone of depression is simulated around the Peoria area despite its proximity to the Illinois River. This simulated cone, while present in reality, is not as deep as it is simulated, likely due to the distorted well and stream geometry in the model as well as the simulation of multiple wells within a single cell.

Future demands simulated in the model out to stress period 198 (year 2060) are based on the Current Trend (CT) scenario developed specifically for this region (Kelly et al., 2018; Meyer et al., 2018). Although heads mostly declined (Figure 54), some localized areas increased because of reduced future demands in the CT scenario. We identified the areas with the largest head declines in the shallow aquifers between 2015 and 2060 using the CT scenario, which included Washburn, Low Point Water District, Benson, Secor, El Paso, Peoria, Peoria Heights, and associated industries. These declines do not necessarily mean that the aquifer is at an immediate risk, but point to the need to conduct local-scale investigations to ensure water quantity issues are not looming.

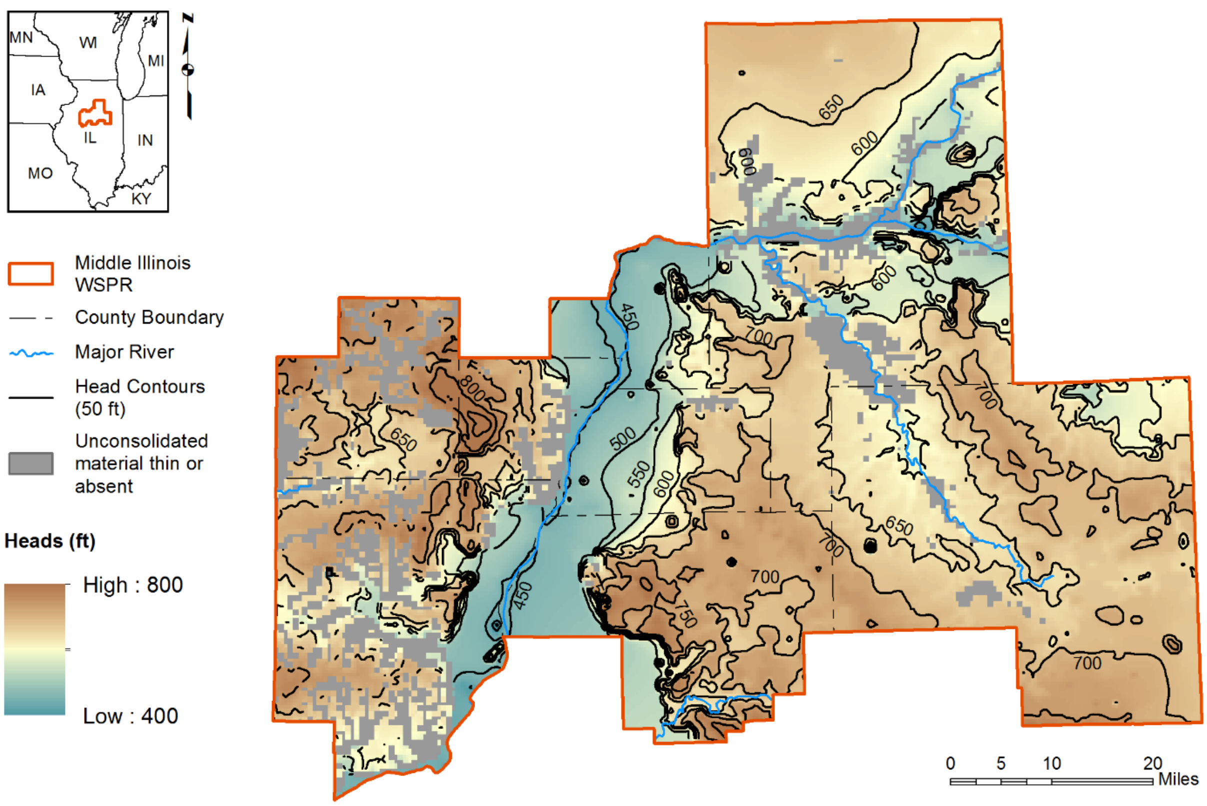

Figure 53: Simulated potentiometric surface of the basal unconsolidated materials for 2015. Reproduced from Kelly et al. (2018)

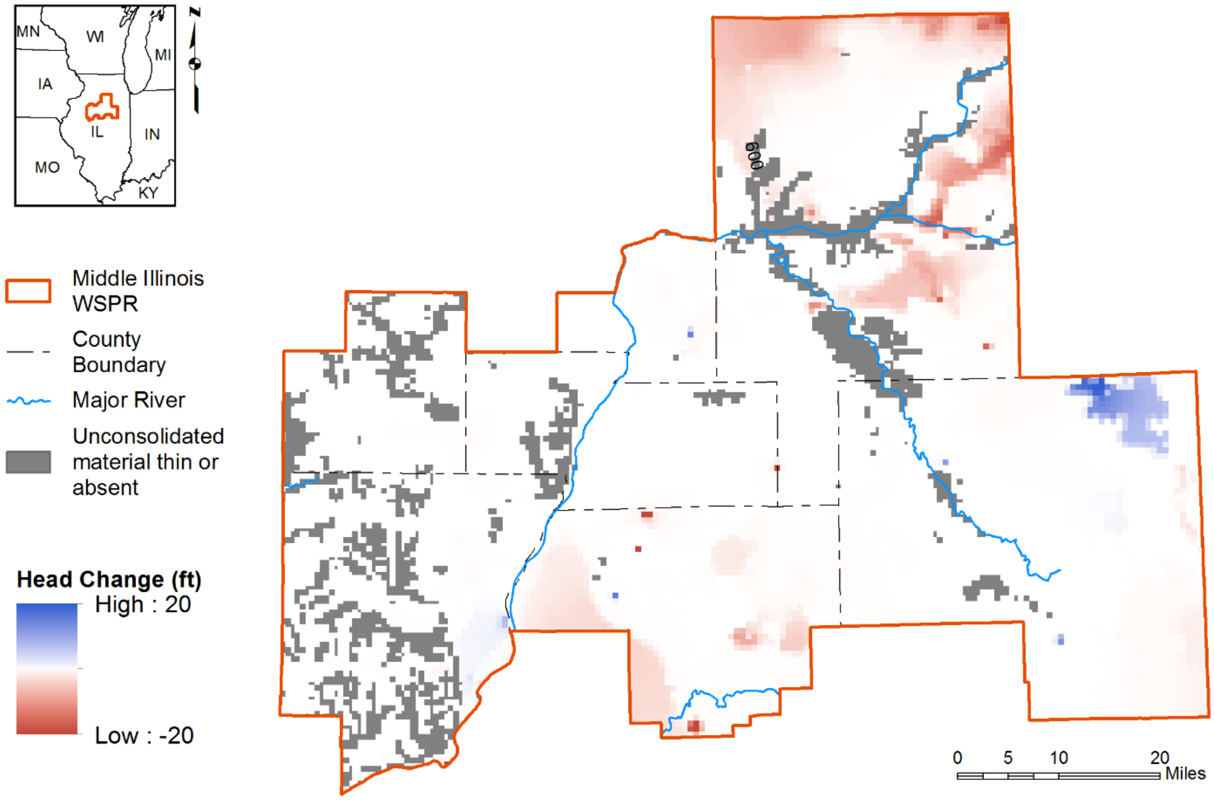

Figure 54: Simulated head change of the basal unconsolidated materials from 2015 to 2060 using the Current Trends (CT) Scenario

8.4 Incorporating the Mahomet Aquifer

8.4.1 Ongoing changes to the Mahomet Aquifer model

The unconsolidated materials of the Mahomet Aquifer region were previously simulated by Roadcap et al. (2011) using MODFLOW-2000 (Harbaugh et al., 2000) on a 1320-foot grid. The primary goal of this model is to simulate groundwater withdrawals from the expanding irrigation network in the region, which at peak pumping is estimated to withdraw more water daily from the aquifer than the city of Chicago takes from Lake Michigan. In addition to irrigation withdrawals, the Mahomet Aquifer serves as a primary aquifer for many cities. Furthermore, domestic and municipal wells are located in the shallower sands overlying the Mahomet Aquifer, which are also included in the geologic framework. Further details on the underlying conceptual and geologic framework and demands can be found in Roadcap et al. (2011).

A major uncertainty in the original Mahomet Aquifer model is the lack of a layer or layers depicting the bedrock in the region. This is particularly true in the northeastern portion of the model domain where the primary sands of the Mahomet Aquifer overlie permeable Silurian Dolomite. Roadcap et al. (2011) approximated a flow exchange between the sand and dolomite by assigning hypothetical wells that added water to the simulation, improving calibration in this area. As irrigation has increased in this same region in recent years, however, a dynamic simulation of this flow exchange is necessary.

To overcome the issue of simulating flow between the unconsolidated sands and dolomite, we have incorporated the Mahomet Aquifer into the IGWFM. To accomplish this, the model was re-gridded to 1250-foot cells that aligned with the 2500-foot IGWFM grid, then was subsequently coarsened. While the geology and recharge were updated in the Mahomet region, the stream network defined in Section 5.1 was used to reflect this more accurate depiction of the true stream network and ensure consistency with the regional model domain.

8.4.2 Calibration results for the Mahomet Aquifer

Model calibration of the Mahomet Aquifer within the IGWFM drifted from the original Mahomet Aquifer model with a mean error increasing from -0.26 feet (Roadcap et al., 2011) to 4.29 feet. Although heads in the Mason County region and Champaign-Urbana remained well calibrated, the heads in the northeastern portion of the Mahomet Aquifer were on the order of 10–20 feet too low. This is likely due in part to the loss of simulated local sand connections between the deep Mahomet aquifer and shallow sands during the process of re-gridding the model. However, another contributing factor is the removal of artificial wells in the original model designed to simulate flow exchange with the bedrock. Rather, this flow exchange is now dynamically simulated, which will likely require adjustment of the hydraulic conductivity and/or storage of the Silurian-Devonian bedrock in the region. Future modeling efforts will focus on improving this calibration, with an emphasis on shifting to seasonal calibration to better capture the impacts of irrigation withdrawals.

8.4.3 Key Mahomet Aquifer Results

This version of the Mahomet Aquifer model, now embedded within the IGWFM, does not supersede the version from Roadcap et al. (2011). It is currently undergoing further calibration to improve the newly introduced flow dynamics. This section documents some of the provision results of the Mahomet Aquifer simulation as in the IGWFM.

The resulting modifications to the IGWFM allow for the simulation of a potentiometric surface that includes both the sands of the Mahomet Aquifer and the surrounding low permeable materials and sand lenses of the Glasford Aquifer (Figure 55), which was not previously simulated in Roadcap et al. (2011). Newly simulated areas can be recognized in this figure as areas with a brighter shade of blue.

Furthermore, the exchange of flow between the basal unconsolidated materials and shallow bedrock are simulated dynamically. This exchange is particularly prevalent in the northeastern portion of the model domain, which coincides with the area where Silurian-Devonian dolomite is at the bedrock surface. Blue shaded areas represent an upward migration of water, and purple shaded areas represent the downward flow of water. Further analysis of the proper rate and spatial distribution of this exchange of water will be a focus for improving the Mahomet Aquifer calibration.

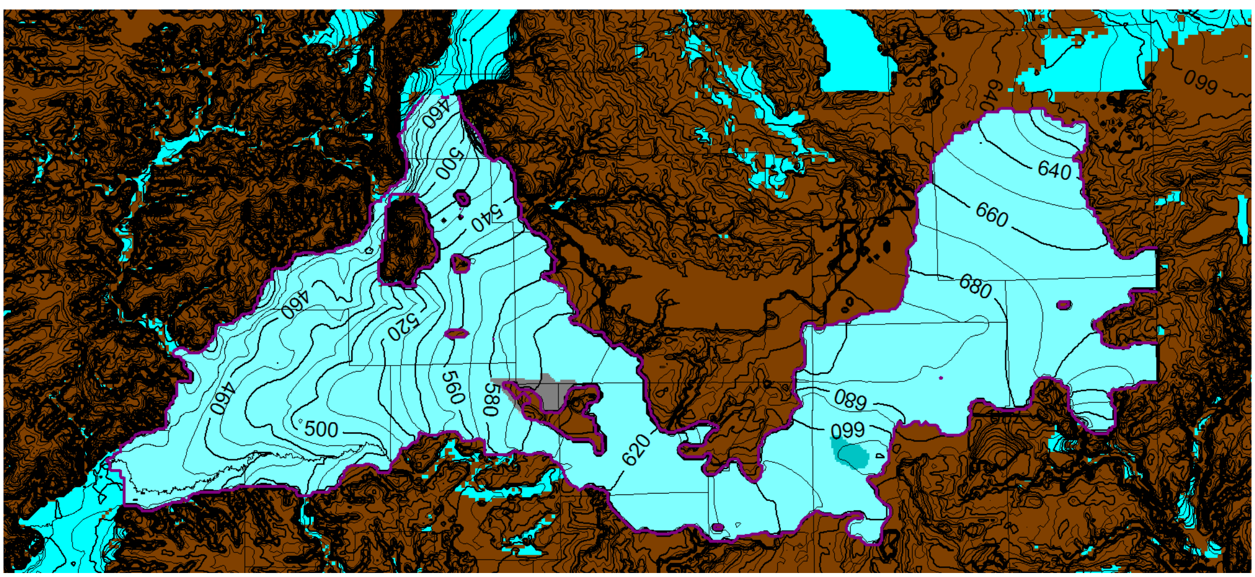

Figure 55: Potentiometric surface for 2015 of the Mahomet Aquifer area, as simulated in the IGWFM. Image is a snapshot from the Groundwater Vistas 6 environment. Contours show the head in feet above mean sea level.

9 Contouring models

Recently, the ISWS has used head-specified MODFLOW models to develop potentiometric surfaces of the Mahomet Aquifer (Roadcap et al., 2011) and the Cambrian-Ordovician Sandstone Aquifer (Abrams et al., 2015). These contouring models honor the fundamental groundwater laws, preserving mass balance and abiding by Darcy's Law. Furthermore, the models are capable of simulating irregular boundary conditions, such as no flow boundaries or surface waters.

Since these initial efforts were completed, further model development has added transient and three-dimensional capabilities to these contouring models, enhancing our capability to understand the systems, animating impacts of withdrawals without the bias of head calibration errors, and conducting preliminary mass balance calculations that take into account changes in storage. The following sections summarize the development and results of each contouring model.

9.1 General contouring model methodology

The contouring models, also referred to as head-specified models, function similarly to the scenario models, using the same basic geologic framework. However, they are distinct in that they explicitly assign observed heads as constant heads in place of groundwater withdrawals. The pumping is then used as a calibration target, at least regionally. This has the advantage of simulating the potentiometric surface exactly at an observation; hence the head error is by definition zero anywhere an observed head occurs. However, observed head data can be noisy, as are the resulting potentiometric surfaces. The head-specified models also have limited predictive capabilities. Hence, they are not a replacement for the traditional scenario model, but rather a complement to provide head maps through a specified period that are not subject to head errors (at least at the observation itself).

9.2 Mahomet Aquifer

The initial contouring model of the Mahomet Aquifer used 141 observations, mostly from a 2005 synoptic measurement supplemented by water levels from new wells installed between 2007 and 2009. Roadcap et al. (2011) assigned a constant head cell in MODFLOW with the water level of each observation (blue points in Figure 56). Similarly, the authors provided river elevations to constant head cells where the streams and the aquifer are hydrologically connected (red squares in Figure 56). The constant heads were added to the seventh layer (Banner Formation) of the already developed Mahomet Aquifer scenario model, replacing pumping wells. The authors made all other layers of the model inactive. The resulting steady-state MODFLOW simulation yielded a potentiometric surface for 2005 that represented non-irrigated conditions.

Recent work has used the dedicated observation network in Champaign County and the Imperial Valley (Mason and Tazewell Counties), where data are collected at frequent (15 minute, 1 hour) intervals, to animate the potentiometric surface in those two areas. The automatically recorded data need to be prepped before developing a contouring model. We developed a script that has two primary functions. First, any data gaps from when the equipment was down or reported an error have to be resolved. The script locates and removes any error codes or outliers.

It also adds any hand measurements into the automatically reported data that fell within any data gap. Finally, the script interpolates between periods of data with no automatically or hand-measured data. The second primary function of the script is to coarsen the time domain, with a user-defined option to select the maximum, minimum, and average head value for each new time interval. This allows for the development of animations at different time scales.

For transient surfaces in the Imperial Valley region, where surface water-groundwater interactions are important, the stream elevations must also be transient. To accomplish this, we assign stream elevations based on gaging stations on the Illinois River at Havana and Kingston Mines and along the Sangamon River at Oakford and Greenview. These data use the same interpolation script as detailed above to prepare it for the model.

Once interpolated, the data are imported into the groundwater flow model as constant head cells, allowing for the generation of transient potentiometric surfaces. Since the models do not explicitly account for recharge, the constant head cells tend to act as point recharge sources, when in fact they are merely observation wells. To overcome this, we increase the hydraulic conductivity in the simulation to smear water added by the constant head cells over the entire model domain. This is particularly important in Mason County where sand is at the surface, but it also appears to be important in Champaign County where the aquifer is semi-confined, meaning that it hydrologically behaves as a confined aquifer but receives some recharge from leaky overhead aquitards.

Transient simulations of the Mahomet Aquifer allow for a comparison to a single surface. In Champaign County, we compare the simulated Mahomet Aquifer surface through time to an average potentiometric surface. This is particularly enlightening during the drought of 2012, when different entities pumped from the aquifer at different times. In July of 2012, during the peak of irrigation pumpage, water levels were at their lowest in the heavily irrigated area of northern Champaign County (Figure 57a). After the irrigation season, the drought persisted, and Lake Decatur levels dropped. Consequently, the Decatur well field switched on, as indicated in Figure 57b for September of 2012. These figures, which are screen captures from an animation available on the ISWS website, provide a tool to understand and communicate differential changes in water levels that can be difficult to ascertain from simple hydrographs, particularly critical for short public presentations. It should be noted that the figures depict the change from average conditions (including pre-, during, and post-drought conditions), not drawdown from pre-drought conditions. Actual drawdown would be more severe.

The concerns related to groundwater in Mason County, where the Banner Formation is at the land surface, are quite different. The influences of streams on the aquifer are critical to understand. We developed an hourly animation for a heavy rain period from June to July 2015 to indicate the sensitivity of the aquifer to stream fluctuations near streams but the relative insensitivity of the aquifer farther away from the streams. Water levels in the aquifer near the rivers increased at a disproportionate rate to the rest of the aquifer from the beginning of the precipitation event (Figure 58a) to the end (Figure 58b). Most of the change in the aquifer was less than 3 feet, but near the Illinois and Sangamon Rivers, the change could be as great as 17 feet.

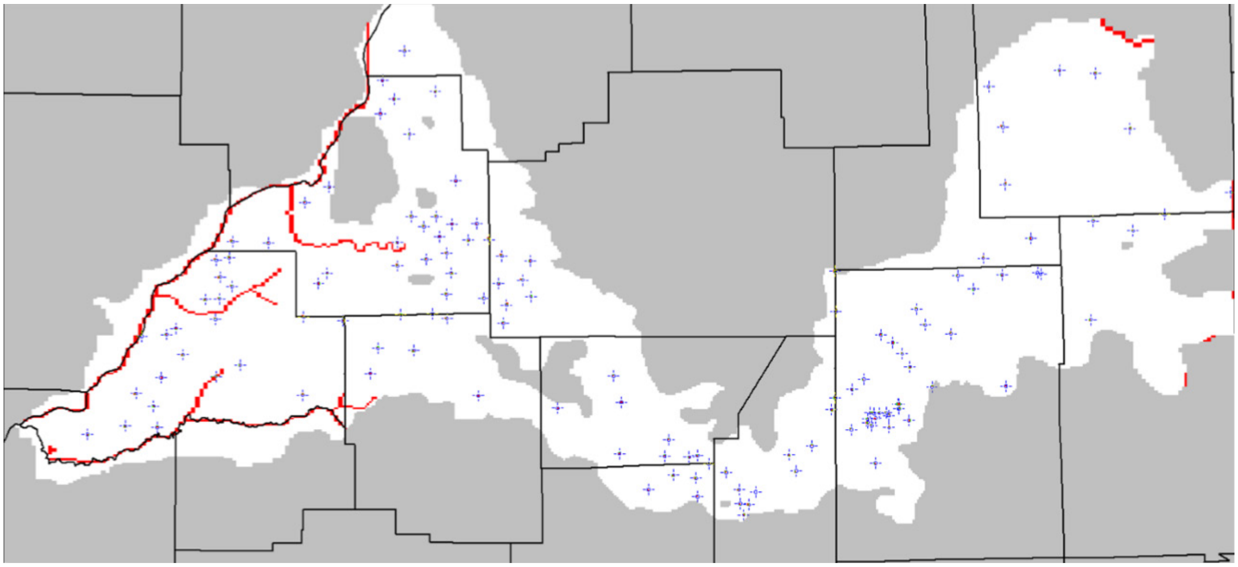

Figure 56: The location of well observations (blue) and rivers (red) used to assign constant heads to the Mahomet Aquifer contouring model

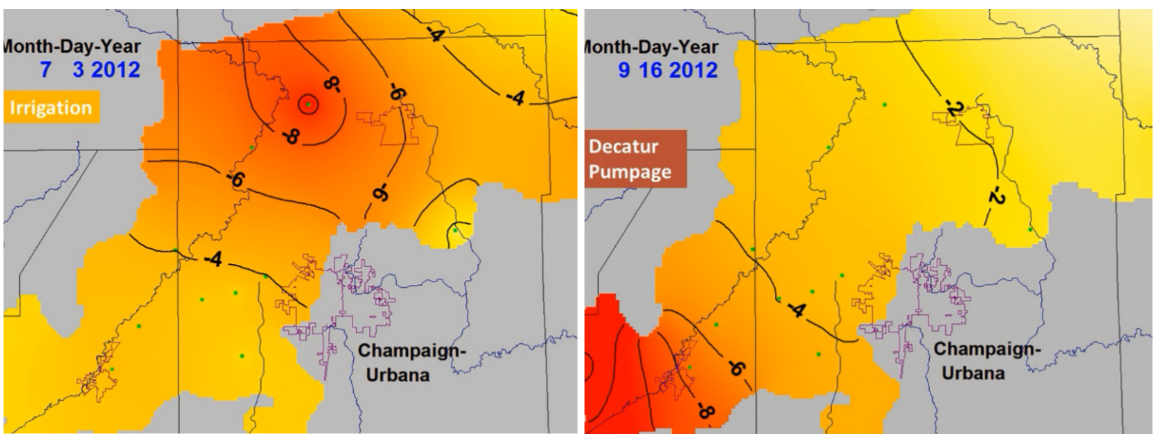

Figure 57: Snapshots from a Mahomet Aquifer animation depicting the difference in head from average conditions during the drought of 2012. The left image occurs during the peak of irrigation pumpage and the right image during the peak of Decatur groundwater withdrawals.

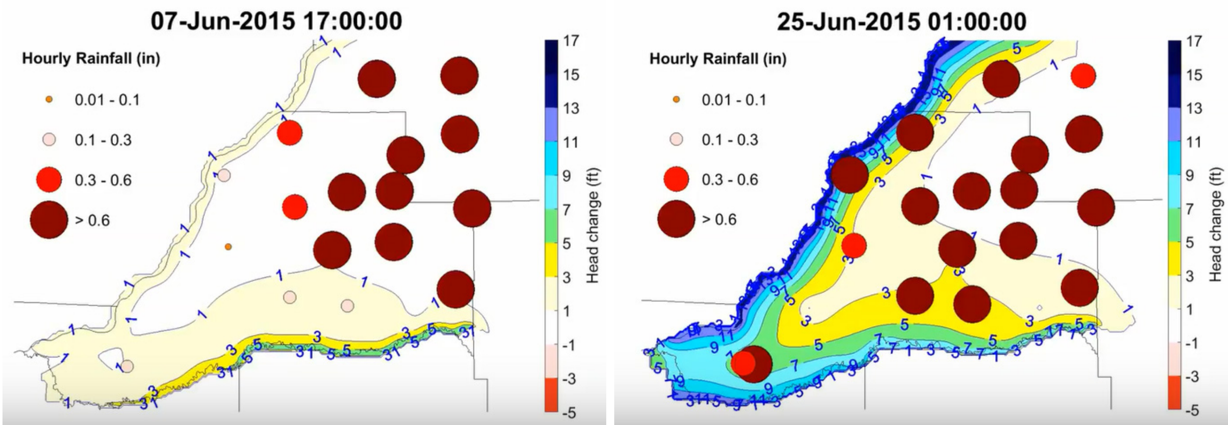

Figure 58: Changes in water levels due to precipitation events in Mason County

9.3 Cambrian-Ordovician sandstone aquifer system

The initial version of the head-specified sandstone aquifer model provided insight into the long-term drawdown observed in northern Illinois and Wisconsin, as well as the desaturation of the sandstone aquifers in northeastern Illinois (Abrams et al., 2015). The authors assigned static water levels from production wells obtained during the 2014 synoptic measurement to constant head cells in a MODFLOW model (Figure 59). The model was a single layer with transmissivity consistent with the combined St. Peter and Ironton-Galesville. Other model inputs included surface water elevations believed to have hydrologic connections to the sandstone, no-flow cells to simulate the Sandwich Fault Zone, and an artificial boundary underneath Lake Michigan derived from the simulation results of Feinstein et al. (2005). The resulting potentiometric surface includes all sandstone wells regardless of their open interval. Steady-state model simulations for other years created a series of potentiometric surfaces that facilitated analysis of long-term changes in aquifer water levels.

By linearly interpolating between observations from production wells during synoptic measurement years (1919, 1943, 1959, 1965, 1971, 1975, 1980, 1985, 1991, 1995, 2000, 2007, and 2014), a transient simulation was developed for the entire history of pumping throughout northeastern Illinois. This procedure is the same as used for the Mahomet Aquifer animation detailed above, with one big distinction. The network of observed production wells contains data that are much sparser in time, which is appropriate for the issues being investigated in northeastern Illinois. While in the Mahomet Aquifer we investigated seasonal fluctuations with a head-specified model, here we investigate long-term declines in heads. Although seasonal influences undoubtedly also play a role, this appears to be minor compared to the long-term decline experienced between each synoptic study.

Another distinction from the Mahomet Aquifer animation is that the well network changed for each synoptic measurement year. As a result, we needed to populate a value for wells that were not measured in a particular year for the transient simulation. To this end, we ran a steady-state simulation for the wells for each particular year, and then assigned the simulated head to any point that was not measured in that year but in previous or subsequent years. As a result, we did not influence the potentiometric surface simulated by the data alone for a specific year when linearly interpolating for the transient simulation.

Abrams et al. (2018) refined this approach by simulating separate surfaces for the St. Peter and Ironton-Galesville, honoring head separation. To create an accurate St. Peter surface, we supplemented the heads from the synoptic measurements with residential well drilling records, which is critical in areas where the St. Peter was shallow and received water via vertical infiltration. On a regional scale the head differences between the two sandstones are minor, but a head separation of over 200 feet occurs in Kendall County where most of the high-capacity wells are open to only the Ironton-Galesville. By properly accounting for this head separation, the head in a synoptic measurement year above a sandstone can now be mapped, providing critical information for at-risk areas to water supply planners. The head-specified model was used to create the current (2014) risk zones for the St. Peter (Figure 47) and Ironton-Galesville (Figure 48) aquifers.

For more information regarding the head-specified model of the Cambrian-Ordovician Sandstone Aquifer System, readers are referred to Abrams et al. (2018). Furthermore, animations depicting the Northeastern Illinois Head-Specified Contouring Model through time can be found at: https://www.isws.illinois.edu/illinois-water-supply-planning/groundwater-flow-modeling. Additional research is currently undergoing peer review to use this head-specified model to understand the sources of water that satisfy pumping, particularly in northeastern Illinois. This section will be updated with results of that research.

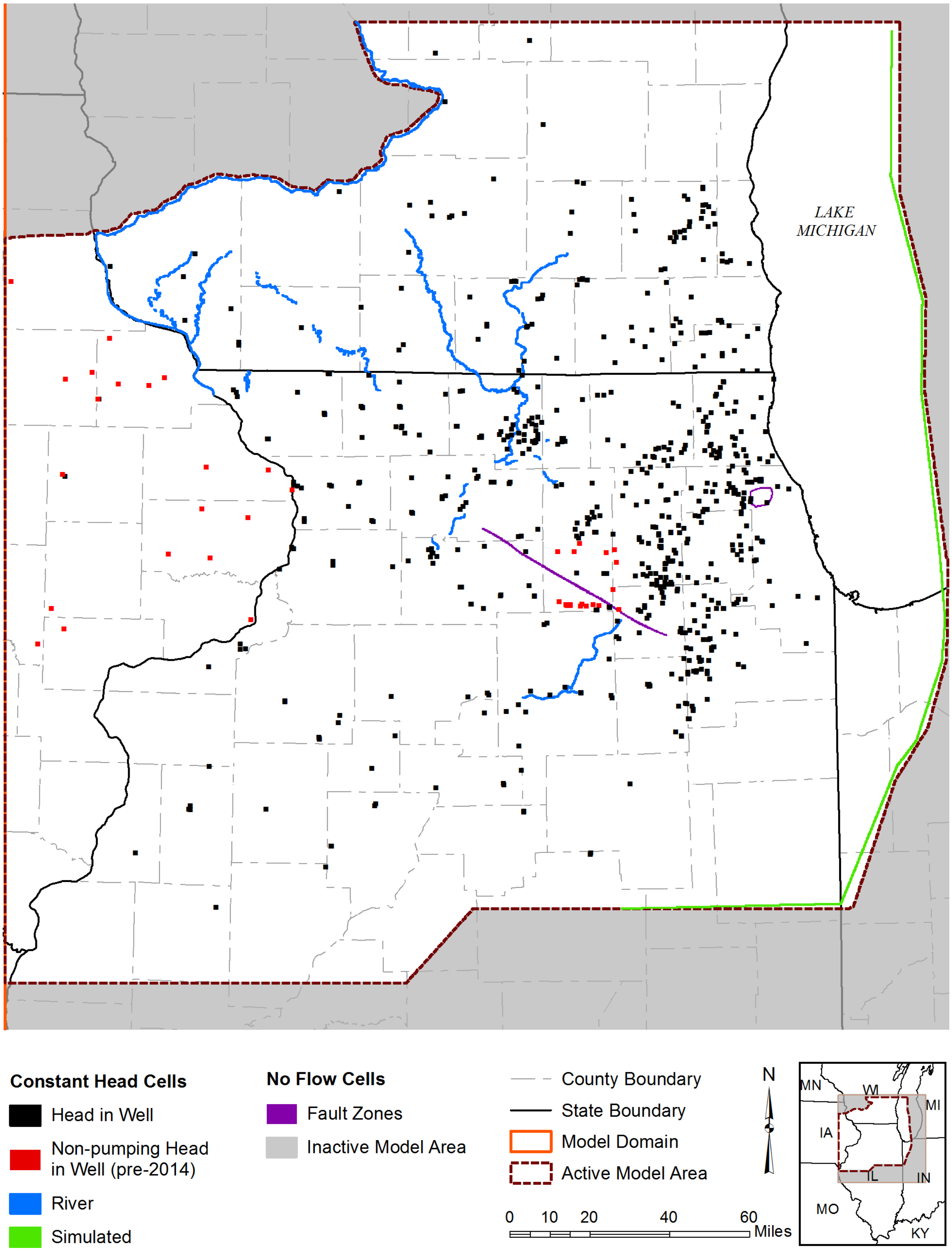

Figure 59: Inputs to the 2014 Cambrian-Ordovician Sandstone Aquifer contouring model (image from Abrams et al. (2015))

10 Future research

The Evolving Network of Illinois Groundwater Monitoring and Modeling Analyses (ENIGMMA) consists of all of the input data, archived models from previous studies, and procedures that are required to update a groundwater flow model. The primary product of ENIGMMA is the Illinois Groundwater Flow Model (IGWFM), which currently extends over the northern portion of Illinois. ENIGMMA is under continuous development to streamline and improve the processes of migrating data into the IGWFM. Likewise, the IGWFM continuously evolves as the data are updated, which for some data are continuous (pumping) but more sporadic for others (geologic surfaces).

This report is a living document, with a new version expected periodically to highlight critical updates to the data underlying the model, procedures used to develop the model, and model results. This section highlights major changes currently planned for ENIGMMA and the IGWFM. It should be noted that changes to ENIGMMA's base data are in turn changes that will also occur to the IGWFM.

Changes to ENIGMMA's data inputs

- Incorporate the detailed geologic studies of the Quaternary (Kane and McHenry Counties) into the ENIGMMA base data.
- Incorporate an updated bedrock surface map and statewide Quaternary analysis using the database approach deployed in the Middle Illinois region. These surfaces have been recently completed by the ISGS and are ready for deployment into ENIGMMA.
- Incorporate irrigation pumping as the information is finalized by IWIP in the coming years.

Changes to ENIGMMA's processes

- Automate the process of importing updated, model-ready withdrawals into the groundwater flow models to accompany the existing script to develop these model-ready withdrawals.
- Automate the calibration process to conduct instantaneous evaluation of a newly run model, particularly to highlight any erroneous new pumping.

Changes to ENIGMMA's output: the IGWFM

- Investigate MODFLOW-6, a newly released object-oriented version of MODFLOW (Langevin et al., 2017). The object-oriented approach may facilitate the linking of local and regional models while maintaining features of MODFLOW-USG essential for the current modeling approach.
- Improve the runtimes of the IGWFM (currently 19 hours).
- Refine the stress periods in the IGWFM to simulate monthly or seasonal pumping changes, an effort that is critical for irrigation evaluation.

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