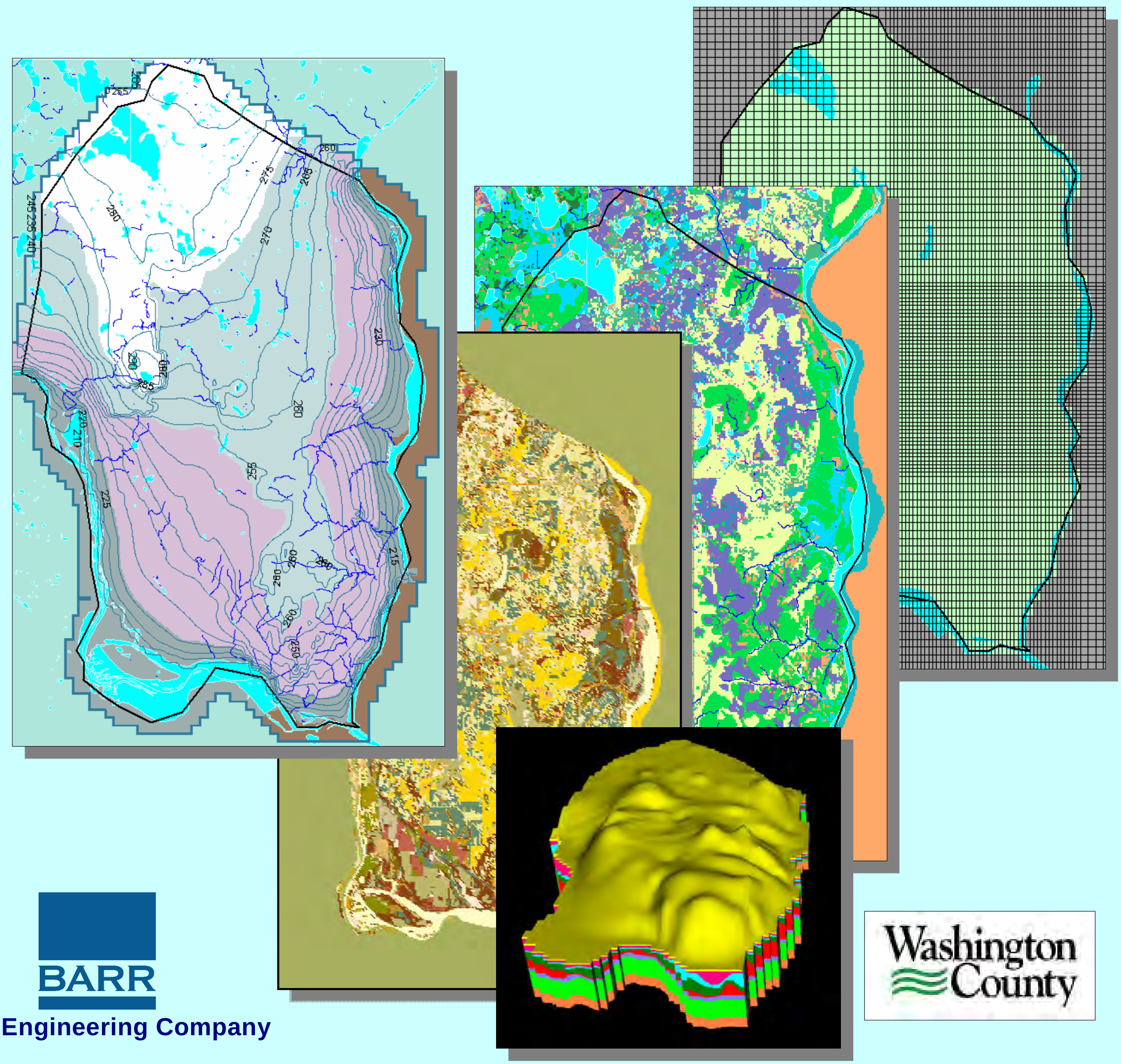
Intercommunity Groundwater Protection:

Sustaining Growth and Natural Resources in the Woodbury/Afton Area

Report on Development of a Groundwater Flow Model of Southern Washington County, Minnesota

June 2005



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Barr Engineering Company

Washington County

Funding for this project was recommended by the Legislative Commission on Minnesota Resources (LCMR) from the Minnesota Environmental and Natural Resources Trust Fund.

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I hereby certify that this report was prepared by me or under my direct supervision and I am a duly Licensed Professional Engineer and Licensed Professional Geologist under the laws of the state of Minnesota.

_________________________ Ray W. Wuolo

Date: June 30, 2005 Reg. No. 19897

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Barr Engineering Company
Washington County

June 2005

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Executive Summary

This report summarizes the construction and use of hydrologic models of southern Washington County, Minnesota, developed through a collective effort of local watershed districts, cities, state agencies, and Washington County. The primary purpose of the project was to develop a predictive tool that can be used to evaluate the "sustainability" of groundwater withdrawals in the Woodbury-Afton area of Washington County. The project was funded over two calendar years, with a start date of January 1, 2004 and a completion data of June 30, 2005. *Funding for this project was recommended by the Legislative Commission on Minnesota Resources (LCMR) from the Minnesota Environmental and Natural Resources Trust Fund. The official LCMR title is "Intercommunity Groundwater Protection 'Sustaining Growth and Natural Resources' in the Woodbury/Afton Area".*

The overall product of this project was a calibrated computer groundwater flow model of the major aquifers in southern Washington County. The groundwater modeling code MODFLOW was used. This groundwater model is a tool to be used to predict the effects of proposed groundwater withdrawals (pumping) on: (1) groundwater levels and pressures; (2) water levels in existing wells; and (3) base flows into Valley Creek (a designated trout stream in southern Washington County). The primary impetus for this groundwater model is to predict the effects of proposed water-supply wells that are planned for the western portion of the City of Woodbury; however, any other groundwater withdrawal in the area can also be evaluated.

Additional products of this project include: GIS files of model parameters and results; a web site with interim products, meeting minutes, and presentations; model input and output files; and this report. The model files are available for use through the Washington County Department of Public Health and Environment.

The groundwater flow model of southern Washington County consists of eight layers that represented, from shallow to deep, the following units: (1) surficial aquifer of glacial deposits; (2) St. Peter Sandstone; (3) Shakopee Formation of the Prairie du Chien Group; (4) Oneota Dolomite of the Prairie du Chien Group (aquitard); (5) Jordan Sandstone; (6) St. Lawrence Formation (aquitard); (7) Upper Franconia Formation; and (8) Ironton-Galesville aquifer. The groundwater model was calibrated to steady-state water levels. A sub-regional model was extracted from the regional model and calibrated to drawdown data collected for the City of Woodbury in 2003 during two pumping tests of newly installed Well 15.

The graphical user interface MIKE SHE was used to simulate hydrologic processes above the water table for the purpose of better estimating the distribution and temporal variability of recharge over the model domain. Factors such as precipitation, seasonal temperature, yearly variations in climate, wind-speed, days of sunlight, soil type, land use, impervious area, topography, crop type, and temperature were included in this MIKE SHE model. The resulting recharge data were incorporated into the MODFLOW model and a re-calibration of the model was performed.

The groundwater flow model was used to predict the future effects of pumping of City of Woodbury wells 15, 16, and 17 on groundwater levels and base flows into Valley Creek. The modeling results suggest that for most pumping conditions, the reduction in the base flow of Valley Creek will likely be too small to accurately measure (i.e. will be in the range of measurement error). The south branch of Valley Creek will most likely be affected. In general, the maximum reduction in base flows will occur in the summer months and will be about 0.5 cubic feet per second, which is about 5 to 15 percent of base flow. Flow from surface runoff would likely further mask this effect.

During extremely dry conditions, such as the simulated condition of August 2018 (which were included in the model to represent very dry conditions similar to 1988), base flows will be lower in Valley Creek (particularly in the south branch) because of climatic conditions and because of regional pumping to meet higher water demands. During this period, higher sustained rates of pumping of Wells 15, 16, and 17 would likely take place (about 2.6 million gallons per day combined for the three wells). Under these conditions, the reduced base flow to the south branch of Valley Creek will likely be about 0.5 cubic feet per second but this reduction might cause the upper portions (about 500 meters) of the south branch to have low or no base flow for a short period, until pumping is reduced and water levels rebound.

These are the best predictions that can be made with the available data and knowledge – as additional information and data are collected, these predictions should be revisited. The model was developed so that interested groundwater scientists and engineers can use the model to evaluate new information.

1 Introduction

1.1 Project Scope and Objectives

This report summarizes the construction and use of hydrologic models of southern Washington County, Minnesota, developed through a collective effort of local watershed districts, cities, state agencies, and Washington County. The primary purpose of the project was to develop a predictive tool that can be used to evaluate the "sustainability" of groundwater withdrawals in the Woodbury-Afton area of Washington County. The project was funded over two calendar years, with a start date of January 1, 2004 and a completion data of June 30, 2005. Funding for this project was recommended by the Legislative Commission on Minnesota Resources (LCMR) from the Minnesota Environmental and Natural Resources Trust Fund. The official LCMR title is "*Intercommunity Groundwater Protection 'Sustaining Growth and Natural Resources' in the Woodbury/Afton Area*".

The overall product of this project is a calibrated computer groundwater flow model of the major aquifers in southern Washington County. This groundwater model is a tool to be used to predict the effects of proposed groundwater withdrawals (pumping) on: (1) groundwater levels and pressures; (2) water levels in existing wells; and (3) base flows into Valley Creek (a designated trout stream in southern Washington County). The primary impetus for this groundwater model is to predict the effects of proposed water-supply wells that are planned for the western portion of the City of Woodbury; however, any other groundwater withdrawal in the area can also be evaluated.

Additional products of this project include: GIS files of model parameters and results; a web site with interim products, meeting minutes, and presentations; model input and output files; and this report. The model files are available for use through the web site or from the Washington County Department of Public Health and Environment.

1.2 Overview of Approach

This project generally consisted of the following elements:

1. A groundwater flow model of southern Washington County was constructed. The finite-difference code MODFLOW (McDonald and Harbaugh, 1988) was used for this purpose. The model was designed in the graphical user interface (GUI) Groundwater Vistas (ver. 4.09 Build 3) (Environmental Simulations, Inc., 2004). The model consisted of eight

computational layers that explicitly represented, from shallow to deep, the following hydrostratigraphic units:

a. surficial aquifer of glacial deposits;

b. St. Peter Sandstone (where present)

c. Shakopee Formation of the Prairie du Chien Group

d. Oneota Dolomite of the Prairie du Chien Group (aquitard);

e. Jordan Sandstone;

f. St. Lawrence Formation (aquitard)

g. Upper Franconia Formation;

h. Ironton-Galesville aquifer.

2. The groundwater model was preliminarily calibrated to steady-state water levels using the automated inverse optimization program PEST2000 (Watermark Numerical Computing, 1999).

3. A sub-regional model was extracted from the regional model using telescoping mesh refinement (TMR) for the purpose of calibrating the model in transient simulations to drawdown data collected for the City of Woodbury in 2003 during two pumping tests of newly installed Well 15. The program PEST2000 was also used in this calibration procedure.

4. The graphical user interface (GUI) MIKE SHE (Danish Hydrologic Institute, 2004) was used to simulate hydrologic processes above the water table for the purpose of better estimating the distribution and temporal variability of recharge over the model domain. The resulting recharge data were incorporated into the MODFLOW model and a re-optimization of the model was performed using PEST2000, with constraints on the recharge parameters in MODFLOW.

5. A number of steady-state and transient versions of the groundwater flow model were developed to predict the future effects of pumping of City of Woodbury wells 15, 16, and 17 on groundwater levels and base flows into Valley Creek.

1.3 Project Organization and Management

This project was managed by Cindy Weckwerth of the Washington County Department of Public Health and Environment, with assistance from Amanda Goebel. Project partners included the Minnesota Department of Natural Resources (MDNR); City of Woodbury, City of Afton, Valley Branch Watershed District, South Washington Watershed District, and Washington Conservation District. These partners developed a Request for Qualifications (RFQ) to select a consultant to develop the groundwater model. A nine-member ranking panel was established to evaluate Statements of Qualifications from invited bidders.

The ranking panel consisted of representatives of the MDNR, Metropolitan Council, Minnesota Geological Survey (MGS), Washington County Department of Public Health and Environment, Washington Conservation District, City of Woodbury, City of Afton, Valley Branch Watershed District, and the South Washington Watershed District. Barr Engineering Company of Minneapolis was selected as the consultant and a contract was entered into that provided for the development of the groundwater modeling products.

Barr Engineering Company's project manager and principal groundwater modeler was Ray Wuolo. He was assisted by hydrogeologist, Tina Pint, surface-water hydrologist, Scott Sobiech, and Valley Branch Watershed District engineer, John Hanson.

1.4 Technical Advisory Committee Meetings

A technical advisory committee (TAC) for this project was established to provide guidance and feedback on the development of the groundwater model and its potential uses. The TAC consisted of representatives of the following organizations:

- Washington County Department . of Public Health and Environment (Cindy Weckwerth and Amanda Goebel)
- Valley Branch Watershed District (John Hanson of Barr Engineering Company)
- South Washington Watershed District (Matt Moore)
- Minnesota Geological Survey (Bob Tipping)
- Science Museum of Minnesota (Jim Almendinger)

- Minnesota Department of Natural Resources (Todd Peterson, Travis Germundson, and Evan Drivas)
- City of Woodbury (Steve Kernik, David Jessup, and Aaron Nelson of City of Woodbury and Mark Janovec of Bonestroo, Rosene, Anderlik & Associates)
- City of Afton (Charlie Devine and Mitch Berg)
- Minnesota Department of Health (Steve Roberston)
- Metropolitan Council (Chris Elvrum)
- Washington Conservation District (Travis Thiel)

Other representatives also attended some TAC meetings.

Scheduled meetings were held at the Washington County Government Center in Stillwater, Minnesota on: January 14, 2004; April 29, 2004; June 15, 2004; September 22, 2004; November 2, 2004; January 20, 2005, and April 15, 2005.

A secure project web site, hosted by Barr Engineering Company (www.barr.com) was established to provide an efficient means of communication and dissemination of data/information. This web site contains meeting minutes/agendas, project work plans, data, interim results, and electronic presentation materials. The web site is to be transferred to Washington County to act as an electronic repository of the model results and files.

1.5 Acknowledgements

Funding for this project was recommended by the Legislative Commission on Minnesota Resources (LCMR) from the Minnesota Environmental and Natural Resources Trust Fund. Material and technical assistance was also provided by the City of Woodbury, the City of Afton, Valley Branch Watershed District, and South Washington Watershed District.

Barr Engineering Company would like to especially thank the following individuals for their assistance on this project: Jim Almendinger of the Science Museum of Minnesota; Chris Elvrum of Metropolitan Council; Bob Tipping of MGS; Todd Peterson of MDNR; Matt Moore of South Washington Watershed District; Greg Eggers of the U.S. Army Corps of Engineers, Travis Thiel of

Washington Conservation District, Mark Janovec of BRA & Associates; Steve Kernik of City of Woodbury; Charlie Devine of City of Afton; and Stu Grubb of EOR, Inc. Extra special thanks goes out to Cindy Weckwerth and Amanda Goebel of Washington County Department of Public Health and Environment for all their planning, facilitation, and encouragement.

2 Hydrology of South Washington County

This section describes the major processes of the hydrologic cycle in southern Washington County and the conceptual models that form the basis for the computer simulations.

2.1 Geologic Setting

Geologic units underneath southern Washington County and throughout the metropolitan area fall into three broad categories: (1) Precambrian volcanic and crystalline rocks; (2) late-Precambrian through Ordovician sedimentary rocks; and (3) Quaternary unconsolidated deposits. The Precambrian volcanic and crystalline rocks generally are not considered major water-bearing units and are at a considerable depth below ground surface in southern Washington County. The late-Precambrian through Ordovician[1] sedimentary rocks make up the major regional aquifers and aquitards[2] in the metropolitan area, and include units such as the Hinckley Sandstone, the Prairie du Chien Group, and the Platteville Limestone. The Quaternary unconsolidated deposits include glacial outwash, glacial till, and alluvial deposits. A hydrostratigraphic column in Figure 1 shows the relationship between geologic units and major aquifers and aquitards in southern Washington County.

2.1.1 Geologic History

Describing how the various geologic units were deposited can be more instructive in placing southern Washington County in a regional hydrogeologic context than simply describing the characteristics of the units. The large-scale hydrogeologic system is far larger than southern Washington County or the seven-county metropolitan area. The extent of the bedrock geologic units is described here in the historical perspective of their depositional origin and subsequent tectonic activity.

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[1] Precambrian and Ordovician are geologic time periods. Precambrian refers to a time about 570 million years ago and older. Ordovician refers to a time about 500 to 440 million years ago.

[2] An aquifer is a portion or combination of geologic units that can transmit usable quantities of water. An aquitard is a portion or combination of geologic units that are of low permeability and generally cannot transmit much water. The term “confining unit” is sometimes used interchangeably with aquitard.

Portions of Iowa, Minnesota, Wisconsin, Illinois, and Missouri were in a depression (called the Ancestral Forest City Basin) covered by a shallow eperic sea in the late-Precambrian (about 570 million years ago). A northern bay of this sea extended over a syncline in the Precambrian Lake Superior Volcanic rocks into southern Minnesota and western Wisconsin. This bay is called the Hollandale Embayment. The Hollandale Embayment extended from north of Hinckley to the Iowa border, deepening to the south. From the late-Precambrian (about 570 million years ago) through the Devonian (about 355 million years ago) the water level in the eperic sea fluctuated causing transgressions (a rising of sea level) and regressions (a dropping of sea level). Depending on the sea level, different sediments were deposited. For example, as the sea level rose, beach sands were deposited (e.g. the Jordan Sandstone), followed by a deeper water environment were carbonate deposits formed from shell-bearing sea animals (e.g. Prairie du Chien Group).

During this depositional process, additional tectonic activity took place, forming a small basin in the Hollandale Embayment, known as the Twin Cities Basin. Faulting of the existing sedimentary rocks took place during the formation of the Twin Cities Basin.

An extended period without significant deposition took place after the Devonian (about 355million years ago), as the seas retreated for the last time. If additional deposition did take place, these rocks have been subsequently eroded away. At the beginning of the Quaternary (about 1.5 million years ago), the great continental ice sheets formed and glaciers moved into the area. The glaciers eroded away all or portions of the upper sedimentary units in many locations. Glacial till deposits were deposited underneath and adjacent to the glaciers. Rivers running from the glaciers deposits sand and gravel (outwash). Ice blocks were left in place to melt as the glaciers retreated. Several glacial advances and retreats took place during the Quaternary.

The glacial rivers incised through the glacial deposits and into the bedrock units as the glaciers retreated. These rivers, and their associated tributaries, changed channel locations upon glacial re-advancement, and subsequent deposits formed buried bedrock valleys. The ancestral Mississippi River and the River Warren (ancestral Minnesota River) incised back into the glacial deposits, forming wide river valleys with alluvial terrace deposits and backwater areas.

2.1.2 Bedrock Stratigraphy

A very general way of looking at the bedrock units in southern Washington County is to imagine a number of layers that are dipping slightly westward, towards Minneapolis and the center of the Twin

Cities Basin. The thickness and textural characteristics of these units can vary from place to place but, in a gross sense, are relatively uniform. A hydrostratigraphic column of the bedrock deposits in southern Washington County is shown on Figure 1. The general characteristics of these units are described below.

1. Mt. Simon Sandstone

The Cambrian Mt. Simon Sandstone is chiefly a coarse, quarztzose sandstone, with the upper one-third containing many thin beds of well-sorted siltstone and very fine sandstone. The lower two-thirds of this unit has few layers of fine-grained sandstone and consists primarily of medium- to coarse-grained sandstone. The basal contact with the Precambrian Solor Church Formation is erosional. The Hinckley Sandstone is also present in southern Washington County but may be difficult to differentiate from the Mt. Simon Sandstone. The upper contact with the Eau Claire Formation is sharp (Mossler and Bloomgren, 1990).

2. Eau Claire Formation

The Cambrian Eau Claire Formation is a siltstone, very fine sandstone, and greenish-gray shale. Some sandstone beds are glauconitic. Minor dolomitic cement is present at the top of the formation. The contact with the overlying Galesville Sandstone is gradational (Mossler and Bloomgren, 1990).

3. Ironton and Galesville Sandstones

The Cambrian Ironton Sandstone and Galesville Sandstone are silty, fine- to coarse-grained, poorly sorted, quartzose sandstone underlain by better sorted, fossiliferous, fine- to medium-grained sandstone. The two units are typically difficult to differentiate. The upper contact between the Galesville Sandstone and the overlying Franconia Formation is sharp (Mossler and Bloomgren, 1990).

4. Franconia Formation

The Cambrian Franconia Formation is composed of thin-bedded, very fine-grained glauconitic sandstone with minor amounts of shale in southern Washington County and displays cross-bedded sandstone features north of Stillwater (Mossler and Bloomgren, 1990).

5. St. Lawrence Formation

The Cambrian St. Lawrence Formation consists of dolomitic shale and siltstone that is generally thin bedded. The contact with the underlying Franconia Formation is gradational. The contact with the overlying Jordan Sandstone is also gradational (Mossler and Bloomgren, 1990).

6. Jordan Sandstone

The upper part of the Cambrian Jordan Sandstone is medium- to coarse-grained, friable, quartzose sandstone that is trough cross-bedded. The lower part of this unit is primarily massively bedded and bioturbated. The upper contact with the overlying Prairie du Chien Group is relatively sharp. The Jordan Sandstone is approximately 60 to 90 feet thick in southern Washington County.

7. Prairie du Chien Group

The Ordovician Prairie du Chien Group contains the Shakopee Formation (upper) and the Oneota Dolomite (lower). The Shakopee Formation is a dolostone that forms approximately one-half to two-thirds of the Prairie du Chien Group and is commonly thin-bedded and sandy or oolitic. The Shakopee Formation contains thin beds of sandstone and chert. The Oneota Dolomite forms approximately one-third to one-half of the Prairie du Chien Group and is commonly massive- to thick-bedded. Both formations are karsted and the upper contact may be rubbly (from pre-aerial exposure). The Prairie du Chien Group is approximately 145-feet thick near St. Paul (Mossler and Bloomgren, 1990).

8. St. Peter Sandstone

The upper one-half to two-thirds of the Ordovician St. Peter Sandstone is fine- to medium-grained quartzose sandstone that generally is massive- to very thick-bedded. The lower part of the St. Peter Sandstone contains multicolored beds of sandstone, siltstone, and shale with interbeds of very coarse sandstone. The base is a major erosional contact. The full section of the St. Peter Sandstone is approximately160 feet thick (Mossler and Bloomgren, 1990). In the western part southern Washington County, the St. Peter Sandstone is present as isolated outcrops, typically capped by the Platteville and Glenwood Formations, which are more resistant to erosion. It is not present in the eastern or far southern portions of southern Washington County.

9. Platteville and Glenwood Formations

The Ordovician Glenwood Formation is a green, sandy shale that overlies the St. Peter Sandstone, where present. The Glenwood Formation ranges in thickness up to 15 feet. The Ordovician Platteville Formation is a fine-grained dolostone and limestone (Mossler and Bloomgren, 1990). Both units are present as isolated "mesas" of limited extent (for example, in the Oakdale area).

2.1.3 Structural Geology and Erosional Limits

The regional dip of the Paleozoic units is toward the west, reflecting the position of southern Washington County on the eastern margin of the Twin Cities Basin. The Twin Cities Basin developed in the Middle Ordovician. The Twin Cities Basin is the result of many small folds and faults in step-wise fashion. The individual folds have a displacement of approximately 100 feet and individual faults have a displacement of 50 to 150 feet.

Faults appear to be much more important structural features in southern Washington County than are folds. One large fold, the Hudson-Afton anticline, is likely better described as a series of northeast-southwest trending normal step faults with displacements of 50 to 150 feet (Mossler, personal communication; Mossler, 2003, unpublished map). Numerous block faults in the southeastern portion of southern Washington County (Denmark Township, north into Afton) were identified by Mossler (2003, unpublished map) during an evaluation of nitrate concentrations in bedrock aquifers (Barr Engineering Co., 2003). The approximate locations of these faults are shown on Figure 2. Total displacement across the fault system from the Mississippi River to the St. Croix River in the Denmark Township-Cottage Grove area is about 250 feet.

Quaternary erosion by glaciers has removed much of the St. Peter Sandstone and younger Paleozoic rocks from southern Washington County, except in the western part of the county. The Prairie du Chien Group and the Jordan Sandstone have been eroded and removed in western Washington County. Directly adjacent to the St. Croix River, the uppermost bedrock is the Ironton-Galesville Formations.

A buried bedrock valley is present, trending north-south from approximately the Lake Jane area to the Cottage Grove 3M facility along the Mississippi River. This bedrock valley is eroded down into the Jordan Sandstone in some locales and had been subsequently filled with glacial deposits. Surface expression of the bedrock valley is evident in southern Washington County as part of the Cottage Grove ravine.

2.1.4 Quaternary History

Continental ice sheets covered southern Washington County and surrounding areas several times over the past 2 million years from two sources in northern Canada, located northwest (Keewatin) and northeast (Labradorean). Keewatin tills were deposited in Washington County first and covered the entire county at one time. After a long period of weathering and erosion, the Labradorean Superior lobe advance during the Illinoian, depositing reddish till and meltwater sediments. Much of these tills have been subsequently eroded.

The dominating glacial activity took place during the Late Wisconinan, beginning with the advancement of the Superior Lobe. Early advance of the Superior Lobe resulted in till deposition and formation of the St. Croix Moraine, followed by retreat, which resulted in outwash deposition. Subsequent re-advancement of the Superior Lobe resulted in deposition of till on top of Superior Lobe outwash. Outwash sand and gravel underlying Woodbury and Cottage Grove was once part of a large, continuous plain across central Dakota County and southern Washington County (Hobbs et al., 1990).

With the retreat of the Superior lobe from the St. Croix Moraine, ice blocks were left behind, which melted and formed lakes in the depressions. Examples of this resulting topography are in the Lake DeMontreville area (Meyer et al., 1990).

The Grantsburg sublobe of the larger Des Moines lobe overrode the St. Croix moraine in northern Washington County but did not materially affect the southern part of the County (Meyer et al., 1990), except for the inclusion of meltwater flow into the St. Croix and Mississippi Rivers. Terrace deposits along the eastern shore of the St. Croix River are likely formed by water flowing from glacial Lake Grantsburg (Meyer et al., 1990).

Glacial Lake Agassiz formed in northern Minnesota, North Dakota, and Canada. Its southern outlet followed the path of the Glacial River Minnesota, but is referred to as the River Warren. The River Warren cut its valley in stages, creating more terraces and alluvial deposition (Hobbs et al., 1990).

As glacial ice sheets retreated from the county, large blocks of ice remained in place and were subsequently covered by outwash sand and gravel. Most of the lakes and bogs in Washington County are in depressions created by the eventual melting of these ice blocks (Meyer et al, 1990).

2.1.5 Quaternary Stratigraphy

The stratigraphy of the glacial and alluvial deposits in southern Washington County is more complex than the bedrock stratigraphy, in part because the depositional and erosional processes responsible for the glacial deposits varied across the county. Abrupt changes in textural characteristics of the sediments are common in glacial materials, resulting in a lateral discontinuity of deposits. Therefore, this discussion of the Quaternary stratigraphy of southern Washington County must be general. A map of surficial geology, developed by the Minnesota Geological Survey, is shown on Figure 3.

The Minnesota Geological Survey developed Arc grids of four major tills in Washington County in a previous study (Figure 4). Most of these tills are in the northern part of the County, in the vicinity of the St. Croix Moraine. In much of southern Washington County, tills are thin or not present. Instead, higher permeability sand and gravel outwash deposits dominate, along with terrace deposits adjacent to the Mississippi and St. Croix Rivers.

2.2 Hydrostratigraphic Units

Hydrostratigraphic units are either aquifers (one or more geologic units capable of transmitting usable quantities of water, dominated by horizontal groundwater flow) or aquitards (one or more geologic units of low permeability, dominated by vertical groundwater flow). Hydrostratigraphic units comprise geologic formations of similar hydrogeologic properties. Several geologic units might be combined into a single hydrostratigraphic unit or a geologic formation may be subdivided into a number of aquifers and aquitards. The "lumping" and "splitting" of geologic units into hydrostratigraphic units is the single most important function of the Conceptual Model. The goal is to simplify the vertical discretization of the aquifer system as much as practical without sacrificing the ability of the computer model to meet the stated purpose and use.

The geologic units that have been selected for the aquifers and aquitards are shown on Figure 1. The Mt. Simon-Hinckley Aquifer is not considered in this evaluation because it is relatively isolated hydraulically from overlying units by the low permeability Eau Claire Formation. The following discussion presents the rationale for the selection of units in this evaluation.

2.2.1 Ironton-Galesville Aquifer

The deepest aquifer considered in this evaluation is the Ironton-Galesville aquifer, which consists of the Ironton Sandstone and the Galesville Sandstone. The Ironton-Galesville aquifer has not been highly utilized because sufficient water supplies can be obtained from shallower units, such as the Prairie du Chien-Jordan aquifer. Recently, the Ironton-Galesville aquifer (along with the Franconia Formation) has undergone greater evaluation by the Minnesota Geological Survey, particularly in western Hennepin County, where the Prairie du Chien-Jordan aquifer is not present.

There are no wells that utilize the Ironton-Galesville aquifer in the western two-thirds of southern Washington County because of the availability of water from shallower aquifers. However, in the Afton area and locations east, the Ironton-Galesville aquifer is the primary source of groundwater.

In deep bedrock conditions, hydraulic conductivity values typically range from 1.5 to 28 feet per day and average about 10 feet/day (based on specific capacity tests). In shallow bedrock conditions, interconnected fracture systems seem to develop, resulting in average hydraulic conductivity values of about 28 feet/day (Runkel et al., 2003).

2.2.2 Franconia Aquifer

The Franconia Formation is often lumped together with Ironton-Galesville Sandstones (as the F-I-G aquifer) or is lumped together with the overlying St. Lawrence Formation as a regional aquitard. After consultation with this project's TAC, it was agreed upon to treat the upper portion of the Franconia Formation as an individual aquifer. The lower portion of the Franconia Formation is a separating confining layer above the Ironton-Galesville aquifer. The major reason for treating the Franconia Formation as a separate aquifer is that it may contribute significantly to the base flow of Valley Creek, where it sub crops below the creek.

2.2.3 St. Lawrence Confining Layer

The St. Lawrence Formation is a regional leaky confining layer (aquitard) that separates the Franconia aquifer from the overlying Prairie du Chien-Jordan aquifer. Runkel et al. (2003) describe the St. Lawrence Formation as having low bulk hydraulic conductivity in the vertical direction and can provide confinement. These confining characteristics are present where the St. Lawrence Formation is relatively deep and overlain by the Jordan Sandstone. However, where the St. Lawrence Formation is at shallow depth, interconnecting fractures make the St. Lawrence Formation a relatively high yielding aquifer. In western Washington County, the St. Lawrence Formation's setting is one most conducive to a confining layer.

2.2.4 Prairie du Chien-Jordan Aquifer

The Prairie du Chien Group and the Jordan Sandstone are typically treated as a single aquifer system in the Twin Cities area; the Prairie du Chien-Jordan Aquifer. The Prairie du Chien-Jordan Aquifer supplies 80 percent of the groundwater pumped in the Twin Cities area, with yields from 85 to 2,765 gpm (Schoenberg, 1990). Groundwater flow in the Jordan Sandstone is primarily intergranular but secondary permeabilities undoubtedly develop due to jointing and differential cementation (Schoenberg, 1990). Groundwater flow in the Prairie du Chien Group is through fractures, joints, and solution features. A small number (perhaps 3 to 5) horizontal fracture zones are responsible for the majority of flow in the Prairie du Chien Group (Runkel et al., 2003).

A tacit modeling assumption that is made when two geologic units are combined into a single aquifer is that there is not a significant head difference between the two units. On a regional basis, this is likely a good assumption; head differences (where available) are relatively insignificant between the two units. However, there is evidence that local differences in head between the two units can develop, especially where pumping is only in the Jordan Sandstone. An example of this phenomenon is in the vicinity of St. Paul Park Well No. 1 and the Marathon Ashland Petroleum Company (formerly Ashland Petroleum) refinery. A pumping and recovery test was performed in the Jordan Sandstone using St. Paul Park Well No. 1 while monitoring at multiple levels in the Prairie du Chien Group and the Jordan Sandstone. A substantial cone of depression developed in the Jordan Sandstone but very little drawdown was observed in the Prairie du Chien Group piezometers (Barr Engineering, 1990). High capacity production wells are also operated in the Jordan Sandstone at the Marathon Ashland refinery with little response in the Prairie du Chien Group. In this area, the two units are distinctly different aquifer systems under hydraulic stresses.

An artificial recharge study on the Prairie du Chien-Jordan Aquifer was conducted by the U.S. Geological Survey in West St. Paul (Reeder, 1976). Reeder (1976) notes that "[a]lthough the Prairie du Chien and the underlying Jordan Sandstone are hydraulically connected, the water levels in the Prairie du Chien wells are at an altitude of 724 feet (221 m) and in the Jordan well at an altitude of 722 feet (220 m)", thus indicating some differences in hydraulic head. During a pumping test in the Prairie du Chien Group, drawdown in the Prairie du Chien Group was noted to be greater than in the Jordan Sandstone. The study indicates that the two units behave differently even though they are hydraulically connected.

Tipping (1992, unpublished MS Thesis) conducted an isotopic and chemical study of groundwater flow in the Prairie du Chien Group and Jordan Sandstone in northern Scott and Dakota Counties. Tipping (1992, unpublished MS Thesis) found that recharge from the Prairie du Chien Group to the Jordan Sandstone was induced, in part, by high capacity pumping in the Jordan (e.g. Apple Valley). In Apple Valley, a sustained vertical gradient between the two units develops. Different isotopic signatures for the two units also manifest themselves in some locations. Tipping (1992, unpublished MS Thesis) notes that the upper member of the Jordan Sandstone (Coon Valley Member) is typically fine-grained, well-cemented, has a lower conductivity than beds above and below it, and may serve locally as an aquitard.

A recent study by Runkel et al. (2003) has demonstrated that the lower portion of the Oneota Dolomite is massive, of low permeability, relatively unfractured, and acts as a regional aquitard that separates the permeable portions of the Prairie du Chien Group (the upper part of the Oneota Dolomite and the Shakopee Formation) from the Jordan Sandstone.

2.2.4.1 Jordan Sandstone

In southern Washington County, some high-capacity wells are completed solely within this unit. The unit is approximately 100 feet thick but may thicken to the south (Bruce Olson, personal communication). The degree of cementation of the Jordan Sandstone varies (Tipping, 1992, unpublished MS thesis). Hydraulic conductivity can vary, depending upon the degree of cementation. Schoenberg (1990) reports a range of horizontal hydraulic conductivity values from 19 to 107 feet/day from field tests.

The Jordan Sandstone subcrops beneath glacial drift and alluvium in major river valleys, which are the primary discharge zones. In these areas, hydraulic head can be expected to be at or slightly above the elevation of the river. Discharge via high-capacity wells is also a significant discharge route. Recharge is primarily through leakage from the overlying Prairie du Chien Group. Flow in the Jordan Sandstone radiates east, west, and south from a groundwater divide that trends north-south and roughly bisects southern Washington County.

2.2.4.2 Basal Oneota Dolomite

The basal Oneota Dolomite is a regional confining layer (aquitard) in southern Washington County and throughout southeastern Minnesota (Runkel et al., 2003). The confining unit is about 40 feet thick and consists of massive, relatively unfractured dolomite. Packer tests performed by the

Minnesota Geological Survey suggested that the unfractured portions of the basal Oneota Dolomite may have hydraulic conductivity values as low as 10^{-4} feet/day (Robert Tipping, personal communication). There is some fracturing that cuts through the basal Oneota Dolomite – this fracturing provides the means for leakage between the Jordan Sandstone, below, and the Shakopee Formation of the Prairie du Chien Group, above.

The level of hydraulic communication between the Jordan Sandstone and the Shakopee Formation can only be tested with pumping tests using wells completed only within the Jordan Sandstone. A small number of such tests have been performed (e.g., at St. Paul Park, Burnsville, Savage, and Woodbury (Bonestroo Rosene Anderlik and Assoc., 2004)). The results of these tests indicate a relatively uniform leakage resistance – typically 2,000 to 6,000 days.

2.2.4.3 Shakopee Formation

Along with the Oneota Dolomite, the Shakopee Formation makes up the Prairie du Chien Group. The areal extent of the Prairie du Chien Group is similar to that of the underlying Jordan Sandstone. Horizontal hydraulic conductivity values are in the same range as those of the Jordan Sandstone.

Flow in the Prairie du Chien Group is dominated by 3 to 5 relatively thin (5 to 10 feet) zones of highly connected horizontal fractures in the Shakopee Formation and the upper part of the Oneota Dolomite (Runkel et al, 2003). Horizontal hydraulic conductivity values within these thin zones can exceed 1,000 feet/day. Between these fracture zones, the hydraulic conductivity is much lower. At a very local scale, these horizontal zones of high flow may not be well connected but regional fractures and joints provide good connection on a more regional basis. This allows the upper part of the Prairie du Chien Group to be treated as a single aquifer system.

Unlike deeper hydrostratigraphic units, the Prairie du Chien Group can be unconfined. Where the drift is thin or absent, the water table resides in the Prairie du Chien Group. Recharge is primarily through leakage from the overlying glacial drift and the St. Peter Sandstone, where it is present. Some additional recharge enters the aquifer in northwestern southern Washington County as underflow from the unconsolidated sediments that abut the subcrop area of the aquifer. Discharge is to the glacial drift in the valleys of major rivers.

2.2.5 St. Peter-Basal Till Aquitard and St. Peter Sandstone Aquifer

The upper part of the St. Peter Sandstone is poorly cemented, granular, and may be used to supply domestic wells. The lower portion of the St. Peter Sandstone is shaley and functions as an aquitard over the Prairie du Chien Group (Palen, 1990). The St. Peter Sandstone has been eroded away over much of central, southern, and eastern Washington County and is present in complete thickness only where overlain by the Glenwood and Platteville Formations.

In those areas where the St. Peter Sandstone is not present, glacial drift or no units overlie the Prairie du Chien Group. In these areas, the St. Peter-Basal Till Aquitard is composed of glacial till or other glacial drift of varying degrees of leakage resistance.

2.2.6 Glacial Drift Aquifer

Glacially deposited sediment can be very complex and unpredictable. The modeling of discrete zones of saturation is typically not possible, given the limited amount of reliable data on stratigraphy, hydraulic characteristics, and hydraulic head. In many areas, the existing data will likely be sparse or so complex that the entire thickness of glacial deposits can only be treated as a single aquifer.

At a given location, the Glacial Drift aquifer may contain several interfingering sand-gravel layers with till; however, these discrete zones may not be correlatable over an extended area. The transmissive sediments are therefore considered part of the same aquifer system and are assumed to be hydraulically connected. In some locations where the upper St. Peter Sandstone is present, it may be included as part of the Glacial Drift aquifer. However, in much of southern Washington County, the saturated portion of the glacial drift is primarily outwash sand and gravel deposits.

The Glacial Drift aquifer is in relatively good connection with local streams and lakes. Recharge is primarily by infiltrating precipitation. Discharge is to streams, lakes, and leakage to underlying aquifers.

2.3 Hydrogeologic Conceptual Model

The *hydrogeologic conceptual model* is a schematic description of how water enters, flows, and leaves the groundwater system. Its purpose is to define the major sources and sinks of water, the division or lumping of hydrostratigraphic units into aquifers and aquitards, the direction of groundwater flow, the interflow of groundwater between aquifers, and the interflow of water between surface waters and groundwater. The hydrogeologic conceptual model is both scale-dependent (i.e.

local conditions may not be identical to regional conditions) and dependent upon the questions being asked. In the case of this evaluation, the conceptual hydrogeologic model encompasses a more regional view (a portion of southern Washington County) and the questions being asked deal with the extraction of groundwater from the Prairie du Chien-Jordan aquifer and the effects of extraction on Valley Creek.

The conceptual hydrogeologic model is depicted on Figure 5, showing the general groundwater flow directions and regional contributions.

The bedrock aquifers are present over a very large area (the Hollandale Embayment) and flow in these aquifers is affected by large-scale, regional features. The Mt. Simon-Hinckley aquifer does not outcrop or subcrop beneath glacial drift in southern Washington County. Consequently, this unit is not in direct hydraulic connection with rivers, lakes, or streams that control the piezometric surface (Delin and Woodward, 1984). Furthermore, the hydraulic connection between the Mt. Simon-Hinckley aquifer and the overlying Ironton-Galesville aquifer is poor in the metro area (Palen, 1990). Its poor connection with overlying aquifers indicates that the Mt. Simon-Hinckley aquifer can be excluded from this evaluation.

2.3.1 Groundwater Flow Directions

Groundwater flows from zones of high piezometric head to low piezometric head. Contour maps of piezometric head have been developed by the Minnesota Geological Survey using water levels for wells in the County Well Index and are presented in Kanivetsky and Cleland (1990).

2.3.1.1 Franconia Aquifer and Ironton-Galesville Aquifer

Groundwater flow in the Franconia aquifer and in the Ironton-Galesville is toward the Mississippi River on the west side of southern Washington County and to the St. Croix River on the east side of the County. A groundwater divide trending approximately north-south is inferred to extend through the center of the County. Unlike the Mt. Simon-Hinckley aquifer, flow in the Franconia aquifer and the Ironton-Galesville aquifer does appear to be significantly influenced by the Mississippi, Minnesota, and St. Croix Rivers in the metro area. The hydraulic head distribution suggests that the Mississippi and St. Croix Rivers are regional discharge zones for the aquifer, which takes place as upward leakage in response to a lowering of hydraulic head in the overlying aquifers. Along the St. Croix River, the Franconia and Ironton-Galesville aquifers are the first bedrock units and likely discharge directly into the St. Croix River and the small tributaries that are incised into the bedrock near the St. Croix River. Along Valley Creek, these units subcrop and likely contribute to the base flow of Valley Creek.

2.3.1.2 Prairie du Chien-Jordan Aquifer

The Prairie du Chien-Jordan aquifer system is heavily influenced by the Mississippi and St. Croix Rivers, which are major discharge zones. Groundwater flow is toward the Mississippi River on the west side of southern Washington County and to the St. Croix River on the east side of the County. A groundwater divide trending approximately north-south is inferred to extend through the center of the County. In southern Washington County, groundwater flow in the Prairie du Chien Group is typically influenced by secondary streams (e.g., Valley Creek).

In eastern Washington County, Quaternary and pre-Quaternary erosion has removed the Prairie du Chien Group and the Jordan Sandstone. Elsewhere, the Prairie du Chien-Jordan aquifer is recharged by downward leakage from overlying units (e.g., the upper St. Peter Sandstone and the unconsolidated surficial aquifer) through the intervening confining units (e.g., the lower St. Peter Sandstone and till layers in the unconsolidated surficial aquifer).

2.3.2 Infiltration

The predominant source of water for the aquifer units in southern Washington County is infiltrating precipitation. Infiltration of direct precipitation is dependent upon the rate and duration of precipitation, the soil type and soil cover, land use, evapotranspiration, and topography. In a steady-state model, the resulting infiltration rate is typically estimated on an annual basis - although seasonal estimates are sometimes utilized.

Traditionally, average values of infiltration have been estimated through the relationship between the transmissivity of an aquifer, the rate of infiltration, and the resulting piezometric head distribution. Transmissivity can be measured or reliably estimated from a number of sources, including pumping aquifer tests and the head distribution is reliably known from the many water-level measurements obtained from wells in the County - these data are listed in the County Well Index. However, a groundwater flow model is required in order to reliably calculate the rate of infiltration. This process of “backing into” infiltration values by fixing the values of transmissivity and matching the simulated heads is called the “inverse method”.

Various numbers have been used for average infiltration in the Twin Cities area. Norvich et al. (1974) estimated that this rate is between 4 and 10 inches per year. Precipitation in the metro area averages between 26 and 32 inches per year, of which 7 to 9 inches per year are available for recharge and overland runoff (Schoenberg, 1990). Schoenberg (1990) estimated that the annual groundwater flow to streams is 1.60 to 4.30 inches of precipitation per year, with an average of 4.07 inches per year. Assuming that long-term groundwater recharge is approximately equal to long-term groundwater discharge to streams (Schoenberg, 1990), annual recharge from precipitation is approximately 1.5 to 4.5 inches per year.

Increased urban development generally results in increased impervious areas, due to buildings and pavement. In many areas of southern Washington County, development is progressing and increased impervious area can be anticipated.

Initial impression would suggest that increases in impervious area would result in decreases in the infiltration rate to groundwater. However, increased impervious area due to development does not equate to decreases in infiltration. The reason for this appears to be that precipitation, after falling on roofs and pavement, is routed to stormwater retention and detention basins where infiltration takes place. The infiltration rates in detention basins tend to be higher than in upland areas because stormwater accumulates, increasing the moisture content in the vadose zone (which increases the unsaturated hydraulic conductivity) and provides a driving head for rapid downward percolation. Also, with increased impervious area, evapotranspiration rates decrease (because of less broad-leaf plants) and soil moisture is used up at slower rates by plant respiration.

A final factor to consider is irrigation – particularly lawn irrigation. During the summer, lawn irrigation is high, which greatly augments the natural recharge rates with water that would otherwise not be available. Evaporation and transpiration losses during this period are high, but excessive lawn watering, beyond the needs of grass, is a widely known practice.

In order to obtain an estimate of the distribution of infiltration, both spatially and temporally, MIKE SHE was employed for this study to obtain deterministic estimates of infiltration rates, independent of the inverse method used in groundwater modeling – this is discussed in subsequent sections.

2.3.3 Regional Discharge

The regional water balance can be estimated, in part, on the basis of groundwater inflows to streams (regional discharge zones). The source of this water enters the aquifer system through infiltrating precipitation for an entire groundwater basin. Groundwater inflows into smaller streams can be estimated from stream-flow gauging records. Base-flow conditions (i.e. the groundwater component of stream flow) typically accounts for most of the flow during the winter months, when runoff is small. On an annual average, approximately 15 to 25 percent of total flow in streams results from groundwater discharge into the streams (Schoenberg, 1990).

In southern Washington County, groundwater flows toward the major discharge zones of the Mississippi and St. Croix Rivers. Local discharge to the gaining portions of smaller streams and tributaries can take place within the surficial aquifers but the effects of these water bodies become negligible with depth.

Various attempts have been made to estimate groundwater inflows into the large rivers in the Twin Cities by detailed gauging of river flows. The most recent efforts were performed by the U.S. Geological Survey, which used sophisticated Doppler measurement techniques to calculate flows in the rivers at several cross sections. In principle, by subtracting the stream flows measured at an upstream section from the stream flows measured at a downstream section (and assuming no tributary inflows), the difference in stream flow should be attributable to base flow from groundwater. In smaller streams, this technique works reasonably well but in large streams, such as the Minnesota and Mississippi Rivers, the error in the measurement is nearly equal to the calculated groundwater inflows – rendering the calculated base flows highly suspect.

The other major source of groundwater discharge in southern Washington County is from wells. Most of the communities in southern Washington County obtain their water supply from high capacity wells. High capacity wells in Washington County are shown on Figure 6.

3 Hydrologic Models

Two hydrologic modeling “packages” were employed in this study. Saturated (i.e. groundwater) simulations were performed using MODFLOW (McDonald and Harbaugh, 1988), using the graphical user interface (GUI) Groundwater Vistas (Environmental Simulations, Inc., 2004). Surface hydrologic processes were modeled using MIKE SHE (Danish Hydrologic Institute, 2004). Surface hydrologic processes included: precipitation; evaporation; transpiration; overland flow (runoff); storage of precipitation in depressions and as snow; and flow/storage in the unsaturated zone.

3.1 MODFLOW

MODFLOW simulates three-dimensional, steady-state and transient groundwater flow (saturated) using finite-difference approximations of the differential equation of groundwater flow:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

where:

K_{xx}, K_{yy}, and K_{zz}: three principal directions of the hydraulic conductivity tensor

W: sources and sinks

S_s: specific storage

h: hydraulic head

t: time

For steady-state simulations, the partial derivative of head with respect to time is zero and the right side of Laplace’s equation, above, equals zero.

MODFLOW was developed by the U.S. Geological Survey and is in the public domain. It is widely used and accepted. The version used in the study is a modified version of MODFLOW-96. These modifications from the standard version of MODFLOW-96 are as follows:

1. The VCONT parameter for the computation of leakance between model layers is computed automatically from values of vertical hydraulic conductivity, which are stored in a separate

array (Environmental Simulations, Inc., 2004). Leakance for the uppermost saturated layer can vary as a function of saturated thickness of the unconfined layer).

2. A modification that prevents cells from becoming dry was implement by Environmental Simulations, Inc. (2004) using the methodology developed by John Doherty (developer of PEST). This modification, sets the transmissivity of a “drying” cell as a very small value (10^{-20} m/d) and sets the saturated thickness at 0.1 m. These modification has been found to be superior to the resaturation routine employed in MODFLOW’s BCF3 package because it provides for far greater computational stability and reproducibility of results. The nature of the vertical discretization employed in the model required the use of this modification. The model will not give correct results unless this modification is employed.

The model must be run using an Environmental Simulations, Inc. (2004) version of MODFLOW-96 that employs the modifications described above and solves MODFLOW in double precision. This program is provided with files for this project.

3.2 Groundwater Vistas

The MODFLOW model was developed using the GUI Groundwater Vistas (ver. 4.09 Build 3) (Environmental Simulations, Inc., 2004). Most model input parameters can be imported into Groundwater Vistas as ESRI shapefiles.

3.3 PEST

The MODFLOW model was “calibrated” through a series of automated inverse optimization procedures using the model-independent parameter estimation software PEST2000 (Watermark Numerical Computing, 1999). Automated inverse optimization is a method for minimizing the difference between simulated results and observations (the “residual” or “objective function”) in a least-squares sense by numerically solving for the derivative (and hence, the minimum) of this objective function.

Using PEST involved making some choices on which parameters (e.g., hydraulic conductivity zones, recharge zones, etc.) would be allowed to vary, the maximum and minimum values in which the parameters’ values could be varied, and initial estimates for the parameters’ values. PEST is not employed until traditional trial-and-error methods have resulted in a reasonable (but not calibrated) modeling result.

Model results (and hence, model calibration) are more sensitive to some parameters than others. Also, some parameters are more highly correlated with other parameters. Judgment and experience are required in selecting the parameters for optimization.

3.4 MIKE SHE

MIKE SHE is a graphical user interface/modeling environment that groups together and couples models of several different hydrologic processes (Danish Hydrologic Institute, 2004). Many processes of water flow can be simulated in MIKE SHE, including saturated groundwater flow. For this study, we opted to utilize MODFLOW for simulating groundwater flow and MIKE SHE for simulating the surface-hydrology processes that interact with MODFLOW. The primary use of MIKE SHE was to obtain deterministic, time-varying, distributed parameter values of recharge.

The following processes were simulated using MIKE SHE: precipitation; storage and melting of precipitation as snow (temperature dependent); direct evaporation; canopy storage on vegetation; soil evaporation; transpiration; topographically controlled runoff (overland flow); storage in depressions too small to be accounted for by topographic data; flow into channel features (such as stream channels); and unsaturated flow between ground surface and the water table. MIKE SHE is capable of simulating other processes (namely channel flow through the program MIKE 11) which were not used in this study.

Unsaturated flow simulation warrants additional discussions here. There are three ways that MIKE SHE can simulate unsaturated flow (which is assumed to be vertical): gravity flow, two-layer water balance method, and using Richards Equation. Both Richards Equation and the gravity-flow method use soil profiles that can have different soil/soil properties with depth. The Richards Equation method was used in this study because it employed the most robust approach of the three methods to computing unsaturated flow.

Richards Equation is expressed as follows:

$$\frac{d\theta}{dt} = \frac{d}{dx} K \left(\frac{d\Psi}{dx} + \frac{dz}{dx} \right) + S$$

where:

Θ: volumetric moisture content, which changes over time as a function of Ψ

Ψ: the matric potential, which is a function of soil type

K: hydraulic conductivity, which also changes with matric potential

S: the input or output of water from the soil (e.g., infiltration, ET)

The Richards Equation is very non-linear, meaning that several variables depend upon one another. Consequently, it can be difficult to solve unless some approximations are made. The primary approximation used in MIKE SHE is to develop relationships between K, Ψ, and Θ using the van Genuchten (1980) approximations.

Even with simplification, the Richards Equation takes considerable computation time and capabilities to solve because the numerical approximations require extensive vertical discretization and because soil properties vary from place to place. MIKE SHE utilizes a method that solves for the Richards Equation at a subset of grid locations that are representative of all of the conditions in the model domain and then applies the results of the simulations to grids of like conditions. Similarities in conditions include: depth to the water table, latent soil moisture content, and soil profile.

4 MODFLOW Groundwater Flow Model

This section describes the construction and calibration of the final groundwater flow model. The methodologies and simulation techniques for estimating recharge using MIKE SHE are described in a subsequent section.

4.1 Model Domain

The model domain (extent of coverage of the model) is shown on Figure 7. The primary area of interest for this study is also shown on Figure 7 and includes the Woodbury-Afton area. However, the model does have application outside of the primary area of interest.

The model domain was selected in order to include the primary discharge zones (the Mississippi and St. Croix Rivers) and to extend sufficiently far north in order for the simulation of pumping in the Woodbury and Afton areas to not be adversely influenced by artificial model boundaries. The northern extent of the model domain encompasses White Bear Lake; a water body that is likely in direct hydraulic connection with major aquifers.

4.2 Horizontal Discretization

The model domain must be subdivided into rectilinear grid cells in order to solve the finite-difference approximations. The regional discretization is shown on Figure 8, although for some simulations, there is further refinement in the area of the proposed Woodbury well filed. The regional mode consists of 111 rows, 80 columns, eight layers, 71,040 total cells, and 52,344 active cells. The maximum grid cell size is 500 by 500 meters. There is no grid rotation with respect to north. Length dimensions are in meters and site coordinates are in UTM NAD 83, Zone 15. The origin offset X coordinate is 493, 796 meters (UTM) and the origin offset Y coordinate is 4,953,660 meters (UTM).

4.3 Vertical Discretization

The model is divided into eight computation layers that are generally assigned to the hydrostratigraphic units shown on Figure 1. Figure 9 shows approximately how the computational layer assignments change from west to east across the model domain.

4.4 Boundary Conditions

Boundary conditions are shown on Figure 7.

4.4.1 Constant-Head (CH) Boundaries

The western and southern boundaries of the model are constant-head (CH) cells that represent the Mississippi River. The eastern boundary consists of CH cells that represent the St. Croix River. Stage elevations (in meters, MSL) were determined from USGS quadrangle maps of the area and include abrupt stage elevations due to lock and dam structures. These boundaries apply only to Layer 1. Constant-head boundaries for Layer 1 are shown on Figure 10.

White Bear Lake, Lake Elmo, Lake Demontreville/Lake Jane, and Lake Phalen are represented as CH boundaries, with stage elevations (in meters, MSL), determined from USGS quadrangle maps. These lakes were assigned as CH cells in Layer 1 because they were deemed to be sufficiently deep to be in direct hydraulic connection with the water table. Portions of Lake Elmo extend down into Layer 2 (due to its depth) but the other lakes are confined to Layer 1.

4.4.2 No-Flow Boundaries

All model edges in MODFLOW are no-flow boundaries. Areas outside of the model domain but within the finite-difference grid were assigned as no-flow boundary cells and were not a part of the computation process. The northwest and northeast portions of the model domain were set as no-flow boundaries. The orientation of these boundaries are perpendicular to the contours of regional groundwater flow as defined in both the MPCA's Metro Model (Hansen and Seaberg, 2000) and the MODFLOW Source-Water Protection model developed for the Minnesota Department of Health (Barr, 2000).

These boundaries are not physical boundaries, but rather hydrologic boundaries. In a laterally isotropic flow field, there is no flow parallel to potentiometric contours; thus, the assignment of this boundary as a no-flow boundary. Constant-head cells could also have been used to define this boundary with similar results.

4.5 River and Drain Package Features

Major tributaries to the Mississippi and St. Croix Rivers were simulated either with MODFLOW's river package or, in the case of Valley Creek, with MODFLOW's drain package. The river and drain packages both require data on river stage (meters, MSL), river bottom elevation (meters, MSL), and river-bed conductance. The primary difference between the drain package and the river package is that if the water table falls below the bottom of a drain cells, there will not be a component of flow from the river to the water table, whereas there will be continued leakage with a river cell.

River and drain features are in Layer 1 only. They are shown on Figure 11.

4.6 High-Capacity Wells

Pumping wells included in the model were those wells with appropriations data listed in the MDNR SWUDS database for 2003. These are shown on Figure 12. For average year or "typical" steady-state simulations, the average annual pumping rate was used (cubic meters per day).

Wells were assigned to the various model layers using well log information (reported in the County Well Index). Some wells spanned more than one layer. For these wells, Groundwater Vistas partitions the pumping rates among the various layers in proportion to the layers' transmissivities. All wells are included in Groundwater Vistas as "analytic wells" – Groundwater Vistas has an internal method for translating these wells to MODFLOW format.

4.7 Base Elevations of Layers

Base elevations of layers vary spatially and generally conform to the stratigraphic base elevations of geologic units (particularly on the east and central portions of the model domain). The bottom of the model (base of Layer 8) represents the base of the Ironton-Galesville Sandstones. ESRI grid data of elevations of bedrock units (UTM NAD83, in meters above mean sea level) were developed and provided by the Minnesota Geological Survey.

Because of faulting on the eastern part of the model domain, computational layers thin and represent different hydrostratigraphic units on the east, compared to the west portions of the model (see Figure 9 for an illustration). Extensive evaluations of grids and shapefiles for bedrock units were performed in order to determine which hydrostratigraphic unit correlated with which computational layer in areas along the eastern margin of Washington County. In addition, a minimum layer thickness of 5 meters was maintained as a precaution toward maintaining computational stability.

The resulting zonations of major hydrostratigraphic units for Layers 1 to 4 are shown on Figure 13 and for Layers 5 to 8, on Figure 14. Final base elevations (meters, MSL) for all eight layers are shown on Figures 15 and 16.

The top elevation of a layer is automatically assigned at the same elevation as the bottom elevation of the layer above. The exception to this is Layer 1, which has a top elevation distribution assigned to it (see Figure 17). This top elevation was established at about 5 meters above the regional water table to maintain unconfined conditions. Top elevation assignments are typically only necessary for solute transport simulations – they are provided in the event that future model usage may employ solute transport simulations.

4.8 Hydraulic Conductivity Values

Hydraulic conductivity values (expressed in meters per day) are assigned to model layers in zones of vertical and horizontal hydraulic conductivity. These zones were assigned and modified during the course of the project to account for new information and to increase the efficacy of the optimization/calibration process. Groundwater Vistas uses vertical hydraulic conductivity values to calculate the VCONT parameter that is used to assign leakance values in MODFLOW. VCONT and leakance parameters are not manipulated directly in this study.

The process of arriving at the final horizontal and vertical hydraulic conductivity values is discussed in the section of this report that addresses model calibration and optimization. The optimized values are shown for the various layers on Figures 18 through 25.

Zones of equal values of hydraulic conductivity were initially assigned on the basis of hydrostratigraphic units. For example, those zones that represented the Jordan Sandstone were originally assigned the same value of horizontal and vertical hydraulic conductivity values throughout the model domain (values were assigned based on experience using regional models in other parts of the metro area). As the optimization process proceeded, zones were subdivided to provide greater flexibility in matching simulated and observed hydraulic head conditions. For example, new zones were assigned to faulted areas or where bedrock units were subaerally exposed and potentially subjected to greater fracturing and secondary permeability formation.

An alternative approach to assigning zones would have been to use the pilot-point approach in PEST ASP (Watermark Numerical Computing, 2001). The pilot-point approach allows for the “regularization” of the hydraulic conductivity field, whereby hydraulic conductivity values at points (called “pilot-points”) are adjusted and a geostatistical gradient between the points is established to populate model grid cells without pilot points. The result is a model in which each grid cell has slightly different values of hydraulic conductivity than its neighbors. This is generally an acceptable approach and often produces a better calibration than the zonation approach. However, we chose not to use the pilot-point approach in this study because zones of equal values were deemed conceptually more defensible and understandable. The likely differences between the two approaches are small.

4.9 Recharge

Recharge is precipitation that infiltrates to the water table. Most of the water in the model is derived from recharge (78 %) – the other 22 % comes from leakage through the bottoms of lakes and streams. Thus, obtaining reliable values of recharge (and the areal distribution of recharge) was critical to this study. Recharge values for the MODFLOW model, which are dependent on many hydrologic and climatic processes, were obtained through simulations using MIKE SHE and are discussed in a subsequent section. In this section, the resulting recharge conditions for MODFLOW are presented.

Recharge values generally vary from one grid cell to the next. MIKE SHE simulations produced annually averaged recharge values for “typical conditions” (Figure 26) and dry conditions (1988, shown on Figure 27). The aerially averaged recharge values for the typical year and the dry conditions are 8.7 and 6.7 inches per year, respectively.

Monthly average recharge values were also computed by MIKE SHE for inclusion in MODFLOW. The period of coverage of these monthly computed values generally is between 1988 and 2002.

4.10 Solvers and Convergence Criteria

The PCG2 Solver (Hill, 1990) was used exclusively in this study. Maximum outer iterations were typically 10 to 25. Maximum inner iterations were typically 30 to 50. Head convergence criterion was set to 0.001. Flow convergence criterion for steady-state simulations was 2 and for transient simulations was 0.001. Mass balance errors were typically in the range of 10^{-5} percent. The PCG2 solver occasionally does not converge even though all convergence criteria are met – if the convergence criteria were met over three successive outer iterations, convergence was deemed to be met.

4.11 Dry-Cell Correction Modification to MODFLOW

Drying and rewetting of cells in MODFLOW is problematic. Attempts, such as the wet-dry option in the BCF3 package of MODFLOW have been used to attempt to address this problem, with varying degrees of success. In this study, a modification to the MODFLOW code was implemented by John Doherty of Watermark Numerical Computing for Groundwater Vistas in which no cell is permitted to dry out. This approach has proven to be much more stable than other approaches and produces very reliable results with much vaster convergence times. This characteristic is especially important in automated inverse optimization.

In brief, cells inadvertently dry up during the iteration process as trial heads “overshoot” the base elevation of a particular layer at some locations. With BCF2, this layer would become permanently dry. With BCF3, rewetting would be initiated, often with unstable results. Doherty’s implementation sets the transmissivity of a cell at a very low value (but not dry) if the computed head in a cell reaches some minimum value above the cell’s base. In essence, the cell acts like a dry cell (or more appropriately, as a perched cell) and does not contribute meaningfully to flow, leakage, or to storage (in transient solutions).

There are several optional variables in the implementation of the dry-cell correction. These were as follows:

- dry cell implementation took place when the simulated hydraulic head was 0.1 meters above the base
- the transmissivity of the dry cell was set to 1×10^{-20} m^2/d
- for transient simulations, the storage was set to 0.2. It was found that model results became erratic at much lower storage values.

The implementation of the dry-cell correction requires that the MODFLOW-96 code MF96WIN32.dll be used as the executable code (ESI, 2004). This is a Windows code, rather than a DOS code and there is not a DOS equivalent. Therefore, to run this model in DOS mode (such as in a batch file), the following command must be used in place of modflow <modflow.in

wmod96 c:\gwv4\tutorial\work\test.m96 /r /p3 /c /t /e

Where "test" is the MODFLOW root file name. The path can be different.

It is important to recognize that <u>this model cannot be executed without using the above executable code</u> (provided on the CD). Trying to import the files into another GUI will not work unless it can access this executable.

4.12 Storage

Storage values are required for all transient simulations but not for steady-state simulations. The confined aquifer storage parameter (applicable to all layers) is the storage coefficient (not specific storage). This value was obtained during transient calibration of the model (discussed in subsequent sections) and is set at 2.0969394e-005. Specific yield for unconfined aquifers is 0.2. If the user is going to transform a steady-state model into a transient model, it is important to make sure that these values are entered in correctly (i.e. do not assume that a steady-state model has the correct values).

4.13 Overview of Calibration/Optimization Process

The calibration (hereafter referred to as "optimization") process employed in this study is schematically illustrated as a flow chart on Figure 28. The overall process was as follows:

1. The regional model was constructed, with some grid refinement in the area of the Woodbury well field. Zones were delineated and assigned initial best guesses for parameter values. A single regional value for infiltration was used as an initial guess.

2. Calibration targets for optimizing the regional model were established.

3. Parameters whose values were allowed to vary during the optimization process were chosen, along with the range of allowable variation. PEST was used to optimize the model.

4. The results of the PEST optimization were evaluated and changes were made to the model. Changes could include additional zonation of some parameters.

5. Steps 3 and 4 were repeated numerous times to improve the optimization.

6. A sub-regional model was extracted from the regional model using Telescoping Mesh Refinement (TMR) processes. The sub-regional area included Valley Creek and the Woodbury Well 15 pumping test.

7. Transient simulations were set up using the TMR model and transient calibration targets were identified.

8. Several optimizations were performed using PEST and the TMR model until satisfactory results were obtained.

9. Parameter values from the TMR optimization were incorporated back into the regional model and the regional model was re-optimized further, with constraints placed on some values, based on the TMR optimization.

10. MIKE SHE was used to calculate time-dependent recharge values using surface hydrologic processes, as well as annually averaged values for typical and dry conditions.

11. The MIKE SHE-derived recharge values for typical annualized conditions were entered into the regional MODFLOW model. Recharge was removed as one of the optimization parameters.

12. The regional model was re-optimized a final time using PEST and the recharge values from MIKE SHE.

Because of the iterative nature of the optimization process, only the final parameter values and the resulting solutions will be addressed (with the exception of the TMR optimization, which will be discussed separately).

4.14 Telescoping Mesh Refinement (TMR) Sub-Regional Model

Telescoping Mesh Refinement (TMR) is the process of constructing a new flow model from a portion of a regional model by extracting both parameter values and a regional model solution. The boundary conditions of this sub-regional model (which is rectangular in shape) are set from the regional head conditions (and are typically head-specified features). The new model covers a smaller area and can be re-discretized. The purpose of using a TMR approach is to be able to perform detailed simulations of a small area in a very computationally efficient manner without sacrificing the effects of the regional flow field.

The area of the TMR extraction is shown on Figure 29 and the re-discretized TMR model mesh is shown on Figure 30. Also shown on Figure 30 are the constant head boundaries that were automatically extracted by Groundwater Vistas from the regional head solution. It is important to note that testing was performed with the TMR model to ensure that the flows into and out of the model from these boundaries did not change significantly during the simulation of the pumping test.

4.15 Regional Steady-State Optimization

4.15.1 Calibration Targets

Calibration targets for the optimization of the steady-state regional model are all groundwater level measurements from wells, in meters above mean sea level. A total of 1,132 equally weighted (weight = 1) head targets were included. For hydrostratigraphic units above the St. Lawrence Formation, calibration target sets developed by the MPCA for the Metro Model (Hanson and Seaberg, 2000) were used (these data had undergone extensive cross-validation checks by MPCA). Deeper units, including the Franconia Formation (Layers 6 and 7) and the Ironton-Galesville Sandstones (Layer 8), did not have MPCA Metro Model data sets. For these units, County Well Index (CWI) data were used. Sources of calibration targets are shown on Figure 31.

Several of the calibration targets penetrate multiple model layers. A weighted average was used to determine the model's solution for comparison in the optimization process (this is automatically generated by Groundwater Vistas when performing a PEST optimization run). The top layer and bottom layer of all steady-state regional calibration targets are shown on Figure 32.

The majority of head targets for the Prairie du Chien-Jordan units are located in the west and central portions of the model domain, where these units constitute the primary water supply for high-capacity and domestic wells. In this area (western and central portions of southern Washington County) there are no head targets for the Franconia Formation and deeper units because those seeking a reliable water supply need not drill this deep. Consequently, there is an inherent bias in the distribution of targets which leads to some unavoidable uncertainty.

Target head values generally represent water levels measured by drilling contractors during the time of well installation. Sources of error in these targets include the following:

- Inaccuracy of water level measurement – drilling contractors (especially for wells drilled decades ago) may not have used precise measuring devices.

- Inaccuracy in well location – many wells are identified only to the nearest quarter-quarter-quarter section (300 to 600 feet of location error).

- Inaccuracy in well elevation – well elevations are typically estimated using 7.5-minute topographic maps and are also subject to errors in location.

- Water levels may not have stabilized at the time of measurement – water levels are typically collected during or immediately after well installation or development and may not have reached equilibrium with the aquifer.

- Hydrostratigraphic units misidentified or not correctly assigned in the databases – the well may actually be screened in a different unit or in multiple units.

- Water level affected by seasonal pumping – depending on where the well is located and at what time of year it was installed, the water level measured by the drilling contractor may have been affected by seasonal pumping.

- Water levels affected by season and year of installation – water levels from different wells typically represent the entire range of possible dates and times of the year and thus are a composite of many years of data.

Given these sources of unavoidable uncertainty in the target values, head targets for regional modeling in Minnesota are typically assigned a likely error of at least +/- 20 feet (about +/- 6 meters). It is not uncommon to find two nearby targets in the same aquifer with substantially different values. The MPCA, in their Metro Model project (Hanson and Seaberg, 2000), gave considerable effort to reducing this error through the use of cross-verification techniques and geostatistics. Also, because this error is both widespread and generally random, the errors tend to be of lesser importance when many targets are used (such as in this study).

4.15.2 Pumping Rates of Wells

Wells for which there are Appropriation Permit records were included as pumping wells in the steady-state optimizations. Average annual rates for the year 2002 were used. It would have been equally valid to not include any pumping in the optimization or to use a different year because the head targets represent measurements from many different years and time periods.

4.15.3 Parameters for Optimization

The first optimization runs included 17 parameters; including 1 recharge zone that covered the entire model domain, all eight horizontal hydraulic conductivity zones, and all eight vertical hydraulic conductivity zones. Results of this optimization provided good matches for deeper bedrock unit targets but tended to predict groundwater levels in the unconfined aquifer too high. Also, base flows to Valley Creek were reasonable but were considered too low, compared to estimated values from monitoring data.

Following these optimizations, additional zonation of hydraulic conductivities were added to the model to include such conditions as fault zones and increased secondary permeability features near the St. Croix River (where deeper bedrock units have been subjected to lithologic release of overburden and subaeral exposure). Some newly discovered target head values in Denmark Township were added to the observations and base elevations of some of the layers were adjusted to reflect newer elevation estimates from the Minnesota Geological Survey. A total of 32 total parameters, including 6 recharge zones, 13 horizontal hydraulic conductivity zones, and 13 vertical hydraulic conductivity zones were used in new optimizations. A total of 303 model runs were required to minimize the objective function.

The TMR model was then optimized to the Woodbury Well 15 pumping test. Following that test, MIKE SHE simulations were performed to deterministically estimate recharge. A final steady-state optimization was performed that used 16 parameters; 8 horizontal hydraulic conductivity zones and 8 vertical hydraulic conductivity zones. A total of 1,132 targets were used.

4.15.4 PEST Optimization Procedure

The primary purpose of automated inverse optimization is to minimize the differences between simulated conditions and observed conditions. For the steady-state optimizations, this means minimizing the difference or residual between the simulated hydraulic head and the measured head (i.e. observed condition) at the calibration target locations. The sum of the squared weighted residuals for all targets is the ***objective function*** that is to be minimized. In this case, all targets were given an equal weight of one. The square of the residual is used because some residuals are negative and some are positive.

Only those parameters selected to vary in the optimization process are allowed to affect the resulting calibration. Some parameters are more correlated than others, which means that different combinations of some parameter values can produce nearly identical results. This is particularly true of horizontal hydraulic conductivity and recharge parameters. Thus, an optimized model may be very non-unique – which is not a desirable outcome. The more (and more varied) types of head targets improves the optimization by reducing this non-uniqueness. Also, placing constraints on the range a parameter can vary (i.e. upper and lower limits) can sometimes assist in reducing non-uniqueness but often this is not a good method because the optimization procedures need to vary the parameter values over large ranges in order to assess the numerical derivative. Fixing one parameter (i.e. not allowing it to vary), adding prior knowledge, and tying parameter values to one another are procedures that are used to improve optimization. The PEST optimization procedure is schematically illustrated in the flow chart on Figure 33.

4.15.5 Final Regional Steady-State Optimization Results

The final optimized model for regional, steady-state conditions has the following calibration characteristics:

- Mean Residual = 0.43 meters
- Residual Standard Deviation = 7.51 meters
- Root Mean Squared Error = 6,410 meters^2
- Residual Standard Deviation/Range = 0.079
- 85% of targets are within 10% of range in head values
- 93% of targets are within 20% of range in head values

A plot that compares simulated to observed heads is shown on Figure 34. A map of calibration residuals is shown on Figure 35. Contours of simulated steady-state hydraulic heads and residuals for all eight layers are shown on Figures 36 through 43.

Relative parameter sensitivities are plotted on Figure 44. The model is most sensitive to the values of horizontal hydraulic conductivity in Layer 8 – the Ironton-Galesville Sandstone aquifer. In part, this is due to the limited number of target values on the western part of the model domain for this unit. The model is also sensitive to horizontal hydraulic conductivity values for Layer 3 – the Shakopee

Formation. The model is least sensitive to vertical hydraulic conductivity values – particularly for the deeper hydrostratigraphic units.

Base flows into Valley Creek were not used as optimization targets (but they could have been used). Instead, base flows were evaluated similar to a verification data set. Upon completion of each optimization, the model's prediction of base flows into the elements that represent Valley Creek were evaluated and compared to the range of values reported for base flows. The following table compares simulated values with ranges of reported values for base flow from a number of sources compiled by the Valley Branch Watershed District:

	South Branch of Valley Creek	**North Branch of Valley Creek**	**Lower Reach of Valley Creek**	**Total base flow of Valley Creek**
Measured/Calculated Values	2 cfs	4 cfs (includes Lake Edith discharge)	Not available	8 to 15 cfs
Model Value	1.9 cfs	3.8 cfs	5.0 cfs	10.7 cfs

4.16 Optimization to Woodbury Well 15 Aquifer Tests

4.16.1 Aquifer Test Description

Two aquifer (pumping) tests were performed in 2003 for the City of Woodbury by Bonestroo, Rosene, Anderlik, and Associates (2004), which involved pumping recently installed Woodbury Well 15, located along Cottage Grove Drive in the eastern part of Woodbury. One test, performed in mid-February 2003, involved 72 hours of pumping at approximately 2,000 gallons per minute (gpm). A second, longer test in November 2003 took place for 30 days at a nearly constant rate of about 997 gpm. Recovery periods followed both tests. Three monitoring well nests, with wells completed in the Prairie du Chien Group, the Jordan Sandstone, and the water-table aquifer were used to monitor drawdowns. A small number of domestic wells in the area were also monitored during the 30-day test. Stream flows in Valley Creek, near where it becomes perennial, were also monitored. A detailed description of the test and the data are in Bonestroo (2004). The locations of the wells are shown on Figure 45.

4.16.2 Optimization Targets

The water levels in monitoring wells were recorded electronically with data loggers – these data were graciously provided by Bonestroo, Rosene, Anderlik, and Associates. The data were converted to drawdown in meters and the thousands of data points were electronically sampled in order to reduce the data set to about 60 drawdown values per well. More values were retained for early time data than for later time data. The 30-day test data were further modified by removing a linear trend in water-reductions that could clearly be seen in the pre-test monitoring and which continued to take place during the 30-day test period and subsequent recovery. This trend appears to be the result of the end of seasonal growing conditions, which could not be simulated at the time the optimization was performed.

All of the target values (drawdown) were given equal weights (value of one). Drawdown was used instead of head because it tends to be a more sensitive indicator of the response to pumping. Measurable changes in base flow of Valley Creek were not observed during the tests so these data were not used in the optimization; however, simulated base flow changes were evaluated in the optimization results to compare with these observations.

4.16.3 Optimization Procedure

Optimization procedures using PEST for this transient pumping simulation are similar to those used in the steady-state, regional model optimization. One obvious difference is that a TMR sub-model was used to make computation more efficient. The other major difference is that the simulation is transient, which introduces new parameters for aquifer storage into the optimization process.

Each model run was a single transient simulation that included:

- 30 days of pumping at 997 gpm – 33 time steps
- 20 days of recovery – 22 time steps
- 39 days of continued recovery – 10 time steps
- 72 hours of pumping at 2,000 gpm – 30 time steps
- 72 hours of recovery – 30 time steps

Six parameters were allowed to vary during the optimization: horizontal hydraulic conductivity values for Layer 3 (Shakopee) and Layer 5 (Jordan); vertical hydraulic conductivity values of Layer 4 (Oneota) and Layer 6 (St. Lawrence Formation); specific yield; and the storage coefficient (applied to all layers). Certainly, other parameters could have been included but the observations collected during the test do not apply directly to them and the parameters would likely have been either insensitive to the observations or strongly correlated with those parameters that were more pertinent to the simulation.

4.16.4 Aquifer Test Optimization Results

The final optimization run involved 75 total model runs. The parameter sensitivities are shown on Figure 46. The most sensitive parameter was the horizontal hydraulic conductivity of Layer 5 (Jordan Sandstone), which is not surprising because this is the unit that is pumped in the test. The optimized value of horizontal hydraulic conductivity for the Jordan Sandstone is on low end of typical values – about 21 ft/day. PEST tried to increase the vertical hydraulic conductivity value of the St. Lawrence Formation beyond a reasonable value. There is not good data to provide guidance on what a reasonable value of vertical hydraulic conductivity of this unit should be but the optimization suggests that Well 15 is receiving some water from the underlying Franconia Formation through the St. Lawrence Formation confining unit. The optimization results also suggest that Woodbury Well 15 seems to be receiving a relatively large amount of its water from the Shakopee Formation by leaking through the Oneota Dolomite.

Several hydrographs that depict the comparison between measured drawdowns and the optimized TMR model's predicted drawdowns are shown on Figures 47 through 52. In general, the optimized model did a very good job of reproducing the monitoring results of the aquifer tests.

The resulting values for the six optimized parameters from the TMR aquifer test model were reported back to the regional model. The regional model was then re-optimized with these values held constant.

5 MIKE SHE Model of Surface Processes

This section describes the MIKE SHE model of surface hydrology processes. The primary purpose for the MIKE SHE simulations was to obtain a better estimate of recharge values and distribution for the MODFLOW model. MIKE SHE (Danish Hydrologic Institute, 2004) can become very complicated because of the nature of surface processes (much more dependent upon transient conditions than groundwater flow) and because many more parameters and phenomenon are modeled than in saturated groundwater flow modeling. It is impossible to provide information on all of the parameters and techniques that were employed as part of this study. Emphasis will be placed on the major processes and assumptions.

MIKE SHE has the capability of simulating multi-aquifer saturated flow using finite differences. In fact, the most recent version of MIKE SHE employs MODFLOW as the computational engine for this part of the simulation. However, the version of MODFLOW in MIKE SHE requires that a uniform grid be used and does not employ the dry-cell correction techniques that are needed in this study. Therefore, MODFLOW was employed separate from MIKE SHE in this study.

5.1 Model Domain, Discretization, and Unit

The model domain used in MIKE SHE is identical to that used in MODFLOW (see Figure 7). The boundaries of the model domain are no-flow. Several of the modeled processes and input parameters require a grid. All grid cells in MIKE SHE are square and equal in size over the model domain. All grid cells are 100 meters by 100 meters.

Most length units are in meters, although some parameters, such as precipitation, are in mm/hr. Coordinates are UTM NAD83, Zone 15.

5.2 MIKE SHE Parameters

5.2.1 Ground-Surface Topography

Ground-surface topography is used in calculating overland flow (runoff) and in unsaturated flow calculations (the depth to the water table is calculated from a water-table surface and the ground surface). Ground-surface topography is entered in meters above mean sea level (MSL).

Two sources for ground-surface topography were used. For the southern portion of the model domain, Washington County provided digital 2-foot contour (20-meter grid) data. These data were re-sampled to obtain the 100-meter grid coverage for MIKE SHE and were combined with 30-meter digital elevation model (DEM) data to cover the entire model domain. The resulting grid is shown on Figure 53.

5.2.2 Precipitation

Precipitation, in the form of rain or snow, is the primary source of water that eventually infiltrates and becomes part of the groundwater system of southern Washington County. Precipitation over the County is not uniform. For example, some storms drop large amounts of rain in one portion of the County but not in another. However, on average, precipitation can be considered to be the same everywhere in the County.

MIKE SHE requires a number of climatological parameters, including daily temperature variations and relative humidity (in the form of dew point). The period of record that was potentially involved in this study included 1975 through 2003. Only one meteorological station near southern Washington County includes all of these data on a daily basis – the St. Paul station. Therefore, daily precipitation records from St. Paul were used. These data are illustrated on Figure 54.

Snow that is stored in the model domain when temperatures are below freezing is transformed into water when the mean daily temperature exceeds 0^{o}C. Snow melts at an assumed rate of 2 mm/day/ ^{o}C.

5.2.3 Temperature and Relative Humidity

Daily mean temperature is used in MIKE SHE to determine if precipitation falls as rain or snow, to control the melting of precipitation stored as snow, and is involved in evaporation and evapotranspiration calculations. Mean daily temperature data was obtained from the St. Paul meteorological station for the period 1975 through 2003. These data are illustrated on Figure 55.

Daily minimum and maximum temperature and dew point were also used to develop data for the reference evapotranspiration surface (discussed in subsequent section). These were obtained from the St. Paul meteorological station for the period 1975 through 2003, as was relative humidity (expressed as dew point).

5.2.4 Vegetation and Land Use

5.2.4.1 Distribution

Land use, as it relates to vegetation, plays a primary role in evapotranspiration – a major part of the water balance, particularly in the summer months. Different vegetative types use water differently. For example, lawn areas that are typical of single-family residential land uses have shallower root systems than corn in an agricultural area but the lawn's root system is relatively stable throughout the year. Conversely, the corn's roots continue to grow from May through August, as does its leafy canopy and evapotranspiration increases throughout the growing season.

Vegetation/land use is assigned in MIKE SHE as a distributed parameter grid. Faced with a potentially huge variety of land uses, we lumped vegetation into seven categories:

1. corn/soybean agricultural
2. single-family residential
3. commercial
4. industrial
5. farmsteads (and very large lot single-family residences)
6. park land
7. paved and open water areas.

Paved and open water areas were lumped together because both represent areas where transpiration is negligible.[3]

The 2000 land use information developed by the Metropolitan Council was used to assign all areas of the model domain one of the seven land use classes. The resulting distribution is shown on Figure 56.

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[3] Transpiration takes place through aquatic vegetation in open water and evaporation occurs on both open water areas and paved areas. However, for the purpose of this study, these hydrologic sinks were deemed negligible.

5.2.4.2 Root Depth and Leaf Area Index

Each of the seven types of land use was assigned characteristics for root depth and leaf area index (LAI). Root depth is a function of the major vegetation type and can vary throughout the year (e.g., corn growth and then harvest) or remain constant (e.g., trees or lawn grasses). Root depths for lawn grasses, trees, and perennial plant types were obtained from the Minnesota Extension Service. Information on corn/soybean depth was obtained from Dr. A.M. Journey, corn researcher at the University of Minnesota.

Leaf Area Index is an indicator of how dense the vegetative canopy is in an area. Satellite or air photo data are typically used to estimate this variable. However, time-domain LAI data are not readily available yet for Minnesota. Therefore, literature values from NASA's EOS web site[4] were used to estimate the seasonal evolution of the LAI for various vegetative categories.

Examples of root depth and LAI for two years of record are shown on Figure 57.

5.2.5 Calculation of Reference Evapotranspiration

MIKE SHE requires a reference evapotranspiration (ET_o) in order to calculate evapotranspiration for the various land-use/vegetation types. The reference evapotranspiration is the evapotranspiration rate from a reference surface not short of water. This reference surface is a hypothetical grass surface with very specific characteristics: "A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23"[5]. The reference crop is typically grass.

The calculation of the reference evapotranspiration can be performed entirely using site-specific climatological and geographic data. It is an extremely involved calculation[5] that uses the following variables:

- mean daily temperature
- maximum and minimum daily temperature

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[4] www-eosids.ornl.gov.vegetation.lai_supoort_images.html

[5] www.fao.org/docrep/xo490e/x490e06.htm

- daily percent sunlight (compared to total possible sunlight)
- daily average wind speed
- relative humidity (calculated from dew point and temperature data)
- Julian date
- latitude and longitude (to estimate sun angle and intensity)

Reference evapotranspiration calculations could only be made on an average monthly basis because of the limited availability of historical data on dew point, percent sunlight, and average wind speed. These calculations needed to encompass the period 1975 through 2003. An example of the calculated reference evapotranspiration is shown on Figure 58. (Note on Figure 58 that the reference ET for the drought year 1988 is much larger than for subsequent years).

5.2.6 Overland Flow (Runoff)

Precipitation that falls on the ground as rain (or melts from accumulated snow) will flow down hill as runoff until it evaporates, is stored in depressions or lakes, or infiltrates into the ground. There are many variables that control runoff, including moisture content (which impedes infiltration), resistance to flow by ground and vegetation (expressed typically as Manning's M), and ground-surface slope (defined by topography).

The definition of the ground-surface topography in MIKE SHE has already been discussed. Topography plays a key role in routing overland flow across the model domain, into channels (such as Valley Creek) and eventually into the St. Croix and Mississippi Rivers. MIKE SHE computes a slope between grid cells to determine the direction in which overland flow should occur. It then routes that flow into the next down-slope grid cell. Also, within each grid cell, a mass balance calculation takes place to determine losses or gains from evaporation, transpiration, seepage into (or out of) the ground as unsaturated flow, or storage of water in depressions (such as lakes, ponds, or wetlands). Water in depressions is allowed to accumulate until (or if) it overflows the depression, based on topography. Large, perennial water bodies are assigned topographic elevations equal to the typical water surface elevation so that runoff does not have to fill these features up.

Because the grid cell sizes are 100-meters on a side, smaller depressions cannot be accounted for by the grid of ground-surface topography. Therefore, a value for depression storage is entered that is set equal to the depth of depressions that are smaller than the 100-meter grid can delineate. For this study, a value of 20 mm (0.78 inches) was used. This should not be confused with the minimum threshold for overland flow to be initiated, which is set at 0.2 mm.

The Manning M (inverse of Manning's n) describes the roughness of channels that carry overland flow. The M value typically ranges from 10 (highly vegetated channels) to 100 (smooth channels). A value of 20 was used in this study.

MIKE SHE can also simulate channel flow using the program MIKE 11, which is similar to HEC-RAS. Overland flow and saturated flow can exchange with channels. A MIKE 11 model was developed for Valley Creek that includes cross-sections and flow structures. However, this MIKE 11 model was found to be too computationally demanding for the purposes of this project. Also, good results were being obtained simply by routing flow via topography.

5.2.7 Unsaturated Flow

5.2.7.1 Soil Grid Code

The Richards Equation was used to simulate unsaturated flow, which results in recharge to the aquifer system. In order to employ Richards Equation, soil profiles must be developed for every area of the model domain. The soil profile describes the soil characteristics (as they relate to unsaturated flow) from the ground surface to the water table. Thus, some knowledge of deposits in the unsaturated zone must be incorporated. This is done, in part, by assigning various areas of the model domain integer codes that relate to a database of soil profiles.

The soil profile involves two components: surface soils and deeper unsaturated soils. Soil survey maps provided information on the surface soils. The Minnesota Geological Survey's shapefile coverages of surficial geology provided information on soils below the ground surface and above the water table. These two data sources were combined into a single ESRI shapefile polygon coverage and 33 general soil profile types were identified. Each soil profile type was assigned a grid number, as shown on Figure 59.

5.2.7.2 Soil Profiles and Unsaturated Flow Characteristics

Each of the 33 grid integer codes has a corresponding unsaturated zone soil profile. An example of such a profile is shown on Figure 60. For each soil profile, soil type and depth are identified, along with vertical discretization of the soil column for the purpose of computing Richards Equation. The discretization includes several very thin (a few centimeters thick) computational layers near the ground surface, where soil moisture changes are most dramatic and where the uptake of water by the roots of plants is taking place. Computational layers thicken with depth because soil moisture differences are less.

Each soil type has two characteristics that must be entered: (1) the relationship between pore pressure (expressed as matric potential) and moisture content (the so-called "moisture retention curve") and (2) the relationship between moisture content and hydraulic conductivity (with hydraulic conductivity equal to saturated hydraulic conductivity at a moisture content of 100 %). The relationships between moisture content, pore pressure, and hydraulic conductivity have been developed empirically by van Genuchten (1980). The van Genuchten variables are entered into MIKE SHE for each soil type. An example of the curve types is shown on Figures 61 and 62.

Values for van Genuchten variables that apply to the various soil types (by textural classification) were obtained from Zhu and Mohanty (2002). There are other publishes sources for these values but the values in Zhu and Mohanty (2002) were used because they are the result of an evaluation based on up-scaling very site-specific values to a regional numerical simulation – a problem similar to this study. Zhu and Mohanty (2002) demonstrated that "effective" parameter values, spatially averaged for scale, can be used in using van Genuchten parameters for large-scale studies. There values, used in this study, are as follows:

	alpha(1/cm)	n	Ks (m/d)	m
Silty clay	0.013	1.32	0.095	0.242
sandy clay	0.032	1.2	0.115	0.167
clay	0.015	1.26	0.148	0.206
silt	0.006	1.65	0.437	0.394
clay loam	0.015	1.4	0.081	0.286
sandy clay loam	0.017	1.32	0.132	0.242

silt loam	0.005	1.65	0.182	0.394
sandy loam	0.022	1.5	0.380	0.333
loam	0.011	1.5	0.120	0.333
sand	0.03	2.9	6.310	0.655

5.2.7.3 Water-Table Elevation

Moisture content increases above the water table and is at saturation in the capillary fringe. As moisture content increases, downward flow to the water table increases but the rate of infiltration into the soil actually decreases. Thus, the water table is an important controlling mechanism on infiltration and recharge.

In a fully coupled model, the water table would be computed by MIKE SHE as part of the saturated flow computation. In this study, where the water table is typically many meters below ground surface, the water table is assumed to be stationary with time for the purpose of computing unsaturated flow. The water table is entered into MIKE SHE on a 100-meter by 100-meter grid, as shown on Figure 63.

The water table was construction by kriging a combination of: (1) water levels from wells reporting either a quaternary aquifer or a bedrock aquifer in which the water table resides and (2) lakes and streams that are likely in direct hydraulic connection with the aquifer. In many locations, there are no data on the water table (only the potentiometric surface of deeper aquifers); therefore there is some uncertainty in this evaluation.

5.2.7.4 Column Classification Grid

Computing Richards Equation at every grid cell (over 100,000) for time steps of as little as 5 minutes would be nearly overwhelming from a computational standpoint. MIKE SHE computes unsaturated flow over a reduced subset of the grid by classifying the grid according to like soil types, vegetation types, and depth to groundwater. This classification is automatic. An example of the reduced classification grid is shown on Figure 64. MIKE SHE classified the unsaturated zone into 565 different computations.

5.2.8 Computational Settings

For nearly every type of problem, MIKE SHE must run simulations in a transient mode whereby hydrologic processes are time-dependent. This is very much different from the conventional approaches in groundwater flow modeling, where steady-state simulations are the rule. The reason transient simulations are required is that surface hydrologic processes are highly responsive to short-term events – particularly precipitation.

In this study, precipitation events are assumed to take place over a 24-hour period because this is the smallest time period of record. Precipitation, temperature, and cropping parameters (root depth etc.) are all entered on a daily basis. Thus the stress periods for simulation are 24 hours in length. Time steps for computation, however, are typically of much smaller duration.

MIKE SHE uses an adaptive time-stepping approach in its solution scheme in which larger time steps are used during periods when there is little change in hydrologic conditions (e.g. in the winter) and much smaller time steps during and after rainfall events. In the period during and after a rainfall event, overland flow, unsaturated flow, and evapotranspiration processes are changing rapidly and require small time periods in order to minimize mass-balance errors.

The maximum allowable time step is always 24 hours. Precipitation-event controls that reduce the time step are as follows:

- The maximum precipitation depth per single time step is 0.5 mm (0.02 inches)
- The maximum amount of infiltration per time step is 5 mm (0.2 inches)
- If the intensity of precipitation exceeds 1 mm/hr (0.4 in/hr), a time step is required

The above are recommendations of the Danish Hydrologic Institute (2004).

Solution of unsaturated flow using Richards Equation by MIKE SHE imposes its own time-step requirements. These include limitations on water-balance errors, the number of iterations per time step, and the maximum allowable water-balance error in the soil profile. Again, Danish Hydrologic Institute (2004) recommendations on setting these conditions were followed.

Maximum time steps rarely exceeded eight hours, even during winter months. During rainfall events in the summer, time steps as small as 7 minutes were noted. A simulation of four consecutive years took approximately 85 hours on a 3 GHz, 1 GByte RAM processor.

The minimum simulation time used in this study was a period of one year. Actual dates are used for starting and stopping simulations – this allows MIKE SHE to use input data referenced to actual dates. Simulations were also initiated using “hot start” data; the final conditions of a previous simulation. “Hot start” provides for soil moisture conditions and overland flow properties that are appropriate for re-commencement of the simulation of hydrologic processes.

5.3 Description of Simulations and Post-Processing

5.3.1 Simulation Periods

Simulations were run for a period beginning in 1987 and extending through 2002, although this period was divided into smaller periods to keep computational times to reasonable levels. In addition, a simulation was run for the period 1978-1980 to obtain results for the period January 1 through December 31, 1979. The year 1979 was deemed to be a “typical year” in terms of precipitation, based on an evaluation of annually averaged data for the period 1975 through 2003.

Prior to beginning a simulation, an time increment must be identified for recording results. Obviously, a time increment that is too small will produce an unmanageably huge collection of files and data. A period of 72 hours was chosen as the time increment for recording results. For flows, each 72-hour period save results that as an accumulated average of the 72-hour period (i.e. the sum of flows of the time steps in the 72-hour period is divided by 72 hours).

5.3.2 Output from Simulations

Each simulation generates results of the following phenomenon as grids and as a water balance in increments of 72 hours:

- precipitation rate
- soil evaporation
- transpiration
- evaporation from interception by the leaf canopy
- evaporation from ponded water

- canopy interception storage
- snow storage
- sublimation from snow
- overland flow (X and Y directions)
- infiltration to the unsaturated zone
- exchange between the unsaturated and saturated zones (i.e. recharge)
- unsaturated zone soil moisture deficit
- overland flow stored in depressions

The water balance component of primary interest is "exchange between the unsaturated and saturated zones", which is recharge to the groundwater system. These results represent the recharge values that are entered as part of the recharge package in MODFLOW. The other parts of the water balance are not particularly salient to this study. (They are available but they are in a MIKE SHE grid form that requires significant post-processing to make them useful in programs such as ArcView).

The post-processing of the recharge component requires the following steps:

1. In MIKE SHE, sign convention is changed so that recharge to the water table is positive and outflows via recharge are negative.[6] Data are in mm/day.[7]

2. Data for each 72-hour period are exported as individual ESRI ASCII grids. Thus, for a one-year period, there are 121 grids.

3. Grids are imported into ArcView. Monthly averages are calculated using Spatial Analyst. These grids are saved as ESRI raster grids. An annual average may also be calculated.

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[6] Negative recharge values do occur in grids near major water bodies, where the water table is only a few feet below ground surface. In these areas, evapotranspiration pulls water from the unsaturated zone, which in turn, pulls water from the water table.

[7] Recharge is kept in mm/day, rather than converting to m/day (MODFLOW's units) in order to keep the number large. ArcView has a limit on the numbers to the right of the decimal point for grids.

4. Point shapefiles are created that contain a year's recharge data on a monthly basis (i.e. one field for each month, plus an annual average). The point coordinates correspond to the centers of the MODFLOW grid cells. Recharge is converted to meters per day.

This approach to post-processing is very time consuming but the resulting shape files can be directly imported into Groundwater Vistas and readily mapped to the appropriate stress period for recharge.

5.3.3 "Typical Year" Results

The "typical year" that is representative of average conditions is 1979. The Year 1979 was characterized by two periods of wet condition – late June and late August-early September. Precipitation fell as snow in January, February, and March, melting in April. April and May were relatively dry. October and November were wetter. Total rainfall for that year was 35.6 inches, which is slightly greater than the long-term average of 29 inches but the rainfall intervals are very typical of average conditions in timing, duration, and intensity. Temperatures were near long-term averages for each month.

The MIKE SHE water balance, averaged over the entire model domain for this "typical" year, is shown on Figure 65 in both cumulative form and as instantaneous conditions. Negative values indicate flows into the unsaturated zone and positive values indicate losses out of the unsaturated zone. The primary components of the water balance are precipitation, evapotranspiration, changes in water stored in the unsaturated zone, flow from the unsaturated zone into the saturated zone (recharge), storage of precipitation as snow, and storage of water as overland flow. Based on these results, the following are noted:

- The cumulative recharge to the saturated zone for the year is about 8.5 inches (24 % of total precipitation).

- Recharge is remarkably flat over the course of the year, increasing only slightly during wet periods. This may be due to the relatively thick unsaturated zone in southern Washington County, which has a large storage capacity and can drain to the water table at a uniform rate over time.

- Water stored in the unsaturated zone increases during wet periods as moisture content increases but decreases, presumably by drainage and evapotranspiration, during other periods of time.

- Cumulative evapotranspiration losses for the year are about 27 inches (74 % of total precipitation). This includes evaporation from surface waters, including the St. Croix and Mississippi River.

The annually averaged distribution of recharge over the model domain is shown on Figure 66. Recharge rates are greatest in the upland areas of eastern Woodbury, Cottage Grove, Denmark Township, and Afton.

5.3.4 "Dry Year" Results

The driest year (least precipitation combined with hot weather) in the last quarter century was 1988. In 1988 total precipitation was 22.4 inches (compared to 29-35 for typical conditions). Groundwater pumping was at historically high levels to meet the lawn watering demands of the region.

The annually averaged distribution of recharge over the model domain for the dry year is shown on Figure 67. The difference in simulated recharge between the typical year and the dry year is shown on Figure 68. The annual average recharge for the dry year over the model domain is about 6.6 in/year (compared to 8.5 in/year for typical conditions).

5.4 Conversion to MODFLOW-Compatible Recharge Format

Recharge value are used in MODFLOW on a cell-by-cell basis through the recharge array file. For transient simulations, each stress period has its own array (but all stress periods are contained within one file).

The recharge grid cells produced by MIKE SHE are a uniform dimension of 100-meters by 100-meters. Grid cells in MODFLOW are of variable size and are generally larger (as much as 500-meters by 500-meters). In order to bring in MIKE SHE results into MODFLOW, the MIKE SHE data were converted to point shapefiles, as described in Section 5.3.2. As a recommendation to Groundwater Vista users, we suggest converting the shapefiles to ASCII XYZ files, with X being the grid columns and Y being the grid rows and then importing the data with the row-column format option. This will negate the need for interpolation (This only works if the grid is identical to the shapefile dimensions). The resulting MODFLOW array was converted back into a polygon shape file.

Figures 69 and 70 show the MODFLOW recharge arrays for simulating steady-state conditions with average annual recharge of "typical" (1979) and "dry (1988) conditions. These are polygon shapefiles. The polygons correspond to the grid cells in MODFLOW. These shapefiles could also be used to import data into other GUIs that allow for the importation of ESRI polygon shapefiles, such as Visual MODFLOW or GMS. Figures 69 and 70 show the recharge values in units of inches per year but in the shapefiles' attribute tables, there are also fields in meters/day (the model's required input units). Also in these shapefiles are fields for monthly infiltration rates that resulted from the MIKE SHE simulations. These can be used to change recharge rates for monthly stress periods in transient simulations.

6 Simulations of Proposed Woodbury Wells

6.1 Purpose and Scope of Simulations

A primary purpose of this study was to build a model that could be used to predict the effects of future pumping of proposed City of Woodbury municipal water-supply wells that are planned for the eastern portion of Woodbury. The primary concern is the effects of pumping of these wells on base flows of Valley Creek (a state-designated trout stream). Another concern was the drawdown effects pumping might cause on nearby wells.

In planning for these wells, as many as 15 new wells had been contemplated in the area along Cottage Grove Drive in eastern Woodbury. In consultation with the Technical Advisory Committee (TAC) for this project, it was agreed that only the first three wells (Wells 15, 16, and 17) would be evaluated in this study. Evaluation of the effects of additional wells would take place after this study was completed and after additional monitoring data had been collected.

The TAC also provided guidance on the type of simulations that would be performed in this study to evaluate the wells. The agreed-upon approach was a transient simulation that projects future pumping in the context of future demand.

6.2 Simulation Parameters

The agreed-upon simulation involves the following parameters:

1. The simulation would begin in the year 2005 and would model conditions through the year 2020.

2. Well 15 would be operational in the year 2005. Well 16 would be operation in 2006 and Well 17 in 2007. No additional wells would be included for this simulation.

3. Pumping rates for all Woodbury wells would be assigned on the basis of projected water demand, which would be based on projected population increases for the simulation period.

4. Projected water demand would include reasonable estimates of variations between winter and summer water use. In other words, there would be a base demand for winter months and a

summer demand that reflects assumed summer water use for assumed climatological conditions. Water demand and model stress periods would be parsed into monthly periods.

5. Future climatological conditions would approximate past conditions, beginning in the year 1988. In other words, 2005 would use recharge from the MIKE SHE simulation for 1988, 2006 would use 1989's results etc.

6. In order to project demand that is a response to climatological conditions (i.e. higher rates of pumping during hot, dry periods), total monthly demand was estimated on the basis of past water usage in past years.

7. Recent (i.e. last three years) apportionment of Woodbury pumping among East Tamarack wellfield wells was used as a guide for which wells would be in operation and their relative pumping rates (compared to total wellfield pumping) would be during various parts of the year. Similar projections were made for Wells 15, 16, and 17, with the assumption that Well 15 would likely operate year-round and Wells 16 and 17 pumping would be more seasonally affected.

8. The effects of future pumping would be evaluated at the following locations:

    a. Monitoring well nests 1, 2, and 3;

    b. Base flows of Valley Creek, divided into the south branch, north branch, main reach, and total stream.

9. Regional drawdown in key aquifer units would also be evaluated for selected time periods.

10. Three transient simulations, with identical recharge conditions but different pumping conditions, would be run for the purpose of facilitating the comparison of effects of Wells 15, 16, and 17:

    a. East Tamarack wellfield operating to meet a portion of future demand (i.e. future demand that would be met by Wells 15, 16, and 17 would not be included and Wells 15, 16, and 17 would not be in model.

    b. East Tamarack wellfield and Wells 15, 16, and 17 all operating to meet future demands.

c. No wells in Washington County operating, for comparison to "undeveloped" condition.

6.3 Transient Simulation Set-Up

6.3.1 Simulation Period, Stress Periods, and Time Steps

The time period that was simulated was the period January 2005 through December 2020 (16 years). The period was divided into 192 stress periods of one month each (days of each stress period varied, depending on the month). Each of these stress periods consisted of four time steps with a time step multiplier of 1.2.

Two model runs were required for each simulation because of the large number of stress periods. An initial simulation covered the first eight years and the remaining eight years were covered by the second. The beginning of the second part of the simulation used the head solution from the last time step of the last stress period from the first part of the simulation.

The first model run of the simulation contained 97 stress periods, instead of 96. The first stress period was 90,000 days (264 years) long with eight time steps. The purpose of this first time step was to re-attain steady-state conditions via a transient simulation in order to minimize errors due to inflows and outflows from aquifer storage. The 90,000 day stress period contained the same recharge and pumping rates as the second stress period, representing January 2005. This is a commonly applied practice in transient modeling. The starting heads for this simulation was the head solution from the typical-year steady-state model.

6.3.2 Recharge

Recharge varied with each time step in the model to simulate month-to-month and year-to-year climatic conditions. The recharge conditions used represented the MIKE SHE solutions for monthly recharge for the period 1988 through 2003. Thus, 1988 recharge was used to simulate 2005, 1989 recharge was used to simulate 2006, and so on. We recognize that this climatic cycle will not be repeated in the years 2005 through 2020, but the approach provides an available framework for varying recharge, based on recent conditions.

6.3.3 Pumping Wells (non-Woodbury Wells)

For all wells except Woodbury wells (existing and future), monthly pumping rates for the period 1988 through 2003 were used (except for the simulation in which all wells were assumed to be turned off). January 1988 pumping rates were used for the 90,000 day initial stress period in all three simulations so that initial conditions would be identical. The total monthly pumping of non-Woodbury wells is shown on Figure 71.

6.3.4 Woodbury Pumping Wells

6.3.4.1 Projecting Future Water Demand

Projections of population growth in Woodbury for the period 2005 through 2025 were obtained from the City of Woodbury. Population increase is expected to be nearly linear, as shown on Figure 72, with approximately 1,757 people added per year.

Water demand in January typically represents base demand (no summer usages; such as irrigation, filling swimming pools, etc.). In the years 1988 through 2002, January water demand has increased nearly linearly. Whereas, July water demand varies considerably, depending on climatic conditions, as shown on Figure 73. During this period, base water demand has increased at a rate of about 190,500 gallons per day (GPD) per year. During this same period, population grew at a rate of about 1,700 people per year. These two values allow future base water demands to be projected for the period of the model simulation (2005-2020).

However, as Figure 73 shows, water demand in summer months is considerably higher than in January and rates fluctuate from year to year. Because the climatic conditions for the period 1988-2002 were used for the simulation of conditions in 2005-2020, the monthly water demand, compared to base water demand for the years 1988-2002 can also be used to project future water demand, *provided that population increases are also accounted for*. This also assumes that water use in the past will be similar to water use in the future. The estimated future month-by-month water demand for Woodbury is shown on Figure 74. These demand are considered to be realistic, based on past water usage.

6.3.4.2 Projected Individual Woodbury Well Monthly Pumping Rates

The model simulations require that the monthly pumping rates of each of Woodbury's existing and future wells be projected in order to realistically simulate water withdrawals for various climatic and seasonal conditions. In order to do this, the water demands shown on Figure 74 must be partitioned to the 14 East Tamarack well field wells and to the three new wells. Well usage for 2001 through 2003 were evaluated in order to approximate how different wells might be used during different parts of the year (peaking vs. base) and how their use cycles from year to year. This evaluation provided some guidance on partitioning flows among the 14 existing wells. The exact partitioning is not that important because the wells are all relatively close together.

Projecting the use of Wells 15, 16, and 17 was more challenging. We assumed that Well 15 is on line on January 1, 2005, Well 16 comes on line in April 2005, and Well 17 will come on line in August 2005. We then assumed that Wells 15, 16, and 17 would be cycled to meet some of Woodbury's base demand throughout the year and that all three wells would need to operate during peak demand months. The pumping schedule for the simulations is shown on Figure 75.

Well 15 is already installed. The estimated locations of Wells 16 and 17 are shown on Figure 76.

6.4 Transient Simulation Results

Portraying the results of transient simulations is always challenging because there are huge quantities of simulation data and it is difficult to show the most relevant results in a succinct manner and not leave out results that may be less relevant but interesting. We have chosen to show the results in terms of hydrographs for key monitoring well locations (from the Woodbury Well 15 aquifer test) and hydrographs of simulated base flows to Valley Creek. We also present snap shots of drawdown in key hydrostratigraphic units at key times during the simulation.

6.4.1 Hydrographs for Woodbury Monitoring Wells

The locations of existing monitoring well nests are shown on Figure 76. Simulated hydrographs for the Shakopee, Jordan, and Ironton-Galesville hydrostratigraphic units are shown for the three monitoring well nest locations[8] on Figures 77 through 85. Each hydrograph shows three conditions: (1) no wells in Washington County pumping; (2) all wells pumping except Wells 15, 16, and 17; and (3) all wells pumping, including Wells 15, 16, and 17. These three simulations allow for the

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[8] Simulated hydrographs are shown for this locations – some locations show hydrographs for units that currently do not have monitoring wells (e.g., the Ironton-Galesville Sandstones).

comparison of the effects of Woodbury Wells 15, 16, and 17 in the context of other pumping in Washington County. Note: the initial condition for all three simulations includes existing wells pumping at January 2005 projected rates – this is why there is an increase (recovery) in water levels for the no-wells-pumping condition.

6.4.2 Hydrographs for Base Flows in Valley Creek

Hydrographs showing the simulated variability of groundwater inflows (base flows) to various portions of Valley Creek are on Figures 86 through 88. Simulated base flows for all of Valley Creek are shown on Figure 89. Base flow values represent the simulation results of cumulative inflow along the specified river reach.

6.4.3 Predicted Drawdown Resulting from Three New Woodbury Wells

For the simulation period 2005-2020, there are nearly 40,000 time periods to choose from to examine the spatial distribution of drawdown. In general, however, summer months (e.g. July and August) experience the largest drawdown, resulting from the greatest withdrawals from future Woodbury Wells 15, 16, and 17. We have selected one time period: late July 2012, as a typical example of high withdrawal rates combined with summer recharge conditions. The combined pumping rate for these wells at this time period is 1,223 gallons per minute (gpm). Predicted drawdown caused by Wells 15, 16, and 17 (i.e. compared to conditions with these wells not pumping but other wells pumping) are shown on figures 90 and 91 for the water table, the Shakopee Formation, the Jordan Sandstone, and the Ironton-Galesville Sandstones.

The predicted cumulative base-flow conditions along the south branch of Valley Creek for the simulated period of July 2012 is shown on Figure 92. The modeling results suggest that pumping of Wells 15, 16 and 17 in the summer will reduce base flows by a marginal amount (about 10 percent or 0.5 cubic feet per second, cfs).

Figure 93 shows the predicted cumulative base flows along the south branch of Valley Creek for the simulation period August 2018. This is a period similar to weather conditions for 1988 (slightly wetter) with high water demands (combined average monthly pumping for Wells 15, 16, and 17 of 1,816 gpm or 2.6 million gallons per day, MGD). Base flows for the various scenario types indicate a reduction of about 1 cfs along the south branch of Valley Creek. Base flows show a greater response to pumping of Wells 15, 16, and 17 for this period, compared to July 2012 – about 0.5 cfs, which is about 15 percent of base flow. The cumulative base flow curve also shows that base flow begins to enter the south branch of Valley Creek about 500 meters further downstream than for July 2012. This result suggests that pumping of Wells 15, 16, and 17, combined with dry conditions in the summer could result in the drying up of portions of up-stream reaches of the south branch of Valley Creek.

6.5 Summary of Results of Simulation of Woodbury Wells 15, 16, and 17

The modeling results suggest that for most pumping conditions, the reduction in the base flow of Valley Creek will likely be too small to accurately measure (i.e. will be in the range of measurement error). The south branch of Valley Creek will most likely be affected. In general, the maximum reduction in base flow will be about 0.5 cfs, which is about 5 to 15 percent of base flow. Flow from surface runoff would likely further mask this effect.

During extremely dry conditions, such as the simulated condition of August 2018 (similar to 1988), base flows will be lower in Valley Creek (particularly in the south branch) because of climatic conditions and because of regional pumping. During this period, higher sustained rates of pumping of Wells 15, 16, and 17 would likely take place (about 2.6 MGD combined for the three wells). Under these conditions, the reduced base flow to the south branch of Valley Creek will likely be about 0.5 cfs but this reduction might cause the upper portions of the south branch have low or no base flow for a short period, until pumping is reduced.

7.0 Additional Study and Modeling Recommendations

This study constructed a model or *tool* for evaluating the effects of pumping on groundwater levels in aquifers and the base flow to Valley Creek in southern Washington County. The best available data and methods were used to make the simulation capabilities of this model as unique and reliable as practical. As new data are gathered (e.g., new water level data, new hydrogeologic data, new pumping test data, etc.) it is important to revisit this model and if necessary make modifications and/or re- optimize the model.

The following are some suggested data collection activities that could lead to a more reliable predictor of the effects of pumping:

- obtain better information on the water table configuration in southern Washington County through shallow wells;
- conduct additional pumping tests with additional monitoring points;
- conduct local studies near the headwaters of the south branch of Valley Creek, such as a local pumping test, to evaluate better the relationship between aquifer head and base flows;
- include monitoring wells in the Franconia Formation and/or the Ironton-Galesville Sandstones to test the response of water levels in these units to pumping in the Jordan Sandstone.

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Description of MODFLOW Files

The following is a description of MODFLOW files supplied with the CD.

Directory	File Name	File Type and Use
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	discret.dat	MODFLOW file for use in providing discretization data to other programs
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	mf96.nam	MODFLOW96 naming file
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	modflow.err	Error log file
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	modflow.in	MODFLOW instruction file for DOS runs
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	Steady_State_typical_year.gwv	Groundwater Vistas file
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	Steady_State_typical_year_calib_targets.dat	Ascii file of steady-state calibration targets for Groundwater Vistas
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	tal.dat	Groundwater Vistas tal file
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	target_calibration_data.out	PEST calibration output data
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.bas	Basic file for typical year simulation
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.bcf	BCF file for typical year simulation
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.cbb	Resulting mass balance file
MODFLOW-Vistas/Regional_Steady_State/	typic.cbw	Resulting mass balance file for wells

Directory	File Name	File Type and Use
Typical_Year		
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.crc	Resulting mass balance file for recharge
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.ddn	Resulting unformatted drawdown file
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.hds	Resulting unformatted head file
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.kzi	Groundwater Vistas array for computing leakance form Kz data
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.m96	MODFLOW96 instruction file for Windows
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.mnw	MODFLOW2000 well file (not used)
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.nam	MODFLOW naming file for MODFLOW88
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.oc	Output control file
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.out	Output file
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.pcg	PCG solver file
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.rch	Recharge array file
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.riv	River package file
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	typic.wel	Well file

Directory	File Name	File Type and Use
MODFLOW-Vistas/Regional_Steady_State/Typical_Year	Typic.drn	Drain package file
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	1988_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	1989_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	1990_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	1991_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	1992_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	1993_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	1994_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	1995_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	1996_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Fil	1997_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day

Directory	File Name	File Type and Use
es		
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	1998_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	1999_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	2000_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	2001_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Regional_Steady_State/Pumping_Rate_Files	2002_average_wells_rates.dat	Groundwater Vistas analytic well text import file for annual average pumping rates for listed year (from SWUDS data base), cubic meters per day
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_month	1988_pumping_repeated_5_times_monthly.dat	Groundwater Vistas analytic well text import file for monthly average pumping rates for listed year (from SWUDS data base), cubic meters per day, repeated for 5 years
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_month	1995(typical)_pumping_repeated_5_times_monthly.dat	Groundwater Vistas analytic well text import file for monthly average pumping rates for listed year (from SWUDS data base), cubic meters per day, repeated for 5 years
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_month	WellImportReport.txt	Groundwater vista report file for imported wells
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	8_no_well.riv	MODFLOW River package array for monthly transient simulation of 1988 conditions repeated over 5 year period with no new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_no_well.wel	MODFLOW Well package file for monthly transient simulation of 1988 conditions repeated over 5 year period with no new Woodbury wells

Directory	File Name	File Type and Use
MODFLOW-Vistas/ Transient_pumping_ Files/5_years_by_ Month\5_year_1988(dry)_by_m	88_no_well._kx	Groundwater Vistas array for horizontal hydraulic conductivity for monthly transient simulation of 1988 conditions repeated over 5 year period with no new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/5_years_by_ Month\5_year_1988(dry)_by_m	88_no_well._kz	Groundwater Vistas array for vertical hydraulic conductivity for monthly transient simulation of 1988 conditions repeated over 5 year period with no new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/5_years_by_ Month\5_year_1988(dry)_by_m	88_no_well._s1	Groundwater Vistas unconfined storage array for monthly transient simulation of 1988 conditions repeated over 5 year period with no new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/5_years_by_ Month\5_year_1988(dry)_by_m	88_no_well._s2	Groundwater Vistas confined storage array for monthly transient simulation of 1988 conditions repeated over 5 year period with no new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/5_years_by_ Month\5_year_1988(dry)_by_m	88_w15.bas	MODFLOW Basic Package for monthly transient simulation of 1988 conditions repeated over 5 year period with Woodbury well 15 pumping
MODFLOW-Vistas/ Transient_pumping_ Files/5_years_by_ Month\5_year_1988(dry)_by_m	88_w15.bcf	MODFLOW BCF Package for monthly transient simulation of 1988 conditions repeated over 5 year period with Woodbury well 15 pumping
MODFLOW-Vistas/ Transient_pumping_ Files/5_years_by_ Month\5_year_1988(dry)_by_m	88_w15.cbb	MODFLOW cell centered flow for monthly transient simulation of 1988 conditions repeated over 5 year period with Woodbury well 15 pumping
MODFLOW-Vistas/ Transient_pumping_ Files/5_years_by_ Month\5_year_1988(dry)_by_m	88_w15.cbw	MODFLOW cell centered flow for wells for monthly transient simulation of 1988 conditions repeated over 5 year period with Woodbury well 15 pumping
MODFLOW-Vistas/ Transient_pumping_ Files/5_years_by_ Month\5_year_198	88_w15.crc	MODFLOW cell centered flow for recharge for monthly transient simulation of 1988 conditions repeated over 5 year period with Woodbury well 15 pumping

Directory	File Name	File Type and Use
8(dry)_by_m		
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15.ddn	MODFLOW unformatted drawdown for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15.hds	MODFLOW unformatted heads for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15.kzi	Groundwater Vistas vertical hydraulic conductivity anisotropy array for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15.m96	MODFLOW 96 naming file for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15.mnw	MODFLOW multi-aquifer well package for monthly transient simulation of 1988 conditions repeated over 5 year period (not used)
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15.nam	MODFLOW naming file for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15.oc	MODFLOW output control file for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15.out	MODFLOW output file for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_	88_w15.pcg	MODFLOW solver package (PCG) for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping

Directory	File Name	File Type and Use
Month\5_year_1988(dry)_by_m		
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15.rch	MODFLOW recharge array for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15.riv	MODFLOW River Package array for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15.wel	MODFLOW well package for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15._kx	Groundwater Vistas horizontal hydraulic conductivity array for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15._kz	Groundwater Vistas vertical hydraulic conductivity array for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15._s1	Groundwater Vista unconfined storage array for monthly transient simulation of 1988 conditions repeated over 5 year period with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	88_w15._s2	Groundwater Vista confined storage array with woodbury well 15 pumping
MODFLOW-Vistas/Transient_pumping_Files/5_years_by_Month\5_year_1988(dry)_by_m	discret.dat	MODFLOW file for use in providing discretization data to other programs
MODFLOW-Vistas/Transient_pumping_	matrix.hds	Temporary unformatted head file used in Groundwater Vistas – not used in modeling

Directory	File Name	File Type and Use
Files/5_years_by_ Month\5_year_198 8(dry)_by_m		
MODFLOW-Vistas/ Transient_pumping _ Files/5_years_by_ Month\5_year_198 8(dry)_by_m	mf96.nam	MODFLOW96 naming file
MODFLOW-Vistas/ Transient_pumping _ Files/5_years_by_ Month\5_year_198 8(dry)_by_m	modflow.err	MODFLOW error log file for Groundwater Vistas
MODFLOW-Vistas/ Transient_pumping _ Files/5_years_by_ Month\5_year_198 8(dry)_by_m	modflow.in	MODFLOW instruction file
MODFLOW-Vistas/ Transient_pumping _ Files/5_years_by_ Month\5_year_198 8(dry)_by_m	tal.dat	Groundwater Vistas tal file
MODFLOW-Vistas/ Transient_pumping _ Files/5_years_by_ Month\5_year_198 8(dry)_by_m	unsat.dat	File used in Groundwater Vistas for Doherty's dry cell treatment calculations
MODFLOW-Vistas/ Transient_pumping _ Files/5_years_by_ Month\5_year_198 8 (dry)_by_m/ with_W_15_pumpi ng_@1000_gpm	88_5- yr_by_month_w_15_at _100_gpm.gwv	Groundwater Vista file for simulation of 1988 climatic conditions on monthly basis repeated for 5 years with Woodbury well 15 pumping at 1000 gpm
MODFLOW-Vistas/ Transient_pumping _ Files/5_years_by_ Month\5_year_198 8 (dry)_by_m/ 5_year_1995(typic al)_by_month	95_5_yr_by_month.gwv	Groundwater Vista file for simulation of 1995 climatic conditions on monthly basis repeated for 5 years
MODFLOW-Vistas/ Transient_pumping _ Files/Yearly_by_	1988_monthly(dry_ year).dat	Groundwater Vistas analytic element import files for transient pumping on monthly basis (12 stress periods) for SWUDS wells in model - 1988

Directory	File Name	File Type and Use
month		
MODFLOW-Vistas/ Transient_pumping_ Files/Yearly_by_ month	1993_monthly(wet_ year).dat	Groundwater Vistas analytic element import files for transient pumping on monthly basis (12 stress periods) for SWUDS wells in model - 1993
MODFLOW-Vistas/ Transient_pumping_ Files/Yearly_by_ month	195_monthly(ave_ year).dat	Groundwater Vistas analytic element import files for transient pumping on monthly basis (12 stress periods) for SWUDS wells in model - 1995
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_n o_wood_wells	13_20nww.bas	MODFLOW Basic File for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_n o_wood_wells	13_20nww.bcf	MODFLOW BCF file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_n o_wood_wells	13_20nww.cbb	MODFLOW cell centered flow file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_n o_wood_wells	13_20nww.cbw	MODFLOW well mass balance for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_n o_wood_wells	13_20nww.crc	MODFLOW recharge mass balance for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_n o_wood_wells	13_20nww.ddn	MODFLOW unformatted drawdown for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_n o_wood_wells	13_20nww.drn	MODFLOW drain package file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_n o_wood_wells	13_20nww.hds	MODFLOW unformatted head file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells

Directory	File Name	File Type and Use
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww.kzi	MODFLOW vertical anisotropy file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww.m96	MODFLOW 96 naming file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww.mnw	MODFLOW multiaquifer well file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells (not used)
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww.nam	MODFLOW naming file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww.oc	MODFLOW output control file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww.out	MODFLOW output file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww.pcg	MODFLOW solver file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww.rch	MODFLOW recharge file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww.riv	MODFLOW river package file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww.wel	MODFLOW well file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_	13_20nww._kx	MODFLOW horizontal hydraulic conductivity file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well

Directory	File Name	File Type and Use
Files/2005_2024_no_wood_wells		field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww._kz	MODFLOW vertical hydraulic conductivity file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww._s1	Groundwater Vistas unconfined storage array for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	13_20nww._s2	Groundwater Vistas confined storage array for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	2005_2012_no_wood_wells.gwv	Groundwater Vistas file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	2013_2020_no_wood_wells.gwv	Groundwater Vistas file for Transient Simulation of Period 2013-2020 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	5_12nww.bas	MODFLOW Basic File for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	5_12nww.bcf	MODFLOW BCF file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	5_12nww.cbb	MODFLOW cell centered flow file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	5_12nww.cbw	MODFLOW well mass balance for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	5_12nww.crc	MODFLOW recharge mass balance for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells

Directory	File Name	File Type and Use
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	5_12nww.ddn	MODFLOW unformatted drawdown for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	5_12nww.hds	MODFLOW unformatted head file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	5_12nww.kzi	MODFLOW vertical anisotropy file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	5_12nww.m96	MODFLOW 96 naming file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	5_12nww.mnw	MODFLOW multiaquifer well file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells (not used)
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	5_12nww.nam	MODFLOW naming file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	5_12nww.oc	MODFLOW output control file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	5_12nww.out	MODFLOW output file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	5_12nww.pcg	MODFLOW solver file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	5_12nww.rch	MODFLOW recharge file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/ Transient_pumping_	5_12nww.riv	MODFLOW river package file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new

Directory	File Name	File Type and Use
Files/2005_2024_no_wood_wells		woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	5_12nww.wel	MODFLOW well file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	5_12nww._kx	MODFLOW horizontal hydraulic conductivity file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	5_12nww._kz	MODFLOW vertical hydraulic conductivity file for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	5_12nww._s1	Groundwater Vistas unconfined storage array for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	5_12nww._s2	Groundwater Vistas confined storage array for Transient Simulation of Period 2005-2012 – Includes Washington County wells and East Tamarack well field but not 3 new woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	east_tam_wells.dat	Groundwater Vistas import file for analytic elements for the East Tamarack well field
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	mf96.nam	MODFLOW96 naming file
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	modflow.err	Groundwater Vistas log error file
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	modflow.in	MODFLOW instruction file
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wood_wells	new_wood_wells.dat	Groundwater Vistas import file for analytic elements for Woodbury wells 15, 16, and 17

Directory	File Name	File Type and Use
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	nowoodwells.dat	Groundwater Vistas import file for analytic elements for all SWUD county wells except Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	tal.dat	Groundwater vistas tal file
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	unsat.dat	File used in Groundwater Vistas for Doherty's dry cell treatment calculations
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wood_wells	WellImportReport.txt	Groundwater Vistas well important log file
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	13_20nw.bas	MODFLOW Basic File for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	13_20nw.bcf	MODFLOW BCF file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	13_20nw.cbb	MODFLOW cell centered flow file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	13_20nw.cbw	MODFLOW well mass balance for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	13_20nw.crc	MODFLOW recharge mass balance for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	13_20nw.ddn	MODFLOW unformatted drawdown for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_	13_20nw.drn	MODFLOW drain package file for Transient Simulation of Period 2013-2020 – No wells at all

Directory	File Name	File Type and Use
Files/2005_2024_no_wells		
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	13_20nw.hds	MODFLOW unformatted head file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	13_20nw.kzi	MODFLOW vertical anisotropy file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	13_20nw.m96	MODFLOW 96 naming file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	13_20nw.mnw	MODFLOW multiaquifer well file for Transient Simulation of Period 2013-2020 – No wells at all (not used)
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	13_20nw.nam	MODFLOW naming file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	13_20nw.oc	MODFLOW output control file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	13_20nw.out	MODFLOW output file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	13_20nw.pcg	MODFLOW solver file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	13_20nw.rch	MODFLOW recharge file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	13_20nw.riv	MODFLOW river package file for Transient Simulation of Period 2013-2020 – No wells at all

Directory	File Name	File Type and Use
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	13_20nw.wel	MODFLOW well file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	13_20nw._kx	MODFLOW horizontal hydraulic conductivity file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	13_20nw._kz	MODFLOW vertical hydraulic conductivity file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	13_20nw._s1	Groundwater Vistas unconfined storage array for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	13_20nw._s2	Groundwater Vistas confined storage array for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	2005_2012_no_wood_ wells.gwv	Groundwater Vistas file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	2013_2020_no_wood_ wells.gwv	Groundwater Vistas file for Transient Simulation of Period 2013-2020 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	5_12nw.bas	MODFLOW Basic File for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	5_12nw.bcf	MODFLOW BCF file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	5_12nw.cbb	MODFLOW cell centered flow file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/ Transient_pumping_	5_12nw.cbw	MODFLOW well mass balance for Transient Simulation of Period 2005-2012 – No wells at all

Directory	File Name	File Type and Use
Files/2005_2024_no_wells		
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	5_12nw.crc	MODFLOW recharge mass balance for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	5_12nw.ddn	MODFLOW unformatted drawdown for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	5_12nw.hds	MODFLOW unformatted head file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	5_12nw.kzi	MODFLOW vertical anisotropy file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	5_12nw.m96	MODFLOW 96 naming file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	5_12nw.mnw	MODFLOW multiaquifer well file for Transient Simulation of Period 2005-2012 – No wells at all (not used)
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	5_12nw.nam	MODFLOW naming file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	5_12nw.oc	MODFLOW output control file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	5_12nw.out	MODFLOW output file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	5_12nw.pcg	MODFLOW solver file for Transient Simulation of Period 2005-2012 – No wells at all

Directory	File Name	File Type and Use
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	5_12nw.rch	MODFLOW recharge file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	5_12nw.riv	MODFLOW river package file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	5_12nw.wel	MODFLOW well file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	5_12nw._kx	MODFLOW horizontal hydraulic conductivity file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	5_12nw._kz	MODFLOW vertical hydraulic conductivity file for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	5_12nw._s1	Groundwater Vistas unconfined storage array for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	5_12nw._s2	Groundwater Vistas confined storage array for Transient Simulation of Period 2005-2012 – No wells at all
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	east_tam_wells.dat	Groundwater Vistas import file for analytic elements for the East Tamarack well field
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	mf96.nam	MODFLOW96 naming file
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_no_wells	modflow.err	Groundwater Vistas log error file
MODFLOW-Vistas/ Transient_pumping_	modflow.in	MODFLOW instruction file

Directory	File Name	File Type and Use
Files/2005_2024_no_wells		
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	new_wood_wells.dat	Groundwater Vistas import file for analytic elements for Woodbury wells 15, 16, and 17
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	nowoodwells.dat	Groundwater Vistas import file for analytic elements for all SWUD county wells except Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	tal.dat	Groundwater vistas tal file
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	unsat.dat	File used in Groundwater Vistas for Doherty's dry cell treatment calculations
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_no_wells	WellImportReport.txt	Groundwater Vistas well important log file
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	13_20nnw.bcf	MODFLOW BCF file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	13_20nnw.cbb	MODFLOW cell centered flow file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	13_20nnw.cbw	MODFLOW well mass balance for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	13_20nnw.crc	MODFLOW recharge mass balance for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	13_20nnw.ddn	MODFLOW unformatted drawdown for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells

Directory	File Name	File Type and Use
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	13_20nnw.drn	MODFLOW drain package file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	13_20nnw.hds	MODFLOW unformatted head file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	13_20nnw.kzi	MODFLOW vertical anisotropy file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	13_20nnw.m96	MODFLOW 96 naming file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	13_20nnw.mnw	MODFLOW multiaquifer well file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells (not used)
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	13_20nnw.nam	MODFLOW naming file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	13_20nnw.oc	MODFLOW output control file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	13_20nnw.out	MODFLOW output file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	13_20nnw.pcg	MODFLOW solver file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	13_20nnw.rch	MODFLOW recharge file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_	13_20nnw.riv	MODFLOW river package file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells

Directory	File Name	File Type and Use
Files/2005_2024_new_wood_wells		
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	13_20nnw.wel	MODFLOW well file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	13_20nnw._kx	MODFLOW horizontal hydraulic conductivity file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	13_20nnw._kz	MODFLOW vertical hydraulic conductivity file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	13_20nnw._s1	Groundwater Vistas unconfined storage array for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	13_20nnw._s2	Groundwater Vistas confined storage array for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	2005_2012_no_wood_wells.gwv	Groundwater Vistas file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	2013_2020_no_wood_wells.gwv	Groundwater Vistas file for Transient Simulation of Period 2013-2020 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	5_12nnw.bas	MODFLOW Basic File for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	5_12nnw.bcf	MODFLOW BCF file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	5_12nnw.cbb	MODFLOW cell centered flow file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells

Directory	File Name	File Type and Use
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	5_12nnw.cbw	MODFLOW well mass balance for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	5_12nnw.crc	MODFLOW recharge mass balance for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	5_12nnw.ddn	MODFLOW unformatted drawdown for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	5_12nnw.hds	MODFLOW unformatted head file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	5_12nnw.kzi	MODFLOW vertical anisotropy file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	5_12nnw.m96	MODFLOW 96 naming file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	5_12nnw.mnw	MODFLOW multiaquifer well file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells (not used)
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	5_12nnw.nam	MODFLOW naming file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	5_12nnw.oc	MODFLOW output control file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_ Files/2005_2024_new_wood_wells	5_12nnw.out	MODFLOW output file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/ Transient_pumping_	5_12nnw.pcg	MODFLOW solver file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells

Directory	File Name	File Type and Use
Files/2005_2024_new_wood_wells		
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	5_12nnw.rch	MODFLOW recharge file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	5_12nnw.riv	MODFLOW river package file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	5_12nnw.wel	MODFLOW well file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	5_12nnw._kx	MODFLOW horizontal hydraulic conductivity file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	5_12nnw._kz	MODFLOW vertical hydraulic conductivity file for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	5_12nnw._s1	Groundwater Vistas unconfined storage array for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	5_12nnw._s2	Groundwater Vistas confined storage array for Transient Simulation of Period 2005-2012 – With all wells, including 3 new Woodbury wells
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	east_tam_wells.dat	Groundwater Vistas import file for analytic elements for the East Tamarack well field
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	mf96.nam	MODFLOW96 naming file
MODFLOW-Vistas/Transient_pumping_Files/2005_2024_new_wood_wells	modflow.err	Groundwater Vistas log error file

Directory	File Name	File Type and Use
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_new_wood_wells	modflow.in	MODFLOW instruction file
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_new_wood_wells	new_wood_wells.dat	Groundwater Vistas import file for analytic elements for Woodbury wells 15, 16, and 17
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_new_wood_wells	nowoodwells.dat	Groundwater Vistas import file for analytic elements for all SWUD county wells except Woodbury wells
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_new_wood_wells	tal.dat	Groundwater vistas tal file
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_new_wood_wells	unsat.dat	File used in Groundwater Vistas for Doherty's dry cell treatment calculations
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_new_wood_wells	WellImportReport.txt	Groundwater Vistas well important log file
MODFLOW-Vistas/ Transient_pumping_Files/2005_2024_new_wood_wells	new_wood_wells.dat	Groundwater Vistas import file for analytic elements for Woodbury wells 15, 16, and 17
MODFLOW-Vistas/ Transient_pumping_Files/misc_data_sets	Well_15_ob_wells.dat	Groundwater Vistas import file for analytic elements for the observation wells of the Well 15 pumping test
Trans_sim_results_spreadsheets	1988_5yrs.xls	Spreadsheet results of hydrograph data for the 1988 by 5 years simulations
Trans_sim_results_spreadsheets	2005-2024_results.xls	Spreadsheet results of hydrograph and flow data for simulations of 2005-2020
Trans_sim_results_spreadsheets	cumulativeflowresults_2005-2012.xls	Spreadsheet results of cumulative flow on south branch of valley creek for 2005-2012
Trans_sim_results_spreadsheets	population estimates for east wellfield modeling.xls	Spreadsheet for estimating population through year 2024
Trans_sim_results_spreadsheets	well_file_maker_LCMR_model.xls	Spreadsheet for making Groundwater Vista-compatible files and computing 2005-2020 pumping rates

In addition to these files there is a directory titled “Groundwater_Vistas_Executables”. This directory contains the following:

- A zipped file of the version of Groundwater Vistas used in this study. The authors of Groundwater Vistas have given permission for those without a license to load and use this software in demo mode (the default mode). This will allow users to open the Groundwater Vistas files for this study and view the contents. It will not allow for saving or altering of files or for running models.

- Two pdf files are included: a copy of the Groundwater Vistas user’s manual and a copy of the Groundwater Vistas’ command reference.

- WMOD96.exe. This is the DOS version of MODFLOW96, compatible with Groundwater Vistas-created MODFLOW files. This version will NOT run the model files for this study correctly because the dry cell-correction features are not implemented.

- MF96WIN32.dll. This is the Windows version of MODFLOW96, in double-precision mode. This is compatible with the Groundwater Vistas-created MODFLOW files for this study and includes the dry cell-correction.

- takaleak.exe. This is a DOS program that converts the Groundwater Vistas-created Kx and Kz arrays to a BCF-compatible format for running MODFLOW in a batch mode.

- pestgv.bat. This is a ascii batch file used in PEST simulations for calling and running MODFLOW. It is provided to illustrate how the windows executable MODFLOW program MF96WIN32.dll can be used in a DOS batch program.

Description of GIS Files

The following are descriptions of ESRI-GIS files included in the accompanying CDs. For many of these files, there are both UTM and County Coordinate versions of the same file. The "County" or "UTM" sub-directory designations are omitted from the table below. For shapefiles, only the root names are provides (there are 3 to 4 files for each shapefile). Metadata files also accompany many of these files. The user should consult these metadata files.

Directory	File Name	File Type	File Type and Use
Background_shape_files	approximate_model_boundary_utm	shape	MODFLOW and MIKE SHE model domains
Background_shape_Files	downstream_distance_meters_for_vb_south_branch	shape	Points in 500 m increments from upstream limit of south branch of Valley Creek to confluence with north branch
Background_shape_Files	dwsma_ramwash1	shape	Drinking Water Source Management Areas in Washington and Ramsey Counties (from MDH)
Background_shape_Files	lakes_in_model_domain	shape	Lakes in model domain (from DNR)
Background_shape_Files	monitor_well_nests_1_2_3	shape	Point locations of Woodbury Well 15 pumping test well nests 1, 2, and 3
Background_shape_Files	proposed_woodbury_wells	shape	Location of Wells 15, 16, and 17 for use in MODFLOW model simulations
Background_shape_Files	ramsey_roads_utm	shape	Roads in Ramsey County (MnDOT)
Background_shape_Files	rams_county_streams_utm	shape	Steams in Ramsey County (USGS)
Background_shape_Files	swuds_2002_wash_county_wells_utm	shape	2002 SWUDS database wells (DNR)
Background_shape_Files	w15_pump_test_wells_utm	shape	Monitoring and domestic wells used in Well 15 pumping test
Background_shape_Files	wash_roads_utm	shape	Roads in Washington County (MnDOT)
Background_shape_Files	was_county_streams_utm	shape	Streams in Washington County (USGS)
Background_shape_Files	water_table_m_computed_from_wells_and_lakes_utm	shape	Contour lines of water table derived from water table grid (meters, MSL)
Background_shape_Files	whpa_ramwash	shape	WHPAs in Washington and Ramsey Counties (MDH)
Grids/infiltration_from_MIKE_SHE	Annual_av_inperyear_legend.avl	Avl legend file	Sets legend for recharge grid files
Grids/infiltration_from_MIKE_SHE/1988_monthly	Infiltration_legend.avl	Avl legend file	Alternative legend for recharge grid files

Directory	File Name	File Type	File Type and Use
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_april_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_aug_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_dec_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_feb_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_jan_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_july_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_june_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_march_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_may_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_nov_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_oct_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1988_monthly	88_sept_av	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1989	Jan_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1989	Feb_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1989	Mar_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1989	Apr_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1989	May_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1989	Jun_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE

Directory	File Name	File Type	File Type and Use
Grids/infiltration_ from_MIKE_SHE/ 1989	Jul_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1989	Aug_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1989	Sep_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1989	Oct_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1989	Nov_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1989	Dec_89	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	Jan_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	Feb_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	Mar_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	Apr_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	May_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	Jun_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	Jul_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	Aug_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	Sep_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	Oct_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	Nov_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1990	Dec_90	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE

Directory	File Name	File Type	File Type and Use
Grids/infiltration_ from_MIKE_SHE/ 1991	Jan_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1991	Feb_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1991	Mar_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1991	Apr_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1991	May_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1991	Jun_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1991	Jul_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1991	Aug_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1991	Sep_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1991	Oct_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1991	Nov_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1991	Dec_91	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1992	Jan_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1992	Feb_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1992	Mar_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1992	Apr_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1992	May_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1992	Jun_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE

Directory	File Name	File Type	File Type and Use
Grids/infiltration_ from_MIKE_SHE/ 1992	Jul_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1992	Aug_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1992	Sep_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1992	Oct_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1992	Nov_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1992	Dec_92	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1993	Jan_93	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1993	Feb_93	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1993	Mar_93	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1993	Apr_93	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1993	May_93	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1993	Jun_93	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1993	Jul_93	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
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Grids/infiltration_ from_MIKE_SHE/ 1993	Sep_93	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1993	Oct_93	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1993	Nov_93	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1993	Dec_93	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE

Directory	File Name	File Type	File Type and Use
Grids/infiltration_ from_MIKE_SHE/ 1995	Jan_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1995	Feb_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1995	Mar_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1995	Apr_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1995	May_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1995	Jun_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1995	Jul_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1995	Aug_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1995	Sep_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1995	Oct_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1995	Nov_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1995	Dec_95	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1996	Jan_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1996	Feb_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1996	Mar_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1996	Apr_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1996	May_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1996	Jun_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE

Directory	File Name	File Type	File Type and Use
Grids/infiltration_ from_MIKE_SHE/ 1996	Jul_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1996	Aug_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1996	Sep_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1996	Oct_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1996	Nov_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1996	Dec_96	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	Jan_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	Feb_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	Mar_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	Apr_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	May_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	Jun_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	Jul_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	Aug_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	Sep_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	Oct_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	Nov_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/infiltration_ from_MIKE_SHE/ 1997	Dec_97	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE

Directory	File Name	File Type	File Type and Use
Grids/infiltration_ from_MIKE_SHE/ typical(1979)recharge	sep_70	Grid	Average monthly infiltration (mm/d) for specified month and year – from MIKE SHE
Grids/topography_ UTM	20m_topo	Grid	Ground surface topography (m, MSL) in 20m grid – from Washington County and DEM data
Grids/topography_ UTM	50m_topo	Grid	Ground surface topography (m, MSL) in 50m grid – from Washington County and DEM data
Grids/topography_ UTM	Wat_tab	Grid	Water table elevation grid (computed from well and lake data)
MIKE_SHE_data/ UTM	Vegetation_map_polygons	shape	Polygon shapefile of the 7 vegetation/land use types that are used in MIKE SHE in grid form
MIKE_SHE_data/ UTM	Veg_shape_legend	Avl legend	Legend for vegetation map
MIKE_SHE_data/ UTM/grids/	Crop_id	grid	Integer code (1 to 7) of vegetation and land use types in grid form
MIKE_SHE_data/ UTM/grids/	Gs_topo_100m	Grid	100-meter grid of ground surface topography (m, MSL) used in MIKE SHE model
MIKE_SHE_data/ UTM/grids/	Soil_id	grid	Integer code (1 to 33) of compiled soil profile types used in MIKE SHE for unsaturated flow modeling
MIKE_SHE_data/ UTM/grids/	Wat_tab_el	Grid	Water table elevation on 100-m grid centers used MIKE SHE modeling of unsaturated flow (m, MSL)
MIKE_SHE/ spreadsheet_data	Daily_precip_and_temp	Excel Spreadsheet	Precipitation and temperature data from St. Paul station – used as input for MIKE SHE
MIKE_SHE/ spreadsheet_data	LAI_&_RD	Excel Spreadsheet	LAI and root depth spreadsheet data for input for MIKE SHE
MIKE_SHE/ spreadsheet_data	Temperature_precip_data_&_Ref_ET	Excel Spreadsheet	Spreadsheet for calculating monthly reference ET for MIKE SHE
model_parameters/ base_elevations	Base_elevation_legend	Avl legend	Legend file for model base elevations (m, MSL)
model_parameters/ base_elevations	Layer_base_elevations_m_utm	shape	elevations for the 8 model layers in m, MSL
model_parameters/ base_elevations	Top_layer_1_m_utm	shape	Elevations for top of Layer 1, m, MSL
model_parameters/ boundary_conditions	Boundary_type_legend	Avl legend	Legend for model boundary types
model_parameters/ boundary_conditions	Boundary_types	shape	Types of boundary conditions in MODFLOW model
model_parameters/ boundary_conditions	Constant_head_values	Shape	Point shape file of constant head values (m, MSL)
model_parameters/ boundary_conditions	Groundwater_model_ grid	Shape	Finite difference grid polygons for MODFLOW model
model_parameters/ boundary_conditions	L1_river_cell_values_ utm	Shape	Values of stage, conductance and bottom elevation for river and drain features in Layer 1 of MODFLOW

Directory	File Name	File Type	File Type and Use
model_parameters/ boundary_conditions	Map_of_ch_boundaries _utm	Shape	Polygon map of constant head boundaries in MODFLOW
model_parameters/ calibration	Residual_meters_ legend	Avl legend	Legend file for plotting model residuals in meters
model_parameters/ calibration	Typical_yr_calibration_ data	Dbf file	Table of calibration residuals for typical year
model_parameters/ calibration/UTM	Steady_state_calibratio n_residuals_utm	Shape	Point data of all calibration residuals
model_parameters/ calibration/UTM	Steady_state_calibratio n_residuals_utm_layer 1	Shape	Point data of calibration residuals for layer 1
model_parameters/ calibration/UTM	Steady_state_calibratio n_residuals_utm_layer 2	Shape	Point data of calibration residuals for layer 2
model_parameters/ calibration/UTM	Steady_state_calibratio n_residuals_utm_layer 3	Shape	Point data of calibration residuals for layer 3
model_parameters/ calibration/UTM	Steady_state_calibratio n_residuals_utm_layer 4	Shape	Point data of calibration residuals for layer 4
model_parameters/ calibration/UTM	Steady_state_calibratio n_residuals_utm_layer 5	Shape	Point data of calibration residuals for layer 5
model_parameters/ calibration/UTM	Steady_state_calibratio n_residuals_utm_layer 6	Shape	Point data of calibration residuals for layer 6
model_parameters/ calibration/UTM	Steady_state_calibratio n_residuals_utm_layer 7	Shape	Point data of calibration residuals for layer 7
model_parameters/ calibration/UTM	Steady_state_calibratio n_residuals_utm_layer 8	Shape	Point data of calibration residuals for layer 8
model_parameters/ calibration/UTM/Stea dy_state_heads_ m_grids	Contours_grids _for heads legend	Avl legend	Avl file for steady-state calibrated head grids
model_parameters/ calibration/UTM/Stea dy_state_heads_ m_grids	Contours_lines _for heads legend	Avl legend	Avl file for steady-state calibrated head shape file for contours
model_parameters/ calibration/UTM/Stea dy_state_heads_ m_grids	Contours_of_l1_ss_hea ds_utm	Shape	Line contours of steady-state simulated heads – typical regional conditions, m, MSL, layer 1
model_parameters/ calibration/UTM/Stea dy_state_heads_ m_grids	Contours_of_l2_ss_hea ds_utm	Shape	Line contours of steady-state simulated heads – typical regional conditions, m, MSL, layer 2
model_parameters/ calibration/UTM/Stea dy_state_heads_ m_grids	Contours_of_l3_ss_hea ds_utm	Shape	Line contours of steady-state simulated heads – typical regional conditions, m, MSL, layer 3
model_parameters/ calibration/UTM/Stea	Contours_of_l4_ss_hea ds_utm	Shape	Line contours of steady-state simulated heads – typical regional

Directory	File Name	File Type	File Type and Use
dy_state_heads_ m_grids			conditions, m, MSL, layer 4
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	Contours_of_l5_ss_heads_utm	Shape	Line contours of steady-state simulated heads – typical regional conditions, m, MSL, layer 5
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	Contours_of_l6_ss_heads_utm	Shape	Line contours of steady-state simulated heads – typical regional conditions, m, MSL, layer 6
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	Contours_of_l7_ss_heads_utm	Shape	Line contours of steady-state simulated heads – typical regional conditions, m, MSL, layer 7
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	Contours_of_l8_ss_heads_utm	Shape	Line contours of steady-state simulated heads – typical regional conditions, m, MSL, layer 8
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	L1_heads	Grid	Grids of steady-state simulated heads – typical regional conditions, m, MSL, Layer 1
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	L2_heads	Grid	Grids of steady-state simulated heads – typical regional conditions, m, MSL, Layer 2
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	L3_heads	Grid	Grids of steady-state simulated heads – typical regional conditions, m, MSL, Layer 3
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	L4_heads	Grid	Grids of steady-state simulated heads – typical regional conditions, m, MSL, Layer 4
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	L5_heads	Grid	Grids of steady-state simulated heads – typical regional conditions, m, MSL, Layer 5
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	L6_heads	Grid	Grids of steady-state simulated heads – typical regional conditions, m, MSL, Layer 6
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	L7_heads	Grid	Grids of steady-state simulated heads – typical regional conditions, m, MSL, Layer 7
model_parameters/ calibration/UTM/Steady_state_heads_ m_grids	L8_heads	Grid	Grids of steady-state simulated heads – typical regional conditions, m, MSL, Layer 8
model_parameters/ K_zones	K_x_legend_m_per_day	Avl legend	Legend file for plotting Kx from MODFLOW model
model_parameters/ K_zones	K_z_legend_m_per_day	Avl legend	Legend file for plotting Kz from MODFLOW model

Directory	File Name	File Type	File Type and Use
model_parameters/ K_zones	K_zones_utm	Shape	Model hydraulic conductivity zones for all 8 layers
model_parameters/ pumping_wells	Steady_state_2003_rates_utm	Shape	Point file with SWUDS wells used in Typical model simulations of steady-state conditions – 2003 average pumping rates, cubic meters per day (DNR)
model_parameters/ recharge	Rech_in_yr_legend	Avl legend	Legend file for plotting recharge in inches per year
model_parameters/ recharge/ 1988_monthly	1988_monthly_rech_m_per_day	Shape	Monthly recharge for 1988 (dry year)
model_parameters/ recharge/ annual	Typical(1979)_recharge_utm	Shape	recharge for 1979 – typical year
model_parameters/ recharge/monthly_ recharge_point_data (UTM)	1989	Shape	Point data for monthly recharge (from MIKE SHE) for specified year – MODFLOW cell coordinates, point data (m/day)
model_parameters/ recharge/monthly_ recharge_point_data (UTM)	1990	Shape	Point data for monthly recharge (from MIKE SHE) for specified year – MODFLOW cell coordinates, point data (m/day)
model_parameters/ recharge/monthly_ recharge_point_data (UTM)	1991	Shape	Point data for monthly recharge (from MIKE SHE) for specified year – MODFLOW cell coordinates, point data (m/day)
model_parameters/ recharge/monthly_ recharge_point_data (UTM)	1992	Shape	Point data for monthly recharge (from MIKE SHE) for specified year – MODFLOW cell coordinates, point data (m/day)
model_parameters/ recharge/monthly_ recharge_point_data (UTM)	1993	Shape	Point data for monthly recharge (from MIKE SHE) for specified year – MODFLOW cell coordinates, point data (m/day)
model_parameters/ recharge/monthly_ recharge_point_data (UTM)	1995 Where's 1994?	Shape	Point data for monthly recharge (from MIKE SHE) for specified year – MODFLOW cell coordinates, point data (m/day)
model_parameters/ recharge/monthly_ recharge_point_data (UTM)	1996	Shape	Point data for monthly recharge (from MIKE SHE) for specified year – MODFLOW cell coordinates, point data (m/day)
model_parameters/ recharge/monthly_ recharge_point_data (UTM)	1997	Shape	Point data for monthly recharge (from MIKE SHE) for specified year – MODFLOW cell coordinates, point data (m/day)
model_parameters/ recharge/monthly_ recharge_point_data (UTM)	88_95_by_month	Shape	Point data for monthly recharge (from MIKE SHE) for specified years – MODFLOW cell coordinates, point data (m/day)
model_parameters/ recharge/monthly_ recharge_point_data (UTM)	Typical_monthly_ (1979)	Shape	Point data for monthly recharge (from MIKE SHE) for specified year – MODFLOW cell coordinates, point data (m/day)

Directory	File Name	File Type	File Type and Use
model_parameters/ recharge/ spreadsheets	88_95_by_month	dbf	Dbf file for recharge from MIKE SHE on monthly basis for period 88 to 95 m/day
model_parameters/ recharge/ spreadsheets	88_95_by_month	Excel Spreadsheet	XLS file for recharge from MIKE SHE on monthly basis for period 88 to 95 m/day
Model_results/ 88_for_5_years	Drawdown_15_legend	Avl legend file	Legend for drawdown of well 15
Model_results/ 88_for_5_years	Drawdown_all_wells_ legend	Avl legend	Legend for drawdown of all wells
Model_results/ 88_for_5_years	Drawdown_jan_vs_jun_ legend	Avl legend	Legend comparing drawdown of January vs June
Model_results/ 88_for_5_years/ drawdown_w15_only	Con_dd_m_jul_l1_15_o nly	Shape	Contours of drawdown in July for well 15 in layer 1
Model_results/ 88_for_5_years/ drawdown_w15_only	L1_w15	Grid	Drawdown for well 15 pumping – July – layer 1
Model_results/ 88_for_5_years/ drawdown_w15_only	L3_w15	Grid	Drawdown for well 15 pumping – July – layer 3
Model_results/ 88_for_5_years/ drawdown_w15_only	L5_w15	Grid	Drawdown for well 15 pumping – July – layer 5
Model_results/ 88_for_5_years/ drawdown_w15_only	L5_w15b	grid	Drawdown for well 15 pumping – July – layer 5 (alternative)
Model_results/ 88_for_5_years/ no_new_wells/utm/gr ids	L1_7_n	grid	Drawdown in layer 1 for July with no new wells
Model_results/ 88_for_5_years/ no_new_wells/utm/gr ids	L3_7_n	Grid	Drawdown in layer 3 for July with no new wells
Model_results/ 88_for_5_years/ no_new_wells/utm/gr ids	L5_7d_n	grid	Drawdown in layer 5 with no new wells
Model_results/ 88_for_5_years/ well_15_at_1000_gp m/utm	L5_aug_yr_1	shape	Contours of drawdown in layer 5 for august in first year of pumping well 15 at 1000 gpm
Model_results/ 88_for_5_years/ well_15_at_1000_gp m/utm/grids	L1_1_1	Grid	Drawdown in Layer 1 in January with well 15 pumping at 1000 gpm
Model_results/ 88_for_5_years/ well_15_at_1000_gp m/utm/grids	L1_7_1	Grid	Drawdown in Layer 1 in July with well 15 pumping at 1000 gpm
Model_results/ 88_for_5_years/ well_15_at_1000_gp	L3_1_1	Grid	Drawdown in Layer 3 in January with well 15 pumping at 1000 gpm

Directory	File Name	File Type	File Type and Use
m/utm/grids			
Model_results/ 88_for_5_years/ well_15_at_1000_gpm/utm/grids	L3_7_1	Grid	Drawdown in Layer 3 in July with well 15 pumping at 1000 gpm
Model_results/ 88_for_5_years/ well_15_at_1000_gpm/utm/grids	L5_1_b	Grid	Drawdown in Layer 5 in January with well 15 pumping at 1000 gpm
Model_results/ 88_for_5_years/ well_15_at_1000_gpm/utm/grids	L5_7_d	grid	Drawdown in Layer 5 in July with well 15 pumping at 1000 gpm
model_results\2005_to_2020\UTM\drawdowns_ft_June_2012	7_2012_dd_ft_l3	Shape	Drawdown in feet for July 2012 in layer 3
model_results\2005_to_2020\UTM\drawdowns_ft_June_2012	7_2012_dd_ft_l5	Shape	Drawdown in feet for July 2012 in layer 5
model_results\2005_to_2020\UTM\drawdowns_ft_June_2012	7_2012_dd_ft_l8	Shape	Drawdown in feet for July 2012 in layer 8
model_results\2005_to_2020\UTM\drawdowns_ft_June_2012	7_2012_dd_ft_wt	Shape	Drawdown in feet for July 2012 in water table
model_results\2005_to_2020\UTM\drawdowns_ft_July_2019	l1_jul_2019_dd_ft_nowood	Shape	Drawdown in feet for July 2012 in water table
model_results\2005_to_2020\UTM\drawdowns_ft_July_2019	l3_jul_2019_dd_ft_nowood	Shape	Drawdown in feet for July 2012 in layer 3
model_results\2005_to_2020\UTM\drawdowns_ft_July_2019	l8_jul_2019_dd_ft_nowood	shape	Drawdown in feet for July 2012 in layer 8
model_results\2005_to_2020\UTM\drawdowns_ft_July_2019	L5_jul_2019_dd_ft_nowood		Drawdown in feet for July 2012 in layer 5
Arc_projects	mike_she_data.apr	Arcview 3 project	Arcview 3 project of MIKE SHE data
Arc_projects	modflow_1988_results.apr	Arcview 3 project	Arcview 3 project of MODFLOW simulation results for dry year
Arc_projects	modflow_2005-2020_results.apr	Arcview 3 project	Arcview 3 project of MODFLOW simulation results for transient simulation of 2005 to 2020
Arc_projects	modflow_model_parameters.apr	Arcview 3 project	Arcview 3 project of MODFLOW input parameters

Glossary of Terms

absolute pressure: (cf gage pressure) the sum of atmospheric pressure plus the pressure due to the height of water above the measuring location.

air-line: device used to measure water levels in wells. Consists of a tube extending to a known depth in the well. Air pressure required to force water out of the tube is measured and converted to depth of water above the bottom of the tube.

alluvial: referring to deposition of sediment by flowing water.

anisotropy: condition in which the magnitude of a physical characteristic varies with direction (e.g., hydraulic conductivity).

aquifer: a formation, group of formations, or part of a formation that contains sufficient saturated, permeable material to yield significant and usable quantities of water to wells and springs.

aquifer test-(see pumping test)

aquitard **-** (see confining unit)

artesian aquifer **-** (see confined aquifer)

available drawdown: for a pumping well, the distance from static water level to approximately 5 feet to 10 feet above the pump intake.

bedrock: rock beneath the soil in an undisturbed state.

barometric efficiency: ratio of changes in water level in well to the change in atmospheric pressure in consistent units.

bioturbated: referring to sediment that has undergone disturbance from burrowing creatures prior to becoming rock.

boundary effects: influences on groundwater flow within an aquifer due to hydraulic features in hydraulic connection with the aquifer, e.g., rivers, lakes, faults, leaky confining units, etc. Boundary effects may increase or decrease the amount of drawdown that would take place if the aquifer were of infinite areal extent.

calcareous: containing calcium carbonate.

calibration: the process of adjusting a groundwater model so that it closely approximates measured observations (typically water levels).

capillary fringe: the zone of saturation above the water table in which water is held by surface tension.

capture zone: The area or volume of the aquifer in which water moves toward a well, spring, or other discharge point.

casing storage effect: deviation from the predicted time-drawdown curve in an observation well caused by pumping of water from storage in the well casing. The result is under-stressing of the aquifer early in the pumping phase. This effect usually dissipates within the first few minutes of the test.

chert: extremely fine-grained silica, similar to flint.

conceptual hydrogeologic model: the abstraction of the main elements of groundwater flow in a particular area, schematically illustrating the relationships between recharge and discharge.

conductance: the hydraulic conductivity of a material, divided by its thickness, and multiplied by an area. Conductance is a term used in the groundwater modeling code, MODFLOW, for parameters of the bottom of rivers, lakes, and drains.

cone of depression: an area of lowered head (water pressure) centered on a pumping well.

confined aquifer: (artesian aquifer) an aquifer in which the water levels in wells stand above the top of the aquifer, and that, when pumped, receives no recharge from or through the confining layers above or below the aquifer.

confining unit: a unit that has significantly lower ability to transmit water than the aquifers that it separates.

contaminant transport: the movement of an undesirable constituent in groundwater.

crystalline: referring to rocks with mineral crystals large enough to be discerned without a microscope. Typically, refers to rocks formed by molten lava that solidified slowly under ground, such as granite.

delayed gravity response: a characteristic of unconfined aquifers, the rate of drawdown in response to pumping declines temporarily due to draining of the dewatered part of the aquifer under the influence of gravity.

Devonian: geologic period from 410 to 355 million years ago.

dolomite: a term for rock that was formerly limestone but has subsequently been changed through a process of "dolomitization", in which some calcium in calcium carbonate has been replaced by magnesium, thereby altering the mineral composition of the limestone.

dolostone: dolimitic limestone.

drawdown: reduction in head (water pressure) in response to pumping, the difference between static water level and the water level at a given time during the pumping phase of a pumping test.

drift: glacially derived or deposited material, including both outwash and till deposits.

elastic response: release of water from storage in an aquifer as the aquifer material compresses and the water expands due to lowering of pressure as a well is pumped.

eperic sea: shallow sea covering portions of the continent.

evaporation: the transformation of water from a liquid to a gas, which occurs at a rate dependent upon humidity, wind, and air temperature.

evapotranspiration: the removal of water from the ground by the respiration process of plants, via their roots, where upon the water is used for plant growth and a portion may be evaporated by the plant.

fault: a structural break in rock, in which movement causes a displacement in elevation.

flowing well: a well completed in a confined aquifer at a point where the head is at a higher elevation than the top of the well casing.

flow-through lake: a lake or pond that is a surface expression of groundwater in which groundwater discharges into the lake along the upgradient side and lake water discharges into the groundwater along the downgradient side.

fossiliferous: containing abundant fossils.

friable: breaks apart easily in the hand.

full penetration: condition in which a well is screened over the entire saturated thickness of an aquifer.

gage pressure: (cf absolute pressure) pressure in excess of atmospheric pressure.

gaining stream: a portion of a stream, creek, or river along which groundwater is discharging into the surface-water body and thereby adding flow to the surface-water body.

glacial deposits: unconsolidated material derived from glaciers.

glacial drift-(see drift)

glacial outwash-(see outwash)

glacial till- (see till)

glacier: a mass of ice with definite lateral limits, with motion in a definite direction, and originating by the compaction of snow with pressure.

glauconitic: containing glauconite – a greenish clay substance formed from fish excreta.

groundwater: water below the surface of the earth, filling void space to saturation and below any capillary fringe.

groundwater model: a mathematical (usually computerized) description of how groundwater flows, using site-specific data and appropriate assumptions. Groundwater models are used to understand, describe, and predict groundwater flow conditions.

head: (see hydraulic head)

hydraulic conductivity: the volume of water at the existing viscosity that will move in unit time under a unit hydraulic gradient through a unit area of aquifer measured at right angles to the direction of flow. Can typically be used interchangeably with “permeability”. Has units of velocity.

hydraulic gradient: the difference in hydraulic head between two measuring points divided by the distance between the measuring points.

hydraulic head: the level to which water in a well would rise measured relative to a datum, commonly sea level.

hydrogeology: the science and study of groundwater and the physical conditions that control groundwater flow.

hydrograph: water level or change in water level at a location, such as a well or river stage monitoring location, plotted as a function of time.

hydrostratigraphic unit: traceable or mappable geologic feature(s) that influences groundwater flow. Examples of hydrostratigraphic units include aquitards and aquifers.

igneous: rocks formed by solidification from a molten state, such as granite and basalt.

infiltration: the process of water (from precipitation, snow melt, or stream loss) soaking below the ground surface and migrating to groundwater.

interference effects: changes in water levels caused by changes of stress on the aquifer other than pumping wells designated for an aquifer test. Interference effects can arise from cycling of pumps in other wells, changes in barometric pressure, changes in river stage or lake level, tides, etc.

isotropy: condition in which the magnitude of a physical characteristic does not vary with direction (e.g., hydraulic conductivity).

karst: the development of extensive interconnected cavities in dolomite and limestone by the dissolution of the rock.

leakance: the opposite of resistance (see resistance).

leaky-confined aquifer: an aquifer in which the water levels in wells stand above the top of the aquifer and that, when pumped, receives discharge from a bounding confining layer or from another aquifer through the intervening confining layer.

limestone: a bedded sedimentary rock consisting chiefly of calcium carbonate.

losing stream: a portion of a stream, creek, or river along which surface water is discharging from the surface-water body and thereby losing flow from the surface-water body.

matric potential: pressure in unsaturated soil, relative to pressure of zero.

metamorphic: rocks formed by changes to sedimentary or igneous rocks through the interaction of pressure and temperature over long time periods.

MIKE SHE: graphical user interface of coupled hydrologic models, developed by the Danish Hydrologic Institute, with capabilities of simulating unsaturated flow, runoff, evaporation, transpiration, channel flow, and saturated flow.

model: an approximation (usually mathematical) that describes a physical phenomenon and can be used for a specific purpose.

MODFLOW: a computer groundwater flow modeling code developed by the US Geological Survey that uses the finite-difference method to solve mathematical equations that describe groundwater flow.

monitoring well: a well completed below the water table for the purpose of obtaining data on water levels and/or water quality.

objective function: the difference between simulated results and measured values, for which inverse optimization codes such as PEST and UCODE attempt to minimize.

observation well: a well, typically not pumping, that is used to monitor water levels.

oolitic: containing oolites – small, spherical deposits of iron hydroxide.

Ordovician: The period during the Paleozoic era between 500 and 440 million years ago.

orifice tube: device used to measure flow rate. Consists of a pipe with a smaller-diameter, circular opening and a piezometer on the pipe centerline. The pressure in the pipe, measured as height of water in the piezometer, is converted to flow rate using charts.

outcrop: the exposure of a geologic unit at the ground's surface. Usually refers to a surface exposure of bedrock.

outwash: sand and/or gravel deposits, often of widespread nature, derived from the melt waters originating from a glacier.

outwash plain: a large, typically flat area where glacially-derived sand and gravel is deposited.

overburden: unconsolidated (loose) soil material that overlies bedrock.

partial penetration: condition in which a well is screened over part of the saturated thickness of an aquifer.

permeability: term commonly used as synonymous with hydraulic conductivity. However, the term intrinsic permeability refers to the proportionality constant relating discharge to fluid characteristics and hydraulic gradient.

piezometer: a tube or well designed to obtain water levels from a discrete depth in an aquifer or aquitard.

piezometric head: the elevation water rises to in a well that is not being pumped.

piezometric surface: the levels to which water will rise in a well that is screened over a short interval. The water table is the most common example of a piezometric surface but confined aquifers can have piezometric surfaces that are either above or below the water table.

potentiometric surface: similar to piezometric surface.

Precambrian: the geologic era older than about 570 million years ago. Precambrian literally means "before life."

pumping test: the process of estimating the transmissivity, hydraulic conducivity, and/or storage conditions of an aquifer by pumping one well at a know rate(s) for a period of time and monitoring the change in water levels in monitoring wells.

Quatenary: The geologic period from about 1.5 million years ago until the present. Includes the Pleistocene epoch, when continental glaciation occurred.

recharge: the addition of groundwater from other sources (typically on the ground surface, such as infiltrating precipitation).

residual drawdown: the difference between static water level and the water level at a given time during the recovery phase of a pumping test.

resistance: a parameter that describes an aquitard's ability to control leakage between aquifers. Expressed in units of days.

Richards Equation: non-linear differential equation that describes the flow of water in the unsaturated zone as a function of moisture content, matric potential, and hydraulic conductivity.

root zone: the area below the ground surface where plants extract water from the soil.

sandstone: rock made from the cementation of sand grains.

saturated thickness: distance between the top and bottom of an aquifer.

sedimentary: referring to rocks formed from the solidification of gravel, sand, silt, or clay. Examples include limestone and sandstone.

seepage face: the surface on a rock or soil exposure where groundwater is discharging (similar to a spring but typically more wide spread). Often associated with road cuts or quarries.

shale: a rock formed by the cementation of mud and clay.

siltstone: a rock formed by the cementation of silt.

sink: a mechanism for withdrawing or discharging groundwater, such as a well.

slug test: a procedure used in a non-pumped well whereby a cylinder of known volume is placed into a well, below the water, and extracted, during which time water levels are monitored. Used to estimate hydraulic conductivity without pumping.

source: a mechanism for adding water to the groundwater flow system, such as infiltrating precipitation.

specific capacity: ratio of pumping rate of a well divided by the drawdown measured in the well after the water level has stabilized.

specific capacity test: the process of pumping a well and monitoring the water level in the well after it is stabilized – used to estimate hydraulic conductivity.

specific retention: ratio of the volume of water retained against the force of gravity in a porous material to the volume of material, due to capillary action.

specific storage: the volume of water a confined aquifer releases from or takes into storage per unit surface area of aquifer per unit change in head (storage coefficient) divided by the saturated thickness.

specific yield: the ratio of (1) the volume of water that saturated porous material under water table conditions will yield by gravity to (2) the volume of the saturated material.

spring: a location on the surface of the earth where groundwater discharges.

steady state: a condition in which groundwater flow, as typically measured by hydraulic head, does not change with time. Mathematically, steady state has a more specific meaning – no change in the storage of water in the aquifer.

steady-state stage: the later part of a pumping test, during which the rate of drawdown becomes negligible.

storage coefficient: the volume of water a confined aquifer releases from or takes into storage per unit surface area of aquifer per unit change in head.

strata: layers of geologic material.

stratigraphic column: a schematic description of the layers of geologic units in a particular area.

stratigraphy: the systematic description of the sequence of layers of geologic units.

subcrop: an area where a geologic unit (typically a bedrock unit) is present immediately below another geologic unit (typically unconsolidated material such as sand, gravel, or clay)

Theis equation: analytical solution for drawdown during pumping of a confined aquifer of infinite areal extent.

Theis curve: time-drawdown curve based on the Theis equation.

till: glacially deposited, fine-grained, silty and clayey deposits of typically low permeability.

transient stage: the early part of a pumping test, during which the rate of drawdown is rapid.

transmissivity: that rate at which water of the prevailing viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

type curve: time-drawdown curve based on an analytical solution (e.g., Theis equation). Actual field measurements may be matched to the type curve to determine aquifer parameters.

unconfined aquifer: (water table aquifer) an aquifer in which the water levels in wells define the top of the aquifer (i.e., unsaturated material with similar texture lies above the water table).

volcanic: referring to rocks formed by the extrusion of molten lava on the ground surface.

water table: the surface of the uppermost, continuous groundwater, below which saturated conditions exists at pressures above one atmosphere.

well efficiency: a measure of head losses at the well that are the result of well construction and pumping. A 100-percent efficient well has no head losses at the well and the water level in the well is equal to the water level in the aquifer immediately adjacent to the well.

well interference: water-level changes measured in a pumped well or observation well caused by another pumped well.

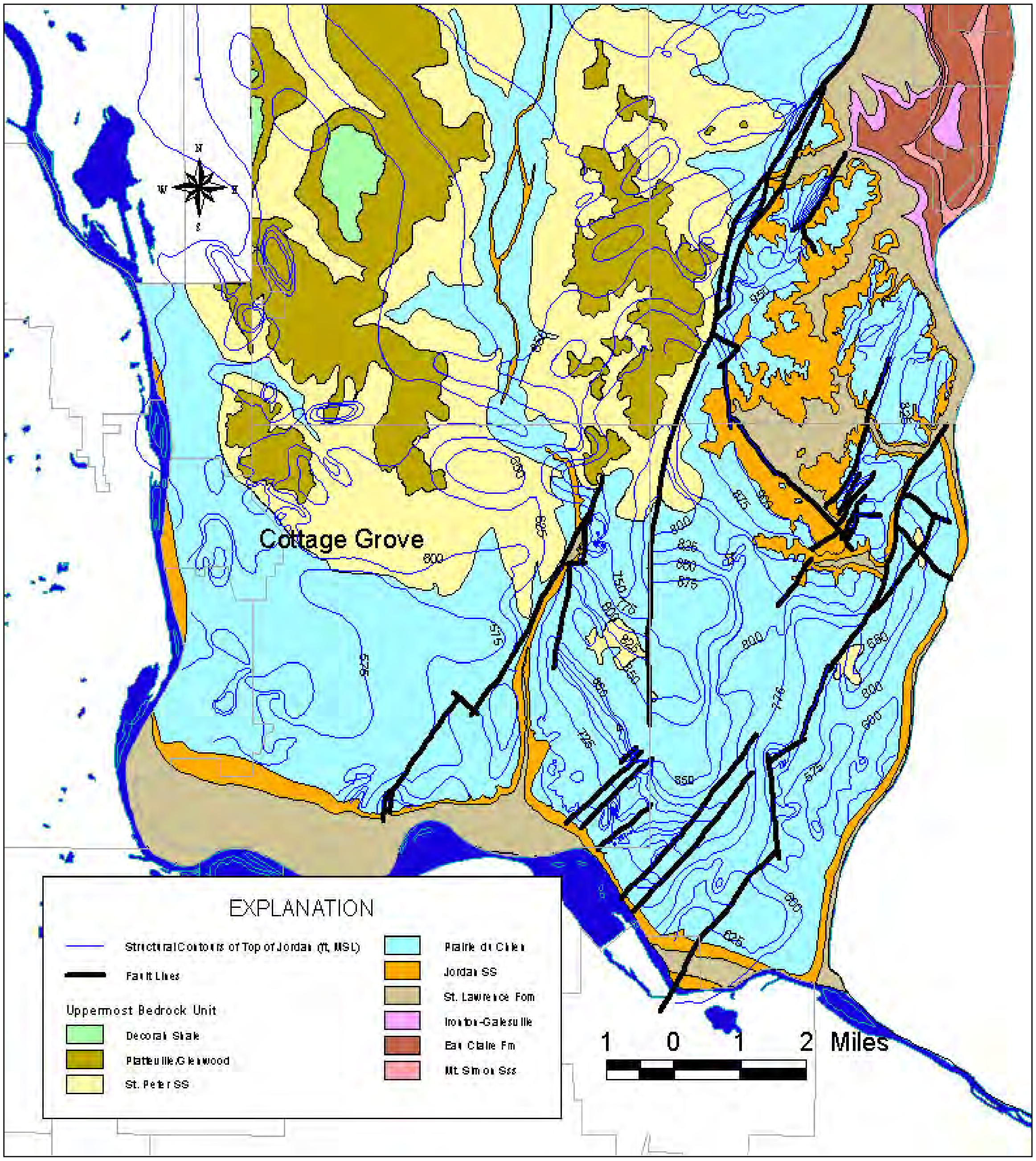
wellhead protection area: the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach the water well or wellfield.

well loss: reduction in the water level in a well during pumping due to losses of energy from turbulence or friction in the well screen and pump.

GEOLOGIC UNITS	DESCRIPTION	HYDROSTRATIGRAPHIC UNIT	MODFLOW Model Layer
Glacial Drift/Recent Alluvium	mostly silt, sand, and gravel with till lenses and lake deposits	Aquifer with some local aquitard units	Typically Layers 1 & 2
Decorah Shale	glauconitic shale	Aquitard	Not in model
Platteville Formation and Glenwood Shale	massive to thinly bedded, fractured dolomite & shale	poorly transmissive aquifer to aquitard	Not in model
St. Peter Sandstone	upper 100 feet is uniform fine sandstone; lower 50 feet is shale	Aquifer Aquitard	Typically Layer 2 Leakance on Layer 2
Prairie du Chien Group	Shakopee Fm (upper unit) contains zones of highly fractured rock; Oneota Dol. (lower) is massive	Aquifer (Shakopee) Aquitard (Oneota)	Typically Layer 3 Typically Layer 4
Jordan Sandstone	medium sandstone with fractures and some cementation	Aquifer	Typically Layer 5
St. Lawrence Formation	dolomitic shale	Aquitard	Typically Layer 6
Franconia Formation	calcareous sandstone to shaley sandstone	Aquifer (upper Franconia) Aquitard (lower Franconia)	Typically Layer 7 Leakance on Layer 7
Ironton-Galesville Sandstones	fine to medium sandstone	Aquifer	Layer 8
Eau Claire Formation	dolomitic shale	Aquitard	Not in model
Mt. Simon and Hinckley Sandstones	sandstone	Aquifer	Not in model
Precambrian Crystaline Rocks	undifferentiated crystalline and volcanic rocks	Aquitard	Not in model

Figure 1

Hydrostratigraphic Column for Southern Washington County



(adapted from Mossler, 2003)

Figure 2

Location of Faults in Southern Washington County

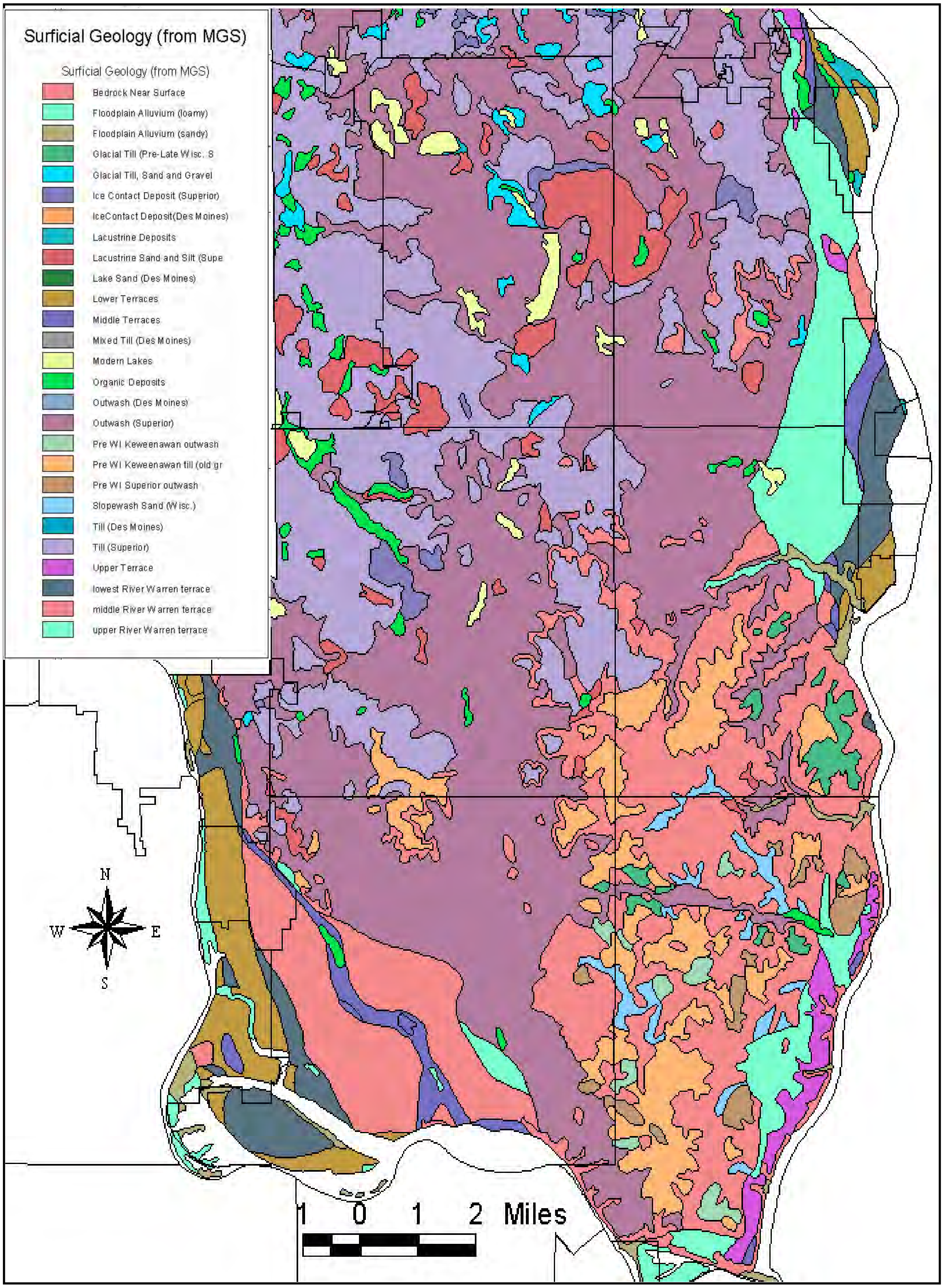
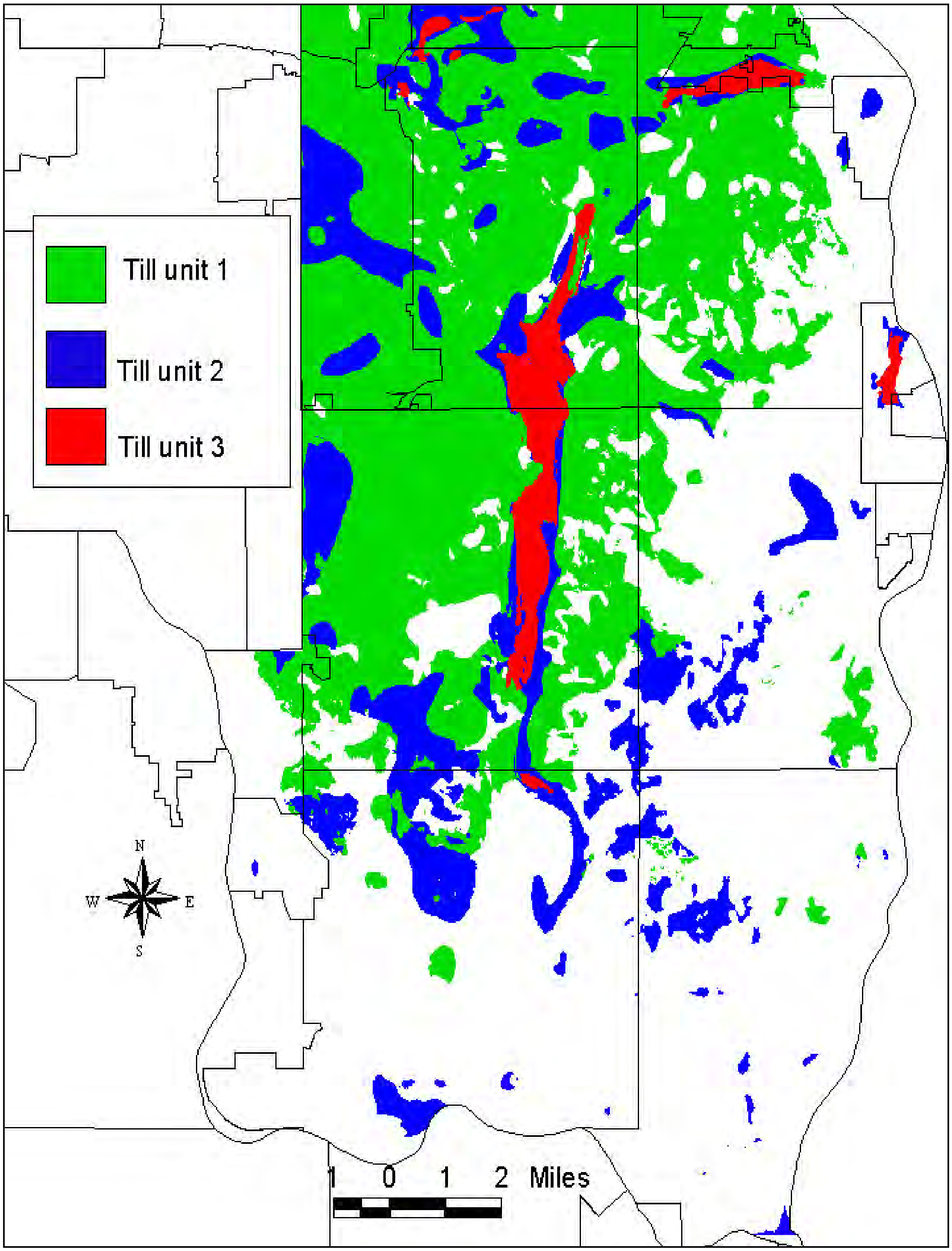


Figure 3

Surficial Geology of Southern Washington County



(adapted from MGS Grid Data)

Figure 4

Glacial Till Units in South Washington County

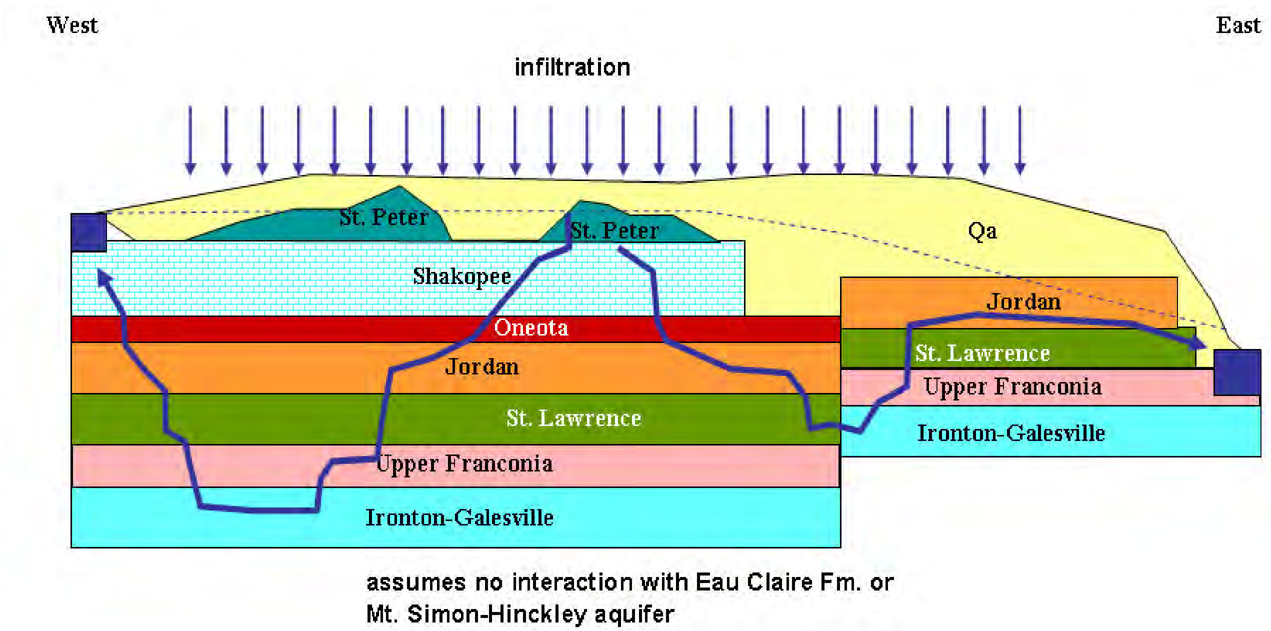


Figure 5

Conceptual Hydrogeologic Model

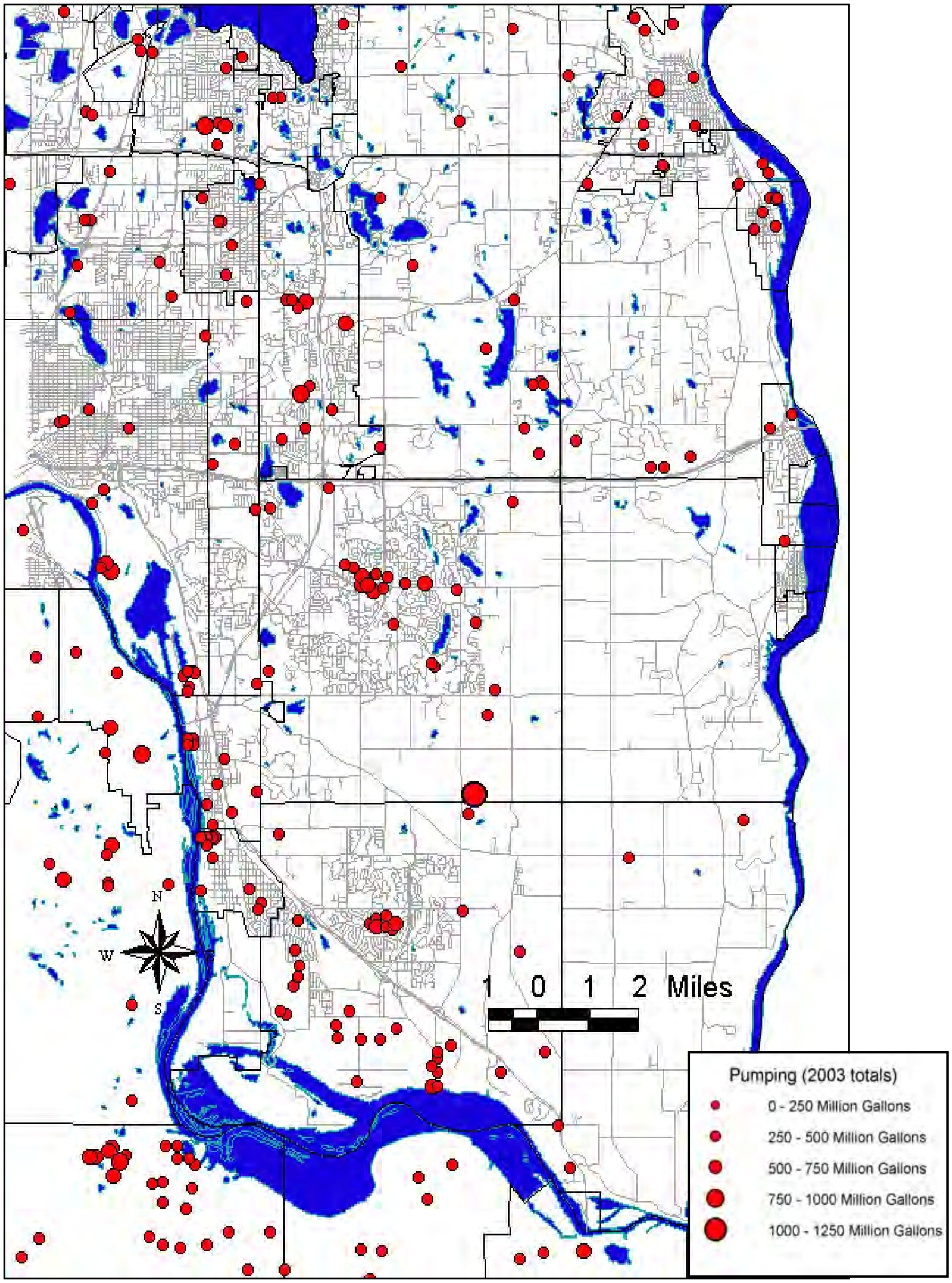


Figure 6

Pumping Rates for Appropriated Wells (2003)

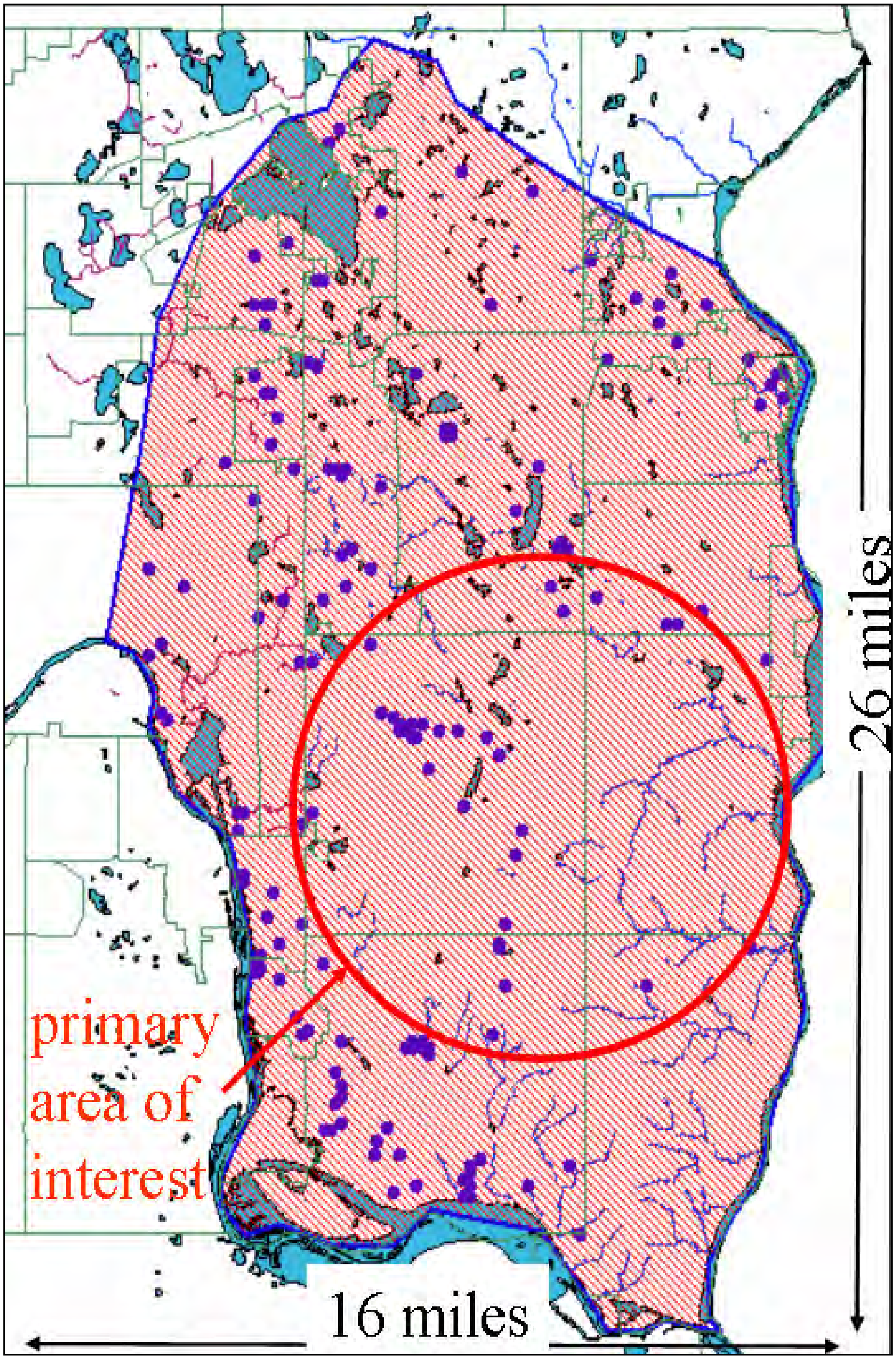


Figure 7

Model Domain and Area of Primary Interest

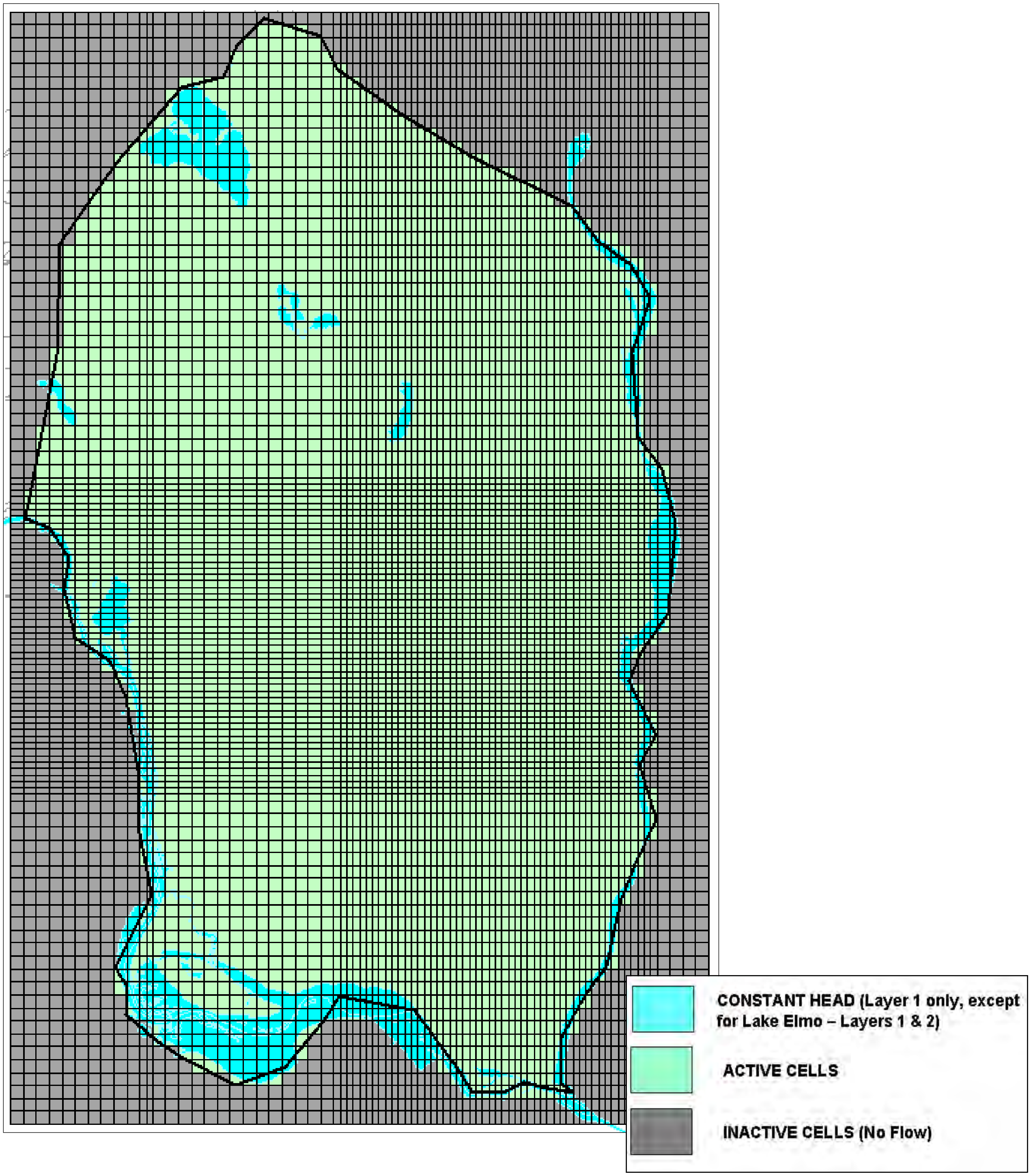


Figure 8

Finite-Difference Grid for Regional Model and Boundary Conditions

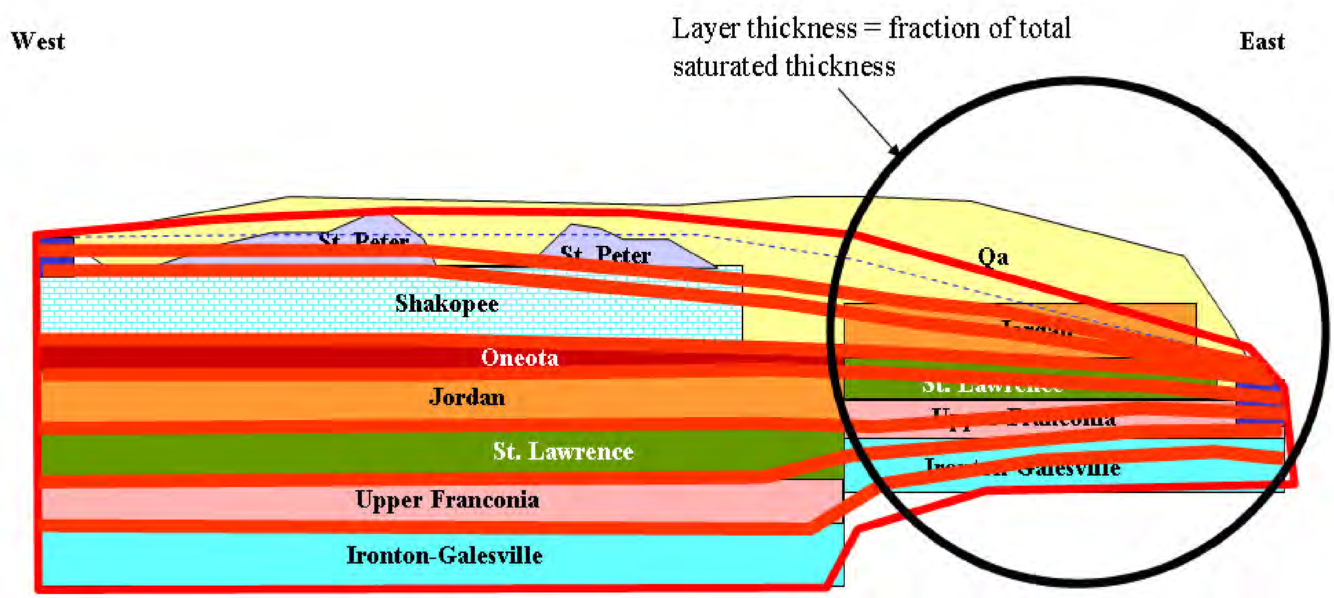


Figure 9

Schematic Illustration of Computation Layer Assignments

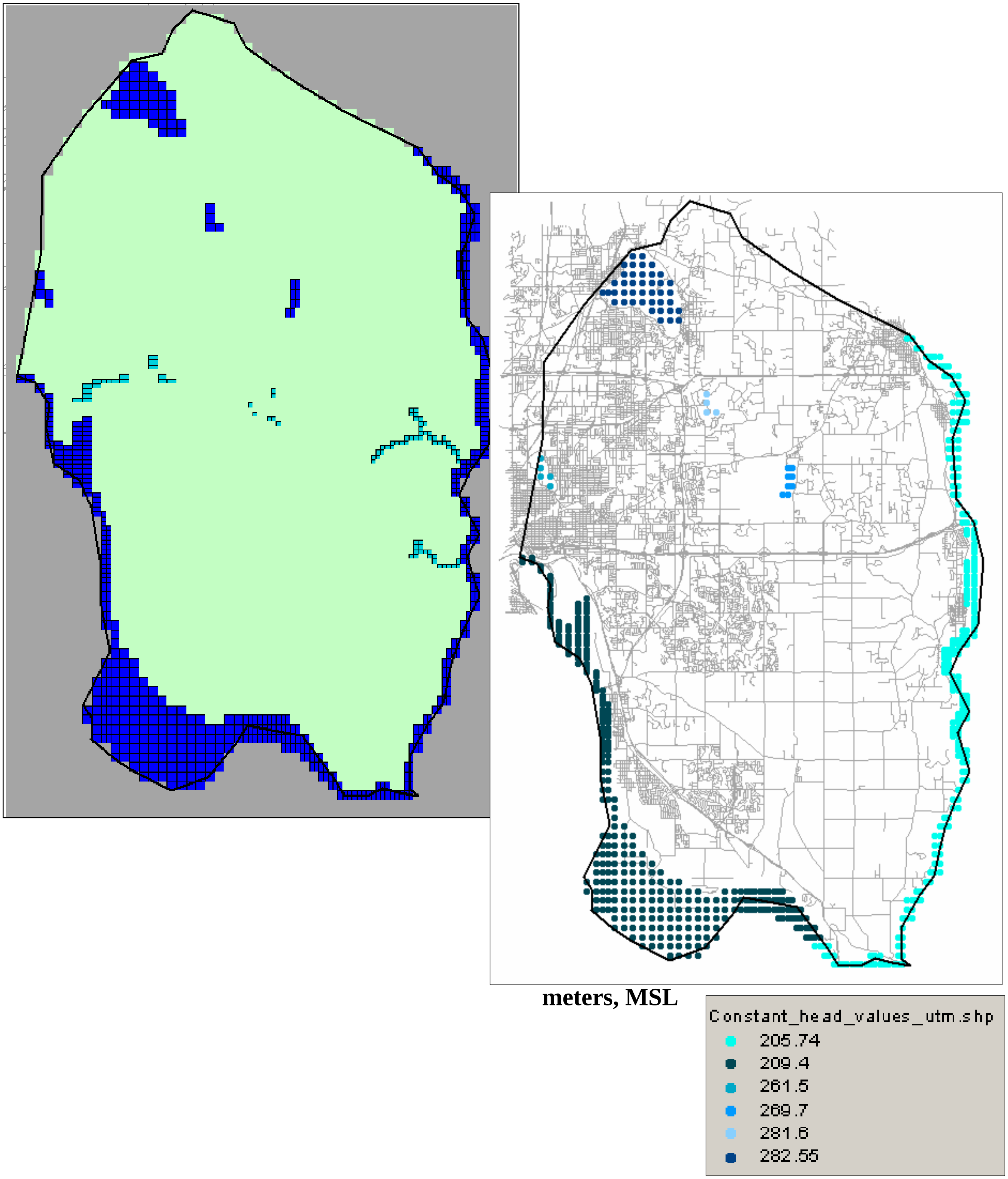


Figure 10

Constant Head Cells in Layer 1

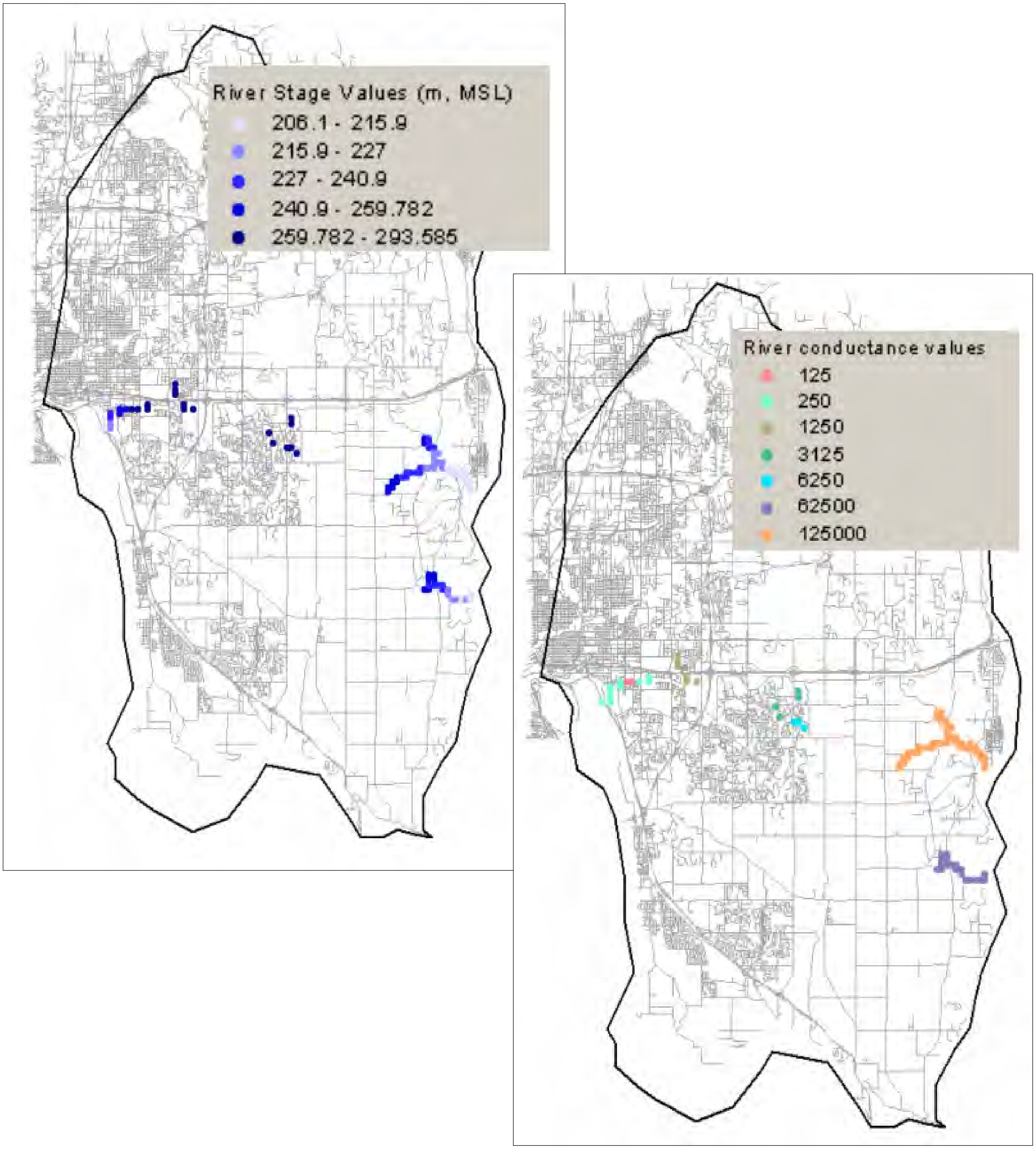


Figure 11

River and Drain Package Features in Layer 1

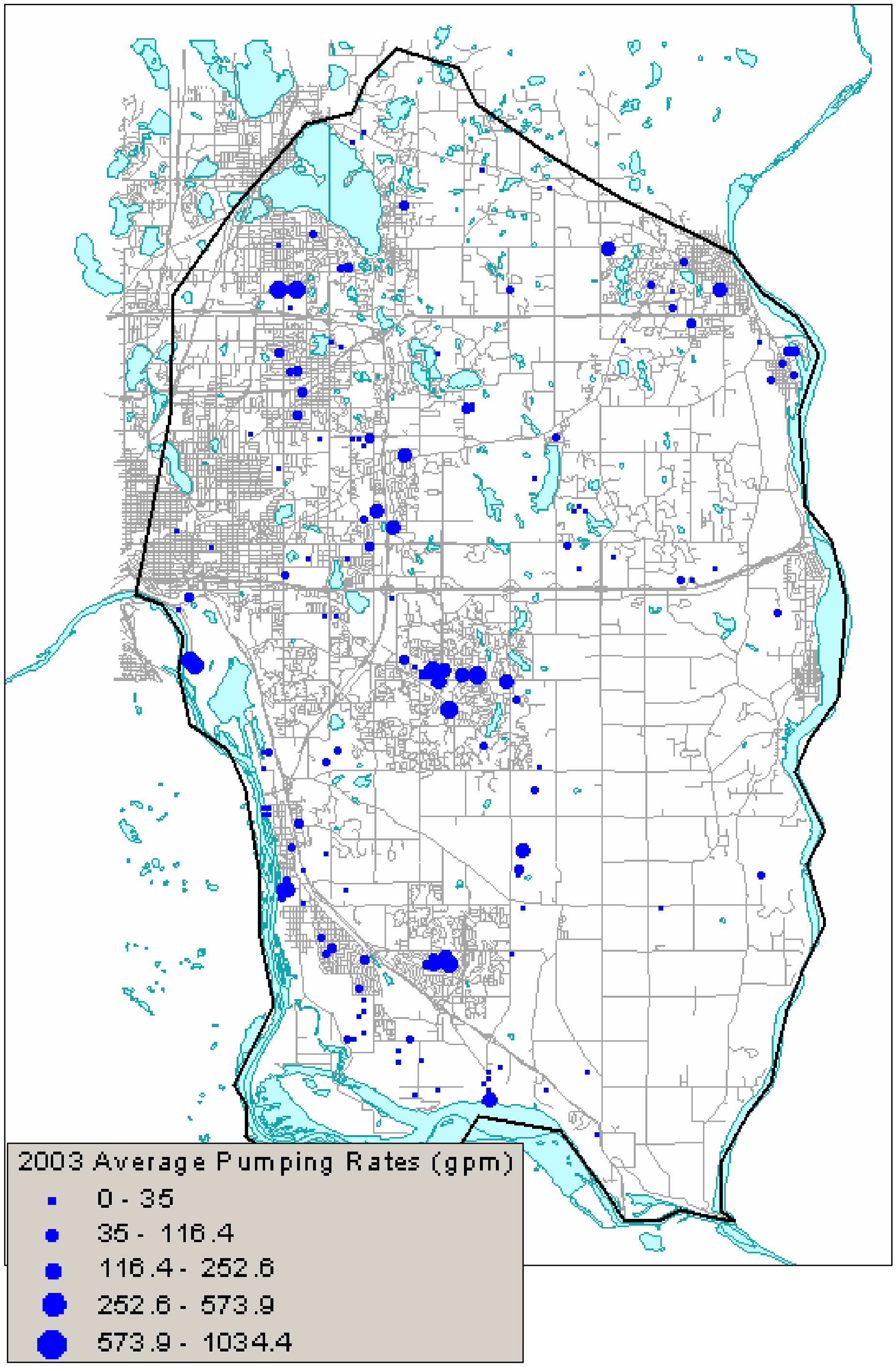


Figure 12

High Capacity Wells in Model (2003 pumping rates shown)

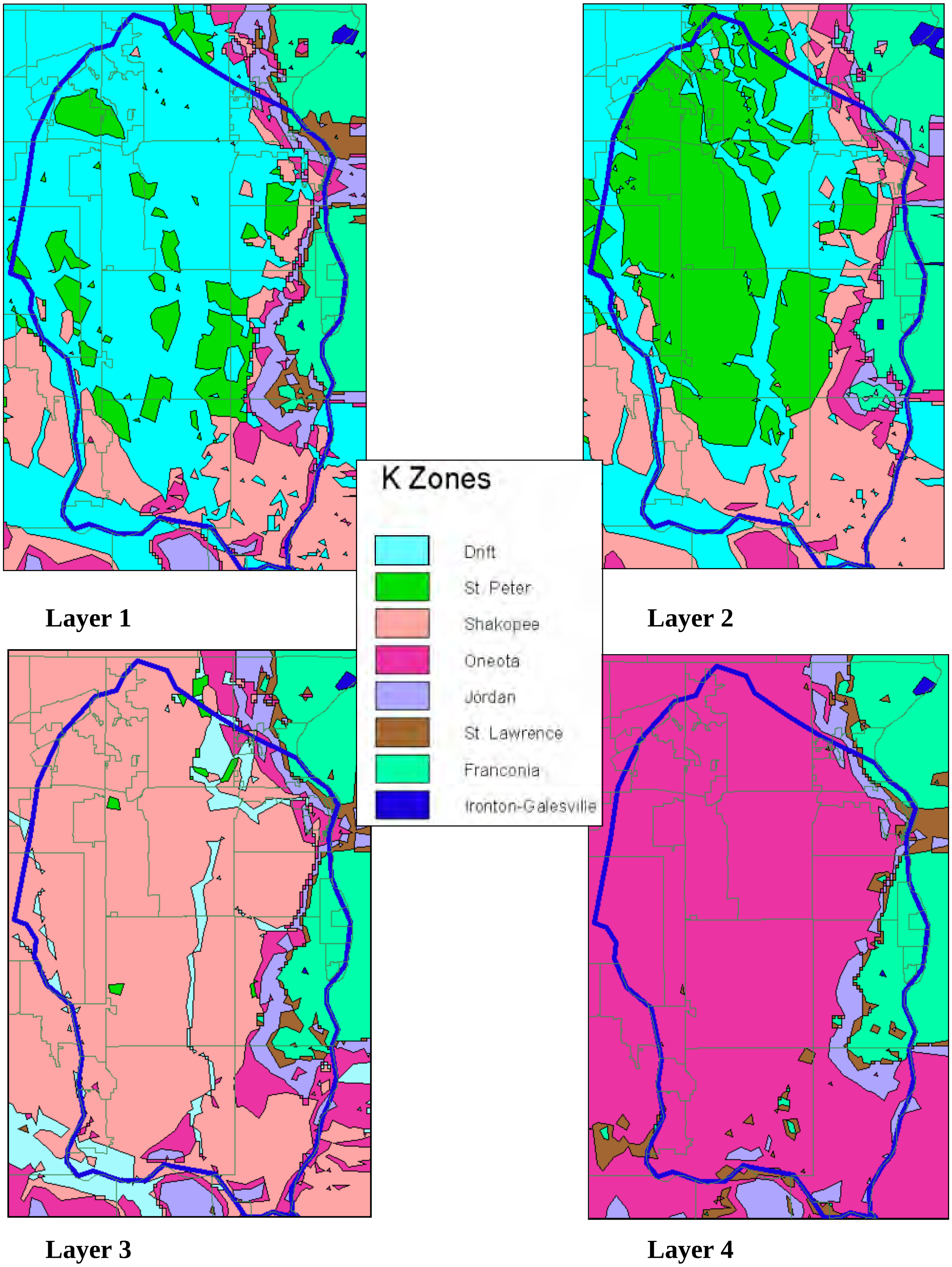
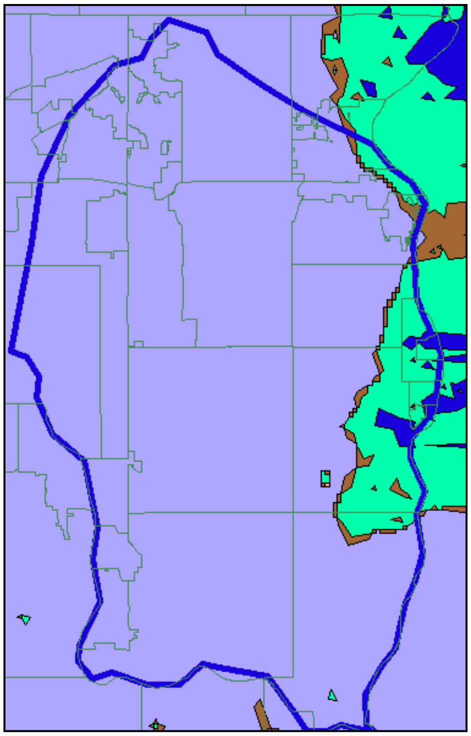
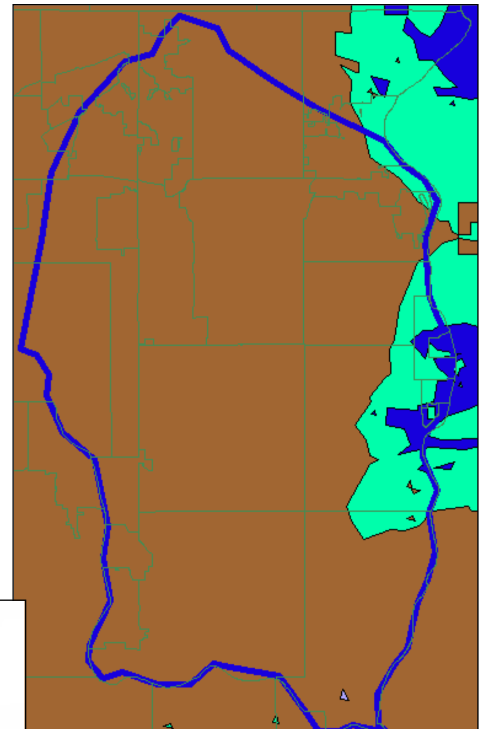


Figure 13

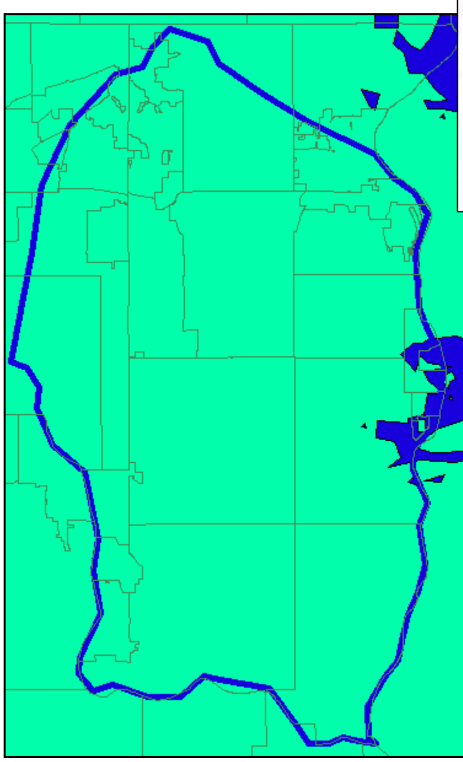
Geologic Representation in Computation Layers 1 to 4

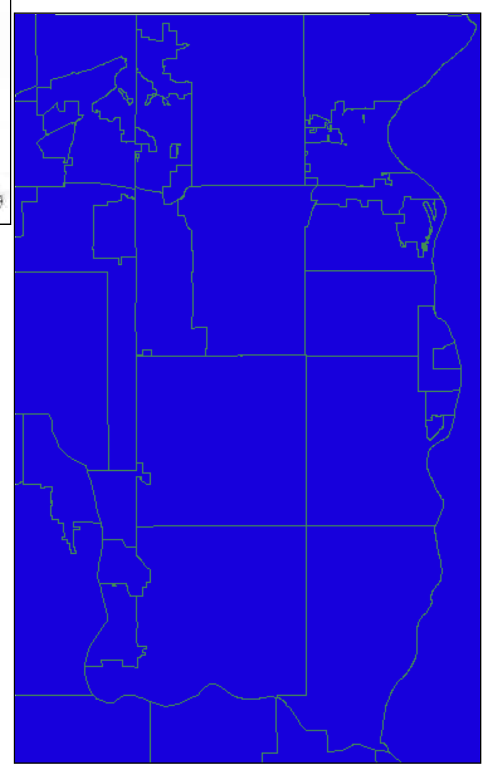


Layer 5



Layer 6





Layer 7

Layer 8

Figure 14

Geologic Representation in Computation Layers 5 to 8

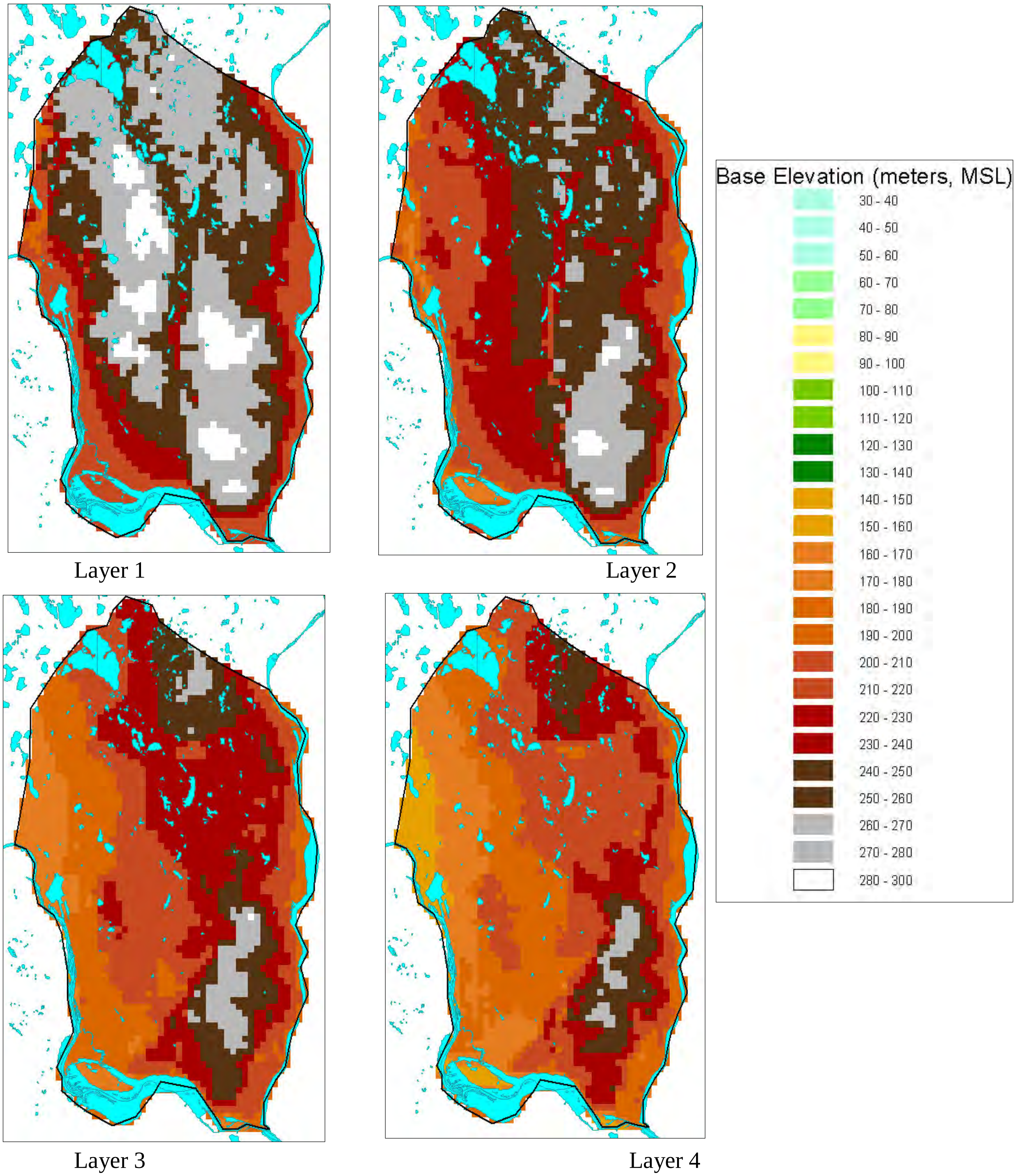


Figure 15

Base Elevations (meters, MSL) of Layers 1 to 4

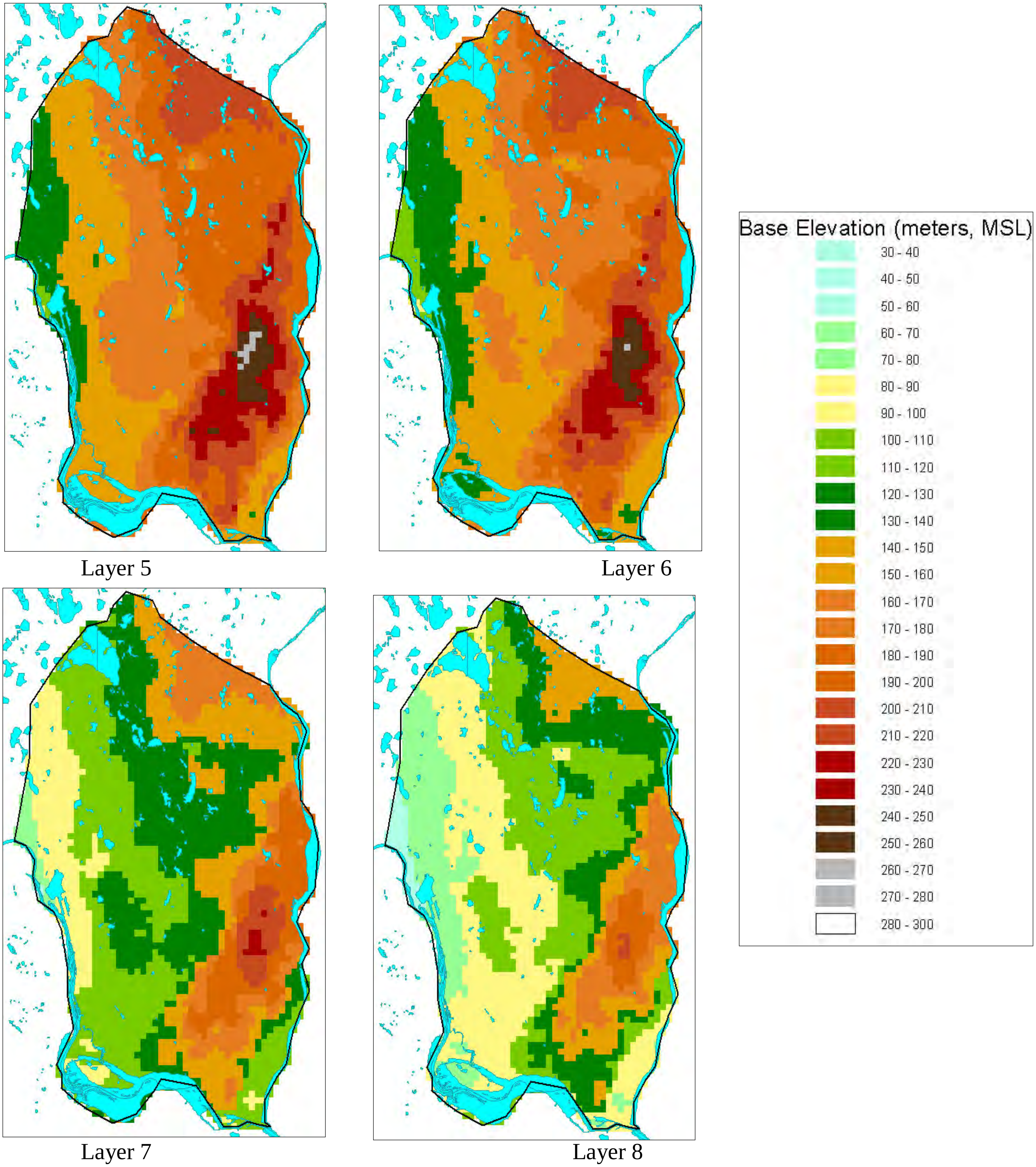


Figure 16

Base Elevations (meters, MSL) of Layers 5 to 8

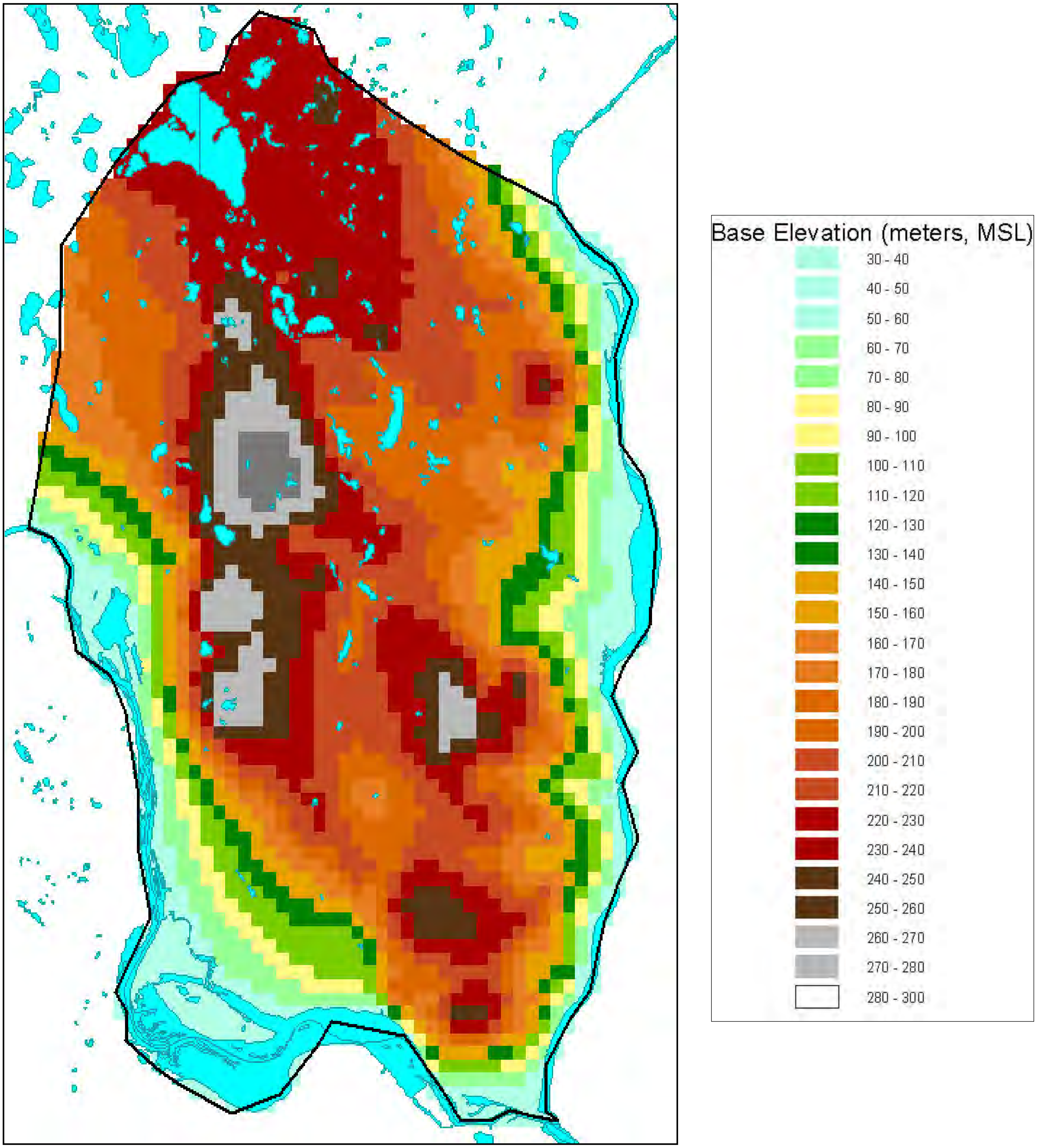
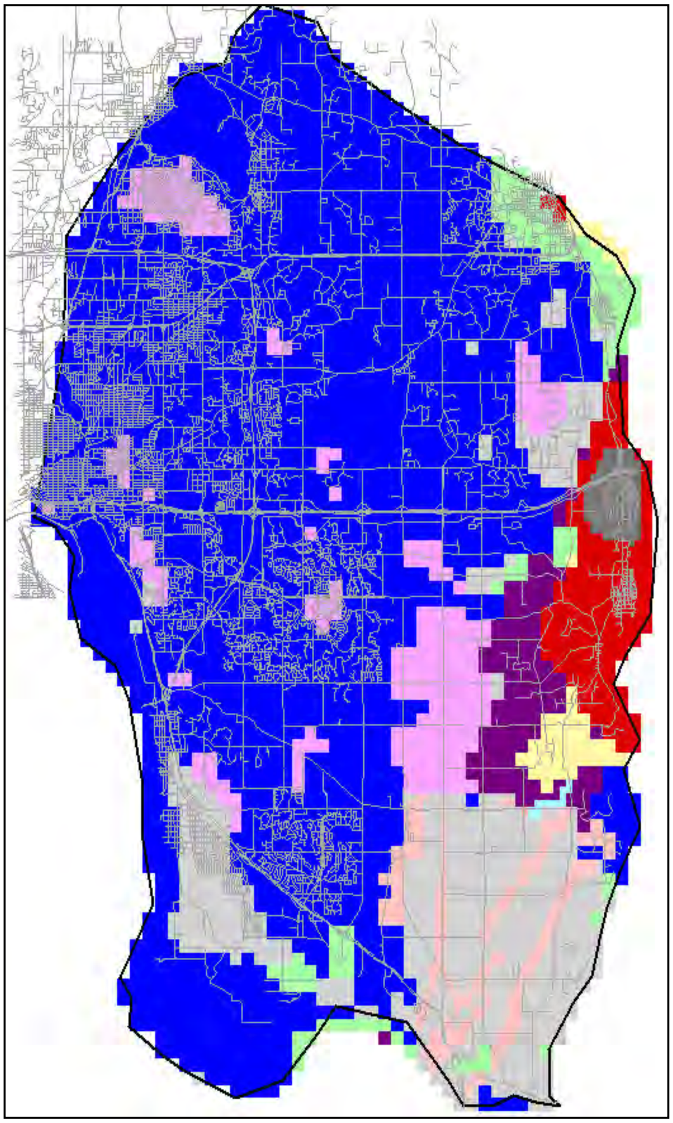
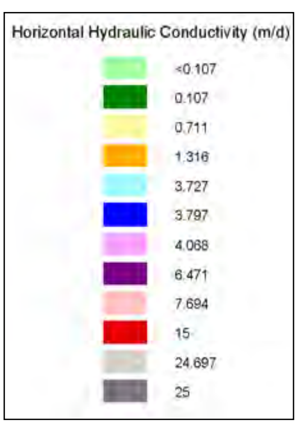


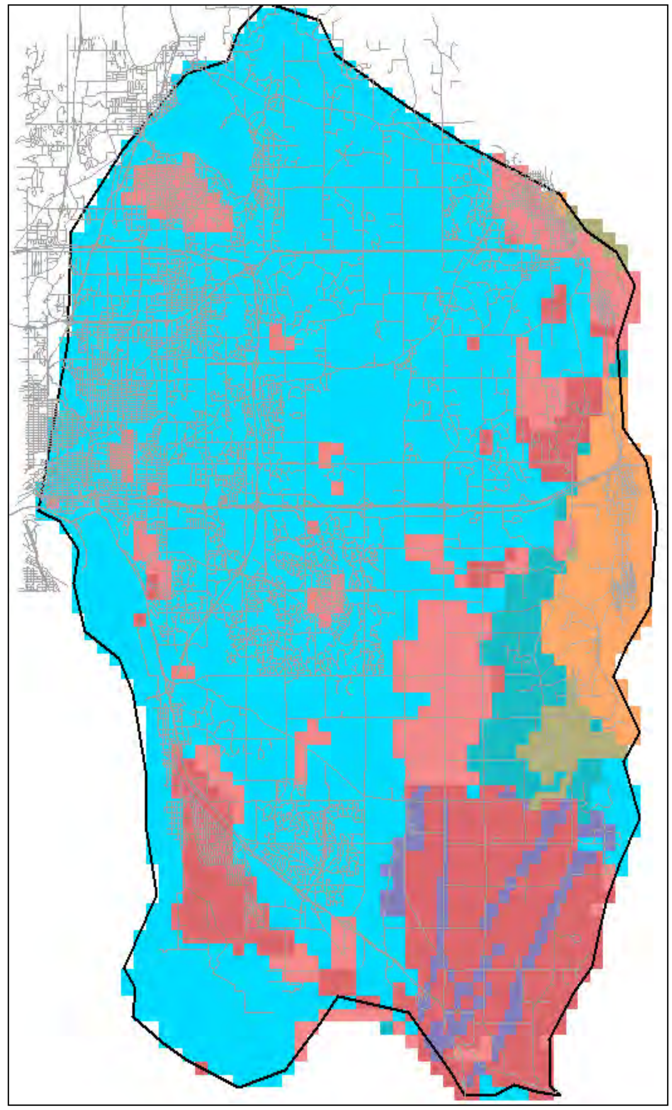
Figure 17

Elevation (meters, MSL) of Top of Layer 1



Horizontal Hydraulic Conductivity





Vertical Hydraulic Conductivity

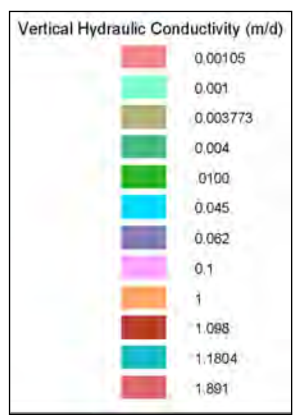
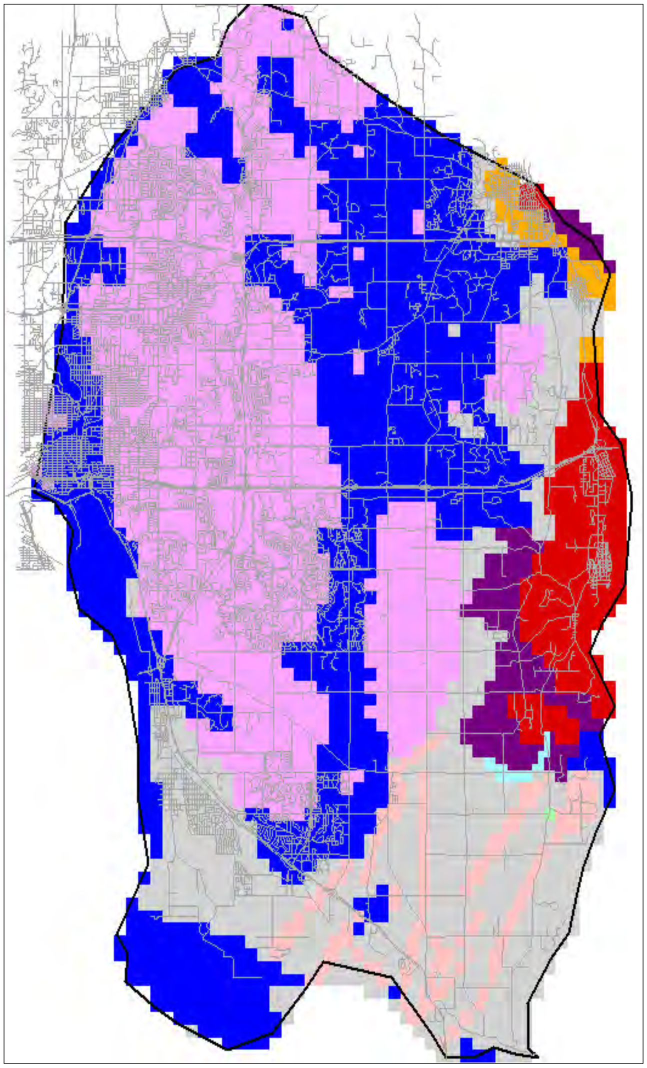
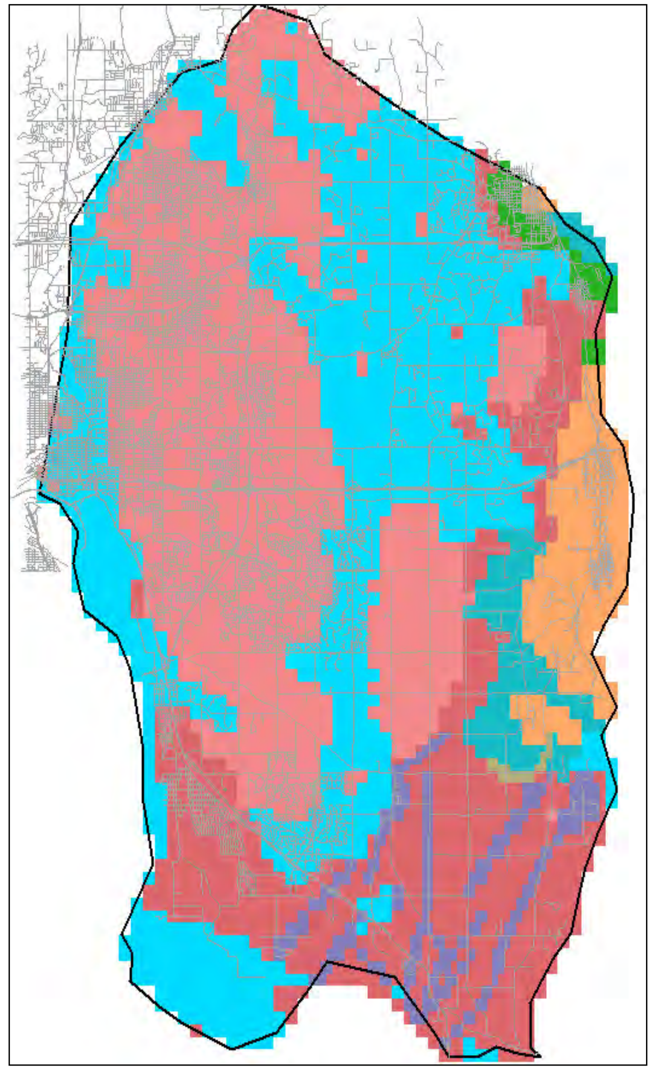


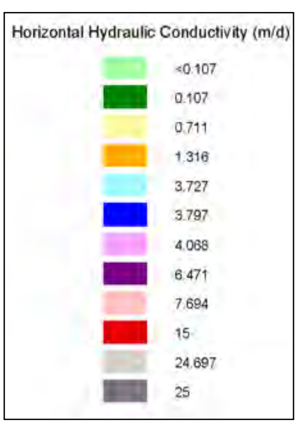
Figure 18

Optimized Horizontal and Vertical Hydraulic Conductivity Zones (Layer 1)





Horizontal Hydraulic Conductivity



Vertical Hydraulic Conductivity

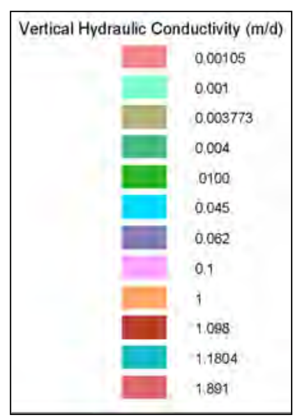
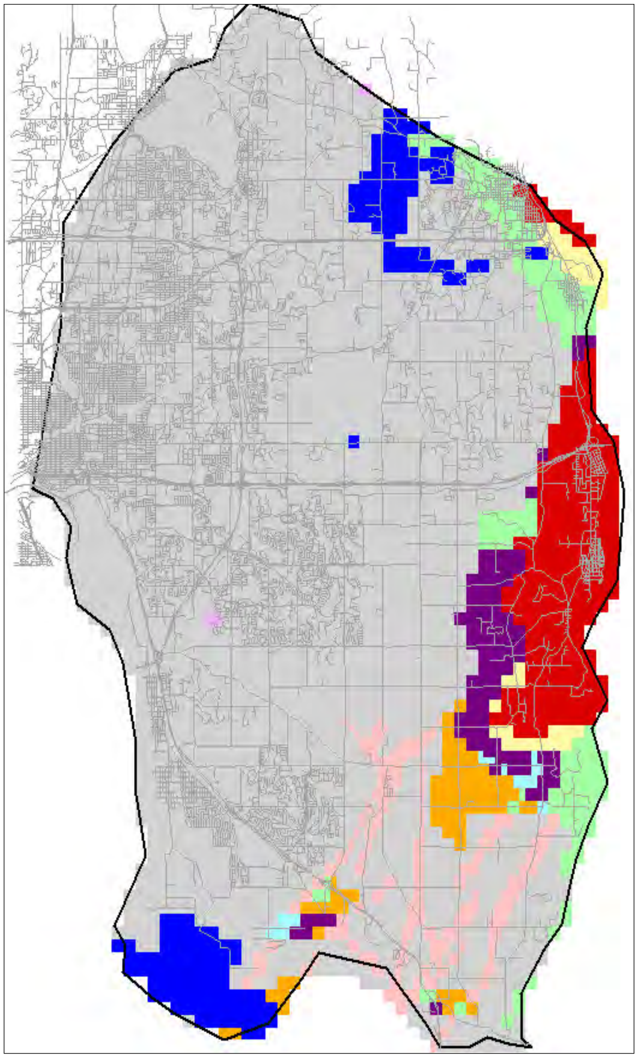
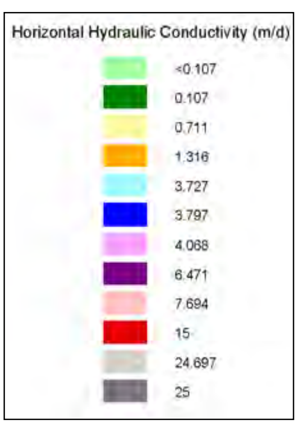


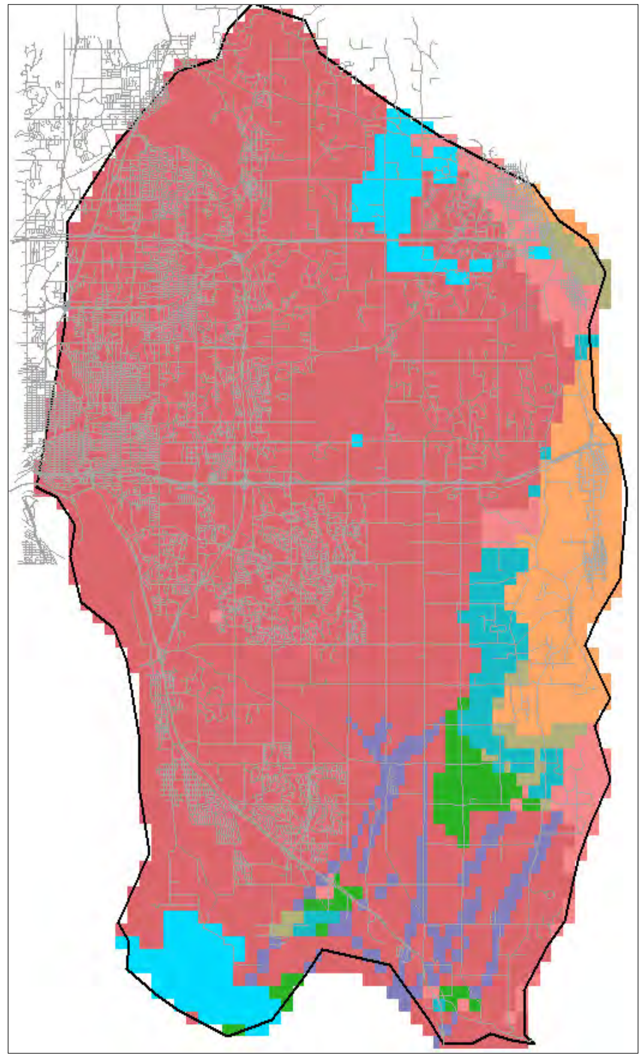
Figure 19

Optimized Horizontal and Vertical Hydraulic Conductivity Zones (Layer 2)



Horizontal Hydraulic Conductivity





Vertical Hydraulic Conductivity

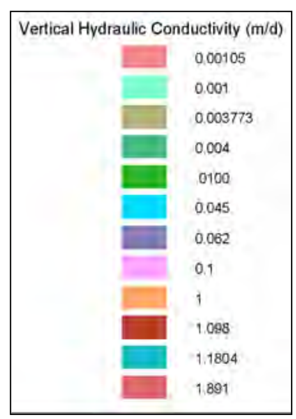
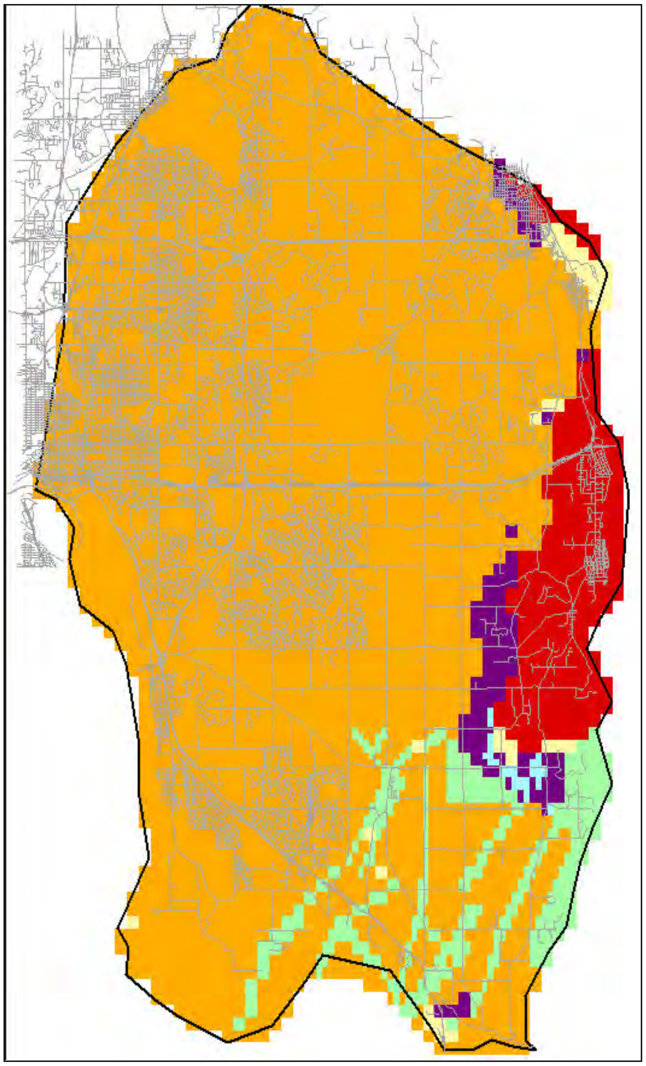
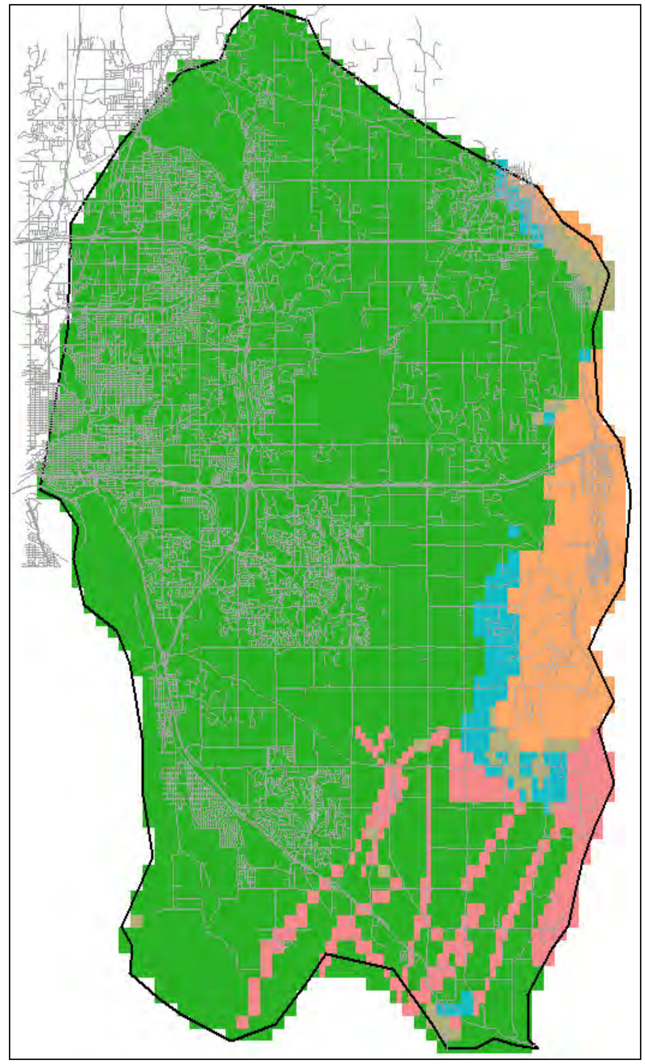


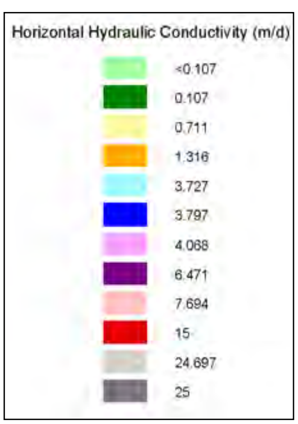
Figure 20

Optimized Horizontal and Vertical Hydraulic Conductivity Zones (Layer 3)





Horizontal Hydraulic Conductivity | **Vertical Hydraulic Conductivity**



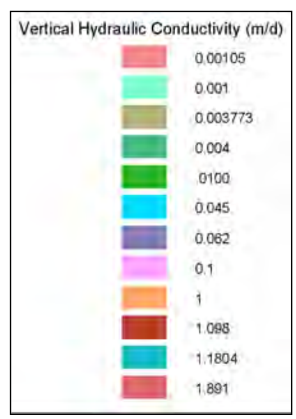
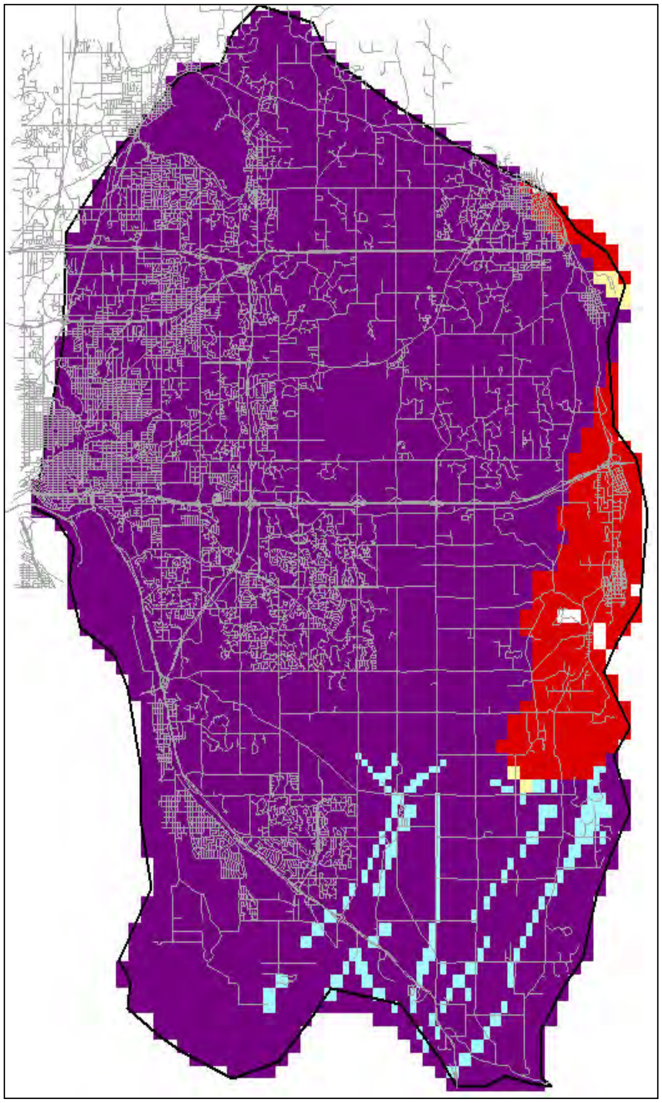
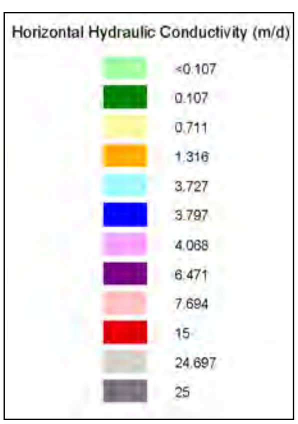


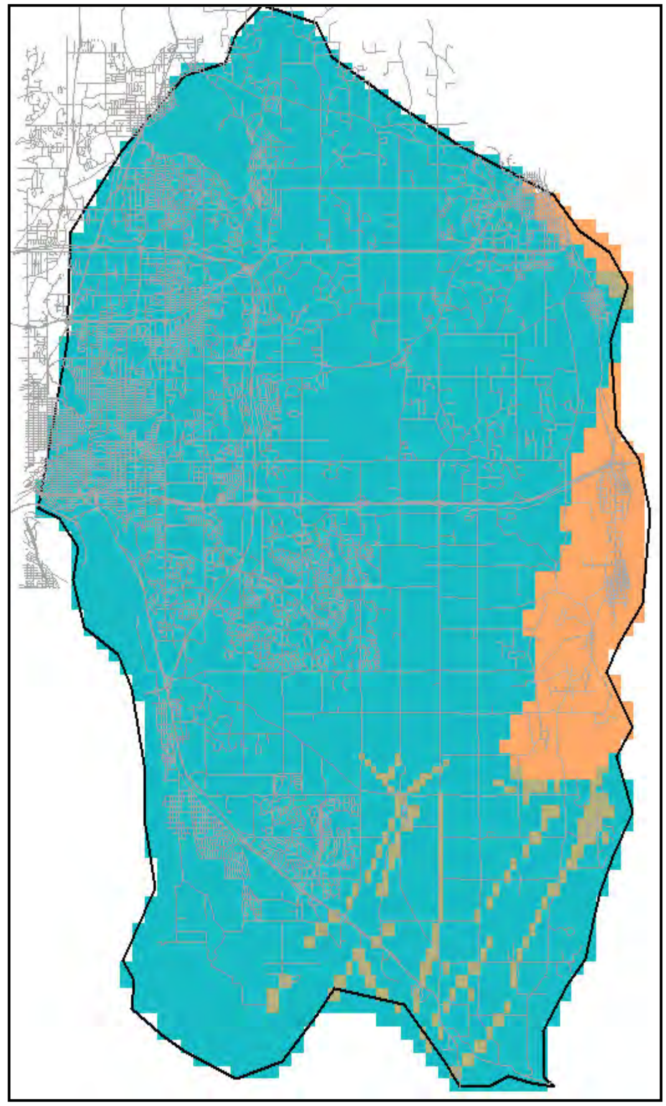
Figure 21

Optimized Horizontal and Vertical Hydraulic Conductivity Zones (Layer 4)



Horizontal Hydraulic Conductivity





Vertical Hydraulic Conductivity

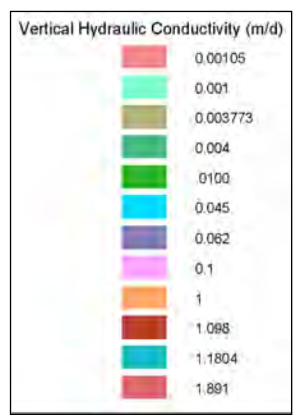
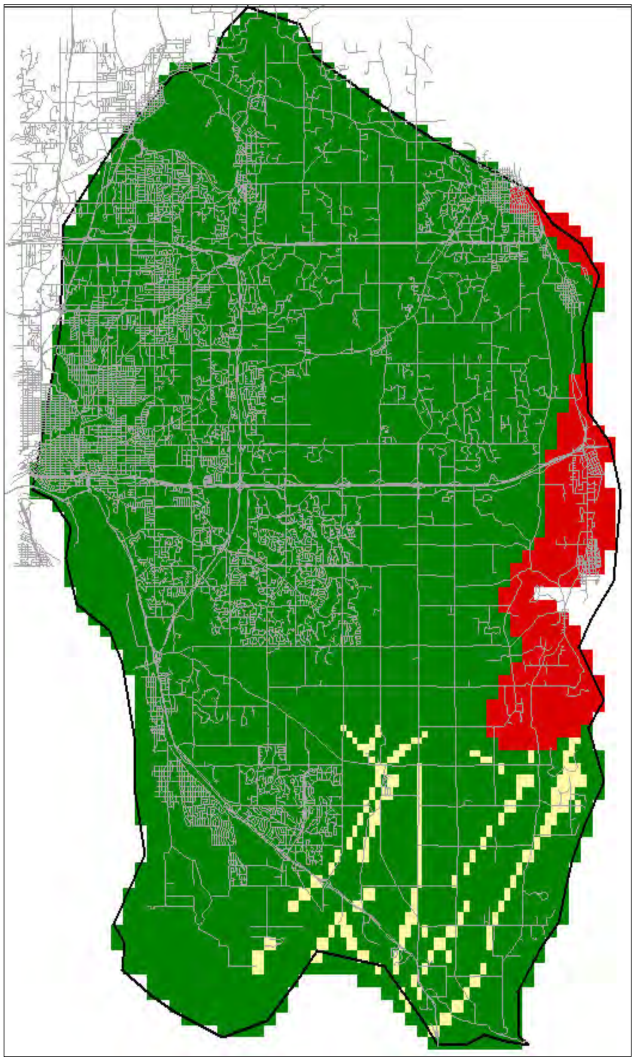
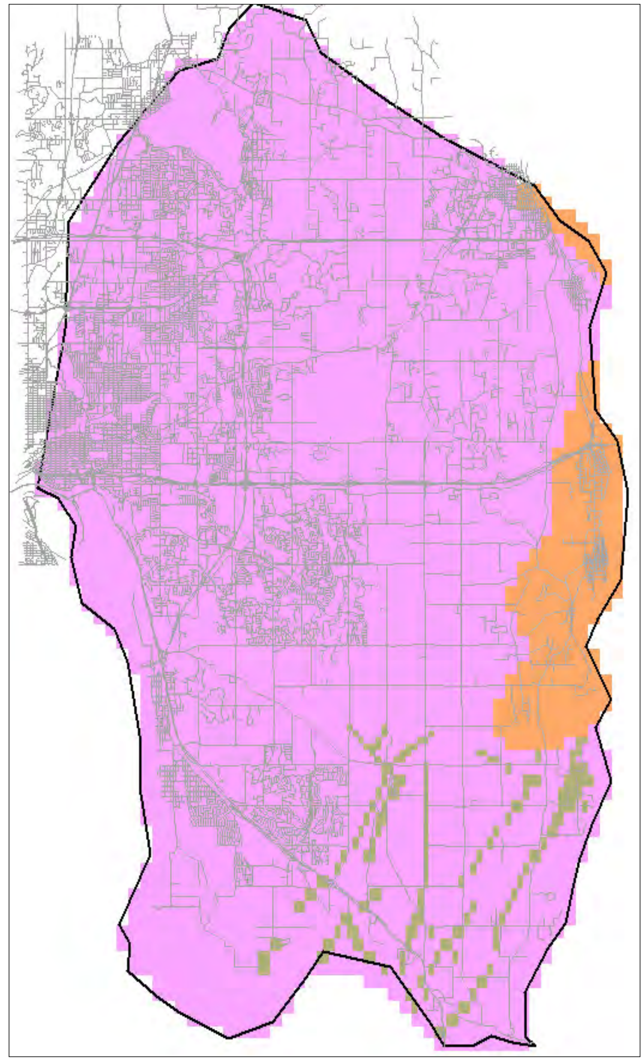


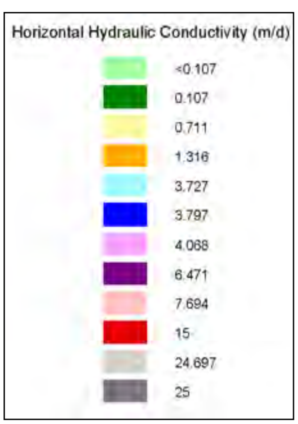
Figure 22

**Optimized Horizontal and Vertical Hydraulic Conductivity Zones
(Layer 5)**





Horizontal Hydraulic Conductivity



Vertical Hydraulic Conductivity

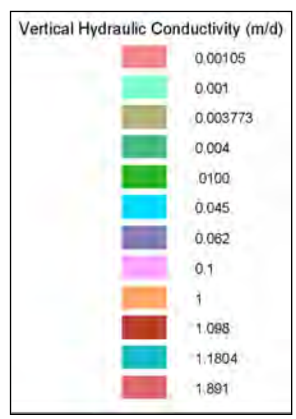
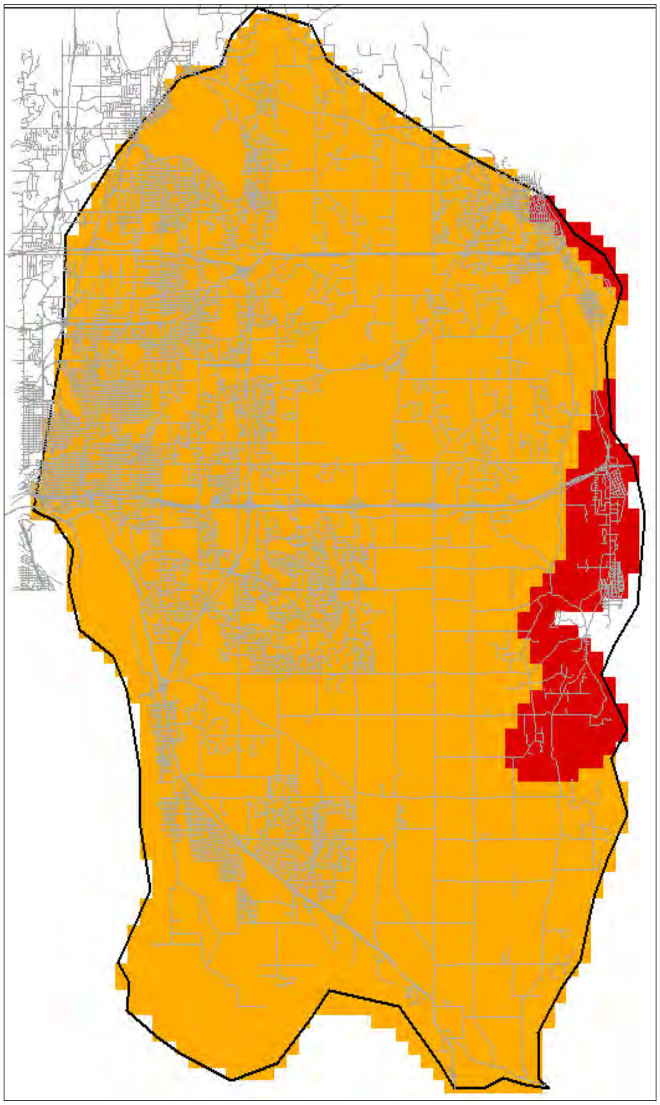
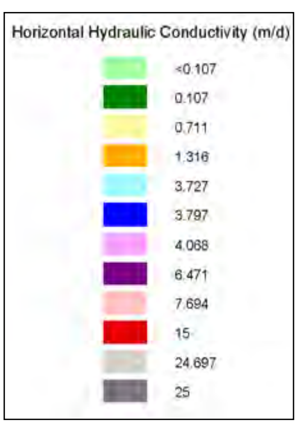


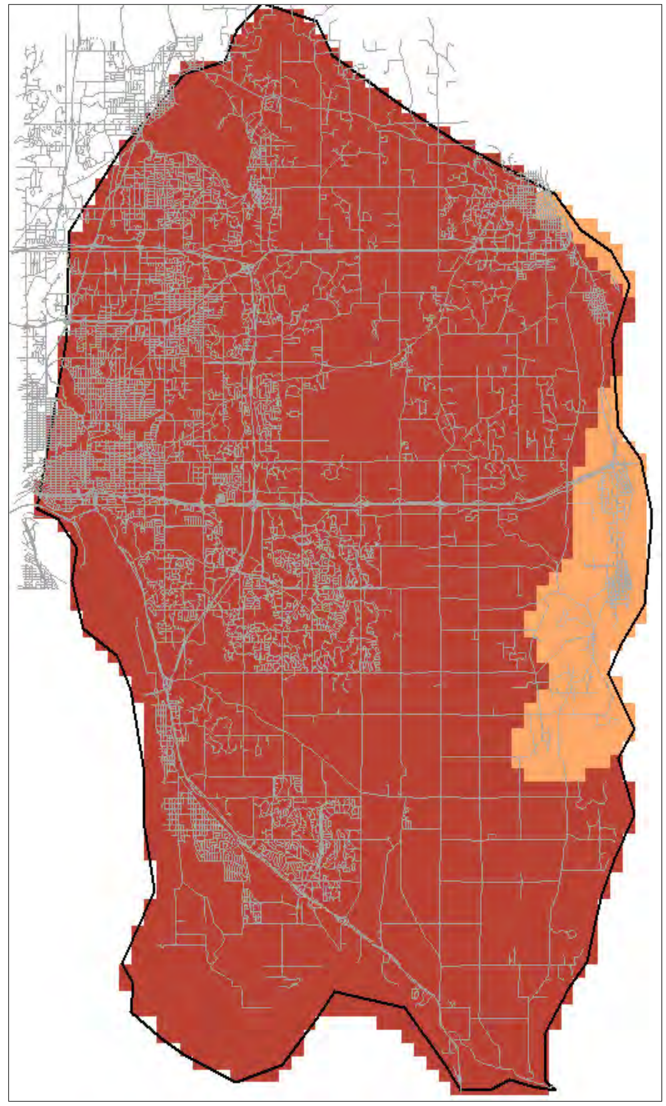
Figure 23

Optimized Horizontal and Vertical Hydraulic Conductivity Zones (Layer 6)



Horizontal Hydraulic Conductivity





Vertical Hydraulic Conductivity

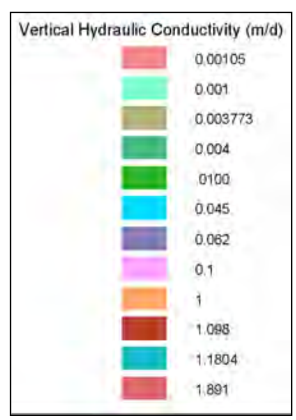
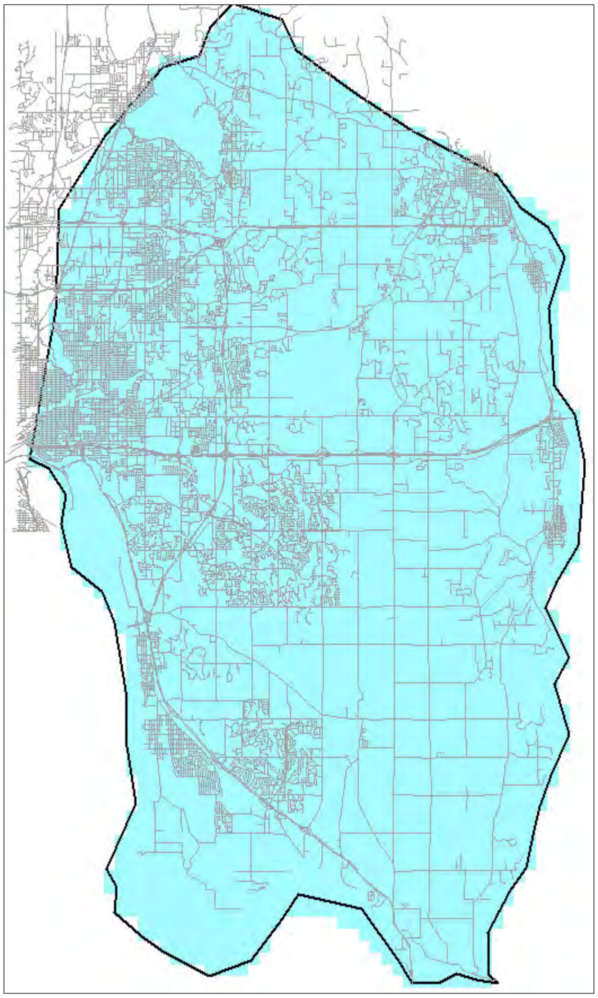
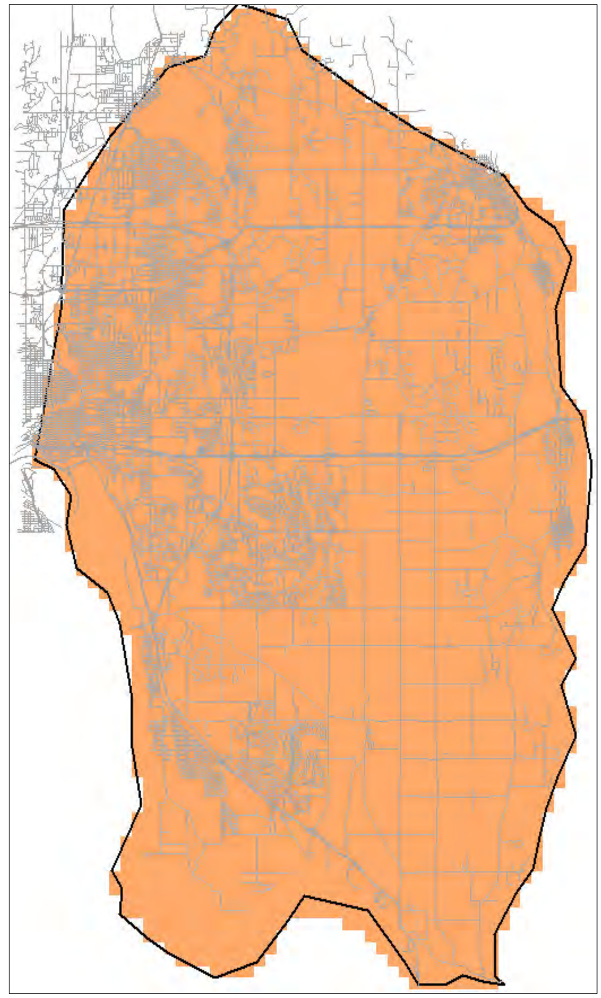


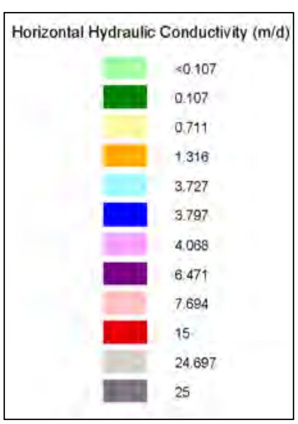
Figure 24

Optimized Horizontal and Vertical Hydraulic Conductivity Zones (Layer 7)





Horizontal Hydraulic Conductivity



Vertical Hydraulic Conductivity

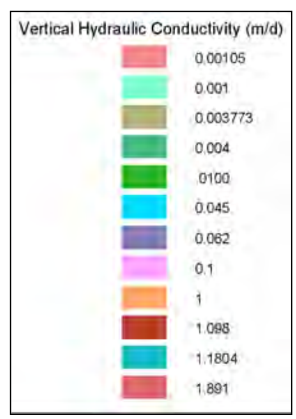


Figure 25

Optimized Horizontal and Vertical Hydraulic Conductivity Zones (Layer 8)

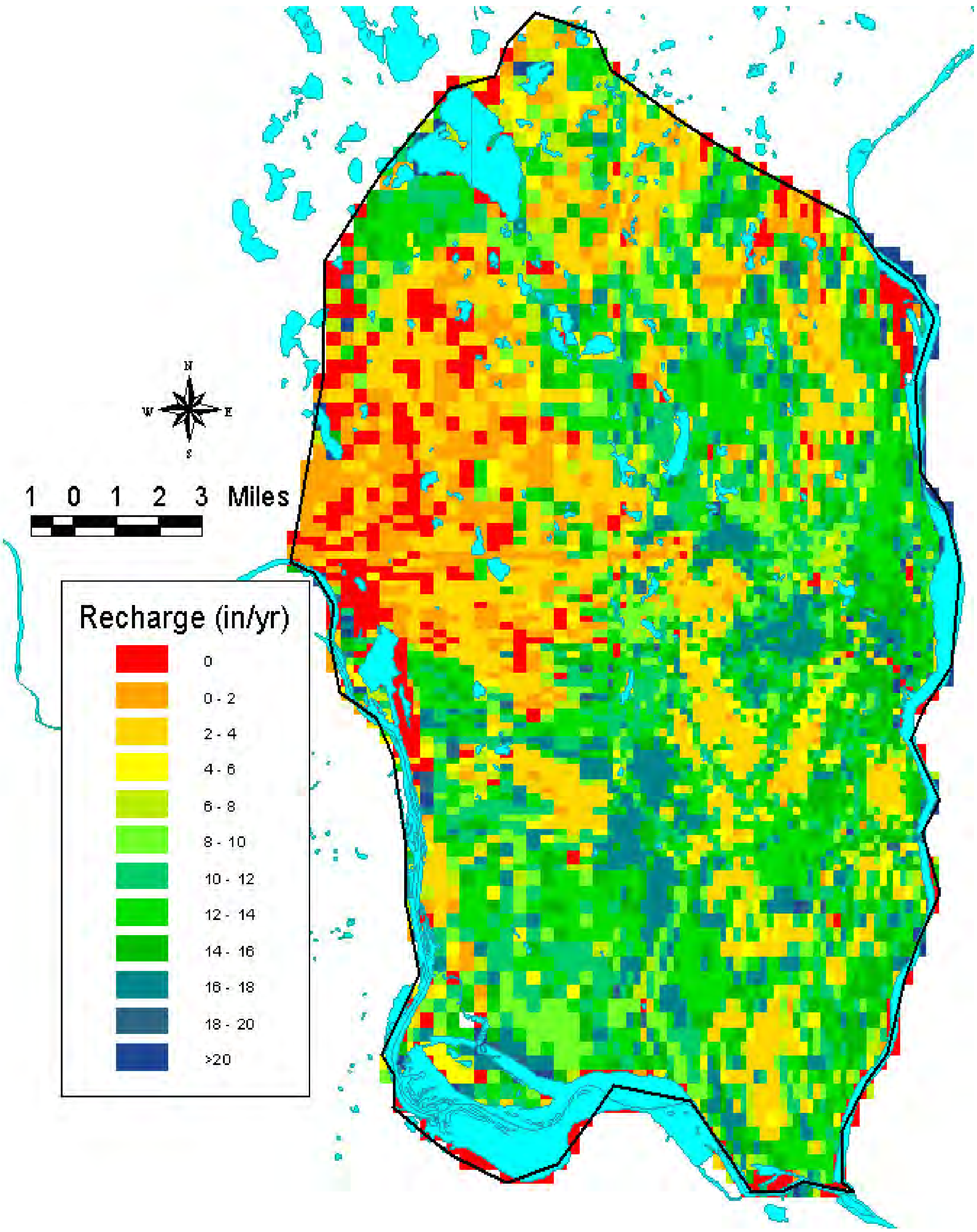


Figure 26

"Typical Year" Annualized Recharge (in/yr) – Derived from MIKE SHE MODEL for Input as Recharge in MODFLOW

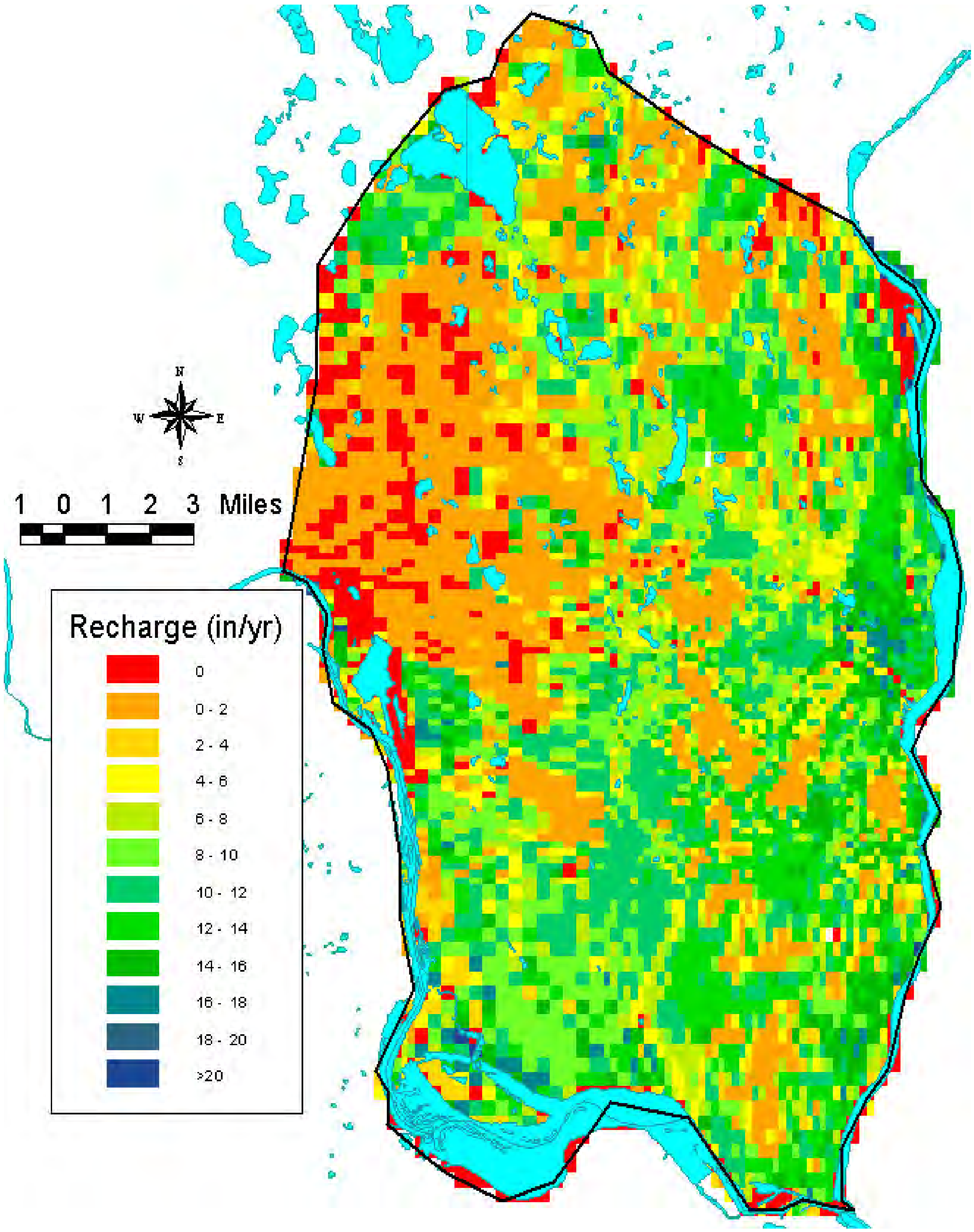


Figure 27

"Dry Year" (1988) Annualized Recharge (in/yr) – Derived from MIKE SHE MODEL for Input as Recharge in MODFLOW

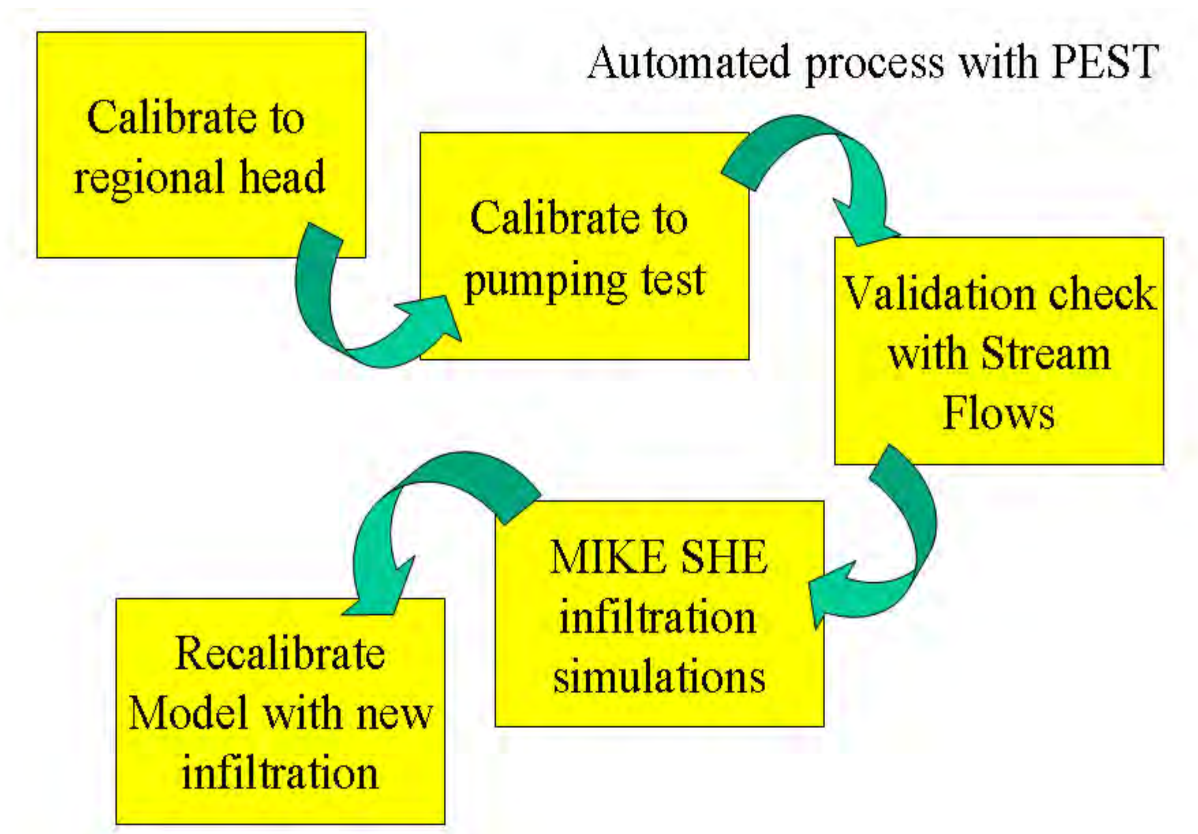


Figure 28

Flow Chart of the Calibration/Optimization Processes

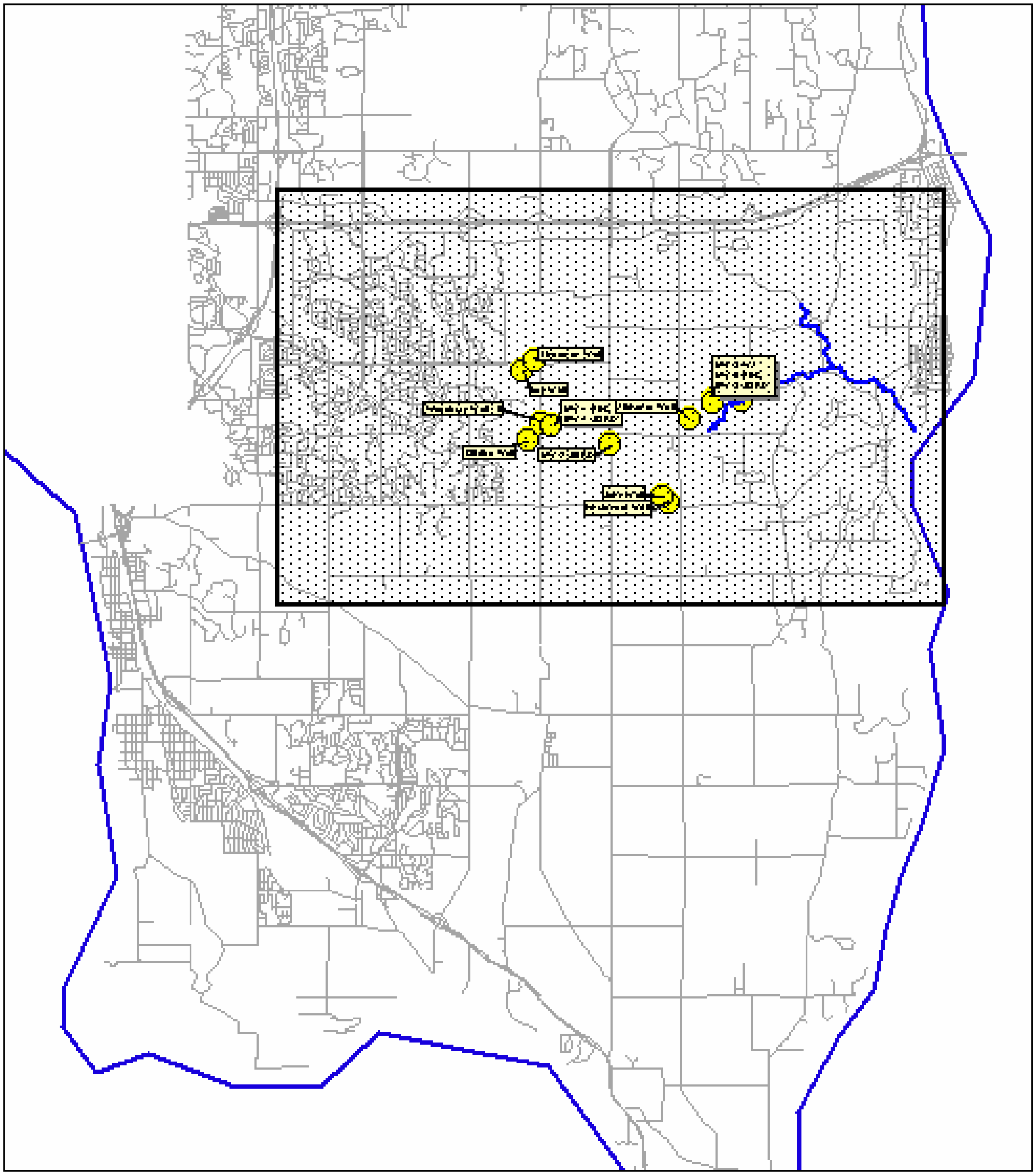


Figure 29

Location of Sub-Regional TMR Model: Woodbury Well 15 Pumping Test

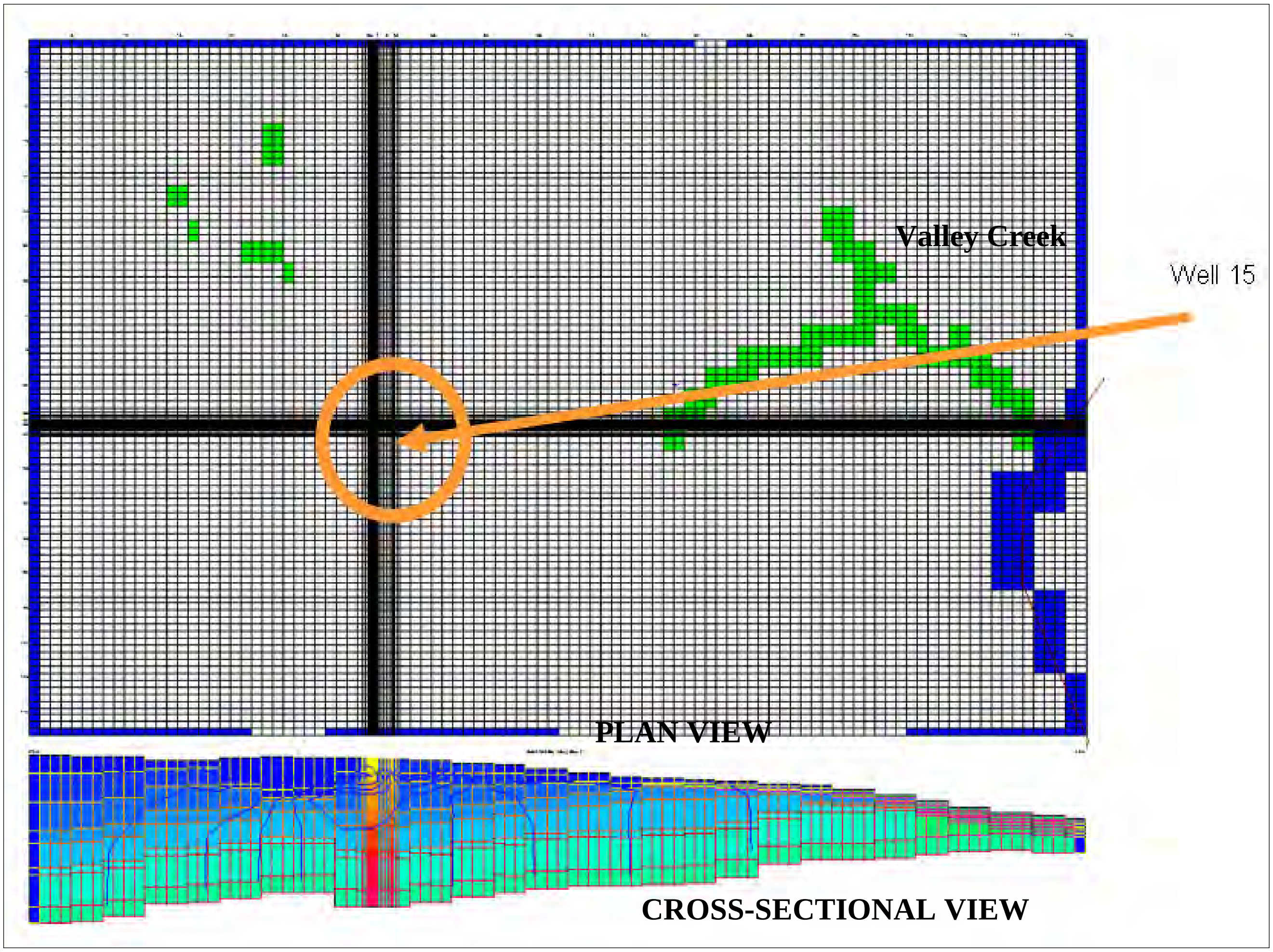


Figure 30

Discretization of the TMR Model for Optimizing to the Woodbury Well 15 Pumping Test

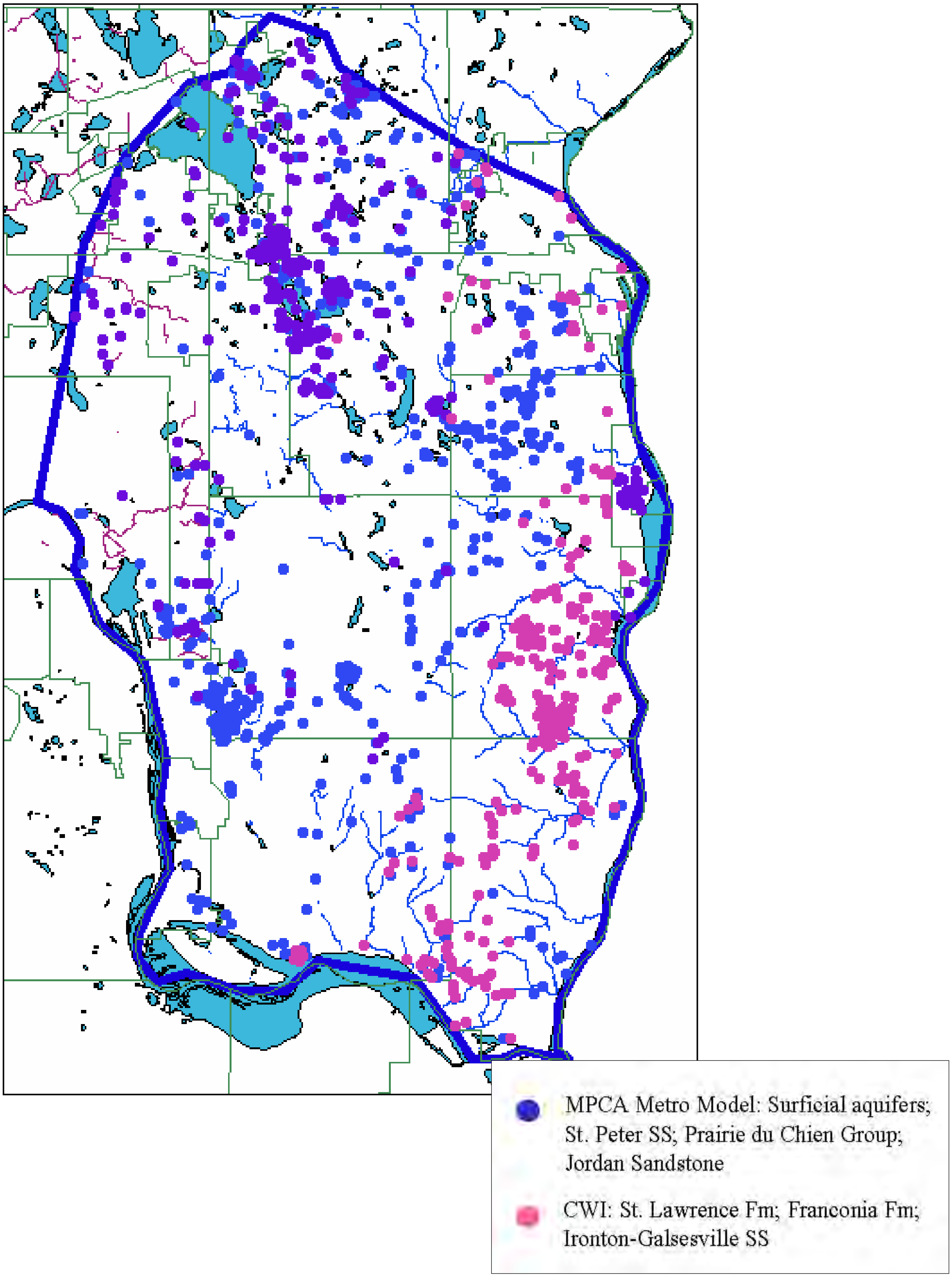
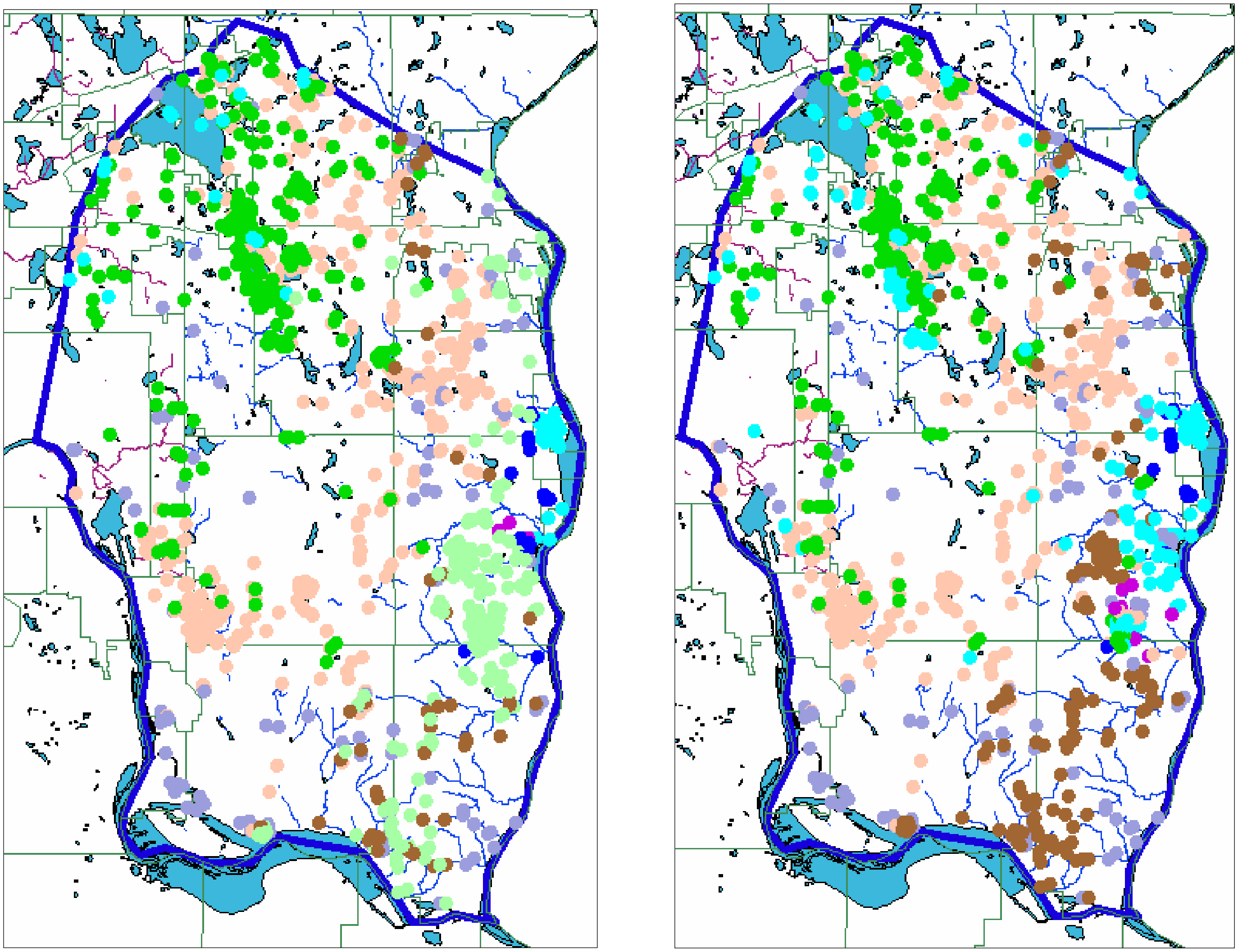


Figure 31

Sources for Regional Steady-State Calibration Targets



Top Layer

Bottom Layer

Several calibration targets are in multiple layers

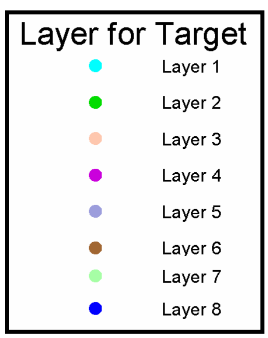


Figure 32

Model Layers Containing Calibration Targets for Regional Model

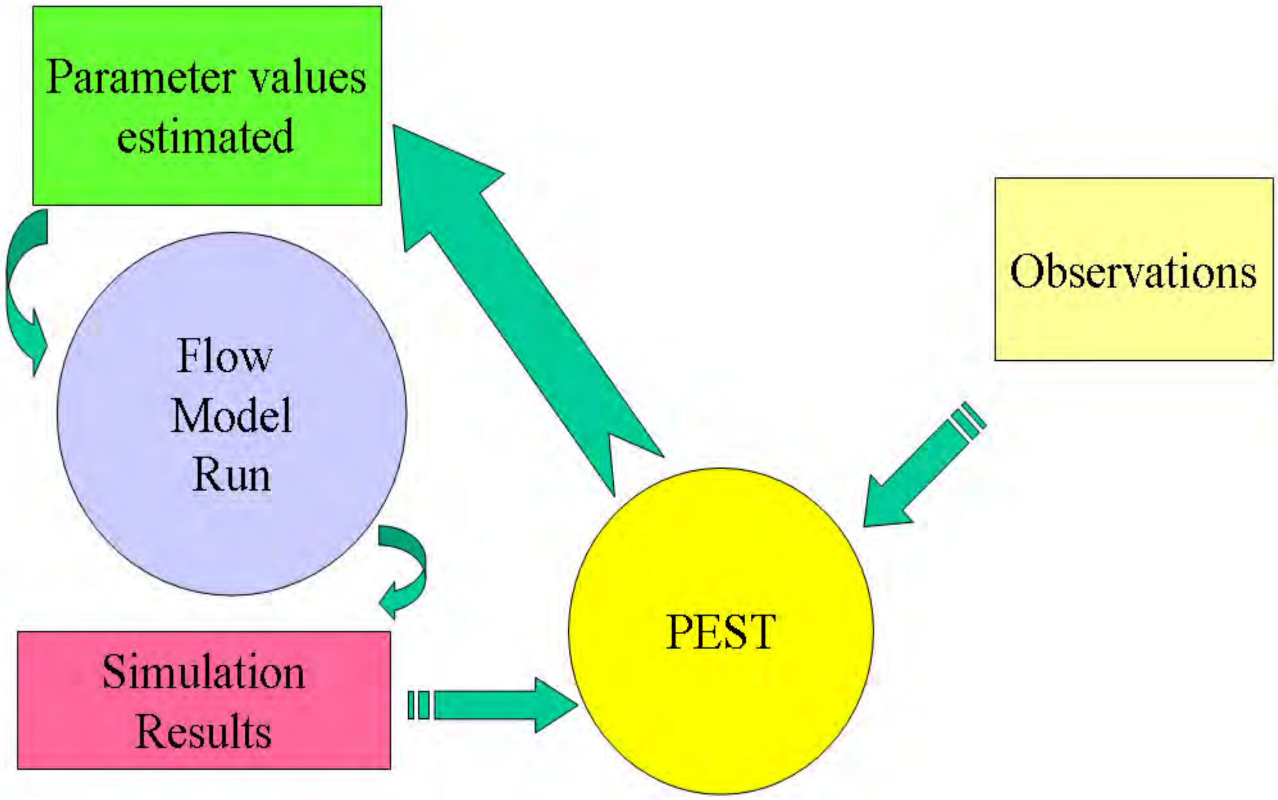


Figure 33

Flow Chart of Inverse Optimization Procedures

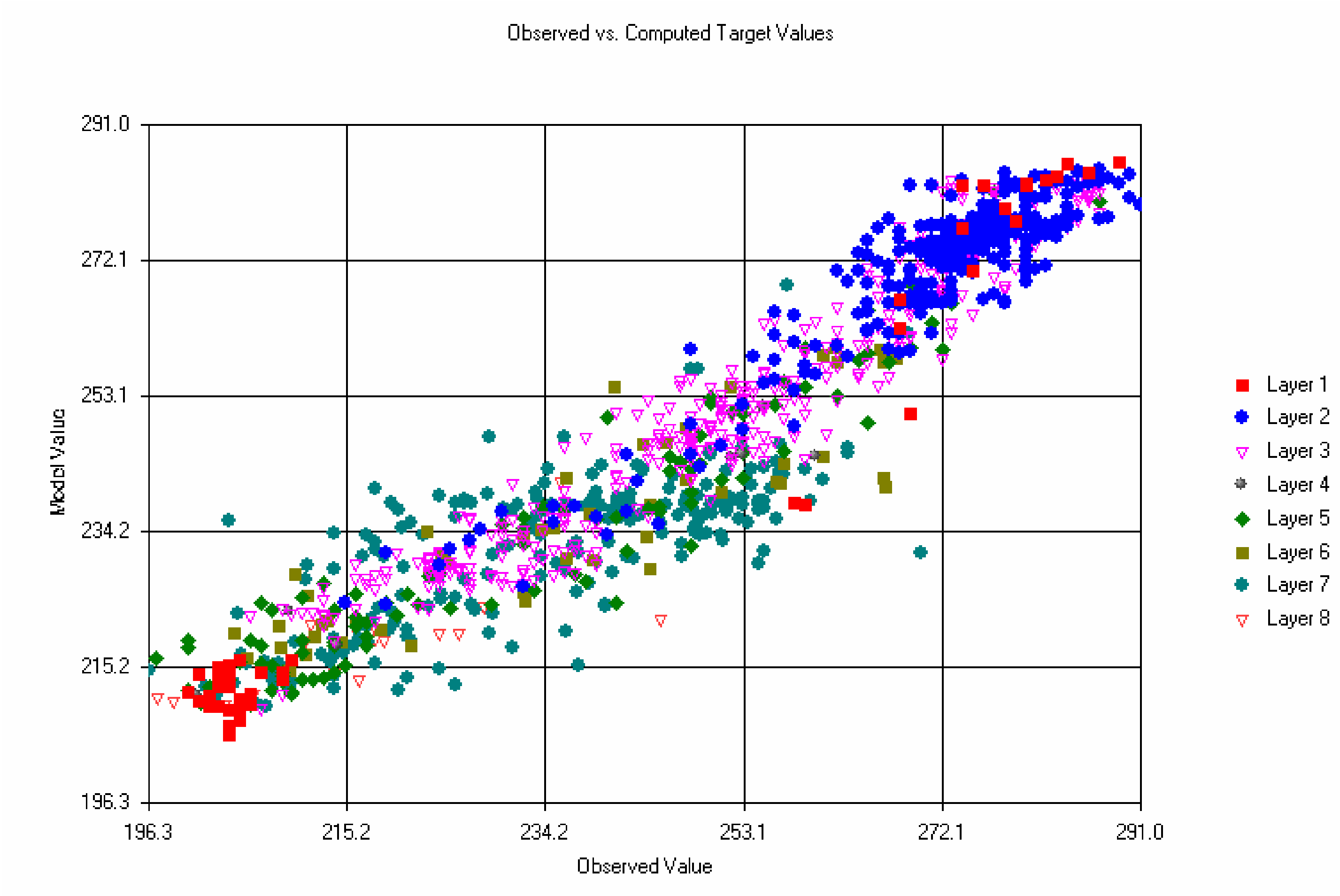


Figure 34

Plot of Simulated and Observed Heads for Steady-State Optimization

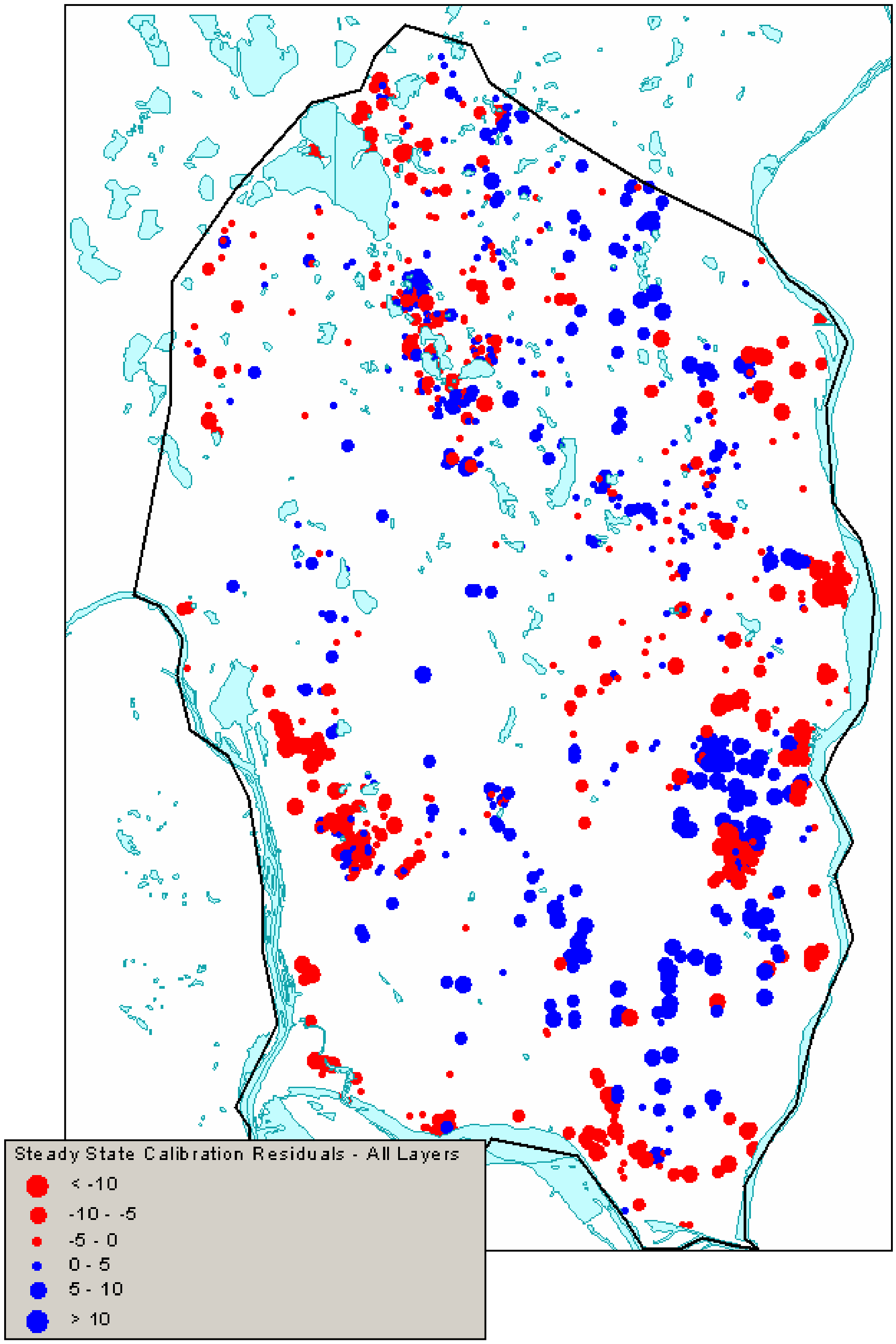


Figure 35

Map of Steady-State Optimization Residuals (meters) for All Layers

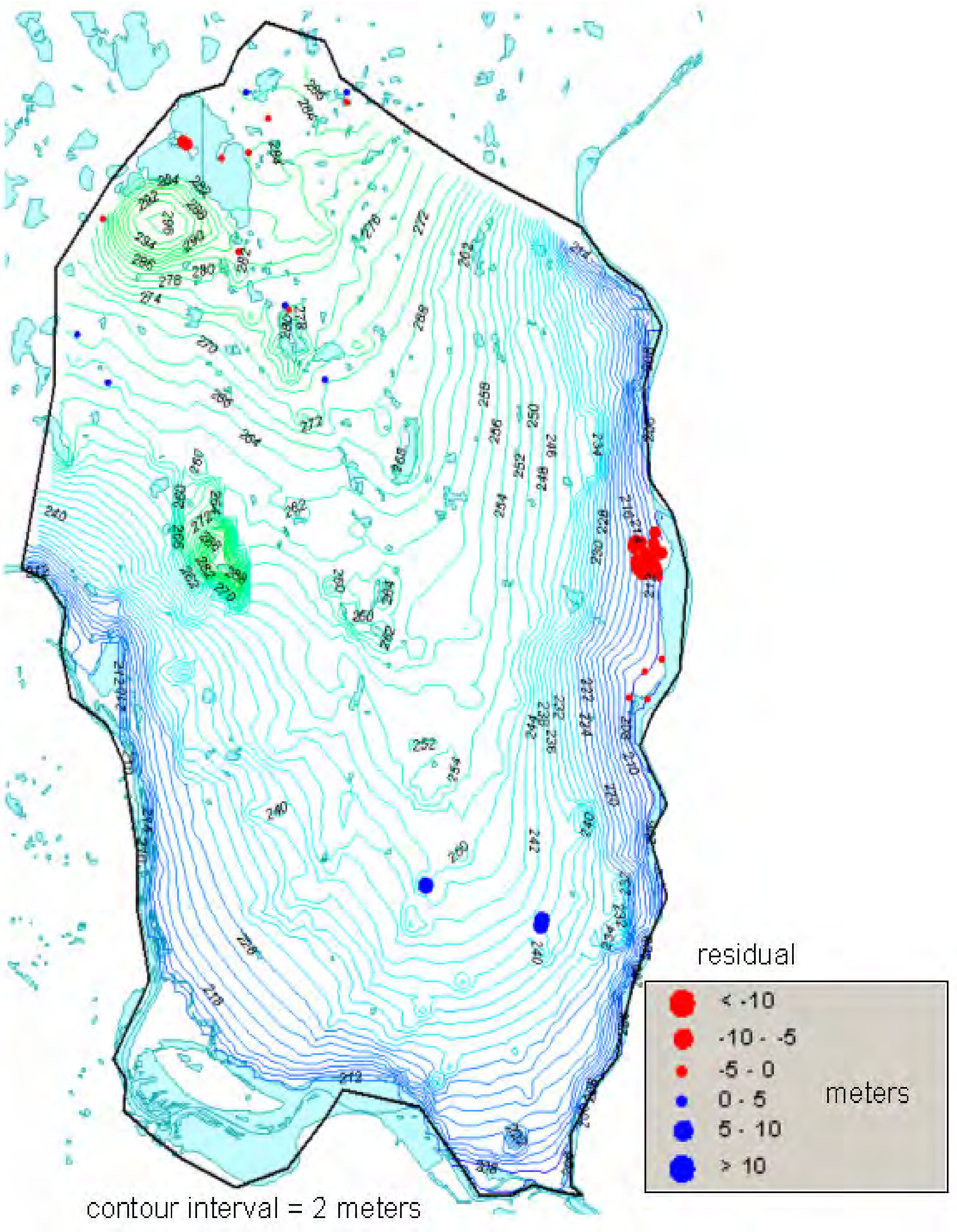


Figure 36

Contours of Steady-State Hydraulic Head and Plot of Optimization Residual for Layer 1

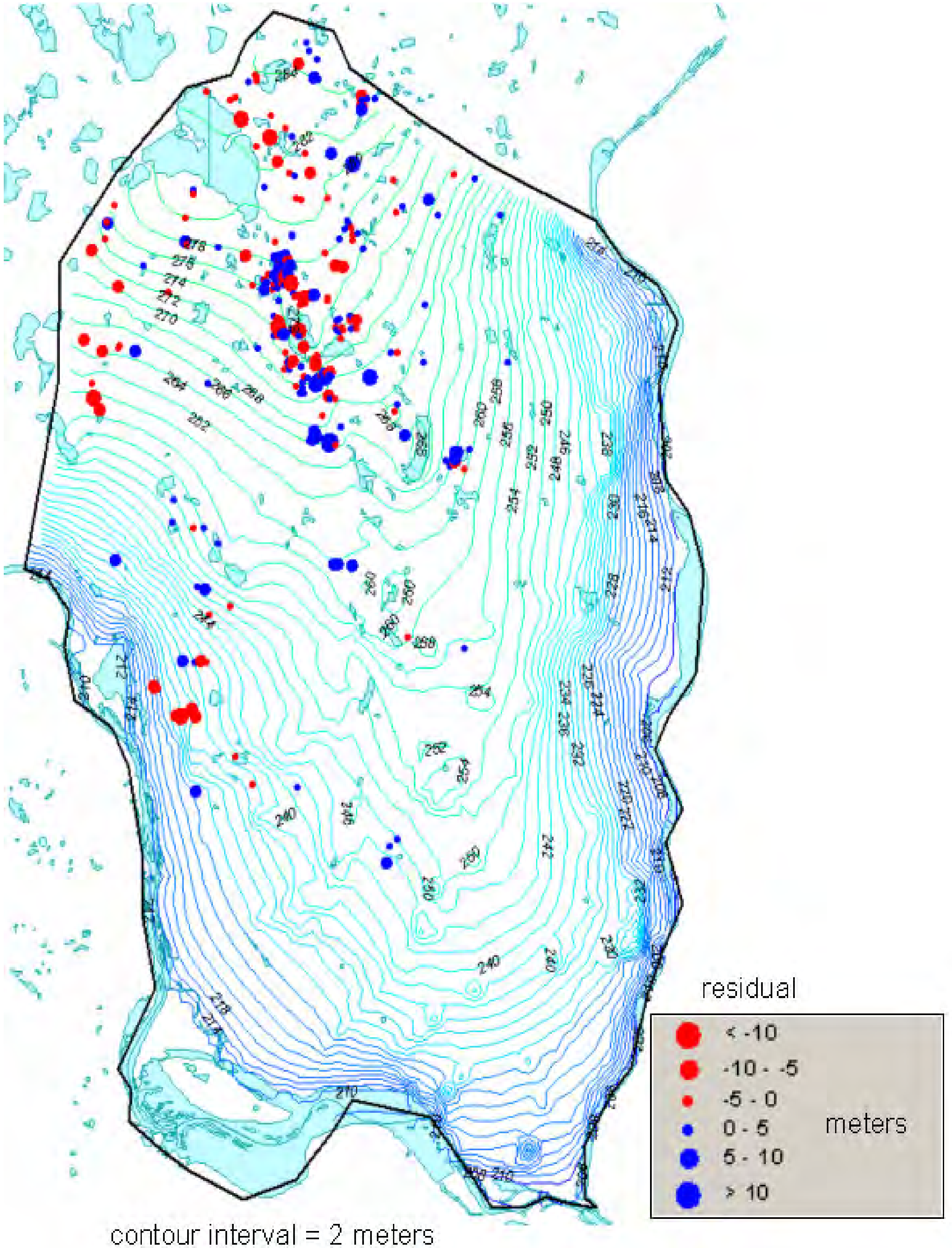


Figure 37

Contours of Steady-State Hydraulic Head and Plot of Optimization Residual for Layer 2

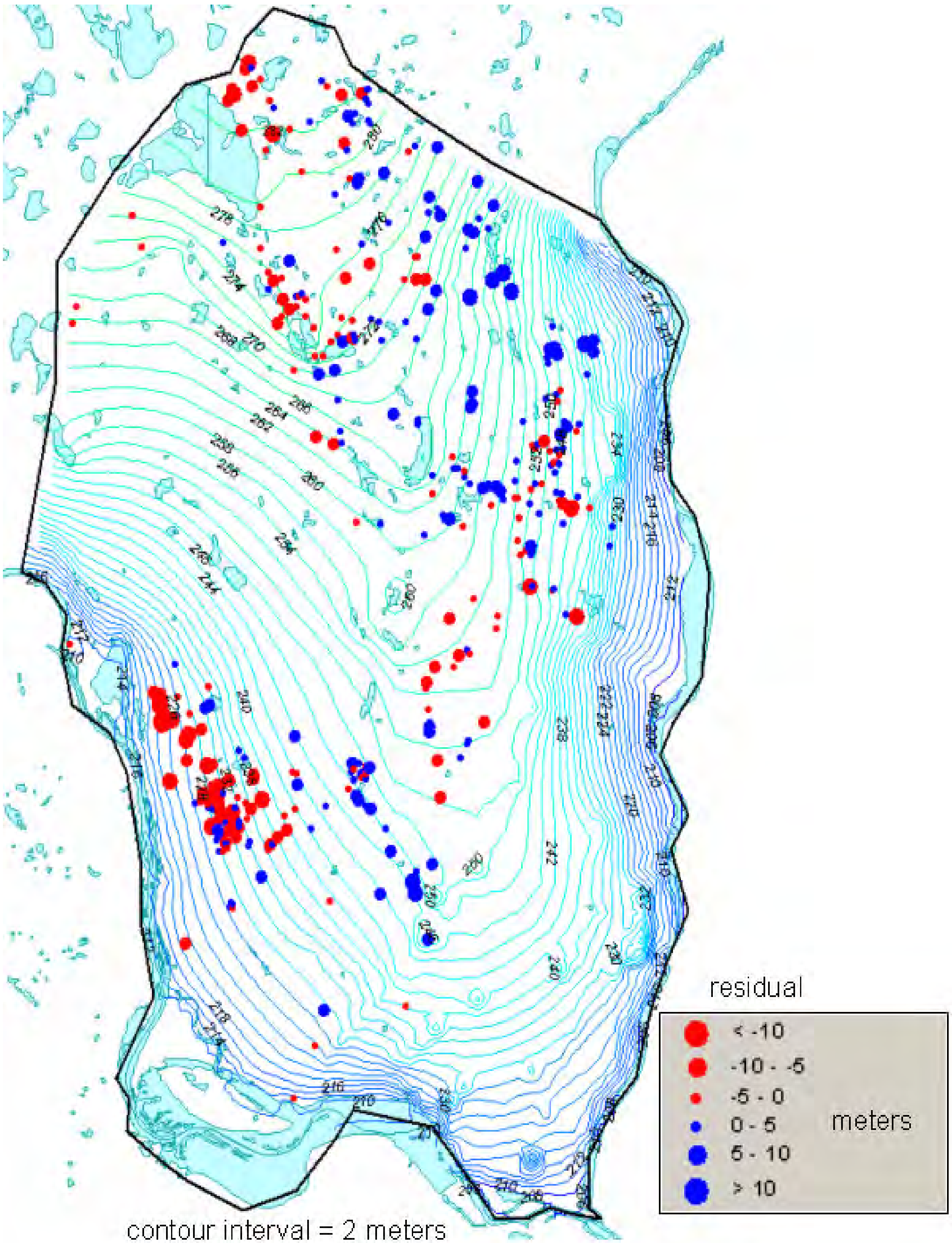


Figure 38

Contours of Steady-State Hydraulic Head and Plot of Optimization Residual for Layer 3

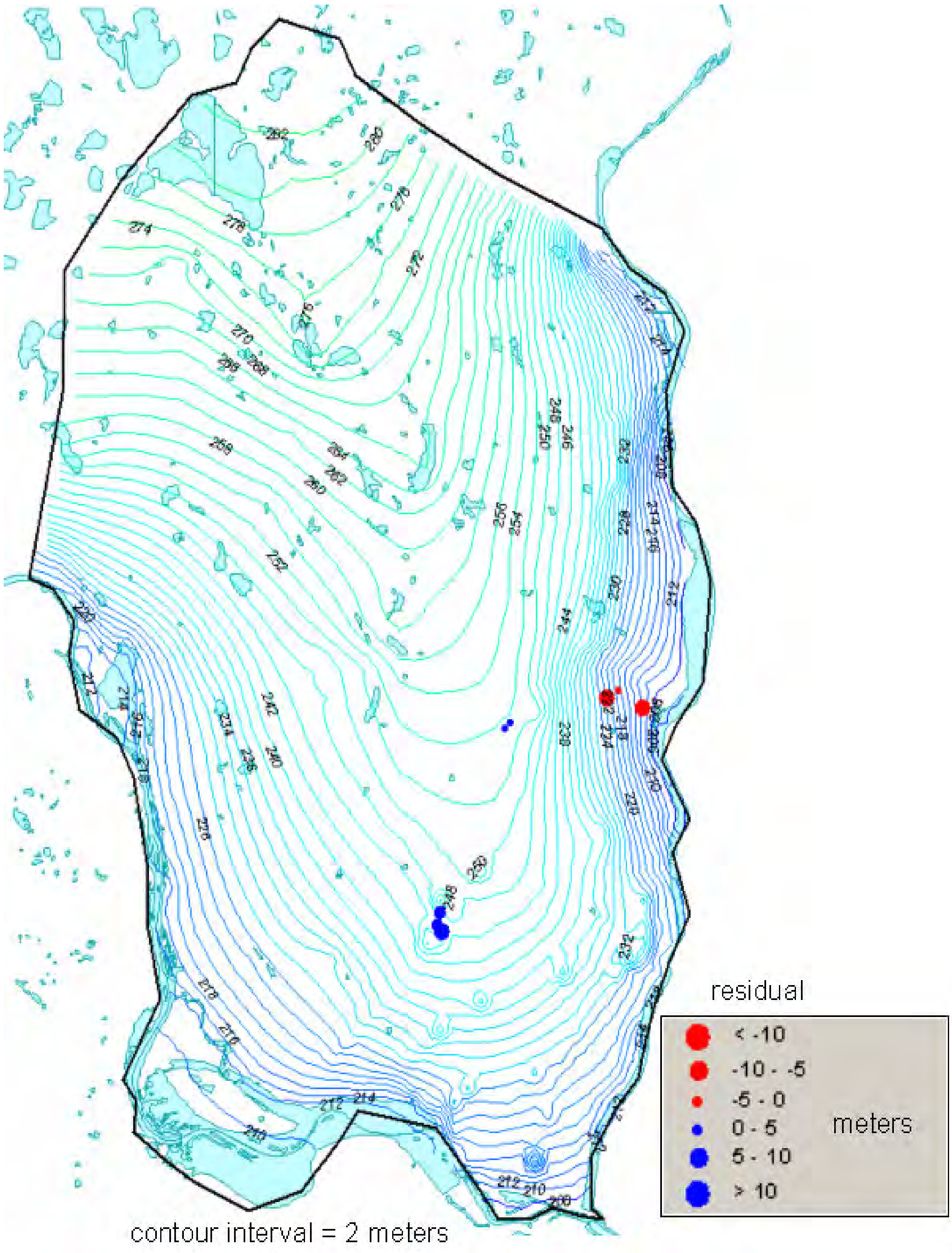


Figure 39

Contours of Steady-State Hydraulic Head and Plot of Optimization Residual for Layer 4

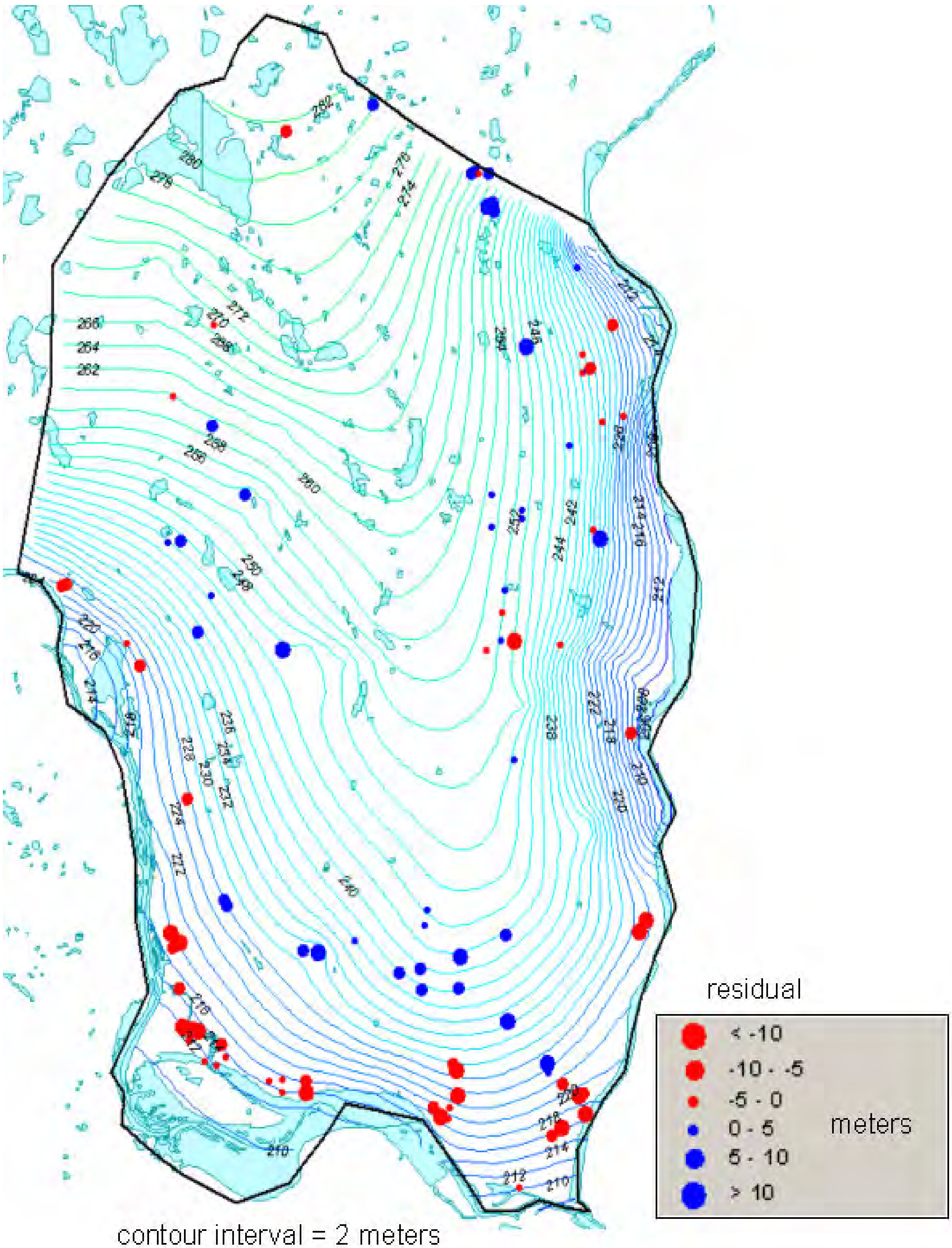


Figure 40

Contours of Steady-State Hydraulic Head and Plot of Optimization Residual for Layer 5

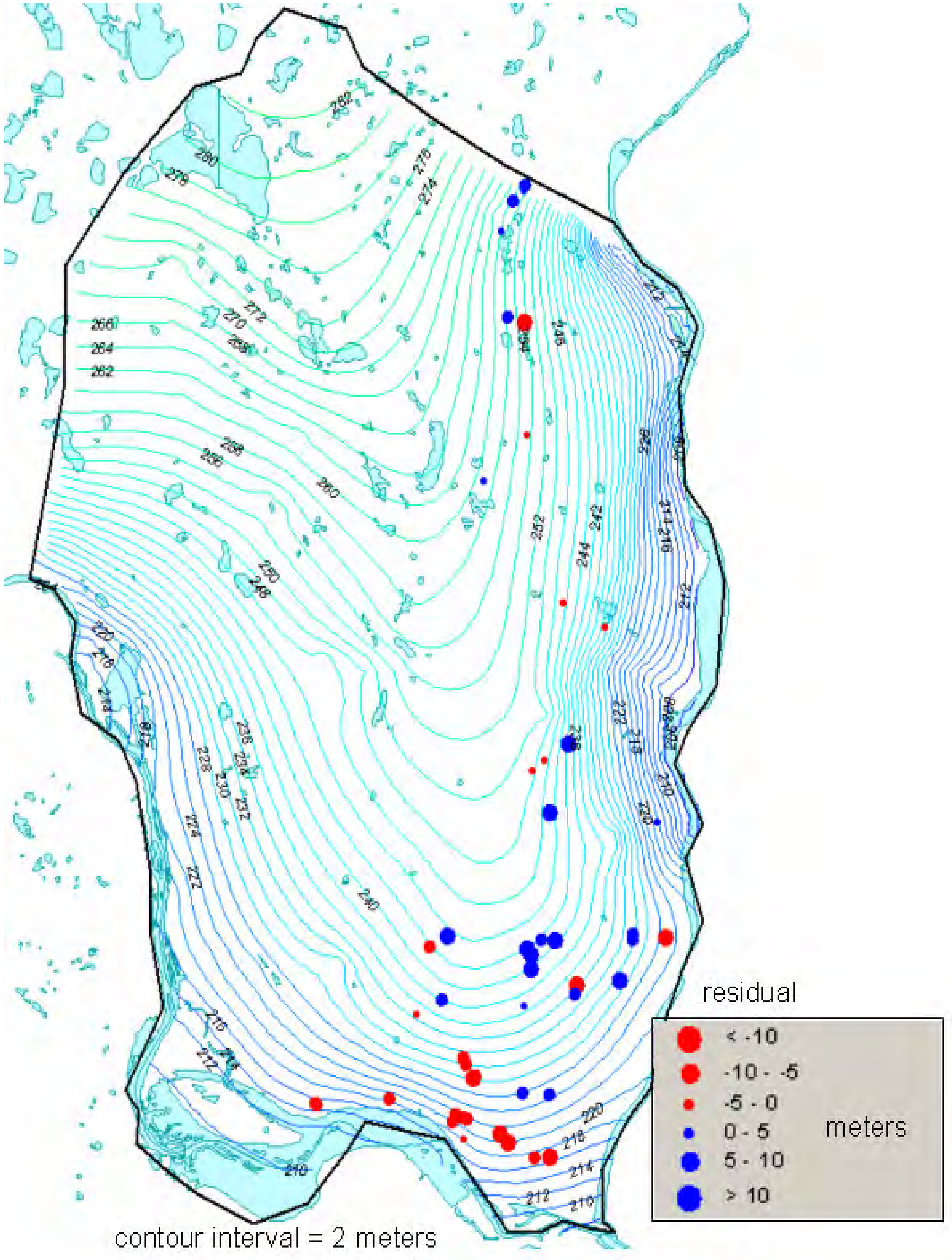


Figure 41

Contours of Steady-State Hydraulic Head and Plot of Optimization Residual for Layer 6

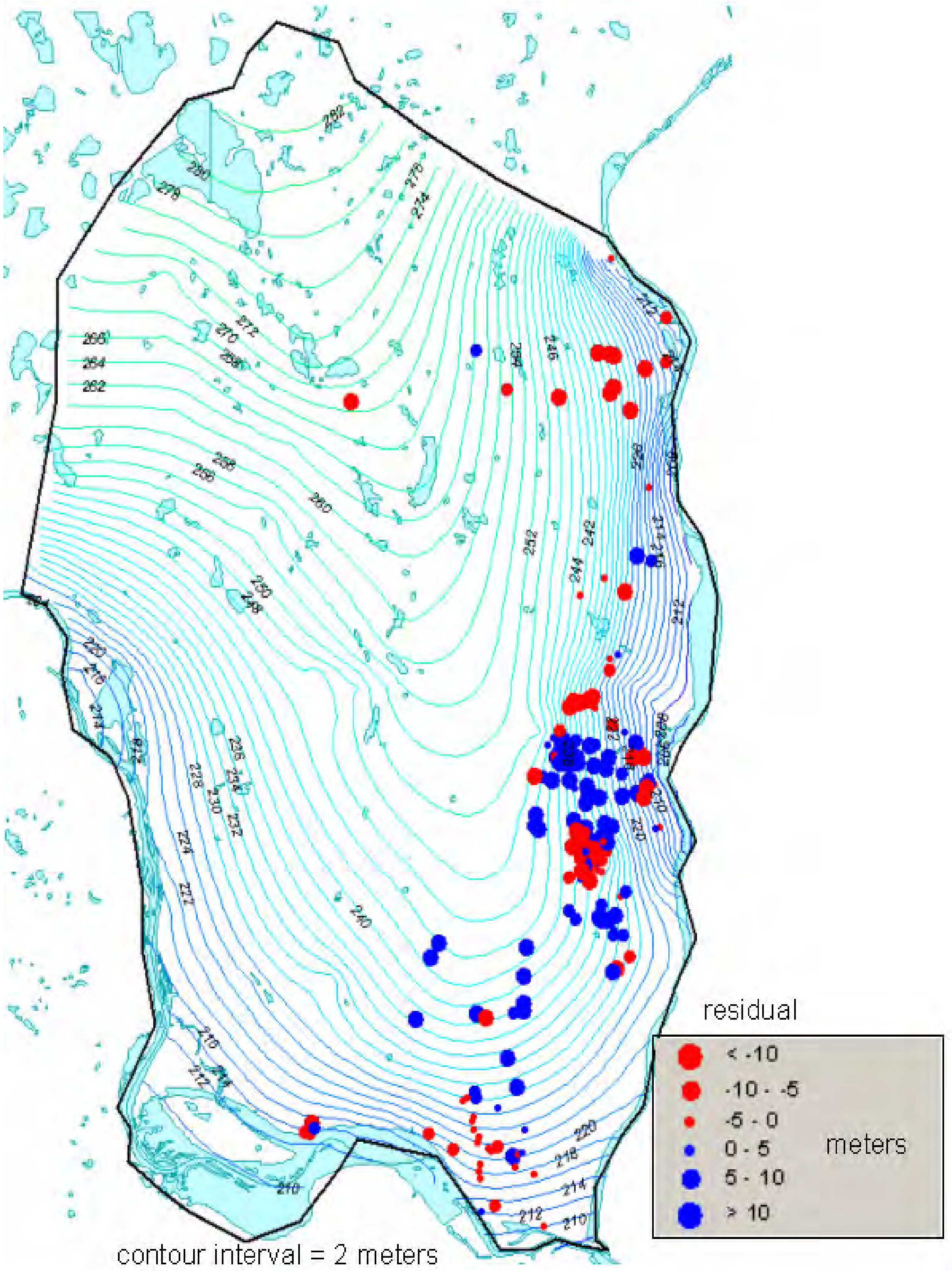


Figure 42

Contours of Steady-State Hydraulic Head and Plot of Optimization Residual for Layer 7

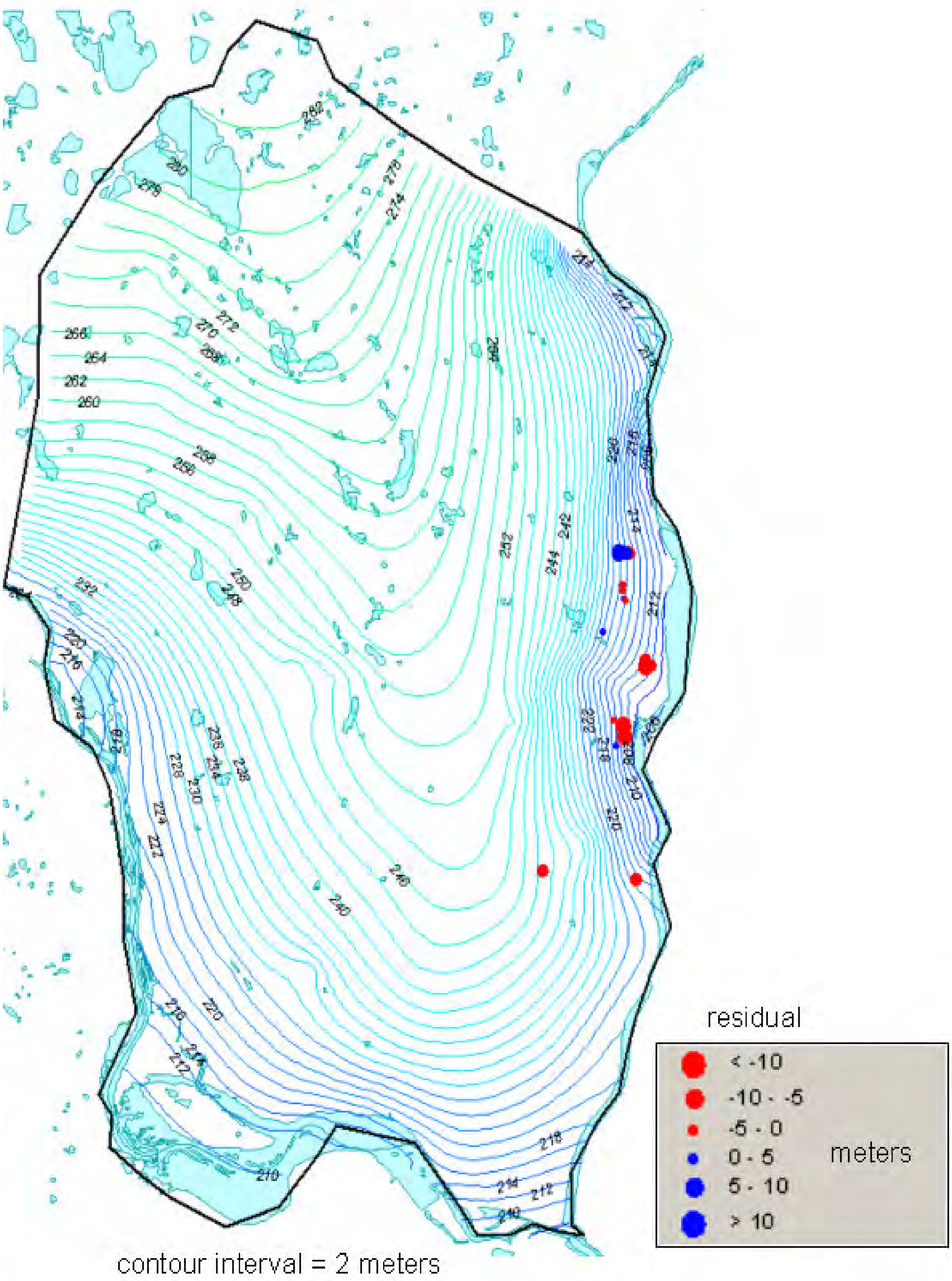


Figure 43

Contours of Steady-State Hydraulic Head and Plot of Optimization Residual for Layer 8

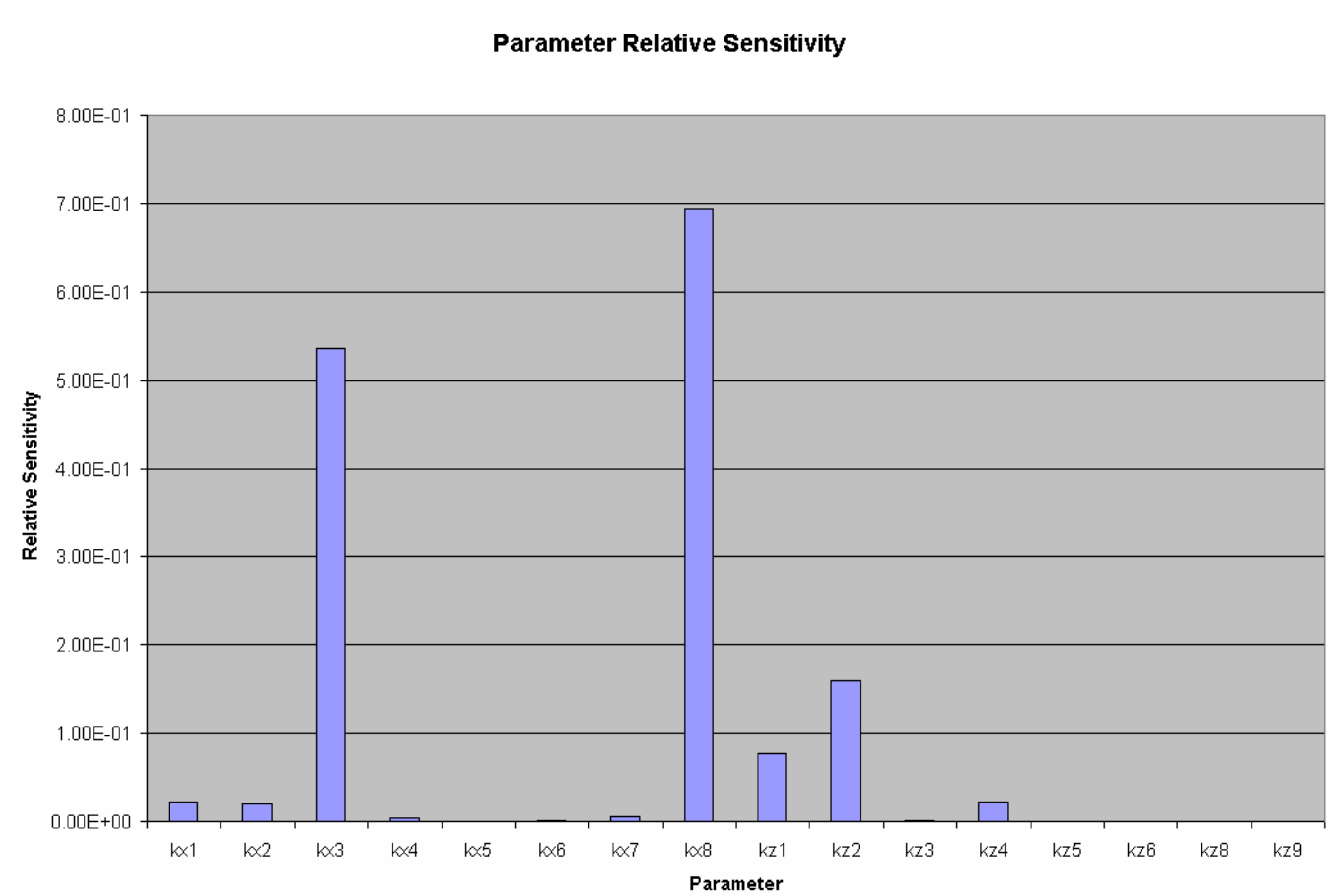


Figure 44

Plot of Relative Parameter Sensitivities for Regional Optimization

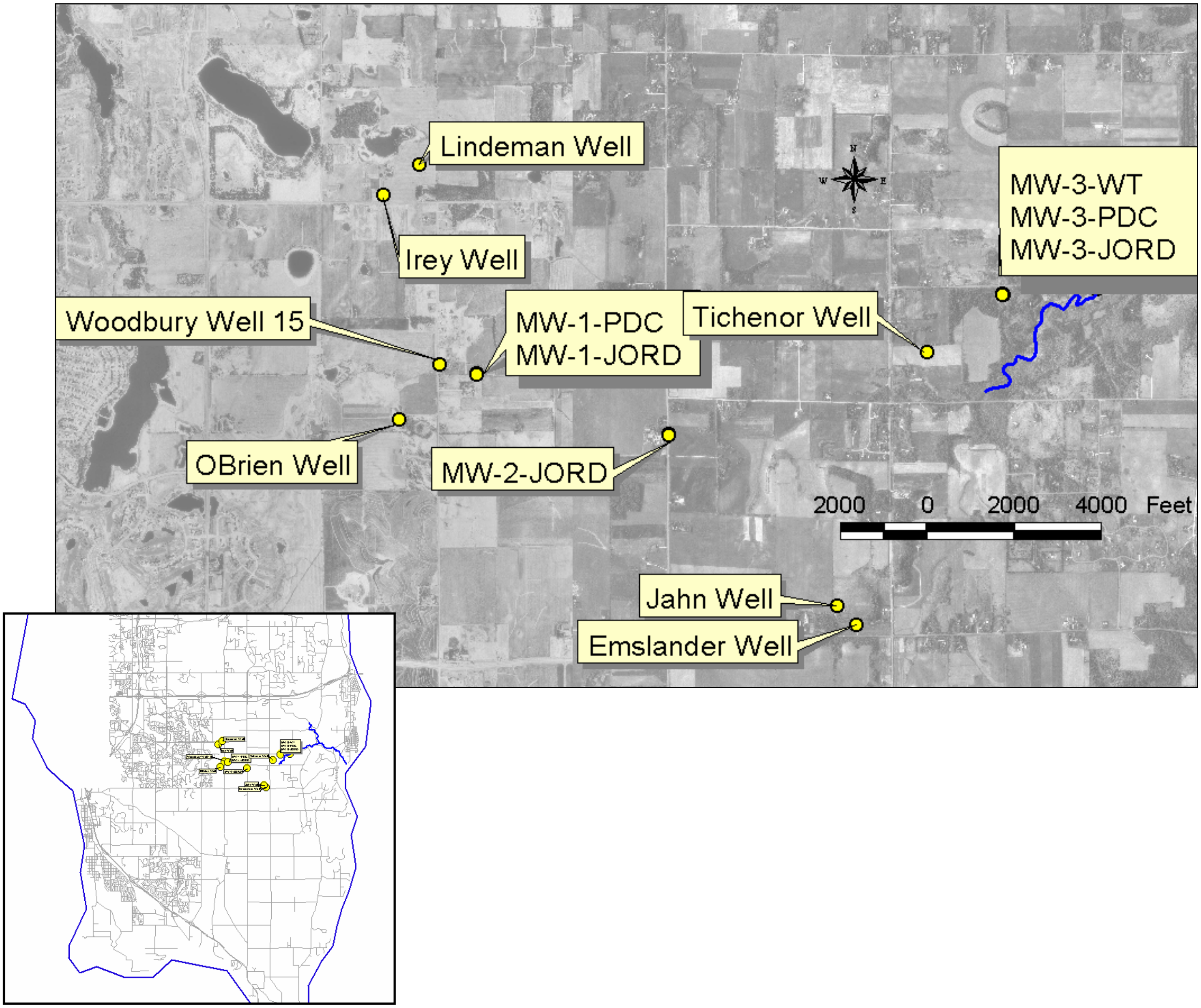


Figure 45

Location of Wells for Woodbury Well 15 Aquifer Tests

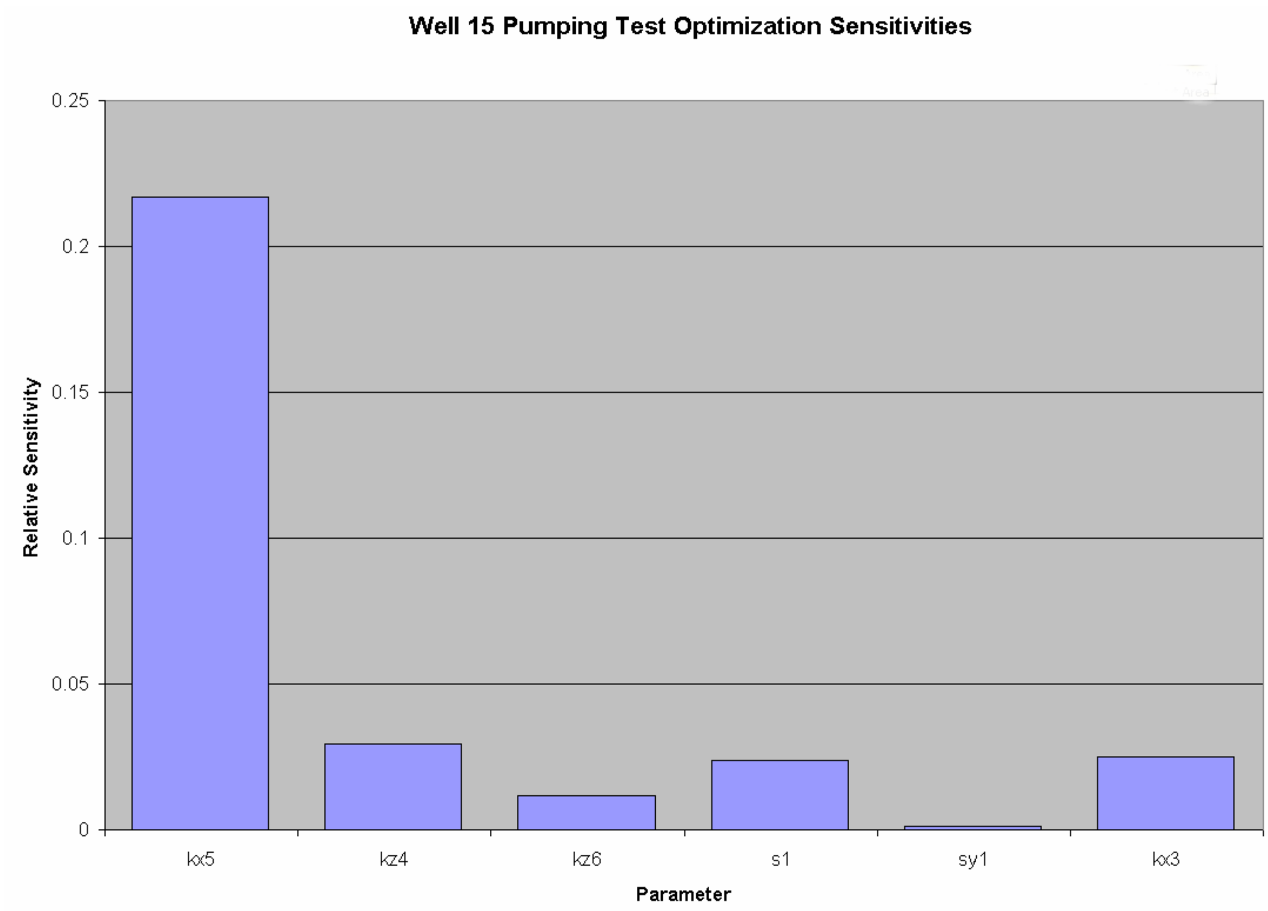


Figure 46

Plot of Relative Parameter Sensitivities for Woodbury Well 15 Aquifer Test Optimization

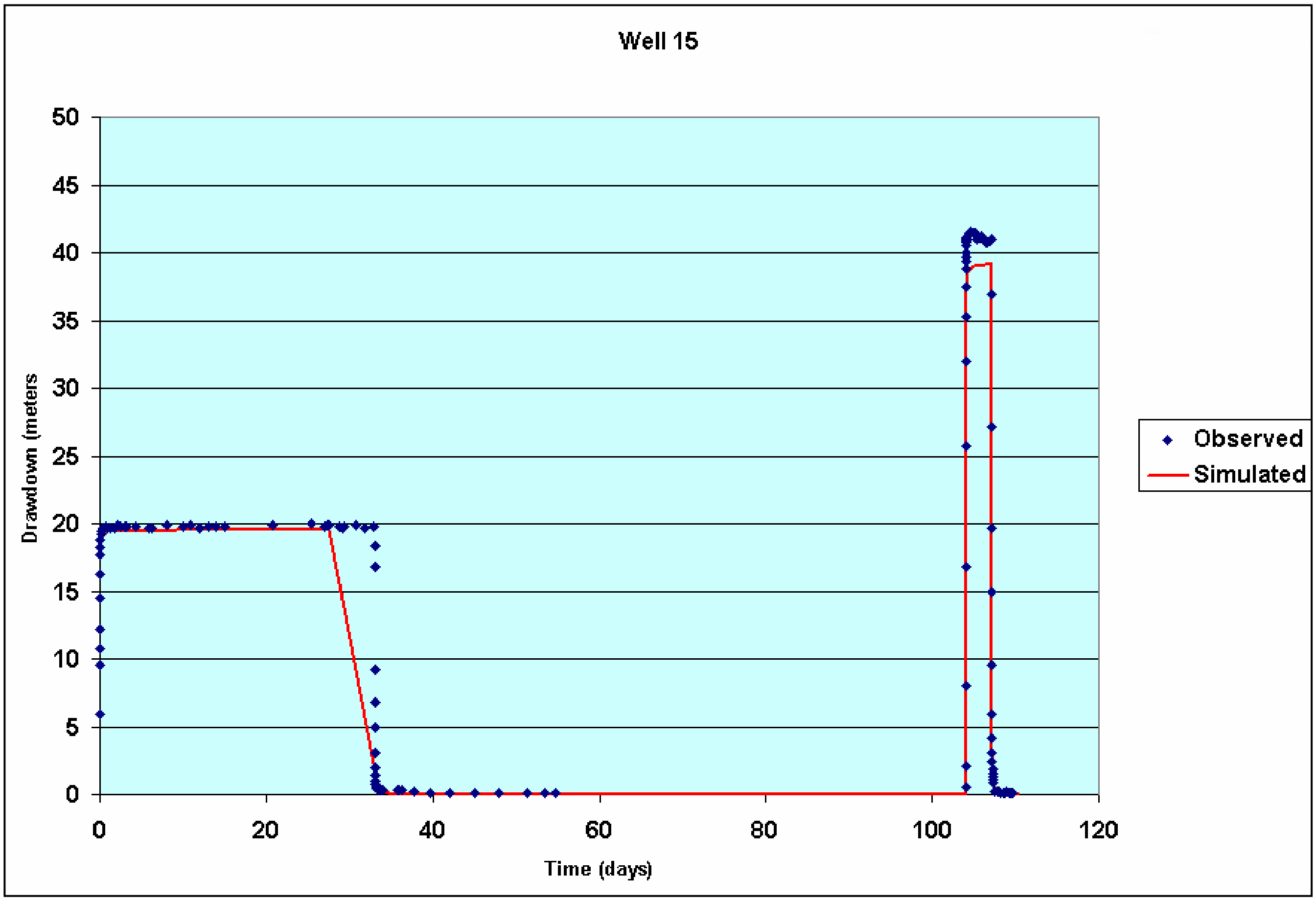


Figure 47

Comparison of Simulated and Observed Drawdowns at Well 15 for Aquifer Test Optimization

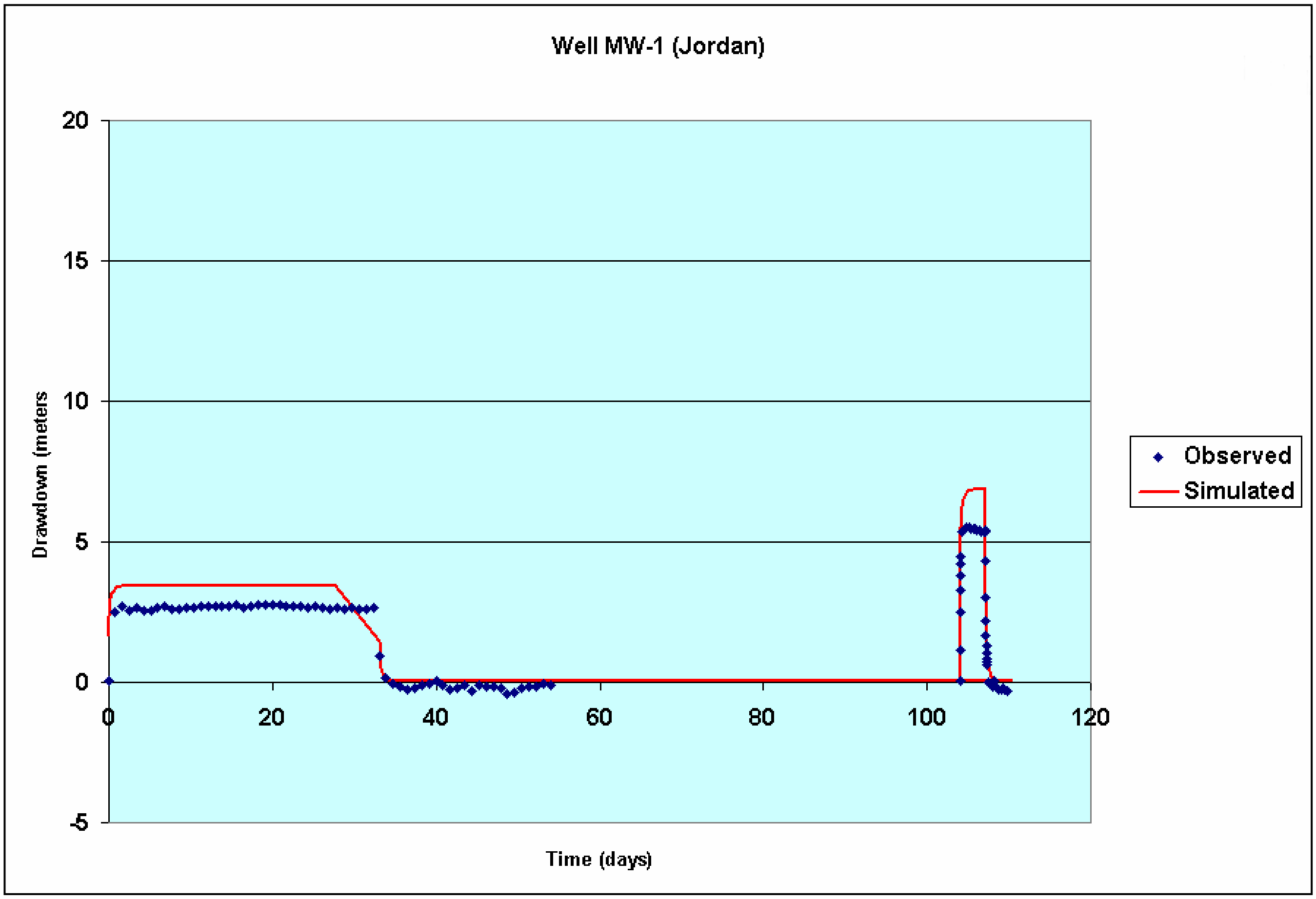


Figure 48

Comparison of Simulated and Observed Drawdowns at Monitoring Well MW-1-Jordan for Aquifer Test Optimization

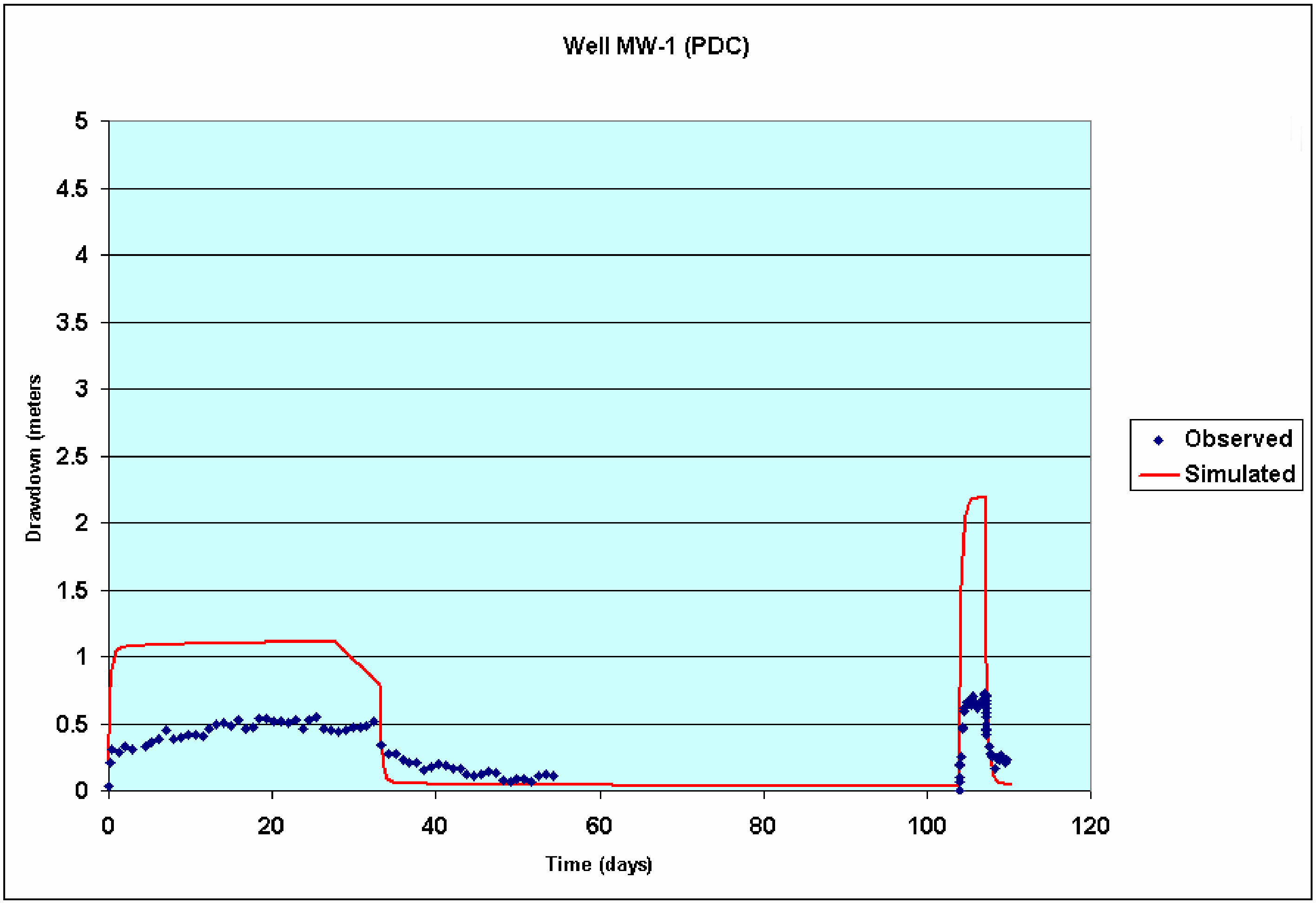


Figure 49

Comparison of Simulated and Observed Drawdowns at Monitoring Well MW-1-PDC for Aquifer Test Optimization

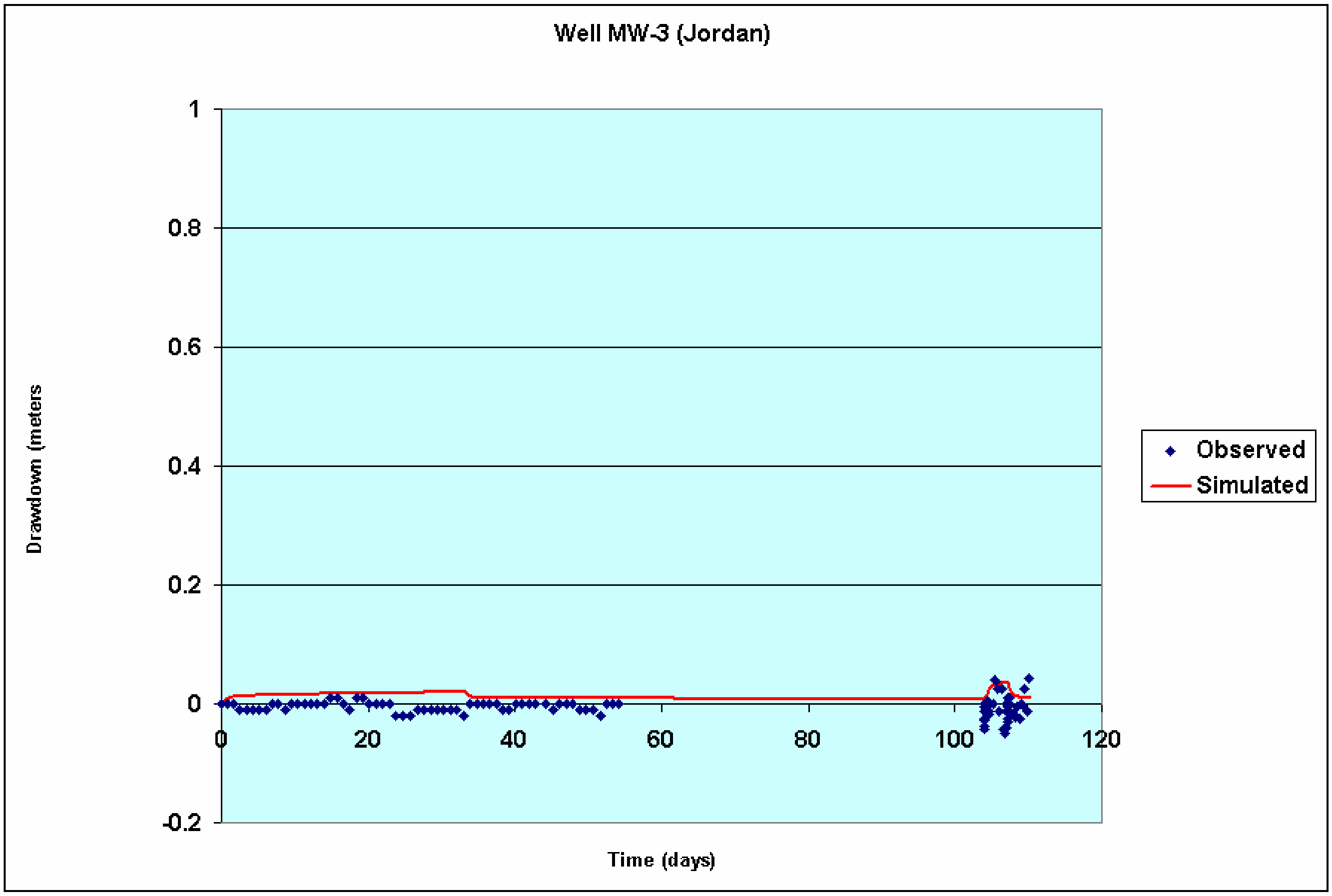


Figure 50

Comparison of Simulated and Observed Drawdowns at Monitoring Well MW-3-Jordan for Aquifer Test Optimization

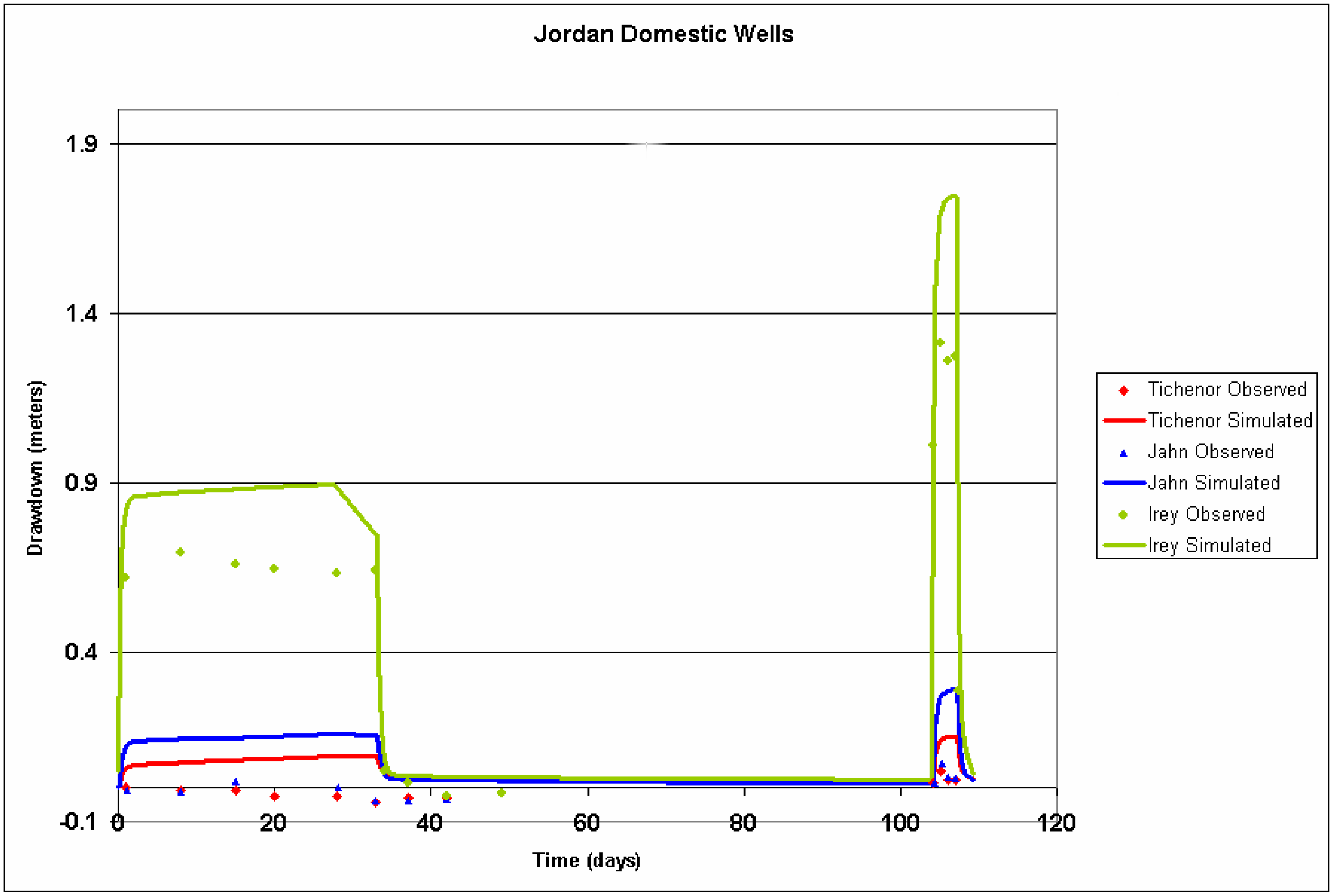


Figure 51

Comparison of Simulated and Observed Drawdowns at Jordan Domestic Wells for Aquifer Test Optimization

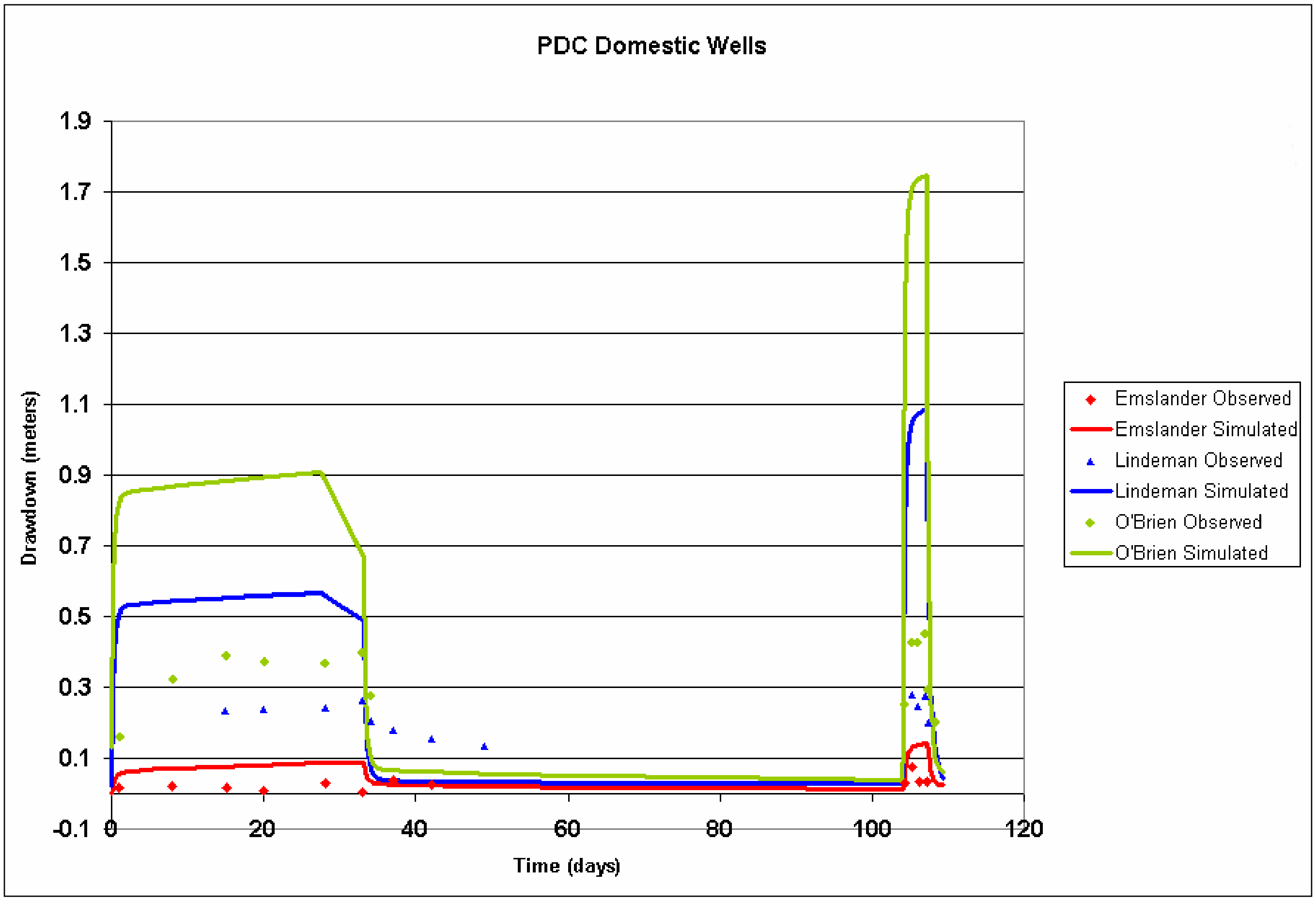


Figure 52

Comparison of Simulated and Observed Drawdowns at Prairie du Chien Group Domestic Wells for Aquifer Test Optimization

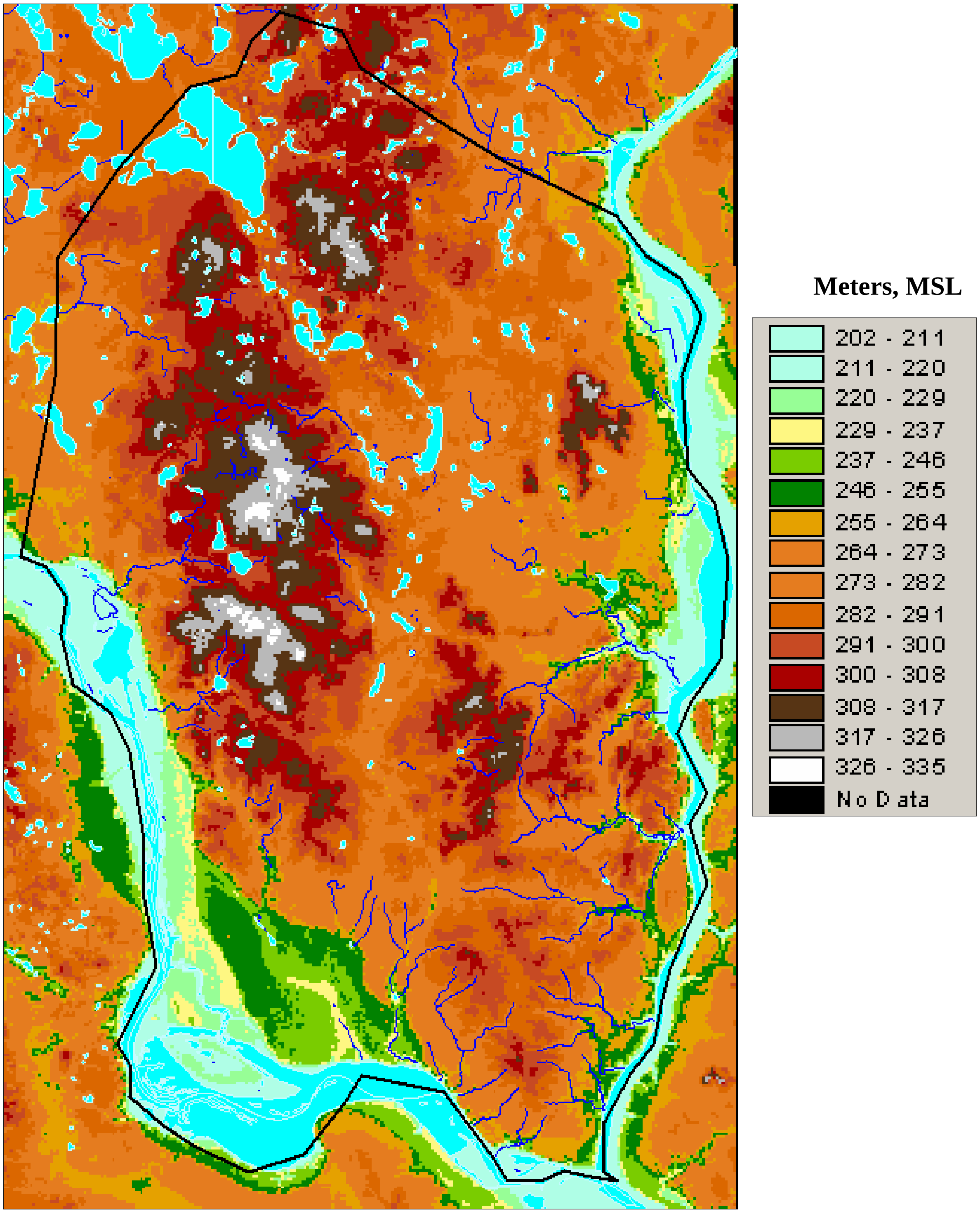


Figure 53

100-Meter Grid of Ground-Surface Topography Used in MIKE SHE Simulations

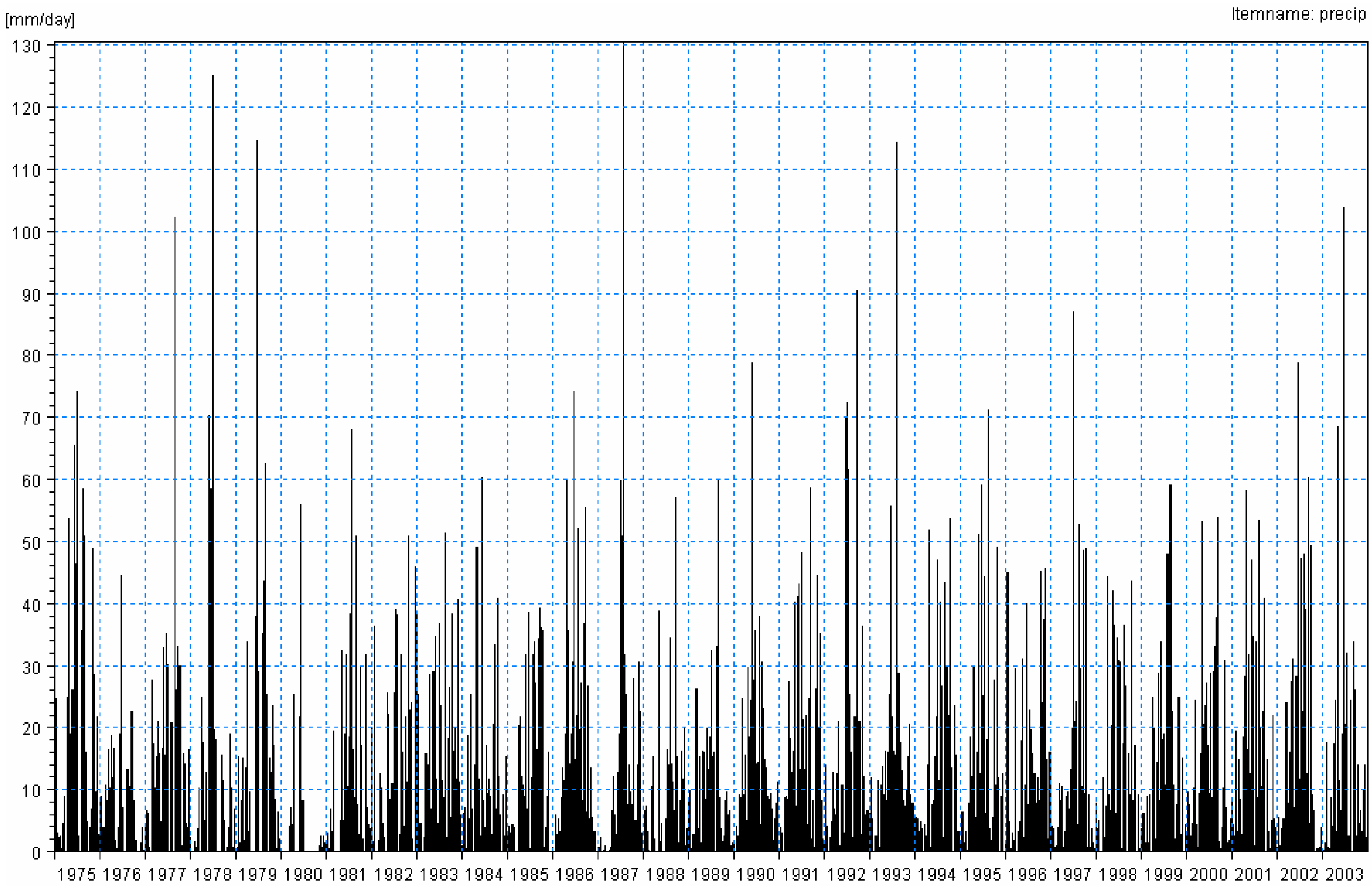


Figure 54

Daily Precipitation, mm, (St. Paul, Minnesota) Used in MIKE SHE Simulations for Period 1975-2003

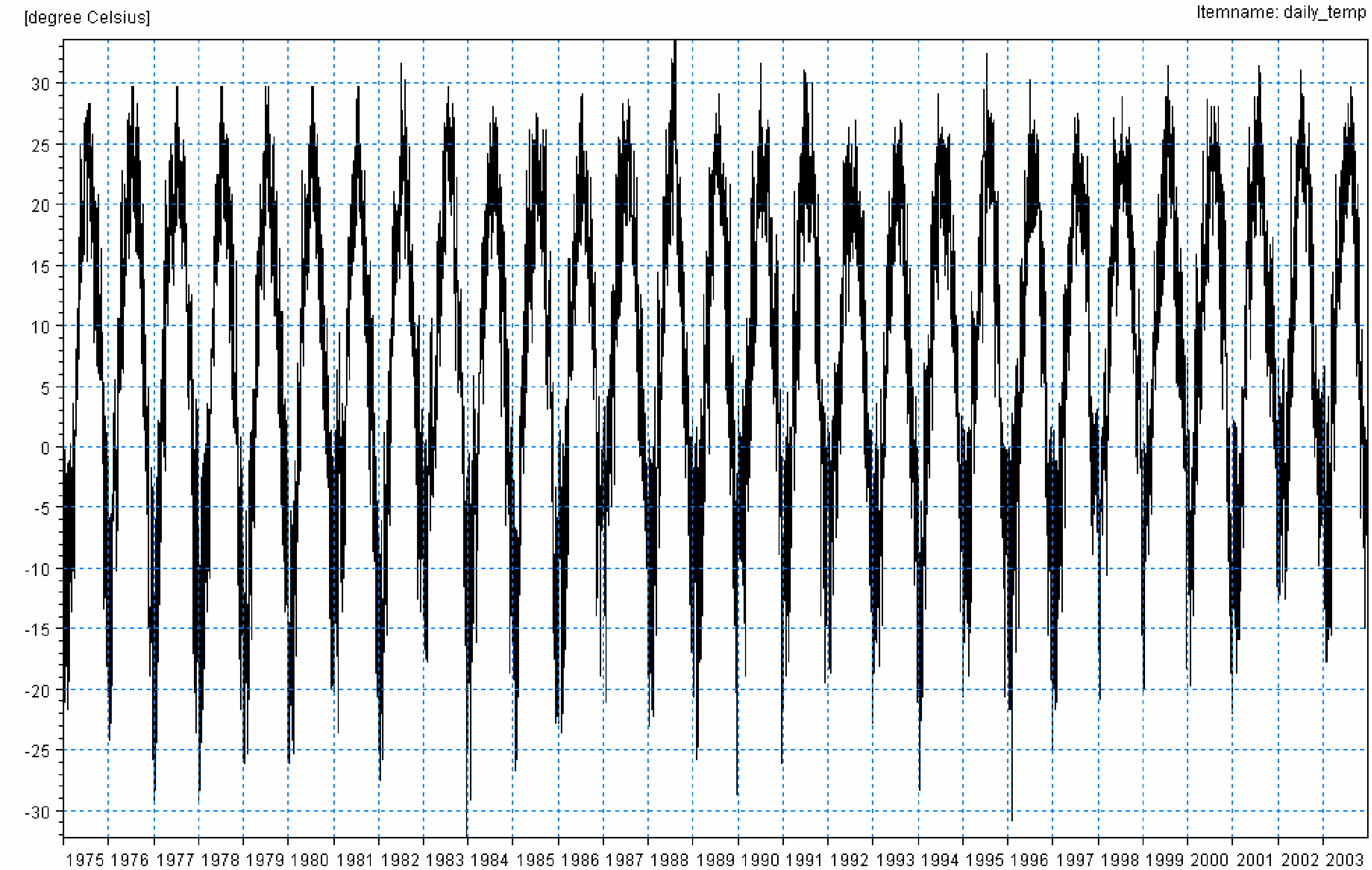


Figure 55

Daily Mean Temperature (^{o}C) (St. Paul, Minnesota) Used in MIKE SHE Simulations for Period 1975-2003

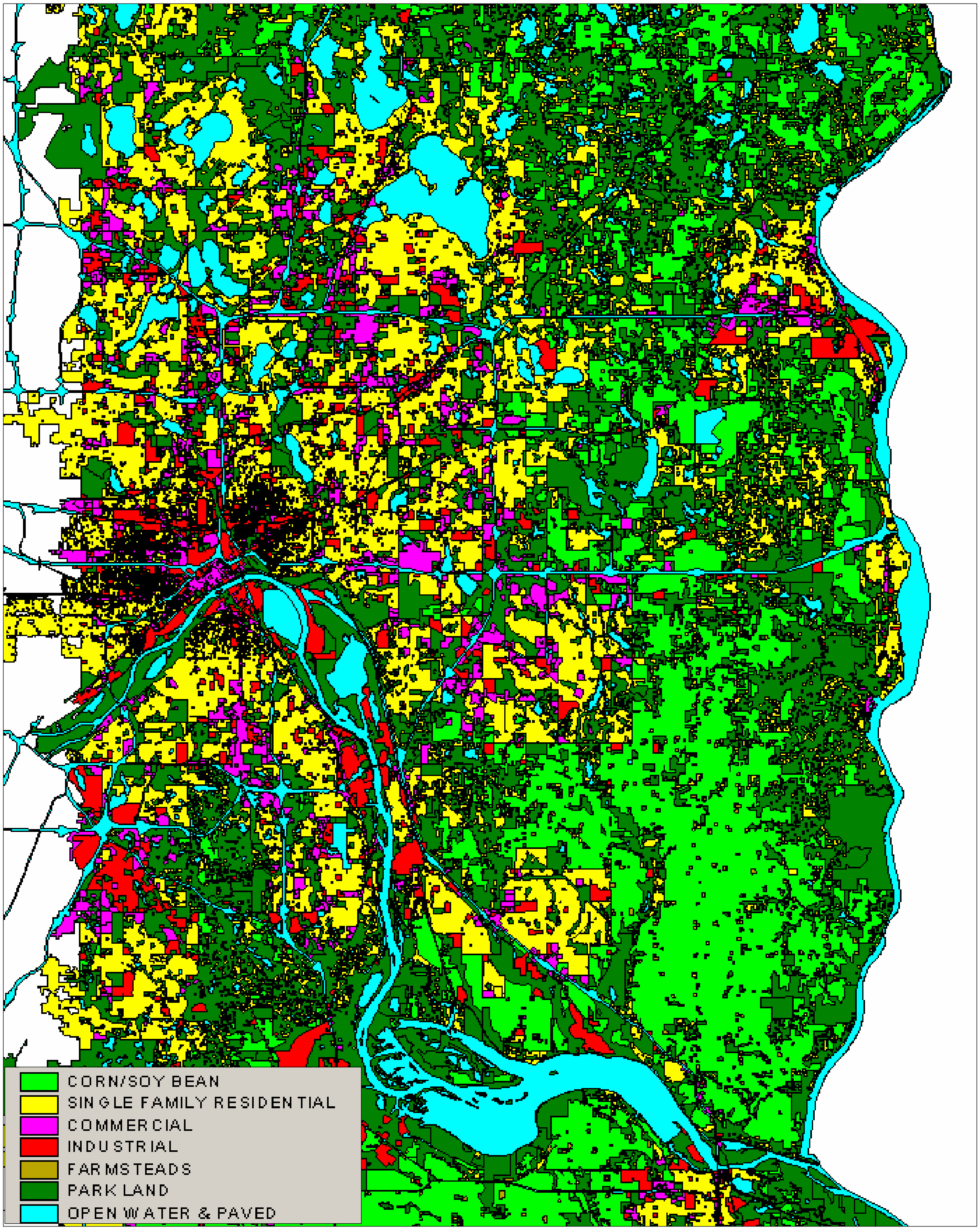
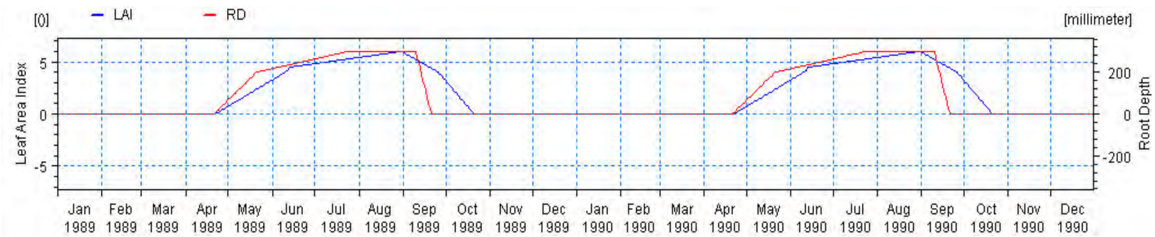


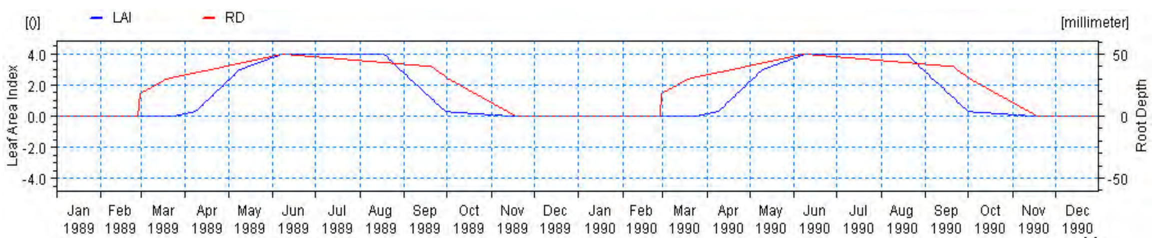
Figure 56

Seven Land-Use/Vegetation Types Used in MIKE SHE Simulations

CORN/SOYBEAN



RESIDENTIAL/LAWN



PARK LAND

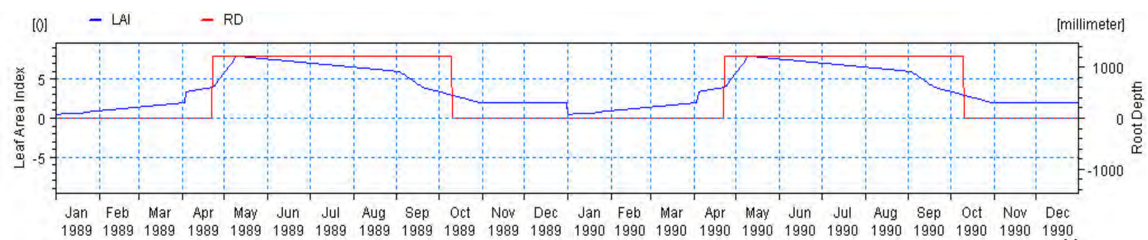


Figure 57

Example of Root Depth and Leaf Area Index Data Used in MIKE SHE Simulations

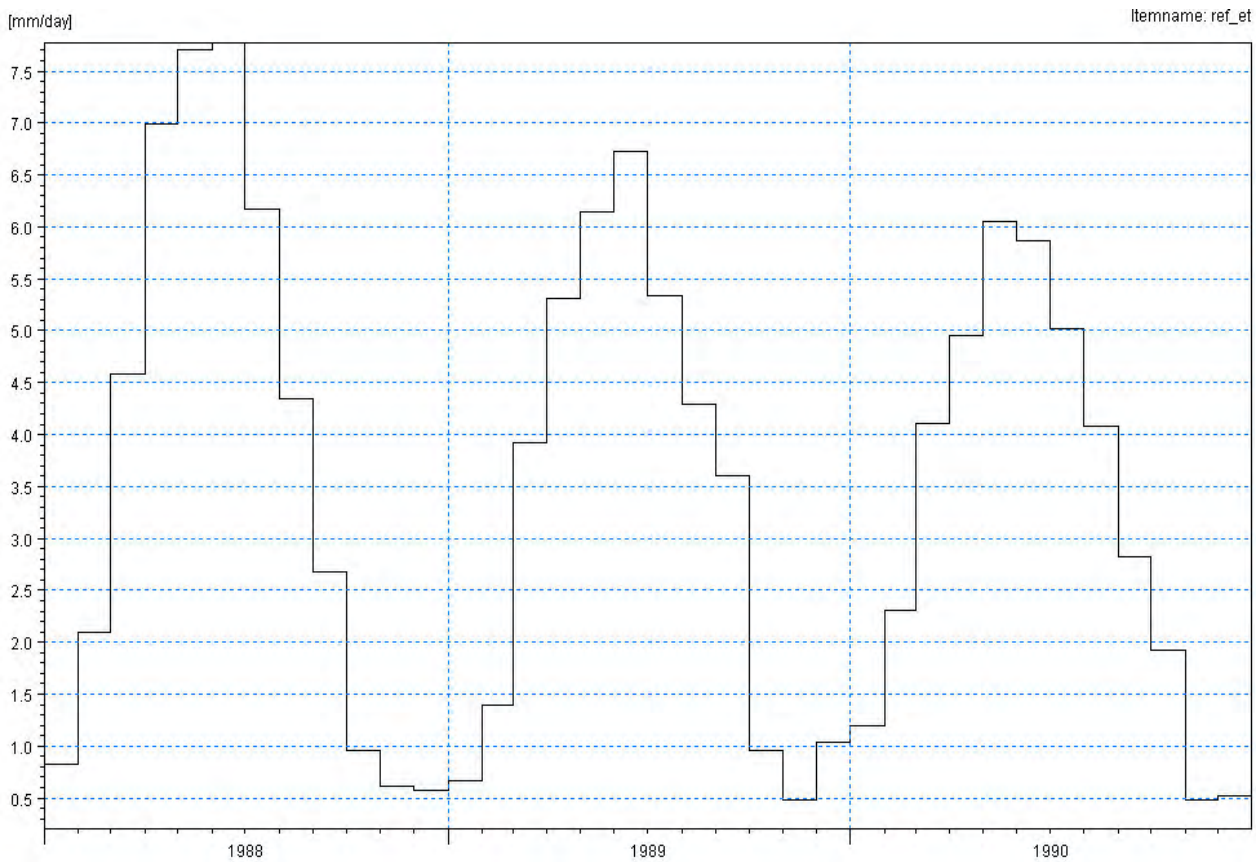


Figure 58

Reference Evapotranspiration Used in MIKE SHE for the period 1988 through 1990

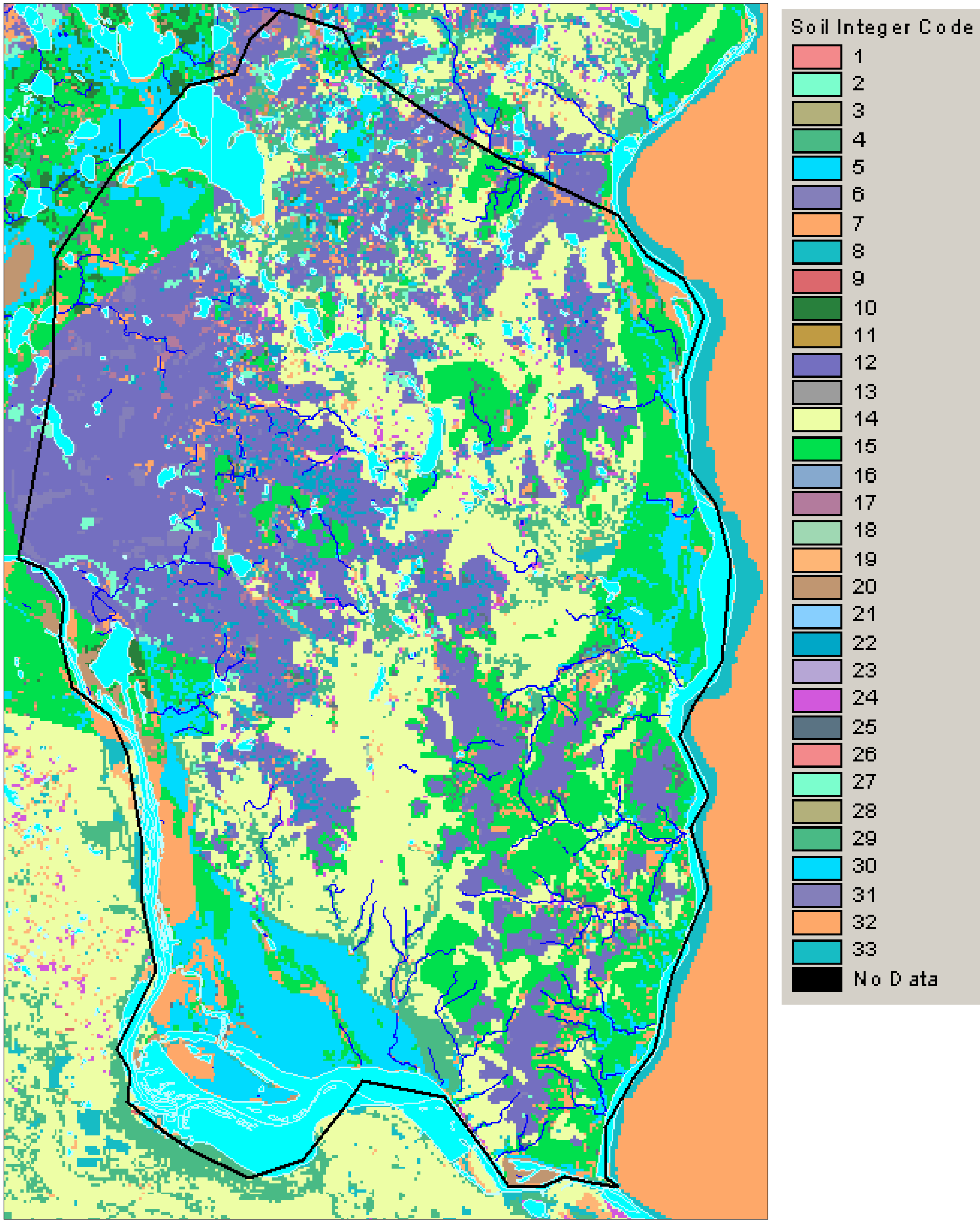


Figure 59

Soil Integer Codes Identifying Soil Profiles for MIKE SHE Unsaturated Flow Modeling

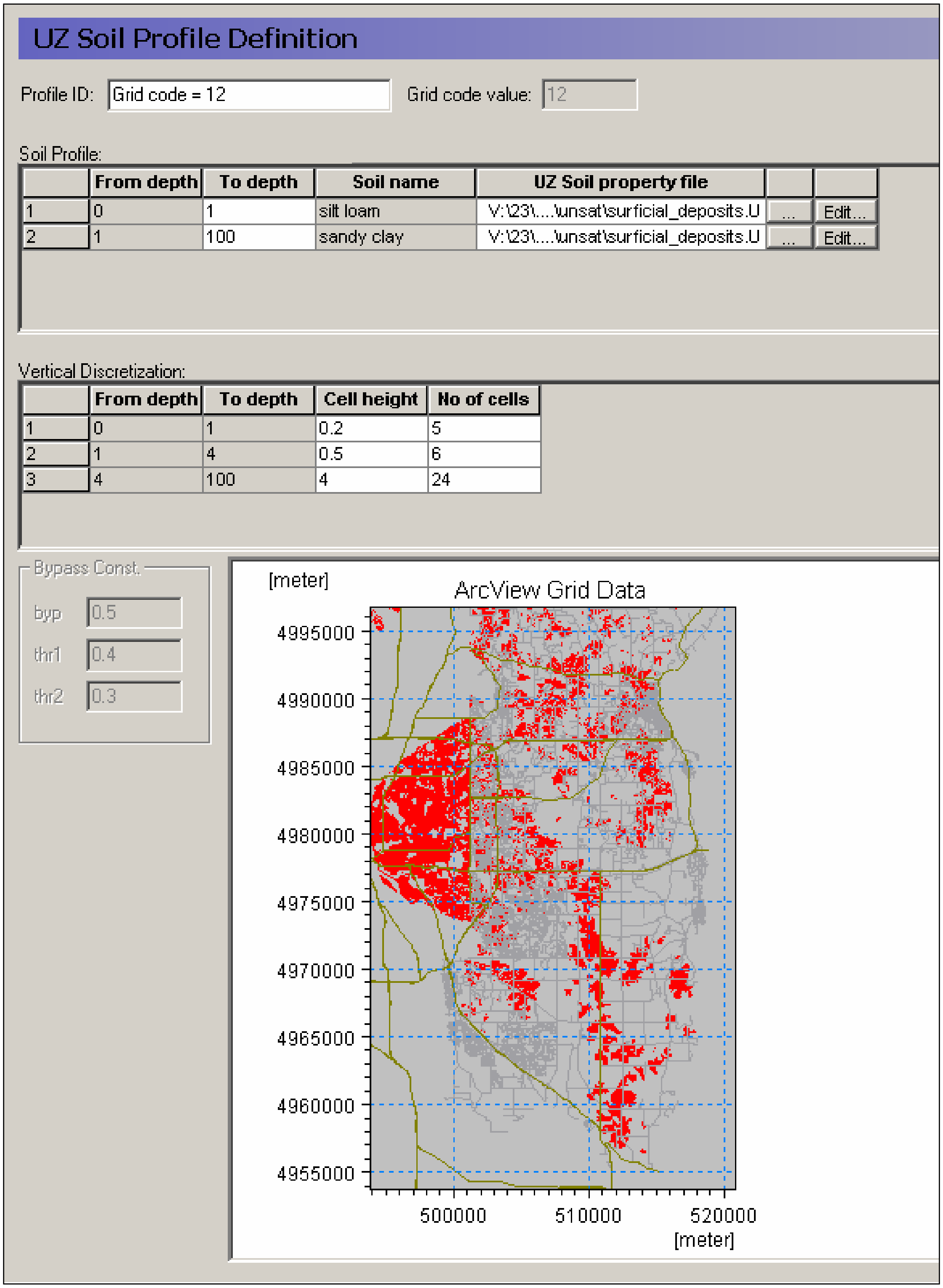


Figure 60

Example of Soil Profile Data

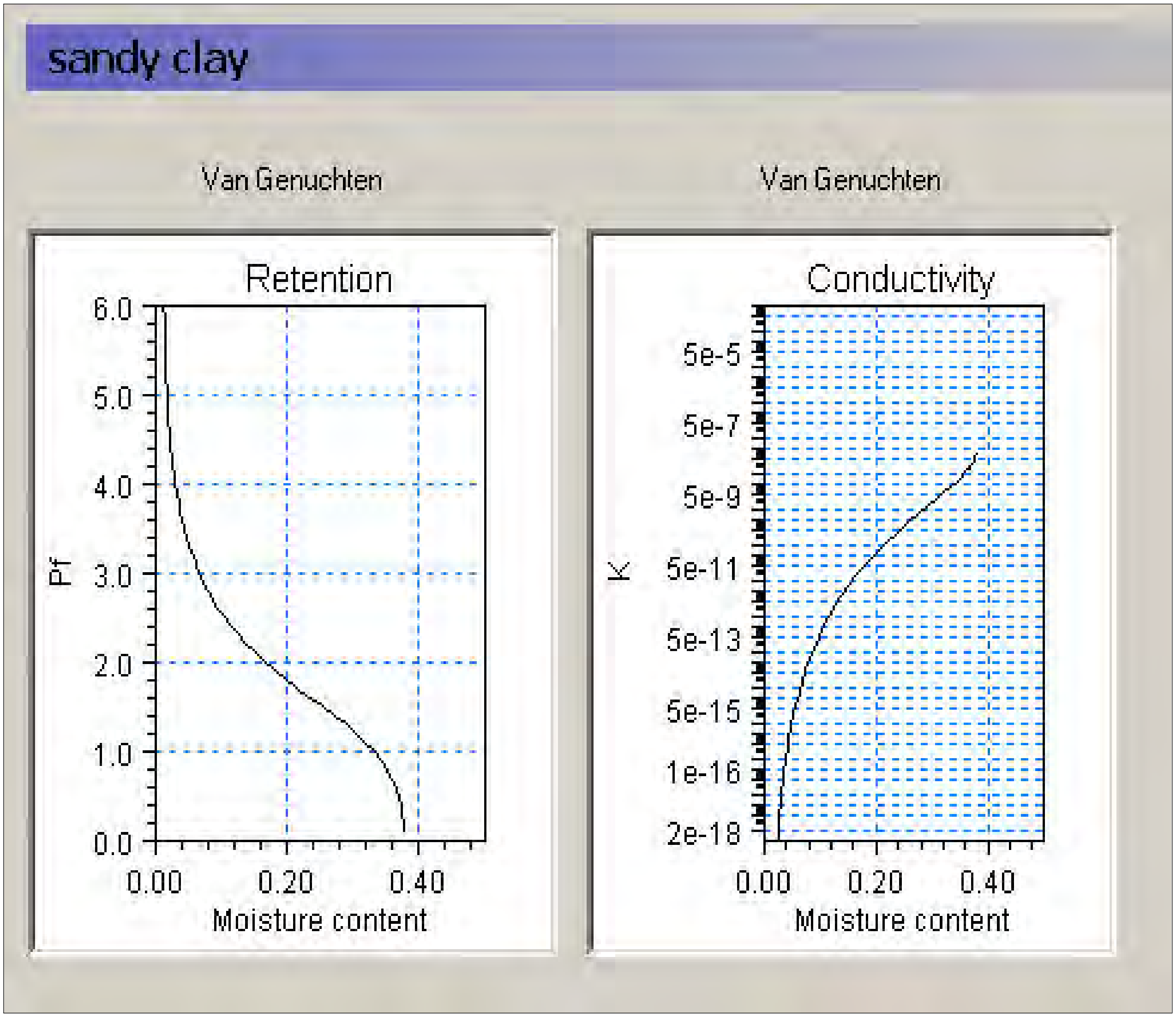
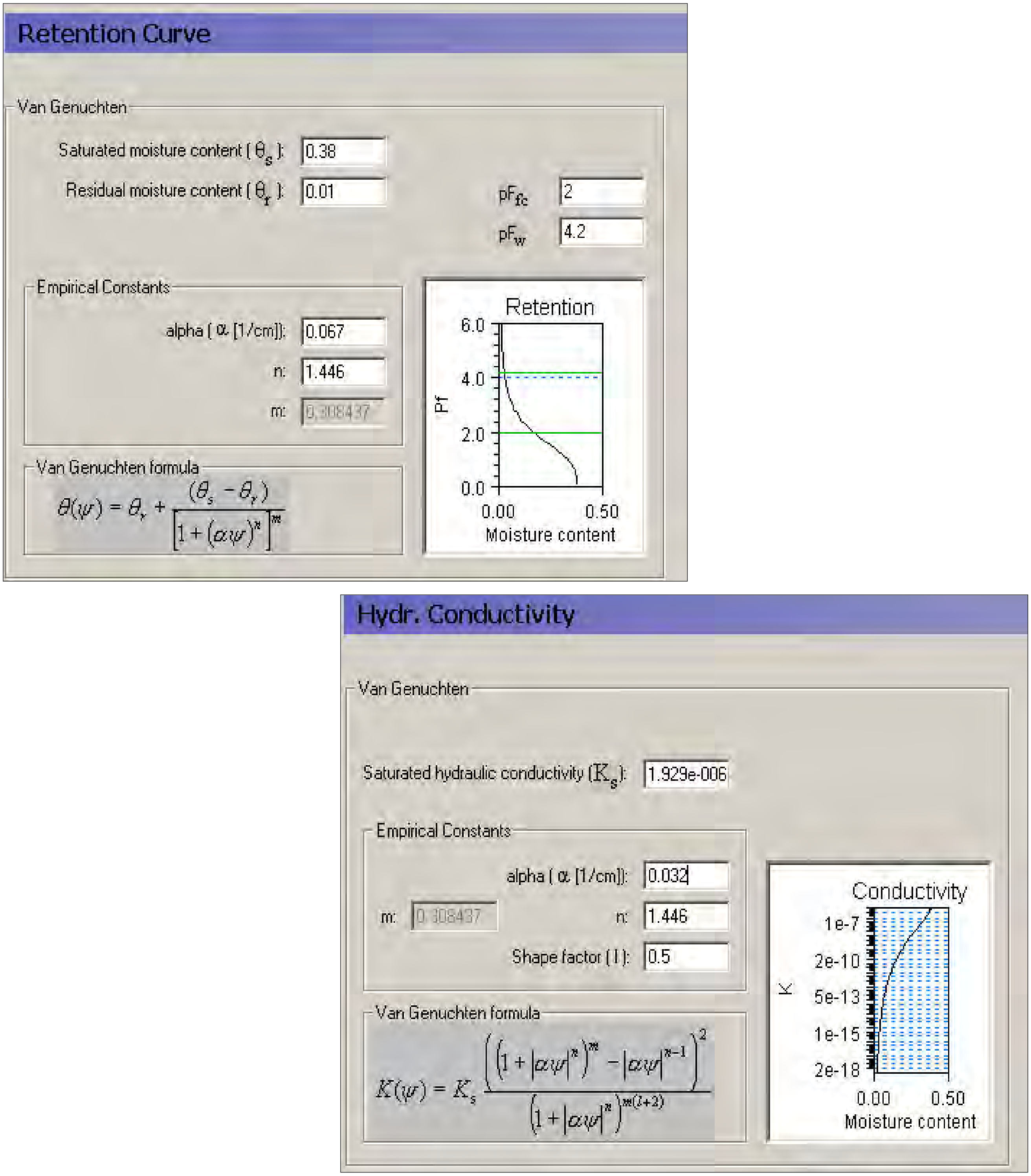


Figure 61

Example of van Genuchten Retention and Conductivity Relationships



$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha\psi)^n\right]^m}$$

$$K(\psi) = K_s \frac{\left(\left(1 + |\alpha\psi|^n\right)^m - |\alpha\psi|^{n-1}\right)^2}{\left(1 + |\alpha\psi|^n\right)^{m(l+2)}}$$

Figure 62

Example of van Genuchten Variables for Soil

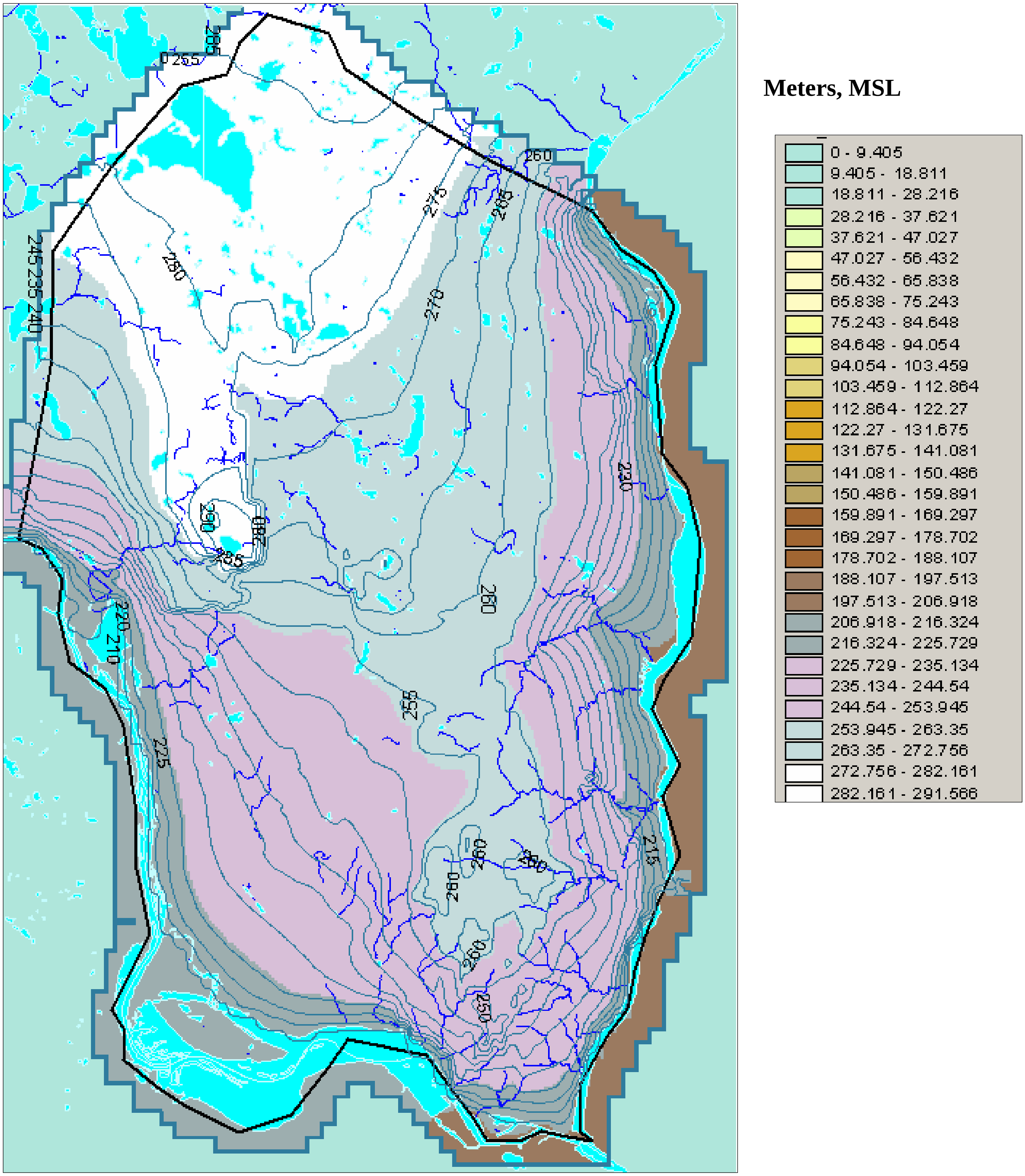


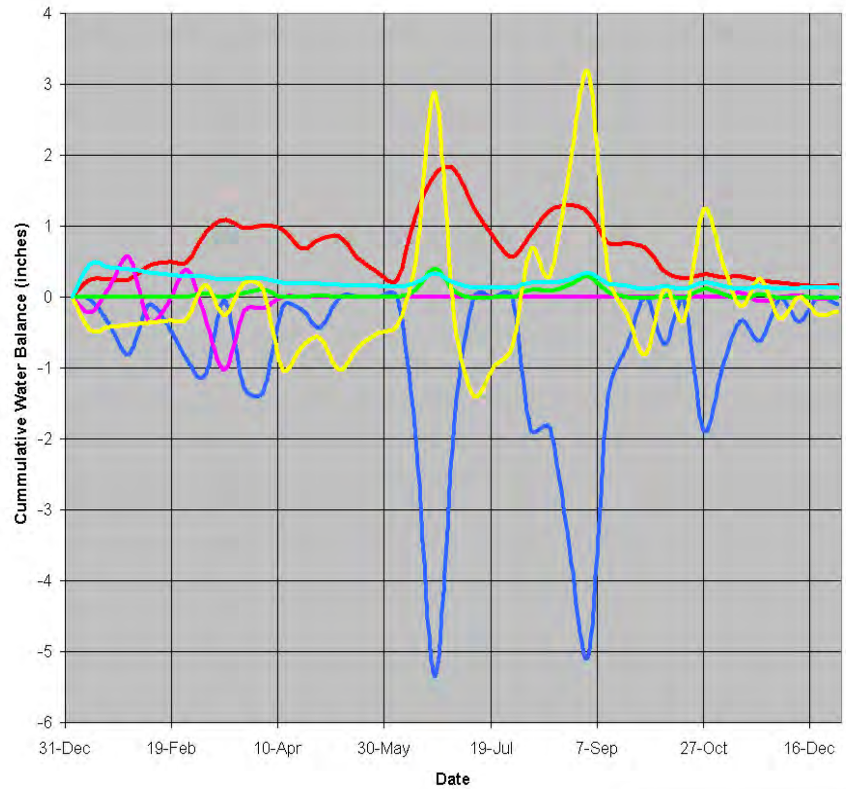
Figure 63

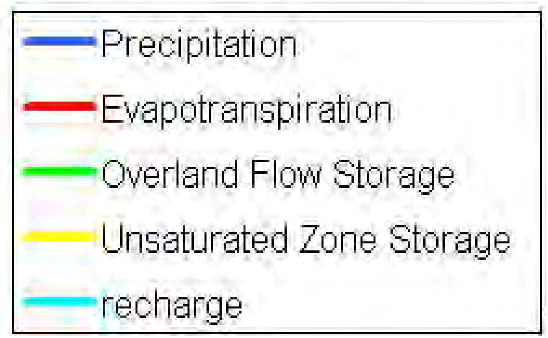
Water Table Elevation for Unsaturated Flow Computations

565 total classifications

Figure 64

Soil Column Classification for Unsaturated Flow Computations





Instantaneous Water Balance

Cumulative Water Balance

Negative values indicate flows into the unsaturated zone and positive values indicate losses out of the unsaturated zone.

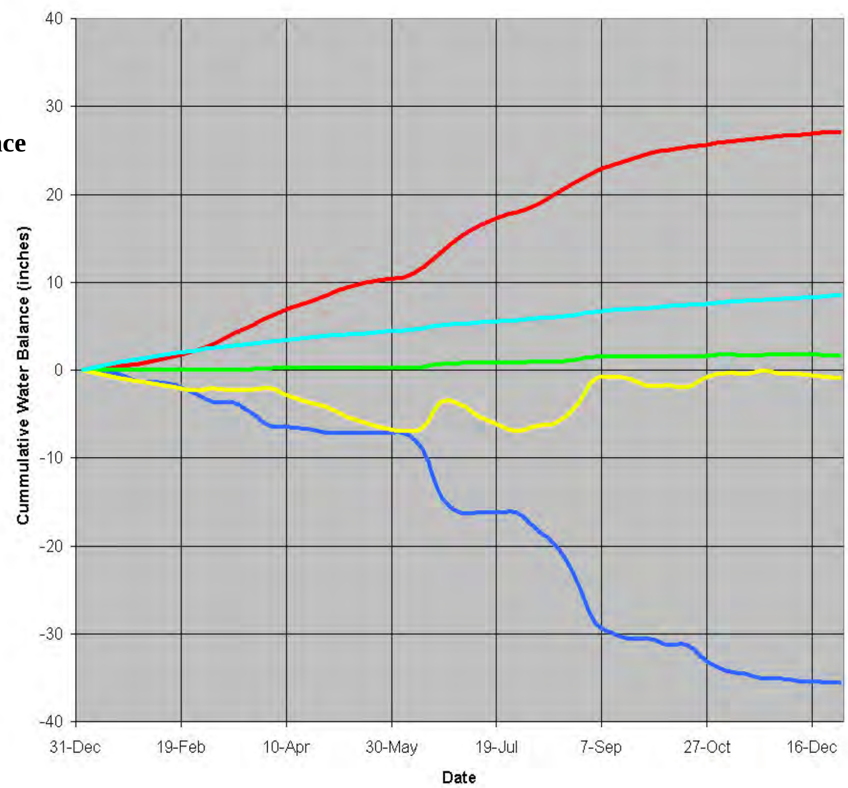


Figure 65

MIKE SHE Water Balance over Entire Model Domain for "Typical Year" (1979)

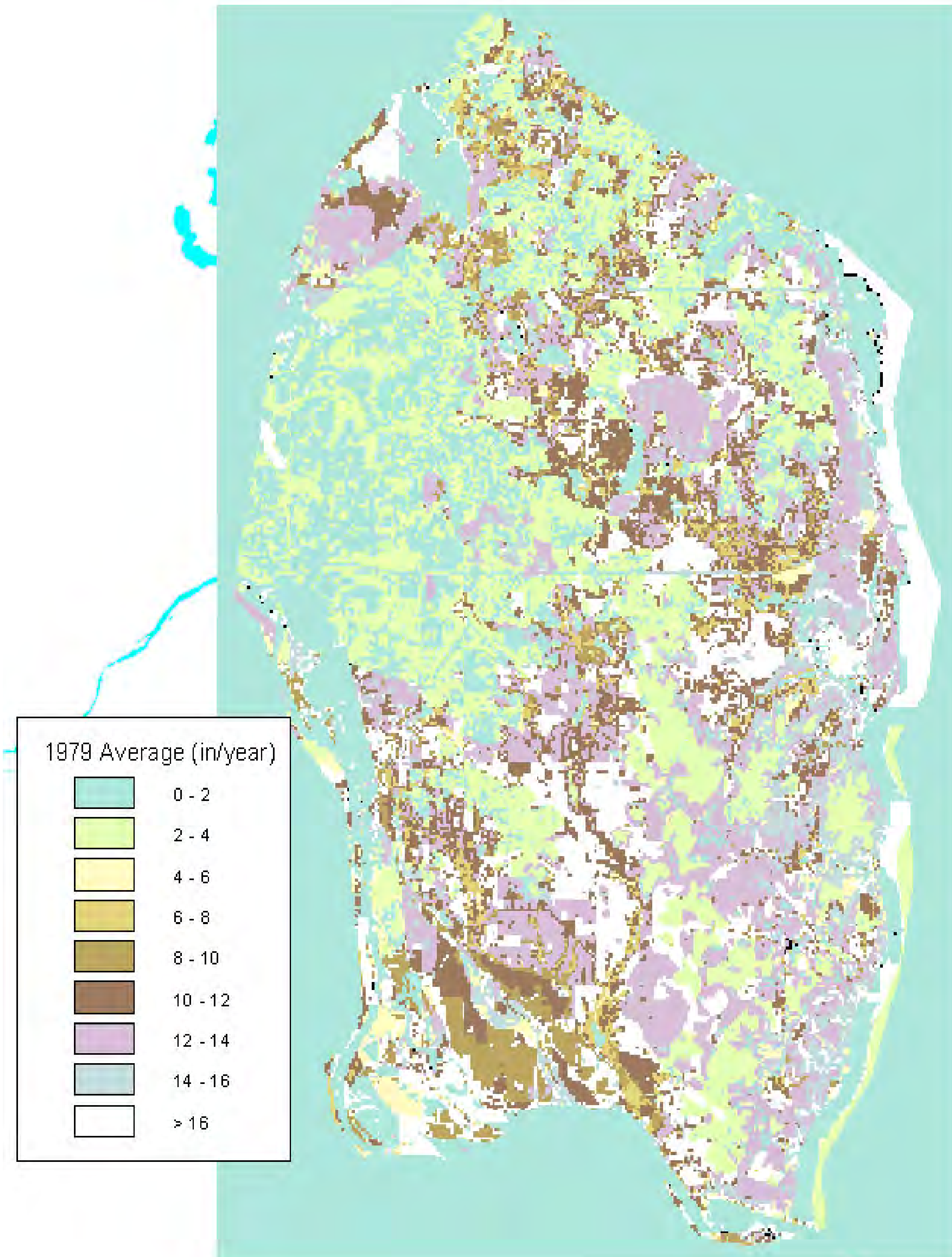


Figure 66

MIKE SHE Simulation of Annually Averaged Recharge for a Typical Year (1979)

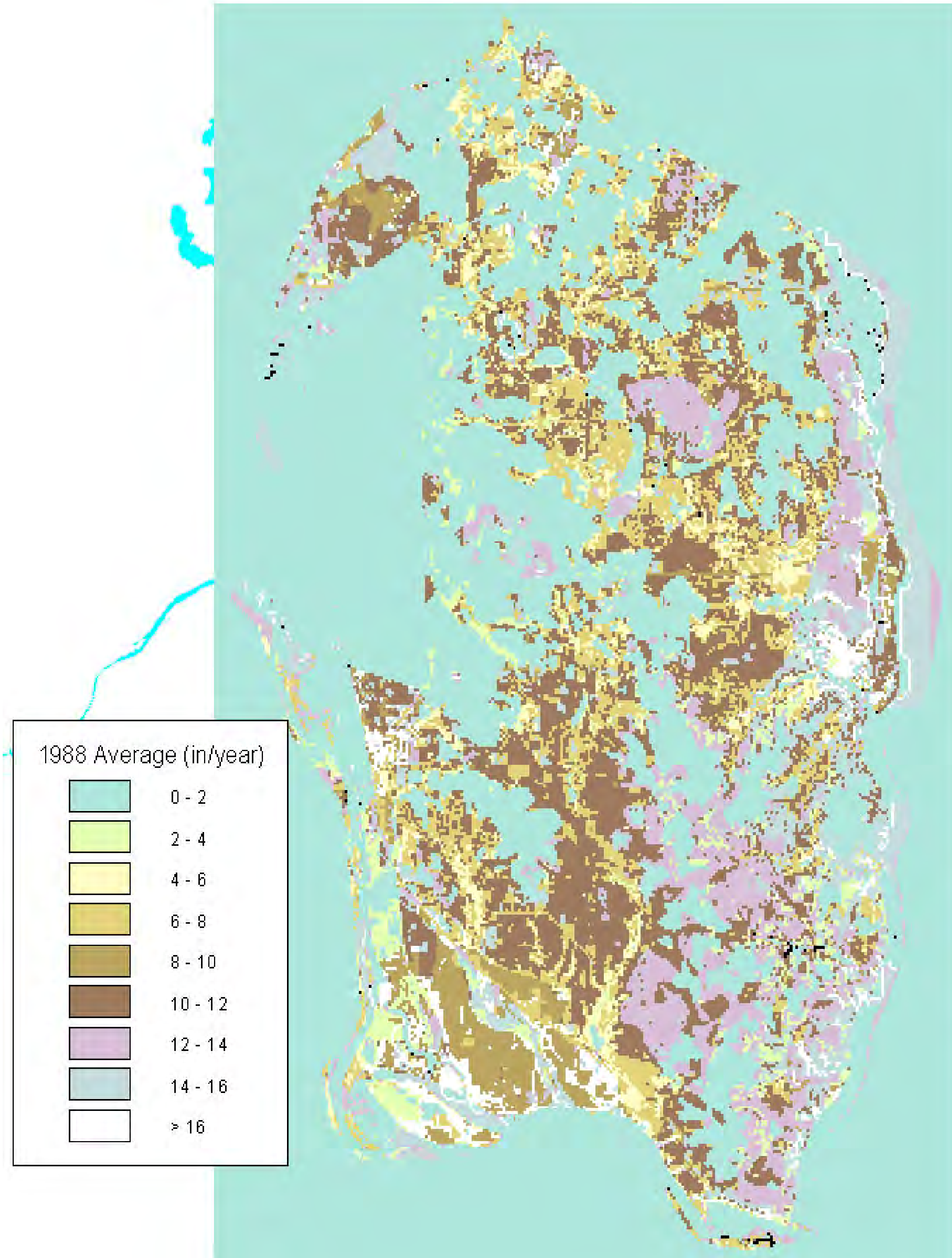


Figure 67

MIKE SHE Simulation of Annually Averaged Recharge for a Dry Year (1988)

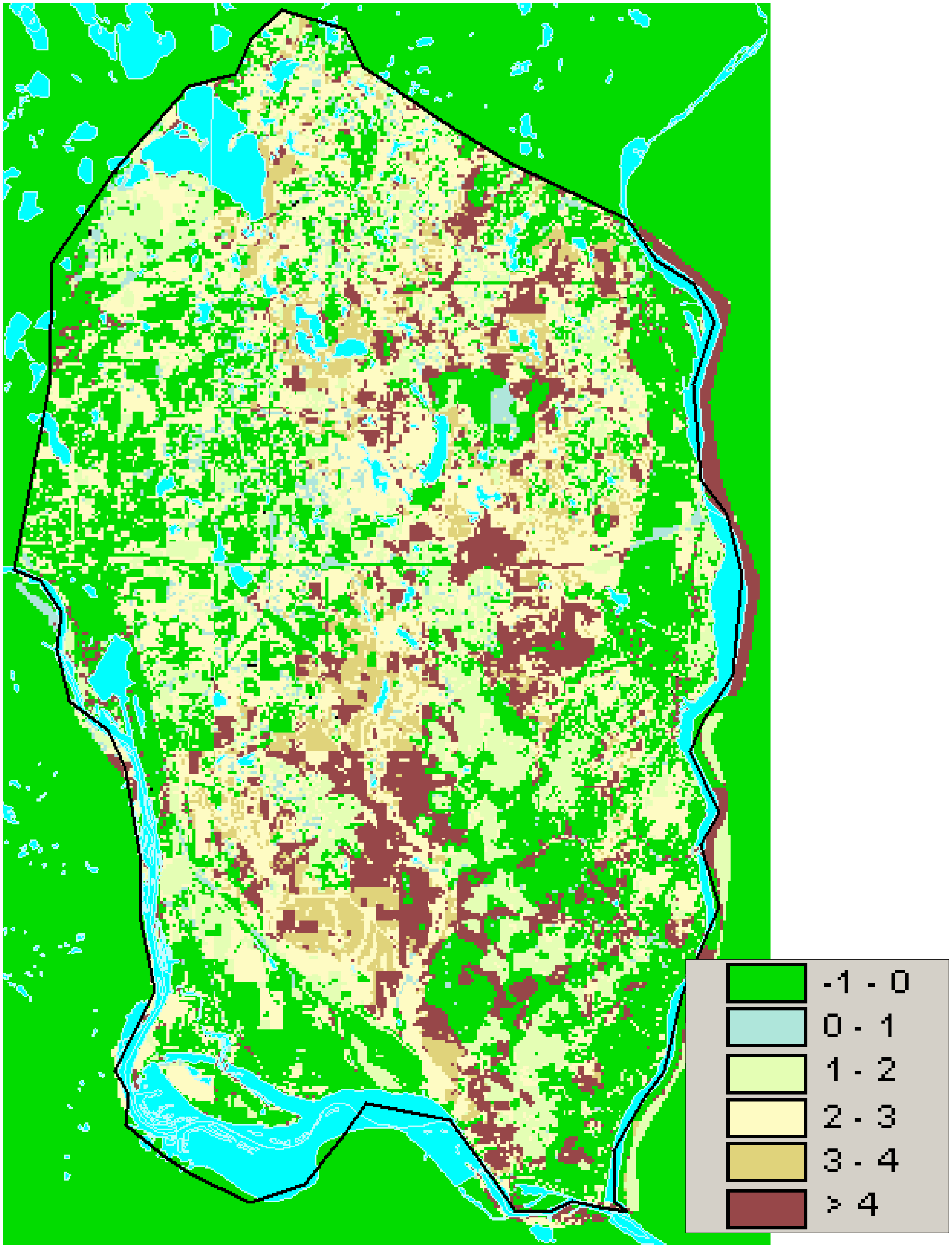


Figure 68

MIKE SHE Simulation of Deficit (in/yr) Between Dry Year and Typical Year Infiltration

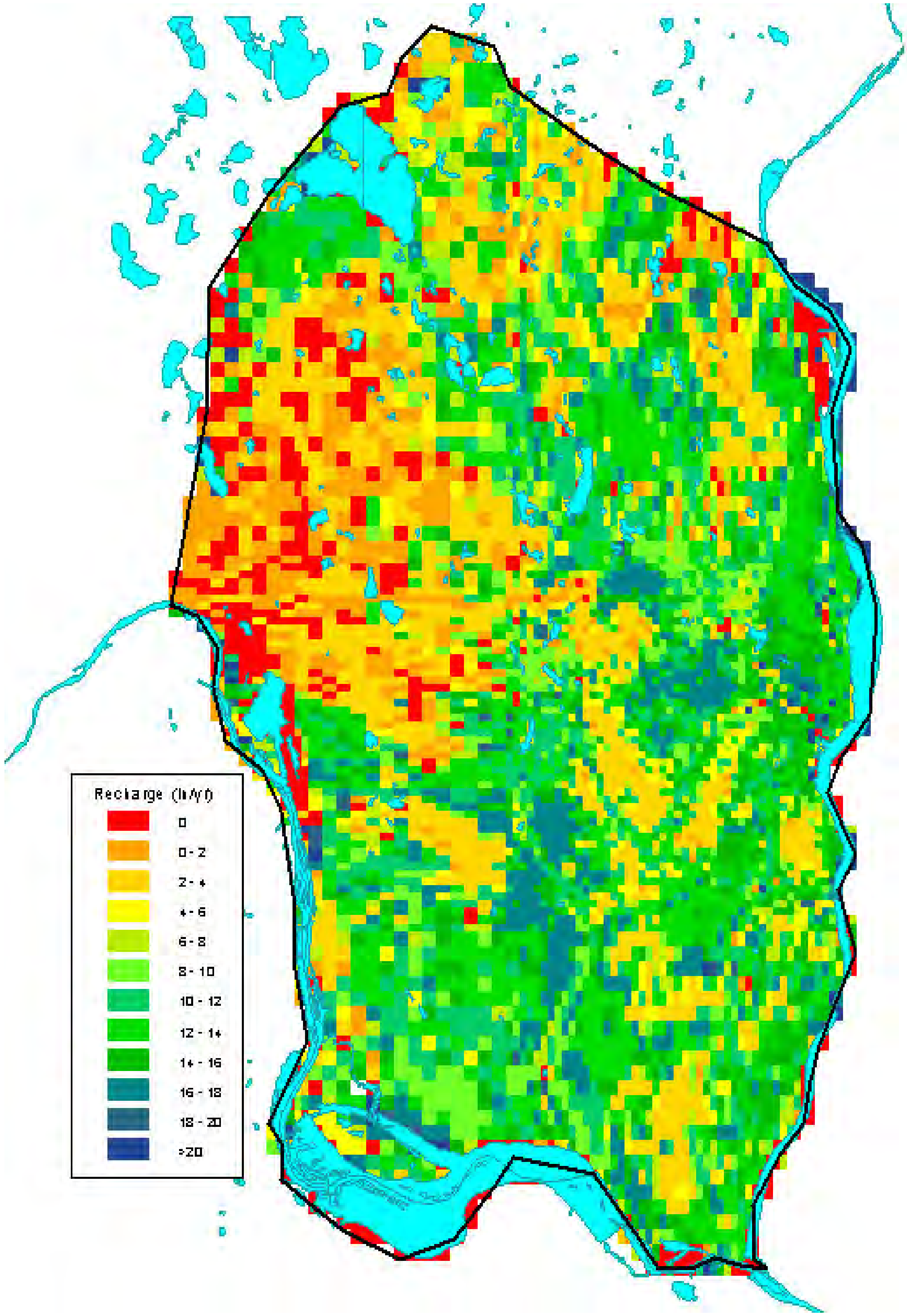


Figure 69

MODFLOW Steady-State Recharge (in/yr) for Typical Conditions

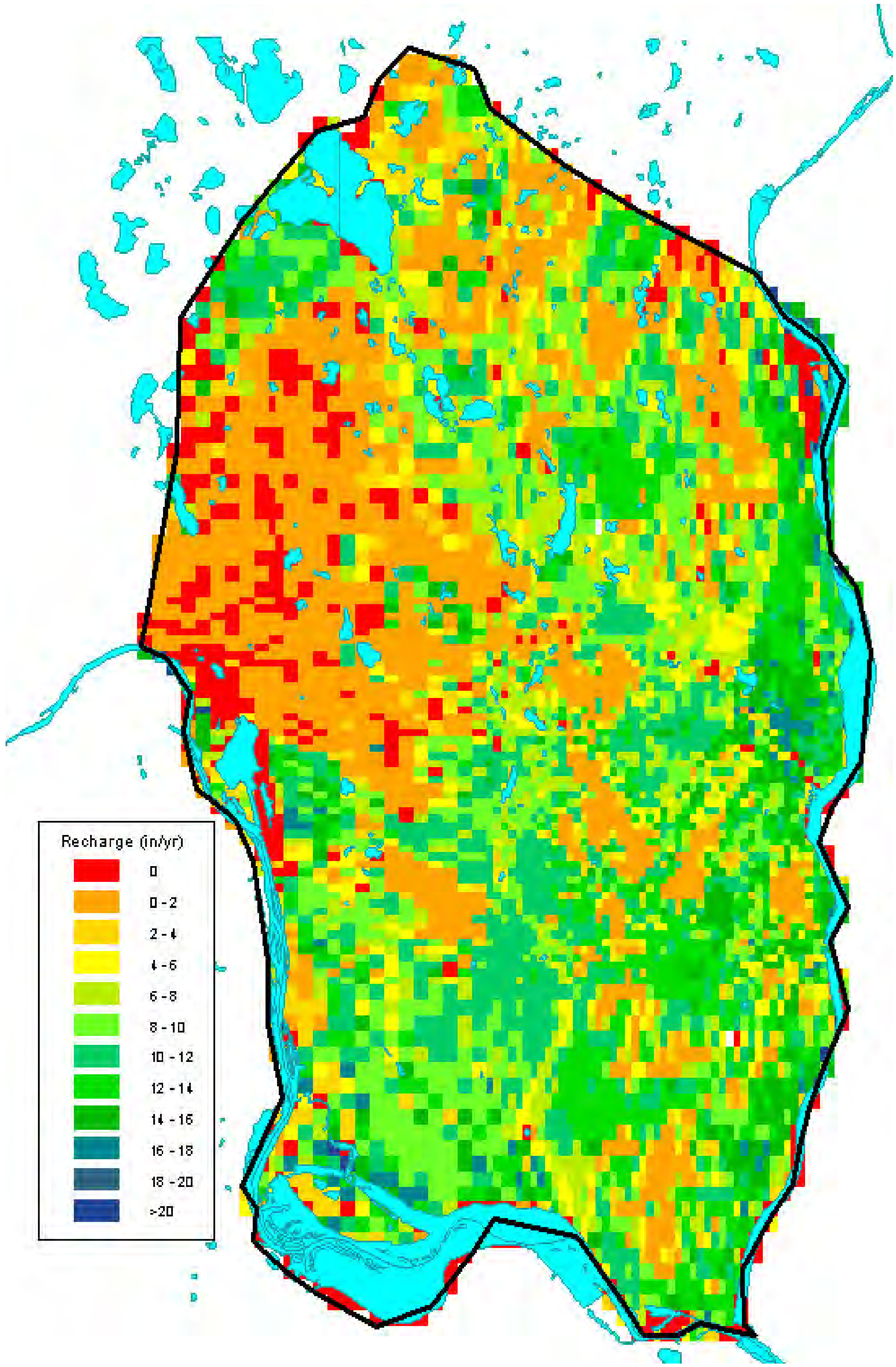


Figure 70

MODFLOW Steady-State Recharge (in/yr) for Dry (1988) Conditions

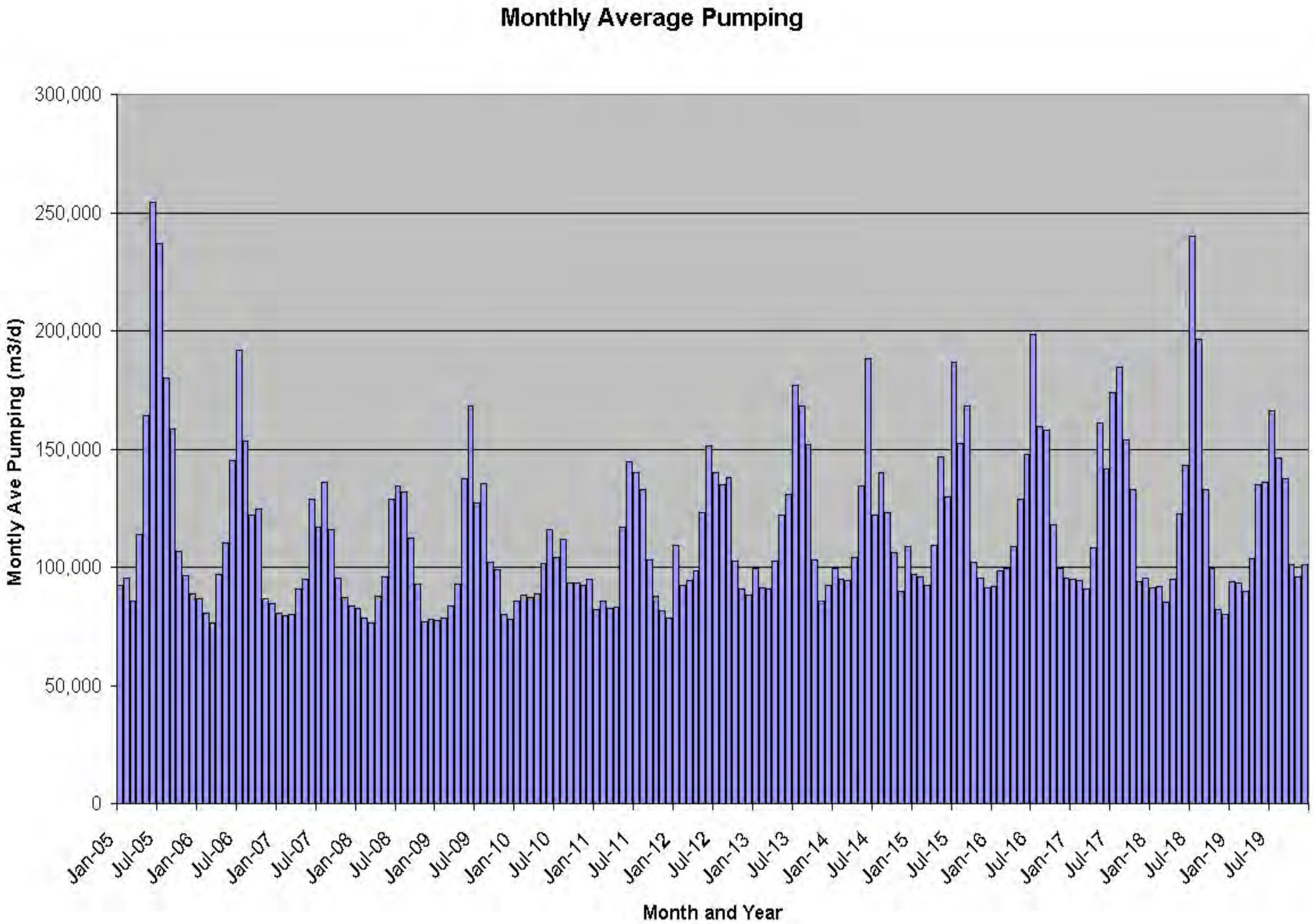


Figure 71

Projected Average Monthly Pumping of non-Woodbury Wells for Transient Simulations (based on pumping records for 1988-2003)

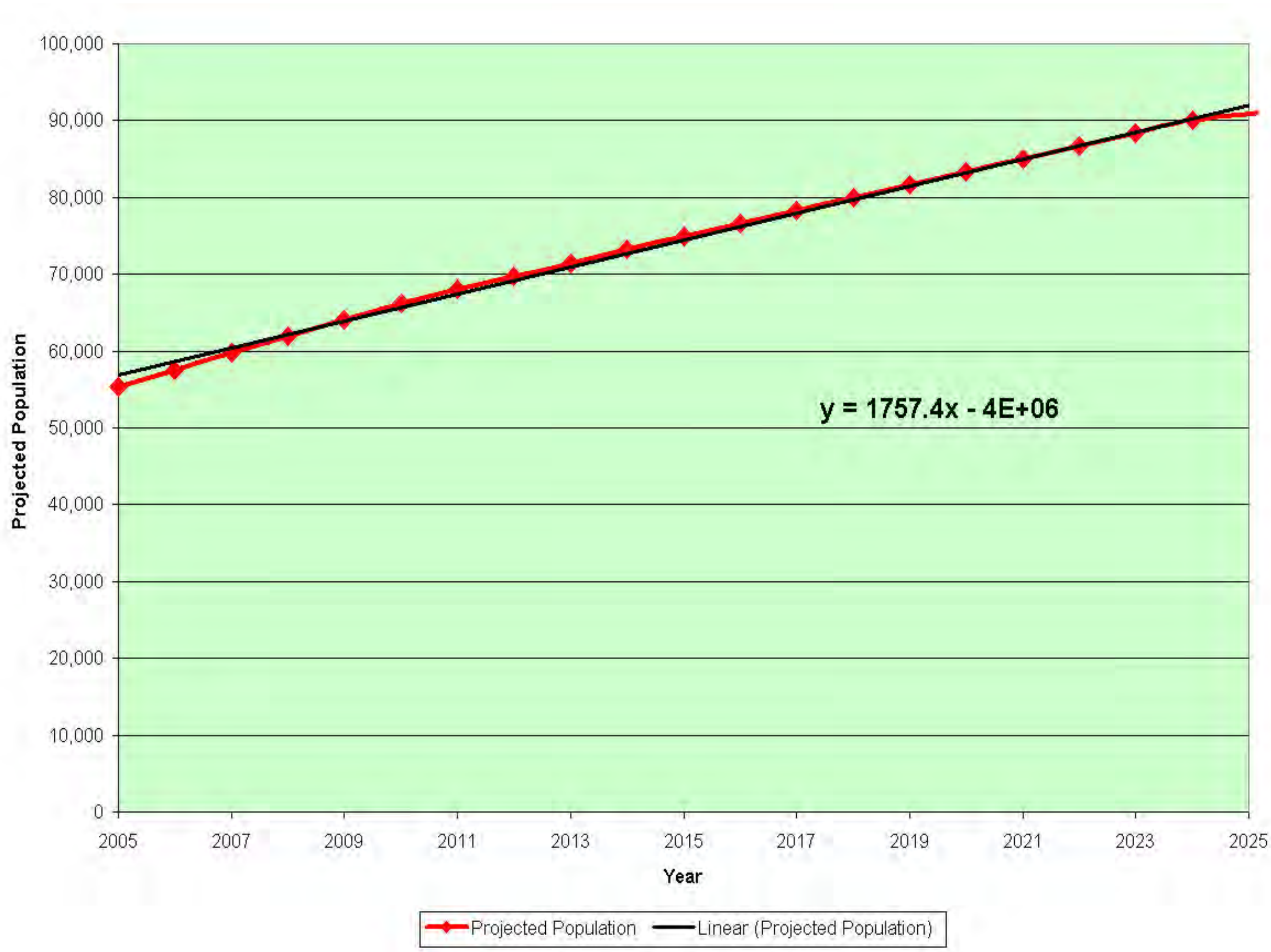


Figure 72

Projected Population for City of Woodbury: 2005-2025

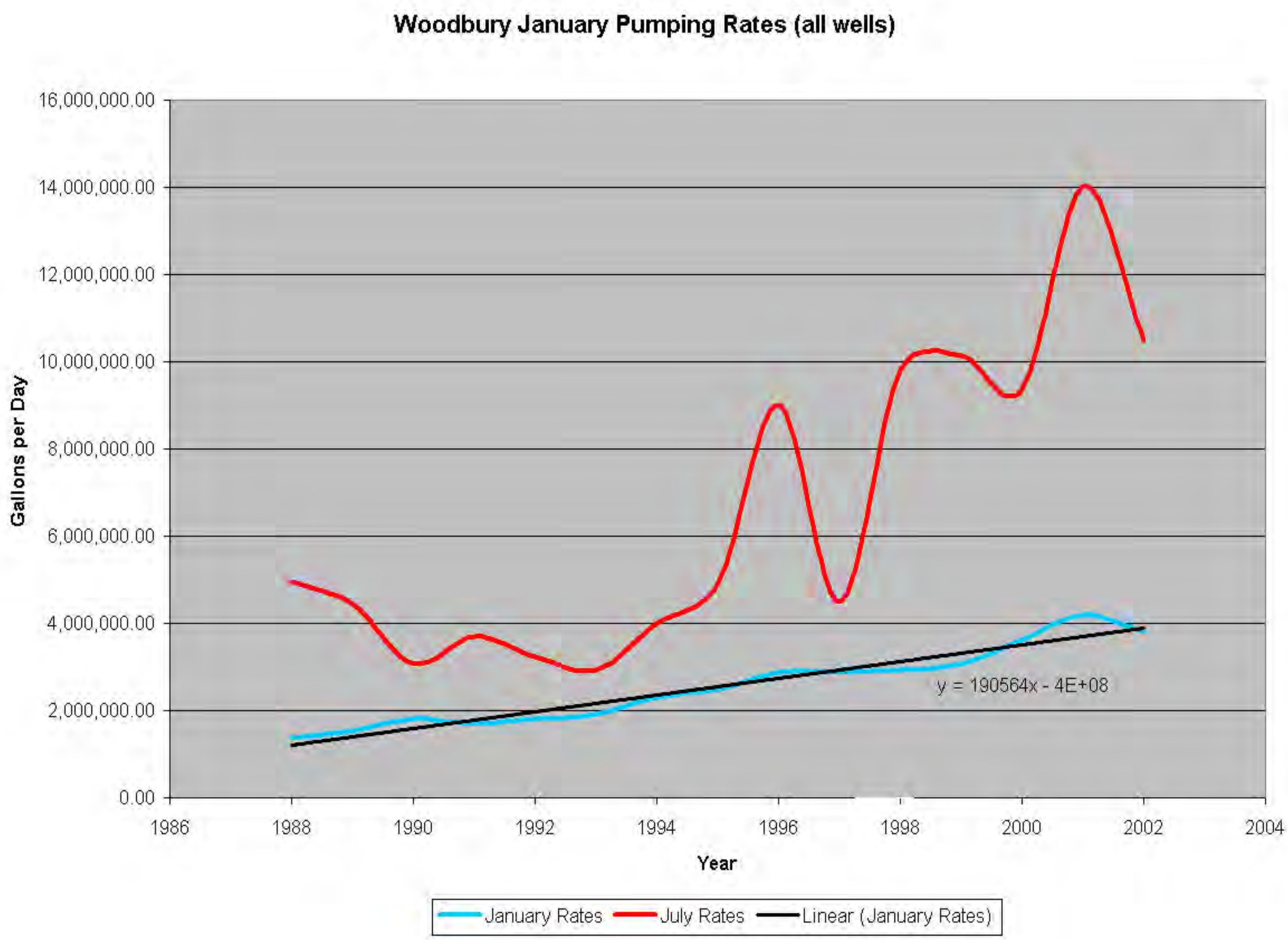


Figure 73

Woodbury Pumping Comparison: June vs. January – 1988 to 2002

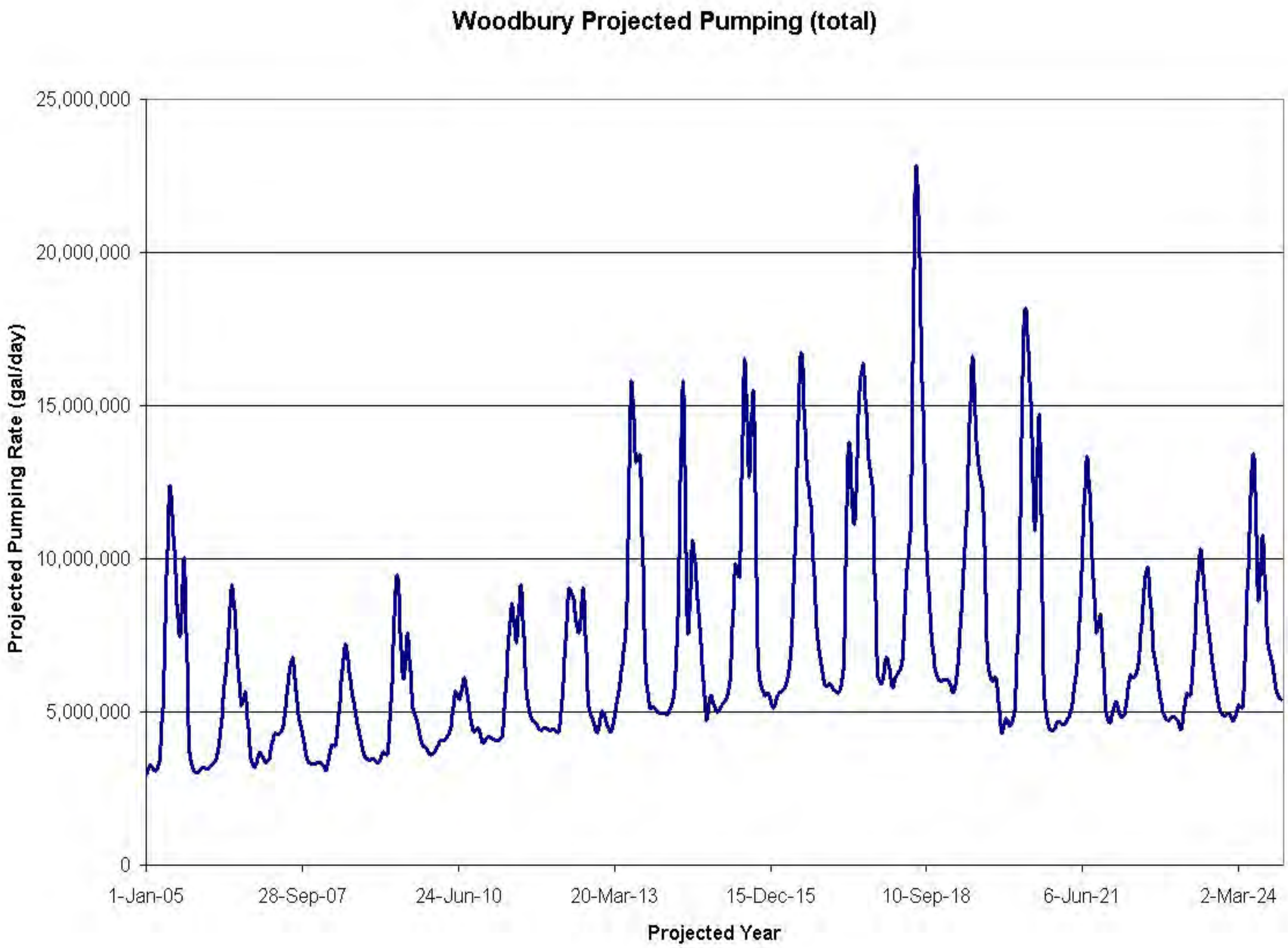


Figure 74

Projected Month-By-Month Water Demand for Woodbury

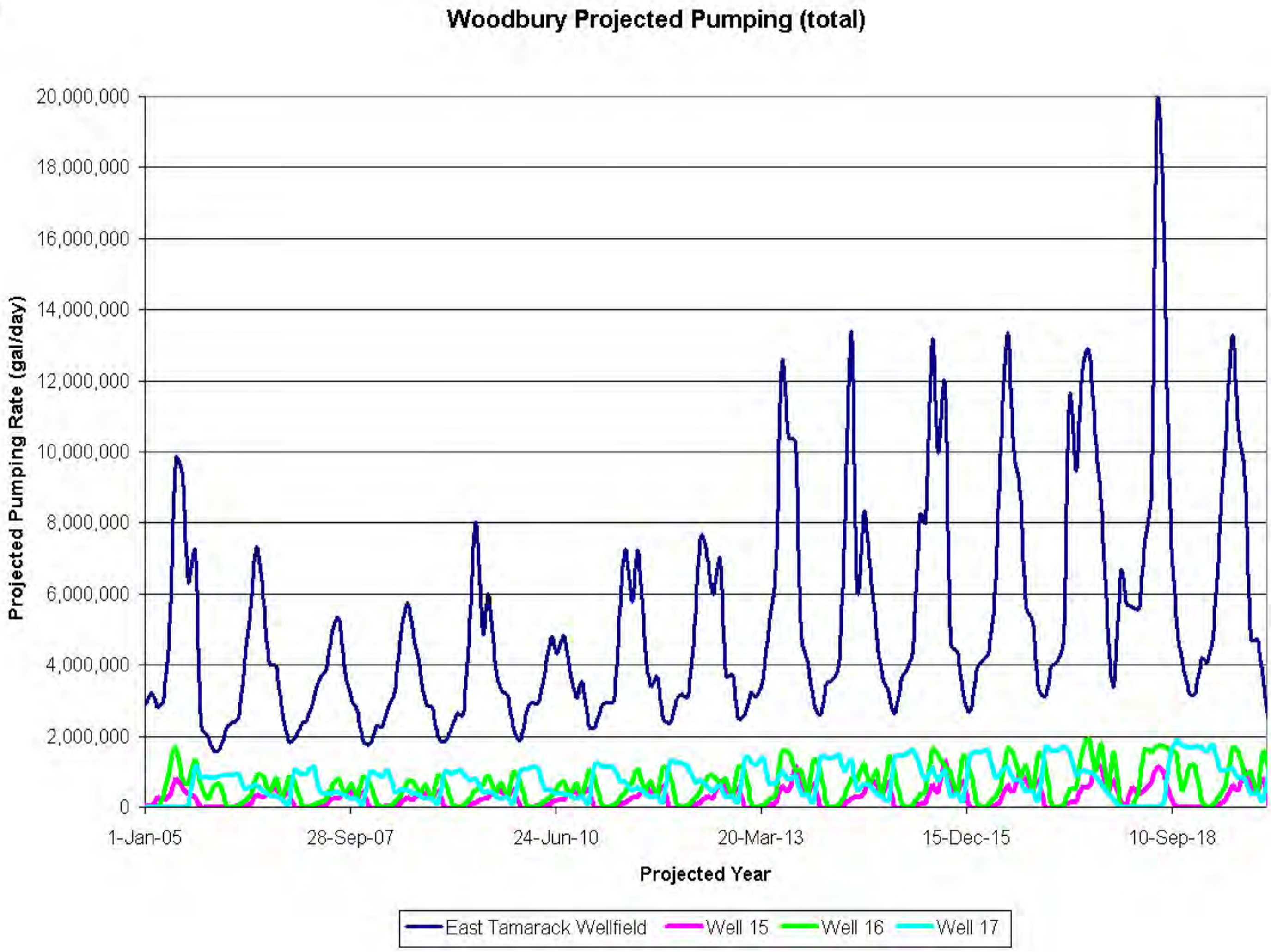


Figure 75

Projected Month-By-Month Water Demand for Woodbury East Tamarack Well Field, Well 15, Well 16, and Well 17

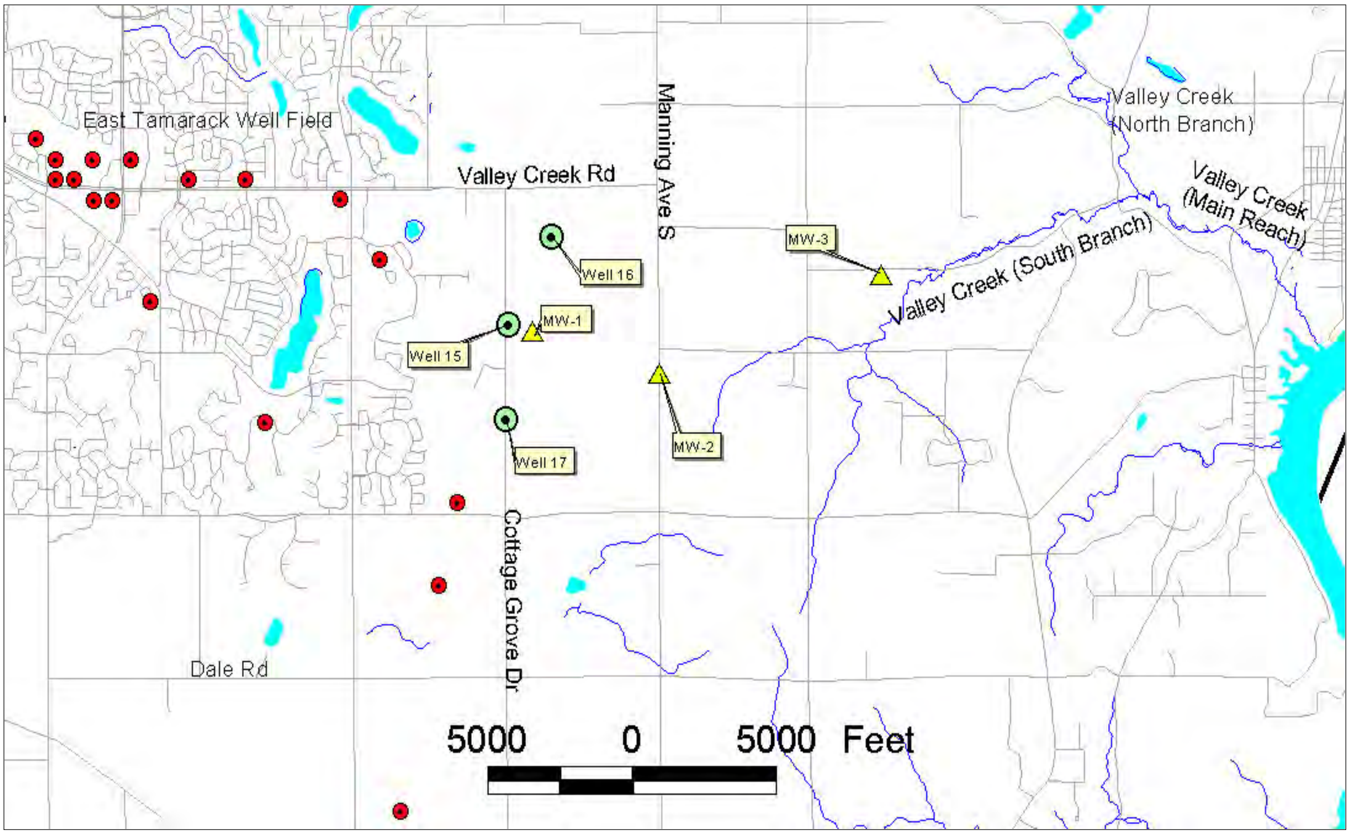
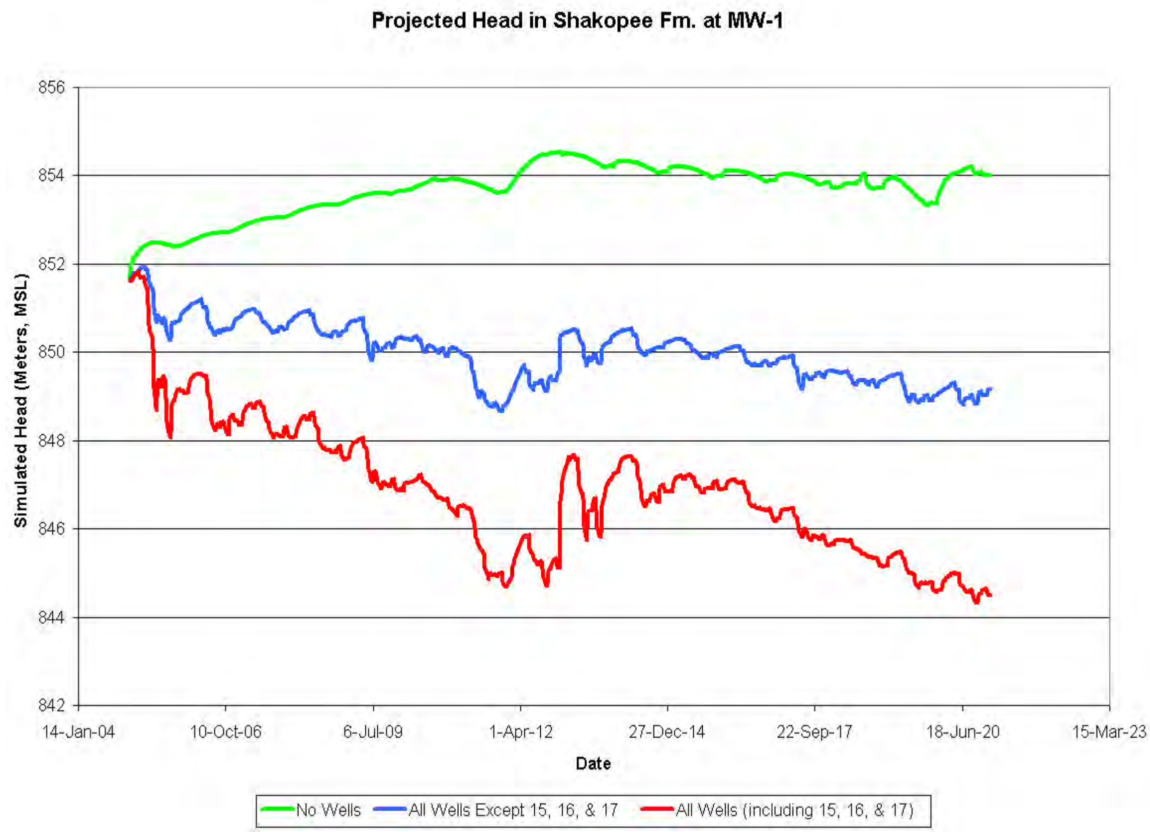


Figure 76

Locations of Pumping Wells, Monitoring Wells, and Stream Reaches of Valley Creek for Transient Simulations



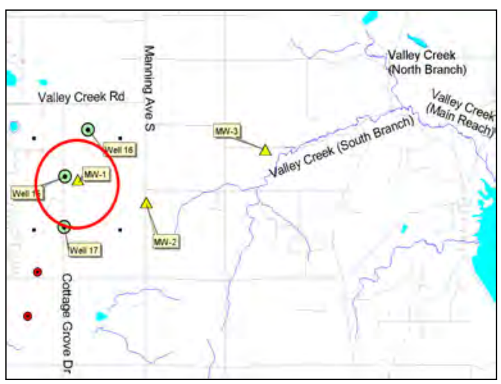
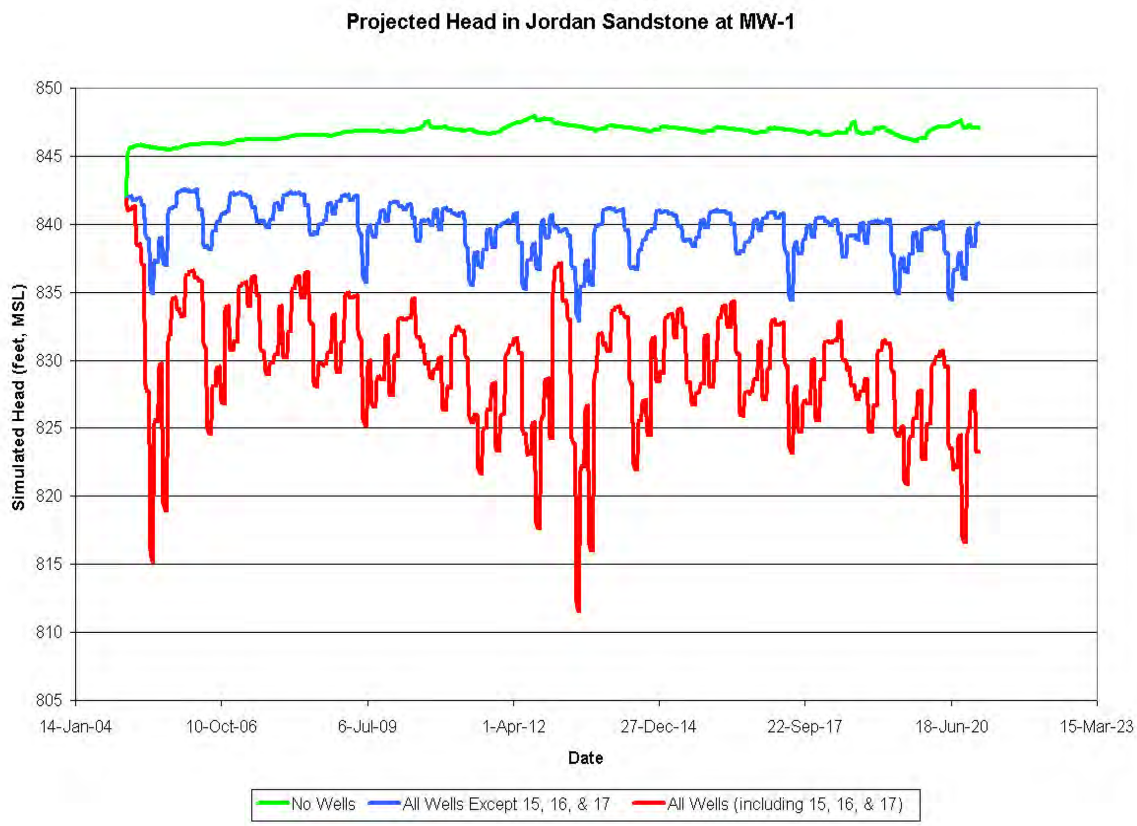


Figure 77

Simulation of Groundwater Levels in Shakopee Formation at Well Nest MW-1: 2005-2020



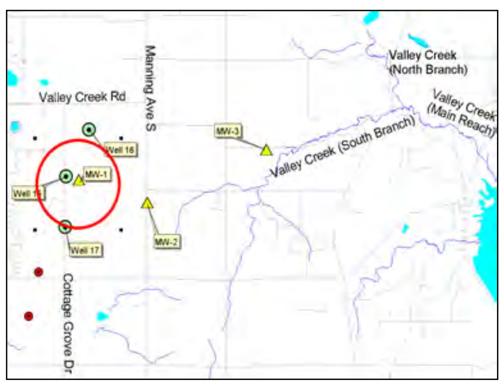
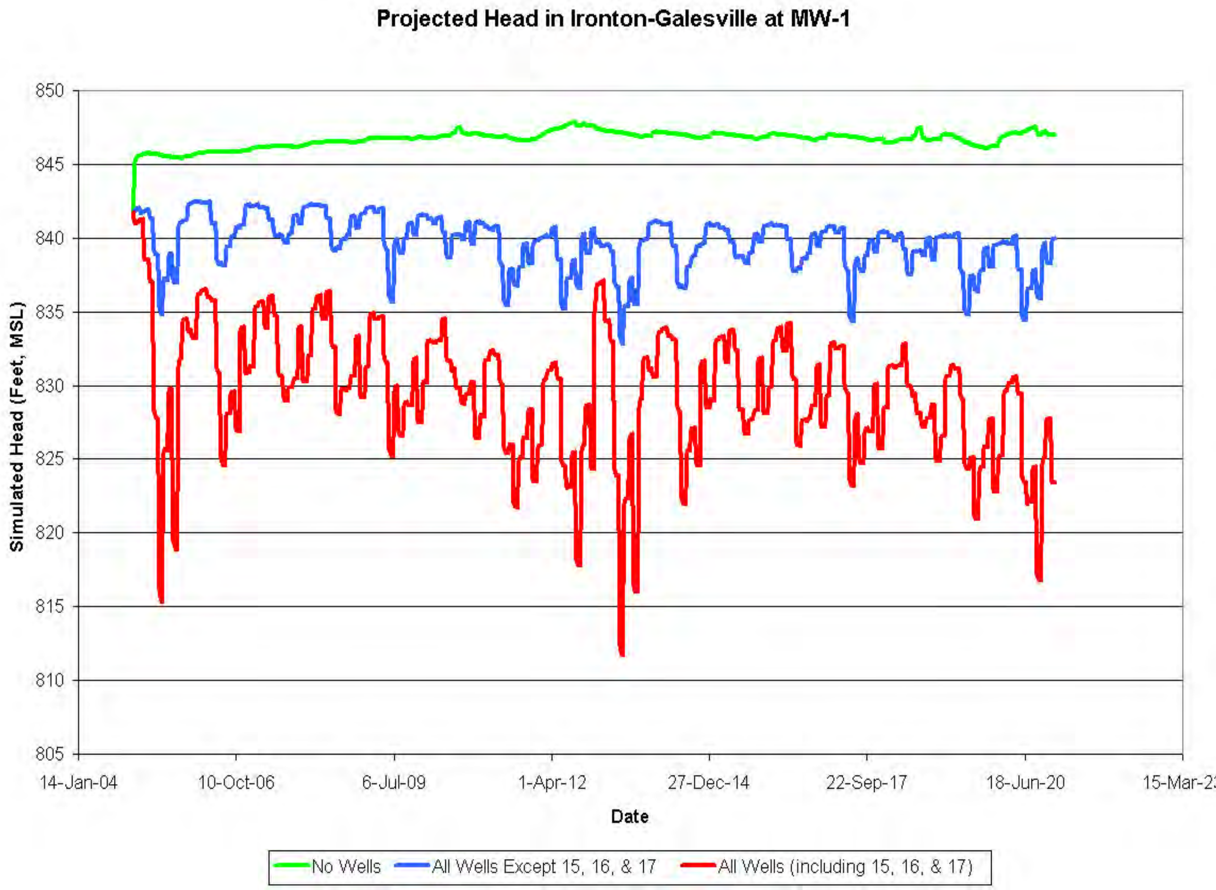


Figure 78

Simulation of Groundwater Levels in Jordan Sandstone at Well Nest MW-1: 2005-2020



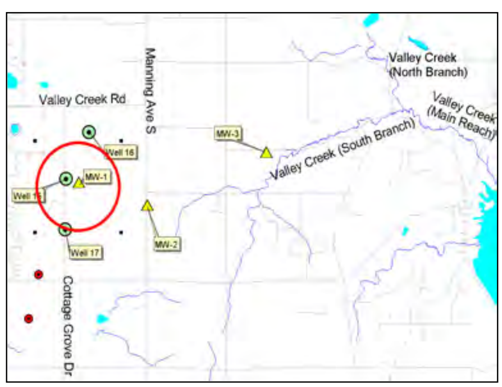
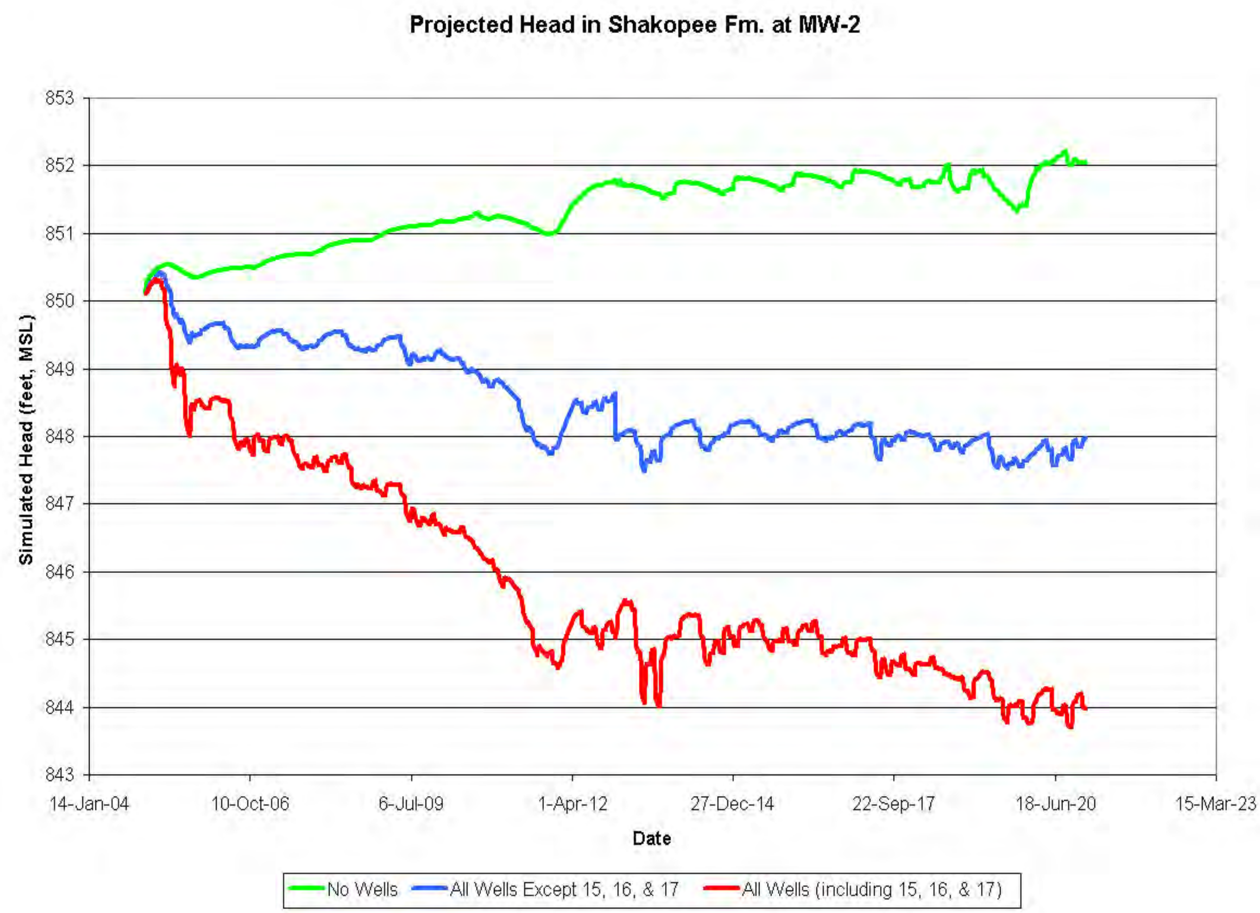


Figure 79

Simulation of Groundwater Levels in Ironton-Galesville Sandstones at Well Nest MW-1: 2005-2020



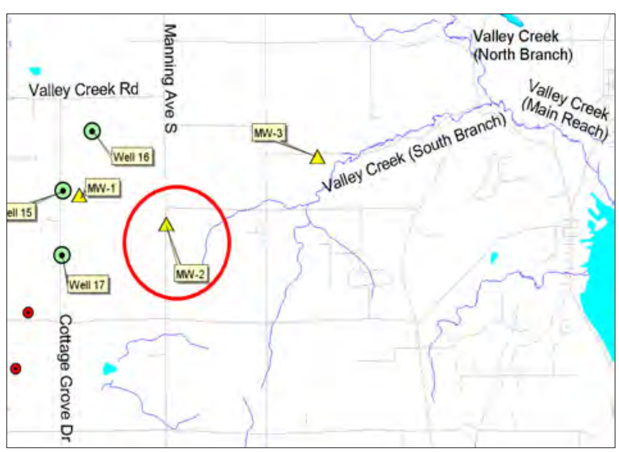
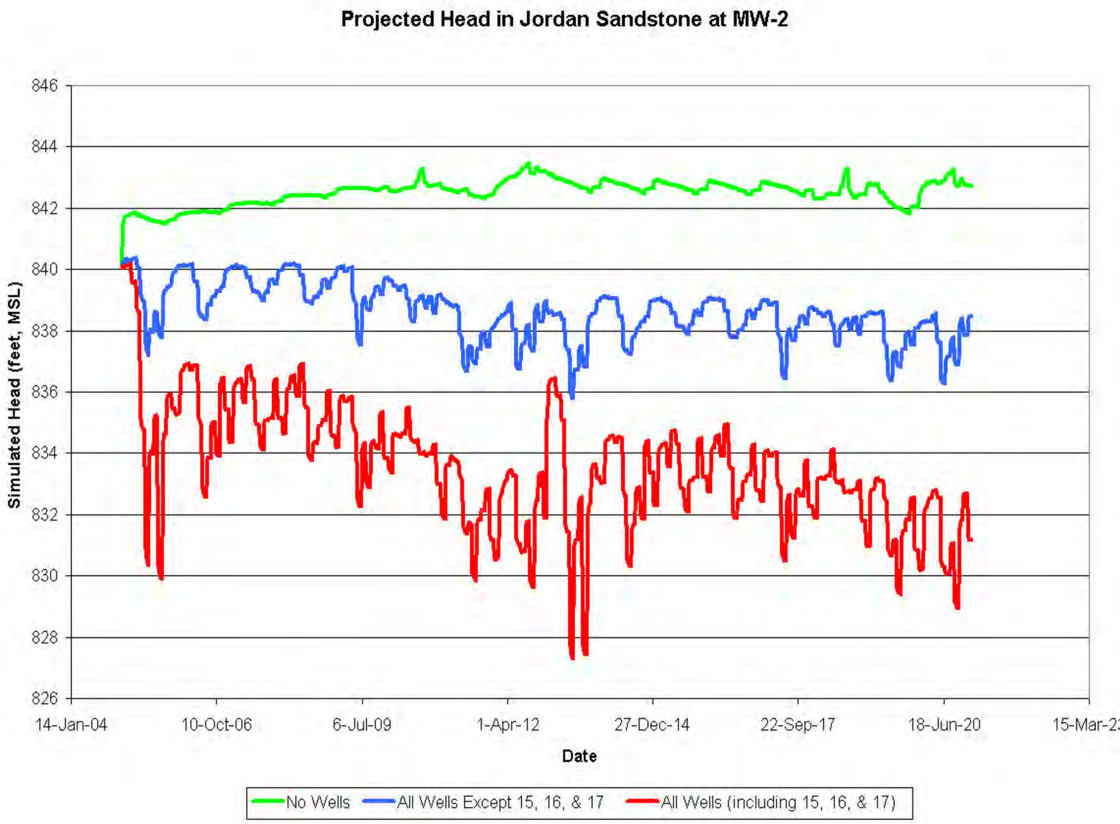


Figure 80

Simulation of Groundwater Levels in Shakopee Formation at Well Nest MW-2: 2005-2020



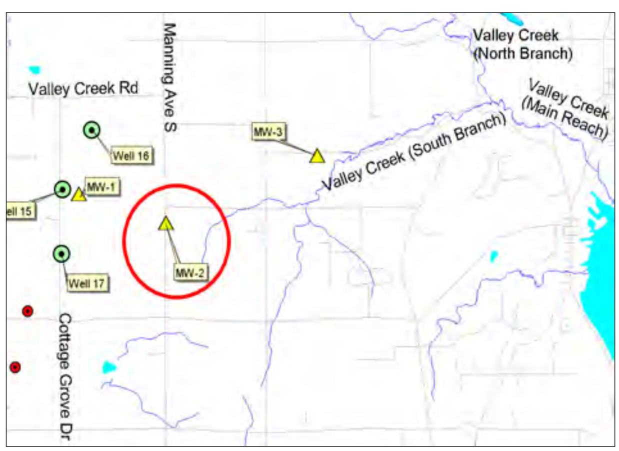
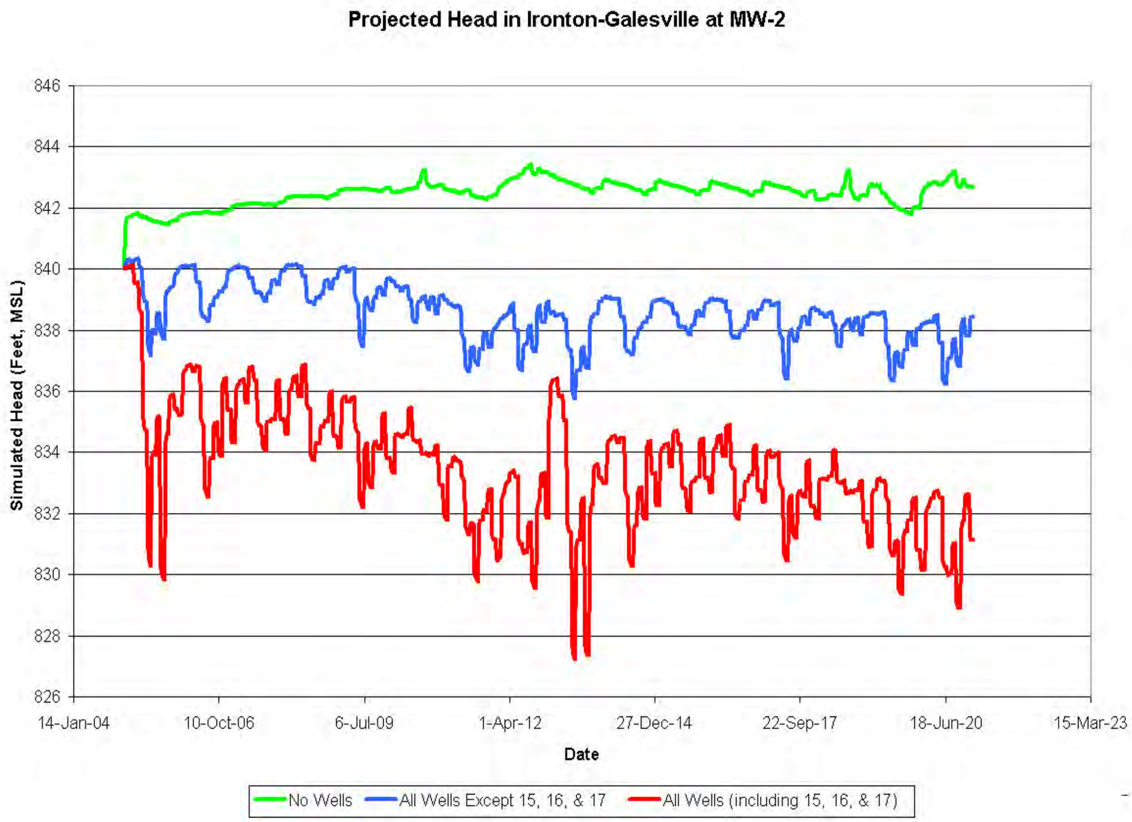


Figure 81

Simulation of Groundwater Levels in Jordan Sandstone at Well Nest MW-2: 2005-2020



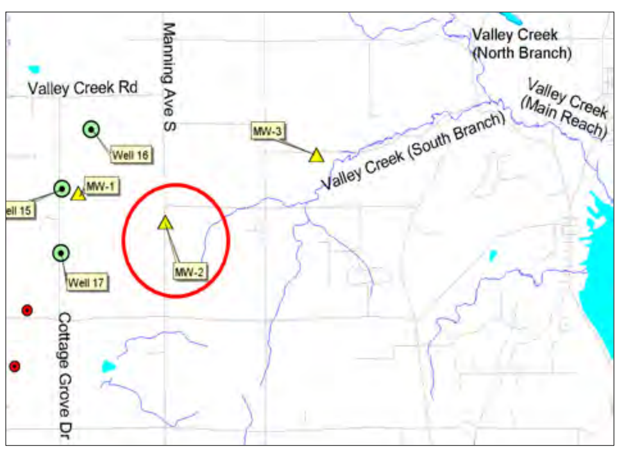
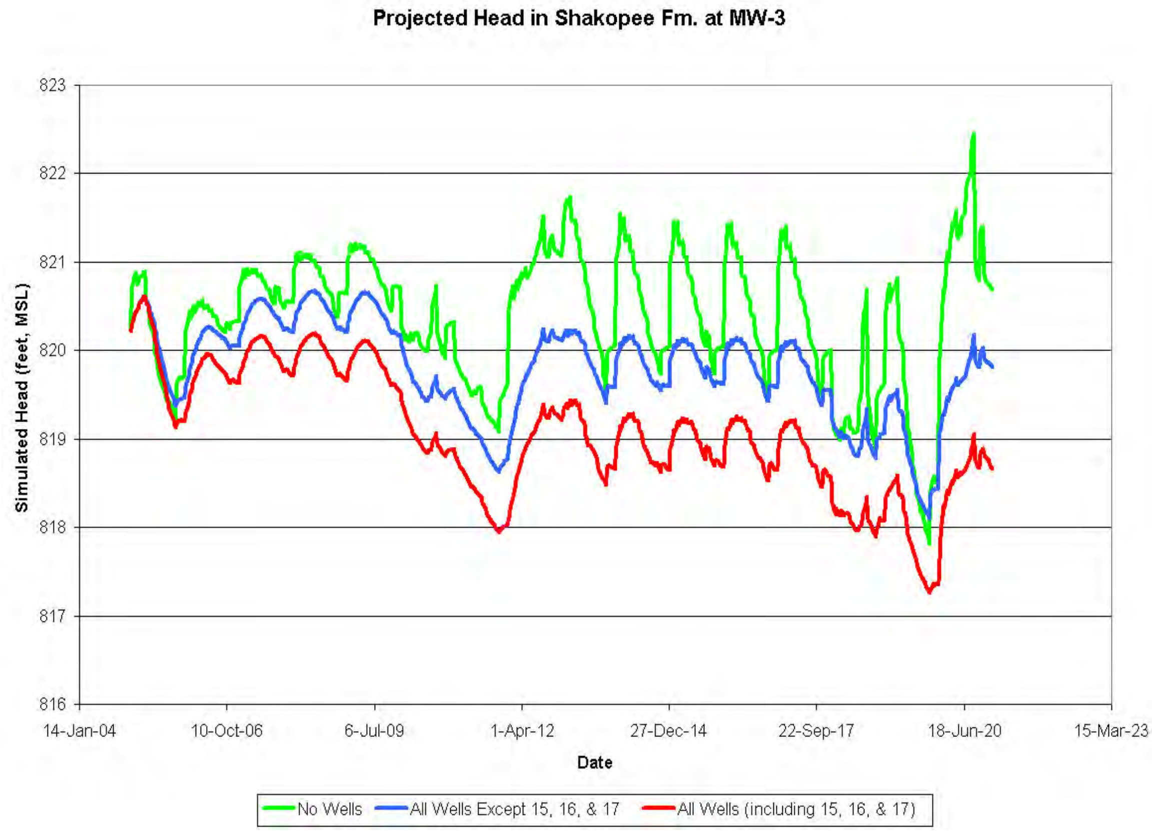


Figure 82

Simulation of Groundwater Levels in Ironton-Galesville Sandstones at Well Nest MW-2: 2005-2020



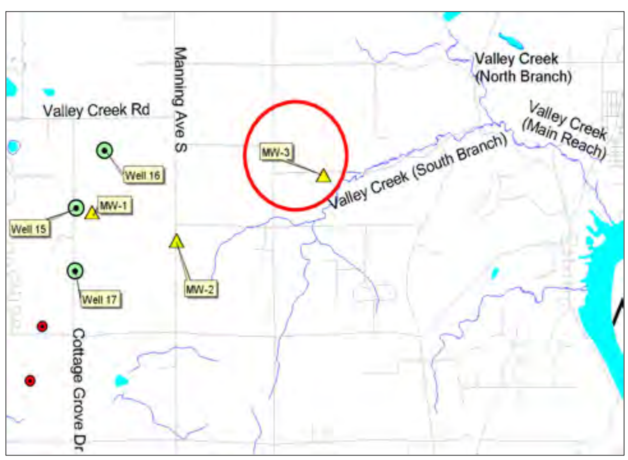
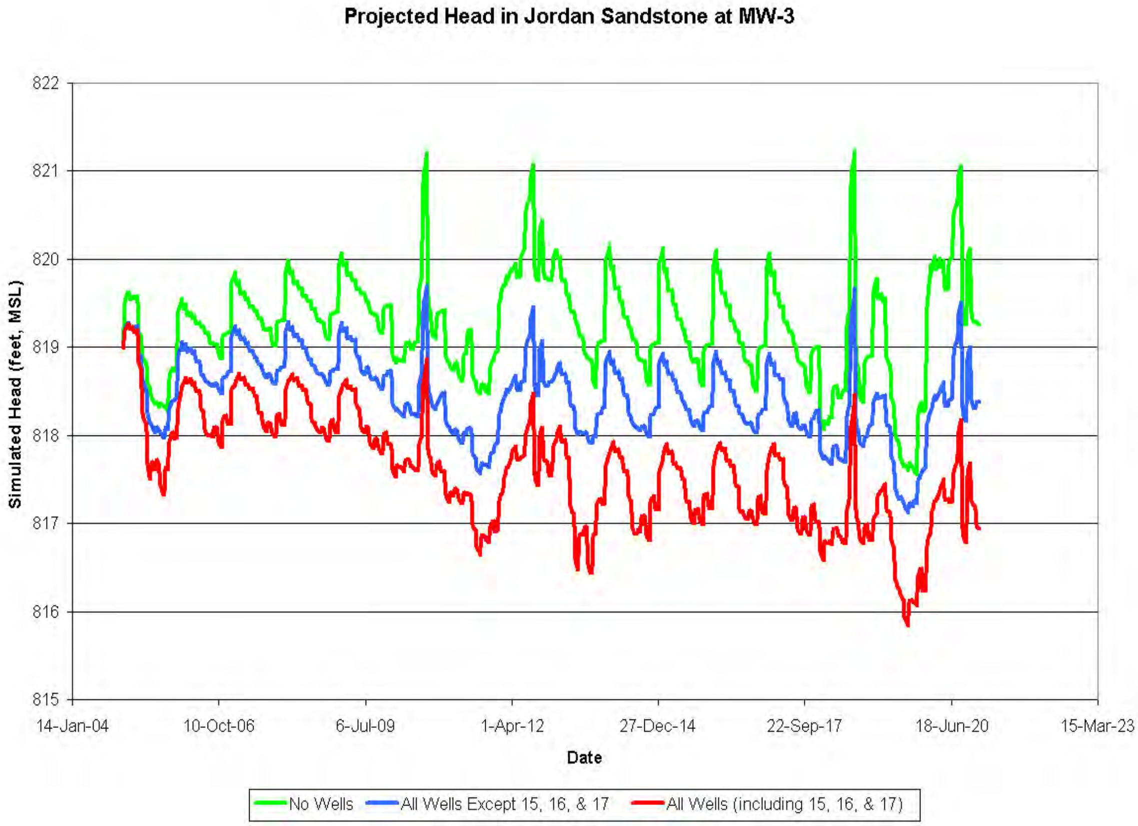


Figure 83

Simulation of Groundwater Levels in Shakopee Formation at Well Nest MW-3: 2005-2020



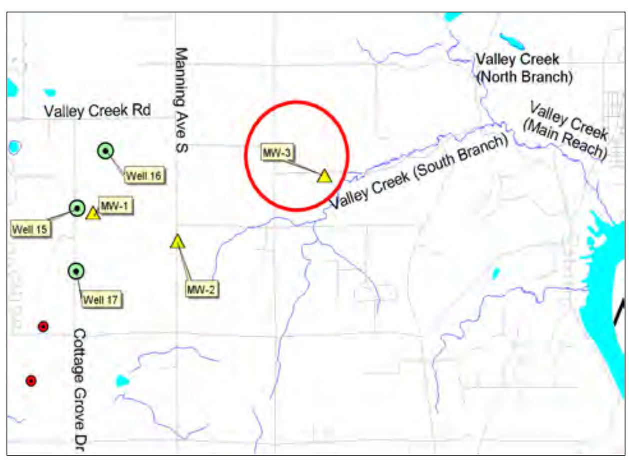
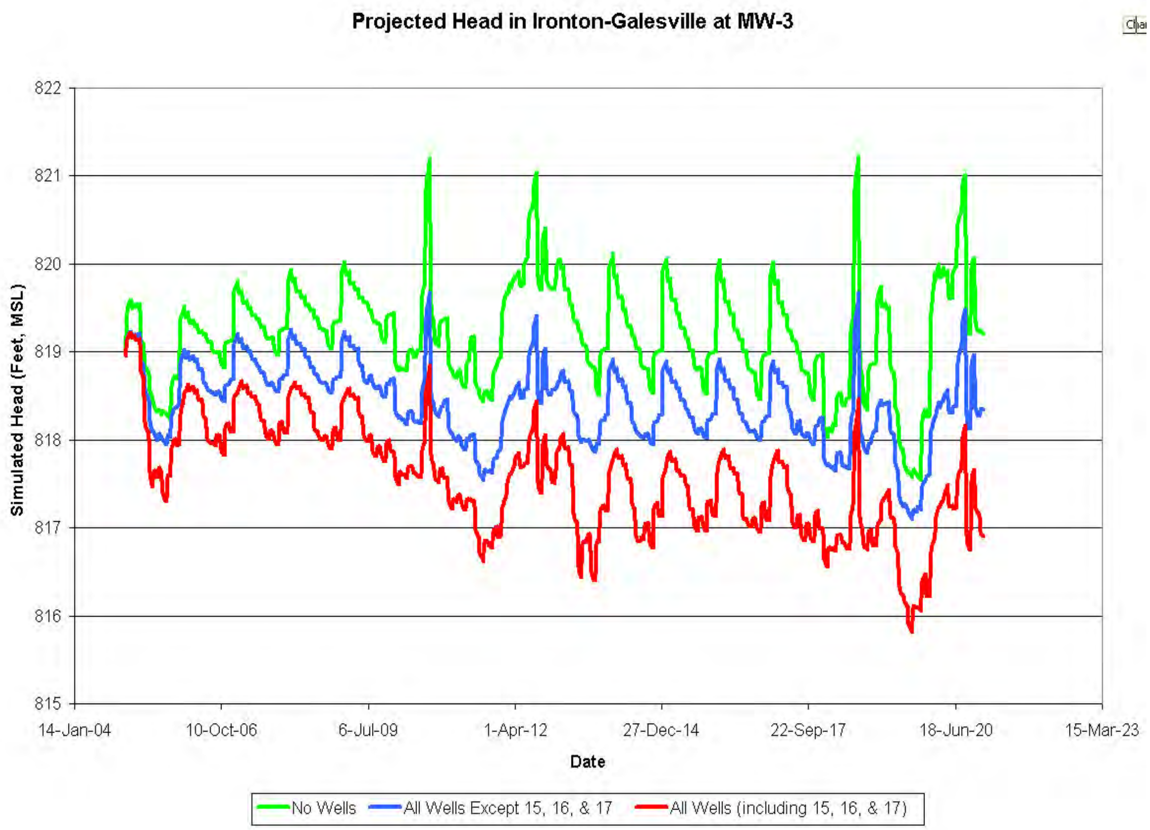


Figure 84

Simulation of Groundwater Levels in Jordan Sandstone at Well Nest MW-3: 2005-2020



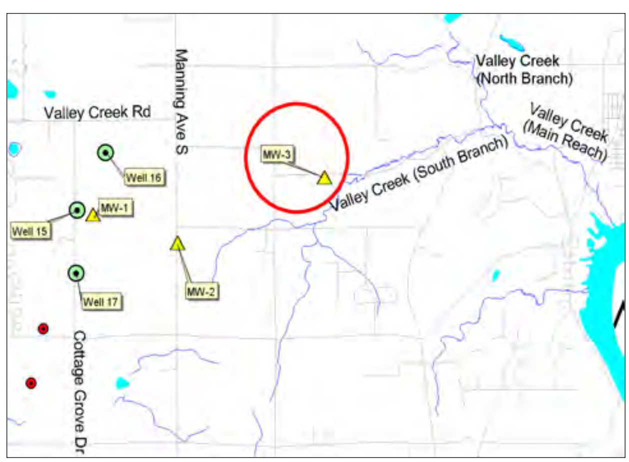
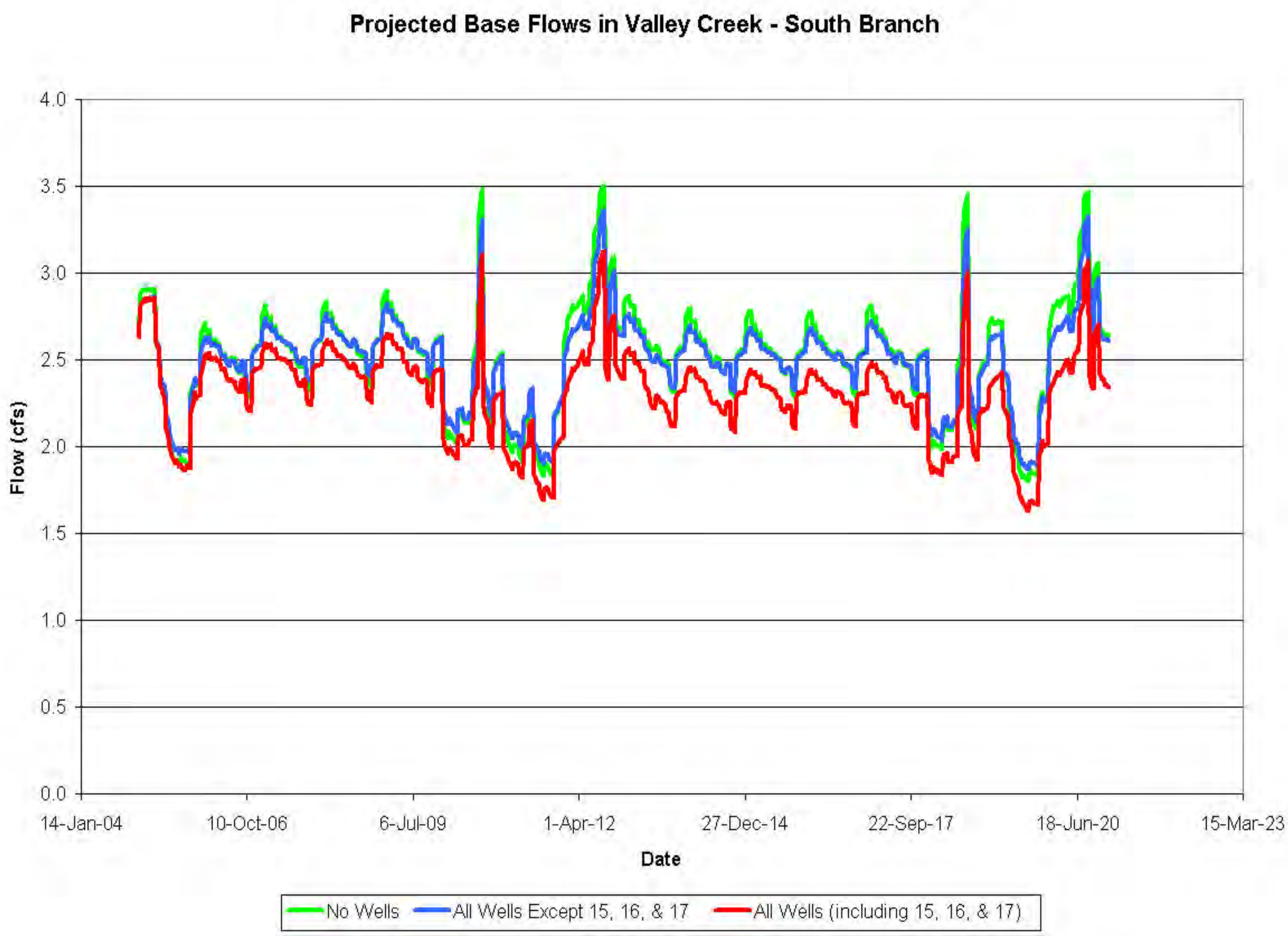


Figure 85

Simulation of Groundwater Levels in Ironton-Galesville Sandstones at Well Nest MW-3: 2005-2020



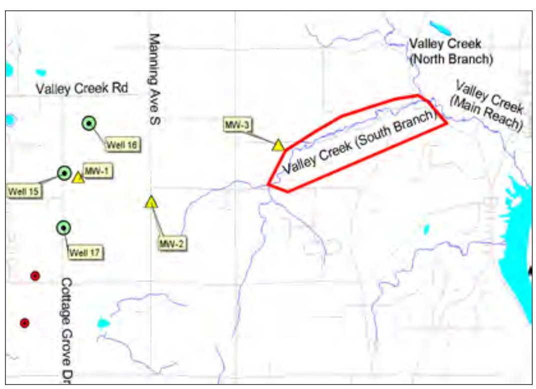
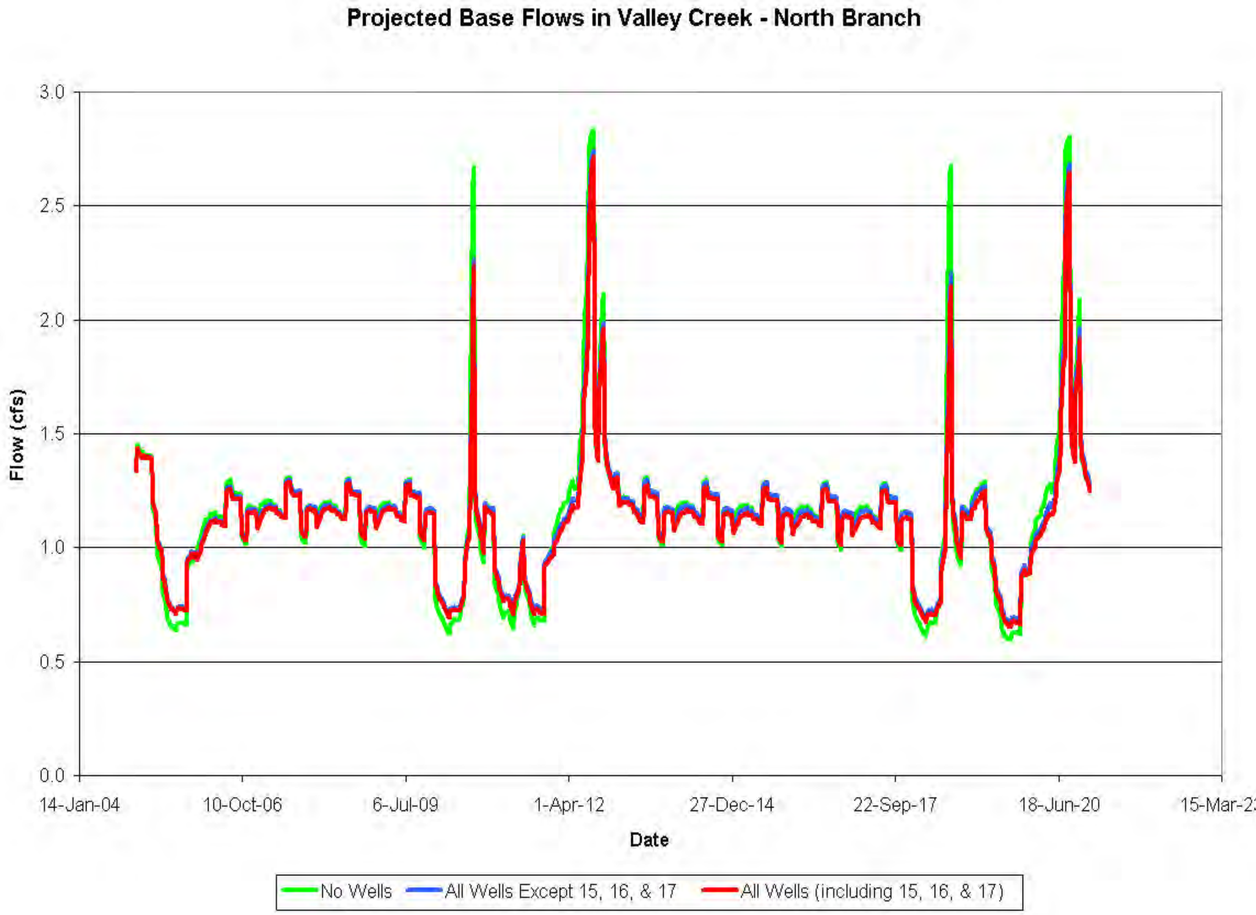


Figure 86

Simulation of Base Flows in South Branch of Valley Creek: 2002-2025



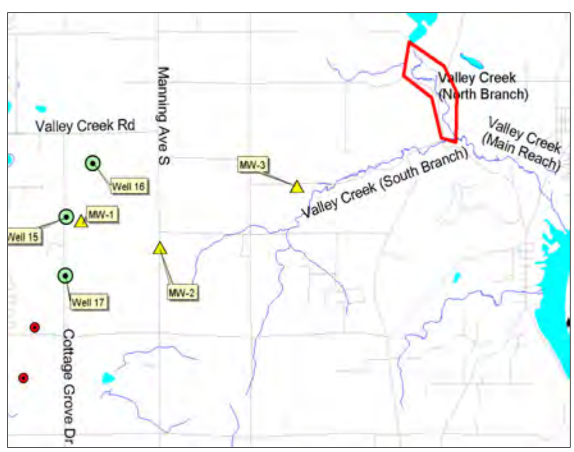
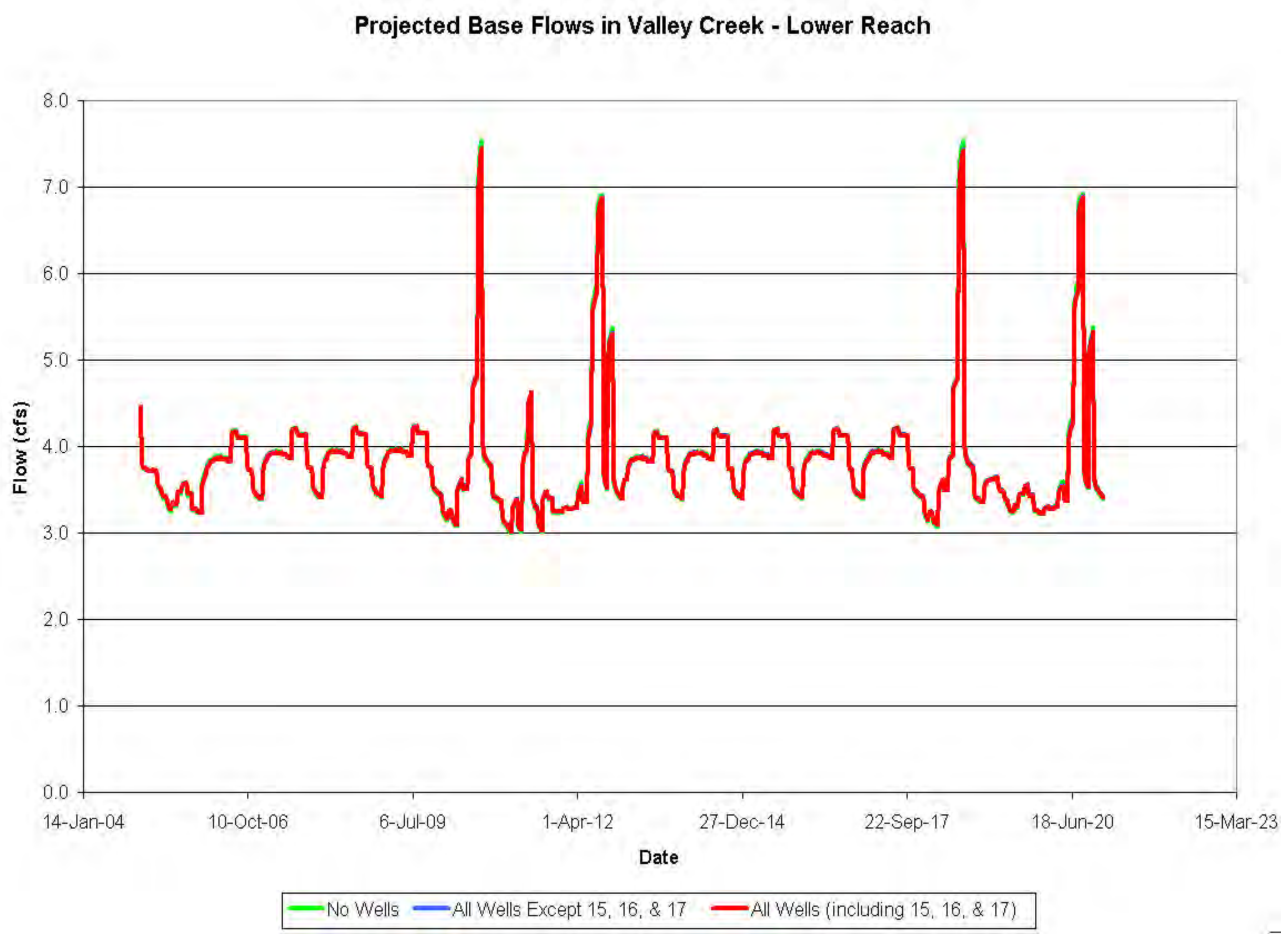


Figure 87

Simulation of Base Flows in North Branch of Valley Creek: 2002-2025



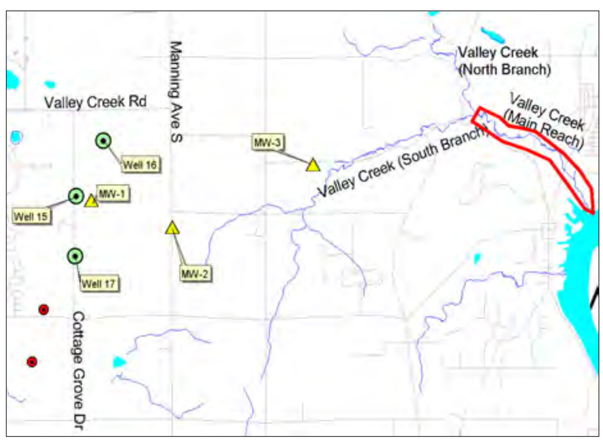
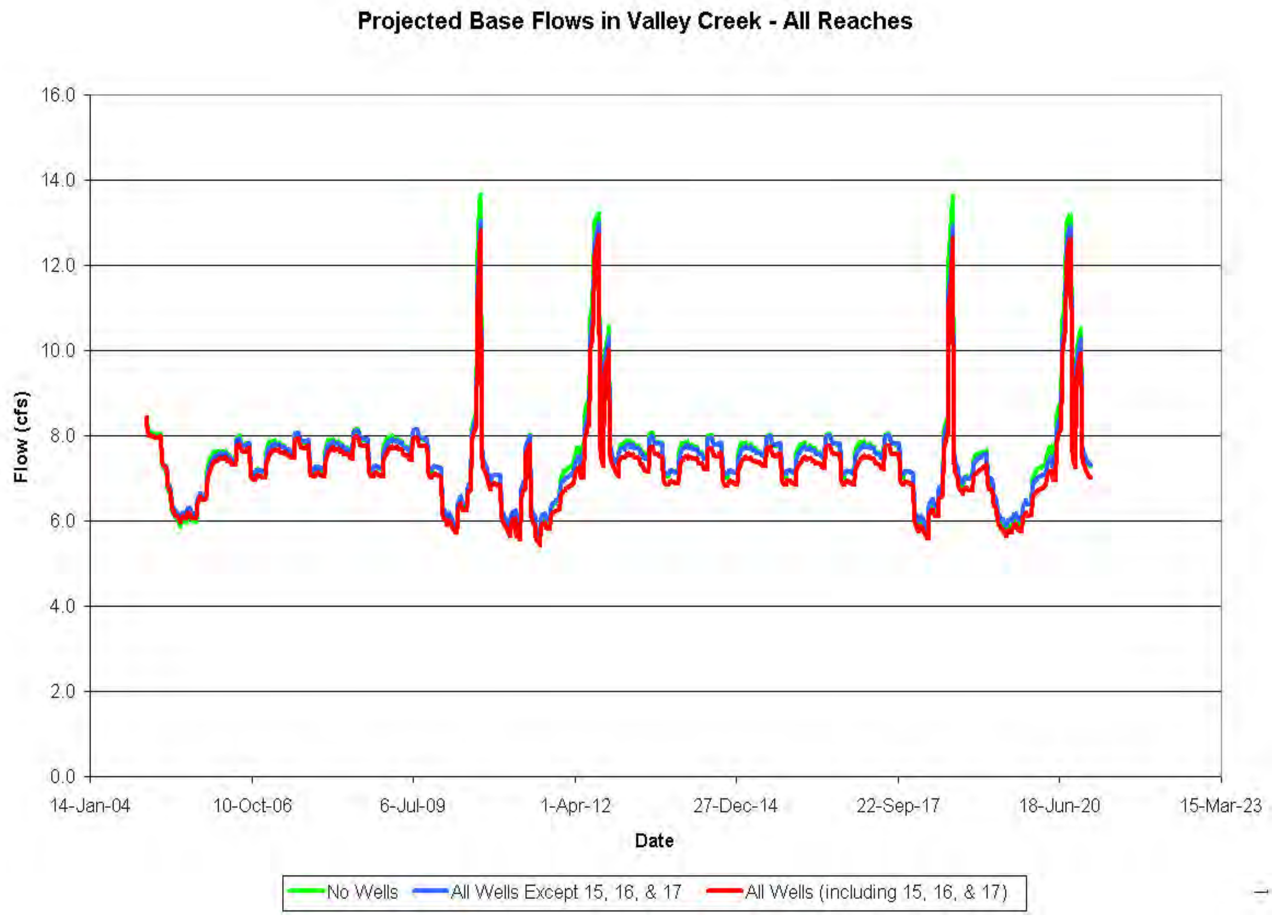


Figure 88

Simulation of Base Flows in Main Reach of Valley Creek: 2002-2025



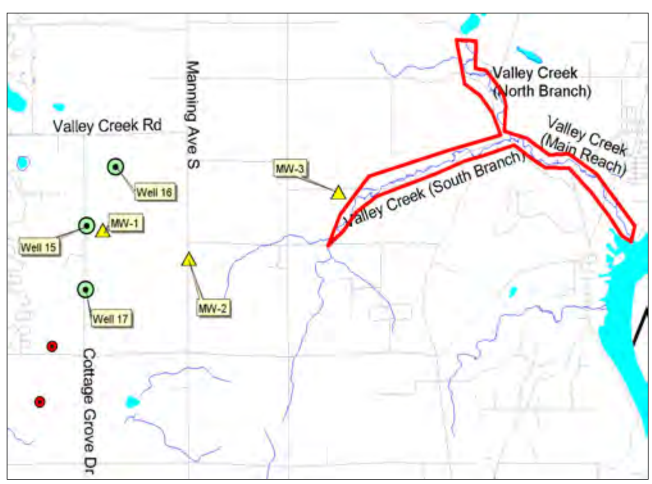
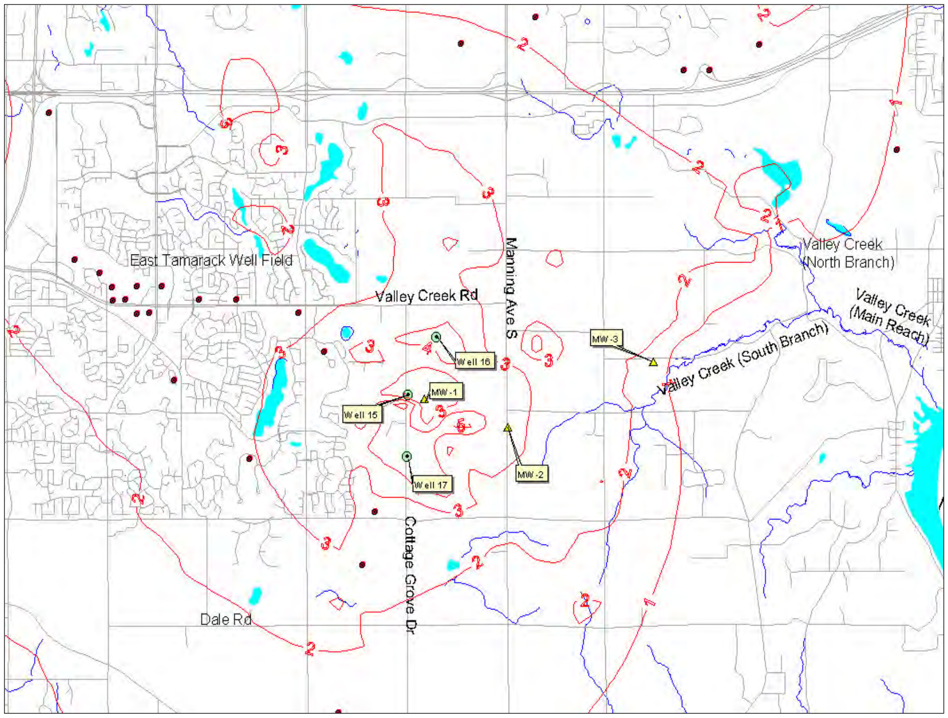
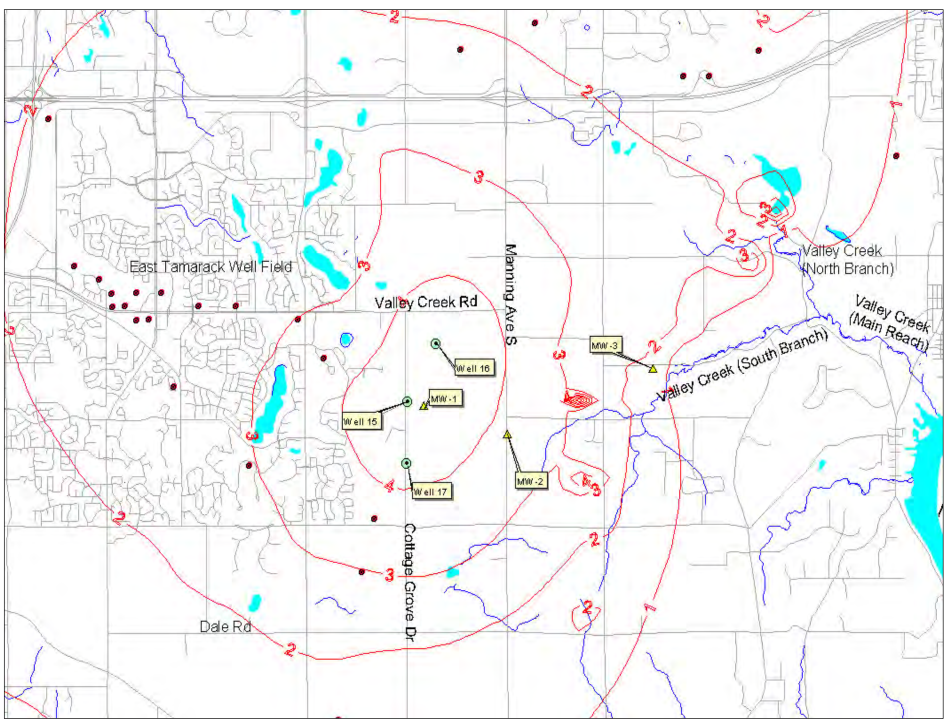


Figure 89

Simulation of Base Flows in All of Valley Creek: 2002-2025



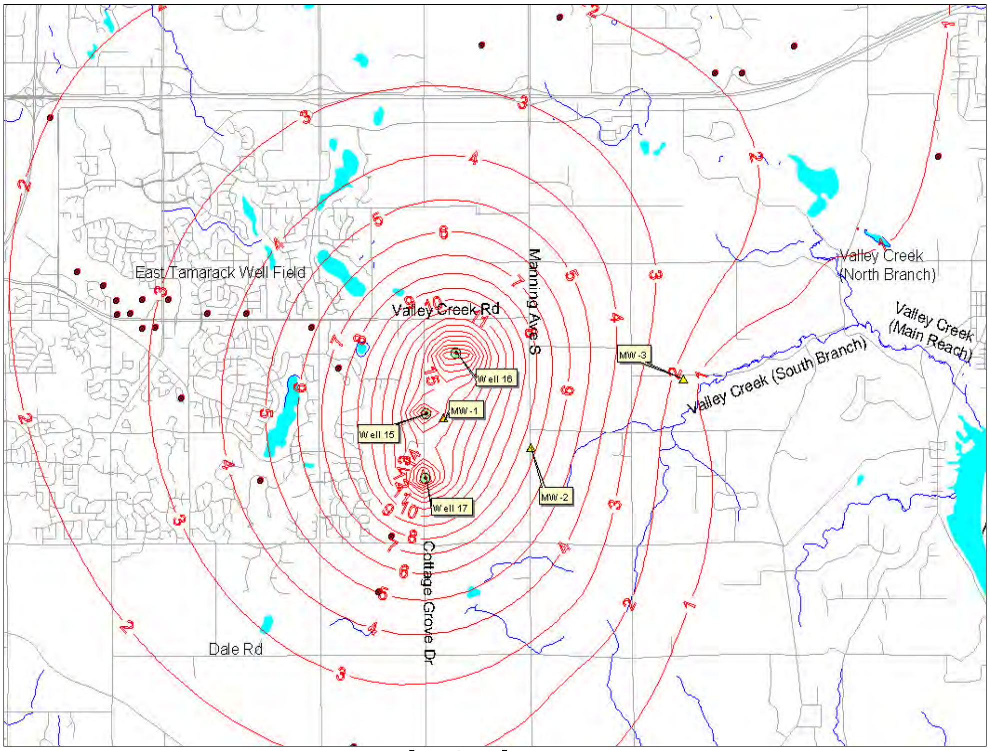
Water Table



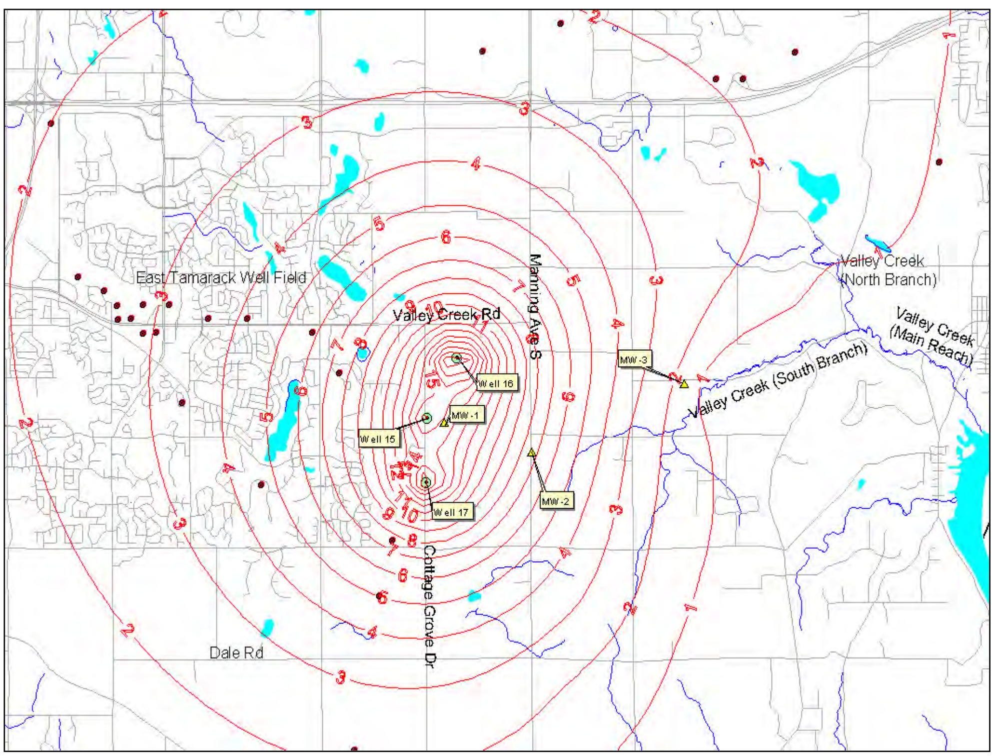
Shakopee Formation
(contour interval = 1 foot)

Figure 90

Predicted Lowering of Head (feet) for July 2012, Resulting from the Pumping of Wells 15, 16, and 17 – Water Table and Shakopee Formation



Jordan Sandstone



Ironton-Galesville Sandstones
(contour interval = 1 foot)

Figure 91

Predicted Lowering of Head (feet) for July 2012, Resulting from the Pumping of Wells 15, 16, and 17 – Jordan Sandstone and Ironton-Galesville Sandstones

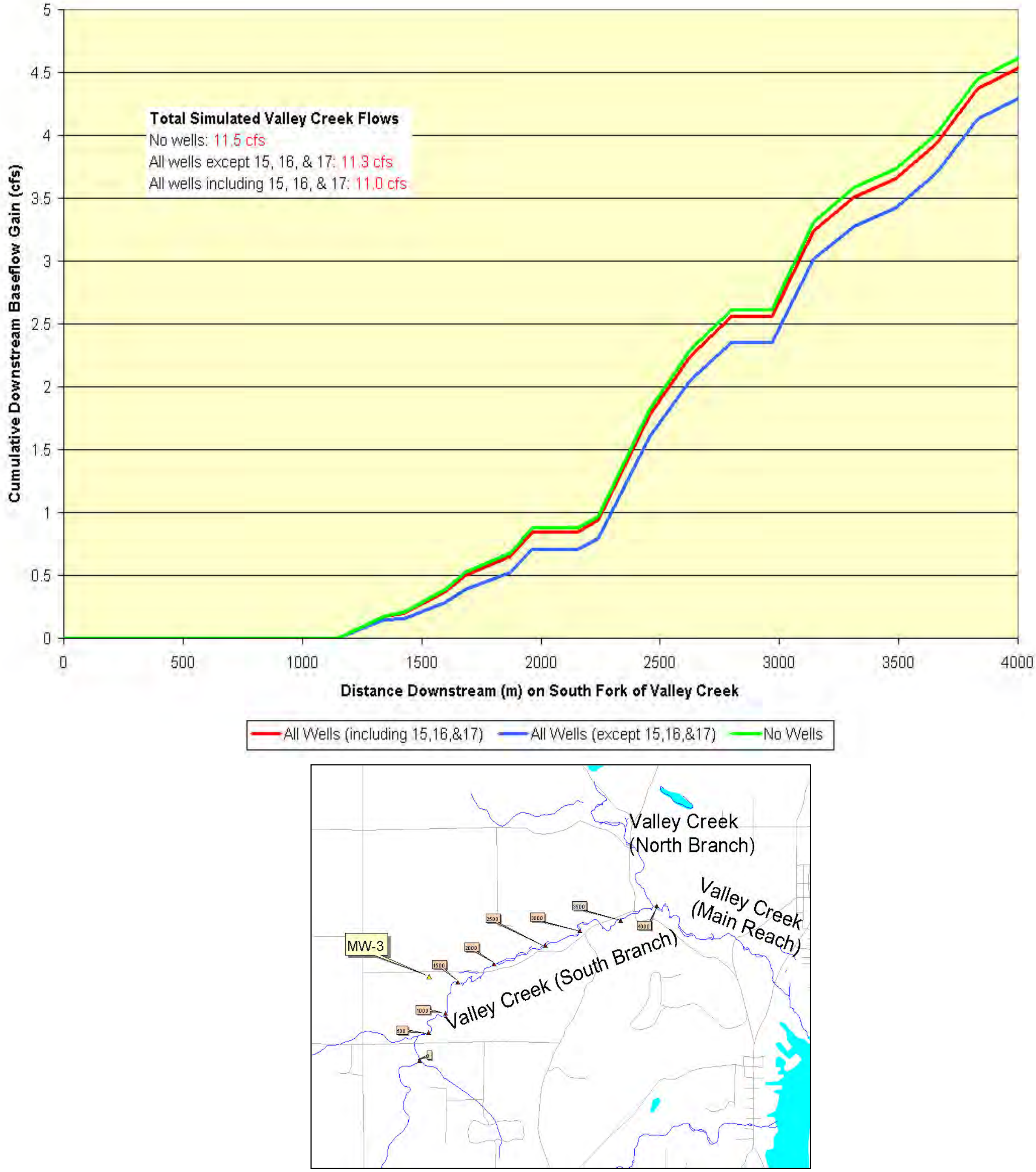


Figure 92

Predictions of Cumulative Base flow with Downstream Distance (meters) Along South Fork of Valley Creek: July 2012

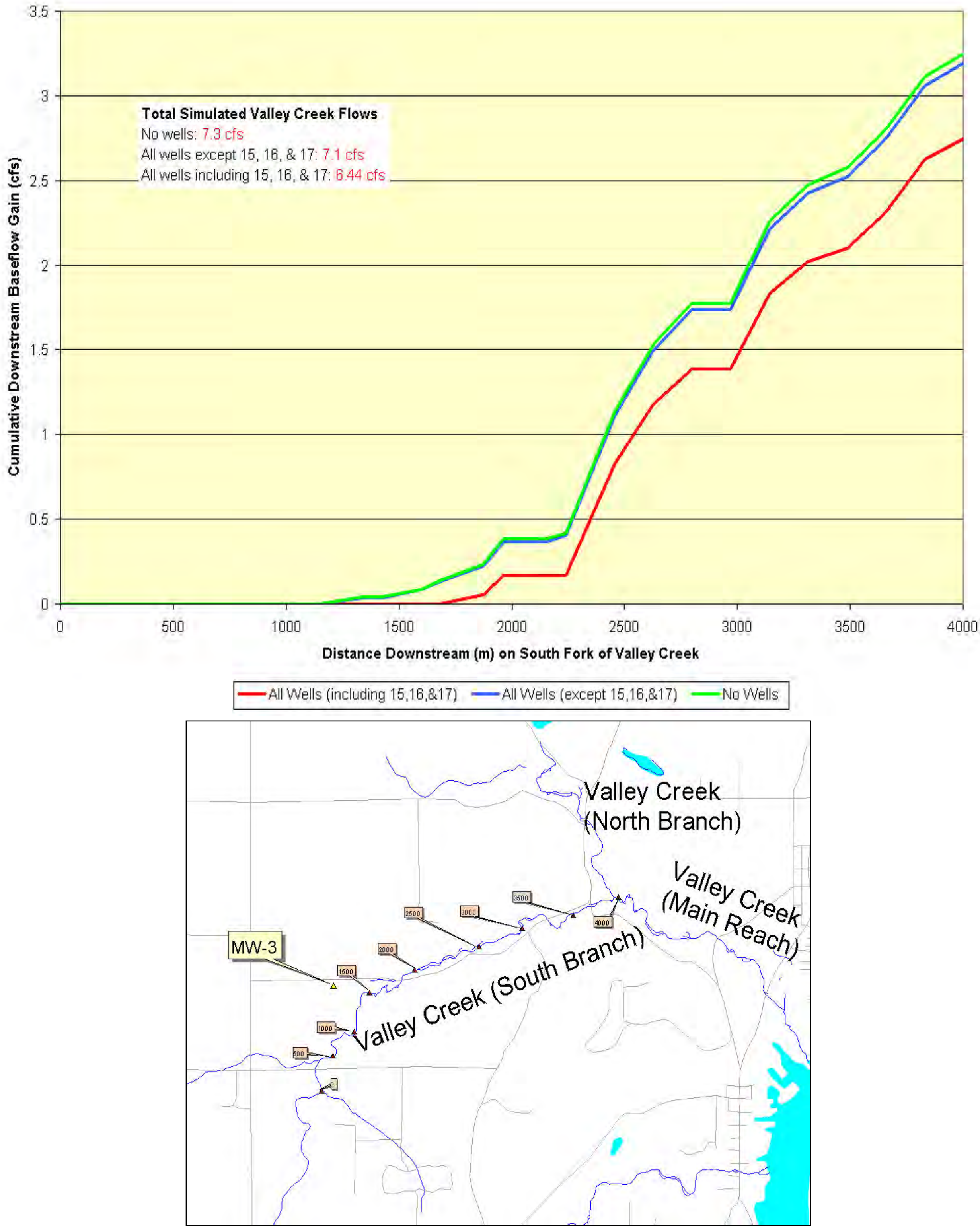


Figure 93

Predictions of Cumulative Base flow with Downstream Distance (meters) Along South Fork of Valley Creek – August 2018