Hydrostratigraphic and groundwater flow model : Troy Valley glacial aquifer, southeastern Wisconsin. [DNR-199] 2008

Mickelson, David M.; Anderson, Mary P.; Dunkle, Kallina
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Hydrostratigraphic and Groundwater Flow Model: Troy Valley Glacial Aquifer, Southeastern Wisconsin

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David M. Mickelson, Professor Emeritus
Mary P. Anderson, Professor
Kallina Dunkle, Research Assistant

Department of Geology & Geophysics
University of Wisconsin-Madison

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Abstract

Groundwater is an important resource in Wisconsin, especially in areas of southeastern Wisconsin outside the surface water divide of the Great Lakes that are prohibited from using water from Lake Michigan by the Great Lakes Compact. Decades of pumping have caused the potentiometric surface in the deep bedrock aquifer to drop several hundred feet, causing some wells to draw water with high salinity and radium. Treating radium is expensive and many communities are looking for good quality shallow groundwater that would not require treatment. Glacial deposits in the Troy Valley could be a possible source of groundwater for municipalities in the area. However, owing to the lack of information on the nature and spatial distribution of the valley deposits, it is uncertain how much water the valley deposits could provide. Three-dimensional hydrostratigraphic and groundwater flow models were constructed in order to determine the effects of pumping of four recently installed municipal wells near Lake Beulah and Vernon Marsh (Walworth and Waukesha Counties) on groundwater levels and nearby surface waters.

Deposits in the buried valley consist of silty and clayey lake sediment, sand, gravel, and till of the Tiskilwa, Holy Hill and Oak Creek Formations. Subsurface data, including geophysical data and well logs, were used to construct a three-dimensional hydrostratigraphic model using the software program Rockworks™ v. 2006. The final model was selected from eleven possible models based on geologic reasoning and the fit to six hydrostratigraphic cross sections constructed from field information. The hydrostratigraphic model was imported into a regional groundwater flow model, which was calibrated to steady-state conditions, using the River Package to represent surface water features.

Steady-state simulations showed the impacts on groundwater heads and flux to surface water features due to pumping from recently installed wells. Sensitivity tests assessed the effect of the fixed flux boundary conditions. Stochastic MODFLOW was used to assess uncertainty in the hydraulic conductivity values of the glacial deposits and the pumping rate of a well near Lake Beulah. MODPATH was used to determine capture zones for the recently installed pumping wells. Two local scale models in the vicinity of Lake Beulah and Vernon Marsh were created using telescopic mesh refinement and the calibrated regional model. These models used the Lake, Stream Flow Routing, and River Packages in MODFLOW so that effects of pumping on surface water levels could be assessed.

Inverse distance weighting appears to produce geologically reasonable results when used to interpolate the spatial distribution of glacial deposits. Uncertainty analysis showed that hydraulic conductivity of the glacial deposits can significantly affect heads under pumping conditions. The results of both the regional and local scale models indicated that pumping in the Troy Valley near Vernon Marsh and Lake Beulah will reduce groundwater heads and groundwater flow to surface water features near the pumping wells. However, groundwater inflow to Vernon Marsh and Lake Beulah calculated by the local scale models is only around 20% of total inflow to these surface water features. Under the fixed flux boundary conditions assumed in the model, the maximum drawdown at depth was predicted to be around 50 ft, while the maximum drawdown of the water table was approximately 7 ft around Lake Beulah and around 22 ft near Vernon Marsh. The regional model is considered to be a good first approximation model for use in groundwater management. However, the calibration of the local scale models is more uncertain; they would benefit from additional calibration efforts.

Acknowledgments

We gratefully acknowledge the help provided by Dr. Michael Fienen (USGS), Dr. David Hart (WGNHS), and Professor Jean M. Bahr (UW-Madison). We thank Dr. John Jansen and Joy Loughry (both with Ruekert-Mielke, Inc.), and Robert J. Nauta (RSV Engineering, Inc.) for sharing their data.

Table of Contents

List of Tables

List of Figures

Accompanying Material

The accompanying CD contains the following information, listed by the folders found on the CD:

1. Hydrostratigraphic Solid Model- This folder contains the input spreadsheet for the solid models and the file (mod) for the final solid model.

2. Troy Valley Regional Model- This folder contains five folders:
    i) Calibrated- Output (lst) file from the calibrated model
    ii) Predictive- The Groundwater Vistas* (gwv) file, initial head (hds) file and output (lst) file from the predictive simulation. The hds file is the solution from the calibrated steady-state model. The input files created by Groundwater Vistas are also included.
    iii) Predictive, 10% in all layers- The output (lst) file from the sensitivity test with 10% additional flux through the southern boundary in all layers.
    iv) Predictive, 10% in layers 8 and 9- The output (lst) file from the sensitivity test with 10% additional flux through the southern boundary in the pumping layers only
    v) Predictive, bottom flux- The output (lst) file from the sensitivity test with 10% additional flux through the bottom boundary

3. Lake Beulah Model- This folder contains three folders:
    i) Steady-State- Output (lst) file from the steady-state calibrated model
    ii) Predictive- Output (lst) file from the steady-state predictive simulation
    iii) Transient- The Groundwater Vistas* (gwv) file and initial head (hds) file from the transient simulation. The hds file is the solution from the calibrated steady-state model. The input files created by Groundwater Vistas are also included.
4. Vernon Marsh Model- This folder contains three folders:
    i) Steady-State- Output (lst) file from the steady-state calibrated model
    ii) Predictive- Output (lst) file from the steady state predictive simulation
    iii) Transient- The Groundwater Vistas* (gwv) file and initial head (hds) file from the transient simulation. The hds file is the solution from the calibrated steady-state model The input files created by Groundwater Vistas are also included.

*All groundwater flow simulations were run using Groundwater Vistas 5, Environmental Simulations, Incorporated.

Chapter 1: Introduction

1.1 Objectives and Scope

Groundwater is an important resource, especially in Wisconsin, where over 800 mgd are pumped from both shallow and deep aquifers (Ellefson *et al.*, 2002). After decades of pumping, the potentiometric surface in the deep bedrock aquifer in the southeastern part of the state has dropped below the water table in the last century and continues to drop an average of 6-10 ft/year (Feinstein *et al.*, 2005). This has led to increased salinity and high concentrations of radium in some wells as water is pulled from deeper parts of the aquifer. Growing communities, such as the City of Waukesha, must find a new source of water or pay the expensive costs of treating groundwater from the deep aquifer for removal of radium. Cities like Waukesha that are outside the Great Lakes surface water basin cannot draw water from Lake Michigan because the Great Lakes Charter of 1985, a voluntary agreement, prohibits the removal of water from the Great Lakes Basin without consent from all eight of the Great Lake states and two Canadian provinces. At the time of the writing of this thesis a new agreement, the Great Lakes Compact, was in the process of being passed into law in the member states and provinces. Wisconsin's Governor Doyle, signed it on May 27, 2008. The Compact is an updated version of the Charter that provides guidelines for determining whether an entity would receive Great Lakes water.

One possible source of groundwater for Waukesha County is the Troy Valley (Fig. 1.1), a deep pre-glacial valley that was probably deepened by subglacial meltwater and is now filled mostly with glacial and related deposits. While the Troy Valley was discovered nearly a century ago (Alden, 1904), relatively little is known about the nature and spatial distribution of the valley fill. Due to this lack of information, it is not certain how much water the deposits in the valley contain or how pumping from the valley might affect lakes, streams, and wetlands (Fig. 1.2).

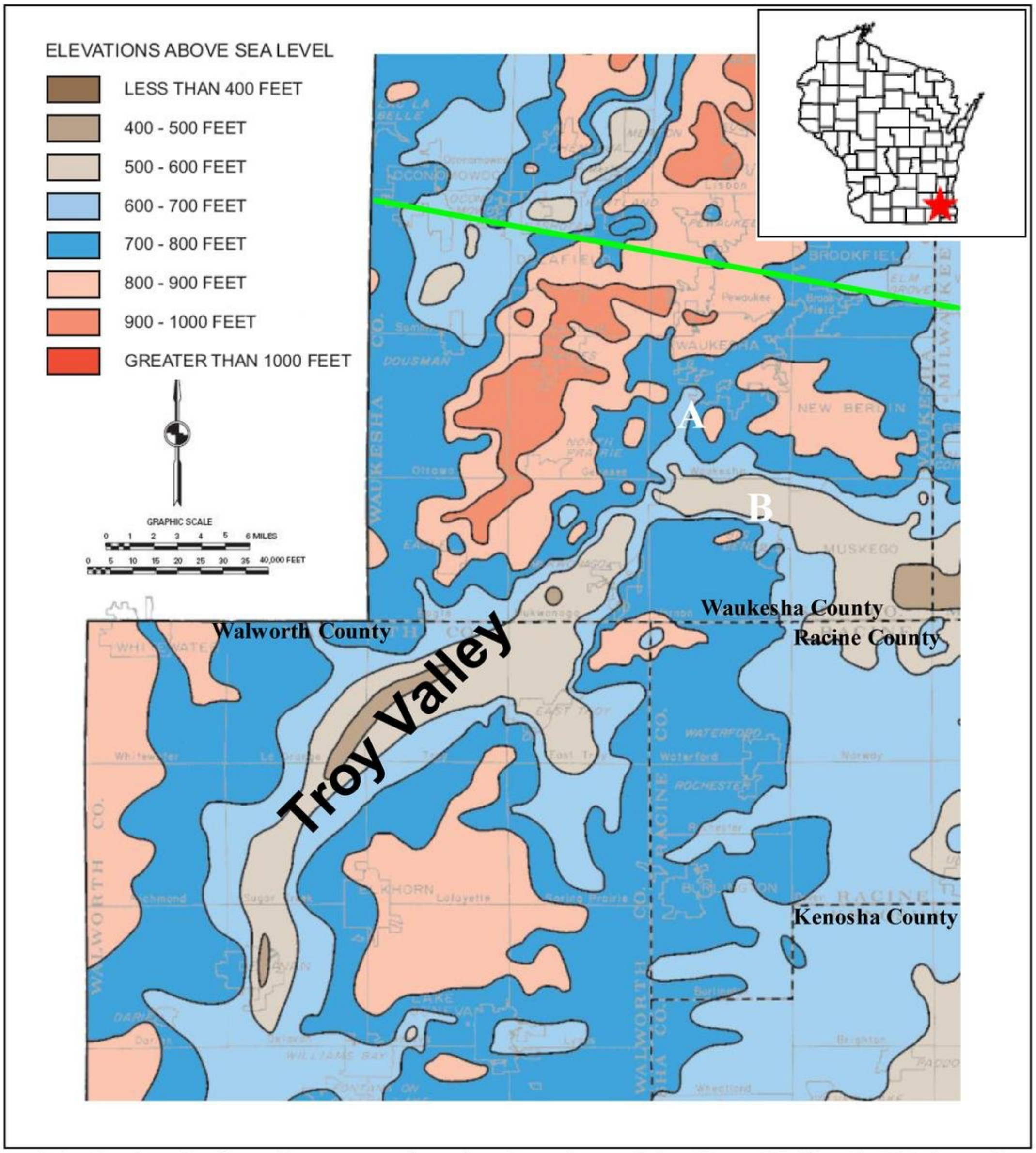

Figure 1.1. Bedrock elevation map, showing location of the Troy Valley in Walworth and Waukesha Counties, Wisconsin. "A" is the northern tributary of the valley near the City of Waukesha and "B" is the east-west trending portion of the valley. The green line indicates the location of the cross section in Waukesha County in Fig. 1.5. (modified from SEWRPC and WGNHS, 2002)

The objectives of this project were to define the character and spatial distribution of deposits in the Troy Valley and to estimate their potential for water supply. A hydrostratigraphic model was used to represent the three-dimensional spatial distribution of deposits and a regional groundwater flow model as well as two local scale models were developed to predict the effects of pumping of four recently installed wells on groundwater and surface water levels in the area around Vernon Marsh and Lake Beulah (Fig 1.2).

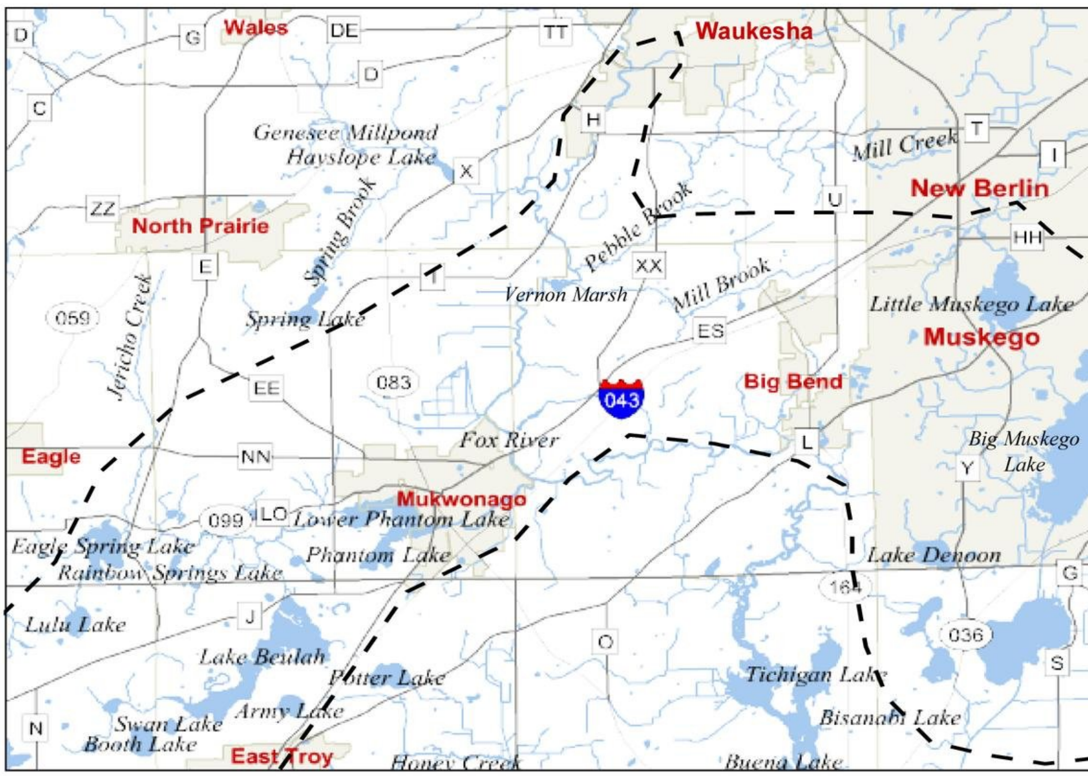

Figure 1.2. Project location, the dashed black line shows the approximate extent of the Troy Valley. Note the numerous surface water features and the cities in the area. See Figure 1.6 for the location of this figure relative to Pleistocene stratigraphic units in southeastern Wisconsin. (modified from DNR Surface Water Viewer, www.dnr.state.wi.us/org/water/data_viewer.htm)

1.2 Background

1.2.1 Previous Work

Alden (1904) used well records to map the subsurface bedrock topography of southeastern Wisconsin and discovered the Troy Valley. Over the last century researchers have considered whether it is a through flowing valley from northern Illinois to Waukesha County, or if a divide exists in Walworth County. Clayton (2001) suggested that the valley was modified by subglacial water, which likely deepened parts of the valley floor. Foley *et al.* (1953), Green (1968), Borman (1976), and Melenberg (1979) also studied the Troy Valley, mainly through geophysical measurements (Ham & Attig, in prep). Since Alden's work, many more wells have been drilled; data from many of these were used in this project.

The deposits in the Troy Valley are over 500 ft thick (SEWRPC and WGNHS, 2002). The saturated thickness is about 400 ft in some places. Batten and Conlon (1993) determined that the northern tributary of the valley, located just south of the City of Waukesha in Waukesha County (Fig. 1.1), would most likely not sustain high capacity municipal wells. Pumping tests determined that the average horizontal hydraulic conductivity for this area is about 0.9 ft/day with a storage coefficient of 1.2×10^{-3}. However, the tributary that runs more-or-less east-west in southern Waukesha County (Fig. 1.1) has more than 200 ft of saturated glacial deposits and may be capable of providing higher yields. In this part of the Troy Valley, the horizontal hydraulic conductivity is reported to be as high as 100 ft/day (Feinstein *et al.*, 2005).

In this region of Wisconsin, the Maquoketa Formation and in some locations also the Sinnipee Group act as a regional aquitard separating a shallow aquifer that consists of unlithified Quaternary deposits and Silurian bedrock from the deep aquifer, which is a sandstone aquifer that includes the Ancell Group and Cambrian age bedrock (Fig. 1.3).

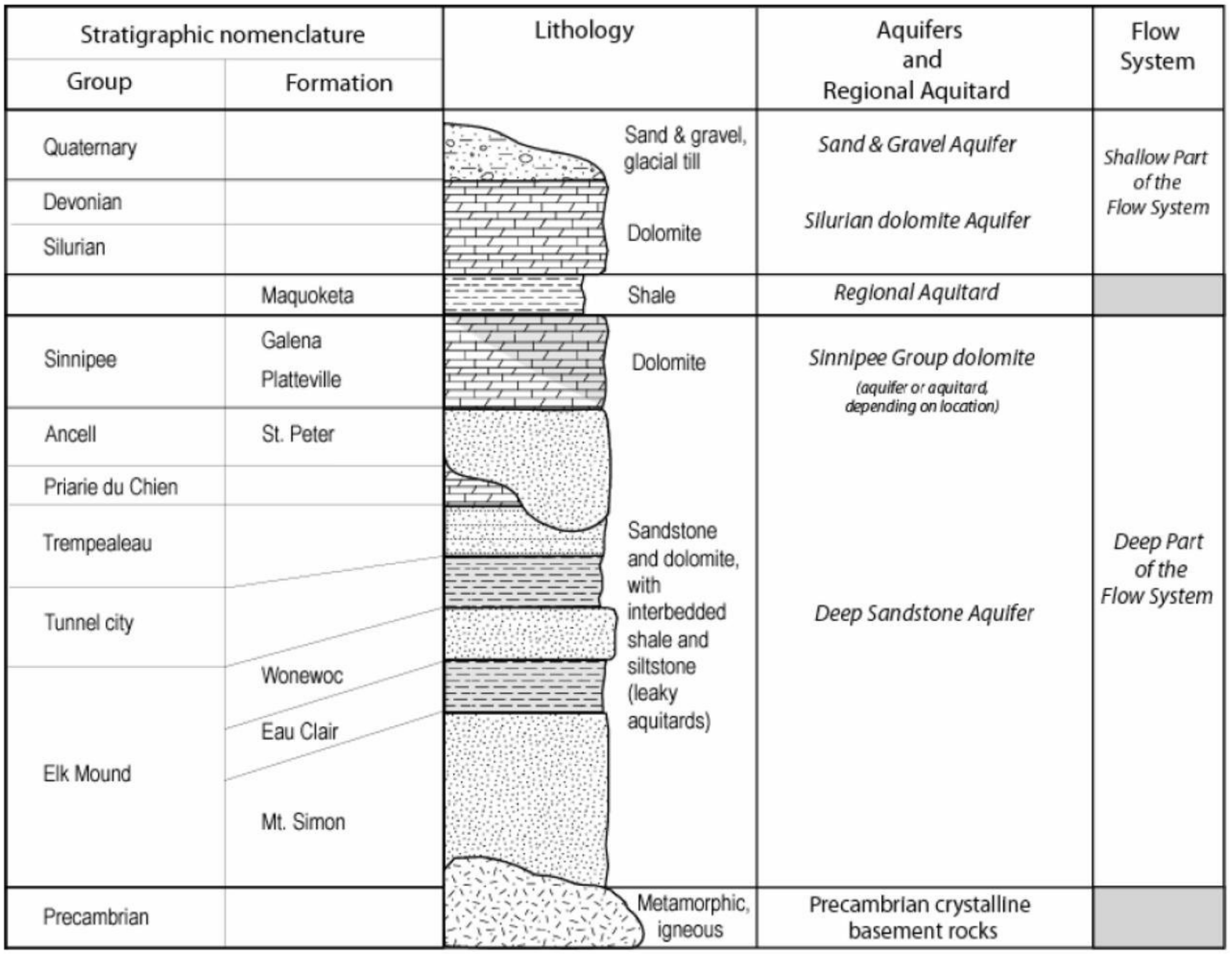

Figure 1.3. Hydrostratigraphic column for southeastern Wisconsin. (from Feinstein *et al.*, 2005)

Feinstein *et al.* (2005) developed a groundwater flow model for the seven county southeastern Wisconsin region (Fig. 1.4) consisting of Washington, Ozaukee, Waukesha, Milwaukee, Walworth, Racine, and Kenosa Counties. The purpose of the model was to determine the effects of both historical and current groundwater withdrawals and to predict the effect of future withdrawals. They used a steady-state model to simulate pre-pumping conditions, which were used as initial conditions in a transient model to simulate the effects of pumping since 1864. The model contains 205 rows, 166 columns, and 18 layers, totaling about 600,000 cells. In the nearfield portion of the model, centered around the seven counties (Fig. 1.4), grid spacing is 2,500 ft by 2,500 ft and increases to grid blocks of nearly 20 square miles at the outermost edges of the model. Only two of the eighteen layers represent the unlithified deposits, including the entire Troy Valley. Since 1864, the center of the cone of depression has shifted from Milwaukee County to Eastern Waukesha County.

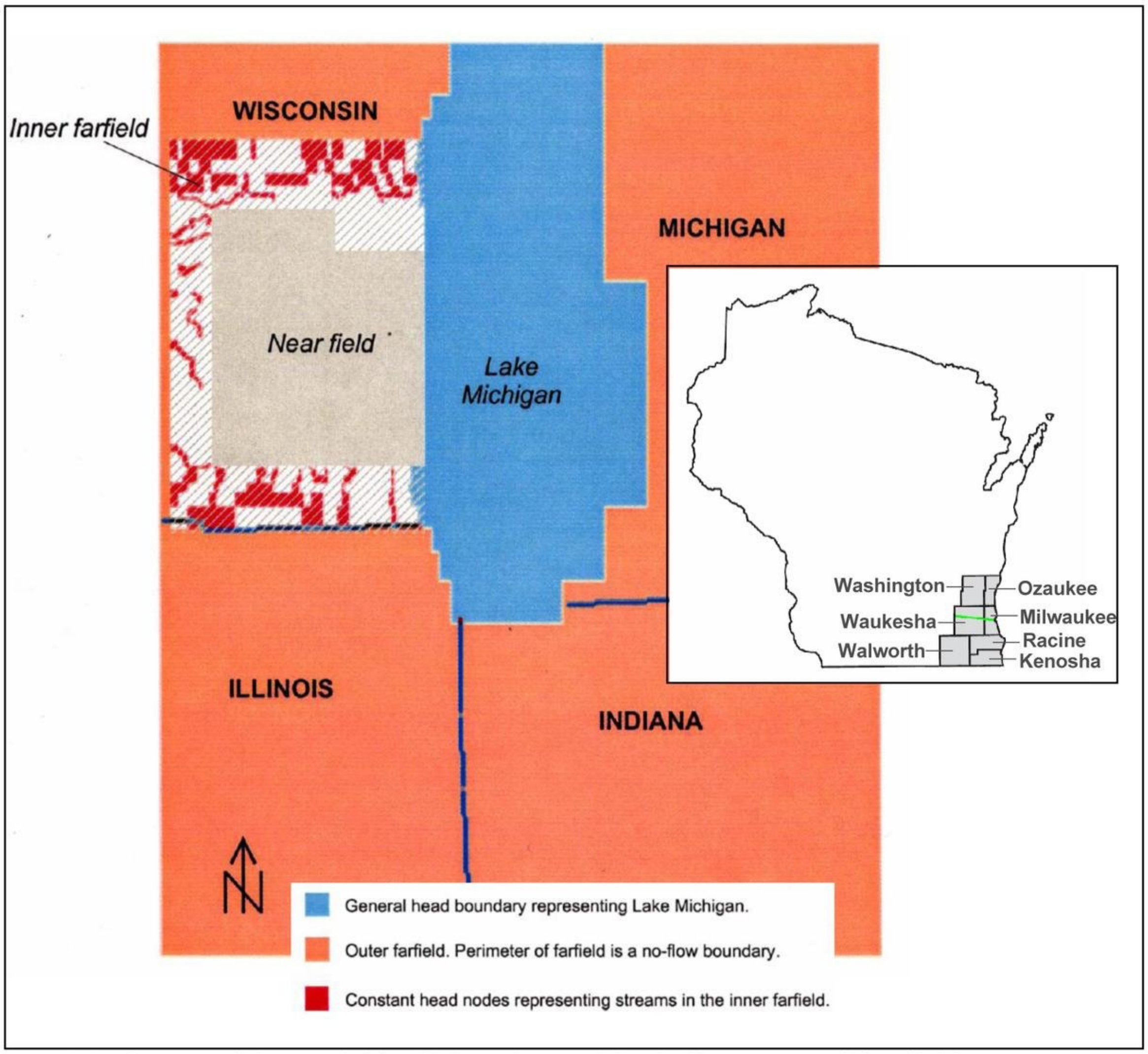

Figure 1.4. Extent of the model by Feinstein *et al*, including near and far fields. Inset shows the seven counties, which compose the near field portion of the model. Green line on the inset indicates the location of the cross section in Fig. 1.5. (modified from Feinstein *et al.*, 2005 and SEWRPC and WGNHS, 2002)

Feinstein *et al.* (2005) found that 71% of the pumped water, from both shallow and deep aquifers (Fig. 1.3), comes from groundwater that otherwise would discharge to surface waters, including Lake Michigan. Consequently, the direction of groundwater flow in the deep aquifer system has reversed from eastward flow toward Lake Michigan to westward flow out of Lake Michigan. In other words, pumping beneath Milwaukee and eastern Waukesha Counties induces lake water to recharge the aquifer. They also found that 82.6% of water pumped from the shallow aquifer comes from water that otherwise would have discharged to surface water features, not including Lake Michigan, or water that is directly pulled from these surface waters due to a reversal of flow. However, it is uncertain which surface waters are most affected because a detailed study of these effects was not made. By extrapolating rates of high capacity well pumping into the future, they determined that by 2020 pumping may increase as much as 40%, producing 100 ft of additional drawdown at the center of the regional cone of depression, which is located in central and eastern Waukesha County.

Other studies of the hydrogeology and hydrostratigraphy in southeastern Wisconsin include one by Simpkins (1989), who investigated the hydrostratigraphy of the Oak Creek Formation, which is the uppermost sediment unit extending from Lake Michigan westward to near Big Muskego Lake (Section 1.3.2), and another by Eaton (2002), who investigated the hydrogeology of the Maquoketa Shale in Waukesha County. Gittings (2005) focused on the hydrogeology of the Mukwonago River Watershed near the City of Mukwonago (Fig. 1.2) and showed that increased urbanization and pumping threatens the wetlands in this watershed. She used $^{87}Sr/^{86}Sr$ ratios to show that water discharging to springs comes from both the sand and gravel aquifer and the bedrock. This indicates that increased impervious cover and pumping will most likely decrease recharge, lower the water table, and decrease the amount of natural groundwater discharge to surface waters.

1.2.2 Current Interest in the Troy Valley

The Troy Valley aquifer is the focus of recent attention as a potential source of water for communities in southeastern Wisconsin. When the first wells were drilled in the deep sandstone aquifer in the late 1800's, the potentiometric surface was as high as 100 ft above the land surface (Egan, 2003). Over a century later, heads in the sandstone aquifer have dropped over 450 feet inside the cone of depression, and wells have started to pull in water with high radium levels. Grundl and Cape (2006) found that the unconfined regions of the deep sandstone aquifer on average have lower levels of radium than the confined portions. In addition, they showed that the amount of radium in the unconfined aquifer is controlled by radium co-precipitation into barite, while in the confined aquifer radium may come from sources of radium in the aquifer itself, the overlying aquitard, or brines originating from the Michigan basin. In 2001, the Environmental Protection Agency (EPA) began enforcing a radium standard of 5 picocurries per liter for drinking water. Groundwater in the wells in the City of Waukesha ranged between 8.5 to 11 picocurries per liter. A failed attempt by the City of Waukesha to convince the courts that bone cancer was not linked to radium means that Waukesha has to meet the EPA standard (Enriquez, 2003). Waukesha has done this by blending water from the shallow groundwater system with the radium contaminated water and also treating their current sources to reduce radium concentrations. Waukesha has also implemented a conservation and protection plan that has reduced per capita water use. However, population growth has resulted in increased total water use (GeoSyntec

Consultants). This means that Waukesha and other cities in the area with similar problems need other water sources, as well as continued water management.

1.3 Site Description

1.3.1 Location

The area of focus for this project is located in southeastern Wisconsin, including parts of Waukesha, Walworth, and Racine Counties (Fig. 1.2). The northernmost part of the Troy Valley is located in this region and surface water features are abundant.

1.3.2 Geology

The depth to bedrock in this region varies from zero where bedrock crops out at the surface to nearly 500 feet in the Troy Valley (Fig. 1.1). The bedrock units slope toward the Michigan Basin to the east; the Waukesha Fault vertically offsets some of these formations (Fig. 1.5). The Troy Valley cuts into three of these units, the Silurian age bedrock, the Maquoketa Formation, and the Sinnipee Group. The Silurian age bedrock and the Sinnipee Group are both dolomite, while the Maquoketa Formation is shale (Fig. 1.3). The western extent of both the Maquoketa Formation and Sinnipee Group occurs in Waukesha County, so that both these and the Silurian rocks are the uppermost bedrock unit in different areas of the county. Below these units is the Ancell Group, which consists mostly of sandstone. The Ancell Group is underlain by Cambrian age rocks that are also generally sandstone. All of these sandstones are part of the deep aquifer used mainly for municipal supply. At the base of the sandstone are Precambrian age granites and quartzites.

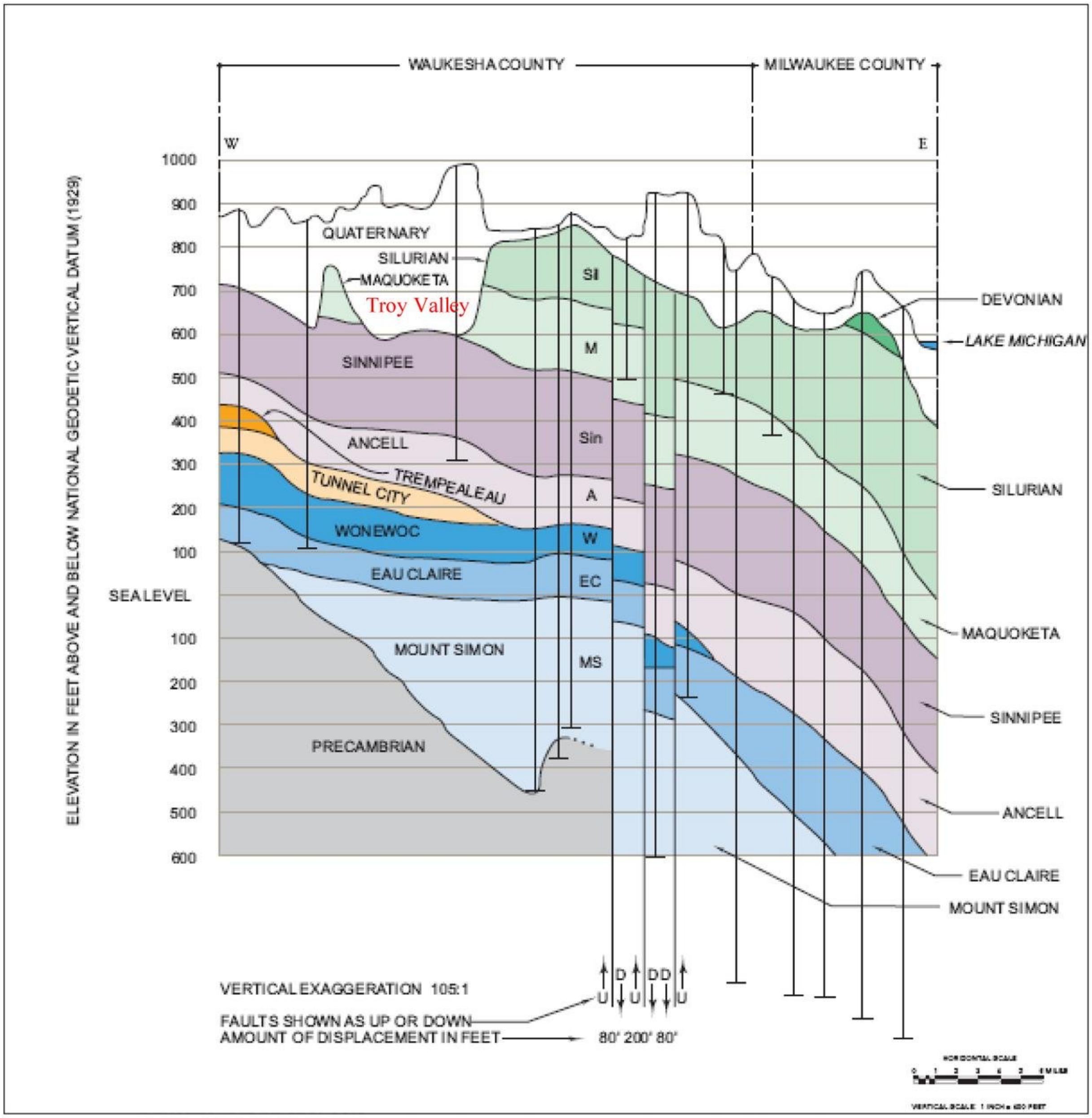

Figure 1.5. West to east cross section through Waukesha and Milwaukee Counties showing the bedrock geology, including the Waukesha Fault. Location of the cross section is shown in Figures 1.2 and 1.4. (from SEWRPC and WGNHS, 2002)

The surficial Quaternary deposits are the focus of this research. Most of the sediment was deposited during the Pleistocene Epoch, when the region was last glaciated. For the purpose of this project the deposits were divided into three groups: till, sand and gravel, and lacustrine silt and clay. Till was directly deposited by the ice sheet and generally consists of poorly sorted material varying from clay to boulder size. Sand and gravel lenses are found within the till. Larger more continuous sand and gravel units are present at depth in the valley. Finally, lacustrine silt and clay was deposited in lakes that formed as the ice sheet retreated. In addition to these Pleistocene age deposits, there are recent thin soil layers or peat deposits in some areas.

In this part of southeastern Wisconsin, there are three Pleistocene age stratigraphic formations: Oak Creek, Holy Hill, and Zenda (Fig. 1.6). These were deposited between about 25,000 and 14,000 years ago, during the last episode of the Wisconsin Glaciation (Mickelson *et al.*, 1984). The Zenda Formation is the oldest unit in southeastern Wisconsin and has upper and lower members, the Tiskilwa and Capron, respectively. The Zenda is found at the surface only in the southwestern corner of Walworth County (Fig. 1.6). However, in the project area the Tiskilwa Member is found locally and is deeply buried below the younger units. The Tiskilwa till is usually a pinkish color and contains about 40-50% sand, 40-50% silt, 5-15% clay, and a few percent gravel (Clayton, 2001). The Holy Hill Formation also has two members, the Horicon and New Berlin, that were deposited approximately at the same time by different lobes of the Laurentide Ice Sheet. The Horicon Member was deposited by the Green Bay Lobe and the New Berlin Member by the Lake Michigan Lobe. Till of the Holy Hill Formation is generally brown in color and is of a similar composition to the Tiskilwa Member, but somewhat sandier and with more gravel. The Oak Creek Formation is the youngest formation found in this area and is gray where unoxidized and brown where oxidized. It is less sandy and more clay rich than the older tills and is often associated with lake sediment (Mickelson *et al.*, 1984).

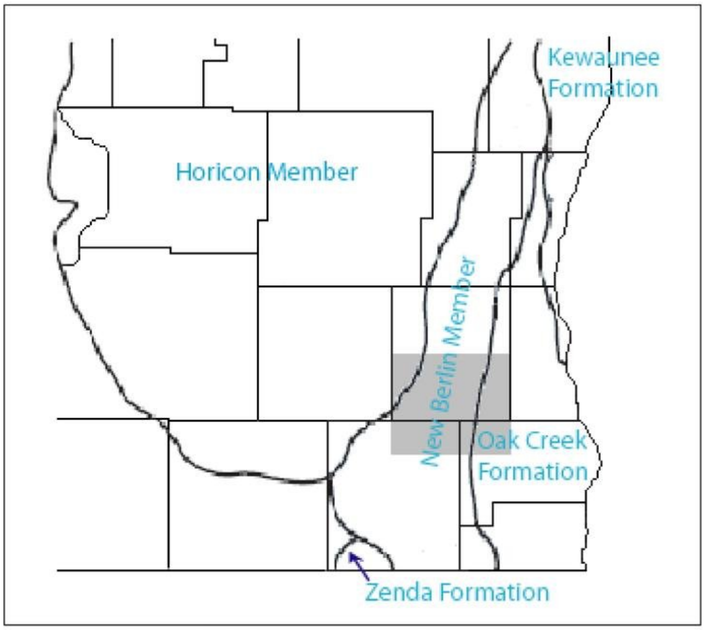

Figure 1.6. Surface distribution of Pleistocene stratigraphic units in southeastern Wisconsin. The shaded region indicates the area shown in Figure 1.2. The Horicon and New Berlin members are part of the Holy Hill Formation. (modified from SEWRPC and WGNHS, 2002)

1.3.3 Surface Water Hydrology

There are numerous surface water bodies in the research area (Fig. 1.2), most of which are located within the Fox River Watershed. All of the major lakes in the area are classified as either drainage, meaning they contain both an inlet and outlet, or seepage, meaning they have neither an inlet or outlet and are dependent on precipitation and groundwater. These lakes are all fairly shallow, with mean depths between 4 and 20 feet. However, Tichigan and Little Muskego Lakes have maximum depths of 65 feet (WDNR, 2005). The largest lake is Big Muskego Lake, covering 2,260 acres.

The major river in the area is the Fox River and its numerous tributaries include the Mukwonago River as well as Pebble and Mill Brooks. These two brooks merge with the Fox River in Vernon Marsh, the largest wetland in the area (Fig. 1.2). Average annual precipitation for southeastern Wisconsin is approximately 32 inches, with 70-80% lost by evapotranspiration and the remaining running off into streams or recharging the groundwater system (SEWRPC and WGNHS, 2002).

The two main surface water features of interest for this project are Lake Beulah and Vernon Marsh. Lake Beulah is located in Walworth County (Fig. 1.2) in the Town of East Troy. Lake Beulah is 834 acres and has a mean depth of 17 ft and a maximum depth of 58 ft. The area around Lake Beulah includes a number of smaller lakes and wetlands. The Lake Beulah Management District, originally set up as Sanitary District #2 of East Troy, is its own government entity (Walworth County Land Conservation Committee Meeting, 2005). The Lake Beulah Management District provides services to its residents such as weed control and lake monitoring in order to protect and maintain Lake Beulah.

Vernon Marsh is located in Waukesha County (Fig. 1.2), north of the City of Mukwonago. Most of the marsh property is owned by the Wisconsin Department of Natural Resources (WDNR) and is called the Vernon Wildlife Area. This area is 4655 acres and is mostly a wetland through which the Fox River runs (WDNR, 2008).

Chapter 2: Hydrostratigraphic Model

2.1 Objective

The three-dimensional distribution of glacial deposits in the Troy buried valley has not been previously studied in detail. Because the hydraulic conductivities of the deposits vary over ten orders of magnitude, it was necessary to determine the three-dimensional configuration of these deposits before constructing a groundwater flow model. The objective for this phase of the project was to create a geologically plausible three-dimensional model of the glacial deposits, assign hydraulic conductivities to each unit, and organize these data so they could be imported into a groundwater flow model.

In order to meet this objective, the glacial deposits were grouped into hydrofacies. A hydrofacies consists of deposits that have similar hydrogeologic properties such as hydraulic conductivity. The hydrofacies were assigned hydraulic conductivity values based on the literature values. However, these values were refined during calibration of the groundwater flow model (Chapter 3). The final hydrostratigraphic model was represented as continuous data but discrete hydraulic conductivity values determined the spatial arrangement of the hydrofacies or hydraulic conductivity zones in the groundwater model. Hence, threshold values of hydraulic conductivity, also estimated from literature values, were used to define the hydrofacies for input to the groundwater flow model.

2.2 Geology Data

2.2.1 Well Data

Well data were obtained from several sources. The largest data sources are the Wisconsin Geological and Natural History Survey (WGNHS) WiscLith Database and Well Construction Report (WCR) Database. These databases include information on almost 12,000 wells that were drilled within the Troy buried valley (Fig. 2.1). However, most of these do not have surface elevation data. The Walworth and Waukesha County databases contain almost 2,000 wells that have elevation data and that also have been checked for location accuracy. Most well locations are accurate to within either 100 or 250 ft (WGNHS personal communication, 2007). Additional well and test boring data were obtained from local consulting firms Ruekert-Mielke, Inc and Layne, Inc (personal communication, 2007). These data have more accurate locations, including elevations, and usually a geologist was present who logged the deposits during drilling.

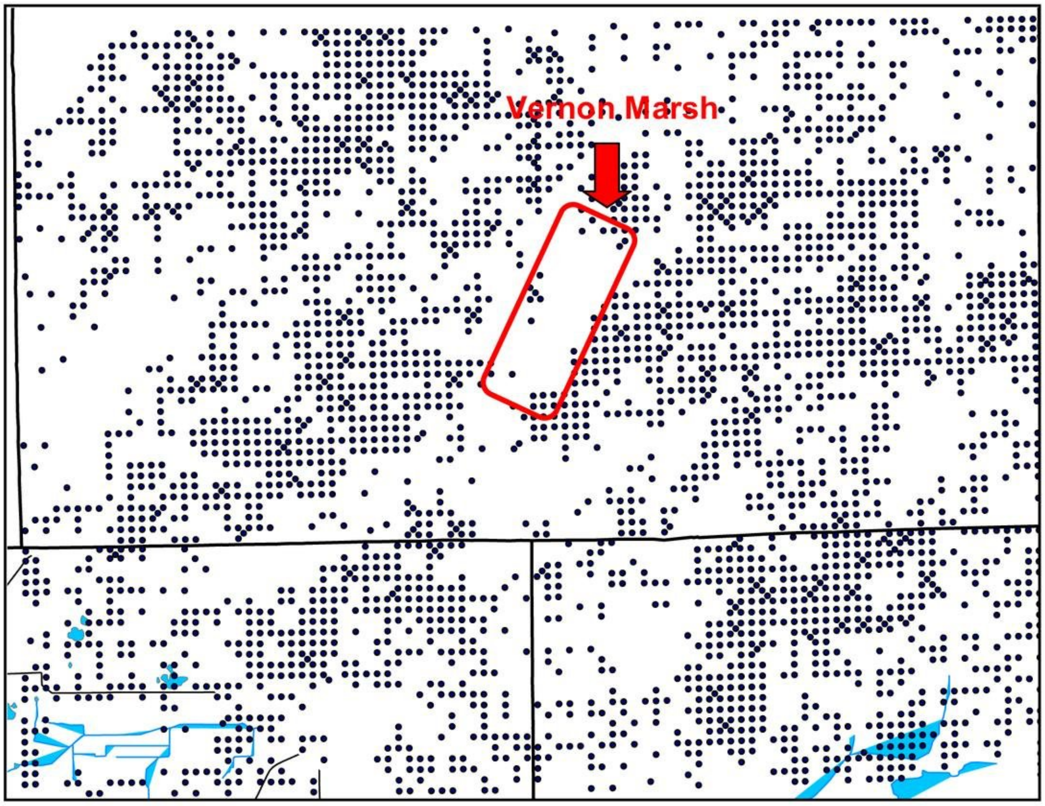

Figure 2.1. Distribution of 11,844 wells in the Troy buried valley area. Note sparseness of well data in Vernon Marsh.

2.2.2 Cross Sections

Six cross sections, mostly perpendicular to the axis of the Troy Valley, were constructed in cooperation with geologists at Ruekert-Mielke, Inc. (Figure 2.2.) In constructing the cross sections, drill holes done by Ruekert-Mielke, Inc. were used because these data are likely more reliable than those from the WCR Database. However, some WCR wells were used to fill in gaps in the cross sections. The cross sections were drawn by hand using a combination of the well or boring logs, topographic maps, and depth-to-bedrock maps. The cross sections show two glacial deposit units, a fine-grained unit that contains all lacustrine, till, and fine sand deposits, and a coarse-grained unit that contains coarser sand and gravel. Figure 2.3 shows one of the final cross sections (see Appendix 1 for others).

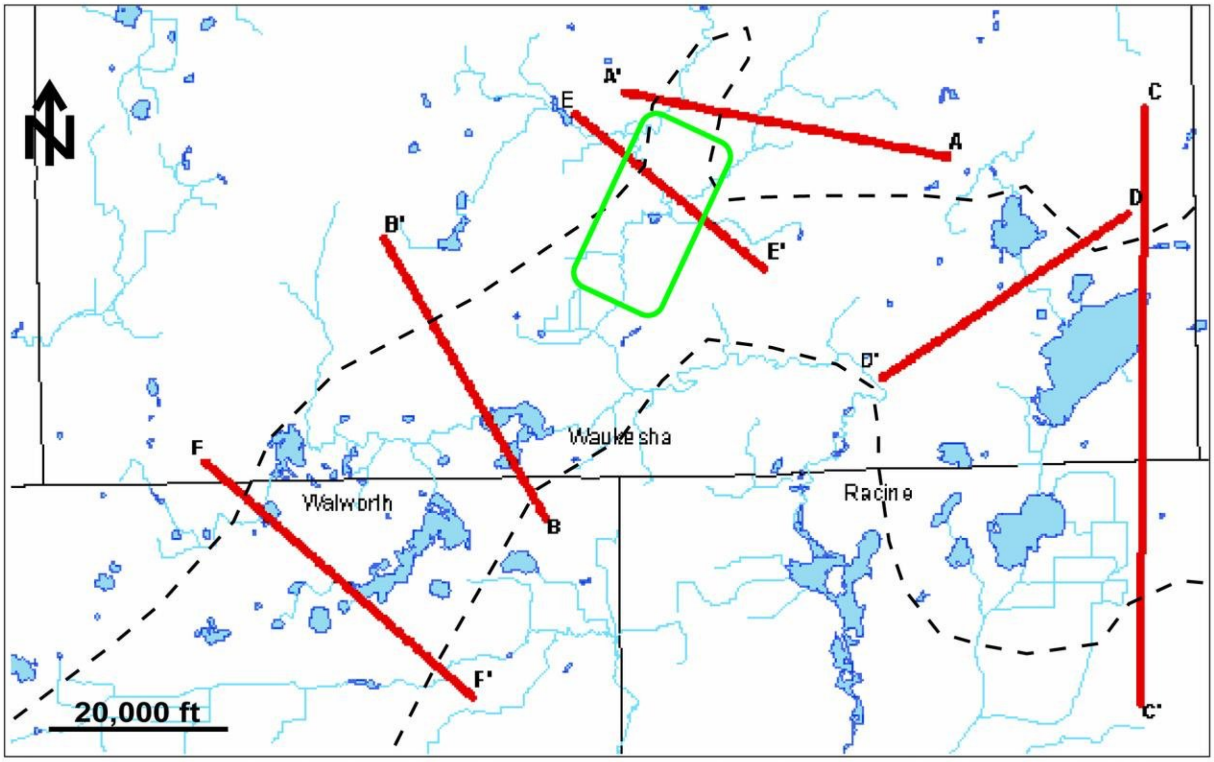

Figure 2.2. Map showing location of cross sections and surface water bodies. Dashed line shows approximate extent of the Troy Valley. Green box indicates the approximate area of the Vernon Marsh.

2.2.3 Geophysics

Geophysical data were also obtained from Ruekert-Mielke, Inc and Layne, Inc (personal communication, 2007). These data included eighteen transects where ground penetrating radar or time domain electromagnetic induction surveys were performed prior to this project. These surveys show that, in general, there is more sand and gravel at depth in the valley and more clay near the surface. Vernon Marsh has few wells (Fig. 2.1) and therefore additional geophysical measurements were performed as part of this project in cooperation with the WGNHS.

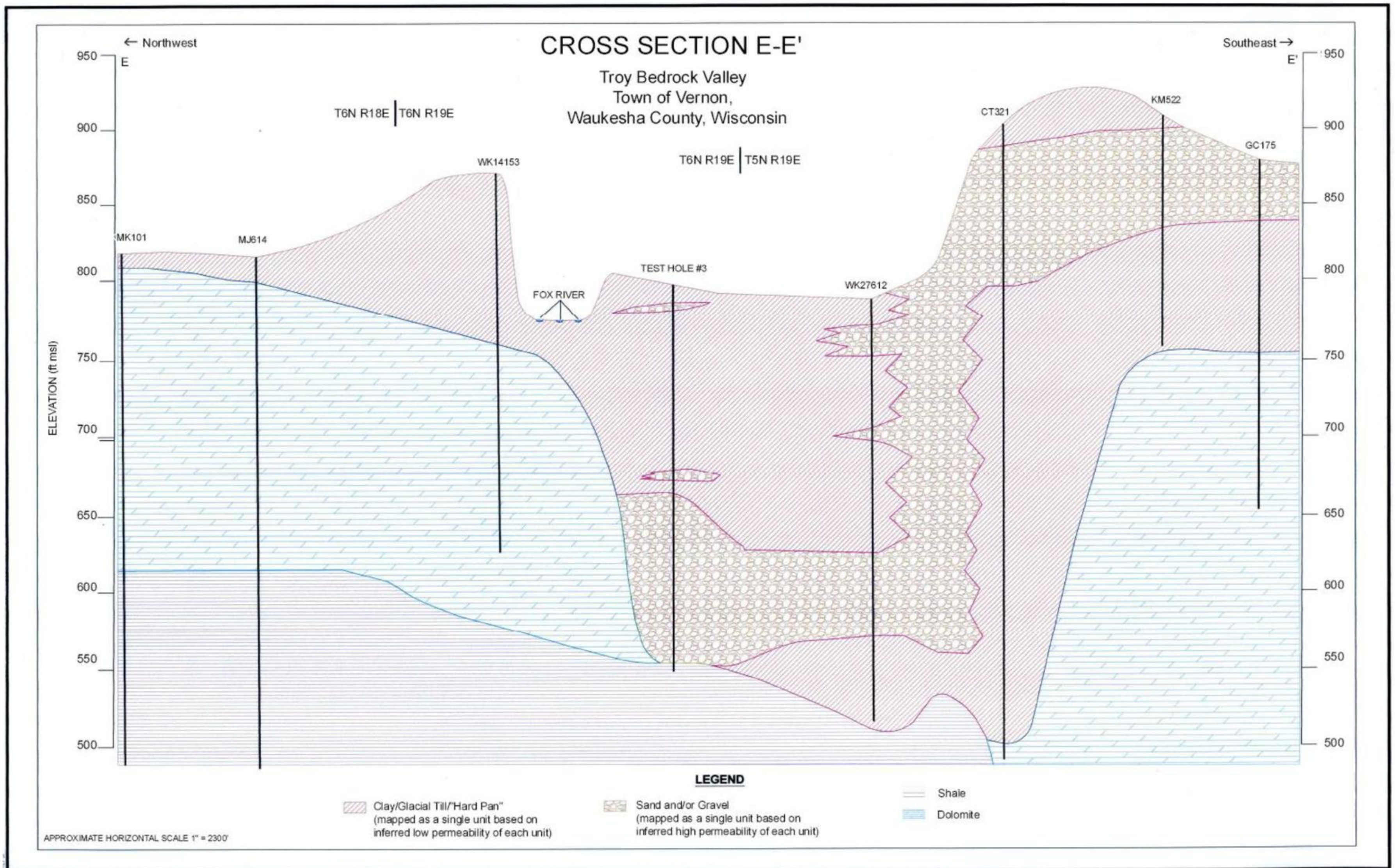

Figure 2.3. Cross Section E-E’, bisects Vernon Marsh. Exact location shown in Figure 2.2.

Electrical conductivity measurements were collected with an EM-31 ground conductivity meter (Fig 2.4). This instrument measures the conductivity of approximately the top 15 feet below the surface by transmitting and receiving a high frequency electromagnetic signal. The results are most strongly influenced by deposits 5 to 8 feet below the surface. Measurements around culverts were disregarded because metal affects the reading. Transects were run on the east and west sides of the marsh (Fig 2.5).

Figure 2.4. Photo of EM-31 at the west side of Vernon Marsh.

The higher values of electrical conductivity in Table 2.1 indicate a slight increase in clay content toward the center of the marsh. The lack of any abrupt decrease in conductivity shows that there are no sand and gravel deposits near the surface.

Vernon Marsh is interpreted as the bed of glacial Lake Vernon (Clayton, 2001), and therefore lacustrine clay and silt are expected near the surface beneath the peat within the marsh. There may be more sand and gravel along the edges of the marsh. The conductivity data provide weak support of this interpretation; borehole data in the marsh would be needed to further constrain stratigraphy beneath the marsh.

Table 2.1. EM-31 west transect data with distance in ft and conductivity in mS/m. Zero feet is located at the west end of the transect (Fig. 2.5). The east transect was similar to the west, indicating slight increase in clay content toward the center of the marsh and was therefore not recorded.

Distance	Conductivity	Distance	Conductivity	Distance	Conductivity
0	39	150	49	280	46
10	39	160	48	290	46
20	37.5	170	47	300	48
30	39	180	46	310	48
40	39	180	45	320	47
50	37	200	45	330	48
60	38	210	46	340	47
70	42	220	46	350	49
80	41.5	230	46	360	48
90	42.5	240	47	370	48
100	43	250	46	380	48
110	46	260	45	390	48
120-140	culvert	270	44	400	48

USGS well WK-1301 was drilled as part of an earlier study of the Troy Valley (Batten and Conlon, 1993) near the edge of the marsh along the Fox River (Fig. 2.5). The well log is very general, with descriptions such as “sand, silty fine, gravel”. Therefore, we logged gamma radiation so that it could be compared to the boring log. Fig 2.6 shows part of the gamma log next to the older drilling log. The high counts correspond to clay, while low values are sand or sand and gravel. The gamma log correlates well with the boring log. From 87-125 ft the boring log lists “clay, sandy, gravel”, while the gamma log indicates areas within this depth range that have higher clay content, such as at 113-114 ft deep. The gamma log also shows a high clay content region around 10-15 ft deep, which agrees with the EM-31 measurements in the marsh that show silt and clay.

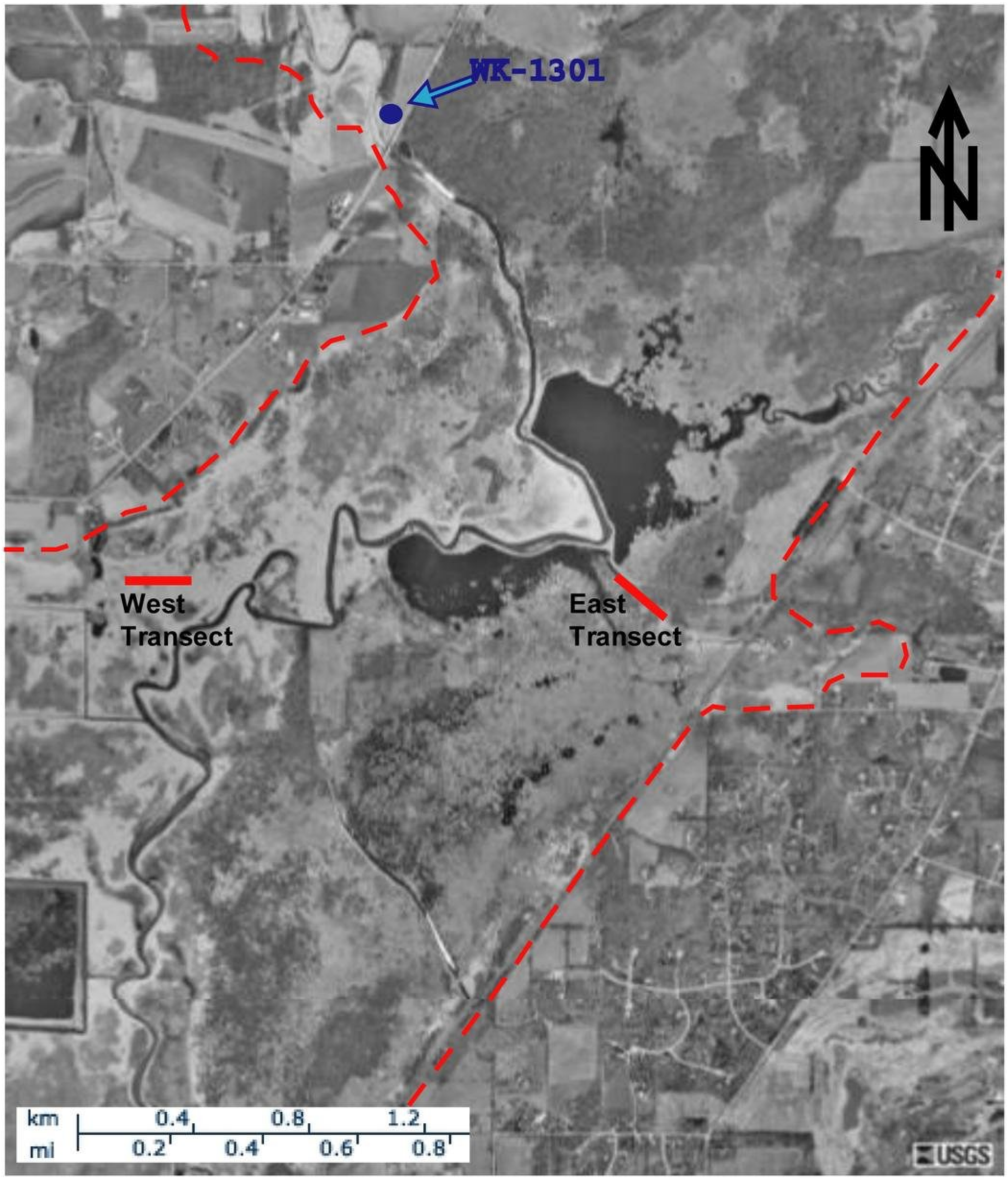

Figure 2.5. Air photo of Vernon Marsh, solid red lines indicate EM-31 transects, the blue dot is the location of well WK-1301. Red dashed lines show approximate extent of the Vernon Marsh.

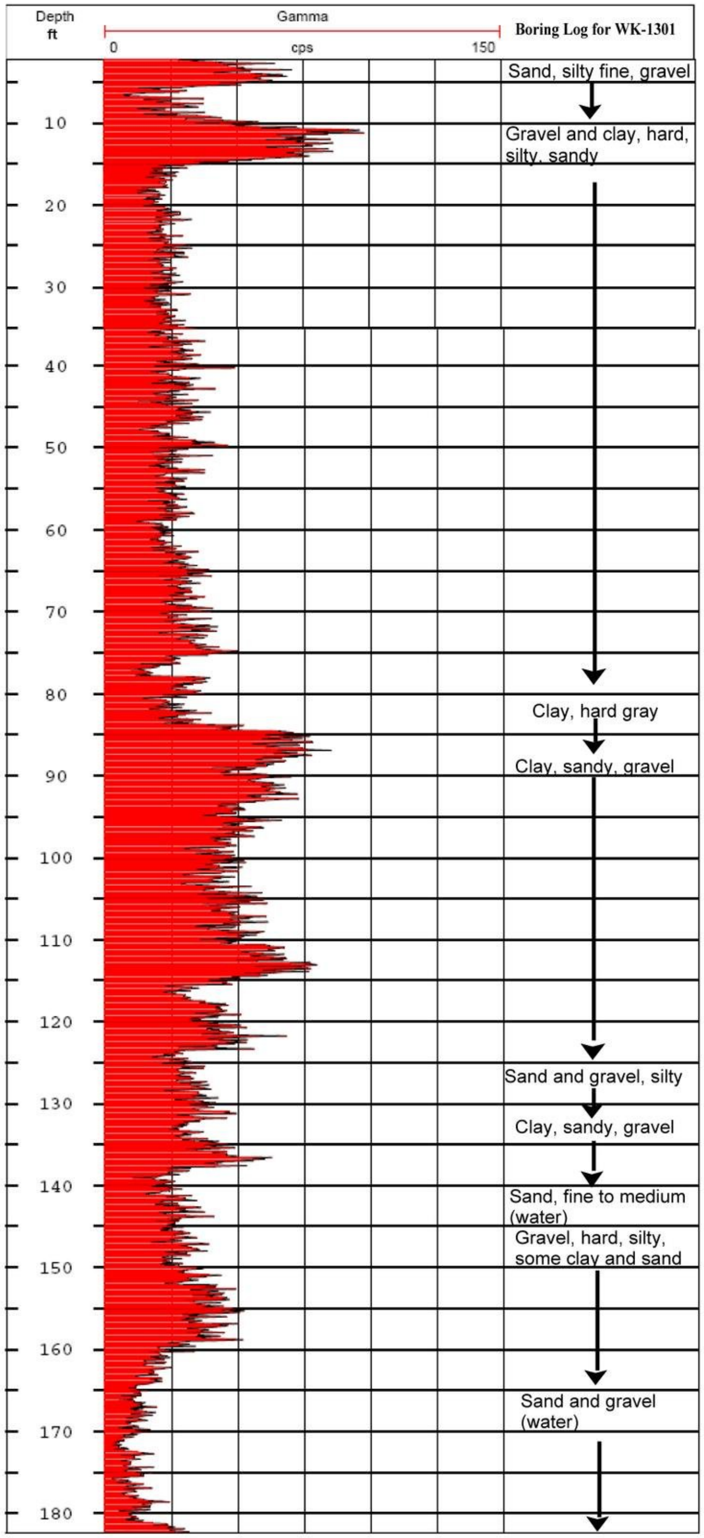

Figure 2.6. Comparison of gamma radiation log in counts per second and boring log for WK-1301. High gamma counts indicate more fine-grained sediment, particularly clay. Low counts indicate sand or sand and gravel.

2.3 Interpreting Well Construction Reports

Well construction reports are submitted by well drillers after a well is completed. Most drillers lack formal geologic training, some logs are written up after well completion rather than onsite, and often subtle differences in sediment are not reflected in cuttings. Therefore, the quality of these data varies considerably. For example, terms such as "hardpan" usually refer to glacial till, but so can stoney clay or clayey gravel, among other designations. Considerable effort was made to be consistent and as accurate as possible in transforming the driller's descriptions into geologic categories.

2.3.1 Three verses Four Units

Initially, the driller's descriptions were separated into three hydrofacies: 1) fine grained till and lacustrine deposits such as clay and silt, 2) mainly silty and sandy till and deposits of intermediate composition, and 3) sand and gravel deposits. However, because of the wide range of hydraulic conductivity of sand and gravel deposits (10^{-1} to 10^{-5} cm/s according to Stephenson *et al.*, 1988), this hydrofacies was subdivided into a sand unit and a gravel unit. These hydrofacies and the driller's descriptions included in each are shown in Table 2.2. The few areas that had peat in the driller's logs were added to hydrofacies two, since the average hydraulic conductivity for peat (Boelter, 1965; Holden and Burt, 2003) is about the same as for glacial till.

2.3.2 Hydraulic Conductivity Determination

Literature values of hydraulic conductivity were assigned to each of the four hydrofacies. Measurements of glacial deposits from North America (Stephenson *et al.*, 1988) were compared with local studies in southern Wisconsin (Simpkins *et al.*, 1990; Anderson *et al.*, 1999) to determine the most likely values for each type of deposit. Field derived values of hydraulic conductivity from the literature were used rather than laboratory derived values because they better account for larger scale features such as weathering horizons and fractures.

Table 2.2. Units in drillers' descriptions that are included in each of the hydrofacies and their corresponding hydraulic conductivity values selected for use in the model.

Hydrofacies 1	Hydrofacies 2			Hydrofacies 3	Hydrofacies 4
clay	hardpan	silty sand	muck sand and gravel	sand	sand and gravel
silty clay	clayey gravel	fine sand and gravel	silty gravel	coarse sand	gravel and boulders
sand, clay	clay and gravel	sand and silt with till	peat	medium sand	fine gravel
silty clay	sand gravel and clay	drift silt sand gravel	top soil and peat	water bearing sand	rubble
clay, sand	clay and stones	clay gravel and silt	clay and peat	blowsand	sand, fine gravel
sandy clay	fine sand	gravel muddy	black muck	quicksand	broken rock
surface clay	clay and cobbles	silty sand and gravel	peat moss	drift sand	boulder
puddle clay	clay and broken rock	muddy sand and gravel	muck	heaving sand	gravel
drift silt sand clay	stoney clay	muck sand	marsh mud		
	Initial Hydraulic Conductivity (cm/s)				
10^{-8}	10^{-5}			10^{-2}	10^{-1}

The hydraulic conductivity of hydrofacies 1 (lacustrine silt and clay and fine grained till) was determined mainly from Stephenson *et al.* (1988), who give a range of 10^{-6} to 10^{-11} cm/s. However, most of their cited data are around 10^{-8} cm/s, so that was the value chosen for these deposits. Till deposits range over seven orders of magnitude in North America (Stephenson *et al.*, 1988), so local studies were used to constrain this range. Simpkins *et al.* (1990) measured field values in southeastern Wisconsin for the Holy Hill and Oak Creek Formations on the order of 10^{-5} and 10^{-6} cm/s, respectively. Because most of the till in

Waukesha County is Holy Hill Formation, 10^{-5} cm/s was chosen for hydrofacies 2 (silty and sandy till).

There is less information about sand and gravel deposits in the literature, and they are often grouped together. Stephenson *et al.* (1988) give a range from 10^{-1} to 10^{-5} cm/s for outwash, which includes both sand and gravel. A study of braided stream deposits in Dane County, WI (Anderson *et al.*, 1999) found sand (hydrofacies 3) deposits on the order of 10^{-2} cm/s and gravel (hydrofacies 4) around 10^{-1} cm/s. So these hydraulic conductivity values were selected for the coarser grained hydrofacies.

A spreadsheet version of the computer code TGuess (Bradbury & Rothschild, 1985) was used to test the choice of hydraulic conductivity values for the sand and gravel deposits. Eight hundred thirty-eight wells screened in either sand or gravel deposits in the Troy Valley were selected for analysis. TGuess uses specific capacity data from driller's logs to estimate aquifer transmissivity, based on the method of Theis *et al.* (1963). Specific capacity information taken from the driller's logs is used along with estimated parameters. The data from the logs include well diameter, change in water level, pumping duration, mean pumping rate, and the interval over which the well is screened. The estimated parameters are storage coefficient, well loss coefficient, and aquifer thickness. The storage coefficient was estimated to be 0.25 based on the literature (Johnson, 1967), assuming the deposits range from medium sand to gravel and are unconfined. The well loss coefficient was assumed to be zero. Finally, the aquifer thickness was assumed to be the saturated screened interval. For open boreholes, which do not have screens, the interval was assumed to be the average of the saturated screen intervals.

Because these are estimated values, a sensitivity analysis was performed for both the storage coefficient and the aquifer thickness for open boreholes. Figures 2.7 and 2.8 show that neither of these parameters has a significant effect on the calculated average values or the range of hydraulic conductivities. Additionally, the spreadsheet has a well bore storage test, which checks that specific capacity test rate and duration were adequate to negate the influence of water removed from the well casing on the measured drawdown (Cobb, 2005). The pumping test duration must be longer than $25r_w^2/T$, where r_w is the well radius and T is transmissivity. All wells that failed this test were not included in the sensitivity analysis.

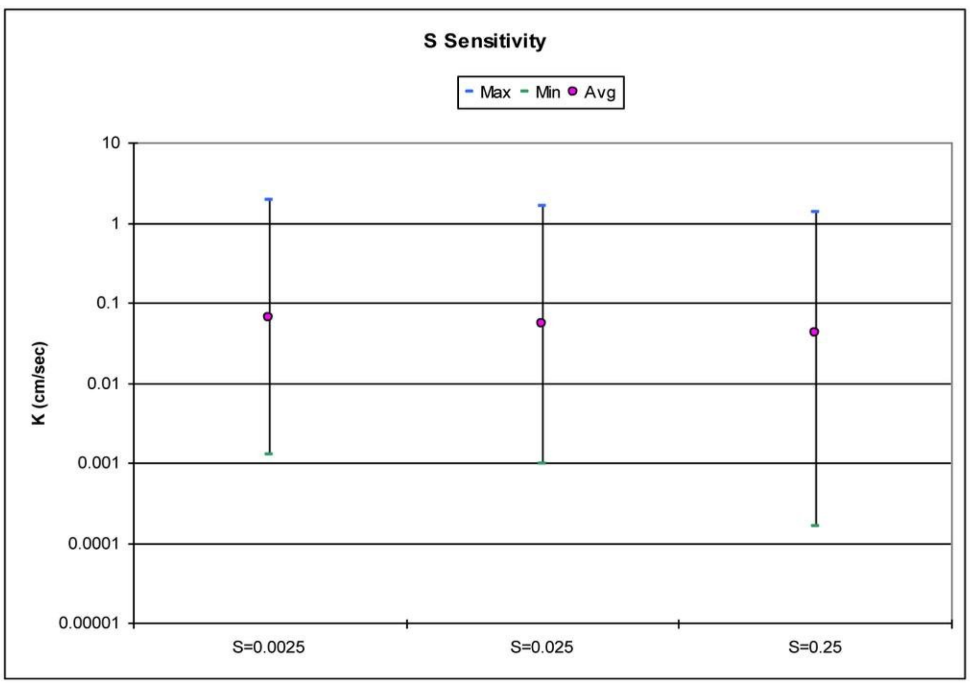

Figure 2.7. Sensitivity of storage coefficient (S). The average, maximum, and minimum values for each of the tested storage coefficients produces the same order of magnitude for hydraulic conductivity. This indicates that storage coefficient has a negligible effect.

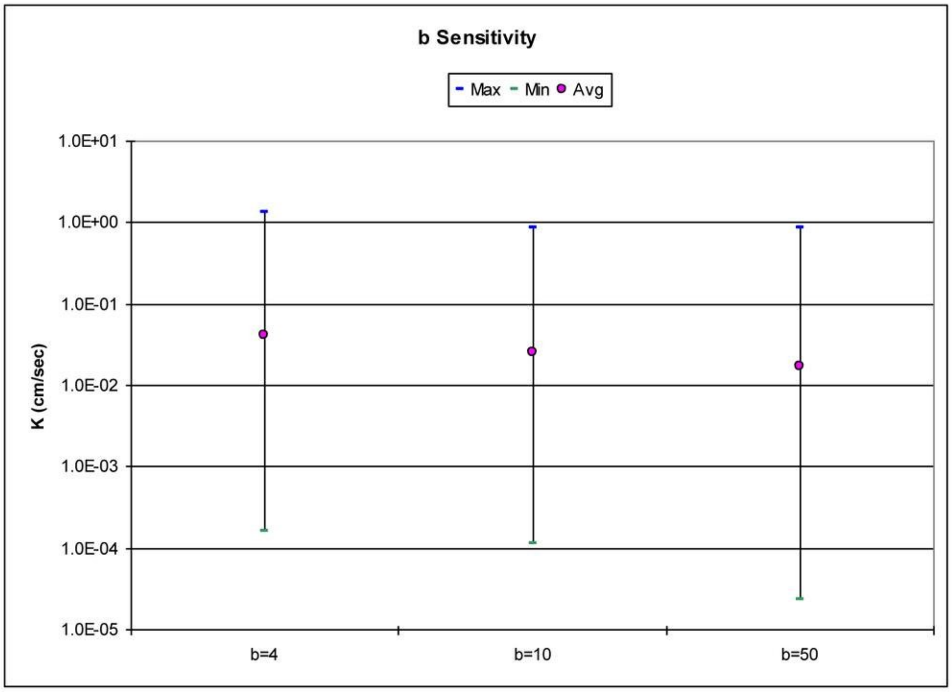

Figure 2.8. Sensitivity of aquifer thickness (b) in feet. The average values for each of the tested aquifer thicknesses for open boreholes produces the same order of magnitude for hydraulic conductivity. Also the minimum and maximum values are within an order of magnitude, indicating aquifer thickness has a negligible effect.

The specific capacity analysis showed that approximately 8% of the wells that were analyzed had a hydraulic conductivity value of the same order of magnitude as the chosen literature value of 10^{-1} cm/s for hydrofacies 4 (gravel), 64% were of the same order of magnitude as the chosen hydrofacies 3 (sand) literature value of 10^{-2} cm/s, and 28% were an order of magnitude lower. The data that were an order of magnitude lower were taken from wells most likely screened in "sand" according to the driller's logs, but could actually be fine-grained sand or silt. Nevertheless, the specific capacity data suggest that hydraulic conductivity values for hydrofacies 3 (sand) and hydrofacies 4 (gravel) of 10^{-2} and 10^{-1} cm/s are appropriate.

2.4 3D Modeling Software

After considering a number of software options, the software Rockworks™ v. 2006 was selected to construct the hydrostratigraphic model. Rockworks™ was selected because it could import the assembled well data, export those data in a format that could be imported into the groundwater model, was inexpensive, fairly easy to use, and creates and displays a 3D model. The well data (1,863 wells) from the WGNHS that had been checked for location accuracy were imported into Rockworks™ using the software's Excel™ template. The wells were then displayed as cylinders in 3D space (Fig. 2.9) to determine if any trends existed in the deposits. The most noticeable feature was the abundance of hydrofacies 1 (lacustrine silt and clay) on the eastern edge of Waukesha County, which was the uppermost unit in almost all of the wells in that region. Visualizing the raw data in 3D was a useful way to develop a general sense of the geology in the region, before allowing Rockworks™ to create a solid model (e.g., a block diagram of the deposits).

2.5 Hydrostratigraphic Model Design

2.5.1 Model Grid and Layers

A grid spacing of 800 ft by 800 ft, with 50 ft vertical spacing was first used in order to limit the amount of time needed for each model run. However, our final goal was a hydrostratigraphic model with nodes having the same lateral spacing as the groundwater model. Therefore, in the selected model a 400 by 400 ft grid spacing was used, creating 339 nodes in the x direction and 251 in the y, for a total of 85,089 nodes per layer. The final grid spacing in the z direction is 10 ft, creating 69 layers. This fine vertical spacing also allows for easier import into the groundwater model.

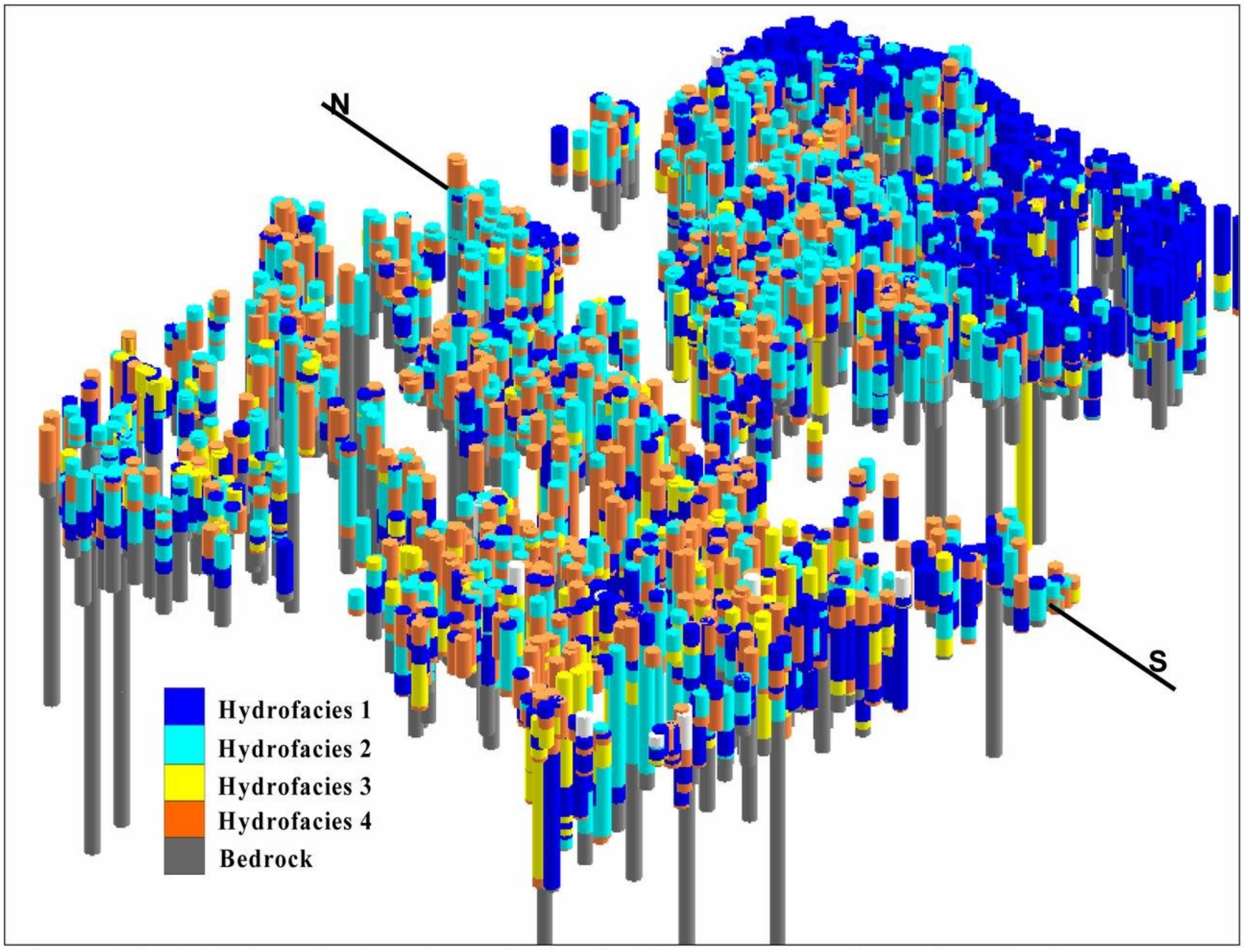

Figure 2.9. Well logs displayed as cylinders in 3D space. Note the surface clay/lacustrine deposits (hydrofacies 1) in the east.

2.5.2 Data used in solid model

Only the well data from unconsolidated sediment were used to construct the block diagram (solid model). All bedrock data were removed from the initial data that had been imported so that only the valley fill would be interpolated. This was necessary because an intermediate hydraulic conductivity zone that does not exist would have been created by the software had the bedrock been kept in the data set. Literature values of hydraulic conductivity (K) were entered into the model as the natural logarithm of K (ln K) due to the large order of magnitude difference between units. Using ln K allows for more accurate interpolations because the differences are equalized across orders of magnitude. The midpoint elevations of each unit in a well were used for the z direction locations. For example, if till was located between 770 and 830 feet then an elevation of 800 ft was used as the z location. This was done because point, not continuous data, are needed in order to create a solid model. The spreadsheet used for data input is included in the accompanying material CD.

2.5.3 Interpolation Scheme

The method of interpolation used in the solid modeling was Inverse-Distance with Weighting. A node is assigned a value (for this study, the ln K) based on a weighted average of neighboring data points. These interpolated values are determined by the following equation: $G_{node} = \Sigma(G_{point}/d^n) / \Sigma(1/d^n)$ where G is the value, d is the inverse of a point's distance from the node that is being solved for, and n is an exponent. This allows the closest points to have the greatest effect on the node's final value, with higher n values causing less influence from more distant points. More weight can be added either horizontally or vertically, by assigning different n values for each. This means that a larger n value assigned to a direction will cause that direction to have less weight in determining a node's value.

2.6 Model Selection

Eleven models with different horizontal verses vertical weighting (Table 2.3) were run. The initial Rockworks™ setting of 2-2 horizontal-vertical weighting was run as a base case. Because the horizontal weighting equals the vertical, there is no preferential weighting in a specific direction. The selection of 2-2 was arbitrary, a model of 1-1 or 100-100, would have given the same horizontal and vertical weighting, but with slightly different results since the number itself indicates how much influence points farther away have on a node, with larger numbers causing less influence from more distant points. The 2-2 model did not produce the surface hydrofacies 1 deposits that are seen in the raw well data (Fig. 2.9). Also, the model showed vertical tubes of sand and gravel (Fig. 2.10), which does not make geologic sense. Therefore, all subsequent models were selected with more weighting in the horizontal direction to reduce this effect.

Table 2.3. Hydrostratigraphic model runs in Rockworks^{TM}. The two numbers for each model indicate the n values for horizontal-vertical weighting. The smaller number is the direction of preferential weight, in this case the horizontal direction. The descriptions give relative amounts of horizontal weighting and the major flaws in each model.

2-2	Base case; no weighting; vertical tubes, no eastern surface clay
0.2-3	Slight horizontal weighting; vertical tubes, no eastern surface clay
0.2-6	Slight horizontal weighting; vertical tubes, no eastern surface clay
0.2-10	Slight horizontal weighting; vertical tubes
1-3	Slight horizontal weighting; vertical tubes, no eastern surface clay
1-10	Slight horizontal weighting; vertical tubes
1-20	Average horizontal weighting; no extreme problems
1-30	Average horizontal weighting; no extreme problems
1-50	Average horizontal weighting; horizontal sand layers
1-65	Extreme horizontal weighting; horizontal sand layers
1-100	Extreme horizontal weighting; horizontal sand layers, no eastern surface clay

All of the models with slight horizontal-vertical weighting (Table 2.3) showed vertical tubes (Fig. 2.10), while those with extreme horizontal weighting began to show continuous horizontal layers of hydrofacies 3 (sand), inconsistent with the six cross sections (Fig. 2.3. and Appendix 1) that indicated the sands are not well connected laterally. At the extreme of 1-100 (Fig. 2.11), the deeper portions of the valley were almost entirely hydrofacies 3 (sand) and once again hydrofacies 1 was not present at the surface. Based on these observations, only two models (horizontal-vertical weighting of 1-20 and 1-30) were considered in the final comparisons. The models were compared based on which was most geologically reasonable and best matched the six cross sections (Fig. 2.12, Fig. 2.3 and Appendix 1). The 1-30 model was the best fit for these two criteria and was rerun with the finer grid spacing of 400 ft by 400 ft (85,089 nodes per layer). Because the interpolation produces an array of hydraulic conductivity values, the final hydrostratigraphic model was compared to the cross sections in order to determine initial ranges of hydraulic conductivity values (Fig. 2.13) for separating the model into four distinct hydrofacies. The ranges for each of the hydrofacies are listed in Table 2.4. Uncertainty in the final selected model was addressed by running multiple realizations of the groundwater flow model (Chapter 3). These realizations were created by selecting different hydraulic conductivity values for each of the hydrofacies, based on literature values. The uncertainty analysis is discussed fully in Chapter 3.

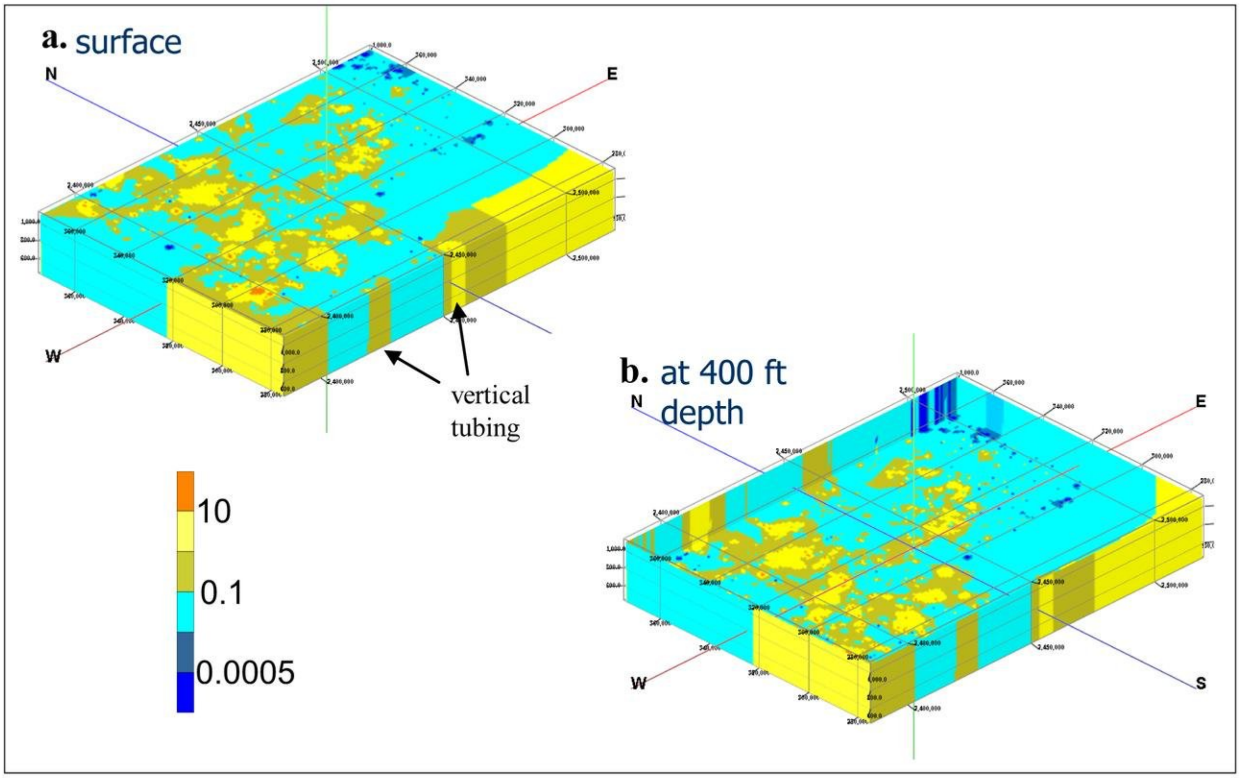

Figure 2.10. 2-2 Horizontal-Vertical Model results displayed at the (a) surface and at (b) 400 ft depth. Note that the layers look nearly identical and there is a vertical tubing effect, especially noticeable along the southern boundary (indicated by arrows). Also, the area of hydrofacies 1 (dark blue) deposits in the east is much smaller than the raw data show (Fig. 2.9) The scale indicates values of hydraulic conductivity in ft/day.

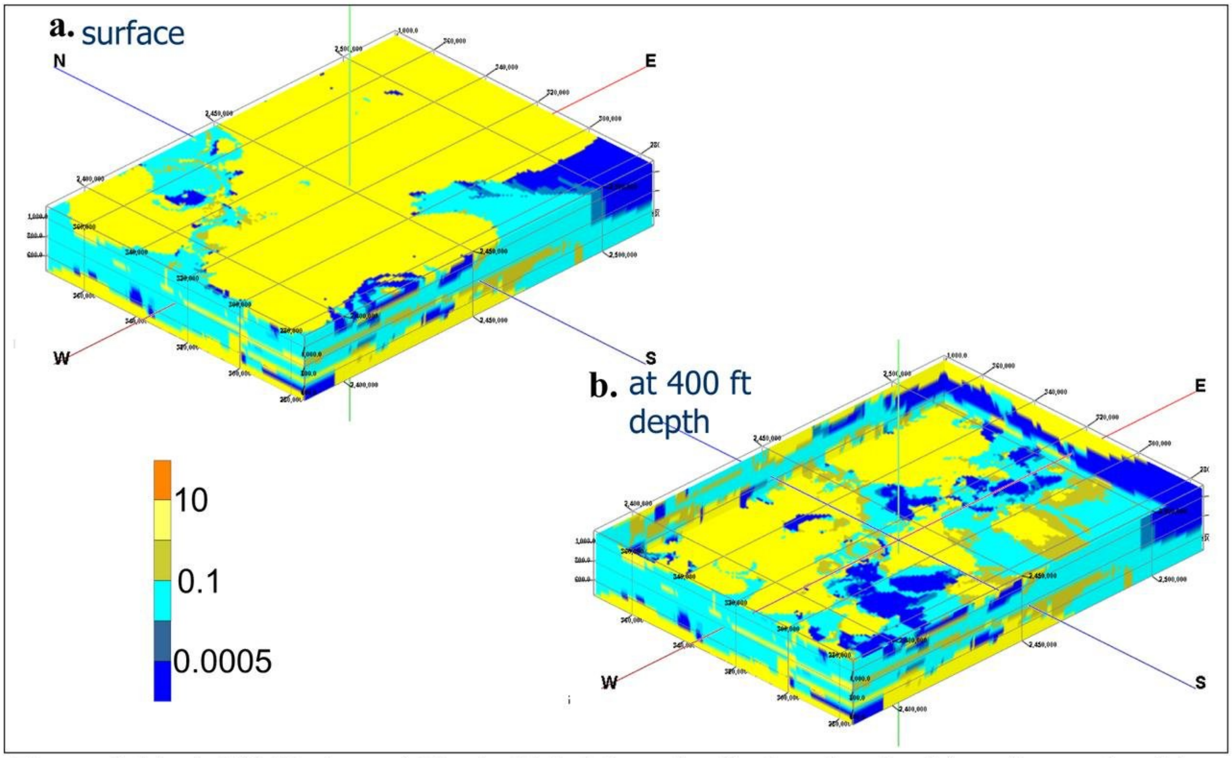

Figure 2.11. 1-100 Horizontal-Vertical Model results displayed at the (a) surface and at (b) 400 ft depth. Note that the surface layer is almost entirely hydrofacies 3, which contradicts the raw data (Fig. 2.9). The scale indicates values of hydraulic conductivity in ft/day.

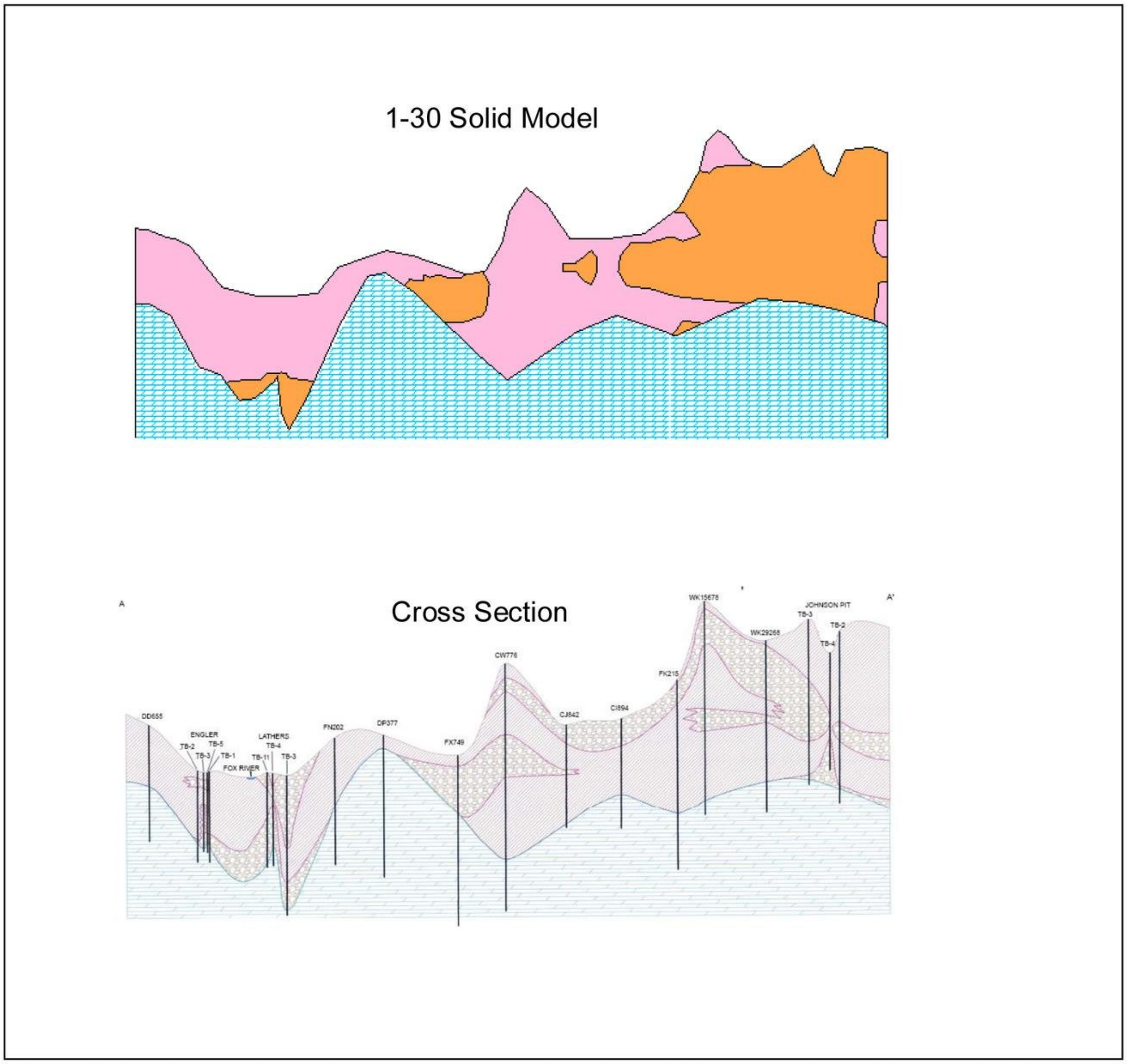

Figure 2.12. Comparison of cross section A-A' to the solid hydrostratigraphic model. The blue represents the dolomite bedrock, pink the finer grained deposits (hydrofacies 1 and 2) and orange/brown the coarser grained deposits (hydrofacies 3 and 4). It is important to note that while the solid hydrostratigraphic model is exactly a straight line from point A to point A', the cross section is not, since many of the wells did not fall exactly on the line and were projected onto the line. This could account for the small discrepancies between the two.

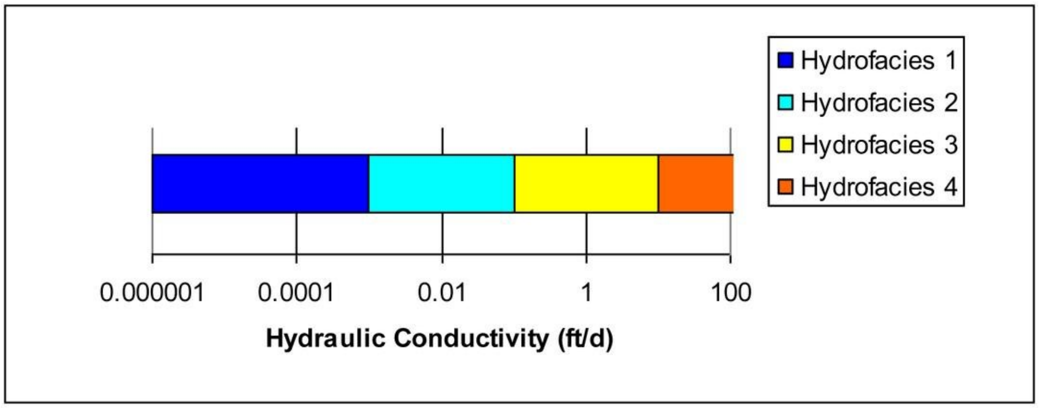

Figure 2.13. Graphical representation of hydraulic conductivity ranges chosen to separate the model into four distinct hydrofacies.

Table 2.4. Hydraulic conductivity ranges in cm/s and ft/d for separating the model into the four hydrofacies (Table 2.2). All future chapters will present hydraulic conductivities in ft/d because the groundwater model is in ft/d.

Hydrofacies	K (cm/sec)	K (ft/day)
1	10^{-8} to 10^{-6}	$1x10^{-5}$ to $1x10^{-3}$
2	10^{-6} to 10^{-4}	$1x10^{-3}$ to $1x10^{-1}$
3	10^{-4} to 10^{-2}	$1x10^{-1}$ to 10
4	10^{-2} to 10^{-1}	10 to 100

2.7 Importing the Hydrostratigraphic Model into the Groundwater Model

The final hydrostratigraphic model (Fig. 2.14, CD Appendix) required processing prior to being imported into the groundwater model. The hydrostratigraphic model covered a slightly larger area than the groundwater model; therefore, the lateral coordinates were adjusted to correspond to the 400 by 400 foot nodes of the groundwater model. The hydrostratigraphic model contains only the unconsolidated deposits; therefore, nodes that were in bedrock had to be determined. This was done by comparing the hydrostratigraphic model data and the elevation data from the groundwater model in a spreadsheet in order to determine whether a particular node contained glacial deposits or bedrock. If a node was bedrock it was assigned to a bedrock unit. Bedrock units are the Silurian dolomite, Maquoketa shale, and Sinnippee dolomite. Next the hydraulic conductivity data were assigned to the appropriate hydrofacies based on Table 2.4. For example, if a node had a hydraulic conductivity value that fell in the hydrofacies 3 range, it was designated as hydrofacies 3. Finally these unit data were imported into the groundwater model as ascii text files.

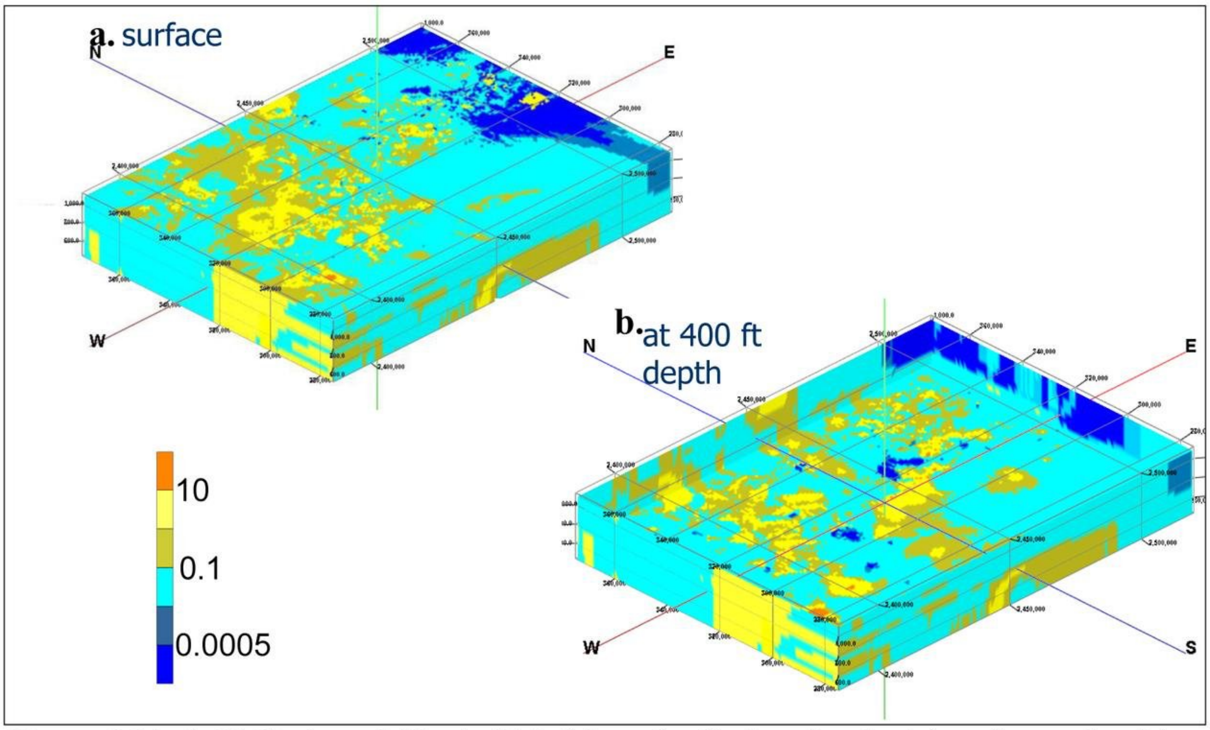

Figure 2.14. 1-30 Horizontal-Vertical Model results displayed at the (a) surface and at (b) 400 ft depth. Note that the surface layer matches well with the raw data (Fig. 2.9), especially in the east, where hydrofacies 1 is present. The scale indicates values of hydraulic conductivity in ft/day.

Chapter 3: Regional Groundwater Flow Model

3.1 Introduction: Modeling Objectives

The main objective for the groundwater flow modeling phase of the project was to determine how much groundwater levels and surface water features in the project area, such as lakes and wetlands, would be affected by pumping from the Troy Valley. In order to address this objective a regional steady-state model was constructed and calibrated. Then, a predictive simulation was run to simulate the effects of pumping from recently installed high capacity wells. Two hundred fifty realizations of the model were run stochastically to assess uncertainty in the hydraulic conductivity values of the hydrostratigraphic units and future pumping rates. Additionally, two local scale models (discussed in Chapter 4) were constructed to simulate impacts in the vicinity of Lake Beulah and Vernon Marsh.

3.2 Model Codes

The United States Geological Survey's (USGS) Modular Ground-Water Flow Model, MODFLOW-2000, was used to simulate groundwater flow in the Troy Valley (Harbaugh *et al.*, 2000). This code was chosen because of its capabilities to simulate three-dimensional groundwater flow in both steady-state and transient conditions and its ability to represent surface water features. The pre- and post-processor Groundwater Vistas (GWV) Version 5.01 (Rumbaugh & Rumbaugh, 2007) was used to set up and run the model. The code PEST (Doherty, 2004), which is a parameter estimation routine, was used in the initial stages of calibration, but the final model calibration was performed manually. The particle tracking code MODPATH (Pollock, 1994) was used to determine the capture zone of the pumping wells simulated in the predictive runs of the model. The MODFLOW models were solved using the PCG2 solver (Hill, 1990), which uses both head change and mass-balance as convergence criteria.

3.3 Model Design

3.3.1 Model Grid and Layers

The Southeastern Wisconsin Regional Planning Commission (SEWRPC) regional model, which has horizontal grid spacing of 2,500 by 2,500 feet in the area of interest and 18 layers of variable thickness (Feinstein *et al.*, 2005) was used to define the boundary conditions for the Troy Valley regional model using the telescopic mesh refinement (TMR, Ward *et al.*, 1987) option in Groundwater Vistas. The Troy Valley regional model has uniform horizontal grid spacing of 400 by 400 feet, with 230 rows and 320 columns. The 11 layers in the Troy Valley regional model have uniform thickness, except for layer 1, which has varying top elevations (Table 3.1). The Troy Valley regional model does not represent the deep sandstone aquifer, since the purpose of the model is to simulated flow in the Troy Valley glacial deposits. Hence the bottom eight layers of the SEWRPC model were removed. The bottom elevation of the top layer was set at 750 ft above mean sea level (amsl), in order to be at least 5 feet below the lowest land surface elevation and also allow the water table to lie entirely within one layer. The top elevations of the first layer were taken from the SEWRPC model and represent land surface.

Table 3.1. Thicknesses and bottom elevations for each layer in the Troy Valley regional model.

Layer	Thickness (ft)	Bottom Elevation (ft amsl)
1	variable	750
2	9	741
3	11	730
4	15	715
5	19	696
6	25	671
7	33	638
8	42	596
9	55	541
10	71	470
11	93	377

3.3.2 Boundary Conditions

Head values were taken from the SEWRPC model along the four sides of the Troy Valley model in every layer and used to specify heads along the side boundaries. The bottom boundary, at the base of layer 11, is a vertical flux boundary implemented by using pumping and injection wells in MODFLOW. The vertical fluxes were calculated using Darcy's law, $Q = -K_zA(dh/dz)$, where K_z is the vertical hydraulic conductivity between layers 10 and 11 of each cell, A is the cross-sectional area of the bottom of the cell, and dh/dz is the vertical head gradient between layers 10 and 11. The head and K_z values used to calculate the vertical flux were initially taken from the SEWRPC model. The top layer (upper boundary condition) has a specified flux equal to the recharge rate from the SEWRPC model. The recharge rate ranges from 1 to 14 in/yr (Fig 3.1). Average annual precipitation for southeastern Wisconsin is approximately 32 inches (SEWRPC and WGNHS, 2002).

For the predictive simulations, the lateral specified head boundaries were converted to specified flux boundaries, using calibrated heads and hydraulic conductivities from the Troy Valley model. The fluxes were calculated using Darcy's law in a similar manner to the layer

11 vertical fluxes, but using horizontal hydraulic conductivity between cells in a layer and the horizontal head gradient in the boundary cells. Also, the layer 11 boundary fluxes were recalculated using the calibrated head and hydraulic conductivity values from the Troy Valley model.

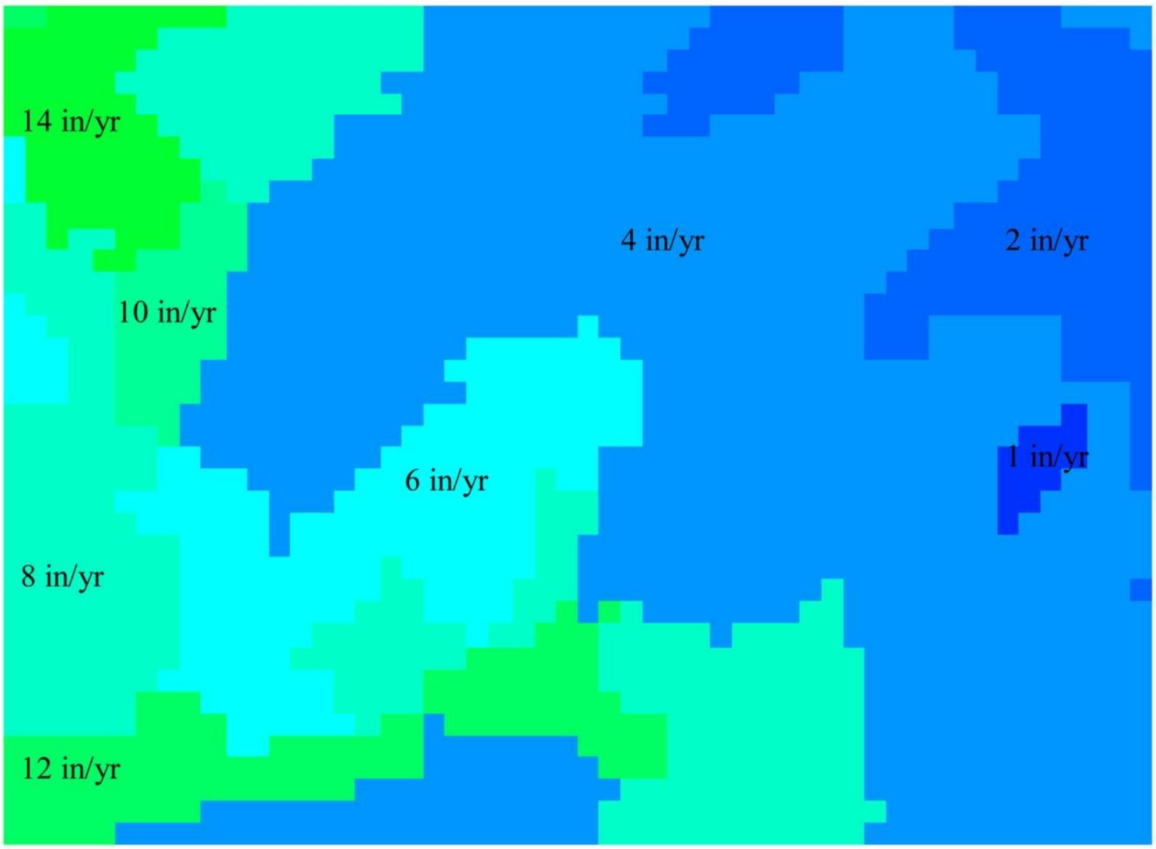

Figure 3.1. Recharge rates used in the Troy Valley regional model, taken from Feinstein *et al.* (2005).

3.3.3 Surface Water Features

The River Package was used to simulate major surface water features in the model area (Fig. 3.2). Surface water features were digitized from a Geographic Information System (GIS) coverage of surface waters in Wisconsin imported to Groundwater Vistas as a map. Three reaches were defined, one for lakes/wetlands and two for streams. Each lake/wetland cell was assigned a length and width so as to encompass the entire surface area of the cell. All stream cells were assigned a length of 400 ft and a width of either 25 or 100 ft, based on average stream widths from topographic maps. Thickness of the streambed and lakebed sediment was arbitrarily set to 1 ft for all river cells and the vertical hydraulic conductivity of the bed was assigned the same value as the vertical hydraulic conductivity of hydrofacies 1 for lake/wetland cells and the same as the vertical hydraulic conductivities of hydrofacies 2 for stream cells. See Table 2.2 for a description of the hydrofacies. Streambed and lakebed elevations were estimated from topographic maps.

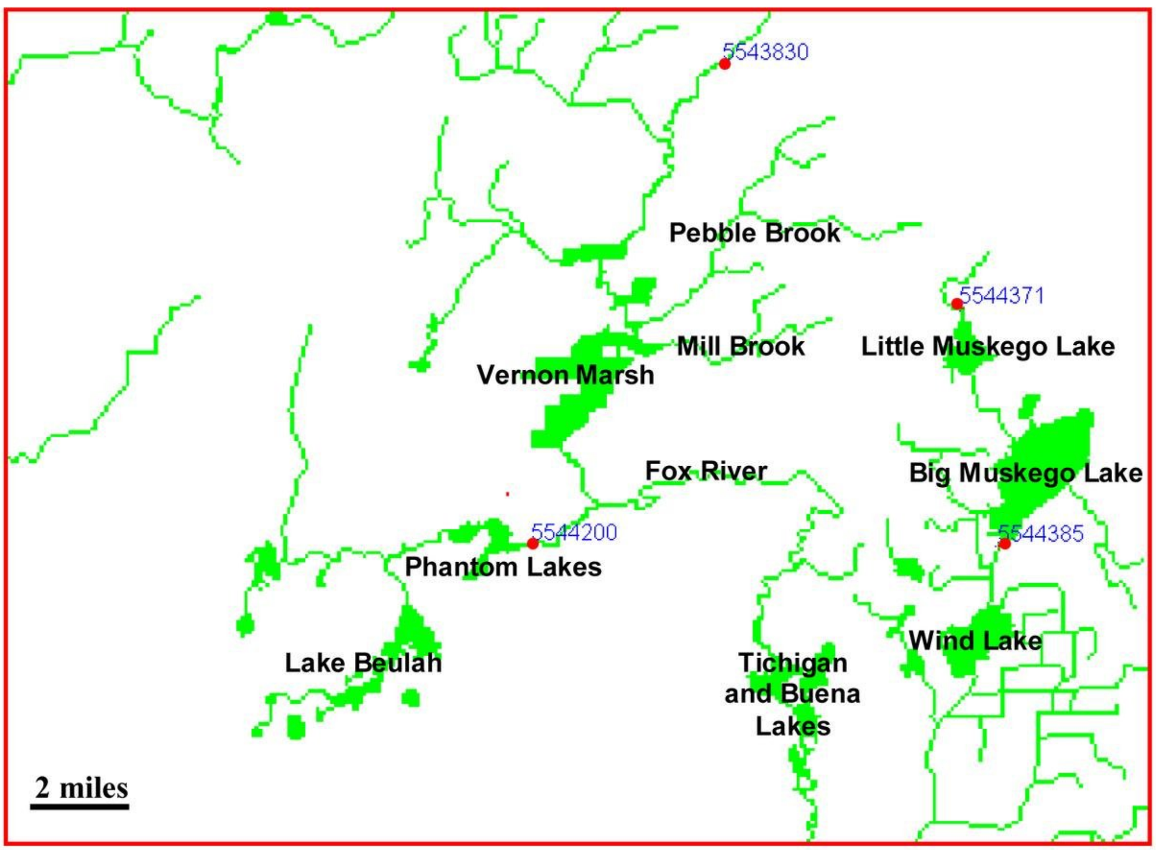

Figure 3.2. Layer 1 of the model showing the cells in the River Package used to simulate lakes, streams, and wetlands (in green). Red dots indicate location of stream flux targets, with USGS gaging station numbers.

3.3.4 Model Properties

Nine different zones of hydraulic conductivity were used, one for each of the four hydrofacies (Table 2.2) and the Silurian dolomite, and two each for the Maquoketa shale and Sinnipee dolomite (one for the surface and one at depth). These units are likely to be more weathered at the surface and thus were assigned a higher hydraulic conductivity value there than at depth. Locations of these zones were based on the hydrostratigraphic model (Chapter 2). All hydraulic conductivity zones were initially assumed to be isotropic and values of hydraulic conductivity were taken from the literature (Section 2.3.2). Hydraulic conductivity zones for each layer are shown in Appendix 2.

3.3.5 Pumping Wells

The MODFLOW Well Package was used to represent high capacity pumping wells. Pumping rates and locations of wells were taken from the SEWRPC model (Fig. 4, Feinstein *et al.*, 2005). Many of the rates were then reduced based on more accurate pumping rates from the Wisconsin Department of Natural Resources. Thirty-four wells were placed in layers 1, 3, 4, 7, 8, and 10 (Table 3.2 and Fig. 3.3). Addition of the pumping wells lowered the water table an average of 4 feet, with a maximum drawdown of 38 feet near well A in layer 1 (Fig. 3.3).

Table 3.2. Layer location and rates of pumping wells in the Troy Valley model. Locations shown in Figure 3.3.

Well	**Layer**	**Pumping Rate (ft^3/d)**
A	1	3.39×10^2
B	3	4.46×10^4
C	3	1.88×10^4
D	3	1.13×10^4
E	3	1.44×10^4
F	4	5.17×10^4
G	7	7.00×10^4
H	7	2.35×10^4
I	7	1.89×10^4
J	7	1.50×10^5
K	7	2.06×10^5
L	7	2.06×10^5
M	8	4.16×10^4
N	8	3.11×10^4
O	8	6.38×10^4
P	10	3.95×10^4
Q	10	8.37×10^4
R	10	1.37×10^5
S	10	9.74×10^4
T	10	1.30×10^5
U	10	8.63×10^4
V	10	1.03×10^5
W	10	4.21×10^4
X	10	5.95×10^4
Y	10	2.61×10^4
Z	10	1.91×10^3
AA	10	5.64×10^3
BB	10	2.07×10^4
CC	10	4.57×10^3
DD	10	2.68×10^4
EE	10	7.98×10^4
FF	10	2.56×10^5
GG	10	5.71×10^4
HH	10	1.07×10^5

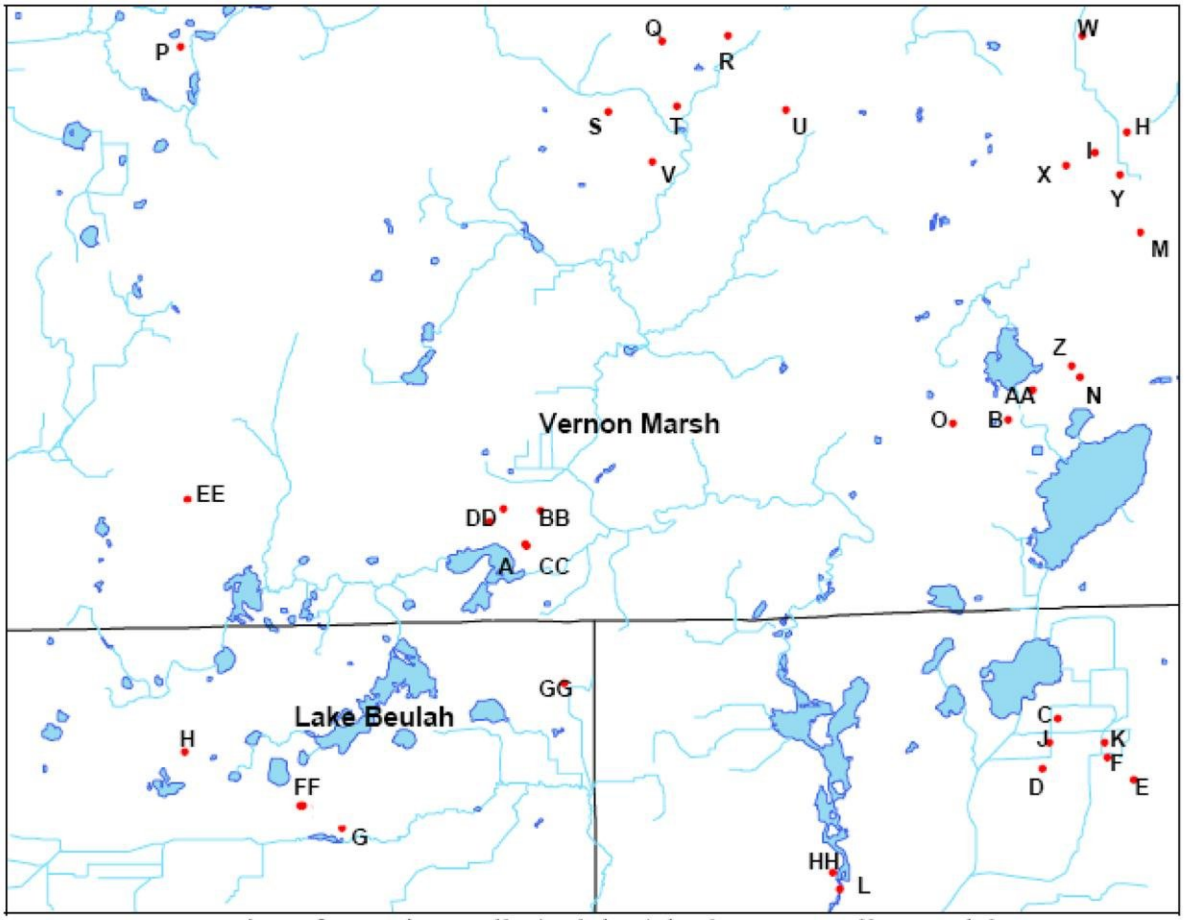

Figure 3.3. Location of pumping wells (red dots) in the Troy Valley model.

3.4 Calibration

Calibration of the regional model was performed using both the inverse code PEST (Doherty, 2004) and manual calibration. PEST was used to determine optimal values of hydraulic conductivity and river and lakebed conductance, (=KLW/M, where K is the vertical hydraulic conductivity of the river/lakebed materials, L is the length of the reach of river in the cell, W is the width of the river/lake, and M is the thickness of the river/lakebed sediments). Although the final calibration was performed manually, parameters that were the focus of the manual calibration were those that were identified to be sensitive parameters using PEST. All the K_x values were the most sensitive, followed by the riverbed conductances, and then the K_z values. The PEST runs also helped find targets that were in the wrong location or layer. The elevations of the well screens for the target wells were estimated from depth below ground surface and surface elevations, which did not necessarily correspond to the Troy Valley model surface elevations. Therefore, these wells were then moved so that they pumped from the correct hydrofacies unit. Two wells were measured only once and one well had over 10 feet of variance in the measurements. The PEST runs indicated these targets needed to have a weight of zero, which means they are highly uncertain. Hence, they were removed for the manual calibration. The PEST results also suggested that using a uniform anisotropy ratio of $K_z / K_x < 1$ where K_z is the vertical hydraulic conductivity and K_x is the horizontal hydraulic conductivity in both the x and y directions, for all four hydrofacies, was appropriate. This was based on the parameter sensitivities calculated by PEST, which consistently had K_x values 1-4 orders of magnitude higher than the K_z values. Finally, K_x and K_z values for the three bedrock units that were determined by PEST were used and held constant during manual calibration. More information on the PEST simulations can be found in Appendix 3.

During manual calibration, K_x of each unit was held constant and values of the anisotropy ratio K_z / K_x of 1:1, 1:10, 1:100, and 1:1000 were tested. The final calibrated model used an anisotropy ratio of 1:10 for the four hydrofacies. Testing of river and lakebed conductance indicated the model was not sensitive to these and the calibrated K_z values of hydrofacies 1 and 2, respectively, were used in the final calibrated model. The calibrated model uses and error closure criterion of 0.001 ft.

3.4.1 Targets and Weights

Three different groups of head targets were used to calibrate the regional model. Group 1 heads were from USGS long term monitoring wells; group 2 were heads taken from the SEWRPC water table map (Map 21, SEWRPC and WGNHS, 2002), and group 3 were well data provided by consulting firms (Fig. 3.4). Group 1 and 2 targets are located entirely in layer 1, while group 3 targets are located throughout the model layers. The number of targets and weights for each group are shown in Table 3.3. Weights were determined based on the credibility of the targets, so that groups that have lower measurement uncertainty received higher weights. The numbers were selected arbitrarily, with group 1 being an order of magnitude higher than the others since these are long term well data and considered most representative of steady-state conditions and also most reliable since they were measured by the USGS. Heads in group 1 were averages taken during the period 1948-2008 or 1992-2008. Group 3 data were given a lower weight because the field measurements fluctuated over 10 feet in a given well, were only taken once after well construction, or were monitored for less than a year and most likely are not representative of static water levels. Group 2 data were given the lowest weight since these points were taken from a water table map.

In addition to the head targets, four flux targets were used in the calibration. These targets are baseflow at long term USGS stream gage stations (Table 3.4) calculated by the USGS for use in the SEWRPC model (Feinstein *et al.*, 2005). Streamflows were adjusted for the amount of flow due to sewage treatment plant effluent, except for Jewel Creek, which was not a target in the SEWRPC model. The large range in baseflow at the Fox River location is due to discharge of treated wastewater estimated to average 1.81 x 10^6 ft^3/d by the City of Waukesha, which causes significant uncertainty in the baseflow estimates.

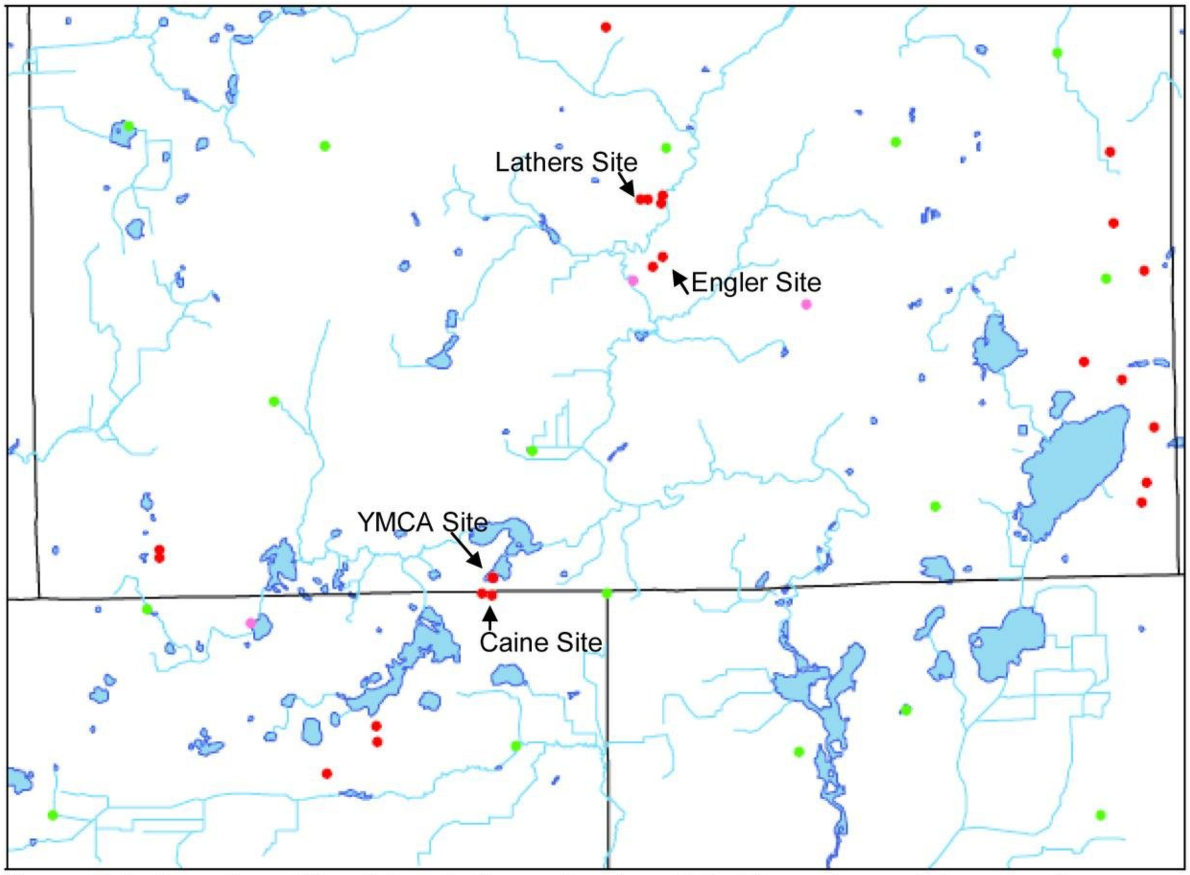

Figure 3.4. Location of head targets for regional model. Group 1 are pink, group 2 green, and group 3 red circles. The four sites used to check the calibration for vertical head gradients are labeled and indicated with arrows.

Table 3.3. The number of targets and weight for each of the three head target groups.

Group Number	Number of Targets	Weight (ft)
1	3	10
2	16	1
3	24	2 or 0

Table 3.4. Flux targets used in calibration. Locations shown in Fig. 3.2. Positive numbers indicate gaining streams, negative losing streams. Q_{50} is the amount of streamflow exceeded 50% of the time, and Q_{80} is the amount of streamflow exceeded 80% of the time.

Stream Gaging Location	Stream Gage Station	Q_{50} (ft^3/d)	Q_{80} (ft^3/d)	Period of Record
Fox River	5543830	2.09×10^6	-8.99×10^5	1964-2007
Jewel Creek	5544371	6.05×10^5	2.59×10^5	2000-2003
Mukwonago River	5544200	3.98×10^6	2.36×10^6	1974-2007
Muskego Lake Outlet	5544385	7.72×10^5	2.97×10^5	1988-2004

3.4.2 Parameter Estimation

Parameters adjusted during the manual calibration were horizontal hydraulic conductivity in nine zones, the anisotropy ratio of K_z / K_x for the four hydrofacies, the vertical hydraulic conductivity of the bedrock units, and conductance of the stream and lakebed sediments (one value in each of the three reaches) in the River Package.

3.4.3 Final Parameter Values

The final hydraulic conductivity values are shown in Table 3.5. The values for horizontal hydraulic conductivity are similar to the calibrated values in the SEWRPC model. Two of the bedrock units, Silurian Dolomite and Maquoketa Shale at the surface, have vertical hydraulic conductivity greater than horizontal hydraulic conductivity. These values were determined during the runs with PEST. Most of the PEST simulations and also the manual calibrations with PEST determined bedrock vertical hydraulic conductivities produced a better calibration than using the anisotropy ratio of K_z/K_x. While generally vertical hydraulic conductivities are less than horizontal hydraulic conductivities, in this case both units are mostly in the shallow subsurface and could contain more fractures in the vertical direction, thus causing a higher vertical hydraulic conductivity value. The river/lakebed conductances had very little effect on the model results and were calculated by using the final calibrated vertical hydraulic conductivity values for hydrofacies 1 and 2 and assuming that the thickness (m) of the river/lakebed sediment was 1 ft. Hence the leakance (K_v/m) for the lakebed sediments was 0.5 d^{-1} and the leakance for the streambed sediments was 1 d^{-1}.

Table 3.5. Final hydraulic conductivity values, K_x indicates horizontal hydraulic conductivity and K_z vertical hydraulic conductivity. The value of K_z/K_x for the four hydrofacies (Table 2.2) was 1:10.

Hydraulic Conductivity		Value (ft/d)
K_x	Hydrofacies 1	5.0
	Hydrofacies 2	10.0
	Hydrofacies 3	59
	Hydrofacies 4	300.0
	Silurian Dolomite	3.6
	Maquoketa Shale, at depth	4.3
	Sinnipee Dolomite, at depth	3.7
	Maquoketa Shale, at surface	48
	Sinnipee Dolomite, at surface	110
K_z	Silurian Dolomite	36
	Maquoketa Shale, at depth	1.4
	Sinnipee Dolomite, at depth	1.8
	Maquoketa Shale, at surface	64
	Sinnipee Dolomite, at surface	48

3.4.4 Calibration Results

The calibrated model (Fig. 3.5) simulated both the head targets (Fig. 3.6) and stream flow targets (Table 3.6) reasonably well. The absolute residual mean of 18.7 ft for head is lower than the value of 20.2 ft reported for the SEWRPC model; the minimum and maximum residuals were a narrower range than those for SEWRPC, which are -75.9 and 96.3 ft, respectively. Two of the targets with large residuals are located in the lower layers (group 3 targets that were assumed zero weight). The others with large residuals are from group 2, which were taken from the SEWRPC water table map, and therefore are less reliable targets.

Although not used as calibration targets, vertical head changes at four sites indicate that the calibrated model captured the vertical gradients fairly well near Waukesha. At the Lathers site (Fig. 3.4), a head difference of -3.5 was measured across 57 feet, while the model simulated a head difference of -1.8, where the minus sign indicates upward flow. At the Engler site (Fig. 3.4), a head difference of 2.9 was measured across 81 feet, while the model simulated a head difference of 1.6 ft. The model did not simulate vertical gradients near Mukwonago very well. At the YMCA site (Fig. 3.4), a head difference of 8.2 was measured across 8 feet, while the model simulated a head difference of -0.35. Finally, at the Caine site (Fig. 3.4), a head difference of 6.1 was measured across 134 feet, while the model simulated a head difference of 0.21.

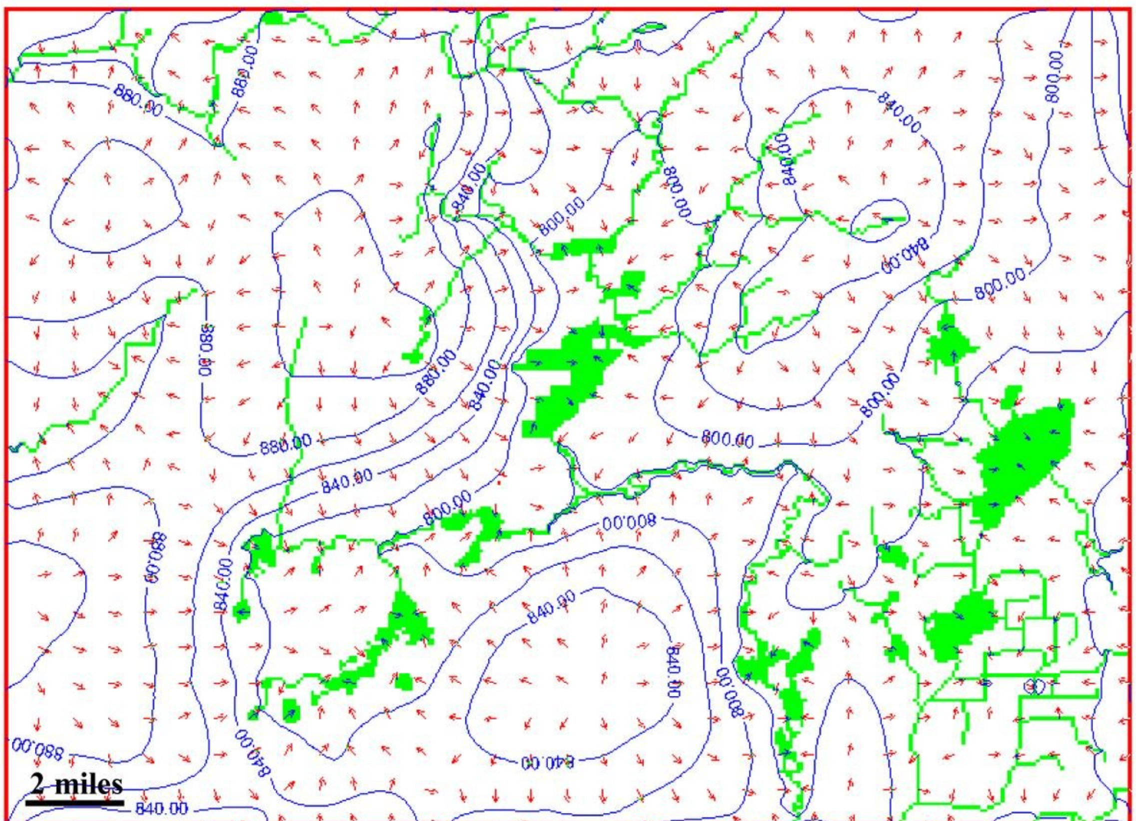

Figure 3.5. Calibrated Troy Valley model water table map. Contour interval is 20 ft, with head values in ft amsl. Arrows indicated direction of groundwater flow.

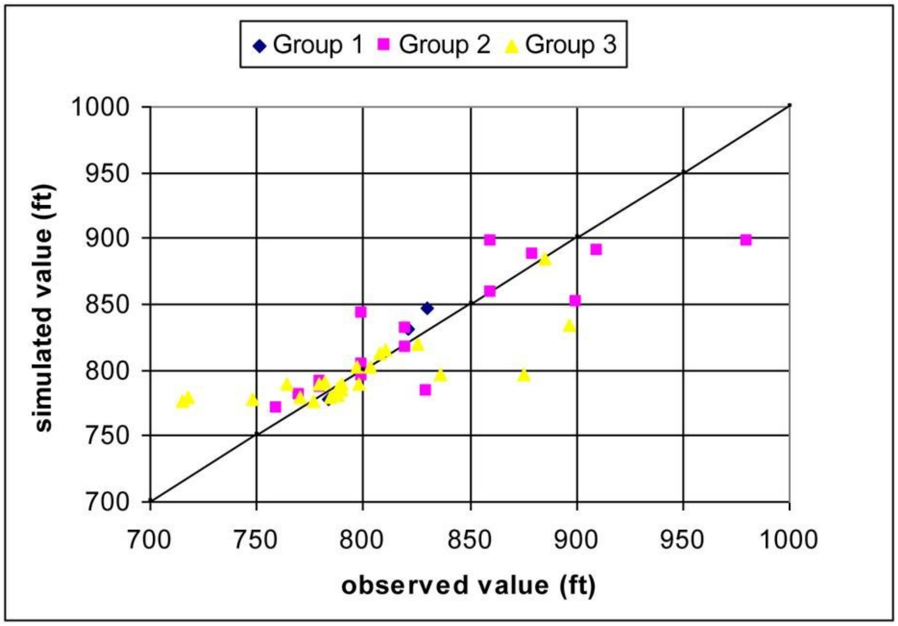

Figure 3.6. Observed verses simulated head values. Targets in group 1 and 2 are located in layer 1, while Group 3 targets are in layers 1, 5, 6, 7, 8, 9, and 10.

Table 3.6. Calibration statistics for the regional model. Stream fluxes (baseflow) are in ft^3/d, with positive numbers for gaining streams and negative for losing. Information on groups given in Table 3.2.

Head Targets

Statistical Measure	All (43) targets	Group 1	Group 2	Group 3
Residual Mean (ft)	-0.0549	-7.60	-8.60	-1.37
Absolute Residual Mean (ft)	18.7	8.67	21.3	18.2
Root Mean Squared Error (ft^2)	3.68×10^4	3.58×10^2	1.50×10^4	2.15×10^4
Minimum Residual (ft)	-61.3	-17.6	-43.9	-61.3
Maximum Residual (ft)	82.6	1.61	82.6	78.7

Stream Flux Targets

Stream Location	Observed Range from Table 3.4	Simulated Value
Fox River	-8.99×10^5 to 2.09×10^6	9.97×10^4
Jewel Creek	2.59×10^5 to 6.05×10^5	8.80×10^3
Mukwonago River	2.36×10^6 to 3.98×10^6	3.31×10^6
Muskego Lake Outlet	2.97×10^5 to 7.72×10^5	7.68×10^5

The simulated stream flux values (Table 3.6) are all within the given Q_{50} to Q_{80} range, except for Jewel Creek. Jewel Creek was measured for only four years (2000-2003), so the observed values may not be representative of long term conditions. Additionally, the observed value was not adjusted for sewage treatment plant effluent, although there may not be any discharged into Jewel Creek. It was given a weight of zero during PEST calibrations. Also, the simulated discharge over the dam at Lake Beulah (1.50×10^6 ft^3/d) provided a good match to the observed range of field measurements (6.78×10^5 to 7.71×10^6 ft^3/d, see Chapter 4).

3.5 Prediction

The calibrated regional model was run with the addition of four recently installed pumping wells (Table 3.7), in order to determine the effects of these wells on groundwater heads and surface water features at steady-state. The Multi-Node Well (MNW) Package (Halford and Hanson, 2002) was used to represent the wells since they are screened in multiple layers. Three of the wells are near Vernon Marsh and the fourth is near Lake Beulah.

Table 3.7. Wells added to the calibrated regional model for the steady-state predictive simulation. Pumping rates for Waukesha Water Utility wells are average daily pumping rates as of June, 2008. The East Troy pumping rate is the estimated rate provided by the Village of East Troy for this well, although the well is currently pumping less. For well locations see Fig. 3.7.

Well Name and Location	Pumping started	pumping (gpm)	pumping (ft^3/d)	Model Layers
Waukesha Water Utility Well #11, North of Vernon Marsh	2005	299	5.75×10^4	5-7
Waukesha Water Utility Well #12, North of Vernon Marsh	2005	681	1.31×10^5	3-7
Waukesha Water Utility Well #13, North of Vernon Marsh	2008	694	1.34×10^5	5-6
Village of East Troy Well #7, South of Lake Beulah	2008	1000	1.93×10^5	8-9

Under the assumed boundary conditions of fixed specified flux, heads are lower by more than 1 ft north of Vernon Marsh as well as areas south and east of Lake Beulah (Fig.

3.7) as a result of pumping. The greatest effect on head is near Vernon Marsh within 8,000 ft from the pumping wells where the maximum head loss is 67 feet in layer 5. There is a maximum water level decline of 47 feet in layer 8 near Lake Beulah, with the greatest effect on head within 2,300 ft from the pumping well in all layers. The average decline in the water table over the entire region as a result of pumping is approximately 0.5 ft, with maximums of 30 ft near Vernon Marsh and 12 ft near Lake Beulah.

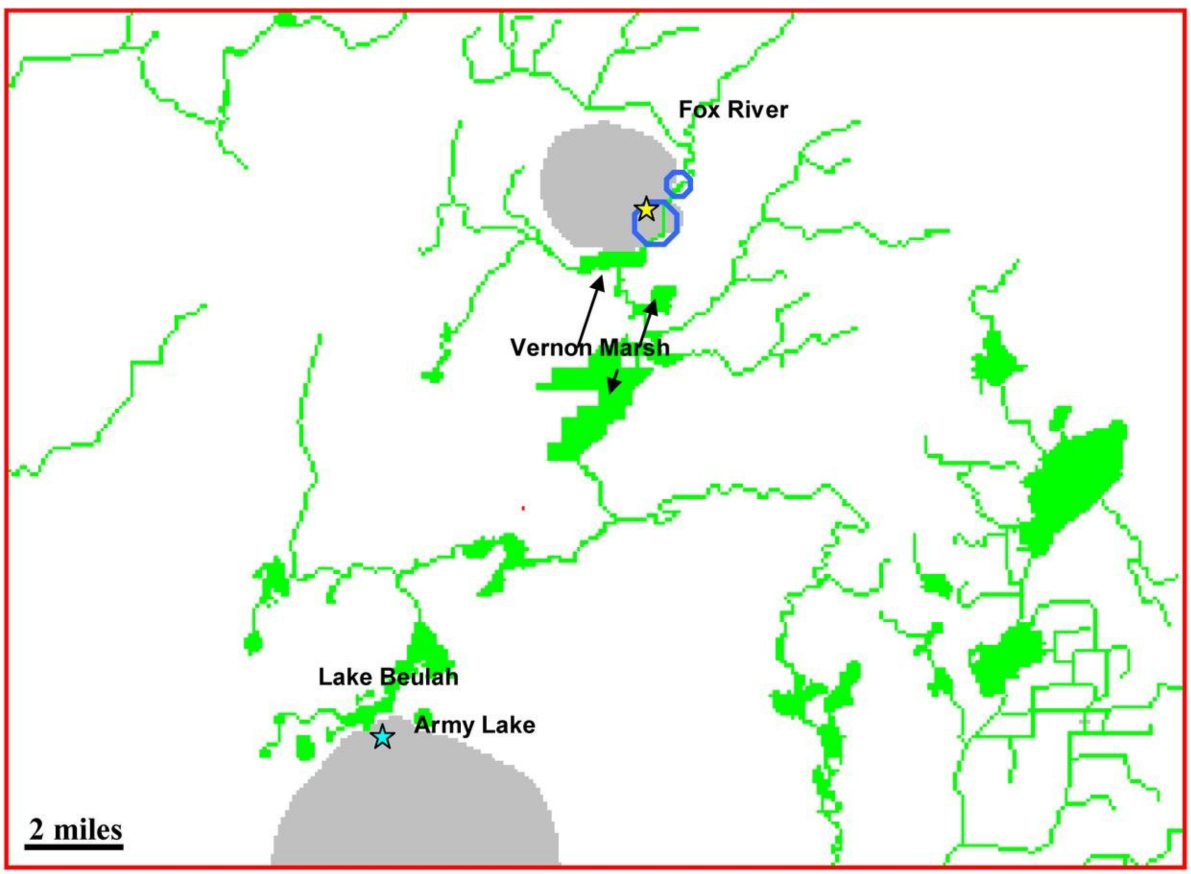

Figure 3.7. Area where heads decline by 1 ft or more as a result of pumping (indicated by gray). The green areas are surface water features. Only layer 1 of regional model is shown, but the same area is affected in every layer of the model. The yellow star is the location of the three pumping wells near Vernon Marsh and blue circled stream reaches are those in which flow is reversed. The light blue star is the location of the well near Lake Beulah.

There are also reductions in flow to Vernon Marsh and Lake Beulah and associated rivers. In two reaches of the Fox River, the flow is reversed and water flows out of the river and into the aquifer (Fig. 3.7). There is an average 18% reduction of groundwater inflow in the northern section of Vernon Marsh and a maximum of 30% reduction in the northernmost portion of the marsh. Reductions in flow occur in Lake Beulah, as well as surrounding lakes. There is a 15% reduction in groundwater inflow to Army Lake and an average of 20% reduction of inflow to Lake Beulah; 6% reductions in flow occur in the connecting streams, lakes and wetlands on the southwest edge of the lake. Heads in the lakes and streams do not change because the River Package fixes heads. In other words, stream and lake heads cannot change during the simulation and therefore act as infinite sources or sinks of water.

The simulation indicates that the well near Lake Beulah causes drawdown at the boundary, as is evident from Figure 3.7, which shows that the affected head area intersects the southern boundary. Under field conditions, the decline in head caused by pumping will induce more water to flow through the boundaries than is allowed under the fixed flux boundary conditions. The predictive simulation, therefore, shows more drawdown and greater reduction in groundwater flow to surface water features than is likely under field conditions. Three sensitivity tests were run with changed boundary fluxes in order to assess the impacts of the fixed flux boundary condition.

The predictive model was run with 10% more flux coming in the southern boundary. This was accomplished by decreasing discharge from extraction wells and increasing rates of injection that were used to simulate the boundary fluxes. (The value of 10% was arbitrarily selected. It should be emphasized that under field conditions the increased flux through the boundary could be more or less than 10%.) The area in which heads were lowered by more than 1 ft (Fig. 3.8) is much smaller. The predictive model was also run with 10% more flux coming in only through the southern boundary in the pumping layers (layers 8 and 9). The area in which heads were lowered by more than 1 ft (Fig. 3.9) is smaller, though not as small as when additional flux enters the entire depth of the southern boundary.

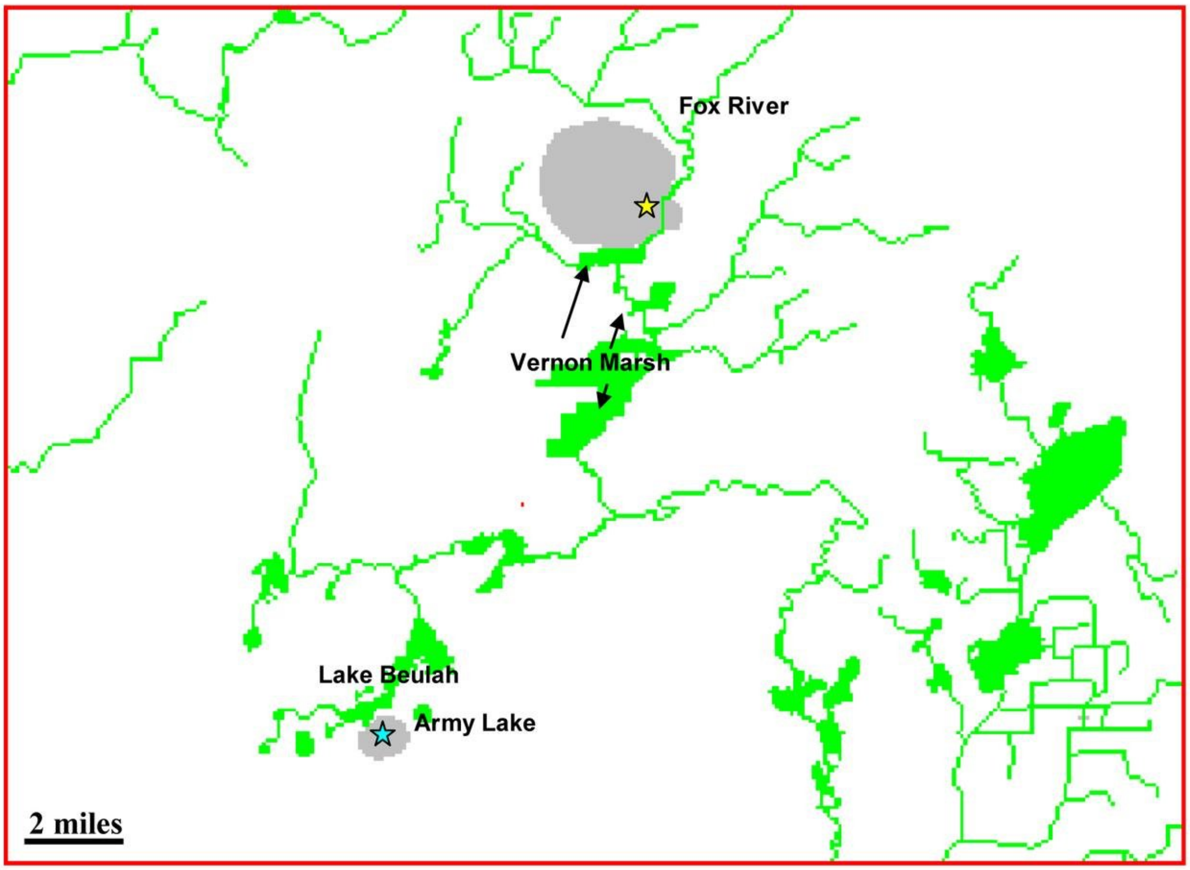

Figure 3.8. Area where heads declined by 1 ft or more (gray) as a result of pumping with a 10% increase in the southern boundary fluxes. The green areas are surface water features. The yellow star is the location of the three pumping wells near Vernon Marsh. The light blue star is the location of the well near Lake Beulah. The affected area around Lake Beulah is much smaller compared to the area shown in Fig. 3.7.

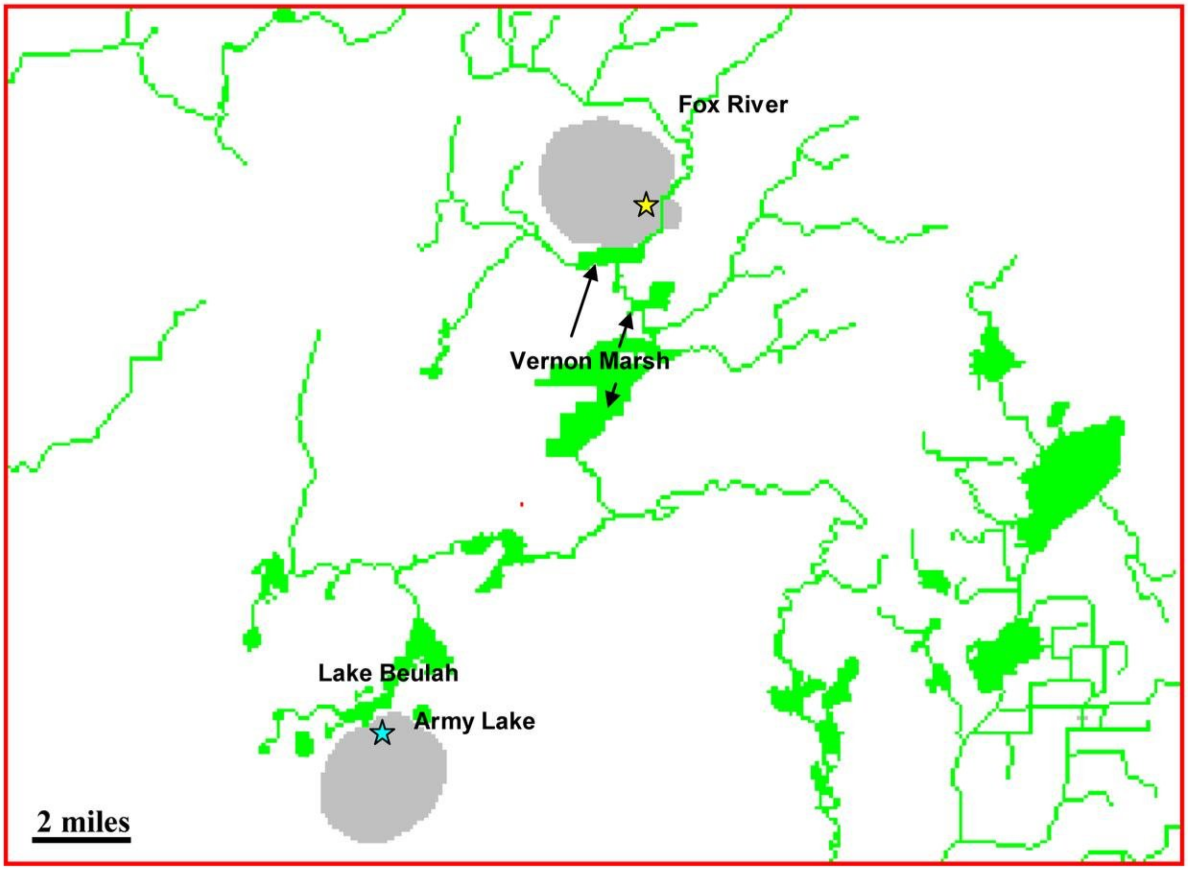

Figure 3.9. Area where heads declined by 1 ft or more (gray) as a result of pumping with a 10% increase in the southern boundary fluxes only in the pumping layers (layers 8 and 9). The green areas are surface water features. The yellow star is the location of the three pumping wells near Vernon Marsh. The light blue star is the location of the well near Lake Beulah. The affected area around Lake Beulah is much smaller compared to the area shown in Fig. 3.7, though not as small as the area shown in Fig. 3.8.

An additional sensitivity analysis was run with 10% more flux coming through the bottom boundary. The results were the same as the initial predictive model (Fig. 3.7), indicating the heads are not sensitive to the bottom flux boundary. The model receives only 0.5% of inflow from the bottom boundary, while 36% enters the model from the side boundaries, 44% enters from recharge at the surface, and 19.5% enters from rivers and lakes. The effects on flows to the surface water features under the four scenarios are shown in Table 3.8.

Table 3.8. Percent reductions to surface water features of interest and maximum head drawdown for the four predictive model scenarios. Percent reduction in flow to the northern quarter of Vernon Marsh and maximum head drawdown near Vernon Marsh were the same for all models, 18% and 67 ft, respectively.

Model	**% reduction in flow to Lake Beulah**	**% reduction in flow to Army Lake**	**% reduction in flow to surface waters SW of Lake Beulah**	**Maximum head drawdown (ft) near Lake Beulah**
base case	20	15	6	47
10% in all layers	4	0	0	45
10% in layers 8-9	16	12	4	47
bottom flux	18	15	6	47

The MODFLOW files for the calibrated model with recently installed pumping wells are included in the accompanying material CD. Output files for the calibrated model and all predictive simulations, including the 3 sensitivity runs, are also included.

3.6 Uncertainty Analysis

The hydraulic conductivity and configuration of the glacial deposits and uncertainty over future pumping rates cause the greatest uncertainty in model predictions. Hydraulic conductivity of the four hydrofacies used to represent the glacial deposits could range over several orders of magnitude. Moreover, it was not possible to accurately delineate the boundaries of the hydrofacies. There also is uncertainty in pumping rates. Stochastic MODFLOW (Ruskauff, 1995) was used within Groundwater Vistas to create and run 250 realizations using a range of hydraulic conductivities of the hydrofacies in order to assess the uncertainty in assigning hydraulic conductivity values to the hydrofacies in the predictive simulation. However, the boundaries of the units were not changed from those established in the hydrostratigraphic model because this type of advanced geostatistical analysis is beyond the scope of this project. Stochastic MODLFOW was also used to evaluate the uncertainty in pumping rates.

The horizontal hydraulic conductivity values of the four hydrofacies were selected as stochastic parameters in a steady-state simulation that included pumping from the new wells (Table 3.9). A uniform distribution of hydraulic conductivity was assumed for each of the hydrofacies, with minimum and maximum values based on literature values and the minimum values for hydrofacies 1 and 2 tested during the calibration process. The lowest hydraulic conductivity values from the literature did not allow enough water to move through the groundwater system and caused unrealistic mounding of the water table and therefore were not used in the stochastic simulations. The simulations assumed a uniform distribution, which uses only upper and lower bounds, so that all values within this range have an equal chance of occurrence. Stochastic MODFLOW generates a random number selected between the minimum and maximum values for each parameter and then runs the calibrated predictive model with these new parameter values to produce a new solution (realization).

Table 3.9. Stochastic parameters, with minimum and maximum K_x values (ft/d) used in Stochastic MODFLOW. See Table 2.2 for description of hydrofacies.

Hydrofacies	Minimum	Maximum
1	1.3×10^{-4}	10
2	2.6×10^{-3}	50
3	3.0×10^{-2}	100
4	6.3	1000

The 250 realizations were conditioned to exclude those with unreasonable solutions. Realizations that had a Root Mean Squared (RMS) error over 4×10^4 ft^2, as well as any realizations that did not converge were excluded. The RMS limit was chosen based on the RMS for the calibrated model with pumping. This left a total of 184 realizations for analysis (Fig. 3.10).

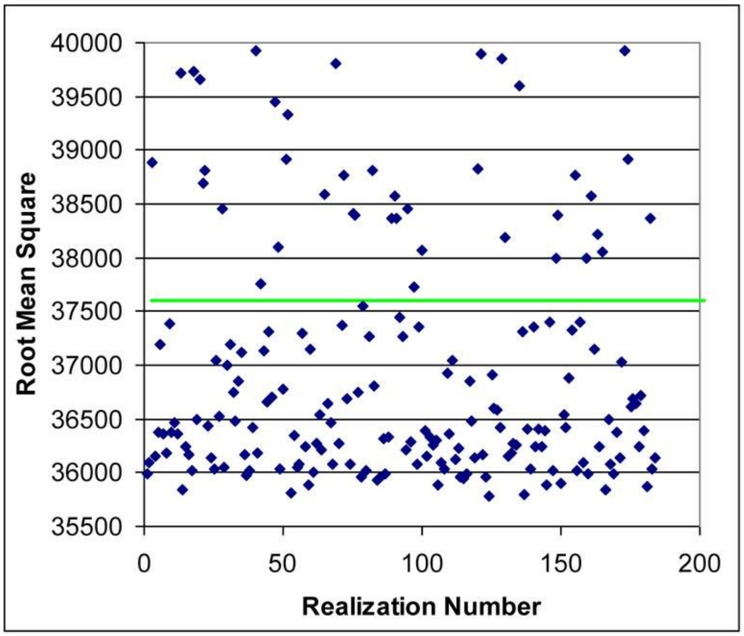

Figure 3.10. Root mean square error for each of the conditioned realizations. The green line shows the RMS value for the calibrated model with pumping. RMS is being used here to show that the conditioned stochastic models are all around the same range as the calibrated model with pumping (i.e., the predictive model discussed in section 3.5). Recall that the RMS for the calibrated model without the recently installed wells is 3.68 x 10^4 ft^2 (Table 3.6).

Four targets were examined in order to determine how each of the realizations affects heads near Lake Beulah and the northern section of Vernon Marsh. These included wells WKEOW1 and BH5 from group 3, which are located between the surface water feature and the pumping wells, and two new targets, Beulah and Vernon (Fig 3.11). These latter two targets were placed on the other side of their respective surface water features relative to the two group 3 targets. Figures 3.12 through 3.15 show the ranges in head at each target for the 184 conditioned realizations. These results suggest that changes in hydraulic conductivity of glacial deposits in the Troy Valley region have little effect on heads near Lake Beulah, but do significantly affect heads in the northern section of Vernon Marsh. This is most likely because three wells are pumping north of Vernon Marsh and only one well is near Lake Beulah. Additionally, the valley is wider near Lake Beulah, with more sand deposits and less till. The combination of these factors causes the overall hydraulic conductivity to be higher in this area and therefore, response to changes in head is less here than in the Vernon Marsh area.

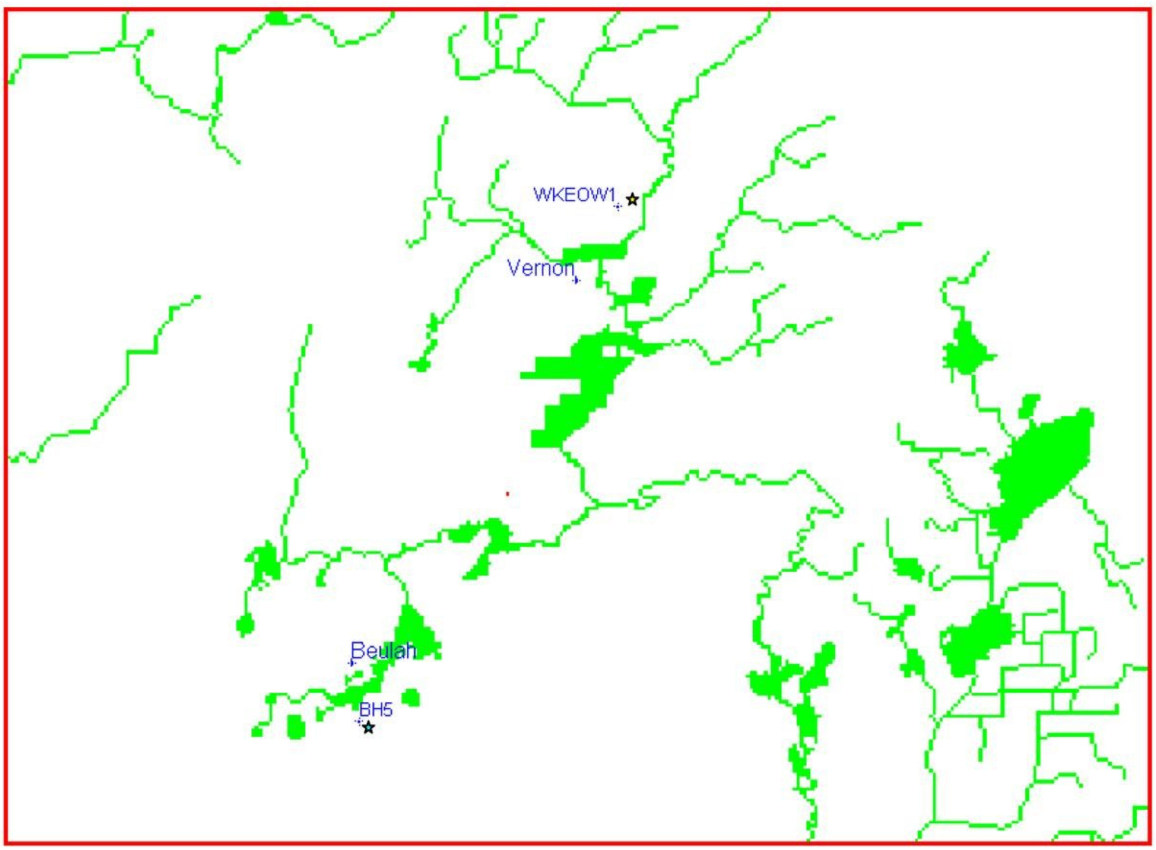

Figure 3.11. Location of targets used to analyze results of the stochastic simulations. The small stars indicate location of pumping wells near Vernon Marsh (yellow) and Lake Beulah (blue).

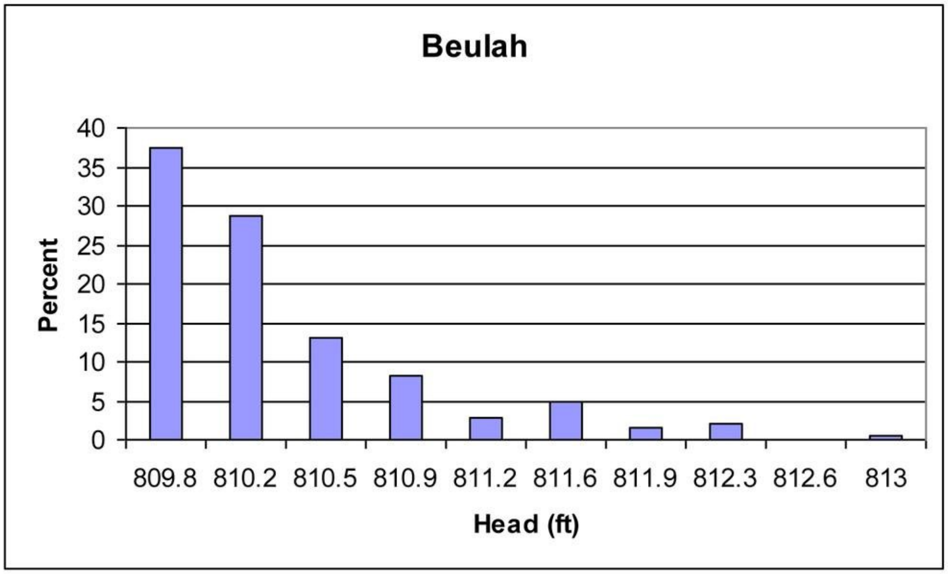

Figure 3.12. Stochastic results for target located north of Lake Beulah (Fig. 3.11) when hydraulic conductivity values of the zones of glacial deposits are the stochastic parameters. The resulting head for the realizations ranges over 4 ft, with 85% of the realizations ranging over 1 ft.

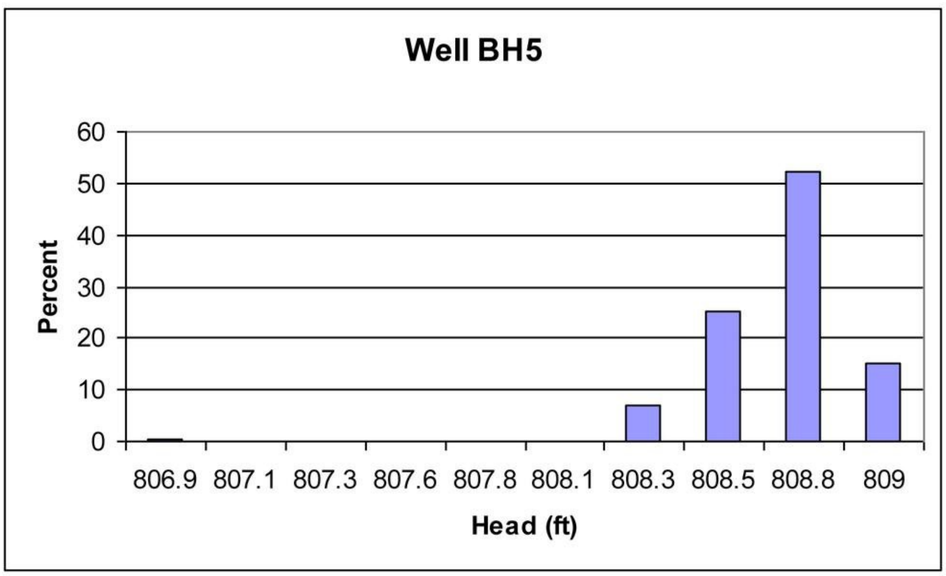

Figure 3.13. Stochastic results for target located south of Lake Beulah (Fig. 3.11) when hydraulic conductivity values of the zones of glacial deposits are the stochastic parameters. The resulting head for the realizations ranges over 2 ft, with 99% of the realizations ranging less than 1 ft.

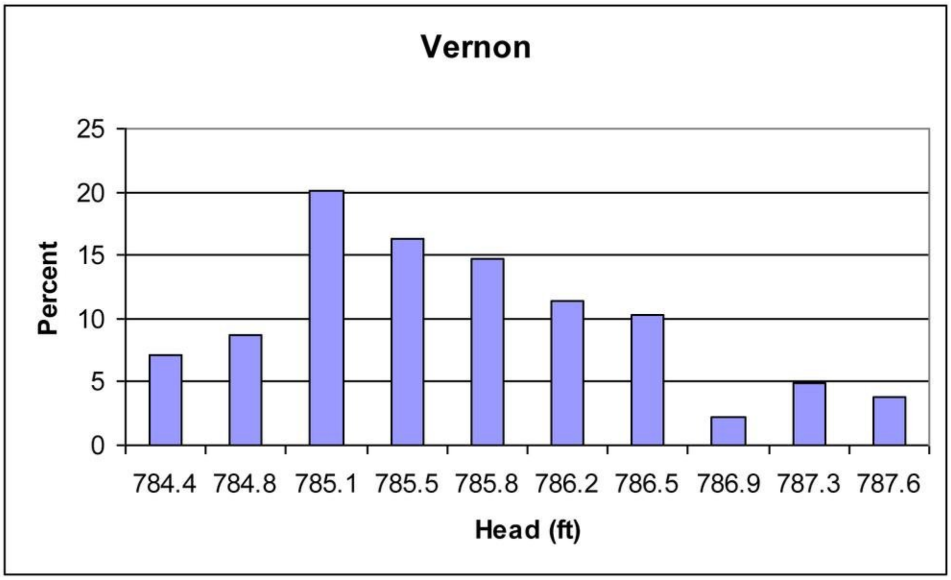

Figure 3.14. Stochastic results for target located south of the northern section of Vernon Marsh (Fig. 3.11) when hydraulic conductivity values of the zones of glacial deposits are the stochastic parameters. The resulting head for the realizations ranges over 3 ft.

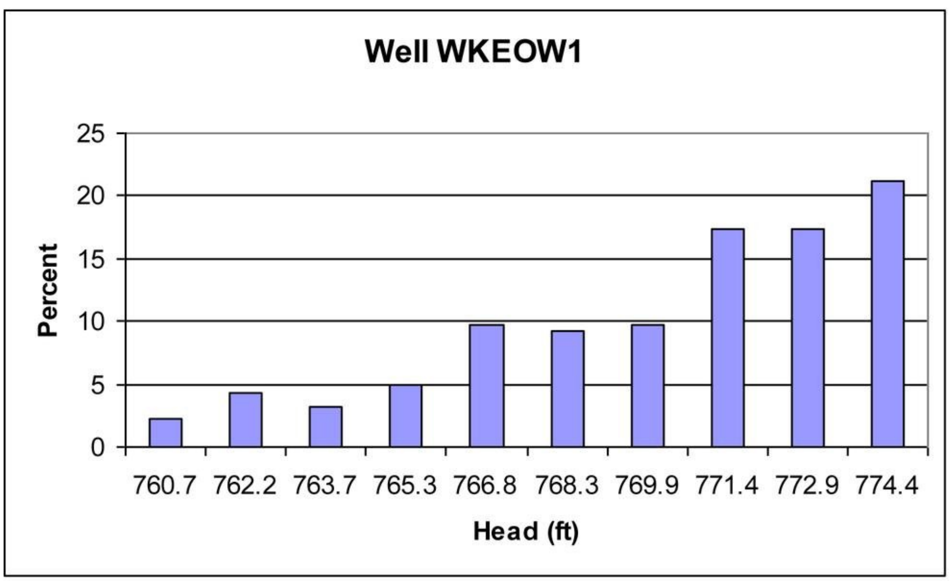

Figure 3.15. Stochastic results for target located north of the northern section of Vernon Marsh (Fig. 3.11) when hydraulic conductivity values of the zones of glacial deposits are the stochastic parameters. The resulting head for the realizations ranges over 13 ft, although 75% of the realizations range over 6 ft.

A second stochastic model was run, also with 250 realizations, setting the rate of the pumping well near Lake Beulah as the stochastic parameter. Calibrated hydraulic conductivity values were used. A uniform distribution of pumping rate was assumed with minimum and maximum values of 500 and 2000 gpm. All realizations converged and had RMS values between 40,000 and 40,500, near the RMS value for the calibrated model with pumping, so that all 250 were used as conditioned realizations. The two targets near Vernon Marsh were not affected at all since the well is too far away to affect Vernon Marsh. However, the target south of Lake Beulah, BH5, indicated that the changes in pumping rate significantly affect the resulting heads there with a range of 6 ft in possible head values from 815.6 to 821.7 ft (Fig. 3.16). The target south of Lake Beulah ranged over less than 1 ft, indicating that pumping rates do not affect heads significantly north of the lake.

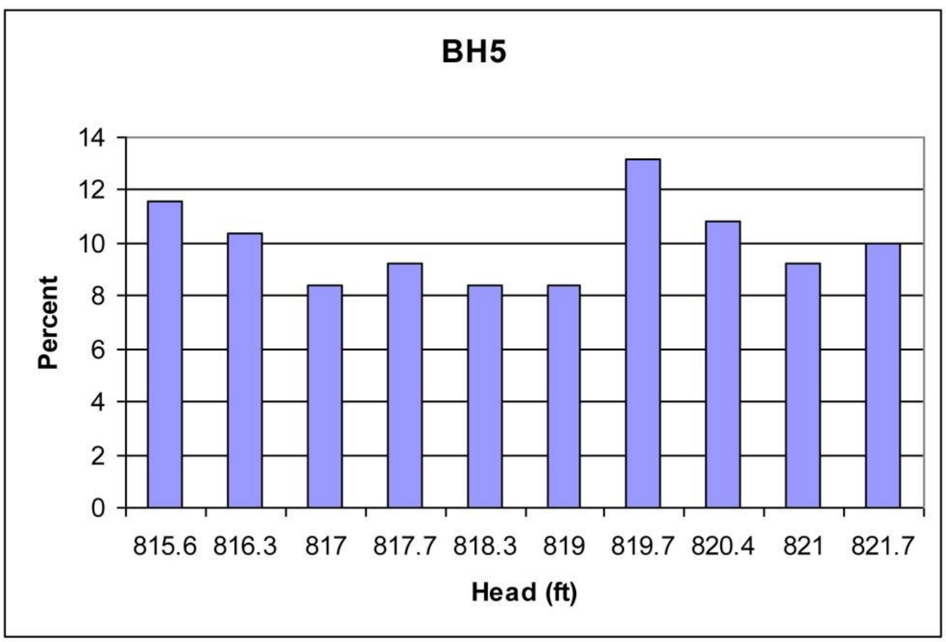

Figure 3.16. Stochastic results for target located south of Lake Beulah (Fig. 3.11) when pumping rate is the stochastic parameter. The resulting head for the realizations ranges over 6 ft.

3.7 Particle Tracking

MODPATH (Pollock, 1994) was used to determine the capture zones of the three new wells near Vernon Marsh and one new well near Lake Beulah. A circle of 50 particles was placed around each well in every layer it penetrates (Table 3.7) and tracked backwards in time. Two of the capture zones for the three wells near Vernon Marsh overlap to form one larger capture zone (Fig. 3.17). The capture zone is smaller than the affected head area because the capture zone delineates the area that directly contributes water to the well, while heads are lowered over a much larger area.

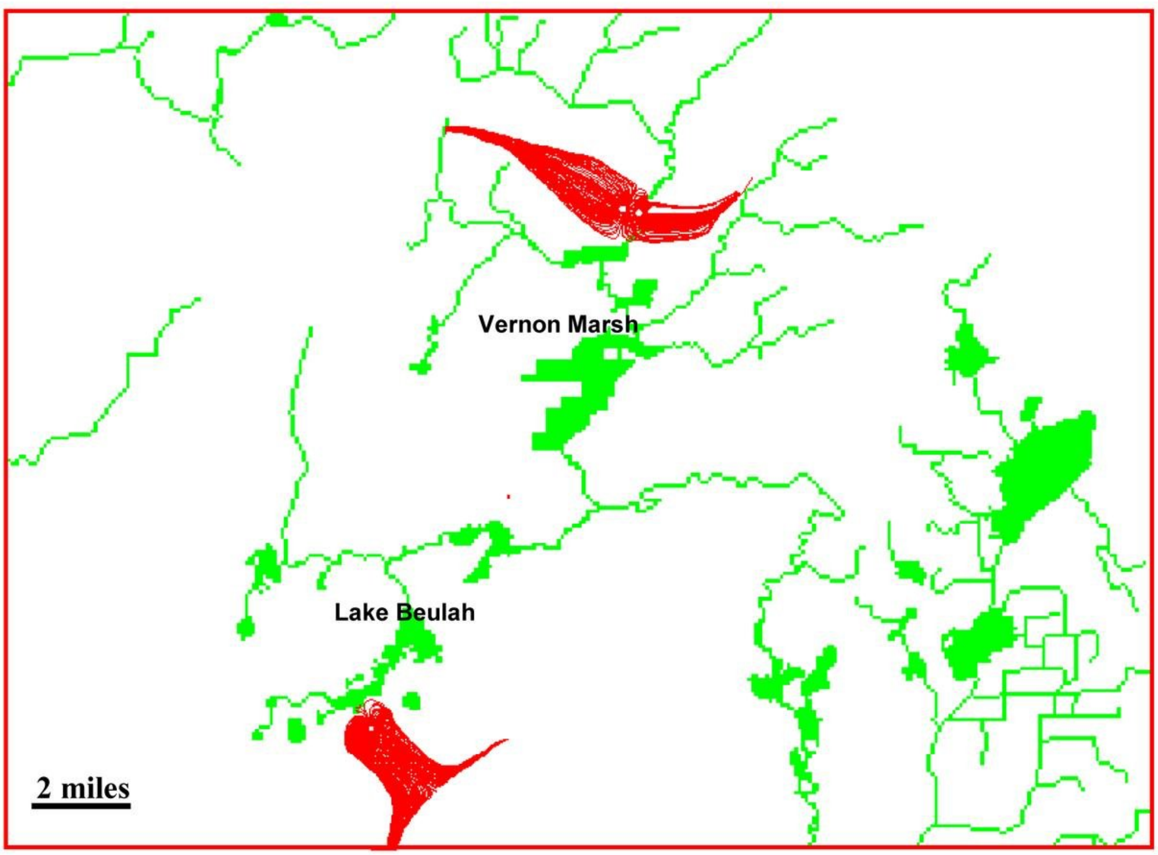

Figure 3.17. Projection of capture zone (red lines trace each particle) for wells near Lake Beulah and Vernon Marsh.

Chapter 4: Lake Beulah and Vernon Marsh Groundwater Flow Models

4.1. Introduction

Two local scale models were constructed to examine effects of pumping four recently installed high capacity wells in the vicinity of Lake Beulah and Vernon Marsh. In the local scale models the Lake Package was used to represent lakes and wetlands and the Stream Flow Routing Package was used to represent streams. The River Package, which was used to represent surface water features in the regional model in Chapter 3, holds surface water levels fixed. However, the Lake Package and Stream Flow Routing Package allow the model to solve for surface water levels. Thus, the objective of the local scale models was to predict the effects of pumping on lake, wetland, and stream levels.

It was necessary to locate the boundaries of the local scale models close to the area of interest (i.e., the lake and marsh) so that the model layers remain nearly horizontal and lake/marsh depths can be simulated accurately. Layer thickness was adjusted in order to represent both the hydrostratigraphy and the lake bathymetry accurately. The proximity of the boundaries causes the simulations to be influenced by the fixed flux boundary conditions. Thus, the simulations show a larger impact of pumping than is likely to occur under field conditions.

4.2. Model Design

4.2.1 Lake Beulah Model

A local model around Lake Beulah was developed from the regional model (Chapter 3) using the telescopic mesh refinement (TMR) option in Groundwater Vistas. The Lake

Beulah model has uniform horizontal grid spacing of 103 by 105 feet, with 208 rows and 320 columns. Vertical grid spacing was changed from the regional model so the lakes in the area could be accurately represented. Layer 10 was omitted since both it and layer 11 are entirely within the Sinnipee Dolomite and the purpose of the model is to simulate flow in the overlying glacial deposits. The vertical bedrock flux boundary was used as the bottom boundary of the local model. The top layer was subdivided into five layers in order to represent the bathymetry of Lake Beulah, producing a total of 14 layers (Table 4.1).

Table 4.1. Thicknesses and bottom elevations of each layer in the Lake Beulah model. The first five layers were adjusted beneath the lake to fit the bathymetry of the lake. Hence, these layers have variable thickness.

Layer	Thickness (ft)	Bottom Elevation (ft)
1	variable	800
2	variable	785
3	variable	775
4	variable	765
5	variable	750
6	9	741
7	11	730
8	15	715
9	19	696
10	25	671
11	33	638
12	42	596
13	55	541
14	164	377

Specified head values were taken from the Troy Valley regional model to define boundary conditions along the four sides of the model. The bottom boundary, at the base of layer 14, is a vertical flux boundary and the top layer (upper boundary condition) is a specified flux boundary as recharge (Fig. 4.1); fluxes were taken from the Troy Valley regional model. Model properties were also similar to the regional model. Hydraulic conductivity zones 8 and 9, which represent bedrock, were not present since the Maquoketa and Sinnipee bedrock units in this region are deep and do not crop out at the surface. The five top layers were given the same hydraulic conductivity zonation as the top layer in the regional model. For the predictive simulations, the lateral specified head boundaries were converted to specified flux boundaries using calibrated heads and hydraulic conductivities from the Lake Beulah model.

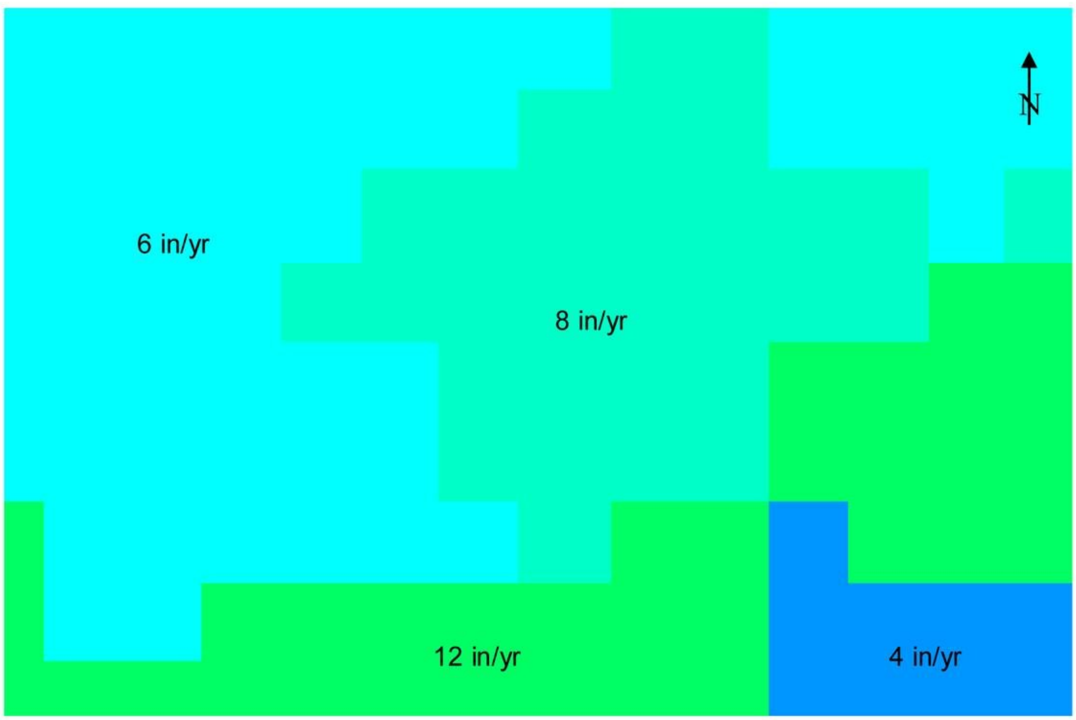

Figure 4.1. Map of recharge rates used for the Lake Beulah model. See Fig. 4.2 for extent of modeled area.

In the Lake Beulah model, surface water features of interest are represented using the Stream Flow Routing (SFR) Package (Prudic *et al.*, 2004) and the Lake Package (Merritt & Konikow, 2000) in order that the model could simulate changes in surface water levels, if any, as a result of pumping. Additional surface water features near the edges of the model are represented with the River Package (Fig. 4.2). All surface waters, despite the package used, were arbitrarily assigned a bed thickness of 1 ft, with vertical hydraulic conductivity of the bed for lake/wetland cells assigned the same value as the vertical hydraulic conductivity of hydrofacies 1 and the same value as the vertical hydraulic conductivity of hydrofacies 2 for stream cells. Streambed and lakebed elevations were estimated from topographic and bathymetry maps. All lake/wetland cells were assigned length and width so as to encompass the entire surface area of the cell, while all stream/river cells have lengths of 105 ft and widths of either 25 or 100 ft, based on average stream widths from topographic maps. Additional parameters used by the SFR package are the streambed roughness coefficient and the slope of the stream channel, which were set to 0.03 and 0.001, respectively, for all streams. The Manning's equation option was chosen to determine depth as a function of stream flow, $Q = (C/n)AR^{2/3}S_o^{1/2}$, where C is a units conversion constant, n is the streambed roughness coefficient, A is the cross-sectional area of the stream, R is the hydraulic radius of the stream, and S_o is the slope of the stream channel.

The Lake Package was used for the following lakes: Army, Beulah, Booth, Pickerel, and Swan, as well as Willow Pond (Fig. 4.2). With the exception of Lake Beulah, the lakes are exclusively in layer 1. Lake Beulah is located in layers 1-5, so that its depth ranges from 28 to 58 ft, with the bathymetry of the lake determined from lake survey maps (WDNR, 1967). Precipitation (32.55 in/yr) and evaporation (31.32 in/yr) from a water balance study for Lake Beulah (RSV Engineering, Inc., 2006) were used for all the lakes in the model.

Lake Beulah was created from three separate lakes over 100 years ago by raising lake levels with an earthen dam (Dow, 2008). The spillway (Fig. 4.3) is located under Walworth County Highway J at an elevation of 807.96 ft amsl. The dam/spillway were simulated by setting the bed elevation of the first stream segment down gradient of the lake equal to the spillway elevation. Initial stream and lake stages (Table 4.2) were based on topographic maps and data from the Wisconsin Department of Natural Resources.

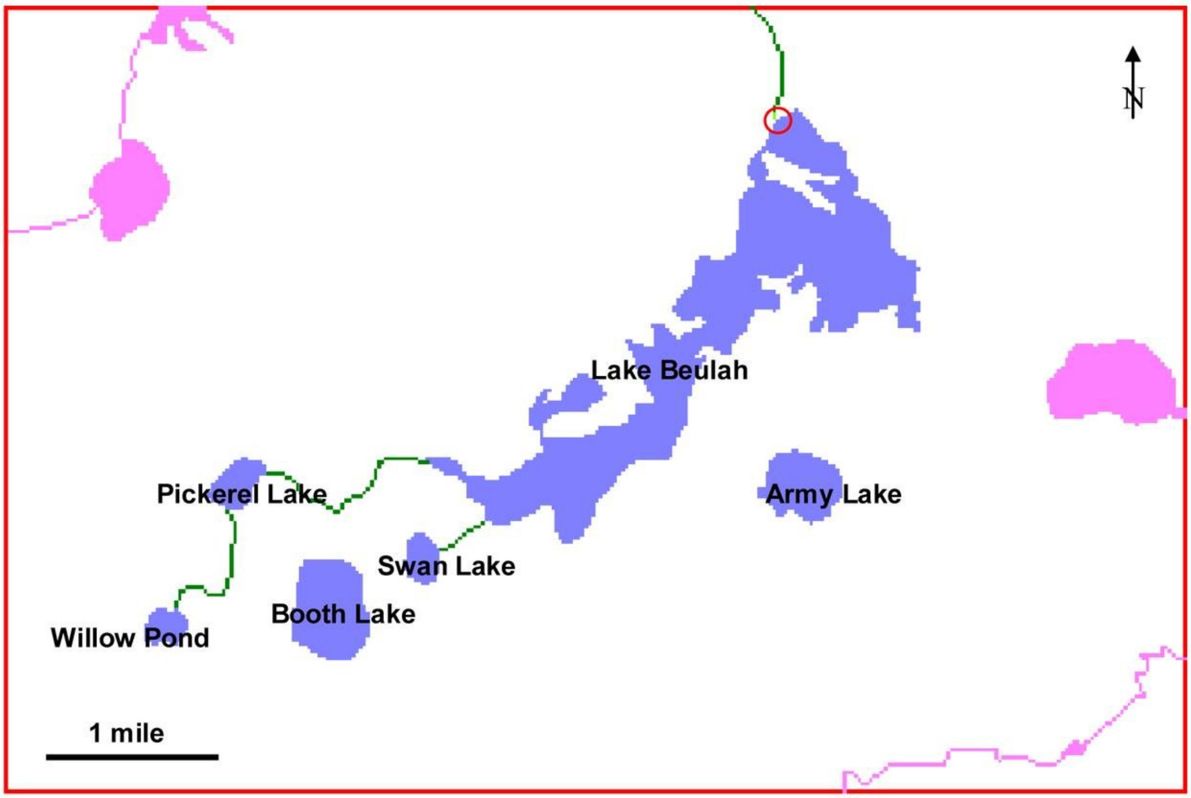

Figure 4.2. Surface water features in first layer of Lake Beulah Model. Cells using the Lake Package indicated by blue cells, those using the SFR package by green, and River Package by pink. The red circle indicates the location of the dam/spillway.

Figure 4.3. Lake Beulah dam and spillway (photo by Mary Anderson, August 17, 2008).

Table 4.2. Initial lake stages for the lakes represented by the Lake Package in the Lake Beulah model taken from topographic maps.

Lake	Initial Stage (ft amsl)
Army	809
Beulah	808
Booth	816
Pickerel	809
Swan	810
Willow Pond	820

Data used in the construction and calibration of the Lake Beulah model were provided by Robert Nauta of RSV Engineering, Inc. These included the elevation of the spillway, streamflow data for 2007-2008 at the outlet of Lake Beulah, elevation of the water table for five wells surrounding Lake Beulah from 2004-2007, and precipitation data for that same time period. Also, an evaporation rate for nearby Lake Pewaukee was provided from a 2003 lake management plan.

A groundwater flow model of the Mukwonago River watershed includes Lake Beulah and was discussed by Bahr & Gittings (2005) as a follow up to Gittings' thesis (Gittings, 2005; also see Chapter 1, Section 1.2.1 of this report of the Troy Valley). Their model contains 36 layers that are approximately horizontal with uniform horizontal grid spacing of 519 by 519 ft. Preferential flow paths in the bedrock were simulated by three 25 ft thick, lateral high hydraulic conductivity zones in the Sinnipee Group. Results indicated that groundwater discharge into the Mukwonago River comes from both the shallow sand and gravel aquifer and the bedrock via preferential flow paths or zones. Analysis of strontium suggested groundwater flowing through these preferential zones mixes with the shallow groundwater in the sand and gravel aquifer before discharging to Lake Beulah.

4.2.2 Vernon Marsh Model

A local model was developed for the area around Vernon Marsh from the regional model. The Vernon Marsh model has uniform horizontal grid spacing of 202 by 202 feet, with 200 rows and 125 columns. Vertical grid spacing was changed only slightly from the regional model in order to represent the surface water features in more detail. The bottom elevation of layer 1 was set to 775 feet, so that the water in Vernon Marsh could be as much as 5 ft deep, otherwise vertical spacing is the same as the regional model (Table 3.1). The bottom boundary is a flux boundary, while the upper boundary is specified flux as recharge (Fig. 4.4). Model properties were the same as the regional model except for the absence of hydraulic conductivity zones 8 and 9, which represent bedrock. Specified head values were taken from the regional model for the four sides of the Vernon Marsh model.

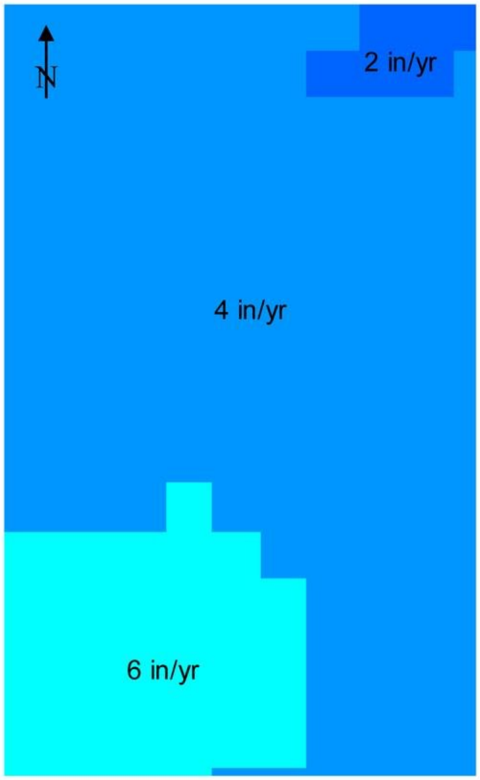

Figure 4.4.
Map of recharge rates used for the Vernon Marsh model. See Fig. 4.5 for extent of modeled area.

In the Vernon Marsh model, the Fox River and Vernon Marsh are represented by the SFR Package (Prudic *et al.*, 2004) and Lake Package (Merritt & Konikow, 2000), respectively. Surface water features near the edges of the model are represented with the River Package (Fig. 4.5). All surface waters, despite the package used, were arbitrarily assigned a bed thickness of 1 ft, with vertical hydraulic conductivity of the bed for lake/wetland cells assigned the same value as the vertical hydraulic conductivity of hydrofacies 1 and the same value as the vertical hydraulic conductivity of hydrofacies 2 for stream/river cells. Streambed elevations and elevation of the bottom of the marsh were estimated from topographic maps. All lake/wetland cells were assigned length and width so as to encompass the entire surface area of the cell, while all stream cells have lengths of 202 ft and widths of either 25 or 100 ft, based on average stream widths from topographic maps. Additional parameters used by the SFR Package are the streambed roughness coefficient and

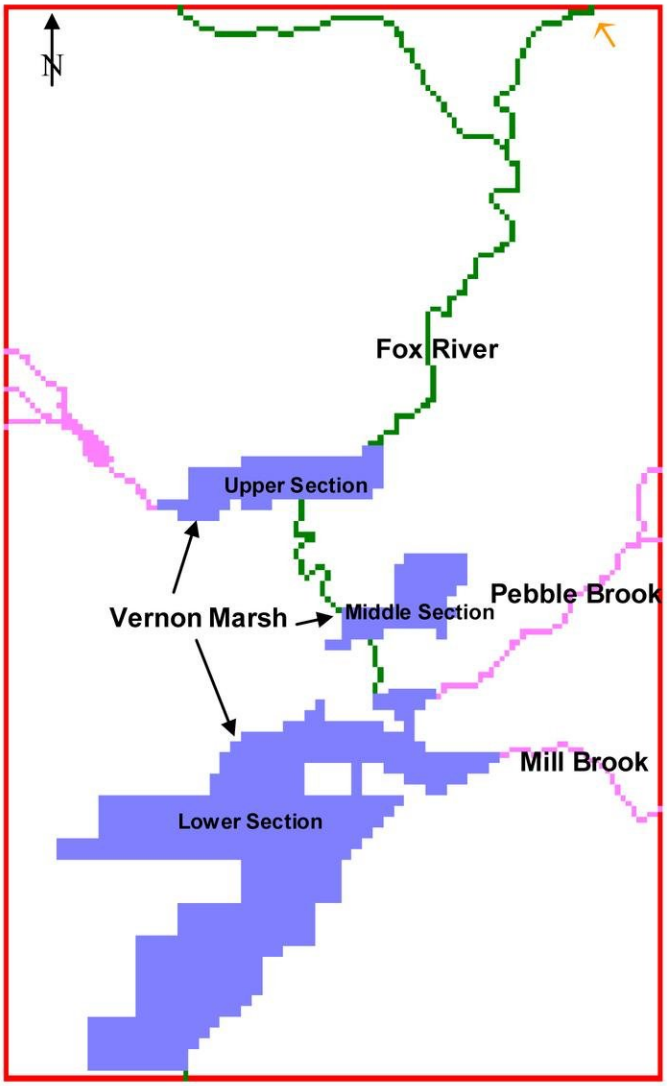

Figure 4.5.
Surface water features in first layer of Vernon Marsh model. Cells using the Lake Package indicated by blue cells, SFR Package by green, and River Package by pink. Orange arrow indicates the reach of the Fox River where sewage treatment flux was added to the stream.

the slope of the stream channel, which were set to 0.03 and 0.001, respectively, for all streams. Discharge into the Fox River from the sewage treatment plant were accounted for by putting 1.81 x 10^6 ft^3/d (Krohelski, personal communication) into the first node of the Fox River (Fig 4.5), which is the average flux of effluent discharged. The Lake Package was used to simulate Vernon Marsh in three sections in order to represent the Fox River flowing through the marsh. All Lake Package cells were located exclusively in layer 1. Initial stream and marsh stages were based on topographic maps and data from the Wisconsin Department of Natural Resources (http://dnr.wi.gov/). All three sections of Vernon Marsh were initialized to a water level of 780 ft amsl.

4.3 Model Calibration

Both local models were calibrated to steady-state conditions using head targets measured during the period 2004-2008. A head closure criterion of 0.005 ft was used for both models.

4.3.1 Lake Beulah Model

Two different groups of head targets were used to calibrate the Lake Beulah model. Group 1 targets, located only in layer 1, were provided by RSV Engineering, Inc. and Group 2 targets, located in layers 1, 10, 11, and 13, were provided by Ruekert-Mielke, Inc. Group 1 has five targets located around the perimeter of Lake Beulah, and group 2 has 7 targets, for a total of 12 targets (Fig. 4.6). All targets were given equal weights of 1. In addition to the head targets, one flux target, located at the outlet of Lake Beulah, was used in the calibration. Discharge measurements at the outlet were provided by RSV Engineering, Inc. Finally, the lake stages (Table 4.2) were used as calibration targets.

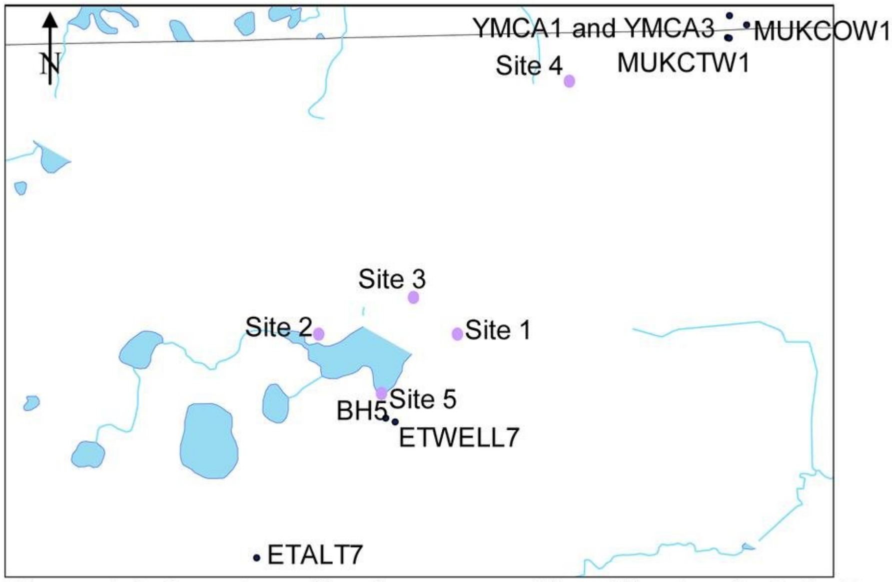

Figure 4.6. Location of head targets used in calibration for Lake Beulah model. Purple dots are group 1 targets and black dots are group 2 targets.

The value of K_z/K_x of the hydrofacies was 1:10, which is the same as in the regional model. The conductance of the stream and lake/wetland sediments and recharge rates were adjusted during calibration. The conductances affected the amount of water entering the lakes and streams in the area. The final calibrated hydraulic conductivity values for the lake and stream sediments were the horizontal hydraulic conductivity of hydrofacies 1 and horizontal hydraulic conductivity of hydrofacies 2, respectively, taken from the calibrated regional model (Chapter 3). The thickness (m) of the river/lakebed sediment was assumed to be 1 ft. The leakance (K_v/m) for the lakebed/wetland sediments was 5 d^{-1} and the leakance for the streambed sediments was 10 d^{-1}. The final recharge rates are 50% less than initial values (Fig. 4.1). During the period for which calibration data are available, the annual average precipitation was below the average (32 in/yr) for the period used in the regional model and average temperatures were higher for the state of Wisconsin (R. Nauta, personal communication 2008 and Wisconsin State Climatology Office website).

The calculated water budgets from the calibrated model (Fig. 4.7) for each of the lakes were approximately balanced to steady-state conditions (Table 4.3) so that total inflow equals total outflow within an order of magnitude. These water budgets were obtained from a simulation with an error criterion of 0.005 ft for the solution of groundwater head. Efforts to obtain better balance by tightening the error criterion were unsuccessful because the model failed to converge using a smaller error criterion.

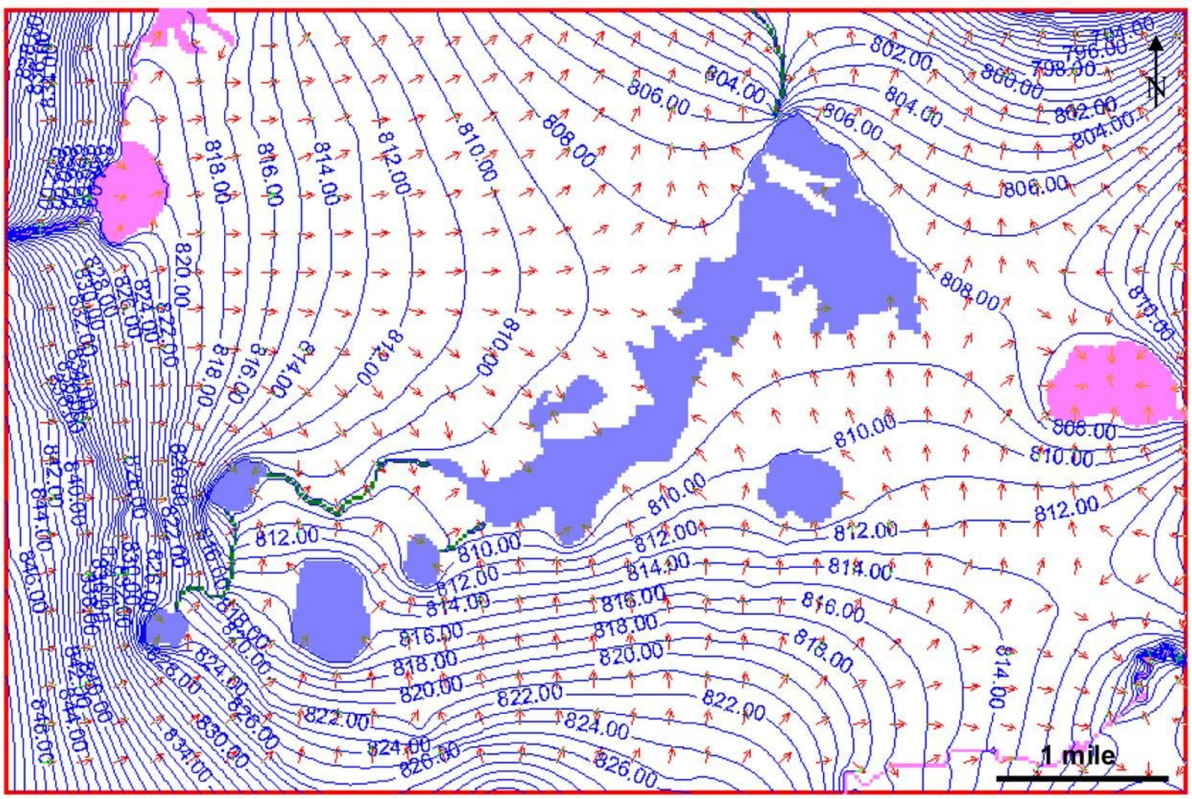

Figure 4.7. Calibrated Lake Beulah model water table map. Contour interval is 1 ft, with head values in ft amsl. Cells using the Lake Package indicated by blue cells, those using the SFR package by green, and River Package by pink. Red arrows indicate direction of groundwater flow.

Table 4.3. Lake budgets for the Lake Beulah model. Total inflow and outflow, as well as individual components are given for each lake. The final row, gw %, is the percent of the total inflow or outflow that is from groundwater.

Component	Army Lake		Lake Beulah		Booth Lake	
	In (ft^3/d)	Out (ft^3/d)	In (ft^3/d)	Out (ft^3/d)	In (ft^3/d)	Out (ft^3/d)
Evaporation		2.43×10^4		2.63×10^5		3.60×10^4
Precipitation	2.53×10^4		2.74×10^5		3.75×10^4	
Surface Flow			7.25×10^5	1.17×10^6		
Groundwater	3.87×10^4	4.88×10^3	2.90×10^5	1.62×10^5	1.22×10^5	9.79×10^4
Total	6.40×10^4	2.92×10^4	1.29×10^6	1.60×10^6	1.60×10^5	1.34×10^5
gw %	60.4%	16.7%	22.5%	10.1%	76.6%	73.1%

Component	Pickerel Lake		Swan Lake		Willow Pond	
	In (ft^3/d)	Out (ft^3/d)	In (ft^3/d)	Out (ft^3/d)	In (ft^3/d)	Out (ft^3/d)
Evaporation		1.06×10^4		8.11×10^3		7.19×10^3
Precipitation	1.10×10^4		8.44×10^3		7.48×10^3	
Surface Flow	1.17×10^5	4.22×10^5		1.05×10^5		6.11×10^4
Groundwater	3.07×10^5	6.57×10^0	1.05×10^5	8.44×10^1	6.12×10^4	3.79×10^2
Total	4.35×10^5	4.33×10^5	1.14×10^5	1.13×10^5	6.87×10^4	6.87×10^4
gw %	70.6 %	0.00152%	92.6 %	0.0744 %	89.1 %	0.552 %

The final lake stages were all within 2 ft of the target value (Table 4.4). The calibrated model simulated the head and flux targets reasonably well (Table 4.4 and Fig. 4.8). The absolute residual mean of 2.77 ft is lower than the value of 18.7 ft in the Troy Valley regional model, as it should be for a local scale model. Although vertical head gradients were not used as calibration targets, they were checked after calibration but as in the regional model, the model did not provide a good fit to the vertical gradients. At the YMCA site (Fig. 4.6), a head difference of 8.2 was measured across 8 feet, while the model simulated a head difference of 0.10. At the Caine site (Fig. 4.6, wells MUKCOW1 and MUKCTW1), a head difference of 6.1 was measured across 134 feet, while the model simulated a head difference of 0.023. Adjustments of vertical hydraulic conductivity and/or the adjustment of the hydrostratigraphic model to include a layer of lower conductivity might improve the calibration to vertical gradients.

Table 4.4. Calibration statistics for the Lake Beulah model. Field data from RSV Engineering, Inc. and Ruekert-Mielke, Inc.

Head Targets

Statistical Measure	All (12) targets	Group 1	Group 2
Residual Mean (ft)	0.331	0.506	0.207
Absolute Residual Mean (ft)	2.77	1.50	3.67
Root Mean Squared Error (ft^2)	140	12.8	128
Minimum Residual (ft)	-4.87	-2.49	-4.87
Maximum Residual (ft)	7.31	1.76	7.31

Well Name	Group	Observed Value (ft)	Simulated Value (ft)
Site 1	1	809.73	808.58
Site 2	1	810.00	808.24
Site 3	1	809.19	808.20
Site 4	1	805.23	807.72
Site 5	1	810.11	808.99
BH5	2	808.00	812.87
ETWELL7	2	810.10	813.80
YMCA1	2	798.00	793.07
YMCA3	2	789.80	793.02
MUKCOW1	2	803.45	796.14
MUKCTW1	2	797.35	796.04
ETALT7	2	825.60	825.94

Lake Stage Targets

Location	Observed Value (ft)	Simulated Value (ft)
Army Lake	809	810
Beulah Lake	808	808
Booth Lake	816	815
Pickerel Lake	809	808
Swan Lake	810	809
Willow Pond	820	822

Flux Target

Location	Observed Avg. Range (ft^3/d)	Simulated Value (ft^3/d)
Lake Beulah outlet	6.78×10^5 to 7.71×10^6	1.17×10^6

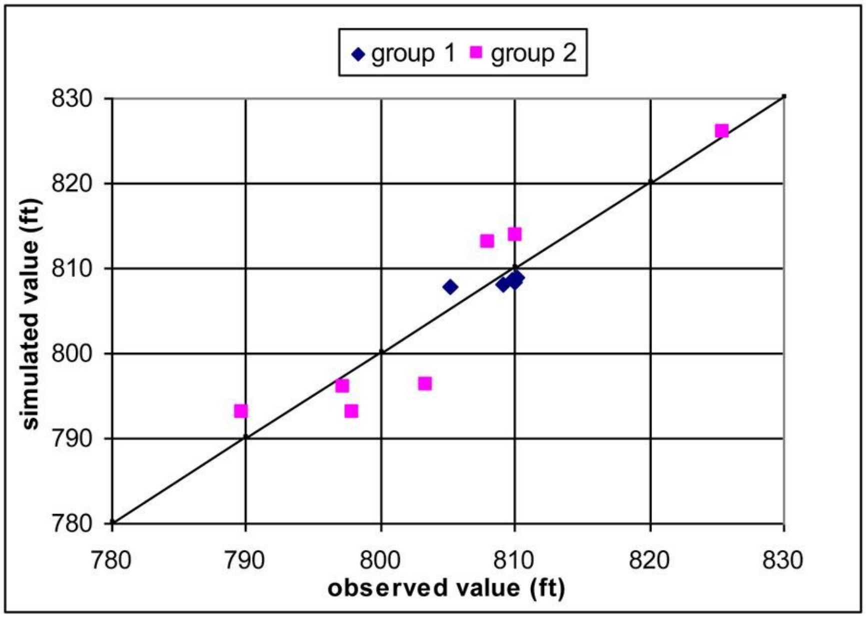

Figure 4.8. Observed verses simulated head values for the Lake Beulah model. Targets are located in layers 1, 10, 11, and 13.

Another unsatisfactory aspect of the calibration is that the lake along the eastern boundary of the model is shown to receive groundwater flow along all sides when it likely is a flow-through lake in the field. Lowering the flux of water entering the model along the adjacent boundary would likely allow the lake to revert to flow-through conditions.

The Bahr & Gittings' (2005) Mukwonago River Inset Model (MRIM) had a total groundwater inflow of 2.03 x 10^5 ft^3/d and groundwater outflow of 5.27 x 10^3 ft^3/d for Lake Beulah (RSV Engineering, Inc., 2006). The groundwater inflow term is comparable to the Lake Beulah model (Table 4.3), but the MRIM simulated much less outflow. In the MRIM, discharge from the lake is confined to the area immediately around the dam, whereas in the Lake Beulah model discharge of groundwater occurs over much of the northern portion of the lake basin (Fig. 4.7). The data used to calibrate both models, except for one target (Site 4, Fig. 4.6), are located in the southern half of the lake. Therefore, it is possible that the northern half of the lake could be mostly groundwater outflow as simulated by the Lake

Beulah model. Differences in results between the models are also likely caused by differences in model construction. The MRIM simulated preferential flow paths or zones in the Sinnipee Group bedrock using high hydraulic conductivity zones. While the Lake Beulah model does not contain these, it has higher horizontal and vertical hydraulic conductivity values than the MRIM, allowing for similar amounts of groundwater to move more easily through the entire extent of the bedrock (layers 9-14 of the Lake Beulah model), instead of through preferential zones. Furthermore, the MRIM simulated Lake Beulah and inflowing and outflowing streams as specified head conditions using the River Package whereas the Lake Beulah model solved for lake level using the Lake Package and simulated the streams using the Stream Flow Routing Package.

4.3.2 Vernon Marsh Model

Six head targets (Fig. 4.9) taken from data provided by Ruekert-Mielke, Inc., were used to calibrate the Vernon Marsh model. All targets were given equal weights of 1. The value of K_z/K_x for the hydrofacies was 1:10, which is the same as in the regional model. The conductance of the stream and lake/wetland sediments and recharge rates were adjusted during calibration. The conductances affected the amount of water entering Vernon Marsh. The final calibrated hydraulic conductivity values for the lake/wetland and stream sediments were the horizontal hydraulic conductivity of hydrofacies 1 and horizontal hydraulic conductivity of hydrofacies 2, respectively, taken from the calibrated regional model (Chapter 3). The thickness (m) of the river/lakebed sediment was assumed to be 1 ft. The leakance (K_v/m) for the lakebed/wetland sediments was 5 d^{-1} and the leakance for the streambed sediments was 10 d^{-1}. The final recharge rates are 50% less than initial values (Fig.4.4). During the period for which calibration data are available the annual average precipitation was below the average (32 in/yr) that was used in the regional model and average temperatures were higher for the state of Wisconsin (R. Nauta, personal communication 2008 and Wisconsin State Climatology Office website).

Figure 4.9.
Location of head targets used in calibration of Vernon Marsh model. Targets are located in layers 2, 5, 6, and 7.

The calculated water budgets from the calibrated model (Fig. 4.10) for each of the marsh sections were balanced to steady-state conditions within the same order of magnitude (Table 4.5). The calibrated model simulated the head targets and marsh stages reasonably well (Table 4.6 and Fig. 4.11). The absolute residual mean of 6.29 ft is lower than the value of 18.7 ft for the Troy Valley regional model, as it should be for a local scale model. Calibrated values for marsh stage are shown in Table 4.7.

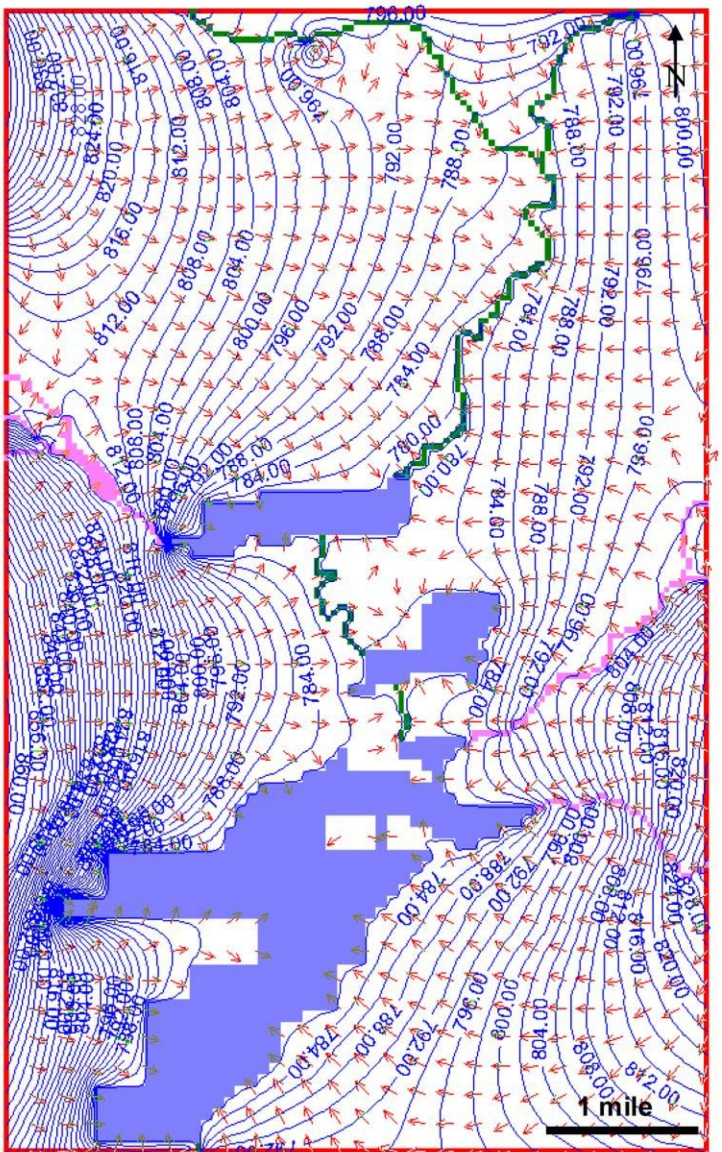

Figure 4.10.
Calibrated Vernon Marsh model water table map. Contour interval is 2 ft, with head values in ft amsl. Red arrows indicate direction of groundwater flow.

Table 4.5. Water budgets for the Vernon Marsh model. Marsh sections are listed from upstream to downstream. Total inflow and outflow, as well as individual components are given for each marsh section. The final row, gw %, is the percent of the total inflow or outflow that is from groundwater.

Component	Upper Section		Middle Section		Lower Section	
	In (ft^3/d)	Out (ft^3/d)	In (ft^3/d)	Out (ft^3/d)	In (ft^3/d)	Out (ft^3/d)
Evaporation		9.63×10^4		6.82×10^4		6.02×10^5
Precipitation	1.00×10^5		7.10×10^4		6.27×10^5	
Surface Flow	2.67×10^6	2.92×10^6	2.94×10^6	3.28×10^6	3.30×10^6	5.02×10^6
Groundwater	2.51×10^5	4.02×10^3	2.20×10^5		1.50×10^6	7.85×10^3
Total	3.02×10^6	3.02×10^6	3.23×10^6	3.35×10^6	5.43×10^6	5.63×10^6
gw %	8.3 %	0.13 %	6.8 %	0 %	28 %	0.14 %

Table 4.6. Calibration statistics for the Vernon Marsh model.

Head Targets	
Statistical Measure	All (6) targets
Residual Mean (ft)	2.04
Absolute Residual Mean (ft)	6.59
Root Mean Squared Error (ft^2)	2.72×10^2
Minimum Residual (ft)	-8.31
Maximum Residual (ft)	8.18

Well	Observed Value (ft)	Simulated Value (ft)
WKEOW1	782.0	787.3
Well 11	789.5	781.3
Well 12	788.5	782.3
Well 13	779.1	787.4
WKLTB1	785.0	780.4
WKLTB10	788.5	781.6

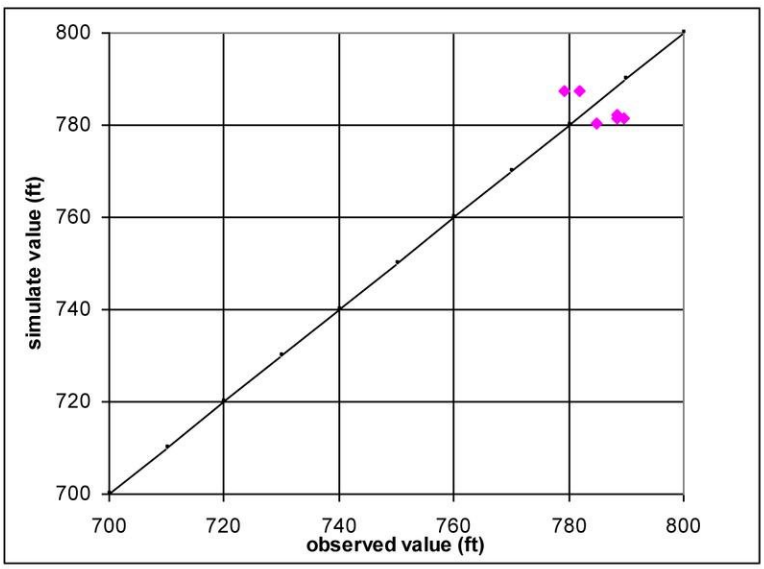

Figure 4.11. Observed verses simulated head values for the Vernon Marsh model. Targets are located in layers 2, 5, 6, and 7.

Table 4.7. Calibrated values for marsh stage.

Marsh Stages		
Marsh Section	Initial Value (ft)	Calibrated Value (ft)
Upper	780	780
Middle	780	779
Lower	780	781

4.4 Predictions

For the predictive simulation, both models were run under both steady-state and transient conditions using the calibrated steady-state solutions as initial conditions. For the transient models values of specific storage were determined based on storage coefficient values from the literature (Johnson, 1967) and average layer thickness for the various deposits. Since the layers each contain multiple deposits, specific storage and specific yield values were assigned to each deposit (Table 4.8). MODFLOW-2000 requires input of specific storage for confined model layers (a layer is confined when the water level is above the top of the layer) and specific yield values for the upper unconfined layer.

Table 4.8. Specific storage values in both the Lake Beulah and Vernon Marsh transient models were calculated by dividing storage coefficient by the average layer thickness. Specific yield is used for unconfined units (those present in the first layer) and specific storage for confined units (those present in all other layers).

Hydrostratigraphic Unit	**Storage Coefficient/ Specific Yield**	**Average Layer Thickness (ft)**	**Specific Storage (ft^{-1})**
Hydrofacies 1	5×10^{-5} / 0.02	20	2.5×10^{-6}
Hydrofacies 2	5×10^{-5} / 0.07	20	2.5×10^{-6}
Hydrofacies 3	5×10^{-5} / 0.2	20	2.5×10^{-6}
Hydrofacies 4	5×10^{-5} / 0.2	20	2.5×10^{-6}
Silurian Dolomite	5×10^{-5} / 0.02	30	2.5×10^{-6}
Maquoketa Shale	5×10^{-6}	65	8×10^{-8}
Sinnipee Dolomite	5×10^{-6}	65	8×10^{-8}

The MODFLOW files for the calibrated Lake Beulah and Vernon Marsh models are included in the accompanying material CD. Output files for the calibrated models, predictive simulations, and transient simulations are also included.

4.4.1 Lake Beulah Model

The Lake Beulah model was run under steady-state conditions with the addition of the new pumping well south of Lake Beulah (Table 3.7), in order to determine the effects of the well on groundwater heads and surface water features, especially lake levels. The well screen is located in layers 12 and 13 in the Lake Beulah model (not 8 and 9 as in the regional model), due to the splitting of layer 1. Heads are lowered by more than 1 ft south of Lake Beulah (Fig 4.12) as a result of pumping, with a maximum water table drop of 7 ft near the pumping well. Lake levels are not affected, but groundwater inflow is reduced more than 10% in four of the six lakes, including Lake Beulah (Table 4.9). These results are similar to the regional model for the area southwest of Lake Beulah, which includes Lakes Booth, Pickerel, Swan, and Willow Pond. Surface water bodies southwest of Lake Beulah have an average reduction of 6% for groundwater inflow in the regional model and averages 7.5% for the Lake Beulah model. The Lake Beulah model predicts reduction in groundwater inflow for Lake Beulah and Army Lake of 40% and 27%, respectively. For comparison, the regional model predicted reductions of 20% and 15%, respectively, for Lake Beulah and Army Lake. However, it is important to remember that groundwater supplies only around 20% of the water inflow to Lake Beulah (Table 4.3). The reduction to Army Lake potentially could cause a relatively greater effect since groundwater contributes around 60% of the inflow to that lake (Table 4.3).

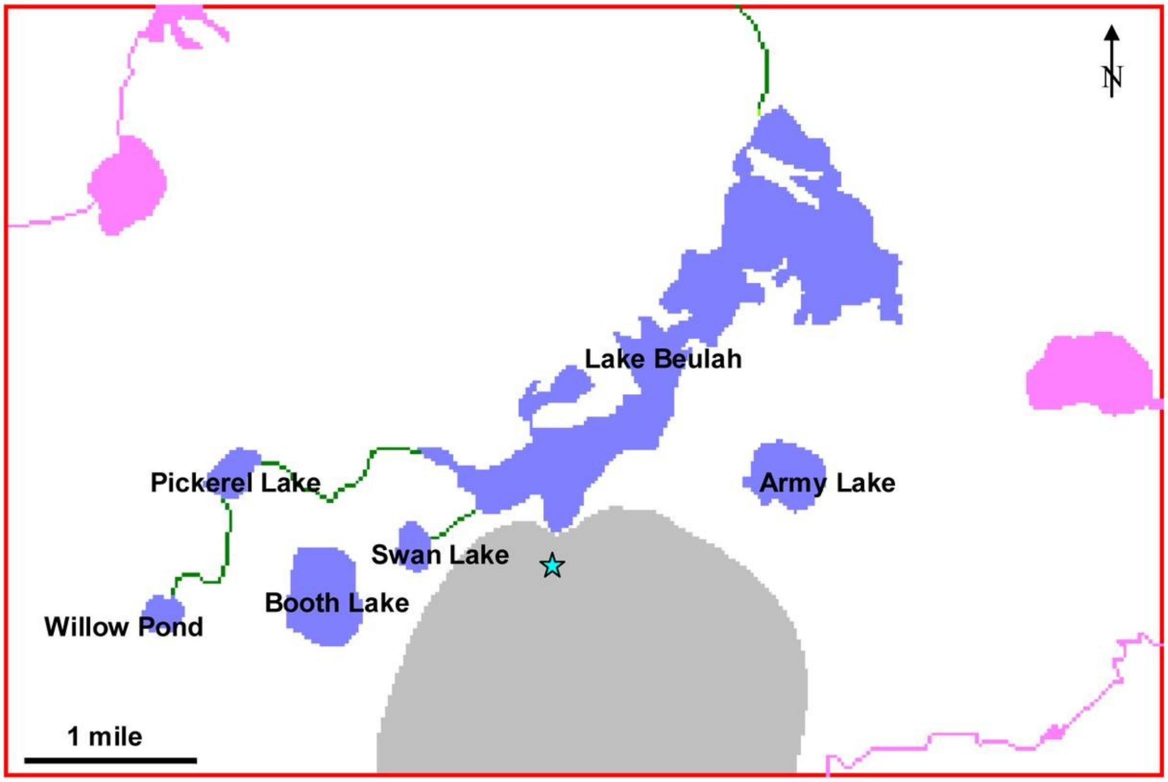

Figure 4.12. Area where heads are lowered by 1 ft or more as a result of pumping in the Lake Beulah model (gray area). Only layer 1 of model is shown, but the same area is affected in every layer of the model, with very small increases in affected area with depth. The blue star indicates the general location of pumping well near Lake Beulah.

Table 4.9. Pumping effects on groundwater inflow for the Lake Beulah model.

Lake	% reduction groundwater inflow
Army	27 %
Beulah	40 %
Booth	12 %
Pickerel	0.03 %
Swan	18 %
Willow	0.92 %

As in the regional model, the cone of depression around the pumping well intersects the southern boundary (Fig. 4.12). In the field, the well will induce more groundwater to flow through the boundary than is allowed under the fixed flux boundary conditions assumed in the model. The predictive simulation is conservative in that it shows the maximum possible impact under the assumptions used in the model.

Three sensitivity tests were run with changed flux boundaries in order to assess the impacts of the boundary condition. The predictive model was run with 10% more flux coming in the southern boundary in all layers of the model by decreasing discharge from extraction wells and increasing injection rates that are used to simulate the boundary flux. (The value of 10% was arbitrarily selected. It should be emphasized that under field conditions the increased flux through the boundary could be more or less than 10%.) The predictive model was also run with 10% more flux coming in only through the pumping layers (layers 12-12) of the southern boundary. A third sensitivity test was run with 10% more flux coming into the bottom of the model. In all three sensitivity tests, the area in which heads were lowered by 1 ft or more is approximately the same as the initial predictive model. The Lake Beulah model is not sensitive to a 10% change in boundary fluxes because there is a smaller extent of boundary in this model than for the regional model and thus a 10% increase does not allow as much water into the area as in the regional model.

The Lake Beulah model was also run under transient conditions with the addition of the new pumping well south of Lake Beulah (Table 3.7) using the storage values in Table 4.8. One stress period of 365 days was used with 240 time steps and a time step multiplier of 1.2. Water levels in the upper portion of the aquifer near the water table reach steady-state after 350 days (Fig. 4.13) while water levels at depth close to the screen of the pumping well reach steady-state within the first day of pumping (Fig. 4.14). The pumping test of this well indicates that steady-state is reached within three days (72 hours) of pumping (Ruekert-Mielke, Inc., personal communication, 2008).

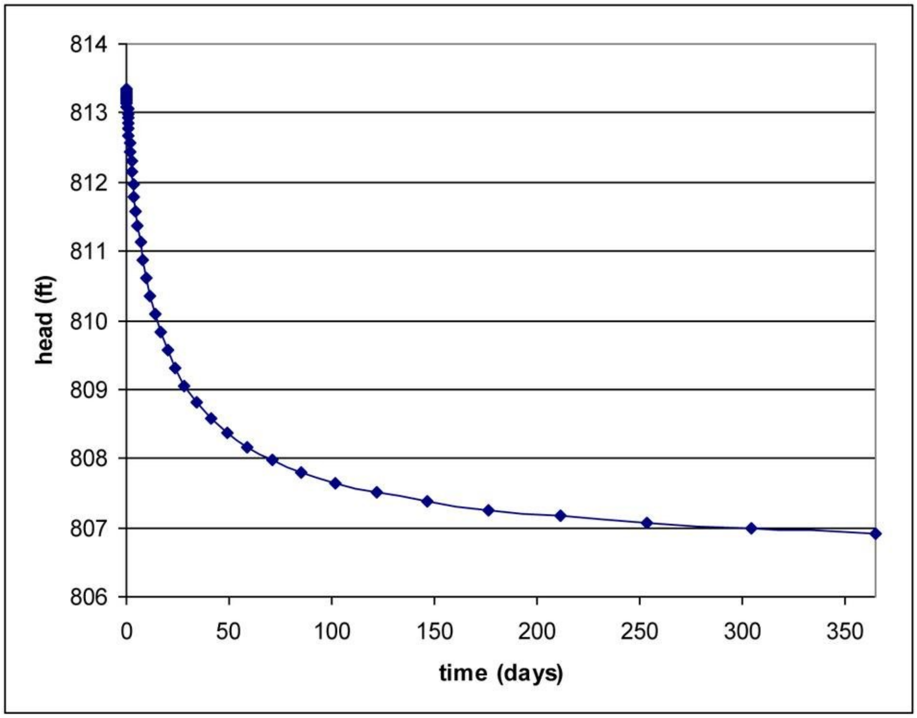

Figure 4.13. Decline in head in a hypothetical monitoring well located at the water table near the pumping well in the Lake Beulah model. Steady-state conditions are reached after approximately 350 days (0.96 years).

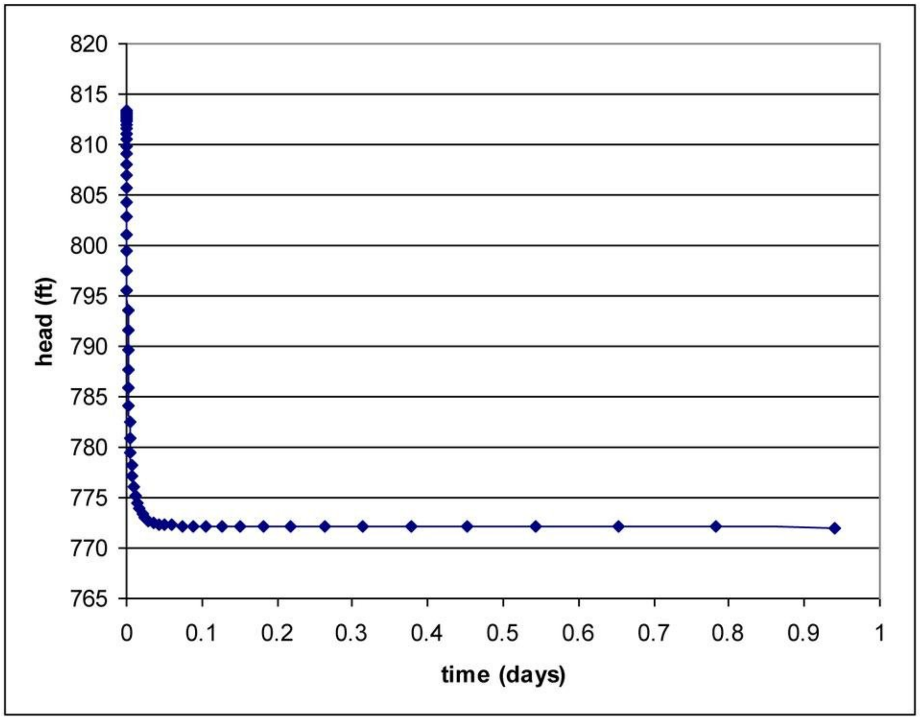

Figure 4.14. Decline in head in a hypothetical monitoring well located near the screen of the pumping well. Steady-state is reached in less than one day.

4.4.2 Vernon Marsh Model

The Vernon Marsh model was run to steady-state with the addition of three recently installed pumping wells (Table 3.7) in order to determine the effects of these wells on groundwater heads and surface water features. Heads are lowered by more than 1 ft north of Vernon Marsh (Fig 4.15) with a maximum water table drop of 22 ft as a result of pumping. The marsh stages change very little with pumping (Table 4.10). The northernmost (upper) part of the marsh has only a 3% decrease in groundwater inflow, but a 40% increase in groundwater outflow (Table 4.10). These results are similar to those of the regional model, which showed an 8% reduction in groundwater inflow to the northernmost section of the marsh. The model predicts the reach of the Fox River directly east of the pumping wells is dry, but the heads directly below the streambed are less than 1 ft below the bottom of the streambed. The streambed elevation, was estimated from topographic maps and could be set too high in the model. With a lower streambed elevation, the stream would not dry up.

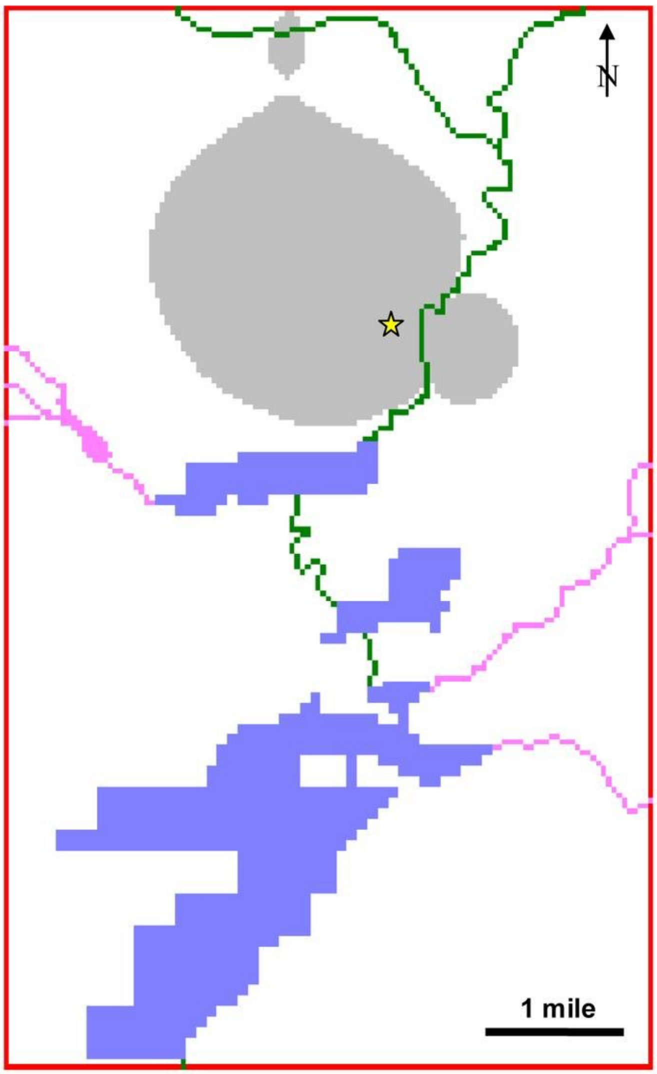

Figure 4.15.
Area where heads are lowered by 1 ft or more as a result of pumping in the Vernon Marsh model (gray area). Only layer 1 of model is shown, but the same area is affected in every layer of the model, with very small increases in affected area with depth. The yellow star indicates the general location of the three pumping wells near Vernon Marsh.

Table 4.10. Pumping effects on stage, groundwater inflow, and groundwater outflow for the Vernon Marsh model. Calibrated and predictive stages are both in ft amsl. Note that only the stage of the upper marsh section is affected by pumping.

Marsh Section	Calibrated Stage	Predictive Stage	% reduction groundwater inflow	% increase groundwater outflow
Upper	779.80	779.73	3 %	40 %
Middle	779.39	779.39	0.5 %	0 %
Lower	781.42	781.42	0 %	0 %

The effect of pumping intersects the northern boundary (Figure 4.15). Two sensitivity tests were run with a changed boundary in the northern half of the model in order to assess the impacts of the boundary condition.

The predictive model was run with 10% more flux coming in the boundary in all layers along the northern half of the model by decreasing discharge from extraction wells and increasing injection rates that are used to simulate the boundary flux. The predictive model was also run with 10% more flux coming in only in the pumping layers (layers 3-7) of the boundary in the northern half of the model. A third sensitivity test was run with 10% more flux coming into the bottom of the model. In all three sensitivity tests, the area in which heads were lowered by 1 ft or more is approximately the same as the initial predictive model. The Vernon Marsh model is not sensitive to a 10% change in boundary fluxes because there is a smaller extent of boundary in the model than for the regional model and thus a 10% increase does not allow as much water into the area. The predictive simulation is conservative in that it shows the maximum possible impact under the assumptions used in the model.

The Vernon Marsh model was also run under transient conditions with the addition of the three recently installed pumping wells (Table 3.7) using the storage values in Table 4.8. One stress periods of 1,491 days (4 years) was used with 480 time steps and a time step multiplier of 1.2. Close to the pumping wells, the model essentially reached steady-state conditions after 1200 days (Figure 4.16).

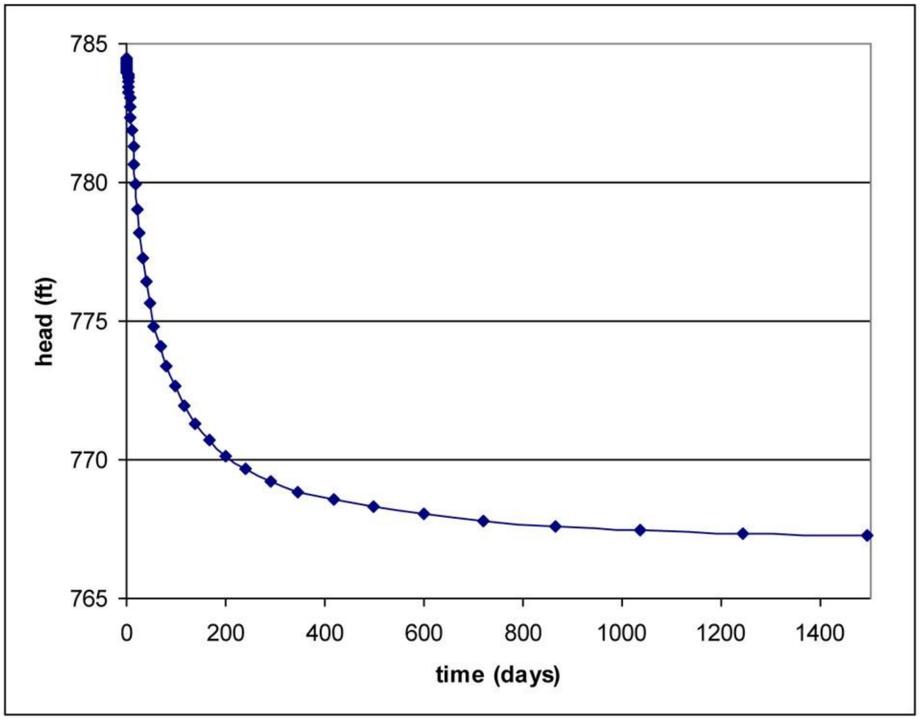

Figure 4.16. Decline in head in a hypothetical monitoring well located at the water table near the pumping wells in the Vernon Marsh model. Steady-state conditions are reached after approximately 1200 days (3.3 years).

Chapter 5: Summary and Conclusions

5.1 Summary

Glacial deposits in parts of the Troy Valley, located in southeastern Wisconsin, are a possible source of groundwater for municipalities in the area. However, owing to the lack of information on the nature and spatial distribution of the valley deposits, it is uncertain how pumping might affect groundwater levels and surface water features. The purpose of this study was to assess the effects of pumping from recently installed high capacity municipal wells in the vicinity of Vernon Marsh and Lake Beulah. Therefore, a regional hydrostratigraphic model and regional and local scale groundwater flow models of a portion of the Troy Valley in southeastern Wisconsin were developed.

A hydrostratigraphic model of the glacial deposits was constructed from subsurface data including geophysical measurements taken by ground penetrating radar, ground conductivity meters, and gamma loggers as well as nearly 12,000 well logs from the WDNR and WGNHS. The software package Rockworks™ v. 2006 was used to construct eleven possible models of the hydrostratigraphy. A final model was selected based on geologic reasoning and six hydrostratigraphic cross sections. Four hydrostratigraphic units were defined and the hydrostratigraphic model was imported into a groundwater flow model.

The Troy Valley regional groundwater flow model was run under steady-state conditions using the River Package to represent surface water features. It was initially calibrated using the inverse code PEST (Doherty, 2004) but the final calibration was performed manually. Forty-three head measurements and four flux measurements were used as calibration targets. Data for these came from the USGS, local consultants, and the

SEWRPC water table map. Seventeen parameters were adjusted during the manual calibration, consisting of horizontal and vertical hydraulic conductivities, the anisotropy ratio for four hydrostratigraphic units that comprise the glacial deposits, and conductances of stream and lakebed sediment.

The calibrated regional model was run with the addition of four recently installed wells that were represented using the MNW Package. The area affected by pumping intersected the southern boundary; so sensitivity tests were performed to assess the impacts of the boundary. Uncertainty in the glacial deposits and future pumping rates were assessed using Stochastic MODFLOW. MODPATH was used to determine capture zones for the recently installed pumping wells.

To assess the effects of pumping on surface water features near the new wells, two local scale models were constructed in the vicinity of Lake Beulah and the Vernon Marsh, using the telescopic mesh refinement (TMR) option in Groundwater Vistas and the calibrated regional model. These models were run under both steady-state and transient conditions and used the Lake, Stream Flow Routing, and River Packages to represent surface water features.

5.2 Conclusions

There are four main conclusions that can be drawn from this work.

1) The use of inverse distance weighting to interpolate the spatial distribution of the glacial deposits in a three-dimensional hydrostratigraphic model produced geologically reasonable results. This was evident in the calibrated regional groundwater flow model, which accurately represented the water table and had a good fit to the calibration targets.

2) The hydraulic conductivity of the glacial deposits can significantly affect the predicted heads under pumping conditions, depending on the location within the modeled area. The uncertainty analysis indicated that heads near Lake Beulah could vary over 4 ft and heads near Vernon Marsh could vary over 13 ft with varying hydraulic conductivities of the glacial deposits.

3) The results of the steady-state regional groundwater flow model indicate that pumping in the Troy Valley near Vernon Marsh and Lake Beulah will reduce groundwater heads and groundwater flow to surface water features near the pumping wells. Because the results of the predictive simulation were influenced by the fixed flux boundary conditions, the simulation shows the maximum possible impact under the assumptions used in the model. Under field conditions, the wells will induce more water to flow into the area than is allowed by the fixed flux boundary conditions. Under fixed flux boundary conditions, an average 18% reduction in groundwater inflow occurs in the northern section of Vernon Marsh and an average of 20% reduction in groundwater flow to Lake Beulah. Flow reverses in reaches of the Fox River north of Vernon Marsh and in the southern portion of Lake Beulah. Results from the Vernon Marsh and Lake Beulah local scale models confirmed the reduction in groundwater inflow although the local scale model predicted 40% reduction in groundwater inflow to Lake Beulah. However, it is important to remember that groundwater supplies only around 20% of the total water inflow to Lake Beulah and less than 30% of the inflow to Vernon Marsh. Furthermore, sensitivity tests on the lateral boundary conditions of the regional model showed that the impacts will be less when more water is allowed to flow through the boundaries.

4) In the local scale models, lake and marsh levels were not affected by the new pumping wells. Under the fixed flux boundary conditions assumed in the model, the maximum drawdown at depth was predicted to be around 50 ft, while the maximum drawdown of the water table was approximately 7 ft around Lake Beulah and around 22 ft near Vernon Marsh. Close to the pumping wells, the full effects of pumping are reached within 350 days for the Lake Beulah model and within 1,491 days for the Vernon Marsh model. However, the calibration of these models is highly uncertain; these models would be improved by additional field data and additional calibration using vertical gradients and transient data from pumping tests.

5.3 Future Work

The hydrostratigraphic model, and thus also the groundwater flow models, could be improved by collection of additional data, especially near Vernon Marsh, which lacks detailed subsurface data. Ideally at least two wells should be drilled to bedrock using rotosonic drilling, which would improve the characterization of glacial deposits in the area. Field testing of these wells with pumping tests/slug tests would provide information on hydraulic conductivity. Additional geophysical work, using ground penetrating radar, for example, would also help to delineate the spatial distribution of glacial deposits.

The use of indicator kriging or another type of geostatistical technique with the hydrostratigraphic model would allow for geologically more realistic assumptions about the deposits than the random distribution used in Stochastic MODFLOW. Additionally, uncertainty of the boundaries of each hydrofacies could be tested using more advanced geostatistical methods. An uncertainty analysis and stochastic analysis could be run on the Lake Beulah and Vernon Marsh models.

Both the regional and local models could be improved by additional field work to determine site specific values of hydraulic conductivity. Additional monitoring wells would provide additional calibration targets that would result in a more accurate model. Furthermore, existing and new vertical head gradients could be used as targets. Transient calibration to pumping test data would also be helpful. The models would benefit from the use of recently improved recharge rates for the area (Hart *et. al*, in press). The improved recharge rates were obtained using a soil-water balance model that includes climate data, soil characteristics, land-use, and topography.

In order to avoid having cones of depression that intersect the model boundaries, the boundaries could be moved farther from the area of interest. This would require additional work on the hydrostratigraphic model, including data collection outside the current boundaries. To avoid the problem of fixed flux boundaries, the lateral boundaries could be modified to general head boundaries. General head boundaries tie the boundary to a constant head some specified distance from the boundary. The model assumes the head there is unaffected by stresses (pumping) within the model. Furthermore, a value for conductance of the area between the boundary and the constant head must be assumed. The use of general head boundaries is a less conservative approach than specified flux, but could be justified for this problem.

The local scale Lake Beulah and Vernon Marsh models, would improve with improvements to the regional model since they were extracted from the regional model and use heads determined by the regional model to set boundary conditions. Additionally, monitoring lake levels and doing additional stream gaging in these areas would provide better calibration targets. Field work to determine site specific precipitation and evaporation rates for the lakes would also be helpful.

The calibrated regional model presented in this report is a good first approximation model, suitable for use in groundwater management. The local scale models, however, are more uncertain and should be used with caution; they would benefit from additional calibration.

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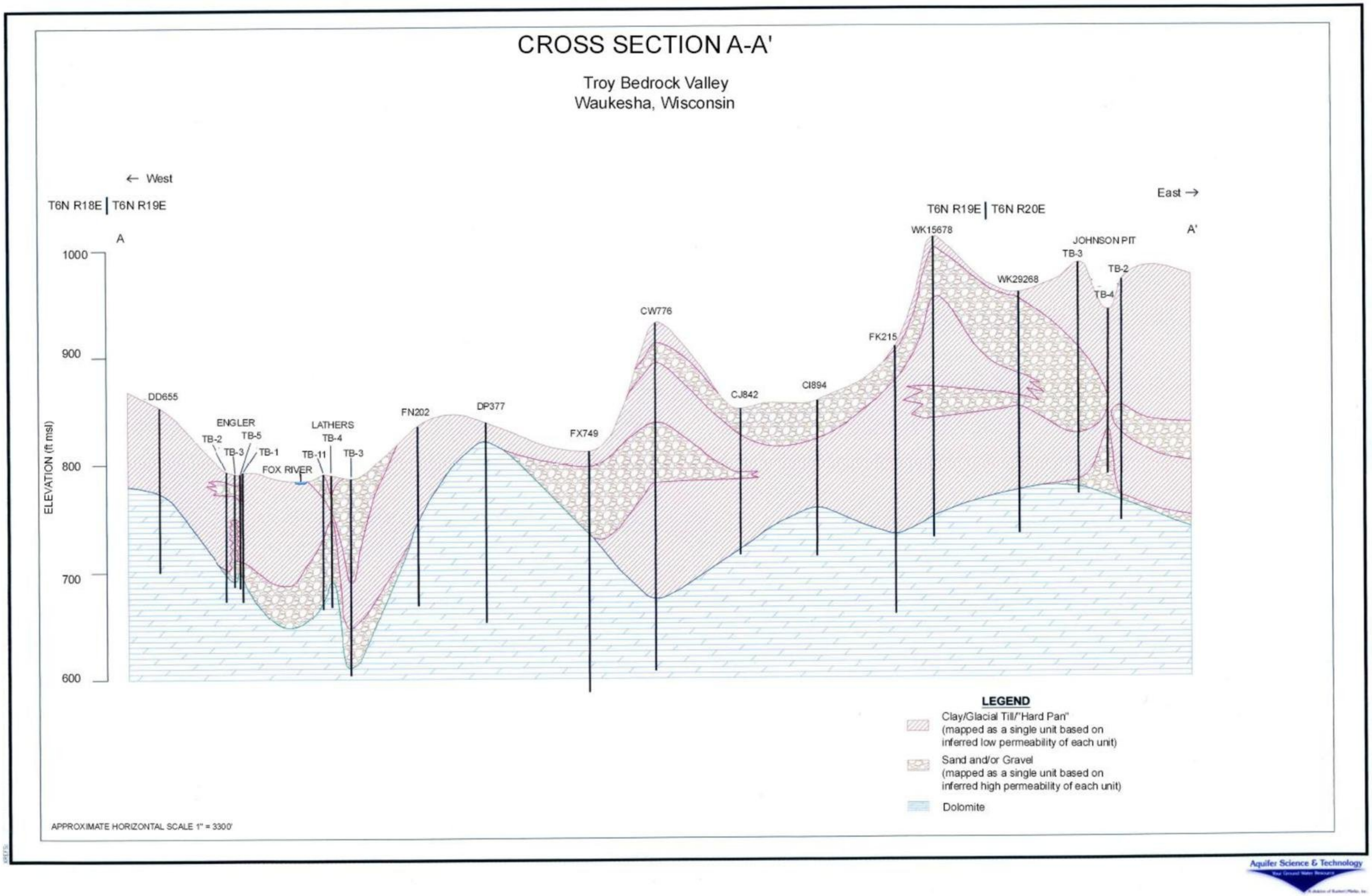
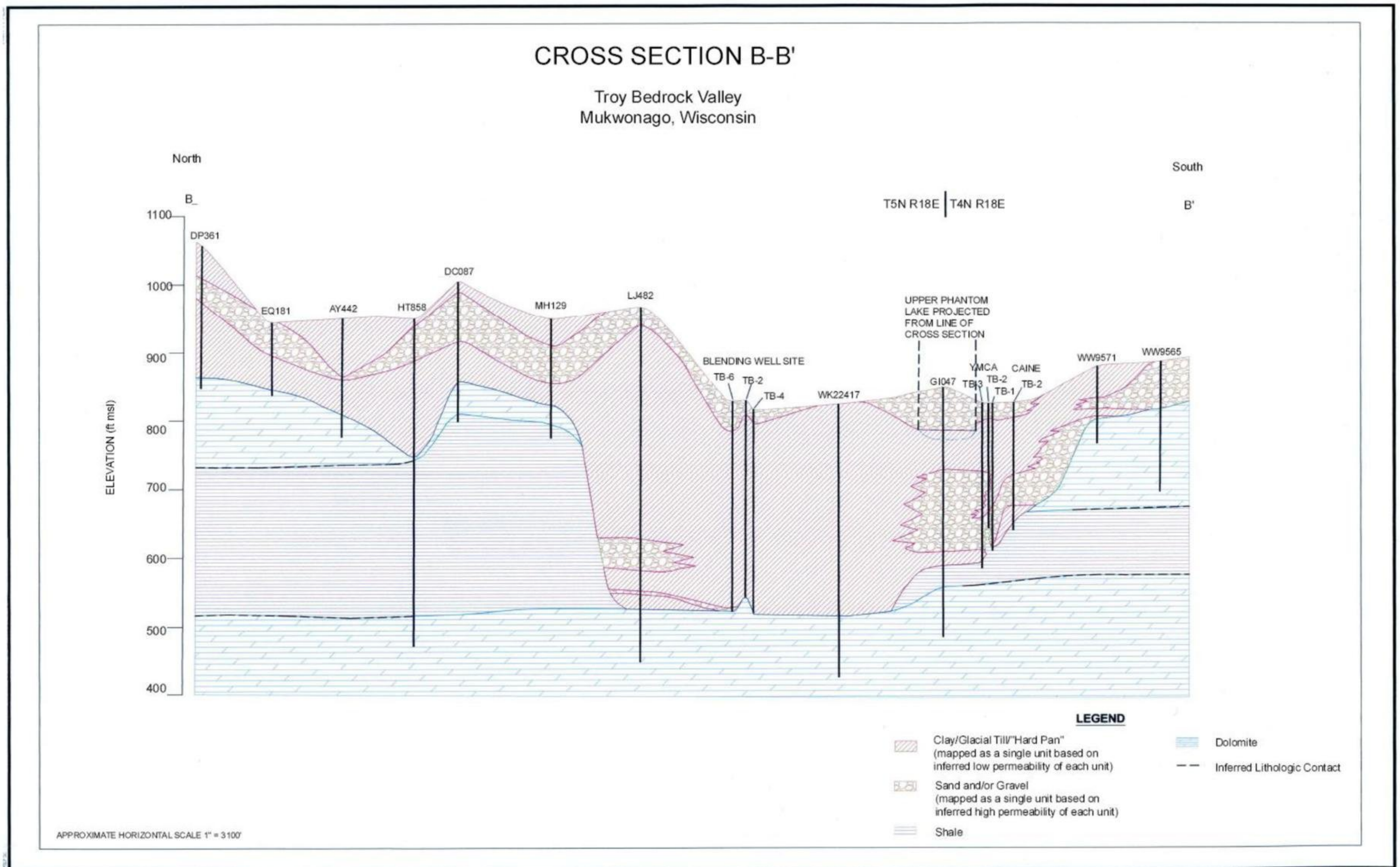
Appendix 1: Troy Valley Cross Sections

Cross sections were prepared in collaboration with Ruekert-Mielke, Inc. They digitized all of the cross sections and provided the well and bore log data that were used in the construction of the cross sections, with the exception of a few wells from the WGNHS database used to fill in the gaps.


CROSS SECTION A-A'
Troy Bedrock Valley
Waukesha, Wisconsin
← West
East →
T6N R18E | T6N R19E
T6N R19E | T6N R20E
A
A'
ELEVATION (ft msl)
1000
900
800
700
600
DD655
ENGLER
TB-2
TB-5
TB-3
TB-1
FOX RIVER
LATHERS
TB-4
TB-11
TB-3
FN202
DP377
FX749
CW776
CJ842
CI894
FK215
WK15678
WK29268
JOHNSON PIT
TB-3
TB-2
TB-4
LEGEND
Clay/Glacial Till/"Hard Pan"
(mapped as a single unit based on inferred low permeability of each unit)
Sand and/or Gravel
(mapped as a single unit based on inferred high permeability of each unit)
Dolomite
APPROXIMATE HORIZONTAL SCALE 1" = 3300'
Aquifer Science & Technology



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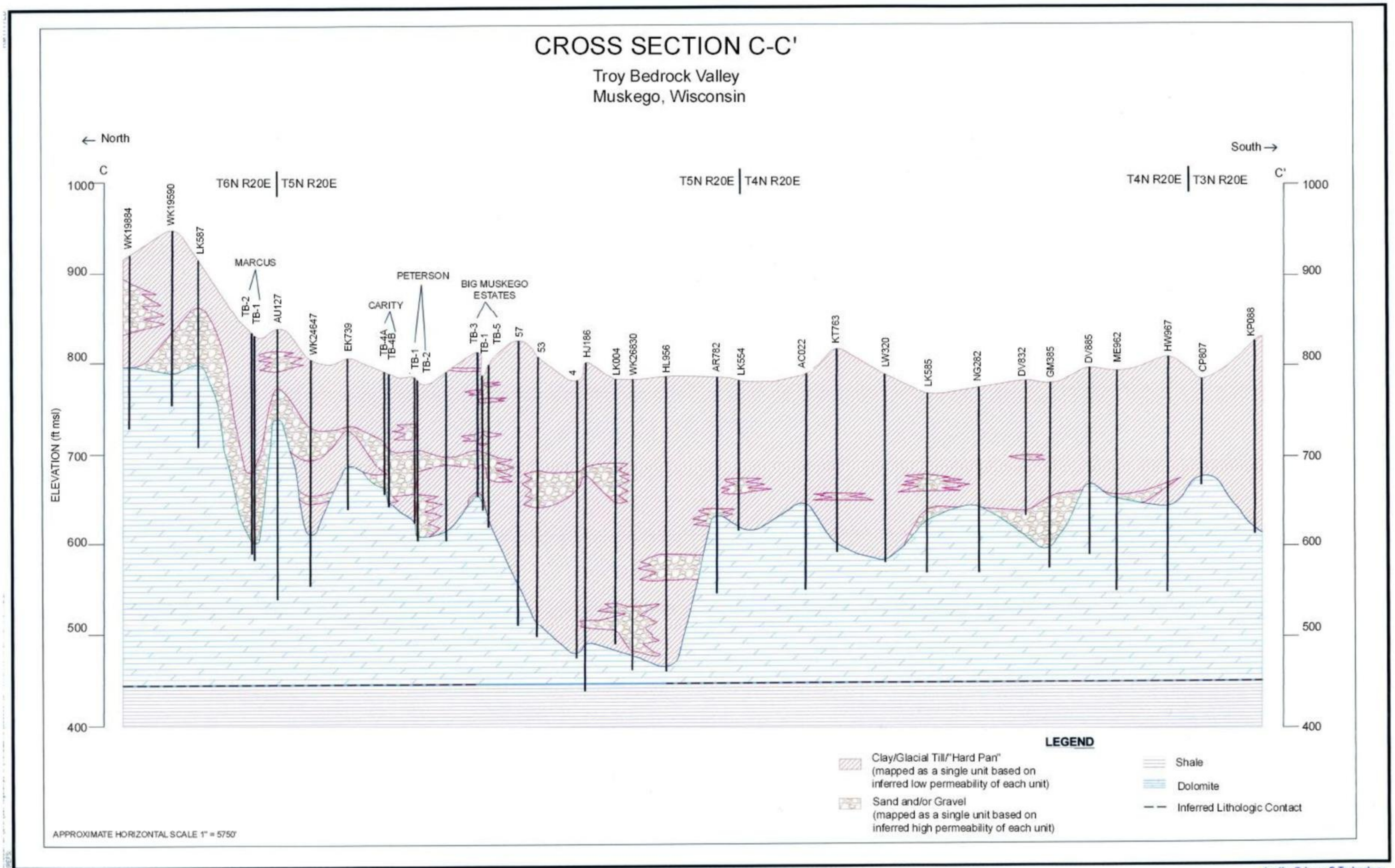
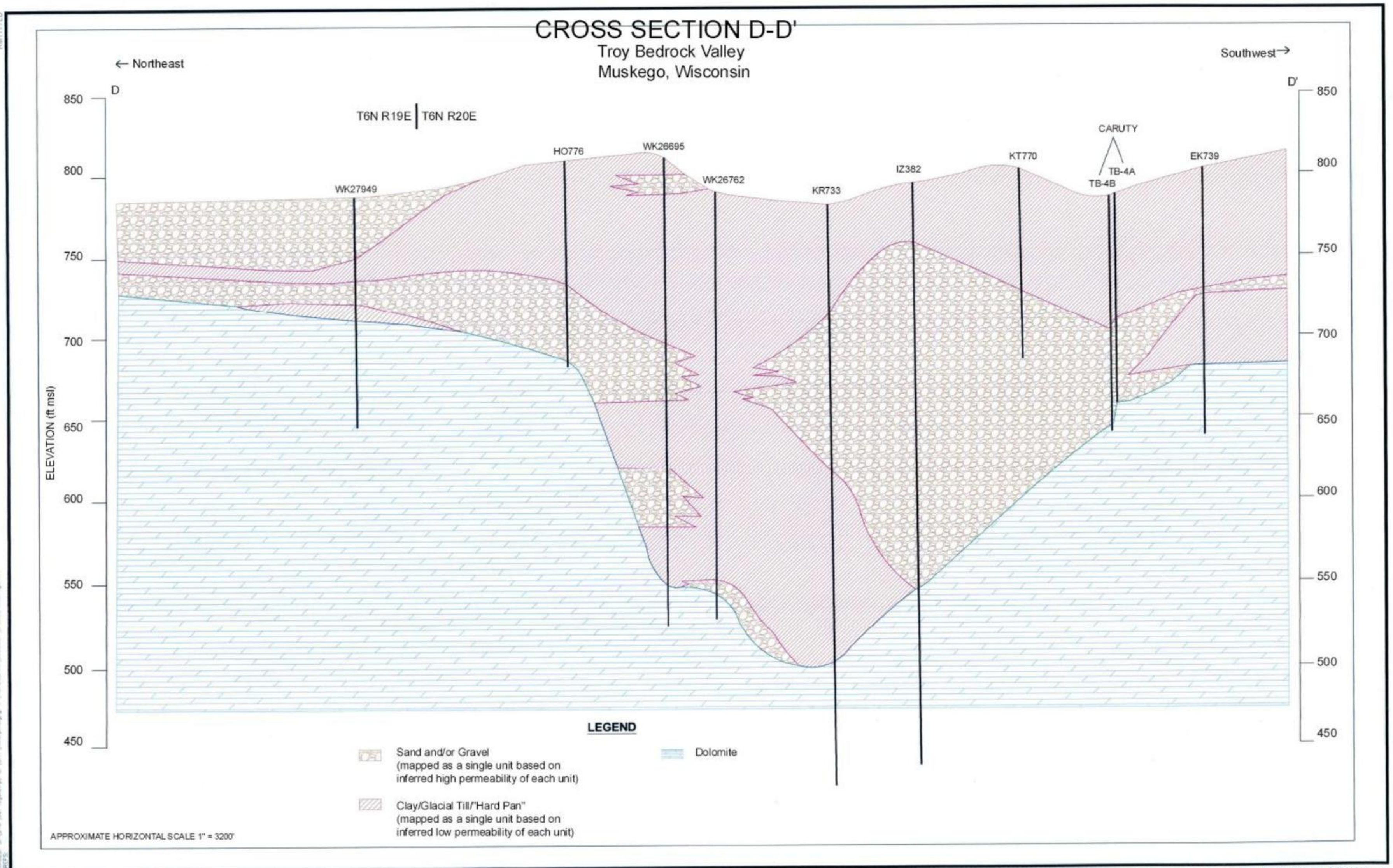

CROSS SECTION C-C'
Troy Bedrock Valley
Muskego, Wisconsin
← North
South →
C
C'
T6N R20E | T5N R20E
T5N R20E | T4N R20E
T4N R20E | T3N R20E
ELEVATION (ft msl)
1000
900
800
700
600
500
400
WK19884
WK19590
LK587
MARCUS
TB-2
TB-1
AU127
WK24647
EK739
CARITY
TB-4A
TB-4B
PETERSON
TB-1
TB-2
BIG MUSKEGO ESTATES
TB-3
TB-1
TB-5
57
53
4
HJ186
LK004
WK26830
HL956
AR782
LK554
AC022
KT763
LW320
LK585
NG282
DV832
GM385
DV885
ME962
HW967
CP807
KP088
LEGEND
Clay/Glacial Till/"Hard Pan" (mapped as a single unit based on inferred low permeability of each unit)
Sand and/or Gravel (mapped as a single unit based on inferred high permeability of each unit)
Shale
Dolomite
Inferred Lithologic Contact
APPROXIMATE HORIZONTAL SCALE 1" = 5750'



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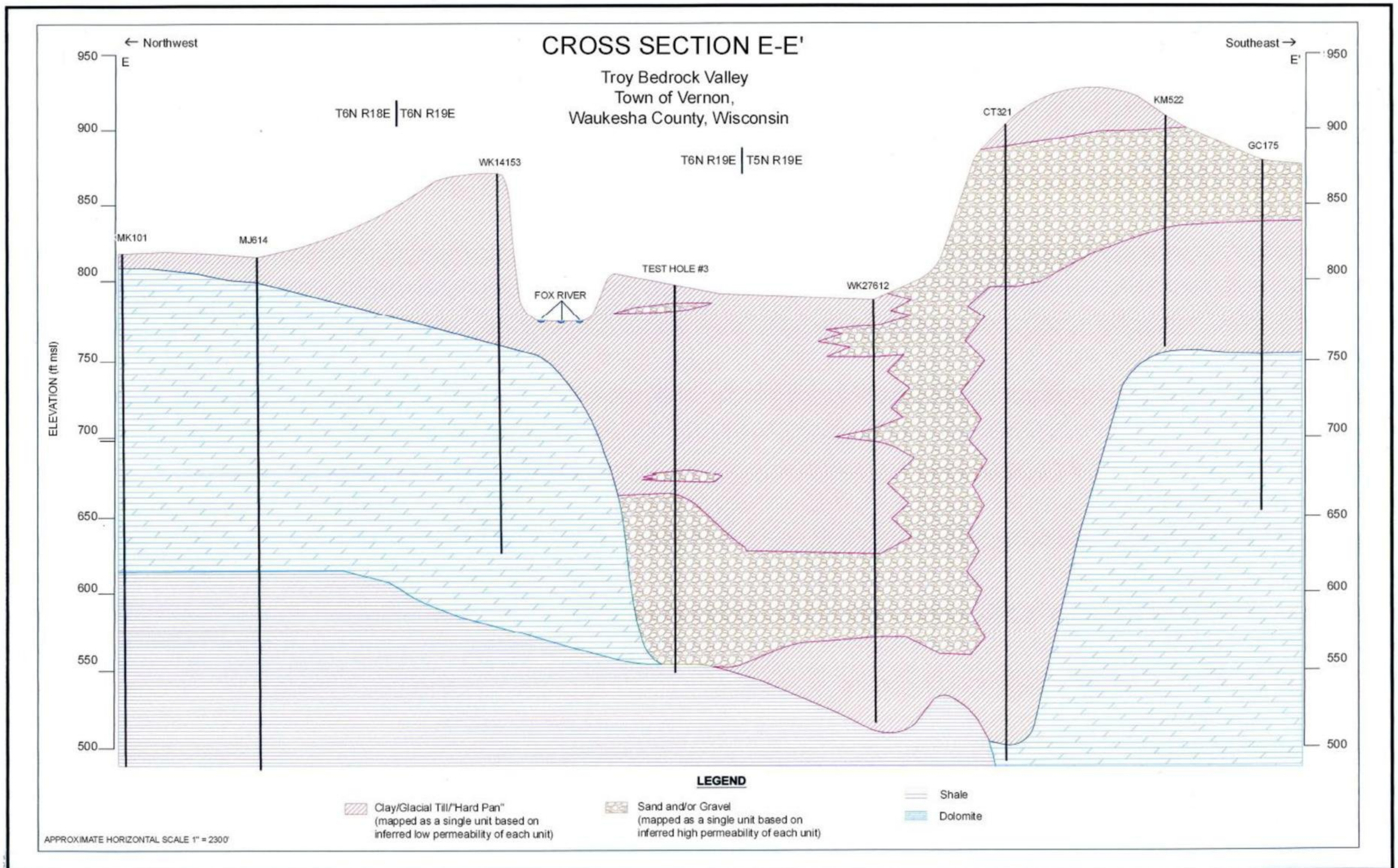

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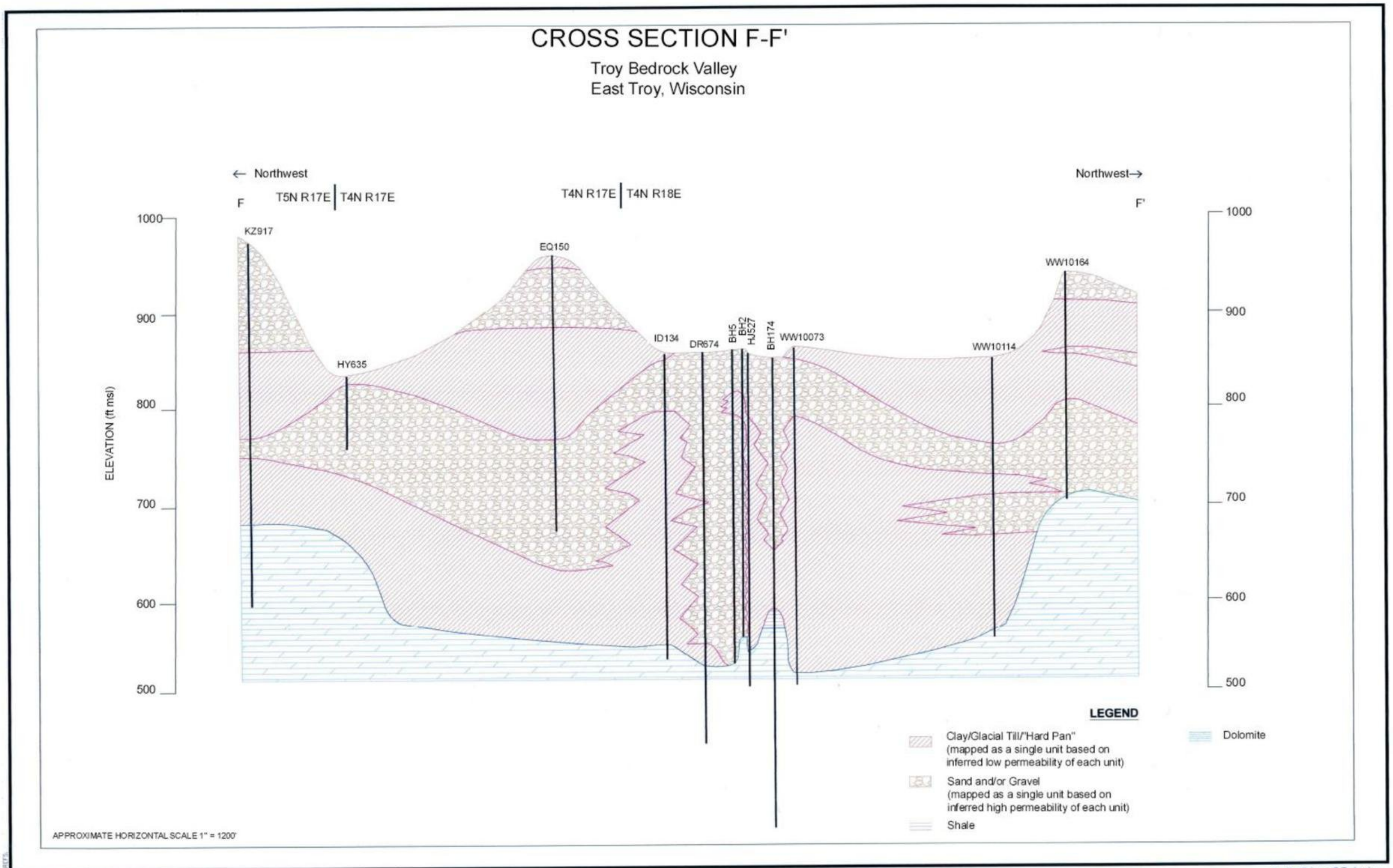
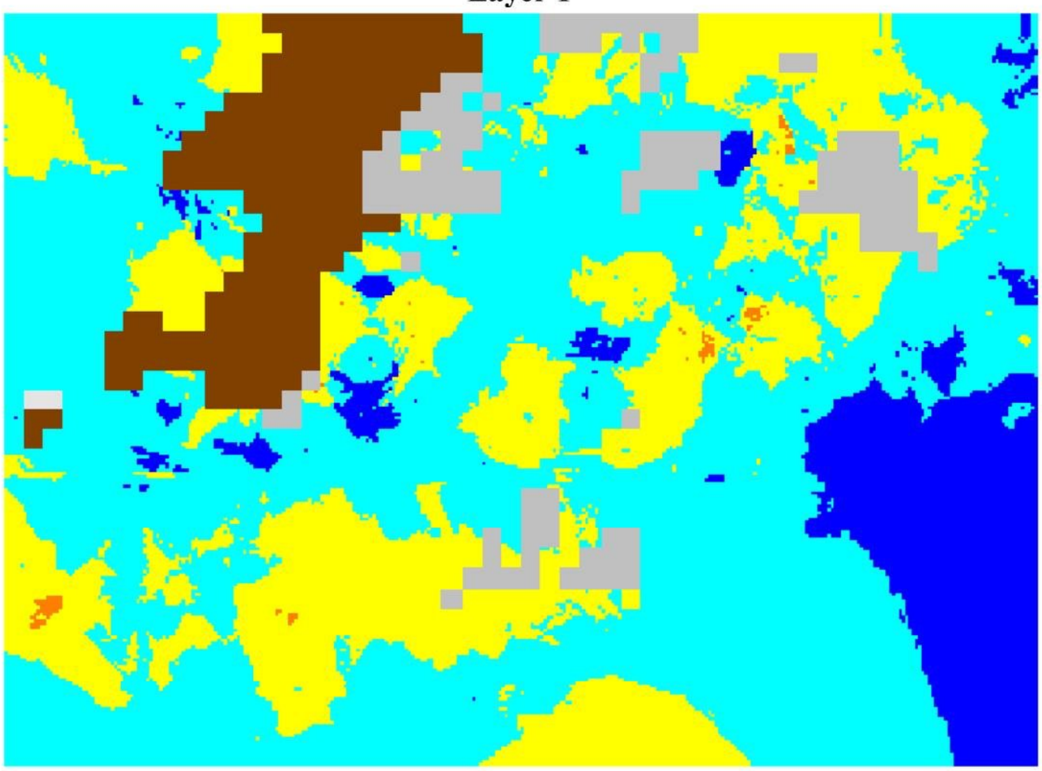

CROSS SECTION F-F'
Troy Bedrock Valley
East Troy, Wisconsin
← Northwest
Northwest→
F
F'
T5N R17E
T4N R17E
T4N R17E
T4N R18E
ELEVATION (ft msl)
1000
900
800
700
600
500
KZ917
HY635
EQ150
ID134
DR674
BH5
BH2
HJ527
BH174
WW10073
WW10114
WW10164
LEGEND
Clay/Glacial Till/"Hard Pan"
(mapped as a single unit based on inferred low permeability of each unit)
Sand and/or Gravel
(mapped as a single unit based on inferred high permeability of each unit)
Shale
Dolomite
APPROXIMATE HORIZONTAL SCALE 1" = 1200'

Appendix 2: Regional Model Hydraulic Conductivity Zones

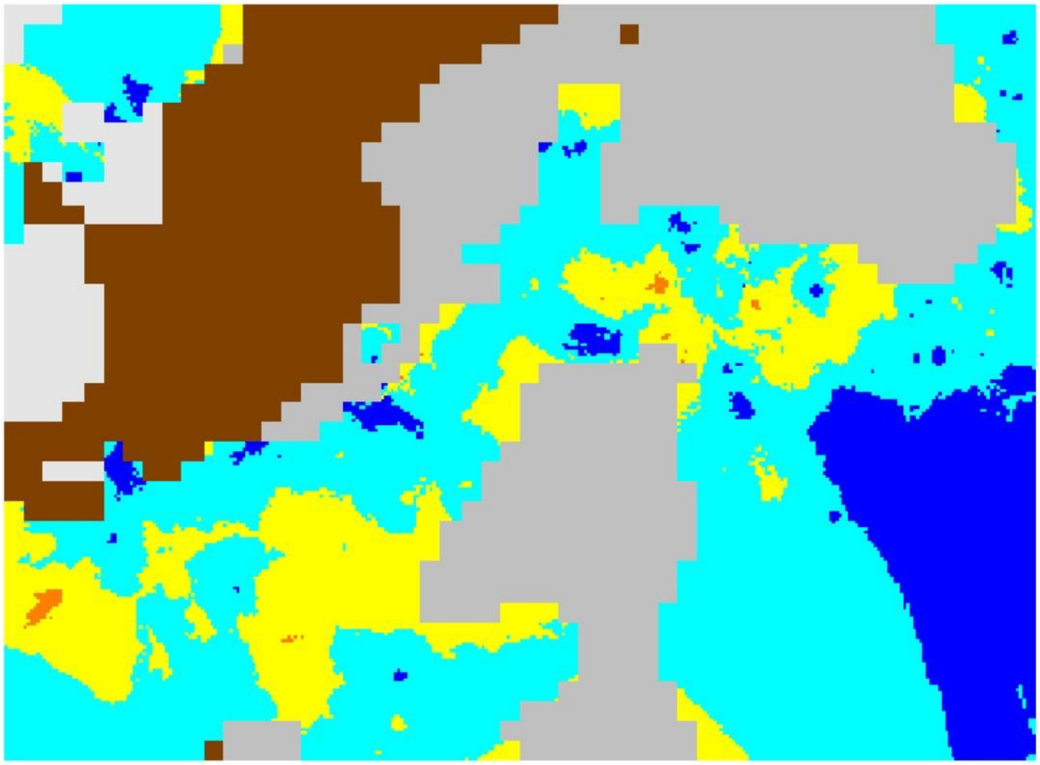
Legend for all layers in the model

Zone 1: Hydrofacies 1
Zone 2: Hydrofacies 2
Zone 3: Hydrofacies 3
Zone 4: Hydrofacies 4
Zone 5: Silurian Dolomite
Zone 6: Maquoketa Shale, at depth
Zone 7: Sinnipee Dolomite, at depth
Zone 8: Maquoketa Shale, at surface
Zone 9: Sinnipee Dolomite, at surface

Layer 1



Layer 2



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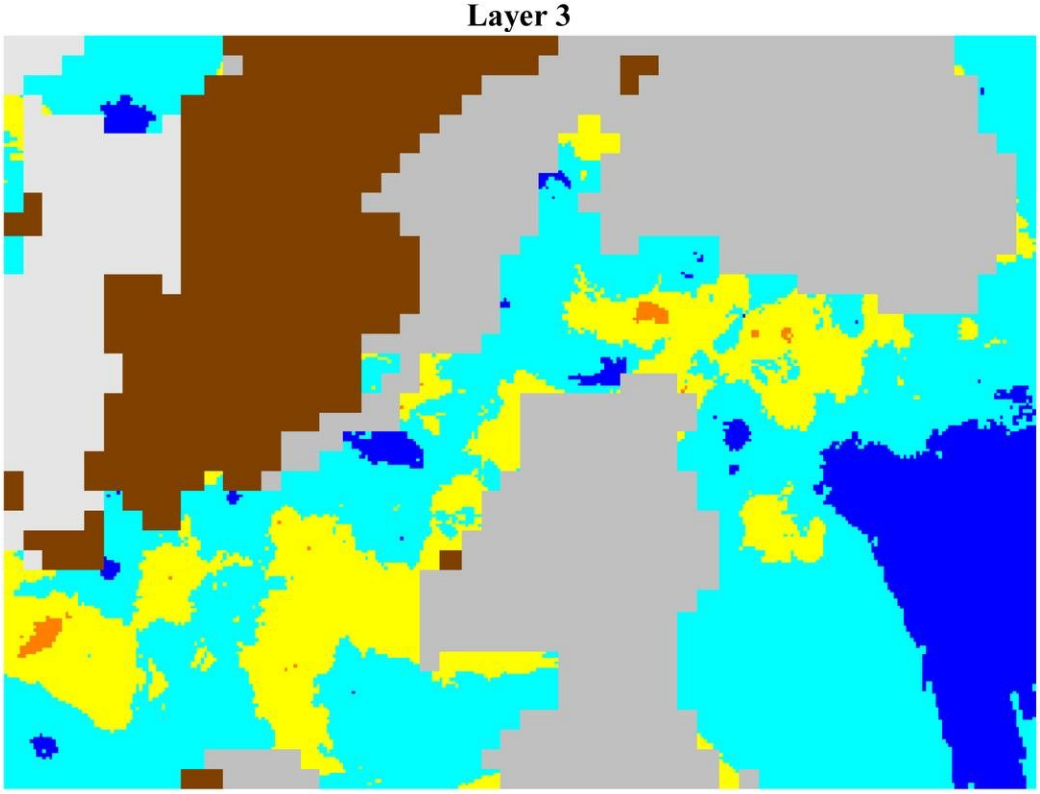

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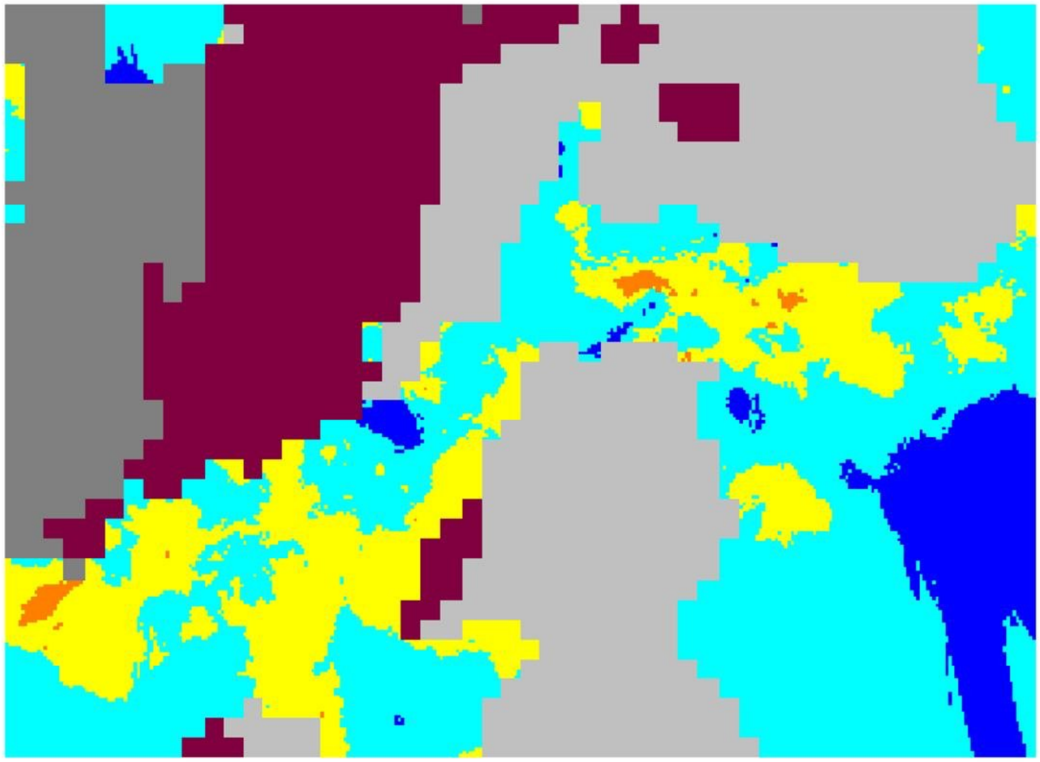
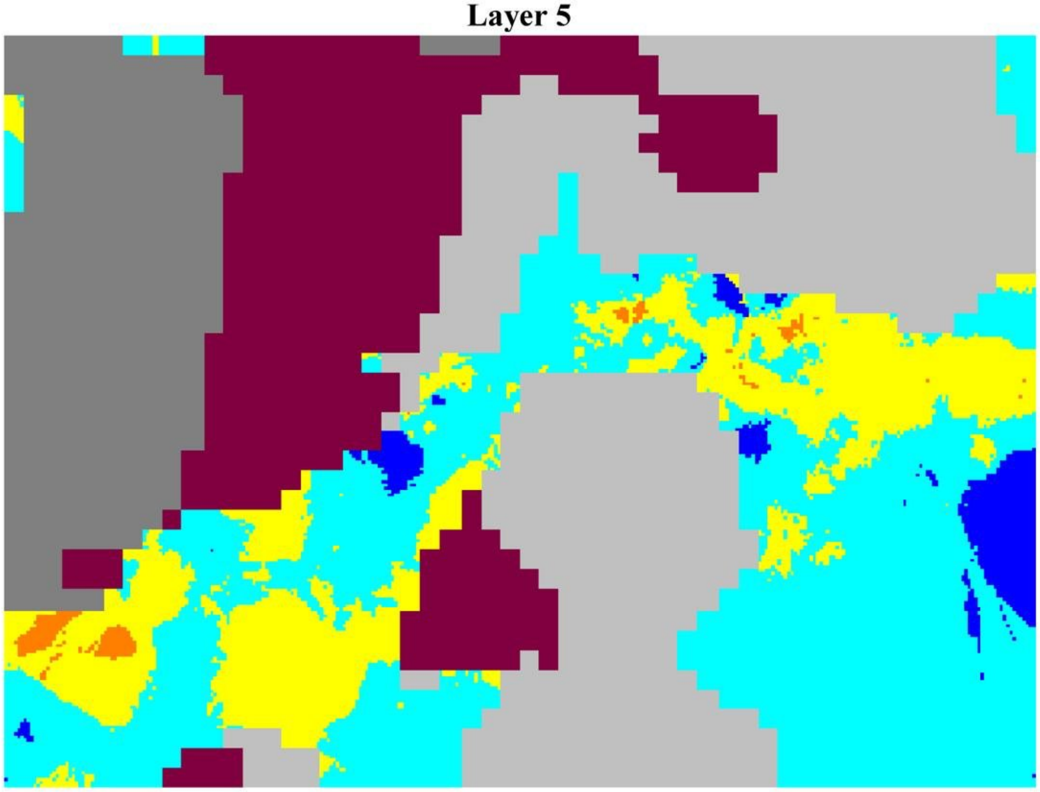
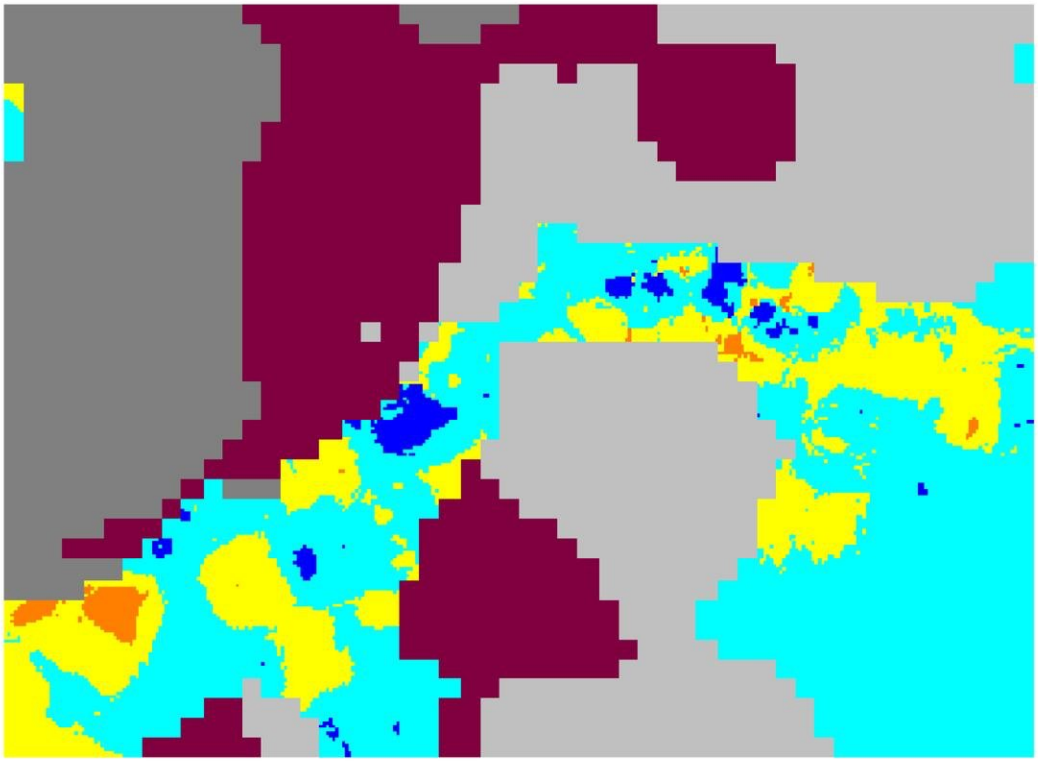


Layer 5



Layer 6



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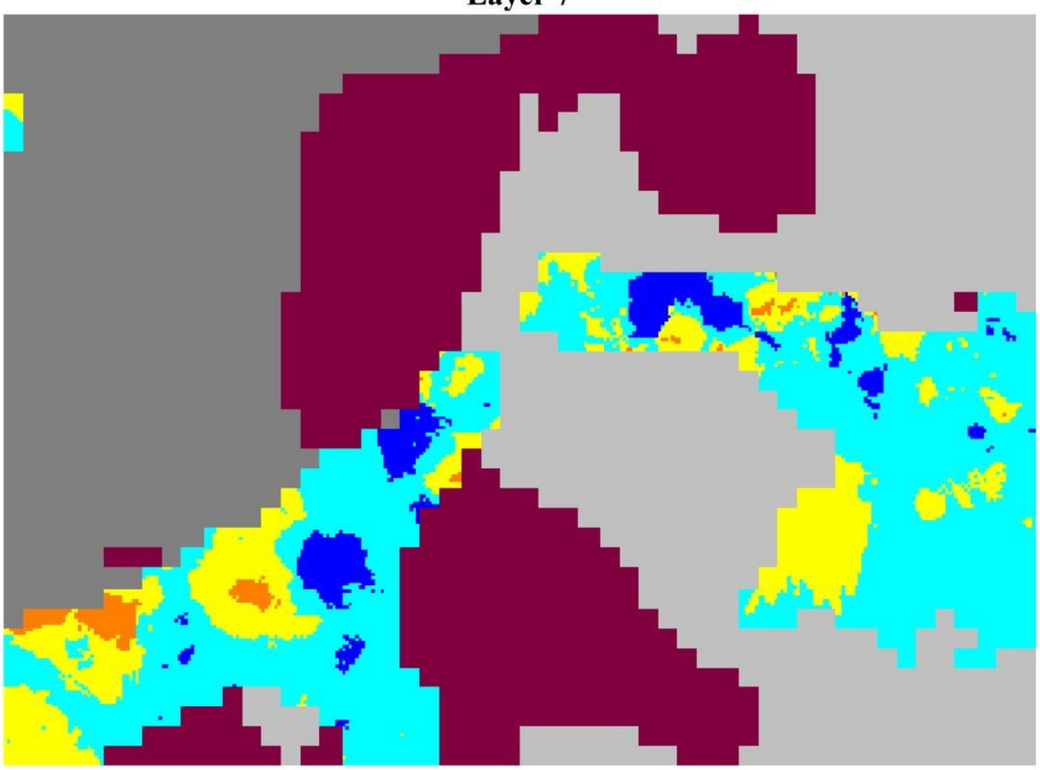

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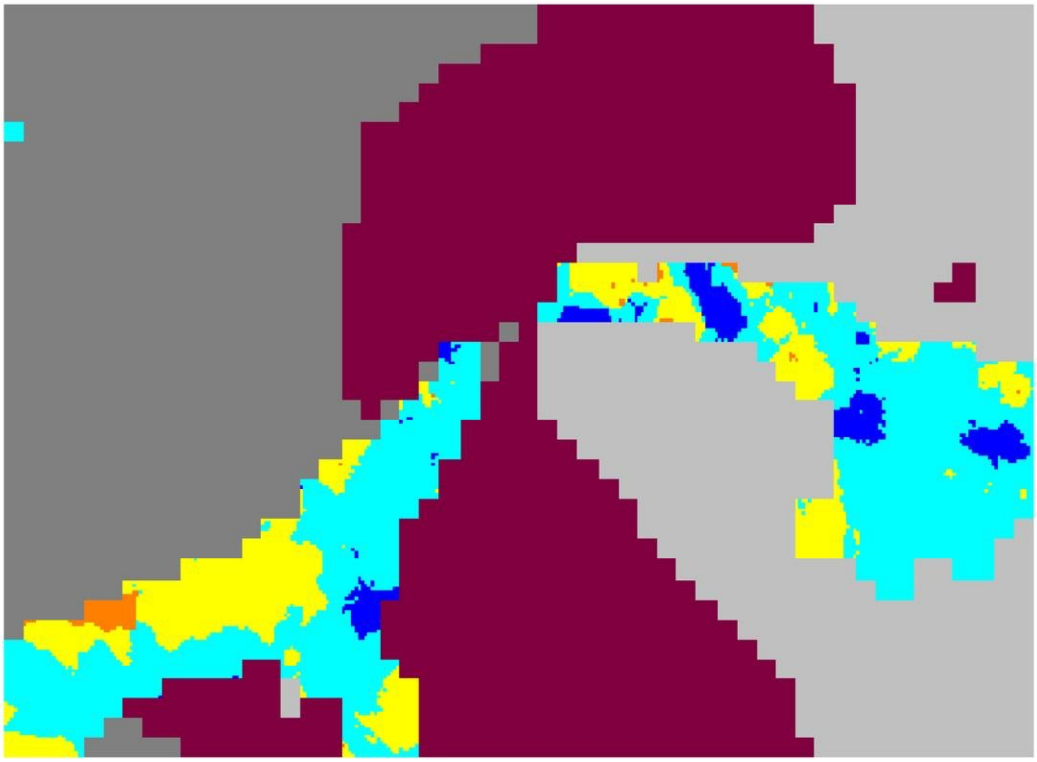
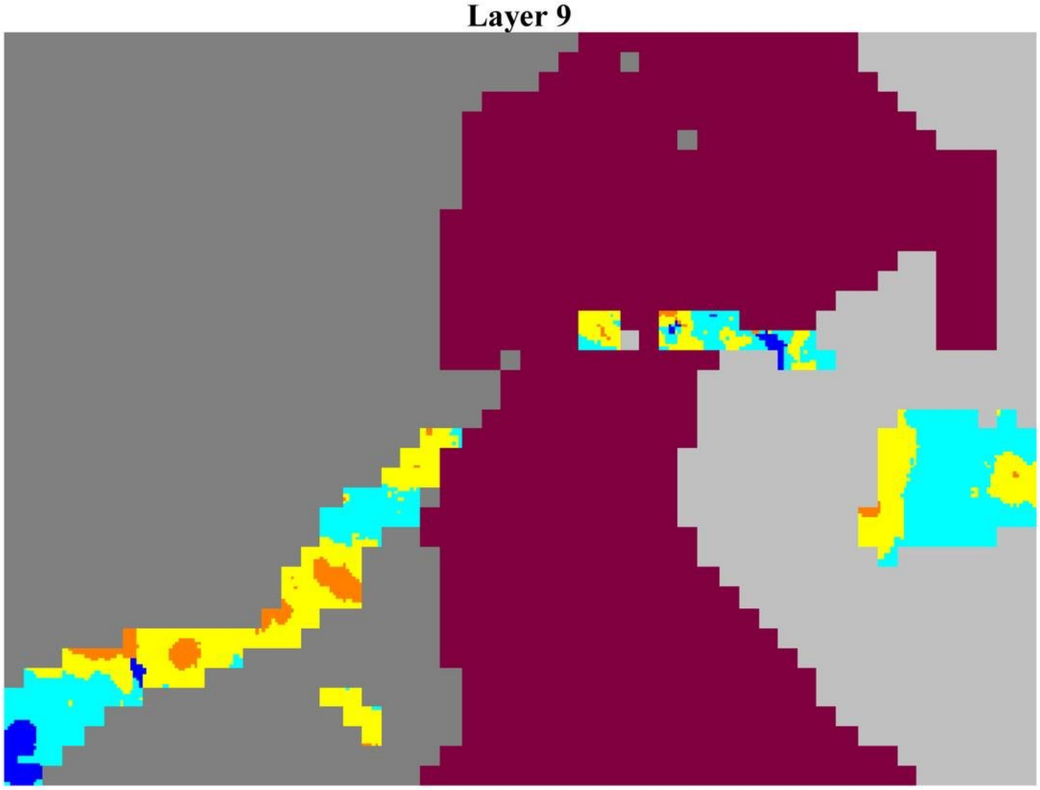
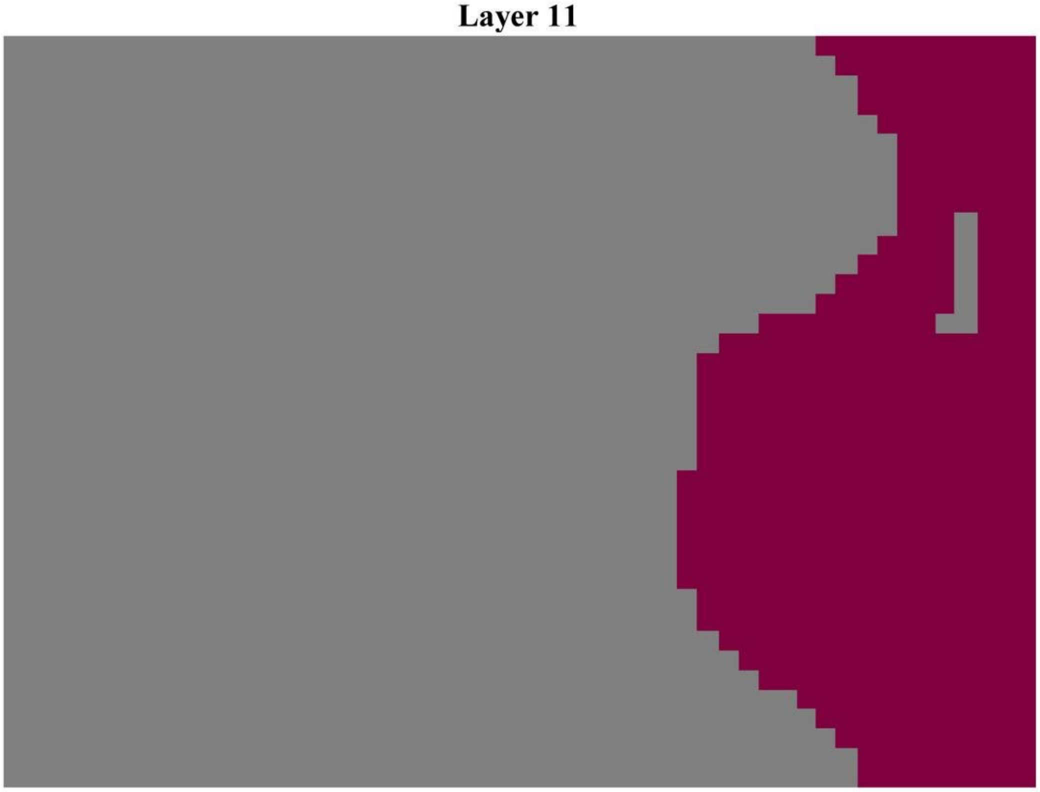


Layer 9



Layer 10

Layer 11



Appendix 3: PEST Parameters

The nine hydraulic conductivity zones (Section 3.3.4) and riverbed conductance for the three river reaches (Section 3.3.3) were chosen as parameters for PEST. The par2par option was used in order to set relationships between parameters. Twenty-one parameters were used, but some of these were ratios used to calculate the actual hydraulic conductivity values for the model (Table A3.1).

Table A3.1 Parameters used in PEST for regional model, along with explanation of each.

Parameter	Explanation
Kx1	Horizontal Hydraulic Conductivity of Clay
Kx5	Horizontal Hydraulic Conductivity of Silurian Dolomite
Kx6	Horizontal Hydraulic Conductivity of Maquoketa Shale, at depth
Kx7	Horizontal Hydraulic Conductivity of Sinnipee Dolomite, at depth
Kz1	Vertical Hydraulic Conductivity of Clay
Kz2	Vertical Hydraulic Conductivity of Till
Kz3	Vertical Hydraulic Conductivity of Sand
Kz4	Vertical Hydraulic Conductivity of Gravel
Kz5	Vertical Hydraulic Conductivity of Silurian Dolomite
Kz6	Vertical Hydraulic Conductivity of Maquoketa Shale, at depth Dolomite
Kz7	Vertical Hydraulic Conductivity of Sinnipee Dolomite, at depth
Kz8	Vertical Hydraulic Conductivity Maquoketa Shale, at surface
Kz9	Vertical Hydraulic Conductivity of Sinnipee Dolomite, at surface
Krat1	Kx2 / Kx1, where Kx2 = Horizontal Hydraulic Conductivity of Till
Krat2	Kx3 / Kx2, where Kx3 = Horizontal Hydraulic Conductivity of Sand
Krat3	Kx4 / Kx3, where Kx4 = Horizontal Hydraulic Conductivity of Gravel
Krat4	Horizontal Hydraulic Conductivity of Maquoketa Shale at depth / Kx6
Krat5	Horizontal Hydraulic Conductivity of Sinnipee Dolomite at depth / Kx7
Riv1	Riverbed Conductance for 25ft wide stream reaches
Riv2	Riverbed Conductance for 100ft wide stream reaches
Riv101	Riverbed Conductance for lake reaches