Integrating Groundwater & Surface Water Management
Southern Washington County

August 2005

Barr Engineering Company
Washington County
Washington Conservation District

Table of Contents

Exhibit
2739
State of Minnesota v. 3M Co.,
Court File No. 27-CV-10-28862

Table of Contents (continued)

List of Figures

Table of Contents (continued)

Table of Contents (continued)

List of Appendices

List of Plates

1. Introduction and Project Organization

1.1 Project Description and Overview

This project was commissioned to develop tools for planners and water-resources managers that will assist them in making decisions that will balance land-use needs with the protection of groundwater and surface-water resources. The primary focus of this study is the protection of the groundwater contribution to surface waters. Decisions makers, equipped with tools that are scientifically based, should be able to better manage land use and water resources by protecting groundwater's role in the health of surface waters. This study makes some recommendations on management strategies, from a science-based view point. However, it is not the purpose of this study to recommend specific policies on the management of groundwater and surface-water resources – we believe that this is the purview of managers and decision makers.

This study was jointly funded by Washington County in conjunction with the Board of Water and Soil Resources (BWSR) Challenge Grant Program. The Washington Conservation District (WCD) played a key role in collecting data for this project. Match funds were also provided by the South Washington Watershed District, Valley Branch Watershed District, Ramsey Washington Metro Watershed District, and Lower St. Croix Water Management Organization, and Middle St. Croix Water Management Organization.

The overall template for this report is intended to be generally similar to the report by Emmons & Olivier Resources (2003) that addresses groundwater and surface-water management in northern Washington County. The similarities provide some cohesion between the northern and southern parts of the County. However, northern Washington County and southern Washington County differ hydrologically – the southern part of the County has fewer lakes, the depth to groundwater is typically much greater, bedrock and structural geology are different, and there are fewer glacial till units. Also, a groundwater-surface-water modeling project has been completed for southern Washington County (Barr Engineering Co., 2005) that provides a scientific basis for estimating the spatial distribution of groundwater recharge and the areas of groundwater contribution to surface-water bodies. This study makes use of this model.

1.1.1 What Does Integrating Surface- and Ground-Water Management Mean?

Integrating groundwater and surface-water management in southern Washington County means recognizing that groundwater flow cannot readily be separated from the rest of the hydrologic cycle. All groundwater was once rainwater and all groundwater eventually discharges to the ground surface. Some (but certainly not all) surface-water features (lakes, wetlands, streams) depend on contributions of flow from groundwater. In many cases such as the trout stream Valley Creek in southern Washington County, cool, clear groundwater is vitally important to ecological health. For water bodies and ecological features that are substantially dependent upon groundwater, surface-water management may need to focus on groundwater management.

Lakes and wetlands are also sources for groundwater, providing recharge by infiltrating water through the bottom sediments. So-called “perched lakes” are common in southern Washington County because of the considerable depth to the water table. These lakes are topographic depressions that receive surface-runoff after spring snowmelt and precipitation events and store this water. Some of the water evaporates or is used by plants but some infiltrates. The rate of infiltration generally increases as water levels in these lakes and wetlands increase. From this point of view, surface-water management helps maintain groundwater conditions by promoting recharge.

Ultimately, management of surface water that holistically integrates groundwater must focus on the primary source of water – infiltrating precipitation. Most of southern Washington County is a “recharge zone” for groundwater but not every area contributes equally to recharge. Recharge through infiltration is a very complex process, involving processes of rainfall, topography, soils, vegetation, climate, and land use. As development and urbanization move into southern Washington County, storm-water management has begun to focus on the need to provide a mechanism and a location to infiltrate water. Development typically increases the percent of impervious area and thereby increases storm-water runoff at the expense of infiltration. Management approaches, such as storm-water infiltration basins, are opportunities to maintain (and sometimes increase) infiltration in developed areas.

1.1.2 What Management Tools are Available?

A key management tool that is a product of this study is a detailed map of typical infiltration (i.e. groundwater recharge) rates across southern Washington County.[1] We believe this is a useful tool because it will provide managers with a quantitative estimation of how much infiltration may be lost from a given land-use change. Equipped with this knowledge, managers can find a scientific-based rational for meliorating the infiltration effects of development by requiring design that produces no net loss in infiltration over a given area.

We have also developed an Excel-based spreadsheet program that allows managers to readily estimate how much total loss of infiltration will be produced by a development of a given size in a given area. Hopefully, this tool will prove useful in helping managers assist policy makers in guiding development and storm-water management. (This program is described in Appendix B)

Just as not all areas equally contribute to the recharge of groundwater, not all areas contribute groundwater to a particular surface-water body. Lakes and streams that receive groundwater as part of their flow have an area of contribution, which is sometimes referred to as a "groundwatershed". Within this groundwatershed, infiltrating precipitation will eventually find its way via groundwater flow to the surface-water body. Some knowledge of the estimated groundwatershed should be useful to managers seeking to protect the quality and quantity of groundwater flowing to lakes and streams. We have developed maps of groundwatersheds for key surface-water features that depend on groundwater to assist managers. Caution needs to be exercised when using these maps because groundwatersheds are affected by high-capacity pumping of wells.

Another spreadsheet-based program (described in Appendix A) allows managers to estimate the effect of a pumping well on groundwater levels in nearby wells (or other observation points) and the effect of a pumping well in the base flow to Valley Creek. This tool should provide some assistance in evaluating the effects of groundwater withdrawals from proposed developments or other land uses.

---

[1] In this study, "infiltration" is synonymous with "groundwater recharge", unless otherwise specified. In this context, infiltration is the water that seeps into the ground and migrates downward below the root zone to reach the water table. Infiltration, as the term is used by many surface-water hydrologists, includes all water that seeps into the ground, regardless of whether or not it ever reaches the water table.

1.2 Project Personnel

Major data collection activities were performed by the Washington Conservation District and were managed by Travis Thiel. Amanda Goebel of Washington County Department of Public Health and Environment provided additional project coordination. Data compilation, analyses, and report preparation were by Barr Engineering Company. Ray Wuolo of Barr Engineering Company managed this effort.

1.3 Technical Advisory Committee

A technical advisory committee (TAC) of voluntary member participation was established to provide guidance and suggestion on the development of this study. TAC members included:

Cindy Weckwerth-Washington County Department of Public Health and Environment
Amanda Goebel-Washington County Department of Public Health and Environment
Steve Robertson-Minnesota Department of Health
Steve Kernik-City of Woodbury
Louise Watson-Ramsey-Washington Metro Watershed District
Ryan Schroeder-City of Cottage Grove
Mark G. Rys-Minnesota Pollution Control Agency
Geoff Delin-US Geological Survey
Jennifer Olson-Emmons and Olivier Resources
John Hanson-Valley Branch Watershed District/Barr Engineering
Todd Petersen-Minnesota Department of Natural Resources (DNR) Waters
Matt Moore-South Washington Watershed District
Travis Germundson-DNR Waters
Bob Fossum- formerly of Washington Conservation District
Travis Thiel-Washington Conservation District
Konrad Koosmann-Washington Conservation District
Jim Almendinger-St. Croix Watershed Research Station, Science Museum of Minnesota
Chris Elvrum-Metropolitan Council
Stu Grubb Emmons & Olivier Resources
Charlie Devine-City of Afton

Rob Ring-Denmark Township
Jim Fitzpatrick-Lower St. Croix Watershed Management Organization
Ryan Schroeder-City of Cottage Grove
Jim Kelly-City of Lake Elmo
Chuck Regan-Minnesota Pollution Control Agency
Bob Tipping-Minnesota Geological Survey
Geoff Delin-US Geological Survey
Laurel Reeves- DNR Waters
Molly Shodeen - DNR Metro Waters
Scott Alexander- University of Minnesota, Dept of Geology & Geophysics
Dave Beaudet-City of Oak Park Heights
Jennifer Olson-Emmons & Olivier Resources
Amal M. Djerrari-Hydrogeological & Modeling Services, Inc.

The TAC committee convened twice during the course of the study, providing valuable guidance on emphasis and priorities.

1.4 Previous Studies

There have been numerous studies in southern Washington County that relate to groundwater in general and to groundwater-surface-water interaction in particular. The Washington Conservation District and the various watershed management organizations have also untaken long-term data collection activities that include groundwater. Groundwater related special studies include the following:

- Geologic Atlas of Washington County: Swanson and Meyer (1990): The Minnesota Geological Survey, as part of the County Geologic Atlas series, developed a 7-plate compendium of the geology and hydrogeology of Washington County.

- Remedial Investigation, St. Paul Park Refinery: Barr Engineering Company (1990): An investigation and remediation of groundwater contaminated by petroleum products at the St. Paul Park Refinery was undertaken. Included in the studies was a comprehensive aquifer test that used one of St. Paul Park's water-supply wells and the development of a MLAEM groundwater flow model.

- Effects of Present and Projected Ground-Water Withdrawals on the Twin Cities Aquifer System, Minnesota: Schoenberg (1990): This U.S. Geol. Survey Water-Resources Investigation developed the first metro-wide, three-dimensional groundwater flow model. Important contributions included the estimation of aquifer parameters and the development of a conceptual model.

- Ramsey County Groundwater Model: Barr Engineering Co. (1999): A groundwater flow model was developed of Ramsey and Washington Counties for the Ramsey Soil and Water Conservation District, to be used primarily for wellhead protection area delineation. The upper three layers of this MODEL were constructed using MODFLOW and were based on a conversion from the MPCA Metro Model, followed by an automated inverse optimization. The lower two layers were Layers 4 and 5 of the Metro Model and were retained in MLAEM. This model was converted in 2000 to a metro-wide MODFLOW model by combining this model with the Scott-Dakota Counties Source-Water Protection Model.

- Source-Water Protection Model for Scott and Dakota Counties: Barr Engineering Co. (1998): A MODFLOW groundwater flow model of Scott and Dakota Counties was developed for the Minnesota Dept. of Health for the purposed of delineating source-water protection areas for wells. Follow-up work (Barr Engineering Co., 2000) involved the incorporation of the previously-developed model of Ramsey and Washington Counties into this model.

- MPCA Metropolitan Area Groundwater Model Project: Hansen and Seaberg (2000): Between 1995 and 2000, the MPCA worked on the development of a regional analytic element groundwater flow model of the Twin Cities metropolitan area that included Washington County. In conjunction with this work, calibration data sets and electronic formulations of hydrostratigraphic units were developed that have proved extremely useful.

- Stream Gauging of Valley Creek and Analytic Element Model of Valley Creek Area: Science Museum of Minnesota (1999): Stream gauging was performed by the Science Museum of Minnesota (SMM) to evaluate base-flow conditions in Valley Creek. A three-layer analytic element method model was developed using the code MLAEM. The three layers of the model represented the Quaternary aquifer system, the St. Peter Sandstone, and the Prairie du Chien-Jordan aquifer. Steady-state simulations were performed to evaluate the relationship between recharge to groundwater and base flows.

- Ground Water Quality in Cottage Grove, Minnesota: Prepared by Ground Water Monitoring and Assessment Program Minnesota Pollution Control Agency (2000). Domestic wells throughout southern Washington County were sampled by the MPCA. An area in Cottage Grove and Denmark Township was identified as having high nitrate levels. Additional studies were sponsored by the Washington County Dept. of Public Health & Environment that led to the Cottage Grove Area Nitrate Study in 2003.

- South Washington Watershed District Infiltration Management Study Phases I and II: Emmons and Olivier Resources (2001). Five natural basins in the Woodbury-Cottage Grove areas of the South Washington Watershed District were studied to evaluate their potential for infiltrating runoff. Groundwater level and water-quality monitoring data from well nests installed around infiltration basins were collected and evaluated by as part of a stormwater infiltration study. Groundwater modeling was performed to evaluate the movement of infiltrated water.

- Woodbury East Alternative Urban Areawide Review (AUAR): Bonestroo Rosene Anderlik & Associates (2002): As part of AUAR process for development of the eastern portion of Woodbury, groundwater modeling was performed to preliminarily predict the effects of up to 15 new water supply wells. Effects evaluated included groundwater level drawdown and changes in base flow to Valley Creek. One of the results of this evaluation was the performance of a comprehensive aquifer test on Woodbury Well 15 in 2003.

- Part 1 Wellhead Protection Plans for Various Municipalities: Woodbury, Cottage Grove, New Port, St. Paul Park, Oakdale, Bayport, and Stillwater have or are completing Part 1 wellhead protection plans. These plans delineate 10-year time-of-travel wellhead protection zones and Drinking Water Supply Management Areas for the wells, typically using groundwater flow modeling.

- Washington County Groundwater Plan: Washington County Dept. of Public Health & Environment: Summarizes existing County-wide groundwater information and develops long-range goals for protecting groundwater.

- Cottage Grove Area Nitrate Study: Barr Engineering Company (2003). This study evaluated the occurrence and fate of nitrate in the Cottage Grove/Denmark Township after a more regional study was completed by the MPCA (2000) that found elevated nitrate levels in several wells. The nitrate study was conducted for the purposes of: (1) determining the general location and types of sources responsible for the nitrate detected in groundwater and (2) Identifying zones of denitrification to determine if there are areas in the Jordan Sandstone in the Cottage Grove vicinity that are more suitable for water supply than others. The study focused on the major geologic units that provide potable groundwater in southern Washington County – the Prairie du Chien Group and the Jordan Sandstone.

- City of Woodbury Well 15 Aquifer Test: Bonestroo Rosene Anderlik & Associates (2004). The City of Woodbury installed three well nests near newly drilled Well 15 (completed in the Jordan Sandstone) and performed two pumping tests: a 72 hour test in February 2003 and a 30-day pumping test in November 2003. High-quality water-level data were obtained from these tests to evaluate the aquifer parameters.

- Spring Inventory of the Lower St. Croix Valley Watershed: Barry (2004): Springs that discharge to the west side of the St. Croix River valley in southern Washington County were located and characterized. Focus on this study was on Connors Lake and associated springs.

- Intercommunity Groundwater Protection: 'Sustaining Growth and Natural Resources in the Woodbury/Afton Area' - Development of a Groundwater Flow Model of Southern Washington County, Minnesota: Barr Engineering Co. (2005). A groundwater-surface water model was developed of southern Washington County with emphasis on the Woodbury-Afton Area for the purpose of assessing the long-term sustainability of groundwater resources in this area. In particular, the modeling study focused on predicting the effects of pumping of the proposed Woodbury East Wellfield wells on groundwater levels and base flows in Valley Creek. The modeling also includes predictions of seasonal and monthly variations on recharge, based on surface-hydrology characteristics.

2. Background

This section provides information on the study area and background data/information pertinent to the management of groundwater in southern Washington County.

2.1 Study Area

The study area includes those portions of Washington County that are south of Highway 36 and the portion of the Middle St. Croix Watershed Management Organization (MSCWMO) north of Highway 36. The study area is shown on Figure 1.

2.2 Regional Surficial Soils

Soils in the study area are shown on Figure 2 and are classified on the basis of their hydrologic group. The hydrologic group classification is based on factors such as soil type, vegetative cover, textural composition and topographic slope – together these hydrologic classifications provide a qualitative indicator of the runoff potential. There are four hydrologic soil groups: A, B, C, and D[2].

---

[2] USDA-SCS, Soil Survey of Ramsey and Washington Counties, 1977

Hydrologic Group	Description
A	Soils having high infiltration rates when thoroughly wet (low runoff potential). Deep, well drained to excessively drained sand or gravelly sand.
B	Soils having a moderate infiltration rate when thoroughly wet. Moderately deep or deep, moderately well drained or well drained with moderate to moderately coarse texture.
C	Soils having a slow infiltration rate when thoroughly wet: soils have a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture.
D	Soils having very slow rates of infiltration when thoroughly wet (high runoff potential): soils consist of clays with high shrink-swell potential; soils have a high permanent water table; soils that have a clay pan or clay layer at or near the surface and soils that are shallow over nearly impervious material.
Urban Land	Areas of development that are covered by asphalt, concrete, and buildings.

2.3 Topography and Physiography

Ground-surface topography varies from approximately 670 feet above mean sea level (MSL) near the confluence of the St. Croix and Mississippi River in the southeast part of the study area to approximately 1,100 feet, MSL in the northwest part of the study area (Oakdale area), as shown on the map on Figure 3. The area along the Mississippi River (particularly in the Grey Cloud Island area) is flat and subject to flooding. Topography is generally rolling in other parts of the study area, with ravine formation in the tributary streams near the Mississippi River in Denmark Township and along the St. Croix River. The topography reflects a combination of factors, including the type and depth to underlying bedrock, glacial history, and recent deposition.

2.4 Climate

The average annual rainfall over the period 1970 through 2004 ranges from 30.1 inches at Hastings Dam (representing the southern part of the study area) to 32.4 inches in St. Paul. The average precipitation at the Stillwater National Weather Service Station for this period was 32.1 inches. Average annual precipitation for these three National Weather Service station for the period 1970 through 2004 is shown on Figure 4 (data source: Minnesota Climatology Office). Monthly precipitation at St. Paul for this period is shown on Figure 5.

Monthly averages for maximum and minimum air temperature at the St. Paul Station are shown on Figure 6 for the period 1975 through 2003. The average of the monthly values is shown on Figure 7. July minimum and maximum temperatures are highest (63.1°F and 85.5°F, respectively). January minimum and maximum temperatures are the lowest (4.5°F and 24.0°F, respectively).

2.5 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[3] sedimentary rocks make up the major regional aquifers and aquitards[4] 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 8 shows the relationship between geologic units and major aquifers and aquitards in southern Washington County.

2.5.1 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

---

[3] 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.

[4] 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.

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.

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 (around 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 (around 570 million years ago) through the Devonian (around 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 (around 355 million 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 (@ 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.

2.5.2 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 8. 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 dolomitc 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).

2.5.3 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 9. 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.

2.5.4 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 De Montreville 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).

2.5.5 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 10.

The Minnesota Geological Survey developed Arc grids of four major tills in Washington County in a previous study (Figure 11). Most of these tills are in the northern part of the County, in the vicinity of the St. Croix Moraine. The tills are described as follows:

Till Unit	**Description**
Till Unit 1	*(st) glacial till (Superior lobe)* – Chiefly sandy-loam-textured, unsorted sediment, with pebbles, cobbles, and boulders; sand, gravel lenses, and beds are common. Commonly overlain by 2 to 5 feet of loess or, where in proximity to units sl or so, thin sand. Includes small areas of thick, loamy to sandy colluvium. *(sti) glacial till, sand, and gravel* (Superior lobe) – Sandy till capped by, and/or interbedded with, sand and gravel. Locally patchy till over thick deposits of sand and gravel. Includes areas too small to distinguish till from ice-contact deposits, and small areas of thick, loamy to sandy colluvial and eolian sediment. *(pst) glacial till (pre-late Wisconsin Superior lobe)* – Chiefly sand-loam-textured, unsorted sediment; pebbles, cobbles, and boulders are common, as are sand and gravel lenses and beds. Overlain in places by more than 5 feet of loess near the St. Croix River valley.
Till Unit 2	*(pkt) glacial till (pre-late Wisconsinian Keewatin deposits)* – Loam-to clay-loam textured, unsorted sediment, with scattered pebbles, cobbles, and boulders; uncommon lenses of stratified

Till Unit	Description
	sediment.
Till Unit 3	*(pst) glacial till (pre-late Wisconsinan Superior lobe)* – Chiefly sand-loam-textured, unsorted sediment; pebbles, cobbles, and boulders are common, as are sand and gravel lenses and beds.

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.

2.6 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 geologic units that have been selected for the aquifers and aquitards are shown on Figure 8. The following discussion presents the rationale for the selection of units in this evaluation. Subcropping bedrock units are shown on Figure 12.

2.6.1 Mt. Simon-Hinckley Aquifer

The Mt. Simon Sandstone and the Hinckley Sandstone are generally not differentiated from one another for hydrogeologic purposes and are considered to function as a single aquifer. The Mt. Simon-Hinckley aquifer is not as well connected to major rivers and streams in the region (compared to other aquifers of younger formations), principally because the overlying Eau Claire Formation is a substantial and areally extensive aquitard.

Data on groundwater movement in the Mt. Simon-Hinckley aquifer is limited but flow is generally different from the overlying aquifers – flowing west-northwest to the pumping centers of the central cities area in southern Washington County. The Minnesota DNR has placed a moratorium on usage of the Mt. Simon-Hinckley aquifer in the Twin Cities because of its isolation from the major river systems and its limited recharge areas. There are no high-capacity wells that utilize the Mt. Simon-Hinckley aquifer in southern Washington County.

One are in southern Washington County that may play a part in recharging the Mt. Simon-Hinckley aquifer is the area along the St. Croix River, where faulting and folding have brought this unit up to near ground surface and may subcrop beneath glacial deposits near the River. These are likely areas of recharge to this aquifer unit.

2.6.2 Eau Claire Formation

The Eau Claire Formation is a substantial confining unit, consisting of 60 to 110 feet of low-hydraulic conductivity siltstone, shale, and silty sandstone. The Eau Clair Formation subcrops beneath glacial deposits near the St. Croix River in southern Washington County and is eroded away in some locations.

2.6.3 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).

2.6.4 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 Minnesota Geological Survey personnel (Tipping, personal communication), it was agreed upon that the upper portion of the Franconia Formation should be treated as an individual aquifer. The lower portion of the Franconia Formation is a separating confining layer above the Ironton-Galesville aquifer. The Franconia Formation may contribute significantly to the base flow of creeks, such as Valley Creek, where it sub crops below the creek.

2.6.5 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.

2.6.6 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 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.

2.6.6.1 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.

2.6.6.2 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.

2.6.6.3 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.

2.6.7 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.

2.6.8 Glacial Drift Aquifer

Glacially deposited sediment can be very complex and unpredictable. 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.

2.7 Hydrologic Watersheds

In southern Washington County there are surface-hydrology watersheds that define the hydrography on the basis of surface topography and there are management districts that encompass these physical districts. The major watersheds define surface-water runoff that makes its way to either the St. Croix River, to the east, or the Mississippi River, to the west (Figure 13). These two major watersheds can be further subdivided into secondary watersheds that feed tributaries and drainages to the St. Croix and Mississippi Rivers (Figure 14).

2.8 Watershed Districts and Management Organizations

Within the St. Croix River and Mississippi River watersheds, there are sub-areas that generally correspond to the smaller watersheds that are managed by watershed districts or watershed management organizations. These include: Brown’s Creek Watershed District; Middle St. Croix Watershed Management Organization; Valley Branch Watershed District; Lower St. Croix Valley Watershed Management Organization; Ramsey-Washington Metro Watershed District; and South Washington Watershed District. The locations of these management organizations are shown on Figure 1.

2.8.1 Brown's Creek Watershed

The Brown's Creek Watershed District (BCWD) formed in 1997 and encompasses portions of the cities of Grant, Hugo, Lake Elmo, Oak Park Heights, and Stillwater, as well as May and Stillwater Townships. The entire watershed is approximately 19,000 acres (29 square miles) in size. The main feature of this watershed is Brown's Creek, a naturally producing trout stream, which flows from the upland portions of the watershed southeast to the St. Croix River and drains the majority of the watershed district (Emmons and Olivier Resources, 2004). Only a small portion of the Brown's Creek Watershed resides in the northernmost portion of this study area.

2.8.2 Middle St. Croix Watershed Management Organization

The Middle St. Croix Watershed Management Organization (MSCWMO) is a joint-powers water management organization that covers approximately 13,000 acres (20 square miles) in the northeast portion of this study's area. The MSCWMO was organized in 1985 and includes portions of Afton, Bayport, Baytown Township, Lakeland, Lakeland Shores, Lake St. Croix Beach, Oak Park Heights, St. Mary's Point, Stillwater and West Lakeland Township. The prominent hydrologic feature is the St. Croix River – all drainage is to the St. Croix River.

2.8.3 Valley Branch Watershed District

The Valley Branch Watershed District (VBWD) was established in 1968 and includes parts of the Cities of Afton, Grant, Lake Elmo, Mahtomedi, Maplewood, North St. Paul, Oakdale, Oak Park Heights, Pine Springs, St. Mary's Point, White Bear Lake, Woodbury, and the Townships of Baytown and West Lakeland in Ramsey and Washington Counties. The watershed is approximately 41,000 acres (64 square miles) all of which is Washington County except for approximately 640 acres, which is in eastern Ramsey County.

There are two prominent hydrographic features in the VBWD: a series of lakes in the northwestern part of the VBWD (e.g., Lake Jane, Lake DeMontreville, Lake Olson, Lake Elmo) and Valley Creek; a highly-valued reproducing trout stream. While about 40 percent of the VBWD is landlocked, if all of its water bodies would overflow, they wouldultimately drain to the St. Croix River.

2.8.4 Lower St. Croix Valley Watershed Management Organization

The Lower St. Croix Watershed Management Organization (LSCWMO) was organized in 1985 to fulfill the watershed planning and management responsibilities of what is now Minnesota

Statutes Chapter 103B. The LSCVWMO is organized under a Joint Powers Agreement between its member communities. The water management organization covers approximately 29,000 acres (46 square miles) in the southeast portion of this study's area. The LSCWMO includes portions of Denmark Township, Afton, Cottage Grove, and that part of Hastings within Washington County. The prominent hydrologic features are the St. Croix and Mississippi Rivers. Most of the surface drainage is to the St. Croix River. Small tributaries to the major rivers originate in ravines and drainages near the major Rivers – mostly as groundwater discharges. Karst features are known in this area and springs are numerous near the St. Croix River.

2.8.5 Ramsey-Washington Metro Watershed District

The Ramsey-Washington Metro Watershed District (RWMWD) was established in 1975 and includes the eastern portion of Ramsey County and the western edge of Washington County, Minnesota. RWMWD covers approximately 33,000 acres (52 square miles) that ultimately drain into the Mississippi River. The watershed includes six actual small watersheds that each drain to the Mississippi River; the Phalen Chain of Lakes, Beaver Lake, Beltline Interceptor, Battle Creek, Fish Creek, and the Blufflands area. There are 5 major creeks, 11 lakes and thousands of wetlands within the RWMWD. The RWMWD also includes all of Landfall and parts of Woodbury and Oakdale in this study's area (principally the Tanner's Lake and Battle Creek areas).

2.8.6 South Washington Watershed District

The South Washington Watershed District (SWWD) was established in 1993. It encompasses approximately 35,000 acres (54 square miles) in the southwestern portion of this study's area and includes the Cities of Woodbury, Newport, St. Paul Park, Grey Cloud Island, Cottage Grove, and small portions of Lake Elmo and Afton. The Mississippi River is the major hydrologic feature, with all drainage flowing to it. Lakes, such as Powers Lake, Armstrong Lake, Marksgraf Lake, Colby Lake, and Wilmes Lake are also important features. A secondary hydrologic feature, the Cottage Grove Ravine, plays an important part in stormwater management practices in the SWWD.

2.9 Land Use

The population of all of Washington County was relatively stable (about 30,000) until approximately 1950, when population began to increase in response to growth of the Twin Cities region. The

County's current population is slightly over 200,000 and is projected to be approximately 330,000 by the year 2030 (see Figure 15).

The Metropolitan Council developed a map of land use in the metropolitan area for the year 2000; a portion of which is shown on Figure 16. Residential land use dominates in the western part of the study area (Woodbury-Oakdale-Cottage Grove area), agricultural land use predominates in the central part of the study area, and park land/preserve/undeveloped land is present over much of the eastern part of the study area.

Land use is expected to change by 2020, in response to population growth. The Metropolitan Council developed a map of planned land use in 2020; a portion of which is shown on Figure 17. The primary changes between 2000 and 2020 are projected to be the eastward expansion of single-family residential properties (mostly in the Woodbury area) and increased mixed use areas along Interstate 94.

3. Comprehensive Hydrologic Monitoring Plan

3.1 Background

Active monitoring programs have been performed by the various watershed management districts/organizations, by the Washington Conservation District, by various Stage Agencies, and in the performance of specialized studies. This section addresses many of these programs and the data produced.

3.2 Lake and Wetland Level Monitoring

3.2.1 Surface-Water Levels

Surface-water stage levels are performed by number of organizations, including private volunteers. A comprehensive record of lake stage has been developed by the Department of Natural Resources and is available through their Lake Finder Website. Data for the period 1989 through May 2005 are plotted in Appendix C.

The Washington Conservation District (WCD) in conjunction with the Minnesota DNR Division of Waters collected Lake/Basin elevation data within Washington County. The DNR and the WCD work together to install approximately 45 staff gauges in the South half of Washington County. The staff gauges are placed at an appropriate location within the water body and the water surface is surveyed with relation to an established benchmark that the DNR has identified. Once the water surface elevation has been determined, the gauge placard is read to determine the gauge zero (what the water surface elevation would be based on a reading of 0.00 on the staff gauge). Using the gauge zero, all readings taken from that gauge until it is removed or reset will reflect a surface water elevation, which the DNR will place into their central database.

3.2.2 Infiltration Study Measurements

Infiltration data was collected for South Washington Watershed District (SWWD) by Emmons and Olivier Resources (2001) for four of five infiltration basins in the SWWD during spring snowmelt runoff events. The four basins include CD-P50 - Eagle Valley Golf Course Basin, CD-P69 - Pioneer Drive Wetland, CD-P76 - Mile Drive Basin, and CD-P82 - County Road 19 Basin. No pumping of runoff during snowmelt conditions into CD-P85 occurred and therefore no data was available.

Infiltration data was collected by measuring the depth of water in each basin over time to determine the change in storage and measuring any inflows or outflows to the basins during the event (Emmons and Olivier, 2001).

3.3 Precipitation Monitoring

3.3.1 WCD Monitoring Methodology

The Washington Conservation District (WCD) collects precipitation data in southern Washington County using two methodologies. The first type of collection employs an automated rain gage. This device is a cylindrical can that is designed to funnel precipitation through a collection cone into a one of two collection chambers (tipping buckets). This collection chambers are designed to fill to a capacity of 0.01 inches and then tip the water out and allow the other chamber to fill. As the tipping bucket fills and begins to tip the water out, a metal device on the opposite end of the tipping bucket passes over a magnetic proximity sensor. This motion over the sensor creates a field, which the data logger recognizes and will record as one 0.01-inch rainfall event.

The second type of precipitation data that is collected isrecorded by volunteers. The WCD establishes volunteers within the county on behalf of the University of Minnesota's State Climatology Working Group (http://www.climate.umn.edu/). The volunteer is provided with a 4-inch cylindrical precipitation collector (rain/snow gauge) that is fitted with a collection cone (at the top of the cylinder) and an inner cylinder designed to measure the amount of precipitation. The volunteer will then place the rain/snow gauge in an appropriate location for collection of precipitation. The volunteer takes a reading at the same time every day, if possible, or as convenient for the volunteer. Along with recording the amount of precipitation, the volunteer is able to make note of anything that might be of value for the data management party.

During the winter season, volunteers are encouraged to make readings, but many do not participate. If snow measurements are recorded, the cone, which is placed on top of the cylinder to collect the rain, is removed along with the inner cylinder. The outer cylinder will fill with snow and the depth of the snow can be measured. This snow can then be melted and poured into the inner (measurement) cylinder to determine water content within the collected snow. The depth of snow on the ground can also be recorded and placed on the observation sheet. Once data is collected for one month, the volunteer either sends the data sheet into the WCD or the University of Minnesota's State Climatology Working Group for incorporation into a database.

3.3.2 WCD Frost/Snow Water Content Monitoring Methodology

Frost depth and frost thaw (from the ground surface) are measured using a “frost tube”, designed by WCD staff. The frost tubes are built using a 7-foot long, sealed, rigid outer CPVC pipe and a pliable 4-foot long vinyl tube inside the CPVC pipe. The vinyl tube is filled with a sand/fine gravel mixture and all gaps and holes are filled with a 0.10% fluoroscein dye/water solution that is poured into the mixture. The dye/water mixture changes from green to red within the tube to indicate whether frozen or unfrozen soil exists. This slurry is used to mimic the effects that temperature would have on saturated ground. The CPVC pipe is placed in the ground to a depth of 4 feet and 3 feet of the pipe is exposed on the surface for visibility. The inner tube is pulled from the outer tube and the frost/thaw measurements are recorded.

Snow depth measurements are estimated by taking the average depth of snow measured at various locations within a 30-foot radius of the frost tube. Water content is determined by using a 4-inch diameter precipitation gage; column of snow is collected in the gage at the average depth and allowed to melt. The melted snow is then placed in a second calibrated tube that is used to measure snow depth to water content ratios and the amount of water from that quantity of snow is recorded.

3.4 Stream Flow

Within southern Washington County, stream flow measurements are conducted by a number of groups, including the WCD, Metropolitan Council Environmental Services, and individual watershed management organizations and watershed districts. Routine measurement is typically augmented by special stream-flow measurement studies.

3.4.1 Valley Creek Monitoring

Valley Branch Watershed District has monitored flows in Valley Creek at five locations for over 25 years (Sites 1 through 5) and has permanent stage monitoring. Detailed gauging also has taken place during a special study conducted by the Science Museum of Minnesota (Almendinger, 2003).

3.4.2 Trout Brook Monitoring

Trout Brook is not routinely monitored. During 2004, the WCD collected stream flow measurements at one location on Trout Brook.

3.5 Groundwater Level Monitoring

3.5.1 Appropriated Groundwater Withdrawals

Groundwater is considered “Waters of the State”. Groundwater withdrawals in excess of 10,000 gallons per day or 1 million gallons per year require a water appropriations permit from the Minnesota DNR. Permit holders must annually report the actual volume of water pumped in each month. Permits may cover more than one installation (i.e. well) but data typically is for each well. Yearly and monthly records are available from the DNR through the SWUDS database.

The average 2003 annual pumping, expressed in gallons per minute (i.e. total annual pumping averaged over one minute) is shown on Figure 18. The Cities of Woodbury and Cottage Grove are the largest users of groundwater for public water supplies. Other significant groundwater withdrawals are the Marathon Ashland Refinery in St. Paul Park and quarry dewatering at Larson Quarry on Grey Cloud Island (not shown). Recent groundwater modeling performed by Barr Engineering Company for Aggregate Industries as part of a permit application to expand mining on Grey Cloud Island has demonstrated that the dewatering effects of mining on Grey Cloud Island are generally limited to the Island itself.

Pumping rates vary from year to year, depending on climatic conditions, and from season to season. Total annual pumping for the period 1988 through 2002 is shown on Figure 19. Lowest pumping rates are typically during January, which reflect basic domestic and industrial demands (i.e. base demand), as shown on Figure 20. Base demand generally rises in direct correlation with increasing population. An analysis of base demand in Woodbury, for example, as part of the LCMR study (Barr Engineering Co., 2005), found that the per capita base demand is about 108 gallons per day.

3.5.2 WCD Groundwater Level Monitoring Methods

The WCD collects groundwater elevation data in two ways, depending on limitations of access to the groundwater source. Typically, observation wells are monitored for elevation, but occasionally residential wells are incorporated into this monitoring scheme. The most standard way to determine elevation is to use an approved electronic water-level meter. With this meter, a probe is lowered into a well casing until the probe reaches the surface of the static water level. Once reached, the electronic water level meter sends back a tone indicating water contact. The probe is then lifted and lowered several times to ensure that the probe has not touched a moist portion of the well casing or another type of interference within the casing. Once certain contact has been made, a measurement must be made to determine the depth of the probe from the top of the well casing or other known measurement hold point. Many approved water level meters have built in measuring units built into the cord that lowers the probe to the water. A reading of this built in scale will give you depth to water surface.

For other water level meters that do not have this form of built in scale, pulling the cord out and measuring the length to the probe from the top of the casing can be performed manually. Once the depth to the water surface from the top of the casing or known measurement hold point is known, translation of this number into elevation of water above mean sea level must be determined. To perform this operation, subtracting the depth to water surface from the elevation value associated with the top of the well casing or other known measurement hold point must be performed will give the desired elevation value.

3.5.3 Domestic Wells

There are approximately 3,600 domestic wells listed in the Minnesota Geological Survey's County Well Index (CWI), as shown on Figure 21. Not all wells in the study area are in the CWI database and some wells may have been abandoned. The aquifer or geologic unit that the wells are completed in is dependent upon what the first reliable water-bearing unit is in a particular area. For example, in southern Woodbury, the Prairie du Chien Group is the shallowest water-bearing unit, whereas in Afton, the uppermost water-bearing unit is typically the Franconia Formation.

3.5.4 DNR Observation Well Network

The Minnesota DNR maintains an observation well network that includes existing wells throughout the state, completed in various hydrostratigraphic units. Water levels are typically measured on a monthly basis. Locations of wells are shown on Figure 22. Examples of hydrographs of these wells are shown on Figures 23, 24, and 25. Hydrographs of all wells are listed in the Excel spreadsheet "DNR_obwell_data.xls."

3.5.5 Woodbury Well 15 Aquifer Test Monitoring

Comprehensive aquifer testing has been conducted on Woodbury Well 15 by Bonestroo, Rosene, Anderlik, and Associates (2004). 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 26.

Additional groundwater level monitoring of wells associated with the pumping of Well 15 and future wells is planned for the future by the City of Woodbury.

3.5.6 Potentiometric Contour Maps

Maps of the potentiometric surface (feet, above mean sea level) for the water table, the St. Peter Sandstone, the Shakopee Formation of the Prairie du Chien Group, the Jordan Sandstone, and the Franconia/Ironton-Galesville units are shown on Figures 27 through 31. These maps are a product of geostatistical contouring of water levels reported in the County Well Index and the results of the calibrated, steady-state LCMR (Legislative Commission on Minnesota Resources) groundwater model (Barr Engineering Co., 2005). Contours of head are not extrapolated into areas where the specified geologic units are not present (eroded away) or where the phreatic surface is below the base of the unit.

3.5.7 Groundwater Monitoring of Infiltration Basins – SWWD

Groundwater level monitoring data from well nests installed around infiltration basins in SWWD were collected and evaluated by Emmons and Olivier Resources (2002) as part of a stormwater infiltration study. The purpose of the groundwater level monitoring was to evaluate the process of water table mounding by infiltrating water under and near infiltration basins and to determine if the mounding will act to limit the rate of infiltration. Water levels were recorded during the fall of 1998 and monthly during 1999 in all of the SWWD-owned monitoring wells. SWWD-collected values were compared with the City of Woodbury monitoring wells that are located near basin CD-P85. The City of Woodbury has been recording water levels in their three wells for several years on a quarterly basis (Emmons and Olivier, 2002).

3.5.8 Groundwater Monitoring of Shallow Groundwater – VBWD

The VBWD has a shallow monitoring well network that has been used to collect groundwater level data for approximately 30 years. Currently, there are 15 such wells being monitored out of a total of

24 – the remaining nine have been destroyed. These wells consist of 1- to 2-inch diameter well points that have been installed to a very shallow depth (and likely were hand-driven). The well measuring points have been surveyed for elevation. Typically, these wells are measured every other month.

Most of the wells are located near lakes or wetlands – the resulting groundwater elevations are typically near the stage level of the nearby water body. Some of these wells may be monitoring perched water systems, rather than the regional water table, because the elevations of the water levels from some of these wells are considerably higher than the elevations of water levels reported in the County Well Index for the shallow aquifer system in the area. A contour map of the monthly average of groundwater level measurements for 2002 is shown on Figure 32 (Valley Branch Watershed District, www.vbwd.org/groundwater.htm).

3.6 Water Quality

3.6.1 Stream and Stormwater Discharge Water-Quality Sampling Methods

Water quality sampling of stream and stormwater discharges are performed by WCD staff using the methods developed by the Metropolitan Council Environmental Services (2003a). Two different types of samples are collected: instantaneous grab samples and flow-weighted composite samples. Grab samples are generally collected during baseflow conditions and composite samples are generally collected during storm (runoff) events. Grab samples may also be collected during storm events, especially if an automatic sampler is not functioning.

3.6.2 Analysis Parameters

WCD and Metropolitan Council Environmental Services analyze for the following water-quality parameters (Metropolitan Council Environmental Services, 2003a):

Aluminum, Filtered	Conductivity[1]	pH[2]
Aluminum, Unfiltered	Copper, Filtered	Pheophytin-a
Ammonia Nitrogen, Unfiltered	Copper, Unfiltered	Potassium, Unfiltered
Bicarbonate Alkalinity, Unfiltered	Dissolved Oxygen	Precipitation[1]
BOD 5-day, Unfiltered	Fecal Coliform Bacteria	Sodium, Unfiltered
BOD Ultimate, Unfiltered	Flow[1]	Stage[1]
Cadmium, Filtered	Hardness, Unfiltered	Sulfate, Unfiltered
Cadmium, Unfiltered	Iron, Unfiltered	Temperature[1]
Calcium, Unfiltered	Lead, Filtered Total	Total Alkalinity, Unfiltered
Carbonate Alkalinity, Unfiltered	Lead, Unfiltered	Total Dissolved Solids
CBOD 5-day, Unfiltered	Magnesium, Unfiltered	Total Kjeldahl Nitrogen, Unfiltered

CBOD Ultimate, Unfiltered	Manganese, Filtered	Total Kjeldahl Nitrogen, Filtered
Chloride, Unfiltered	Manganese, Unfiltered	Total Organic Carbon, Unfiltered
Chlorophyll-a, Pheo-Corrected	Mercury, Methyl	Total Phosphorus, Filtered
Chlorophyll-a Trichromatic Uncorr.	Mercury, Unfiltered	Total Phosphorus, Unfiltered
Chlorophyll-b	Nickel, Filtered	Total Suspended Solids
Chlorophyll-c	Nickel, Unfiltered	Turbidity[2]
Chromium, Filtered	Nitrate N, Unfiltered	Volatile Suspended Solids
Chromium, Unfiltered	Nitrite N, Unfiltered	Unfiltered Zinc, Filtered
COD, Filtered	Ortho Phosphate, Filtered	Zinc, Unfiltered
COD, Unfiltered	Ortho Phosphate, Unfiltered	Phosphate, Unfiltered

1 Continuous and routine in-situ measurements
2 Laboratory and in-situ measurements

Stream samples are collected on a regular basis during baseflow conditions. In the winter, monthly grab samples are obtained if ice conditions allow. In the spring, summer, and fall, baseflow grab sampling frequency may increase to twice per month. Depending on specific site conditions, additional grab samples might be obtained to help further characterize water quality. In addition to the baseflow grab samples, flow-weighted composite samples are collected by the automatic samplers during all storm runoff events in the open-water (ice-free) season. About 10-15 storm events per year are characterized via composite sampling, although this number can vary depending upon rainfall frequency and distribution (Metropolitan Council Environmental Services, 2003a).

3.6.3 Tritium and Stable Isotopes

Limited tritium and stable isotope analyses have been performed in the study area. Almendinger (2003) collected tritium data and ^{18}O and ^{2}H (deuterium) data to evaluate groundwater age (tritium is used to determine if water is pre- or post-atomic atmospheric testing, or 50 years) and to distinguish between meteoric waters and waters that have has some evaporation, such as lakes (heavier isotopes of oxygen and hydrogen tend to become enriched in evaporating water bodies. The Minnesota Department of Health performs or requires tritium analyses on community water supply wells to determine well vulnerability for wellhead protection programs.

As part of the Cottage Grove Area Nitrate Study (Barr Engineering Company, 2003) some isotopic nitrate analyses were performed on water-well samples to evaluate the source of nitrate in groundwater. Nitrogen is typically ^{14}N but can be enriched in ^{15}N in manure, compared to atmospheric sources and anhydrous ammonia.

3.6.4 Major Ion Chemistry

Major cations (calcium, magnesium, sodium, potassium and atypically fluoride, nitrate, manganese, and iron) and anions (sulfate, chloride, and carbonate-bicarbonate) are present in groundwater and surface water at mg/L (part per million) concentrations, compared to ug/L (part per billion) concentrations for less-common dissolved constituents. Because they have high concentrations, they are typically easier and cheaper to analyze for. Also, the ratio in which these major ions are present in water can be indicative of the water's source, evolution, and relationship to other water sources (e.g., comparing surface waters with groundwater).

Limited major ion chemistry data is available in the study area and is limited to special studies (e.g., Almendinger, 2003; Barry, 2003).

3.6.5 Cottage Grove Area Nitrate Study

The study of the occurrence and fate of nitrate in the Cottage Grove/Denmark Township area was performed by Barr Engineering Company (2003) after a more regional study was completed by the MPCA (2000) that found elevated nitrate levels in several wells (Figure 33). The nitrate study was conducted for the purposes of: (1) determining the general location and types of sources responsible for the nitrate detected in groundwater and (2) Identifying zones of denitrification to determine if there are areas in the Jordan Sandstone in the Cottage Grove vicinity that are more suitable for water supply than others. Groundwater samples were collected and analyzed for nitrate (Figure 34). Nitrogen isotopes were evaluated to determine if a source type of nitrate could be discerned. Groundwater flow modeling was used to estimate the flow paths of groundwater throughout the study area and to identify recharge areas for various points of interest. The study focused on the major geologic units that provide potable groundwater in southern Washington County – the Prairie du Chien Group and the Jordan Sandstone.

Nitrate in the Prairie du Chien Group appeared to correlate with agricultural land use in areas sampled where the Prairie du Chien Group is the uppermost bedrock. The groundwater in the uppermost bedrock appeared to be highly susceptible to nitrate contamination where it underlies agricultural land. Higher concentrations of nitrate were also detected in both the Prairie du Chien and Jordan aquifers in the area just west of East Cottage Grove where ponds and wetlands on top of the bedrock valley are fed by run-off from agricultural land.

A number of faults, generally trending southwest to northeast were discovered during the course of the study. A north-south trending buried bedrock valley in the eastern part of Cottage Grove may have been formed where these faults intersect and zones of weakness in the rock had formed. The nitrate present in groundwater in the Jordan Sandstone appears to correlate with these faults – particularly a fault in eastern Cottage Grove, just west of the buried bedrock valley. The Jordan Sandstone is the uppermost bedrock unit along the axis of the buried bedrock valley and is susceptible to nitrate contaminated water that infiltrates through the unconsolidated material of the bedrock valley. The fault zones appear to be areas of higher horizontal and vertical permeability, which may be responsible for relatively rapid migration of nitrate-containing groundwater southward, along the fault zones and downward into the Jordan Sandstone.

The Prairie du Chien is the uppermost bedrock across the southeastern portion of the study area and the topography promotes flow of surface water run-off to the St. Croix and Mississippi Rivers. The groundwater in the Jordan Sandstone in the southeastern portion of the study area was found to be low in nitrate most likely do to denitrifying condition1 in the aquifer in this area. Therefore, in this area the Jordan Sandstone appears to be protected from the nitrate contamination even though the land use across this entire southeastern area is agricultural and faulting is prevalent.

3.7 Natural Resources

3.7.1 Background

3.7.1.1 Percent Impervious Area

Methodologies currently under development by the University of Minnesota allow for an estimation of the percent of impervious area using air photo imagery, combined with ground-surface “calibration”. Using air imagery from 2000, a map of percent impervious area has been developed and is shown on Figure 35. As can be seen from this map, the percent impervious area in Washington County is low.

3.7.1.2. Natural Resource Inventory

A Natural Resource Inventory (NRI) involves the evaluation of the relationship between biological and physical features of a landscape. Assemblages of plants, animals, and physical features (soils, slope, and climate) are considered in the NRIs. Undisturbed areas, such as woodlands, wetland and prairies are part of the NRI process but areas that have been substantially affected by human activities are not included.

Natural Resource Inventories have been performed for The City of Woodbury (Bonestroo Rosene Anderlik & Associates, 1996), the City of Cottage Grove (Bonestroo Rosene Anderlik & Associates, 1998), Denmark Township (Barr Engineering Company, 2002), and the City of Afton (Emmons & Olivier Resources, 2001). The VBWD completed a NRI for most of the Lake Elmo Park Reserve in 2003.

3.7.1.3. Minnesota Land Cover Classification System

The Minnesota Land Cover Classification System (MLCCS) is a relatively new tool for natural resource managers and planners. It was developed by the Minnesota Department of Natural Resources - Metro Region, in cooperation with other state, federal and local agencies, the system is unique in that it categorizes urban and built up areas in terms of land cover, rather than land use.

Development of the MLCCS began in 1998 during efforts to conduct a natural resource inventory and management plans for a portion of the Mississippi River corridor in the metro region. Existing data from aerial and satellite photos was too coarse and it was presented in terms of land use -- such as industrial, commercial, residential -- rather than land cover. Such data offered little information about the amount or type of vegetation or the amount of artificial surfaces covering a parcel of property. To address these shortcomings, the DNR convened a steering committee comprised of representatives from the National Park Service, the U.S. Fish and Wildlife Service, the Corps of Engineers, the Dakota Soil and Water Conservation District, Ramsey County Parks, Friends of the Mississippi River and Great River Greening. The group created a hybrid system incorporating the National Vegetation Classification System (NVCS) and the Minnesota Natural Heritage native plant community types, along with a cultural classification system to distinguish among different types and amounts of land cover, vegetation and impervious surfaces.

The classification system consists of five hierarchical levels. At the highest level, land covers are divided into either Natural/Semi-Natural cover types or Cultural cover types. The Natural/Semi-Natural classification system is a hybrid of the NVCS and the Minnesota Natural Heritage plant communities. The NVCS is used for the top three levels of the system, while Level 4 and Level 5 rely on Minnesota Natural Heritage community types as follows:

- Level 1 - General growth patterns (e.g. forest, woodland, shrub land, etc.)

- Level 2 - Plant types (e.g. deciduous, coniferous, grasslands, forbs, etc.)
- Level 3 - Soil hydrology (e.g. upland, seasonally flooded, saturated, etc.)
- Levels 4 - Plant species composition, (e.g. floodplain forest, rich fen sedge, jack pine barrens, etc.) and 5

The Cultural classification system is designed to identify built-up / vegetation patterns and an areas imperviousness to water infiltration. Most other land inventory classification systems, such as the USGS Anderson system, employ land use terminology (e.g. urban, commercial, residential). This system distinguishes among land cover types at the following levels of detail:

- Level 1 - Presence of built-up elements (i.e. built-up vs. cultivated land)
- Level 2 - Dominant vegetation (trees, shrubs, herbaceous)
- Level 3 - Plant type (deciduous, coniferous, etc.)
- Level 4 - Percent of impervious surface or soil hydrology
- Level 5 - Specific plant species

This cultural classification is unique in that it emphasizes vegetation land cover instead of land use, thus creating a land cover inventory useful for resource managers and planners.

Not all of the study area has been classified using the MLCCS system as of June 2005. Those areas with MLCCS classification from the Minnesota DNR are shown on Figure 36. The classification system is not shown because of the numerous categories – these data are best accessed through GIS.

3.7.1.4. Minnesota County Biological Survey

The Minnesota County Biological Survey (MCBS) began in 1987 as a systematic survey of rare biological features. The goal of the Survey is to identify significant natural areas and to collect and interpret data on the distribution and ecology of rare plants, rare animals, and native plant communities. Native plant communities are the primary focus of this survey. A native plant community is a group of native plants that interact with each other and with their environment in ways not greatly altered by modern human activity or by introduced organisms. These groups of native plant species form recognizable units, such as oak savannas, pine forests, or marshes, that tend to repeat over space and time. Native plant communities are classified and described by considering vegetation, hydrology, landforms, soils, and natural disturbance regimes. The survey results for the study area, showing native plant communities, are in Figure 37.

3.7.1.5 MCES Lake Ecological Class Ranking

Metropolitan Council Environmental Services (MCES) has developed a relative ranking of the overall ecological condition of lakes in the Metro area, based on the physical habitat condition and the known probability of significant biological features. There is considerable correlation between lakes that have high quality physical habitat and those that have high biological importance (Metropolitan Council Environmental Services, 2003b). A value is a 1 (moderate), 2 (high), or 3 (outstanding), with a value of three being the best overall ecological condition, is assigned to the lakes. The 2003 ranking results are shown on Figure 38 for lakes in the study area. Mud Lake, Lake Elmo, Cloverdale Lake, Lake Edith, the St. Croix River, and Spring Lake (Mississippi River) received a ranking of outstanding.

4. Groundwater Resource Assessment and Classification

4.1 Lakes

There are many fewer lakes in southern Washington County, compared to northern Washington County and with the exception of Lake Elmo, most of the lakes in southern Washington County are considerably shallower than in the northern part of the County. The principal reason for fewer lakes in the southern part of the County is the absence of substantial St. Croix moraine deposits (which are in abundance in the northern part of the County). Moraine deposits tend to be dominated by lower permeability clay-rich tills and pothole lakes, formed by the melting of stagnant ice blocks during retreat of glacial ice. In place of moraine deposits are extensive sand and gravels outwash materials. These outwash materials are generally of high permeability and not conducive to the retention of surface water.

Another factor (and likely related to the more permeable glacial deposits) is the depth to groundwater in southern Washington County – the water table in many places is over 100 feet deep. Local perched groundwater conditions can be encountered and shallow lakes and wetlands are typically perched above the water table.[5]

In the study of the northern part of Washington County (Emmons and Olivier Resources, 2004), extensive analyses were performed to determine the interaction of individual lakes with the groundwater system, including comparisons of lake stage fluctuations with precipitation, geologic conditions, and water quality. These are appropriate methods for the hydrologic setting in the northern part of the County, where groundwater is relatively shallow, lakes are abundant, and glacial deposits are complex. However, these methods are either not applicable or are unnecessary in southern Washington County. For example, a comparison of hydraulic head measurements in Quaternary deposits near many lakes in southern Washington County and lake-related conditions, such as lake elevations, and bathymetric data clearly reveals that these lakes are perched. Perched

---

[5] By definition, a perched water table has unsaturated deposits beneath it. A perched lake would have unsaturated deposits between the lake bottom and the regional water table.

lakes undoubtedly provide some recharge to the underlying groundwater flow system, although the amount and extent is typically difficult to quantify.

Similarly, the most important groundwater discharge features (in terms of quantity) are the largest “lakes” in southern Washington County: the St. Croix and Mississippi River. The St. Croix and Mississippi Rivers receive nearly all of the groundwater flow in the southern part of the County as contributions to base flow. Some of the tributaries to the Mississippi and (in particular) the St. Croix Rivers intercept a portion of this recharge before it reaches the major rivers.

Lakes in the area were classified as “discharge”, “flow-through”, “perched”, and “recharge”, based on their likely interaction with the regional groundwater system. The characteristics of these lakes are as follows:

- Discharge Lakes – Lakes that are in direct hydraulic connection with the regional water table (determined by evaluating water level data from well data bases, from the bathymetric characteristics of the lake, and from information on outflows compared to inflows) and receive groundwater inflow that is likely greater than groundwater outflow. The most obvious example of a discharge lake is Spring Lake, which is a portion of the Mississippi River. Lake Elmo is also a discharge lake with an outlet that removes inflowing water.
- Flow-Through Lakes – Lakes that are in direct hydraulic connection with the regional water table but without an outlet that *significantly* removes the inflowing groundwater. Examples include Lake Jane and Lake DeMontreville. Groundwater flows into the lake primarily in the upgradient areas but discharges back into the water-table system on the downstream end, resulting in nearly a net zero groundwater balance. During the course of the year, there can be situations when the lake is “gaining” or “losing” with respect to groundwater but on average, groundwater flows through.
- Perched Lakes – Lakes with bottoms above the regional water table. These lakes may be connected to local perched water table conditions but they do not receive inflows of regional groundwater. A wetland could also be classified as a perched lake. Typically lake bottom sediments are very fine and of low permeability and/or there are clay layers that prevent surface waters from leaking out the bottom at a rate faster than surface processes can replenish the water. Lakes with very different water levels in close proximity are a common indicator of perched conditions. Perched lakes can contribute recharge to the groundwater

system but not at a rate substantially higher than infiltrating precipitation. An example of a perched lake in the study area is Markgraf Lake.

- Recharge Lakes – Recharge lakes have water levels that are higher than the regional water table but are large enough and deep enough to contribute significant flow to the regional groundwater system. Colby, Powers, and Tanners Lakes are believed to fall into this category.

Figure 39 shows the lakes in the study area, classified according to these criteria. Very small lakes (which are almost always perched) may not be included.

4.2 Groundwater Dependent Resources

4.2.1 Streams and Creeks

Like lakes, streams and creeks can either recharge groundwater or receive flow from groundwater. Typically, a stream will perform both functions, depending on location (and in some cases, time of the year). In general, stream flow in the uppermost sections of a stream is derived from surface runoff, particularly during spring freshet or after rainfall events. As the stream flows to the confluence of larger water bodies, erosional down-cutting of the stream bed places the stream in closer proximity to the water table. Where the elevation of the stream falls below the adjacent water-table elevation, groundwater begins to flow into the stream, contributing to the steam's base flow; the stream becomes a "gaining stream". Locally streams can lose flow to groundwater and regain the flow further down stream, such as between meanders.

4.2.1.1 Use of Stream-Flow Measurements

Careful stream-flow measurements at various locations along stream reaches are the best indicator of whether a stream segment is gaining or losing, with respect to groundwater interaction. Base flow gains or losses are computed as the difference in measured flows between to locations along the stream (provided the measurements are taken at nearly the same time). A major complicating factor in the calculation of base flows is the contribution of surface flows to the stream reach. Tributary flows are obvious sources (and can be accounted for by additional stream-flow gauging) but overland runoff and discharge of water from other sources can result in an overestimation of base flows. For this reason, base-flow calculations are best performed using stream-flow data during low-precipitation periods, such as the fall and winter.

Stream-flow measurements are also prone to error and this error can occasionally be of the same order of magnitude as the base flows that are being estimated. In smaller streams, inaccurate cross-section surveys, insufficient measurements of flow velocity along the cross section, and variations on the stream bottom (i.e. rocks) all potentially contribute to stream-flow errors. Control cross sections, such as culverts and bridge crossings provide a more stable condition for reproducibility of results that can lead to reliable development of rating curves that represent the relationship between stream stage and flow. For large streams, such as the Mississippi or St. Croix Rivers, the upstream contribution of flow is so great that the inherent error in measuring flow is greater than the base flow along a reach.

4.2.1.2 Valley Creek Stream Flows

An extensive evaluation of the watershed hydrology of Valley Creek was performed by J.E.. Almendinger of the St. Croix Watershed Research Station – Science Museum of Minnesota (2003) and comparisons were made with another local trout stream – Brown's Creek (which is north of the area of this study). Almendinger found that hydrographs of Valley Creek flow during runoff events displayed a single peak, whereas there generally were two peaks on the Brown's Creek hydrographs. The small, single peak on the Valley Creek hydrographs was interpreted to be the result of little or no contribution of overland runoff from either pervious or impervious surfaces. In other words, the hydrographs suggest that flows in Valley Creek are principally derived from discharging groundwater. Almendinger estimated that in 1999, 92% of total annual flow was base flow from groundwater and outflow from in-channel lakes and wetlands.

Isotopic analyses by the Science Museum of Minnesota suggests that groundwater that discharges as base flow into Valley Creek is relatively young (less than 50 years old, according to tritium levels) and meteoric in origin, as opposed to seepage from lakes with evaporative signatures (according to ^{18}O and ^{2}H isotopic ratios).

Almendinger (2003) performed stream gauging and sampling at several locations along Valley Creek, as shown on Figure 40. Median base flow at the mouth (Station 5 on the figure) as recorded by Valley Branch Watershed District for the period 1973 to 1993 is 15.2 cubic feet per second (cfs) and rose to 19.4 cfs during 1997-1998 when precipitation was about 40% greater than normal. The median baseflow measured by Almendinger (2003) for 1999 was 17.2 cfs. These base flow values represent the cumulative gains (minus losses) of stream flow from groundwater throughout Valley Creek's course, including North and South Branches. Approximately 50% (8.6 cfs) of the total base flow originated from the South Branch and 40& (6.7 cfs) came from the North Branch. Only 1.8 cfs came from flow along the main stem of Valley Creek.

Numerous springs near the headwaters of the South Branch (highlighted on Figure 41). Almendinger found that the headwaters area of the South Branch contributes almost 94% of the total base flow to the South Branch of Valley Creek. Groundwater temperatures in the South Branch were also found to be typically below 15°C similar to groundwater temperatures.

4.2.1.3 Valley Creek Chemistry

Almendinger (2003) compared major ion chemistry in Valley Creek, in lakes, and in groundwater for the purpose of evaluating the contribution of groundwater to Valley Creek flows. Concentration data for major ions were converted to milli-equivalents and plotted on trinary Piper Diagrams (Figure 42). Groundwater was found to be calcium-magnesium-bicarbonate water, which is typical of most groundwater in the Metro area.

Major ion chemistry of lakes in the watershed showed more variability with respect to sodium and chloride, which Almendinger hypothesized was due to road salt runoff. However, the proportion of calcium, magnesium, and bicarbonate was similar to groundwater.

The major ion chemistry of Valley Creek during typical, or base flow conditions, cluster on the Piper Diagrams with groundwater, indicating similar major ion chemistries. Run-off flows had higher sodium and chloride (Almendinger, 2003). Trace levels of metals and very low levels of pesticides.

4.2.1.4 Trout Brook Stream Flows

During 2004, the WCD conducted automated stream-flow measurements near the mouth of Trout Brook. Stream flows varied from 0.87 cfs in early June 2004 to 0.13 cfs in November 2004. The median stream flow was 0.42 cfs (Figure 43). Given the small watershed of Trout Brook, most of the flow appears to be groundwater-derived base flow, originating in a fashion similar to the base flow of Valley Creek.

Groundwater elevation data suggest that the potentiometric surface of the regional aquifer systems intersect the ground surface of Trout Brook approximately where Trout Brook becomes a perennial stream. This takes place much closer to the regional discharge feature (the St. Croix River) than Valley Creek, which likely accounts for the lower base flows in Trout Brook, compared to Valley Creek.

4.2.1.5 Other Stream Flows

The WCD collected flow data at several other locations in 2004, including the Cottage Grove Ravine Park Lake outlet, the Highway 94 Rest Area Pond outlet, Kelles Coulee, O'Conners Lake Creek, and on Valley Creek at Stagecoach Road. Hydrographs of these flows are in Appendix E. Valley Creek flows are discussed above.

Flows in the Cottage Grove Ravine Park Lake outlet suggest that groundwater likely does not contribute to these flows. There may be a small (less than 0.01 cfs) baseflow contribution at the Highway 94 Rest Area outlet and in Kelles Coulee (less than 0.02 cfs). The flow along O'Conners Lake Creek is a very uniform value ranging between slightly less than 0.1 cfs to about 0.16 cfs, indicating that flow in this creek is likely the result of groundwater baseflows.

4.2.2 Springs

Springs are locations where groundwater visibly discharges to the ground surface. Springs are very common in the vicinity of regional discharge features, such as the St. Croix and Mississippi Rivers, but are most noticeable in areas where bluffs delineate a pronounced topographic break between upland areas and river valleys. This is why springs are commonly recognized in the St. Croix River valley (due to bluff features) but are less common in areas where there is a broad flood plain, such as the area near Spring Lake and the Mississippi River. Springs develop where: (1) the potentiometric surface is above the ground surface and (2) there are geomorphic, structural, or depositional features in the geologic deposits that channel flow into discrete areas.

Springs are also well-developed at the headwaters to the South Branch of Valley Creek (Almendinger, 2003), where the ground surface of the valley "canyon" intersects the potentiometric surface. Faulting in the area, combined with the contact with the lower permeability Oneota Dolomite may contribute to the clustering of springs at this location, although no definitive evidence has been collected to prove this.

Active karst terrain, displaying features that include fractured limestone, solution enhanced cavities, sinkholes, interrupted drainage, and springs, have been identified in the study area – particularly in the southeast portion (Denmark Township) (Barry, 2003). The DNR has identified karst-related features in this area, as shown on Figure 44.

4.2.2.1 Connors Lake Spring Study

Barry (2003) evaluated Connors Lake – a body of water with a perennial inlet stream and no outlet stream (indicating that water is leaving the lake through the subsurface. Five springs were located along the edge of the St. Croix River near Connors Lake (Figure 45). The springs are described as reemerging flow from Connors Lake, in the Prairie du Chien Group adjacent to the St. Croix River. Chemical analysis of the water indicated nitrate levels in the range of 2 to 4 mg/L, indicating anthropogenic impacts. Connors Lake and the springs have similar macro ion signatures (see Piper Diagram on Figure 46). The study preliminary concludes that Connors Lake is linked to the springs but recommends dye tracing to verify.

4.3 Infiltration and Recharge

4.3.1 Infiltration Processes

“Infiltration” and “recharge” are used synonymously in this study to mean: *water that seeps into the ground and reaches the regional water table.* This definition is somewhat different than common usage because it differentiates between all water that seeps into the ground and water that moves downward, below the root zone of plants and eventually becomes saturated groundwater. In other words, some seepage (in fact, most seepage) is used by plants in their evapotranspiration processes and never recharges the groundwater system.

Infiltration is a complex process. The following factors play significant roles in infiltration:

- temperature, humidity, sun angle, duration of sun;
- type of crop, rooting depth, canopy cover, and vegetative libido;
- land use, impervious area;
- soil type, texture, saturated hydraulic conductivity;
- topography;
- depth to the water table;
- soil moisture content; and

- type of precipitation (rain or snow) and duration/intensity of precipitation.

While it is impossible to accurately account for every variable, an approach was used in this study that employed the results of comprehensive groundwater modeling and surface-water hydrology modeling techniques to quantify typical recharge rates over southern Washington County.

4.3.2 MIKE SHE Modeling Approach

This study makes use of the results of groundwater-surface-water modeling of southern Washington County that was performed as part of a grant from the Legislative Commission on Minnesota Resources (LCMR) (Barr Engineering Co., 2005). As part of that study, the modeling system MIKE SHE (Danish Hydrologic Institute, 2004) was used to model infiltration conditions under a variety of conditions using historical climatological data. Details of the approach can be found in Barr Engineering Co. (2005) and are summarized briefly here.

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.

MIKE SHE utilizes a method that solves for unsaturated flow using 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.

The MIKE SHE analyses produced conditions for dry years, wet years, typical years, and historical monthly conditions. A “typical year”, representative of average conditions is 1979, is applicable to this study. 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 about 8.5 inches (24 % of total precipitation). Recharge does not vary much 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 typical year are about 27 inches (74 % of total precipitation). This includes evaporation from surface waters, including the St. Croix and Mississippi River.

4.3.3 Map of Typical Recharge Rates

A primary result of the MIKE SHE simulations of southern Washington County is a detailed map of the estimated "typical" annual recharge rate. This map, included in this report as Plate 1 and reproduced in smaller form as Figure 47, is a product of the simulation of the various hydrologic processes described above as part of the LCMR modeling study (Barr Engineering Co. 2005). Also available is an ESRI shapefile of this information, using 100-meter by 100-meter polygons.

Less recharge takes place during drought years, such as 1988, when precipitation is low and temperatures are high. MIKE SHE simulations were also performed for 1988. The difference in estimated infiltration rates between typical conditions and drought conditions provides some indication of the sensitivity of recharge in a given area to drought conditions. This sensitivity is shown on Figure 48. Areas of high and very high sensitivity are locations where recharge rates are most affected by drought conditions. These areas may present opportunities for partially offsetting the effects of drought through augmented infiltration in dry periods.

4.3.4 Map of Infiltration Potential

As previously stated, "infiltration" and "recharge" are used synonymously in this study to mean *water that seeps into the ground and reaches the regional water table.* The MIKE SHE analyses produced an estimated distribution of this recharge, based on a myriad of factors, including topography, vegetation, and precipitation. There are likely many locations where the physical conditions (soil, depth to bedrock, depth to groundwater, etc.) would allow for much more infiltration, provided there was more available water. The obvious example is the construction of an infiltration basin, where stormwater runoff is routed to a topographic low (natural or constructed). In such circumstances, topography and vegetation (i.e. the evapotranspiration component of the water balance) are controllable variables, as is the input of water. The amount of water that can be infiltrated in such a setting is controlled primarily by (1) soil type (hydraulic conductivity), (2) depth to groundwater (potential for water-table mounding to reduce infiltration), and (3) depth to bedrock (potential for transient or permanent perching conditions on top of rock).

Managers and planners will likely need to have some estimate of an area's potential for infiltrating stormwater above and beyond the "natural" groundwater recharge rates. The primary purpose for infiltrating more water than is required to maintain groundwater recharge rates is the protection of water-quality conditions of surface-water bodies. Runoff from impervious surfaces may have elevated levels of contaminants, such as metals or hydrocarbon compounds – infiltrating this runoff has the potential from allowing natural to mitigate these conditions.

In this study, two tools were developed to assist managers in estimating the infiltration potential of a location. The Excel-based infiltration program, described in Appendix B, provides for an estimation of the area needed for an infiltration basin, based on the hydrologic grouping of the soil and the proposed percent impervious area. The second tool is a map of "infiltration potential", shown on Figure 49 (and included as a point shapefile on a CD included with this report). The "infiltration potential" is based on soil hydrologic grouping (A, B, C, or D), depth to the regional water table, and depth to bedrock (relative to water table) according to the following criteria:

Infiltration Potential Ranking	Hydrologic Grouping	Depth to Water Table	Water Table above or Below Bedrock Surface?
Very High	A	> 2 ft	Either
High	A and B	> 2 ft	Either
Moderate	A, B, and C	Typically > 2 ft	Typically above bedrock
Low	B, C, and D	< 2 feet	Typically below bedrock
Very Low	C, and D	< 2feet	Typically below bedrock

A numerical rating system was devised for each criterion and the rating values were summed to arrive at a relative infiltration potential ranking. Most of the study area ranks as having a "high" infiltration potential, due to the sandy soils, and considerable depth to the water table. Areas near discharge zones tend to have lower rankings because the water table is generally shallower.

The infiltration potential ranking can be used as a general guide for locating infiltration features, such as stormwater basins. It is not a substitute for site-specific data.

4.4 Groundwater Recharge and Discharge

4.4.1 Groundwater Recharge and Discharge Areas

Nearly all of southern Washington County is an area of groundwater recharge. Groundwater discharge takes place only in areas where the water table is at or near the ground surface; along the St. Croix River, along the Mississippi River, in the Lake DeMontreville-Lake Jane-Lake Elmo area, in Valley Creek, and in the smaller drainages in Afton and Denmark Township (e.g., Trout Brook). These areas are shown on Figure 50. This figure was developed by subtracting the gridded ground-surface elevations from the computed water-table elevation and adding 5 meters to account for seasonal water elevation variations and grid density granularity.

Groundwater discharges *in the study area* are estimated for typical, steady-state conditions from the groundwater model developed as part of the LCMR project (Barr Engineering Co., 2005) as follows:

Discharge Feature	Discharge (cubic feet per second, cfs)
St. Croix River	73 cfs
Mississippi River	41 cfs
Valley Creek	10 cfs
Trout Brook	5 cfs
Other miscellaneous drainages near St.Croix and Mississippi Rivers	25 cfs

Pumping Wells	28 cfs
Total Discharge	**182 cfs**

Distribution of discharges along the St. Croix and Mississippi Rivers in the study area are shown on Figure 51.

In addition to recharge by infiltrating water, groundwater in southern Washington County is recharged by leakage from some lakes as leakage through the bottom and sides of the lakes. Larger lakes with significant components of recharge include the following: Powers Lake (2 cfs); Tanners Lake (2 cfs); and Colby Lake (1.5 cfs).

4.4.2 Groundwater Zones of Contribution to Surface-Water Bodies

As previously described, most of the water that infiltrates into the ground and reaches the water table in Washington County finds its way to the Mississippi or St. Croix Rivers, where it is discharged. Some groundwater discharges into other surface-water bodies and then re-infiltrates into the groundwater system. And some groundwater discharges into surface-water bodies and becomes surface water.

More than one aquifer can contribute water as discharge into surface-water bodies and because groundwater flow patterns differ slightly from one aquifer to the next, the area of contribution of groundwater to surface waters can be complex. In addition, there can be seasonal variations, as well as the effects of groundwater pumping, that can alter the area of groundwater contribution. Fortunately, the LCMR groundwater model can be used to help estimate the areas of groundwater contribution to the major surface-waters in southern Washington County.

The methodology for determining groundwater zones of contribution to surface-water bodies is analogous to the delineation of wellhead protection areas for wells – a groundwater model is used in conjunction “backward in time particle tracking” to estimate the zones of contribution. As with wellhead protection areas, groundwater time-of-travel criteria are employed. For most surface-water bodies that receive groundwater, a 10-year time-of-travel criteria was used but for some water bodies that receive a larger contribution (e.g., Valley Creek and Trout Brook), a 100-year zone of contribution was also delineated. For time-of-travel computations, an effective porosity of 0.25 was used. Steady-state simulations, with 2002 average pumping rates for appropriated wells and “typical” recharge rates (annual average) were used.

The resulting groundwater zones of contribution are shown on Figure 52. These zones are considered to be estimates of average conditions and are based on the assumptions of the LCMR groundwater model (Barr Engineering Co., 2005). These could also be called “groundwater sheds”. It is important to note the following:

1. The zones represent contributions from the entire aquifer system – groundwater in many cases is flowing up from deeper aquifers into the surface-water bodies.
2. The zones could change, depending on climatic, seasonal, and pumping conditions.
3. These zones *do not* represent areas beyond which there hydrologic effects such as pumping have not effect on base flows. In other words, changes in the hydrology outside of the zones of contribution can and will have an effect not only on the shape of the zone but also on the amount and source of water to the surface-water body.

4.4.3 Simulated Flow Paths for Stormwater Basins in SWWD

Infiltration studies were performed for South Washington Watershed District (SWWD) by Emmons and Olivier Resources (2001) of five infiltration basins in the SWWD: CD-P50 - Eagle Valley Golf Course Basin; CD-P69 - Pioneer Drive Wetland; CD-P76 - Mile Drive Basin; CD-P82 - County Road 19 Basin; and CD-P85. Infiltration rates were estimated and water-quality samples of groundwater were collected. Groundwater modeling, using the analytic element method code MLAEM (Strack Consulting, Inc.), was also performed to estimate where infiltrated water from these basins would likely migrate to.

The simulations reported in Emmons and Olivier Resources (2001) concluded the following:

- mounding of the water table should not be a problem in the vicinity of the infiltration basins;
- much of the infiltrated water will migrate vertically downward to lower aquifers;

The simulations were steady state and high-water levels of the ponds were used to simulate constant infiltration rates – a condition that the report notes is extremely unlikely and represents a worse-case approach.

The LCMR model of southern Washington County (Barr Engineering Co., 2005) is another tool that can be used to evaluate the infiltration ponds. Because the type of model used (MODFLOW) allows for transient simulations, the infiltration through the bottom of the pond from spring snow-melt conditions was simulated. Infiltration was applied to ponds CD-P50, CD-P69, CD-P76, and CD-P82 over a two month stress period (April-May) for a simulation period of 10 years. Infiltration rates during the two month period were assumed to equal approximately ½ of the maximum infiltration rate, as reported by Emmons and Olivier Resources (2001).

An effective porosity of 0.25 was applied to all model layers. Infiltration was applied via increased values of recharge at the pond locations. The finite-difference grid was refined in the area of the ponds. The solute transport code MT3DMS was used to simulate a non-reactive tracer in the recharge water, in order to simulate over time the migration of the infiltrated stormwater. The results at 10 years are shown on Figures 53 and 54 for the surficial aquifer, the Shakopee Formation, the Jordan Sandstone, and the Franconia Formation.

The results of the simulations of the LCMR model indicate the following:

- Mounding of the water table is not significant – this agrees with the results of Emmons and Olivier (2001).
- Much of the infiltrated water migrates downward to deeper aquifers – again, this is also a conclusion of Emmons and Olivier (2001). The majority of flow is in the Shakopee Formation. Some stormwater is predicted to find its way into the Franconia Formation.
- The infiltrated stormwater generally migrates southwest and west toward the Mississippi River – generally toward Newport. The modeling results suggest that the buried bedrock valley that trends north-south in the approximate location of the Cottage Grove Ravine area does not substantively affect groundwater flow. This is contrary to the conclusions of Emmons and Olivier (2001) but is in agreement with the findings of the Cottage Grove Nitrate Study (Barr Engineering Co. 2003).

4.4.5 Wellhead Protection Areas and Drinking Water Source Management Areas

Most public water suppliers that utilize wells are required to have a wellhead protection plan prepared. Most water suppliers in southern Washington County have completed their plan in accordance with a program that is administered by the Minnesota Department of Health. Wellhead Protection Areas (WHPAs) are delineated for wells and well fields typically using a groundwater flow model and groundwater time-of-travel criteria. A groundwater time-of-travel to the well of 10 years is typically used. Encompassing the WHPAs are Drinking Water Source Management Areas (DWSMAs), which are geographically definable areas in which wellhead protection management strategies are undertaken. Wellhead protection programs are generally updated every five years or sooner if new wells are constructed. The Minnesota Department of Health maintains a GIS database of WHPAs and DWSMAs. The WHPAs and DWSMAs for the study area are shown on Figure 55.

4.4.6 Guidelines for Water-Supply Wells Near Faults

The Cottage Grove Area Nitrate Study (Barr Engineering Company, 2003) recommended that farming practices across the study area should be examined to determine if a correlation exists between farming practices (e.g., form of nitrogen applied or application rate) and the lower nitrate concentrations in the Jordan Sandstone in the southeastern region of the study area that municipal well siting near the faults should be avoided, where possible, to reduce the chances of elevated nitrate levels in the wells.

Guidelines were suggested to minimize the potential for nitrate contamination of future water-supply wells by delineating areas for installing or avoiding future water-supply wells in areas near known faults. Figure 56 shows the recommended guidelines from the Cottage Grove Area Nitrate Study.

5. Strategy and Tools for Integrating Groundwater and Surface Water Management

5.1 Statement of Need

It is not the intention of this document to present recommendations for strategies, policies and rules that should be adopted by Washington County and Local Government units, including watershed districts and management organizations. Policy organizations should make these decisions for themselves, based on their knowledge of the needs of their areas and constituencies. This document does provide tools to assist managers and policy makers in the formulation of strategies and rules. In this section, recommendations on how to use these tools are presented.

5.2. Protection of Groundwater Recharge

Groundwater recharge takes place when and where water from surface-water bodies or direct precipitation seeps into the ground and moves downward to the water table. Recharge is the key part of the hydrologic cycle that provides groundwater to deeper aquifers, water to wells, and base flows to streams, springs, and lakes. Nearly all of southern Washington County is a recharge zone for groundwater.

As land use changes, topography and vegetation are altered and the percent of impervious area tends to increase. Depending upon the type of stormwater management, water that falls on impervious area may be routed to nearby open areas or infiltration basins, or routed to more distant locations. Land use changes provide the potential for changing the location of groundwater recharge and the rate of groundwater recharge.

Development of previously undisturbed or open areas usually results in increased impervious area from buildings and pavement. Curb and gutter stormwater management typically involves the routing of runoff from a large area into centralized infiltration basins. These basins become focused areas for infiltration. Because infiltration basins typically are wet after runoff events, there is a driving hydraulic head in the basin to force fasting infiltration and recharge of water than would otherwise take place in open areas. Thus, there exists the potential for overall increases in recharge to the groundwater, albeit with a different distribution. This is not to say that infiltration basins always promote more infiltration – rather, it is to state that development and increased impervious area does not necessarily equate to decreased groundwater recharge.

If groundwater recharge is reduced, over time groundwater levels will begin to drop. The areas of influence of water-supply wells will extend farther out to obtain the same amount of water (and in drought years, pumping typically increases, causing the areas of influence to be even more widespread). The overall result of permanent and significant reduction in recharge will be reduced base flows to streams, lakes, and wetlands that depend on groundwater and ultimately ecological damage. Thus, it is likely in the interest of most parties to work to keep groundwater recharge from being reduced.

The key tool for maintaining recharge is knowledge of how much recharge takes place in a given area. The maps (and associated electronic files) and the corresponding Excel-based program developed in this study are intended to assist managers and policy makers in making decisions about how to mitigate lost recharge in a given area. The first piece of information should answer: How much recharge will be lost by a given development? For example, if the recharge rate in an area is 6 inches per year and a development will result in 3 acres (130,680 square feet) of impervious area, then about 65,300 cubic feet of water a year (0.9 gallons per minute) will either be removed from the recharge water balance or must be re-infiltrated nearby in order to keep the overall recharge to groundwater unaffected. If managers are seeking a “no net recharge loss” policy or approach, this tool will allow them to scientifically justify the quantity of infiltration required.

5.3. Protection of Groundwater Quality

The overall groundwater quality in southern Washington County is very good. Anthropogenic sources of groundwater contamination fall into two main categories: agricultural (non-point sources) and point sources (e.g., leaking storage tanks, dumps, etc.). The MPCA has the responsibility of addressing point sources and this effort generally will not fall under the auspices of regional managers (except in cooperative efforts).

Susceptibility to pollution is a function of the permeability of the surficial soils, the natural of the underlying bedrock, and the depth to bedrock

Non-point agricultural sources have impacted groundwater quality in southern Washington County, primarily as nitrate contamination in the Cottage Grove area. Stormwater infiltration in basins does not appear to be the cause (nitrate levels in stormwater are generally low). Rather, nitrate contamination is generally believed to be from the application of anhydrous ammonia on agricultural fields (Barr Engineering Co., 2003). Fault systems in the bedrock appear to allow nitrate contaminants to migrate to deeper aquifers in the Cottage Grove-Denmark Township area. Denitrifying conditions in the bedrock in Denmark Township help to keep nitrate levels lower in the southeastern part of the County.

Wellhead protection programs implemented by the Minnesota Department of Health (MDH) provide management strategies for protecting groundwater quality over a 10-year time-of-travel zones in the area of contribution of water-supply wells.

There are currently four MDH-designated Special Well Construction Areas (formerly known as “well advisory areas”) located within southern Washington County. These three areas are:

1. Lakeland/Lakeland Shores Special Well Construction Area
   This area covers small portions of Afton, near Stagecoach Trail (CSAH 21) and West Lakeland Township, south of Interstate 94 as well as Lakeland and Lakeland Shores.

   Groundwater in the Lakeland Special Well Construction Area contains petroleum products, Freon, and solvents at concentrations that exceed drinking water standards. There appear to be two plumes, a northerly plume containing Freon and petroleum products, and a southerly plume containing solvents. In 1987, the MDH issued a Well Advisory for portions of Lakeland, Lakeland Shores, Afton and West Lakeland Township. The advisory prohibits the deepening of existing wells into lower bedrock formations or the drilling of new wells into lower bedrock formations. The advisory requires plan approval before the construction of new water supply wells in drift or shallow bedrock aquifers.

   Residents of homes where contaminant levels exceeded drinking water standards were initially provided with bottled water, but are now connected to a municipal water system. No other remedial actions were taken.

2. Baytown Township Groundwater Contamination Site/Special Well Construction Area
   This area begins just west of the Lake Elmo Airport and extends eastward to the City of Bayport and the St. Croix River. It includes portions of the City of Lake Elmo, Baytown Township, West Lakeland Township, and Bayport.

The entire area of contamination in the Baytown Township Groundwater Contamination Site is approximately six square miles. Volatile organic compounds (VOCs) were first found in the groundwater in 1987. Additional well sampling showed VOC contamination across a wide area. In 1988 the MDH issued a well-drilling advisory for portions of West Lakeland Township, Baytown Township, and the City of Bayport. This advisory puts limits on the construction of new wells, and requires additional water testing of new wells. The well drilling advisory, now known as the “Special Well Construction Area,” remains in effect today. It has recently been expanded to reflect the spreading of the contaminants.

The main contaminant found is trichloroethylene (TCE). TCE is commonly used for metal cleaning and degreasing, and as a dry cleaning solvent. Another contaminant, carbon tetrachloride, has also been found at very low concentrations in a limited number of wells. Carbon tetrachloride was used in the past as a grain pesticide to kill insects.

Early sampling found the highest levels of TCE in groundwater beneath the Lake Elmo Airport. For this reason, the MPCA requested that the Metropolitan Airports Commission (MAC), the owners of the airport, conduct an investigation and address the contamination. MAC agreed to do so, and entered into a formal agreement with the MPCA in 2000.

Since 1987, investigators have been trying to identify the source and extent of the contamination, as well as determine the direction it is moving. Monitoring wells have been installed in and around the Lake Elmo Airport to keep track of the contaminants. In addition, water samples have been collected periodically from several hundred private wells in the area to check for contaminants.

In the spring and fall of 1999, MAC sampled about 300 private wells to monitor levels of contaminants in wells that had been previously affected and also identify any new wells that may have become contaminated. The sampling results showed that levels of TCE continue to be highest at the Lake Elmo Airport and immediately to the east. TCE levels increased in some wells and decreased in others. A number of new wells were also found to have TCE contamination.

Sampling has continued since 1999 to monitor contaminants. Wells with higher levels of contamination are sampled more frequently to monitor for changes in TCE levels. Sampling has also focused on better defining the extent of the contamination and targeting wells that were considered at risk of exceeding health-based standards.

Activity at this site increased dramatically in February of 2002 when the MDH changed its advice to an interim exposure limit of 5 micrograms per liter based on new information on the toxicity of TCE. There will be a new Health Risk Limit established in the near future that may be different than the current recommended exposure limit. Once a new Health Risk Limit for TCE has been adopted in state rules, a long-term sampling program will be developed.

Since 2002, the MPCA and the MDH have sampled hundreds of wells (about 320 in 2002) in Baytown Township, West Lakeland Township, and Lake Elmo. To date, 149 have TCE levels exceeding the interim exposure limit of 5 micrograms per liter. The highest TCE levels in the Prairie du Chien aquifer have been found west of the airport and south of the railroad. The highest TCE levels in the Jordan aquifer have been found along 40th Street North, between Neal Avenue and Northbrook Boulevard. Maps showing the concentrations of TCE in the Prairie du Chien and the Jordan aquifers (plume maps) are available on the MDH website (http://www.health.state.mn.us/divs/eh/hazardous/sites/washington/baytown/index.html). Other maps are also available on the website. Both figures also show the outline of the Special Well Construction Area (SWCA). Not all of the wells within the SWCA have TCE contamination. Groundwater movement in the area is generally west to east. Most of the existing private residential wells are within the Prairie du Chien aquifer. Bayport's municipal water supply and a few newer residential developments in eastern Baytown Township have wells drilled into the Franconia aquifer. In 2003, TCE was detected for the first time in private wells drawing from the Franconia aquifer. TCE levels are above the interim exposure limit along the eastern edge of the SWCA. Also in 2003, TCE was found for the first time in one of Bayport's municipal (Franconia) wells. TCE levels in this well have been increasing, but are below the interim exposure limit.

When the TCE concentration in the water for a home exceeds the exposure limit, the MPCA provides home delivery of bottled water until a granular activated carbon (GAC) whole house filter can be installed (provided by the MAC). As of late 2002, over 25,000 gallons of bottled water were delivered to area residents. The GAC systems completely remove the TCE from the water. For wells not eligible for the MAC program, Baytown Township and West Lakeland Township passed ordinances that provide for governmental supervision of GAC filters installed by individual homeowners. The Minnesota state legislature also passed a law in 2003 that requires homeowners within the Baytown SWCA who have private wells to notify buyers at the time of sale that the property is within an SWCA.

In 2004, the MPCA found a major source of the TCE contamination one mile northwest of the Lake Elmo Airport. TCE concentrations of up to 50 milligrams per liter were detected on the site of a former metal fabricating shop in Lake Elmo. (See MPCA news release at: http://www.pca.state.mn.us/news/data/newsRelease.cfm?NR=263786&type=2.)

Up to date and more detailed information about this site can be obtained from the MDH and the MPCA.

3. Washington County Landfill Special Well Construction Area.
This landfill is located one-quarter mile south of Lake Jane, in the City of Lake Elmo. Washington County owns the landfill and operated the landfill under a solid waste permit authorized in 1969. In early 1981, the MPCA received a hotline tip that hazardous wastes were placed in the landfill. Subsequent sampling in 1981 detected volatile organic chemicals (VOCs) and sampling done by MDH in 1982 detected VOCs including trichloroethylene and tetrachloroethylene in private drinking water wells.

In 1982, the MDH issued a well advisory. The advisory alerted well contractors and local officials to the problems of groundwater contamination in the area of the landfill and instructed that the MDH be contacted before any well construction is undertaken within one mile of the area. The boundaries were revised in 1983 based upon findings of a technical investigation. The landfill is located in an abandoned gravel pit and is hydraulically connected to the Prairie du Chien-Jordan aquifer. The natural ground water flow direction is generally to the southwest.

A remedial system, consisting of gradient control wells and spray irrigation of effluent began operating in late 1983. The system effectively removed organic compounds from the water and reversed the spread of contamination. In May of 1986, Lake Elmo received a grant to construct a public water supply to serve the homes adversely affected by the landfill. A program was also initiated to seal the wells once the homes were connected to the public water supply. The remedial system was discontinued and the site was capped.

Recently, the MPCA and the MDH sampled groundwater in the areas south and southeast of the landfill. Based on the sampling results, the MPCA concluded that some of the waste disposed at the landfill contained perfluorooctanoic acid (PFOA), a persistent, widely-distributed contaminant. Appendix A-4.6 contains an August 2004 fact sheet produced by the MPCA and the MDH on the topic.

4. St. Paul Park and Newport Special Well Construction AreaThe MDH designated a special well construction area for portions of St. Paul Park and Newport in 1997. Groundwater in portions of the designated area has been contaminated as a result of spills, leaks, or disposal of chlorinated solvents and petroleum products at several industrial sites including the Ashland Refinery, the former Aero Precision Engineering Company, and the former Park Penta Corporation. Several groundwater plumes originating from these (and possibly other) sites have spread to the west and southwest toward the Mississippi River. Groundwater contaminants include petroleum products, several volatile organic chemicals (VOCs), and pentachlorophenol.

Contamination has been found in the Prairie du Chien bedrock formations. Lower contaminant concentrations have also been detected in the underlying Jordan aquifer.

Remedial measures have been implemented, but it will take many years before groundwater is fully protected in the designated area.

5.4 Protection of Surface-Water Areas of Contribution

Another tool for managers and other decision makers that is a product of this study are maps that depict the area of groundwater contribution to the base flows of surface-water features. For some features, 10-year and 100-year groundwater time-of-travel zones are depicted. These zones of contribution can be used a guides in assessing land uses, similar to wellhead protection areas (for wells) or watersheds (for surface-flows).

By knowing the approximate area of groundwater contribution to a surface water, the water-quality component of base flow can be addressed. For example, if a land use is proposed that is within the 10-year time-of-travel area of contribution for a stream, additional scrutiny or policy measures might be implemented to reduce the risk of (1) groundwater contamination and (2) the flow of contaminated water to the stream.

Unlike watersheds, groundwater areas of contribution, or “groundwater sheds” are not static – they can change seasonally, from year-to-year, and more permanently as pumping from high-capacity wells change. Thus, the zones should not be viewed as constant conditions.

5.5 Protection of Potentiometric Head and Stream Base Flows

Valley Creek is the dominant stream in the study area and over 90 percent of its typical flow is base flow derived from groundwater. Regional groundwater pumping has the potential for causing drawdown in the potentiometric head of aquifers, resulting in reduced flow in Valley Creek. This same condition likely also applies to Trout Brook. Thus, the health of these steams is dependent upon maintaining the groundwater contribution. This will pose a challenge to managers as development in the study area progresses.

High capacity wells are permitted by the Minnesota Department of Natural Resources – Division of Waters. A regional surface-water – groundwater flow model was developed (Barr Engineering Company, 2005) to assist policy makers and regulators in evaluating future high capacity wells. However, the Department of Natural Resources does not regulate pumping rates of lower capacity wells, such as domestic wells or community wells that do not meet the appropriations requirement thresholds. It is possible that a low-capacity well, located near a stream that depends on groundwater as base flow, could have a greater impact on stream flows than a much higher capacity well, located farther away.

An Excel-based program was developed as part of this study to assist managers in assessing the potential impacts of new low-capacity wells on regional piezometric heads and on the base flow of Valley Creek. This program provides non-hydrogeologists the ability to access and use the LCMR groundwater model without the need of specialized training or knowledge. Caution must be used in applying this program and it must be remembered that this program is only as good as existing knowledge and is not a substitute for professional judgment.

6. Findings and Suggestions for Implementation

6.1 Summary of Study Findings

This study compiled and evaluate existing data on groundwater (and surface water as it relates to groundwater) and collected new data (by the Washington Conservation District) to supplement the existing data. The relationship of surface-water resources to groundwater was the primary area of focus.

The study found that unlike northern Washington County, there are few lakes in the southern part of the County and that many of the lakes (particularly the smaller lakes) are perched above the regional water table. A groundwater divide bisects the study area approximately north-south and this groundwater divide extends down at least through the Ironton-Galesville aquifer. Groundwater in all aquifers (with the exception of the much deeper and isolated Mt. Simon-Hinckley aquifer) flows either east and discharges into the St. Croix River or west-southwest and discharges into the Mississippi River. The majority of the study area is a “recharge area”.

Valley Creek receives at least 90% of its base flow from groundwater. Using the groundwater model developed in a previous LCMR project (Barr Engineering Company, 2005), the “groundwatershed” and groundwater time-of-travel was delineated for Valley Creek, as well as Trout Brook and some of the lakes in the study area that receive groundwater inflows.

A map of typical groundwater recharge rates was developed that shows typical annual recharge values of about 2 to 18 inches per year. This map was developed through the use of a MIKE SHE model as part of the LCMR project (Barr Engineering Co., 2003). An Excel-based spreadsheet program was also developed to allow users easy access and manipulation of these data.

Soil type, depth to groundwater, and depth to bedrock were considered in the development of a map of “infiltration potential”, which ranked areas within the study area based on the area’s likely ability to infiltrate stormwater. The hydrologic group classification for various areas was also implemented into the Excel-based spreadsheet program. The vast majority of the study area has high to very high infiltration potential, owing to the sandy glacial outwash soils in the area and the large depth both to bedrock and to the water table.

6.2 Suggestions for Implementations

It is not the purpose of this study to recommend specific policies – that is the privilege and responsibility of managers, regulators, and policy makers. The purpose of this study was to compile existing information, analyze this information, and develop tools that could be used by managers to make and implement policy.

Recognizing that various jurisdictions, agencies, and areas have different priorities and issues, the following suggestions for implementation of the information and tools developed as part of this study are respectfully submitted.

6.2.1 Using Information and Tools Related to Groundwater Recharge Rates

Tools for evaluating recharge to groundwater (maps and program) could be used to evaluate proposed land-use changes, such as development, re-grading, and increased impervious area. The tools provide estimates on the current rate of recharge to groundwater at a particular location. Because decreasing recharge to groundwater may reduce base flows to streams and other groundwater-dependent features, these tools could help in implementing a “no net loss of recharge” policy.

An example might be a proposed retail center development. Proposed changes to land use accompanying a retail center development may include substantial increases in impervious and disturbed areas, which would result in reduced soil infiltration and reduced recharge to groundwater. Plate 1 could be used to evaluate how much loss in recharge at that location might take place. A more quantitative approach could also be taken using the Excel-based infiltration program that accompanies this Study. The infiltration program would provide an estimate of how much loss in groundwater recharge would likely occur and provide an estimate of the quantity/rate of induced recharge that would be necessary to offset the effects of increased impervious area.

In fact, the rate of recharge to groundwater in most areas is relatively small (2 to 18 inches per year) and this amount could easily be compensated for in most circumstances by small infiltration basins. Because infiltration basins may be required for the protection of surface water quality by reducing off-site runoff, infiltration from basins for this purpose would likely be far larger than the infiltration required to maintain a no net loss of groundwater recharge. It is not inconceivable that as development progresses in an area, the rate of recharge to groundwater could increase substantially over natural conditions through the use of infiltration basins.

6.2.2 Using Information and Tools Related to Infiltration Potential

Term “infiltration potential” that is used in this study refers to a combination of soil conditions (as described by the soils hydrologic group), depth to groundwater, and depth to bedrock that indicate a particular location’s relative ability to infiltrate storm water. Infiltration potential can be used by managers and policy makers to guide the location and sizing of infiltration features, such as infiltration basins, in a given area in order to infiltrate a specified quantity of storm water. The typical reason for infiltrating storm water is for the protection of the water quality of receiving waters.

Obviously it would be desirable in most instances to minimize the surface area of an infiltration basin (unless the basin is to be used for recreational activities or to evaporate the water). Where soil, geology, and groundwater conditions are conducive to higher rates of induced infiltration, smaller basins can be used to infiltrate larger quantities of water. Information on the relative rate of infiltration that can be achieved in a particular area may be useful to managers and policy makers looking to site basins. The tool for this purpose could be the map of infiltration potential developed as part of this Study.

Perhaps a better tool is the infiltration program. This program uses information on hydrologic grouping and depth to groundwater to estimate the size of basin that would be required to infiltrate a 72-hour storm event. It ties the calculation to the amount of available area and percent impervious area. This information could be used by managers, planners, or designers to size infiltration basins and to determine if sufficient land is available for infiltration, given a proposed development.

6.2.3 Using Information Related to Groundwater Areas of Contribution

For surface waters that receive a portion of their flow as base flow from groundwater, it may be desirable to pay particular attention to activities within the surface water’s area of contribution, or “groundwater shed”. This may be particularly important for protecting a stream’s water quality.

Plate 2 of this study is a map that shows the estimated areas of contribution for surface-water bodies using a groundwater time-of-travel criterion, similar to that used for water-supply wells in the Minnesota Department of Health’s Wellhead Protection Program. Plate 2 was developed using the LCMR surface-water – groundwater model and takes an approach identical to that used in wellhead protection area delineation. For most water bodies, a zone in which it takes 0-10 years for groundwater to travel to the receiving water body is delineated, but for Valley Creek and Trout Brook, longer travel times are also shown.

Activities within the 10-year time-of-travel zones may have a greater likelihood of adversely impacting the water quality of the receiving stream. Work by Almendinger (2003) demonstrated that groundwater entering Valley Creek was generally young (less than 50 years old) and contained nitrates that likely have an agricultural origin within the Creek's groundwater shed. As infiltration basins are constructed in the groundwatershed, there is the potential for runoff to migrate from the basins to the water bodies, containing contaminants. In addition to contaminants, elevated temperatures may ensue from runoff waters that could be warmer than distributed precipitation.

Managers and policy makers may want to examine land-use practices in areas of contributions to ensure that they are compatible with goals for the water bodies that receive this groundwater.

6.2.4 Evaluating the Effects of Wells on Surface-Water Bodies

High-capacity wells that require appropriations permits are evaluated by the DNR-Division of Waters. Domestic and other lower capacity wells are regulated by the Department of Health in terms of siting and construction but not in terms of the effects of pumping.

The LCMR Study (Barr Engineering Company. 2005) was performed, in part, to develop a tool to evaluate the effects of proposed high-capacity pumping in Woodbury on base flows of Valley Creek. This same model can be used to evaluate lower pumping rate wells on the Creek and on groundwater levels in the area. The Excel-based well program that is part of this Study is a tool that will allow managers to evaluate proposed wells in order to estimate whether or not those wells will cause (1) meaningful reductions in the base flow of Valley Creek (a designated trout stream) or (2) drawdown in nearby wells or wetland areas that might be considered adverse. Wells that may be of particular concern are wells near Valley Creek or clusters of wells that individually do not pump at high rates but together pump at a rate approximately a small community water-supply well.

References Cited

Almendinger, J.E., 2003. Watershed hydrology of Valley Creek and Browns Creek: trout streams influenced by agriculture and urbanization in eastern Washington County, Minnesota, 1998-99, St. Croix Watershed Research Station, Science Museum of Minnesota, 80 p.

Barr Engineering Company, 1990. Remedial Investigation, St. Paul Park Refinery, prepared for Ashland Petroleum Company.

Barr Engineering Co., 1998. Source-Water Protection Model for Scott and Dakota Counties.

Barr Engineering Co., 1999. Summary Report, Ramsey County Groundwater Model. 45 p.

Barr Engineering Co., 2000. Source-Water Protection Model for Scott and Dakota Counties – modifications and inclusion of Ramsey-Washington Counties into model.

Barr Engineering Co., 2003. Wellhead Protection Plan for the City of Newport, Minnesota – Part 1.

Barr Engineering Co., 2005. 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, 66 p.

Barry, J., 2004. Spring inventory, mapping and characterization, Lower St. Croix Watershed, Washington County, Minnesota, Senior Thesis, University of Minnesota Dept. of Geology & Geophysics, 25 p.

Bonestroo Rosene Anderlik & Associates, 1996. Draft Report, Natural Resources Inventory, City of Woodbury.

Bonestroo Rosene Anderlik & Associates, 1998. Final Report, Natural Resources Inventory, City of Cottage Grove.

Bonestroo Rosene Anderlik & Associates, 2002. Woodbury East Alternative Urban Areawide Review (AUAR), 114 p.

Bonestroo Rosene Anderlik & Associates, 2004. City of Woodbury Well 15 Aquifer Test Report, 27 p.

Emmons & Olivier Resources, 2001. Infiltration Management Study, Phase II Report, prepared for South Washington Watershed District.

Emmons & Olivier Resources, 2003. Integrating Groundwater and Surface Water Management, Northern Washington County.

Hansen, D.D., and J.K. Seaberg, 2000. Metropolitan Area Groundwater Model Project Summary- Lower Aquifers Model Layers 4 and 5; Ver. 1.00.

Metropolitan Council Environmental Services, 2003a. Quality Assurance Program Plan: Stream Monitoring. Prepared by Environmental Monitoring and Assessment Section, Water Resource Assessment Section, 25 p.

Metropolitan Council Environmental Services, 2003b. Regional Report - Aquatic Resource Assessment For the Twin Cities Metropolitan Area Natural Resources Inventory and Assessment, 19 p.

Minnesota Pollution Control Agency, 2000. Ground Water Quality in Cottage Grove, Minnesota. Prepared by Ground Water Monitoring and Assessment Program. June.

Schoenberg, M.E., 1990. Effects of present and projected ground-water withdrawals on the Twin Cities aquifer system, Minnesota: U.S. Geol. Survey Water-Resources Investigation Report 90-4001, 165 p.

Science Museum of Minnesota, 1999. Monitoring and Modeling Valley Creek Watershed. St. Croix Watershed Research Station.

Swanson, L. and G.N. Meyer (eds.), 1990. Geologic Atlas of Washington County, Minn Geol. Survey County Atlas Series, Atlas C-5, 7 plts.

Washington County Dept. of Public Health & Environment, 2003. Washington County Groundwater Plan: 2003-2013, 104 p.

Appendix A: Description of Well Effects Program

Introduction

A Microsoft Excel-based program was developed as part of the South Washington Groundwater Study that allows limited prediction of the effects of hypothetical or proposed pumping wells on (1) groundwater levels and (2) the base flow (groundwater contribution) of Valley Creek. The program uses the MODFLOW groundwater flow model that was developed by Barr Engineering Company (2005) as part of the LCMR project. The program allows individuals with little or no experience using groundwater flow models to access the MODFLOW model, add a pumping well, and evaluate some of the resulting information.

The user does not need to know how the LCMR MODFLOW groundwater flow model was constructed or how it works, although that information is valuable in understanding the limitations and assumption that are inherent in the model. In summary, this model includes all of the major aquifers (excluding the Mt. Simon-Hinckley aquifer, which is the deepest aquifer in the metro area). The program accesses that portion of the model in southern Washington County, south of Highway 36 (but also includes that portion of the Middle St. Croix WMO that is north of Highway 36).

The program requires Excel 97 or newer. Excel 2000 is recommended. The program should work on Windows 98, but it has not been tested. Any version newer than Windows 98 should be sufficient.

Overview of Program

The program allows the user to enter in the location of a pumping well (hypothetical, planned, or existing[1]). The location is entered by Township, Range, Section, quarter-quarter-quarter-quarter section. A graphic is provided in the program to assist the user in identifying the appropriate nomenclature for the quarter-quarter-quarter section. The user must estimate the depth of the well

---

[1] The user is cautioned that most high-capacity wells (i.e. those wells with appropriations permits) are already in the model, pumping at an average annual rate for 2002. The user should not add these wells in. Smaller wells, such as domestic wells, are not in the model and can be added. Also, a newly proposed high-capacity well can be evaluated in the model.

below ground surface (if the well is open over a long interval, the user is recommended to enter the mid-depth of the well opening or screen).

The user will also need to know the average pumping rate of the well. In southern Washington County, a typical family-of-four residence uses, on average, about 0.5 gallons per minute (gpm). Other rates can be entered. All pumping rates are in gpm (gallons per minute). This is a “steady-state” rate, which means that the program assumes that this rate occurs continuously all year long. The user will need to exercise judgment is choosing the appropriate rate, whether it be an average rate or a seasonal rate. If, for example, the user wishes to evaluate a “worse-case” condition, a peak summer rate could be used but a word of caution – it takes days to weeks for some wells to reach a near-steady-state condition so the program might overestimate the effects of pumping for seasonal conditions.

The program allows the user to enter up to four locations at which the steady-state drawdown effects of the well are predicted. Drawdown is the drop in water level (or hydraulic head) at a given location and depth that is the result of pumping. Drawdown at one location can be different at different depths. At least one location must always be specified. The location could even be the pumping well itself. The user could, for example, use the four available locations to evaluate the drawdown at four different depths, located at the same place. As with the pumping well, the location of the observation points are entered by Township, Range, Section, quarter-quarter-quarter-quarter section. A graphic is provided in the program to assist the user in identifying the appropriate nomenclature for the quarter-quarter-quarter section. All pumping and observation wells will be located in the model at the center of the Township, Range, Section, quarter-quarter-quarter-quarter section.

After entering the location data, the model performs the following tasks automatically:

1. Creates the well input file for the MODFLOW program with the user-specified pumping well.
2. Runs the MODFLOW model.
3. Extracts the drawdown information at the locations that were specified by the user.
4. Extracts the baseflow estimate to Valley Creek and converts any reductions in baseflow to a percentage of the baseflow without the well (thus, it reports changes in baseflow as a percentage of the pre-well baseflow).

5. Presents the results.

The user will not need to directly manipulate any model files or output files – everything is self-contained in the Excel spreadsheet file.

Installing the Program

On the CD, in the directory PROGRAMS, you will find a subdirectory called :SWGW_MODEL. This subdirectory must be copied onto your C: drive in the directory c:\program files. Thus, when you are finished copying, you should have a new directory on your C: drive that is **c:\program files\swgw_model** (capitals and small case are interchangeable). The program will not run if it is any other directory!

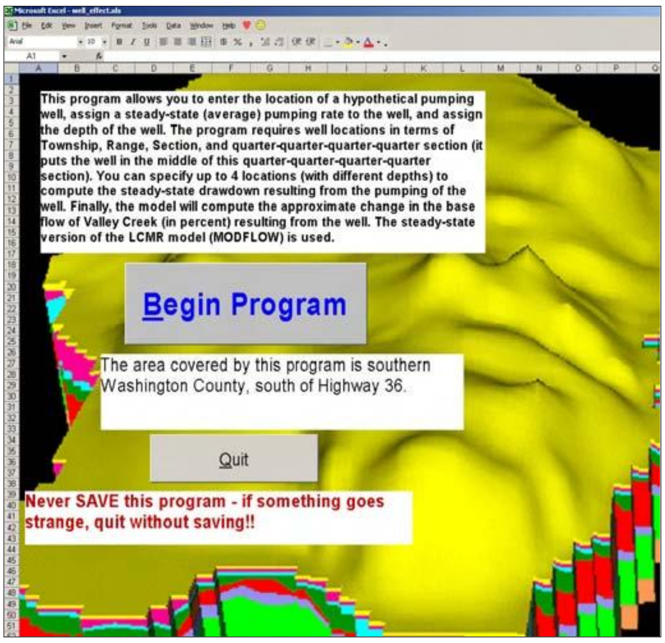
Once you have copied the swgw_model directory to your C: drive, you will need to go into c:\program files\swgw_model and select ALL files in the directory. Then, right click your mouse to access the Properties menu. Make sure that “read only” is unselected.

There are many files in this directory but only one file should ever be used or opened by the user – the Excel workbook file “well_effects.xls”. NEVER OPEN ANY OTHER FILE OR YOU MAY CORRUPT THE PROGRAM.

If you like (and this is recommended), you may make a shortcut to your desktop. Do this by right-clicking anywhere on your desktop and selecting New, then Shortcut, and browse to your c:\program files\swgw_model directory. Select well_effects.xls. You should now have a new icon on your desktop. DO NOT PHYSICALLY MOVE THE FILE WELL_EFFECTS.XLS – the program will not work. You should only be creating a shortcut.

Running the Program

To begin the program, double click on the file “well effects.xls” (or on the shortcut). This will open the program. The user will be presented with the following screen:



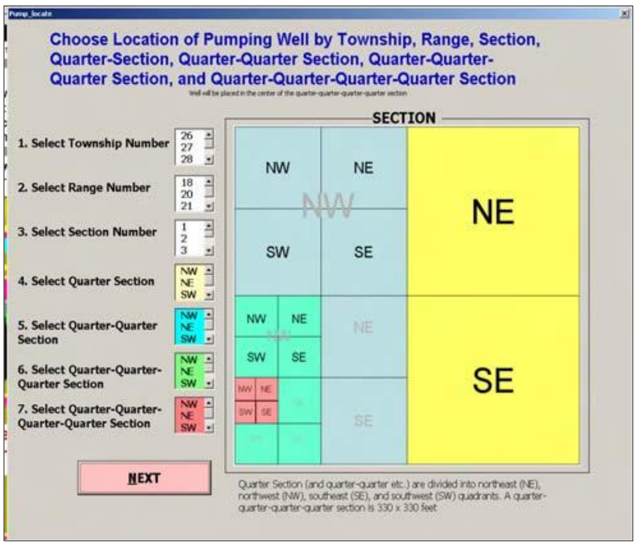
This program allows you to enter the location of a hypothetical pumping well, assign a steady-state (average) pumping rate to the well, and assign the depth of the well. The program requires well locations in terms of Township, Range, Section, and quarter-quarter-quarter-quarter section (it puts the well in the middle of this quarter-quarter-quarter-quarter section). You can specify up to 4 locations (with different depths) to compute the steady-state drawdown resulting from the pumping of the well. Finally, the model will compute the approximate change in the base flow of Valley Creek (in percent) resulting from the well. The steady-state version of the LCMR model (MODFLOW) is used.

The area covered by this program is southern Washington County, south of Highway 36.

Never SAVE this program - if something goes strange, quit without saving!!

The user is cautioned to NOT use any menu or tool bar commands. Instead, the user must use the buttons in the various dialogue windows. On this first screen, the user can click on the Begin Program button or, to quit, the Quit button. **NEVER NEVER NEVER** SAVE THIS PROGRAM OR IT WILL MAKE THE PROGRAM IN OPERABLE AND CORRUPT THE FILES.[2]

Pressing the Begin Program command will present the user with a new window for entering the location of the pumping well in terms of Township, Range, Section, quarter-quarter-quarter-quarter section:



Choose Location of Pumping Well by Township, Range, Section, Quarter-Section, Quarter-Quarter Section, Quarter-Quarter-Quarter Section, and Quarter-Quarter-Quarter-Quarter Section

Well will be placed in the center of the quarter-quarter-quarter-quarter section

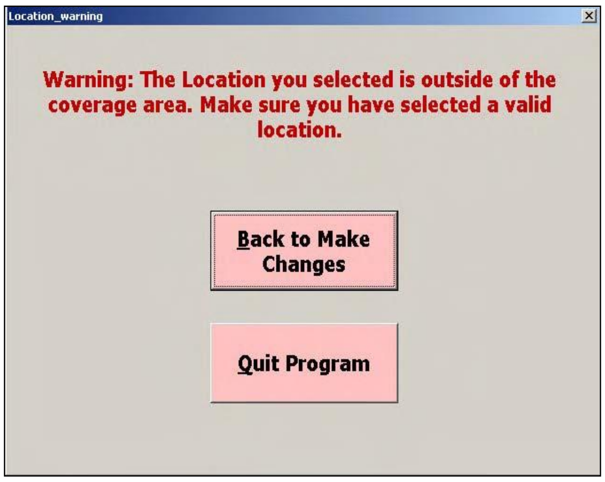
Quarter Section (and quarter-quarter etc.) are divided into northeast (NE), northwest (NW), southeast (SE), and southwest (SW) quadrants. A quarter-quarter-quarter-quarter section is 330 x 330 feet

The user must select a Township, Range, Section number, quarter section, quarter-quarter section, quarter-quarter-quarter section, and quarter-quarter-quarter-quarter section. The graphic and the text boxes are color coded to assist in the nomenclature. The user must select (by scrolling and clicking) a value for each parameter.

Only the Township and Range numbers in the study area are available. However, for any Township and Range, there will be the choice of 36 sections and all four quadrants (NW, NE, SW, and SE). It is possible to select a Section number (or quarter-quarter-quarter-quarter section) for a particular Township and Range that is not in the study area. If you do this, the following warning message will appear:

---

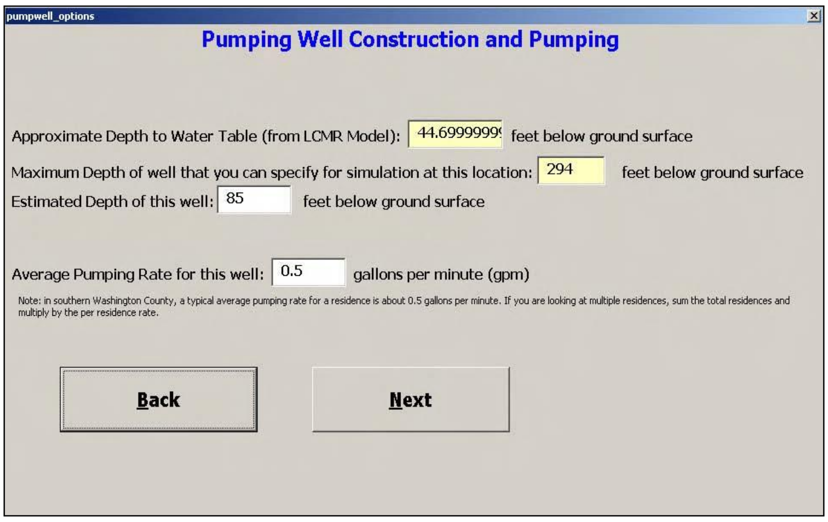
[2] If you ever accidentally do save the program (or otherwise make an error), it is recommended that you re-install the entire subdirectory from the CD.



Warning: The Location you selected is outside of the coverage area. Make sure you have selected a valid location.

At this point, you can go back and make changes or, if you are not sure of your Township, Range, Section number, you can quit the program and consult your map.

Once you have successfully entered the location of your pumping well and pressed the Next button, a window will appear that allows you to enter in the depth of the well and the pumping rate of the well.



Pumping Well Construction and Pumping

Approximate Depth to Water Table (from LCMR Model): 44.6999999(feet below ground surface

Maximum Depth of well that you can specify for simulation at this location: 294 feet below ground surface

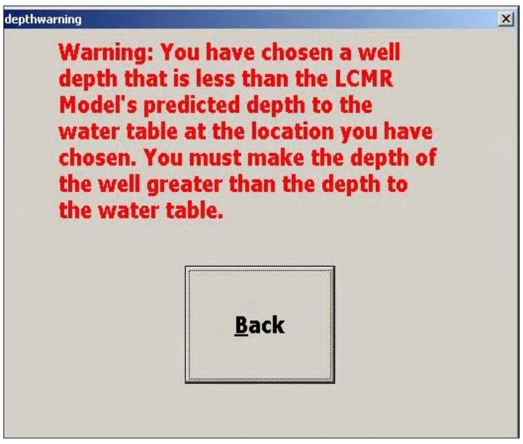
Estimated Depth of this well: 85 feet below ground surface

Average Pumping Rate for this well: 0.5 gallons per minute (gpm)

Note: in southern Washington County, a typical average pumping rate for a residence is about 0.5 gallons per minute. If you are looking at multiple residences, sum the total residences and multiply by the per residence rate.

The boxes with yellow background provide information on the approximate depth to the water table (in feet below ground surface) and the maximum depth that can be specified (in feet below ground surface) at this location. The water-table depth is from the LCMR model. The maximum depth represents the depth to the base of the Ironton-Galesville aquifer – the base of the LCMR model. You cannot change anything in the yellow boxes.

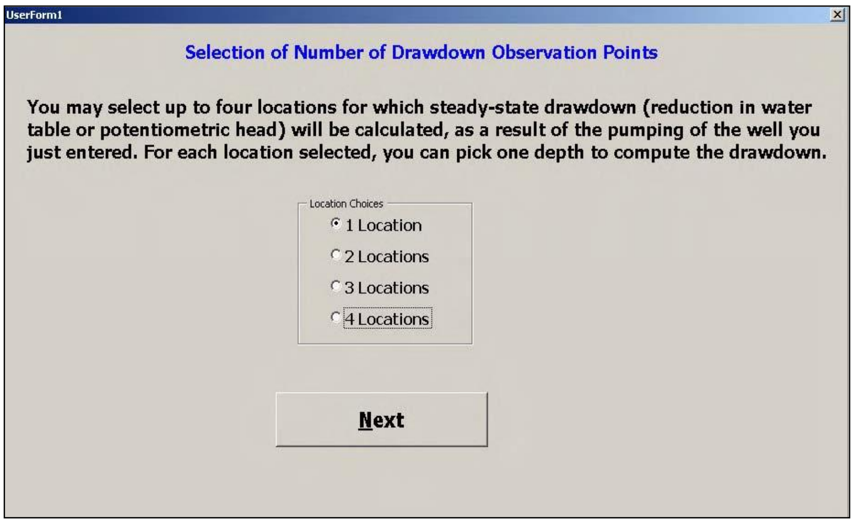
The user must enter the depth of the pumping well in feet below the ground surface and the average pumping rate of the well, in gallons per minute. At this point, the user can select the Back button to change the well location. When finished entering the depth and pumping rate data, the user presses the Next button.



Warning: You have chosen a well depth that is less than the LCMR Model's predicted depth to the water table at the location you have chosen. You must make the depth of the well greater than the depth to the water table.

If the depth of the well is less than the depth to the water table, a warning window will appear. Likewise, if the depth of the well is greater than the maximum permissible depth, a warning window will appear. The depth is necessary information because the program must assign the well to a model layer.

Once the well depth and pumping rate are properly selected, a window will appear that allows the user to choose the number of "observation points" – locations where you want the model to compute drawdown. At least one location must be selected. The same location can be selected for all four points, as well. The default is one location.



Selection of Number of Drawdown Observation Points

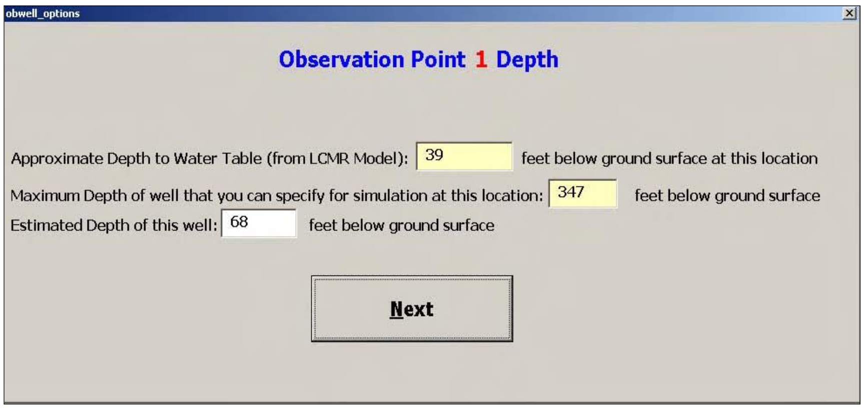
You may select up to four locations for which steady-state drawdown (reduction in water table or potentiometric head) will be calculated, as a result of the pumping of the well you just entered. For each location selected, you can pick one depth to compute the drawdown.

Location Choices

● 1 Location
○ 2 Locations
○ 3 Locations
○ 4 Locations

Pressing the Next button will cause a window to appear that allows the user to enter the location of the first observation point in terms of Township, Range, Section, and quarter-quarter-quarter-quarter Section. This window is identical to the window for the pumping well. The well is entered in the center of the quarter-quarter-quarter-quarter section. As with the pumping well, if a non-valid location is selected, a warning window will appear and will continue to appear until a valid location is entered.

After the location of the first observation point is correctly entered and the Next button is pressed, a window will appear that allows the user to enter the depth of the observation. This depth can be thought of as the depth of the well screen of an observation well. As with the pumping well, a warning window will appear if the depth is less than the water table depth or is greater than the bottom of the Ironton-Galesville aquifer. Note that the observation point number appears in red at the top.



Observation Point 1 Depth

Approximate Depth to Water Table (from LCMR Model): 39 feet below ground surface at this location

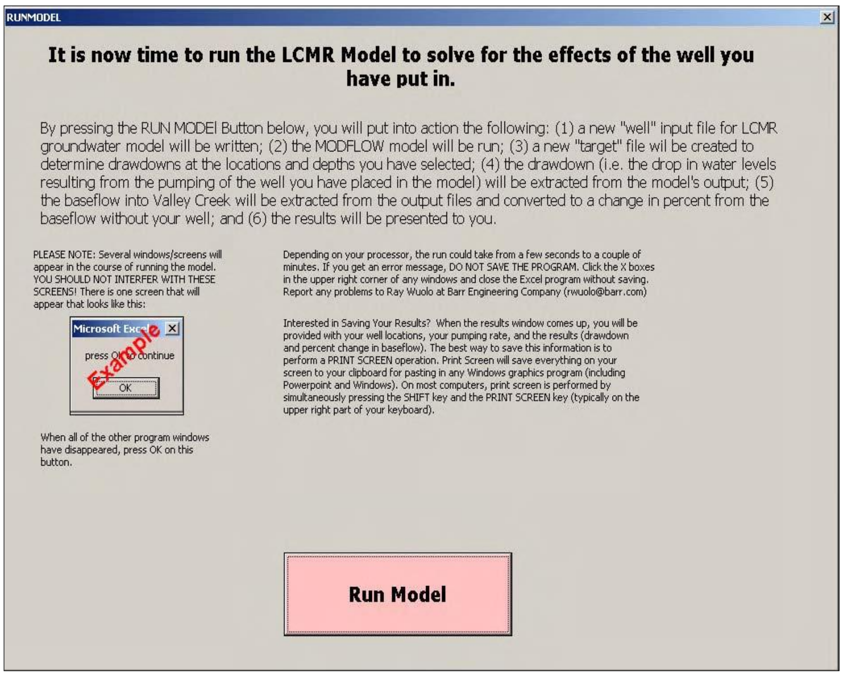
Maximum Depth of well that you can specify for simulation at this location: 347 feet below ground surface

Estimated Depth of this well: 68 feet below ground surface

The location and depth are entered for each successive observation point, up to and including the final number specified by the user.

When all of the observation point data have been entered, a screen will appear that allows the user to commence the preparation of the data files, running of the model, and extraction of the model results.

The user need not be concerned with any of these details – they are performed automatically when the Run Model button is pressed.



RUNMODEL

It is now time to run the LCMR Model to solve for the effects of the well you have put in.

By pressing the RUN MODEl Button below, you will put into action the following: (1) a new "well" input file for LCMR groundwater model will be written; (2) the MODFLOW model will be run; (3) a new "target" file wil be created to determine drawdowns at the locations and depths you have selected; (4) the drawdown (i.e. the drop in water levels resulting from the pumping of the well you have placed in the model) will be extracted from the model's output; (5) the baseflow into Valley Creek will be extracted from the output files and converted to a change in percent from the baseflow without your well; and (6) the results will be presented to you.

PLEASE NOTE: Several windows/screens will appear in the course of running the model. YOU SHOULD NOT INTERFER WITH THESE SCREENS! There is one screen that will appear that looks like this:

When all of the other program windows have disappeared, press OK on this button.

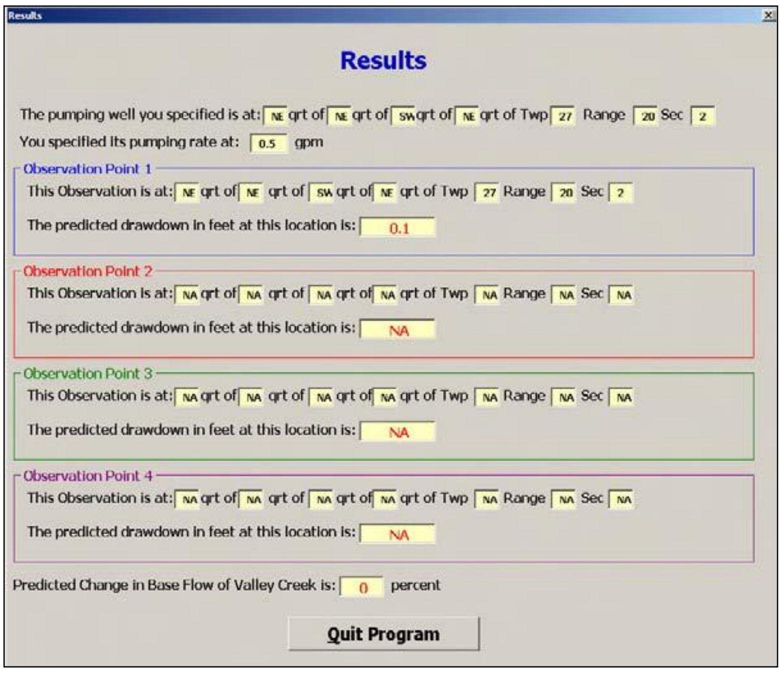
Depending on your processor, the run could take from a few seconds to a couple of minutes. If you get an error message, DO NOT SAVE THE PROGRAM. Click the X boxes in the upper right corner of any windows and close the Excel program without saving. Report any problems to Ray Wuolo at Barr Engineering Company (rwuolo@barr.com)

Interested in Saving Your Results? When the results window comes up, you will be provided with your well locations, your pumping rate, and the results (drawdown and percent change in baseflow). The best way to save this information is to perform a PRINT SCREEN operation. Print Screen will save everything on your screen to your clipboard for pasting in any Windows graphics program (including Powerpoint and Windows). On most computers, print screen is performed by simultaneously pressing the SHIFT key and the PRINT SCREEN key (typically on the upper right part of your keyboard).

Once the Run Model button is pressed, a series of windows will appear and disappear. Do not click on or otherwise manipulate these windows – they represent activities beyond the control of the user, such as file preparation, model iteration, and data extraction. This operation could take only a few seconds but may take as long as a minute with a very slow processor. When the simulation is complete, a small Microsoft Excel window will appear with an OK button (see example in window above). The user must press this OK button to continue.

The model results are presented in the following window:

The location of the pumping well and each specified observation point is given. The user-entered pumping rate is shown, the drawdowns for each observation point are listed, and the predicted percent change in baseflow of Valley Creek is reported at the bottom of the screen. Those observation points not specified are reported with the NA (not applicable) value.



Results

Results

The pumping well you specified is at: NE qrt of NE qrt of SW qrt of NE qrt of Twp 27 Range 20 Sec 2

You specified its pumping rate at: 0.5 gpm

Observation Point 1

This Observation is at: NE qrt of NE qrt of SW qrt of NE qrt of Twp 27 Range 20 Sec 2

The predicted drawdown in feet at this location is: 0.1

Observation Point 2

This Observation is at: NA qrt of NA qrt of NA qrt of NA qrt of Twp NA Range NA Sec NA

The predicted drawdown in feet at this location is: NA

Observation Point 3

This Observation is at: NA qrt of NA qrt of NA qrt of NA qrt of Twp NA Range NA Sec NA

The predicted drawdown in feet at this location is: NA

Observation Point 4

This Observation is at: NA qrt of NA qrt of NA qrt of NA qrt of Twp NA Range NA Sec NA

The predicted drawdown in feet at this location is: NA

Predicted Change in Base Flow of Valley Creek is: 0 percent

To quit the program, press the Quit Program button. DO NOT EVER SAVE THIS PROGRAM. The best way to save the results is to perform a "print screen" command when the Results window appears. Typically, this involves simultaneously pressing the shift key and the Print Screen key at the same time. A picture of what is on your screen will be pasted to the Windows clipboard. This image can then be copied to any of a number of programs, including Word and PowerPoint.

If multiple simulations are to be run, the user must quit the program each time and begin the operation over. There is not mechanism for saving previously entered data.

Some Guidance for Using the Program

This program was developed to allow managers and decision makers to have limited access to a sophisticated computer groundwater flow model without the need for specialized training and experience. It is not a substitute for evaluation by a trained hydrogeologist. Likewise, there is always the potential for conditions to be different from those represented by the model. It is the sole responsibility of the user to apply this program correctly.

The model will likely find use in the evaluation of proposed well installations, to determine if a well could have adverse impacts on nearby wells or Valley Creek. For example, if a development is proposed with 40 residences – each with its own well, the best way to use this program to evaluate the effects of those wells is to lump the pumping into a single well, located approximately near the center of the development and pumping at a rate equal to the estimated rate of all 40 wells together. For example, if the average water use of a residence is 0.5 gpm, the well could be assumed to pump at a rate of 20 gpm. An alternative approach would be to run the program 40 times – once for each well and then add the drawdown effects for each of the wells (effects are additive).

Because there are many macro programs imbedded in this workbook, the program will not run unless the security of the macro is set to "low". Do this by selecting Tools from the Excel menu, select Macro, and select Security. Change the security to "Low".

Appendix B: Description of Infiltration Program

Introduction

As part of the LCMR Modeling project (Barr Engineering Company, 2005), estimates of infiltration rates (i.e. recharge rates to the water table) for typical climatic conditions were developed using the modeling code MIKE SHE. The recharge rate is a function of many conditions, including topography, soil type, previous soil moisture conditions, temperature, wind speed, time of year, vegetation, etc. An ESRI shapefile of the resulting recharge rate is included as part of this groundwater study. However, not all managers and decision makers may have access to ArcView or ArcGIS, or they may not have the training or expertise in using GIS. For those users, this program has been developed which allows access of that information through a familiar Excel Workbook format.

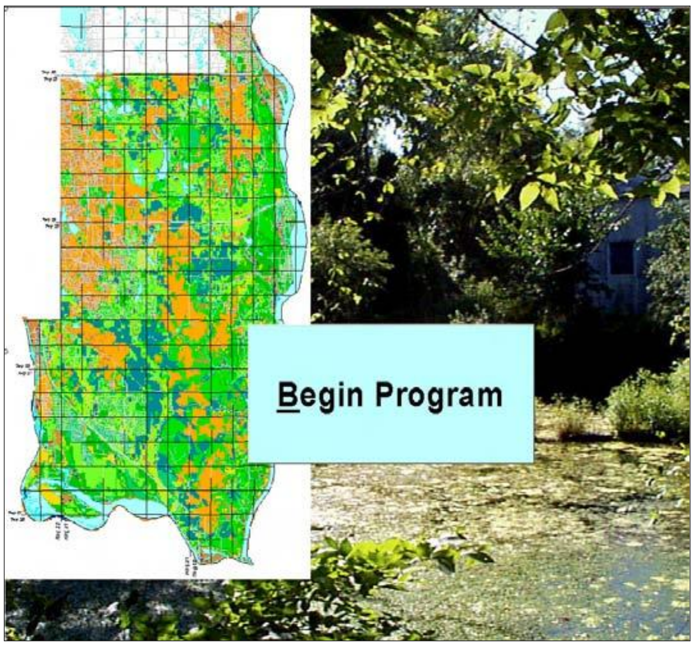
This program accesses model-derived results from that portion of the model in southern Washington County, south of Highway 36 (but also includes that portion of the Middle St. Croix WMO that is north of Highway 36). The program requires Excel 97 or newer. Excel 2000 is recommended. The program should work on Windows 98, but it has not been tested. Any version newer than Windows 98 should be sufficient.

Unlike the Well Effects program, no outside programs or files are accessed and this Excel Workbook (Infiltration.xls) can be copied from the CD to any location on the user's hard drive and accessed. After copying to the hard drive, the user must right click on the file and access the file properties to make sure that "read-only" is not checked.

Running the Program

The Workbook "infiltration.xls" is opened similar to any other Excel program. Because there are many macro programs imbedded in this workbook, the program will not run unless the security of the macro is set to "low". Do this by selecting Tools from the Excel menu, select Macro, and select Security. Change the security to "Low".

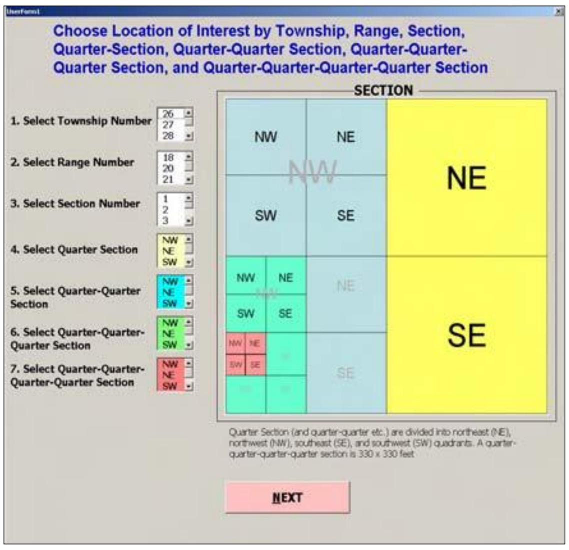
Once opened, the following screen will appear:



Press the light-blue Begin Program button to begin.

A new screen will appear that allows the user to select the location of interest by Township, Range, Section, and quarter-quarter-quarter-quarter section.

The user must select a Township, Range, Section number, quarter section, quarter-quarter section, quarter-quarter-quarter section, and quarter-quarter-quarter-quarter section. The graphic and the text boxes are color coded to assist in the nomenclature. The user must select (by scrolling and clicking) a value for each parameter.

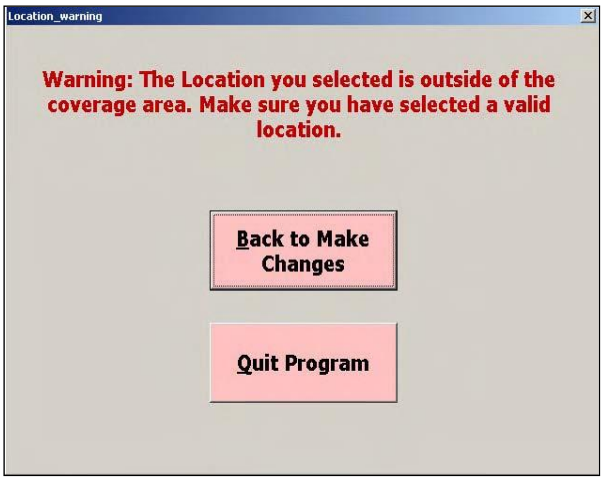

UserForm1

Choose Location of Interest by Township, Range, Section, Quarter-Section, Quarter-Quarter Section, Quarter-Quarter-Quarter Section, and Quarter-Quarter-Quarter-Quarter Section

1. Select Township Number 26 27 28
2. Select Range Number 18 20 21
3. Select Section Number 1 2 3
4. Select Quarter Section NW NE SW
5. Select Quarter-Quarter Section NW NE SW
6. Select Quarter-Quarter-Quarter Section NW NE SW
7. Select Quarter-Quarter-Quarter-Quarter Section NW NE SW

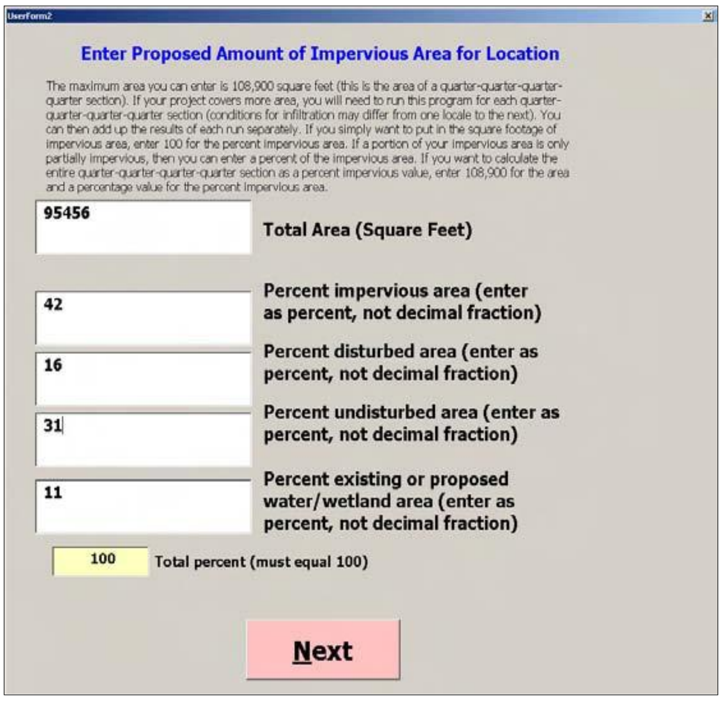
Quarter Section (and quarter-quarter etc.) are divided into northeast (NE), northwest (NW), southeast (SE), and southwest (SW) quadrants. A quarter-quarter-quarter-quarter section is 330 x 330 feet

Only the Township and Range numbers in the study area are available. However, for any Township and Range, there will be the choice of 36 sections and all four quadrants (NW, NE, SW, and SE). It is possible to select a Section number (or quarter-quarter-quarter-quarter section) for a particular Township and Range that is not in the study area. If you do this, the following warning message will appear:


Location_warning

Warning: The Location you selected is outside of the coverage area. Make sure you have selected a valid location.

At this point, you can go back and make changes or, if you are not sure of your Township, Range, Section number, you can quit the program and consult your map.



Enter Proposed Amount of Impervious Area for Location

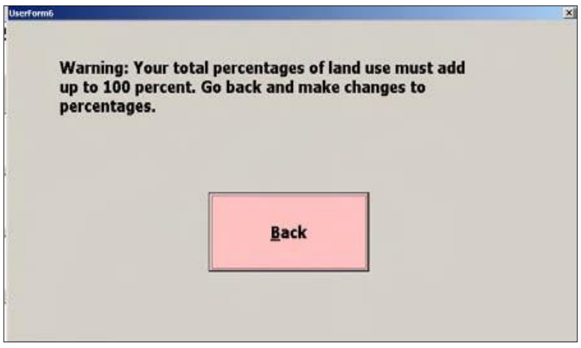
The maximum area you can enter is 108,900 square feet (this is the area of a quarter-quarter-quarter-quarter section). If your project covers more area, you will need to run this program for each quarter-quarter-quarter-quarter section (conditions for infiltration may differ from one locale to the next). You can then add up the results of each run separately. If you simply want to put in the square footage of impervious area, enter 100 for the percent impervious area. If a portion of your impervious area is only partially impervious, then you can enter a percent of the impervious area. If you want to calculate the entire quarter-quarter-quarter-quarter section as a percent impervious value, enter 108,900 for the area and a percentage value for the percent impervious area.

95456	Total Area (Square Feet)
42	Percent impervious area (enter as percent, not decimal fraction)
16	Percent disturbed area (enter as percent, not decimal fraction)
31	Percent undisturbed area (enter as percent, not decimal fraction)
11	Percent existing or proposed water/wetland area (enter as percent, not decimal fraction)
100	Total percent (must equal 100)

Once you have successfully entered the location of interest and pressed the Next button, a window will appear that allows you to enter information on area and percent imperviousness (existing or proposed).

The first item is the area to be considered. The largest area you can specify is 108,900 square feet (2.5 acres) – this is the size of a quarter-quarter-quarter-quarter section. If the area you are evaluating is larger, you should probably perform the program's calculations for each quarter-quarter-quarter-quarter section because conditions will likely vary from one location to the next.

Within the total area considered (box 1), you must specify the following: (1) percent impervious area; (2) percent disturbed area; (3) percent undisturbed area; and (4) percent or water or wetland area. Percents are all entered as percents – not as decimal fractions. The percentages should be for proposed conditions. The total percentages must equal 100 exactly. The total percentage (yellow box) will change as the numbers in the percentages change. If you press the Next button without the total equaling 100 percent, you will get a warning message.



Warning: Your total percentages of land use must add up to 100 percent. Go back and make changes to percentages.

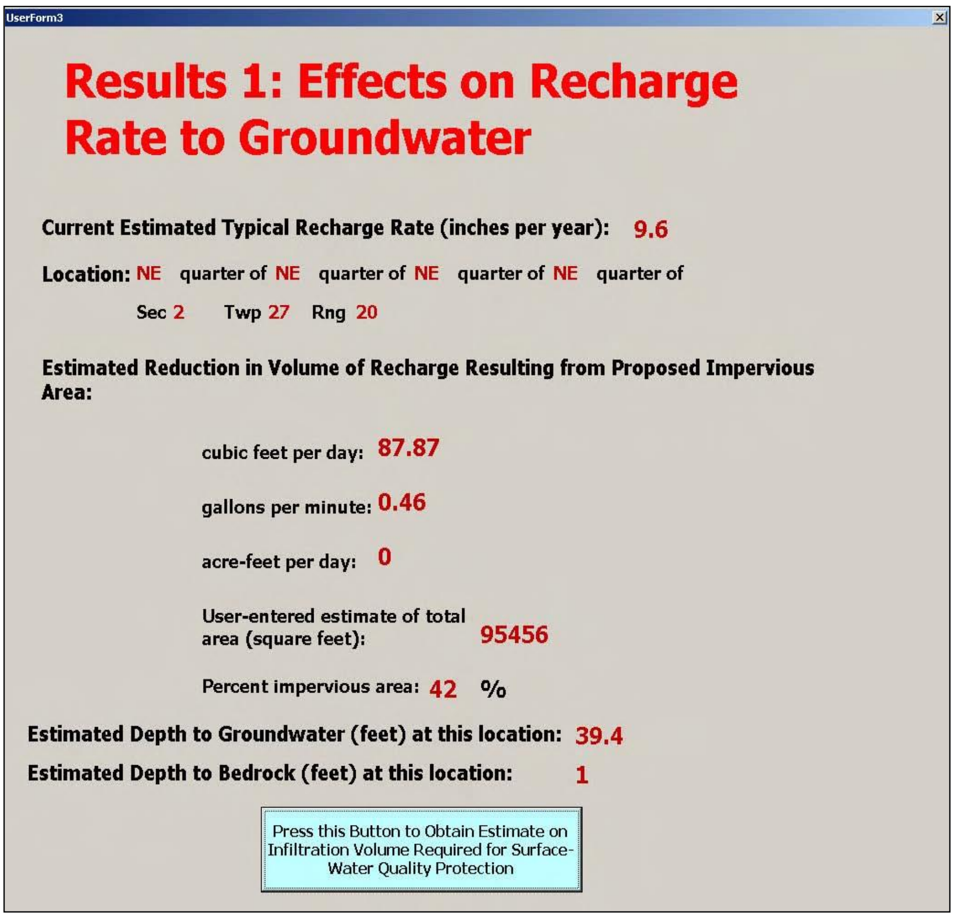
Once the area and percentages are correctly entered, the program will first compute the effects of the impervious area on recharge to the groundwater system[1]. Essentially, what the program is telling you is "This is how much groundwater recharge you are likely going to lose by putting in this much impervious area." Put another way, if the

---

[1] Recharge is differentiated from infiltration – recharge is infiltrating water that is not captured by the roots of plants but makes its way to the water table. Recharge is typically less than infiltration in this context.

management goal is to have no net loss of groundwater recharge, then the program will provide the manager with how much this loss will be so that strategies can be implemented to infiltrate and recharge some of the lost water.

The results window will appear as follows:



Results 1: Effects on Recharge Rate to Groundwater

Current Estimated Typical Recharge Rate (inches per year): 9.6

Location: NE quarter of NE quarter of NE quarter of NE quarter of

Sec 2 Twp 27 Rng 20

Estimated Reduction in Volume of Recharge Resulting from Proposed Impervious Area:

cubic feet per day: 87.87

gallons per minute: 0.46

acre-feet per day: 0

User-entered estimate of total area (square feet): 95456

Percent impervious area: 42 %

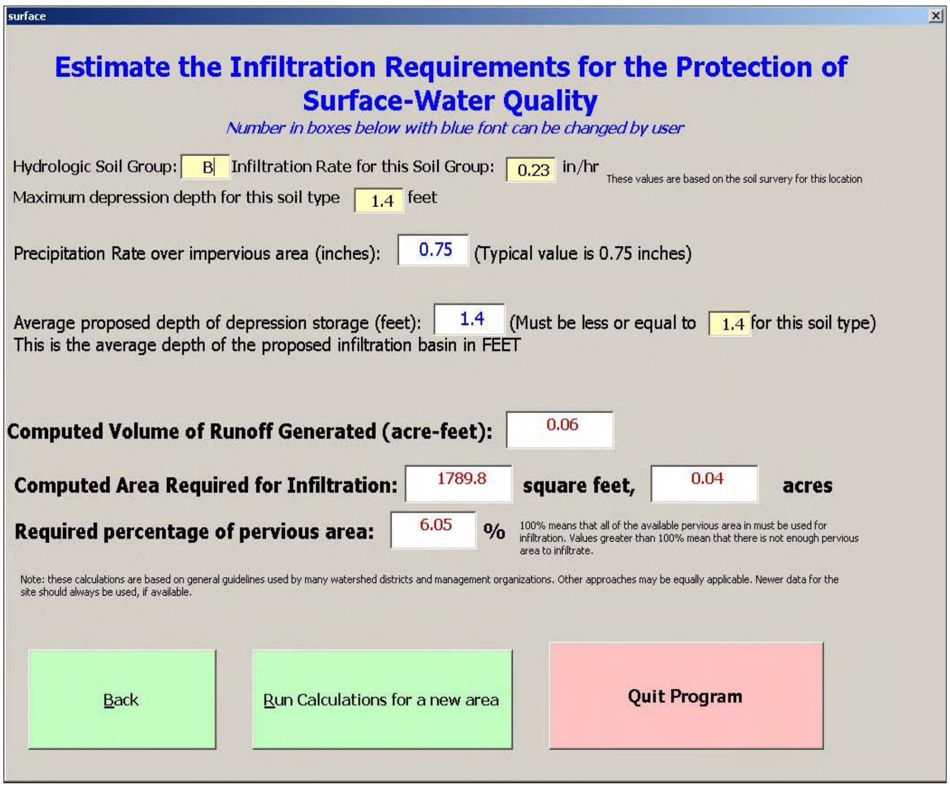
Estimated Depth to Groundwater (feet) at this location: 39.4

Estimated Depth to Bedrock (feet) at this location: 1

The first line is the amount of recharge (in inches per year) that is estimated to be currently taking place at this location. The second and third lines parrot-back the specified location. The estimated reduction in the volume of recharge that results from this proposed development is shown on the next lines in cubic feet per day, gallons per minute, and acre-feet per day. The user-entered area and percent impervious area are reported in the next lines. The final two lines list the estimated depth to groundwater (feet below ground surface) and the estimated depth to bedrock (feet below ground surface) at this location. These last two items are sometimes important in certain requirements for infiltration.

Maintaining groundwater recharge conditions may be one management goal. Other management goals may necessitate re-infiltrating more water than is required to maintain recharge. The most common driver is to re-infiltrate storm water for the purposes of protecting the water quality of receiving bodies, such as streams. By pressing the blue button at the bottom of the screen, the calculations for surface-water quality protection are implemented.

Many watershed districts and watershed management organizations require infiltration basins that are based on the soils' hydrologic grouping (A, B, C, and D). The hydrologic grouping is pared with a maximum infiltration rate and maximum depth. The program automatically determines the hydrologic soil group and the infiltration rate (in inches per hour) that corresponds to this group. The Maximum Depression Depth for the particular soil grouping is also determined.



Estimate the Infiltration Requirements for the Protection of Surface-Water Quality

Number in boxes below with blue font can be changed by user

Hydrologic Soil Group: B Infiltration Rate for this Soil Group: 0.23 in/hr These values are based on the soil survery for this location

Maximum depression depth for this soil type 1.4 feet

Precipitation Rate over impervious area (inches): 0.75 (Typical value is 0.75 inches)

Average proposed depth of depression storage (feet): 1.4 (Must be less or equal to 1.4 for this soil type)
This is the average depth of the proposed infiltration basin in FEET

Computed Volume of Runoff Generated (acre-feet): 0.06

Computed Area Required for Infiltration: 1789.8 **square feet,** 0.04 **acres**

Required percentage of pervious area: 6.05 **%** 100% means that all of the available pervious area in must be used for infiltration. Values greater than 100% mean that there is not enough pervious area to infiltrate.

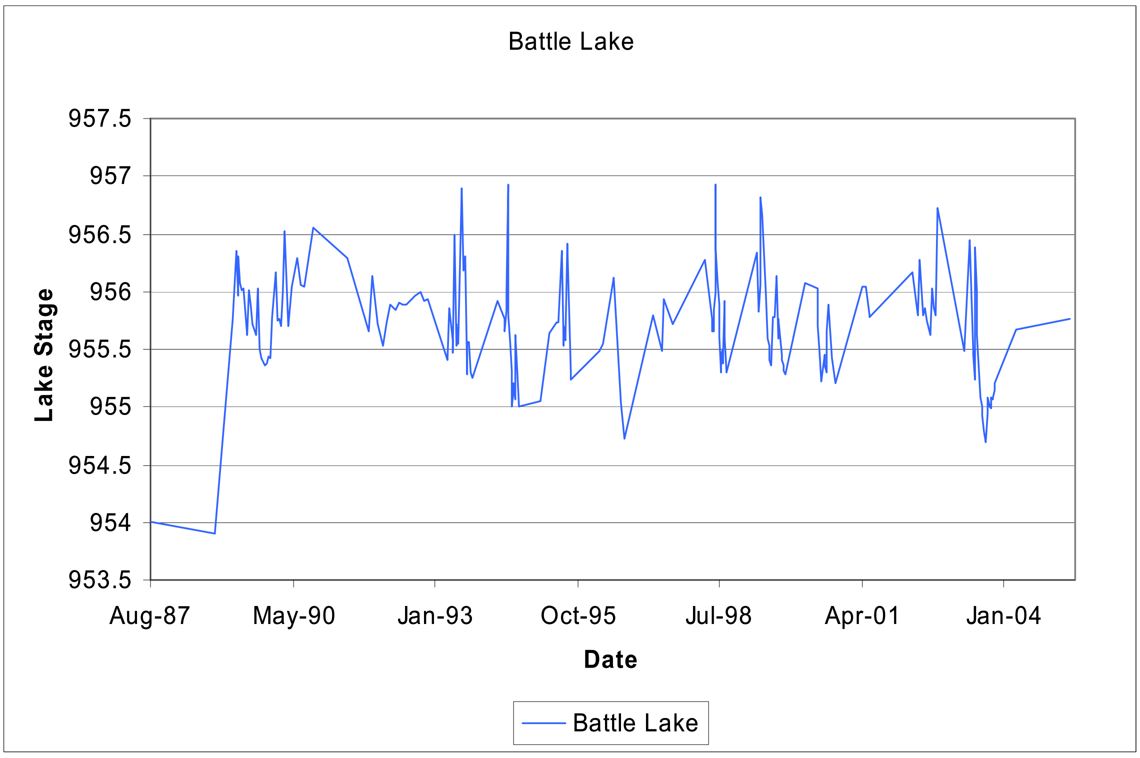
Note: these calculations are based on general guidelines used by many watershed districts and management organizations. Other approaches may be equally applicable. Newer data for the site should always be used, if available.

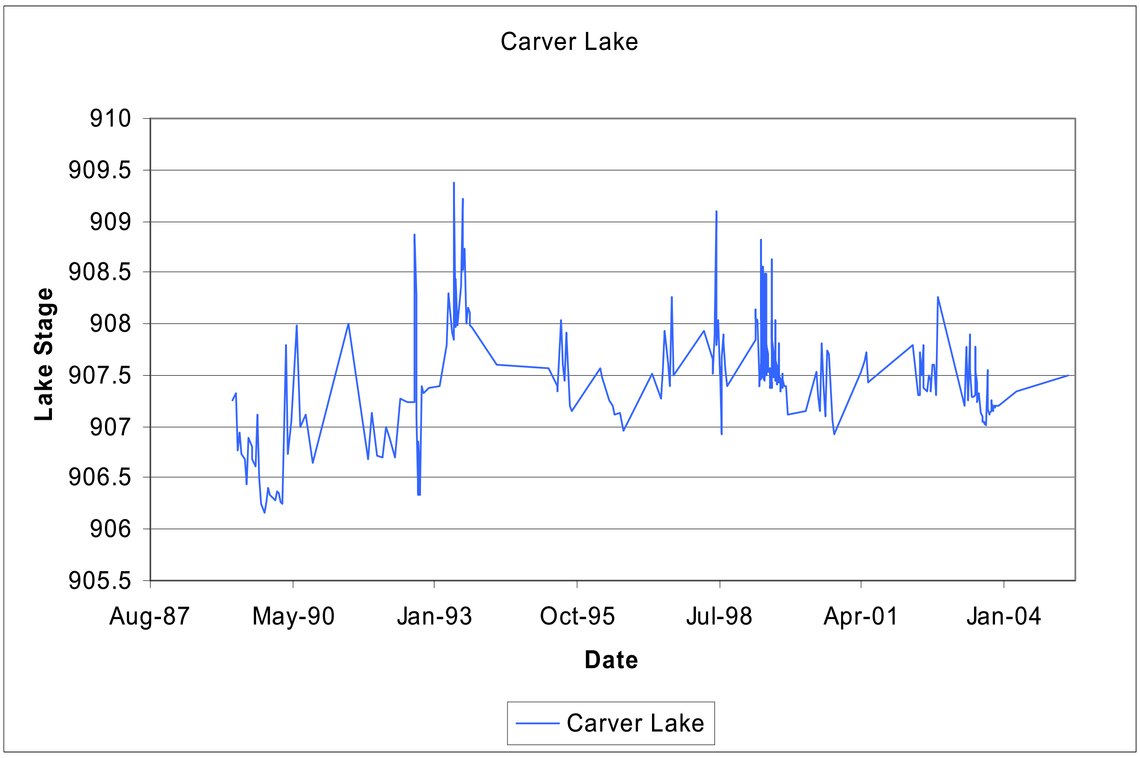
A commonly used requirement for sizing basins for water-quality protection is a precipitation rate of 0.75 inches for 72 hours, applied over the impervious area. This is the default value but the user can change this value (all numbers in boxes with blue fonts can be changed by the user). Typically, the average depth of a basin cannot exceed the Maximum Depression Depth for the particular soil type – but this value can be overridden by the user. The program automatically will compute the generated run-off volume (in acre-feet), compute the area required for infiltration (in square footage and acres), and list the percentage of available pervious area (i.e. undisturbed area) that would be used for infiltration. Obviously, if this percentage is greater than 100 percent, then there would not be enough undisturbed area to accomplish the infiltration.

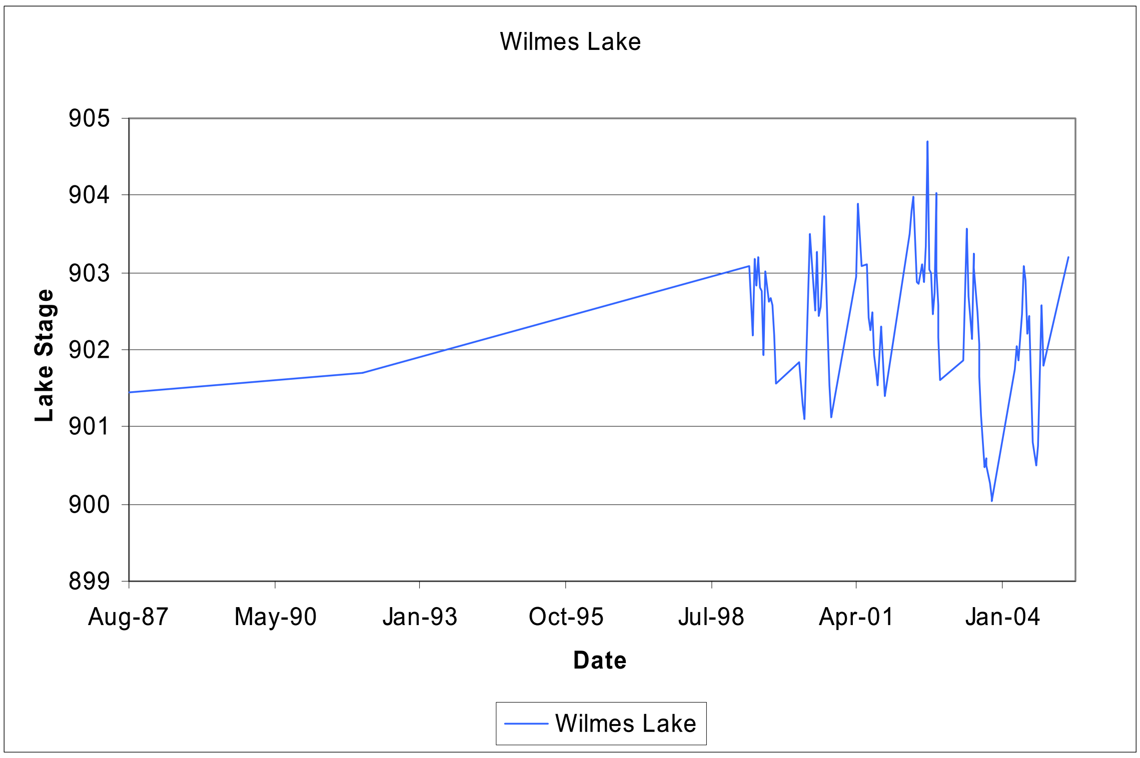
The user can re-run computations with new areas and/or new assumptions as many times as desired. There is no provision for printing or saving. To quit the program, press the Quit Program button. DO NOT EVER SAVE THIS PROGRAM. The best way to save the results is to perform a "print screen" command when the Results windows appear. Typically, this involves simultaneously pressing the shift key and the Print Screen key.

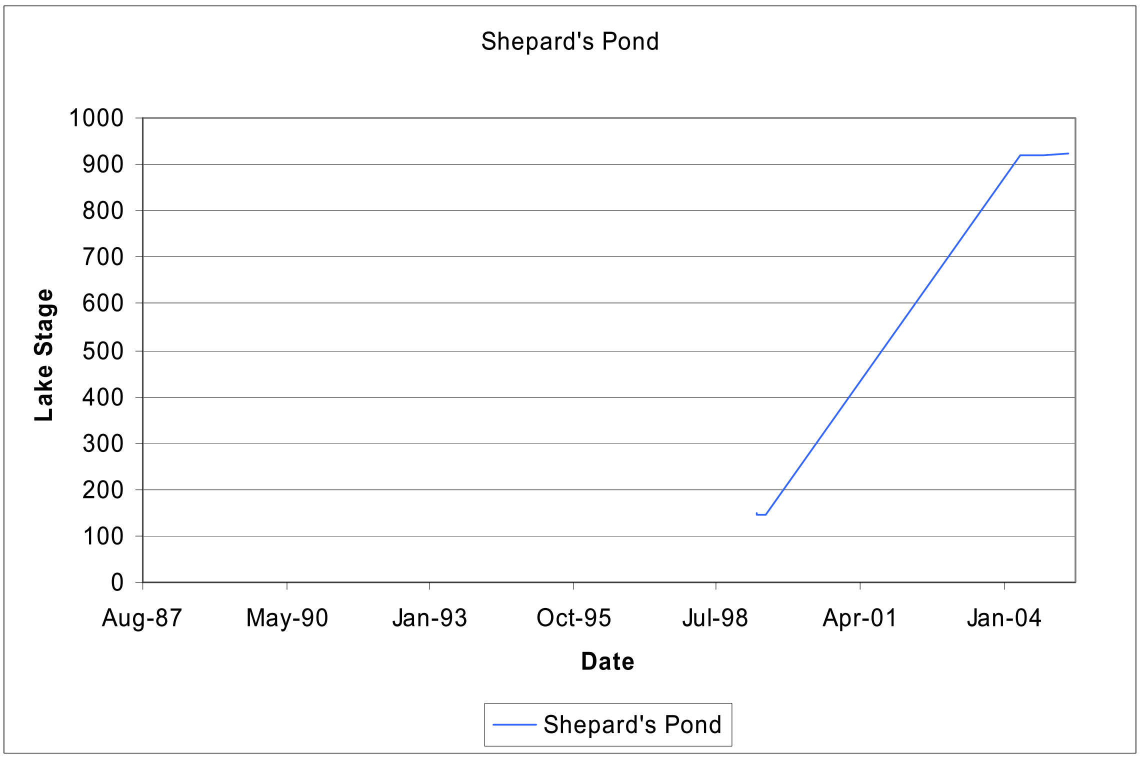
Appendix C: Lake Level Data Plots

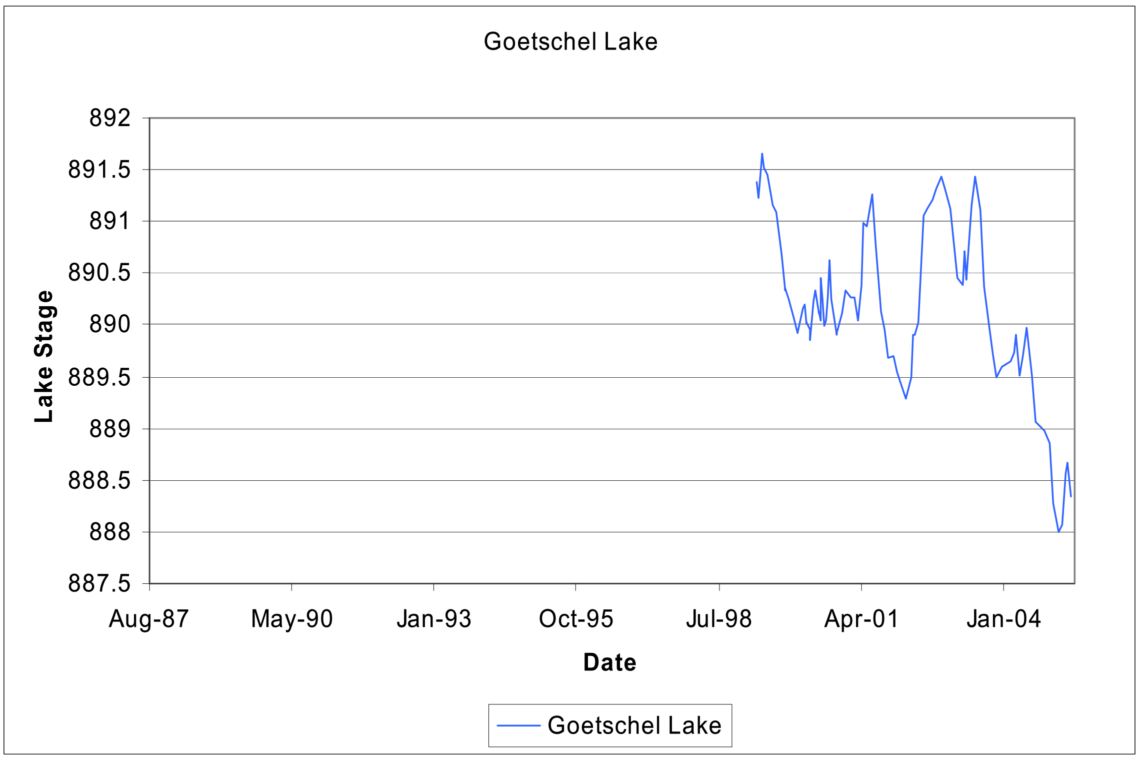
The plots in this appendix are compiled from lake monitoring data collected from a variety of sources and listed on the Minnesota Department of Natural Resources Lake Finder website.

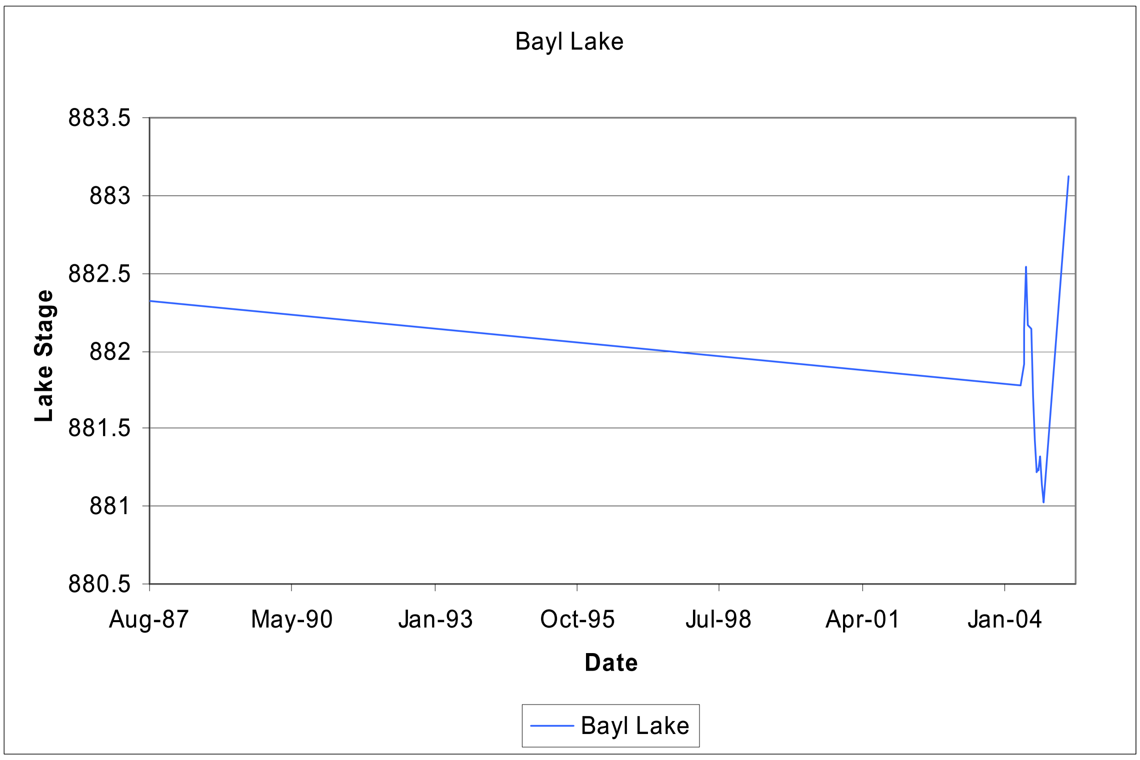

Battle Lake
957.5
957
956.5
956
955.5
955
954.5
954
953.5
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Battle Lake

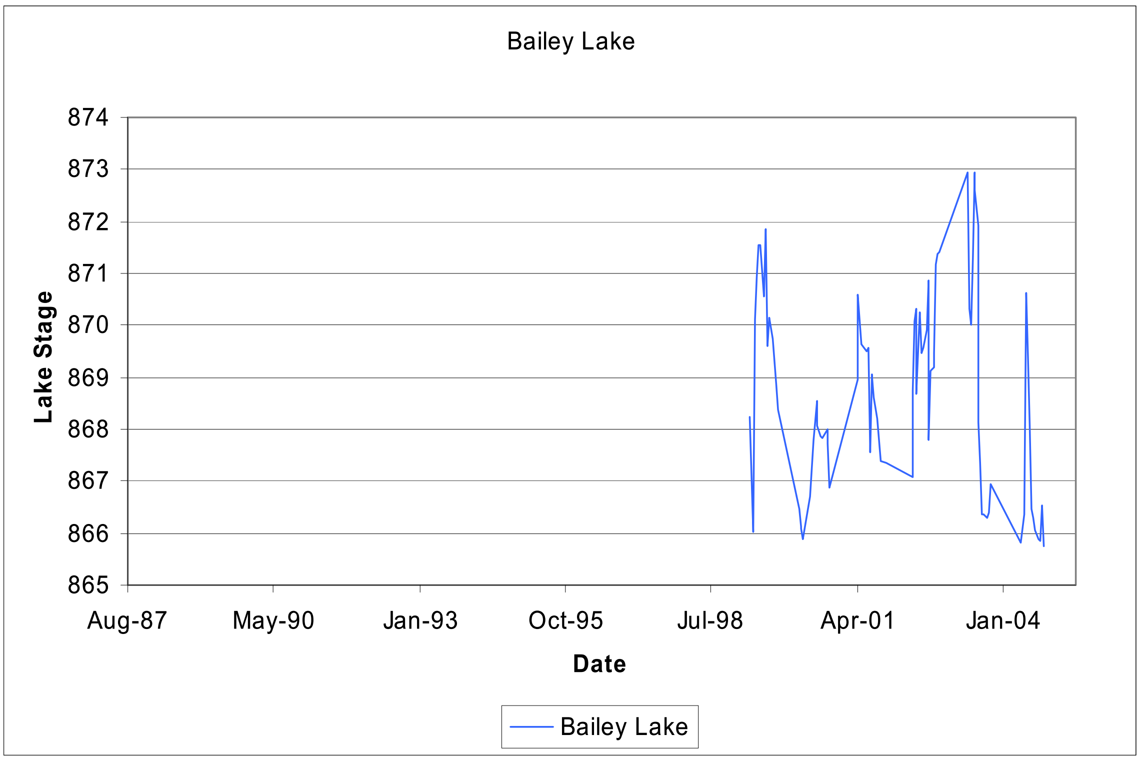

Carver Lake
910
909.5
909
908.5
908
907.5
907
906.5
906
905.5
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Carver Lake

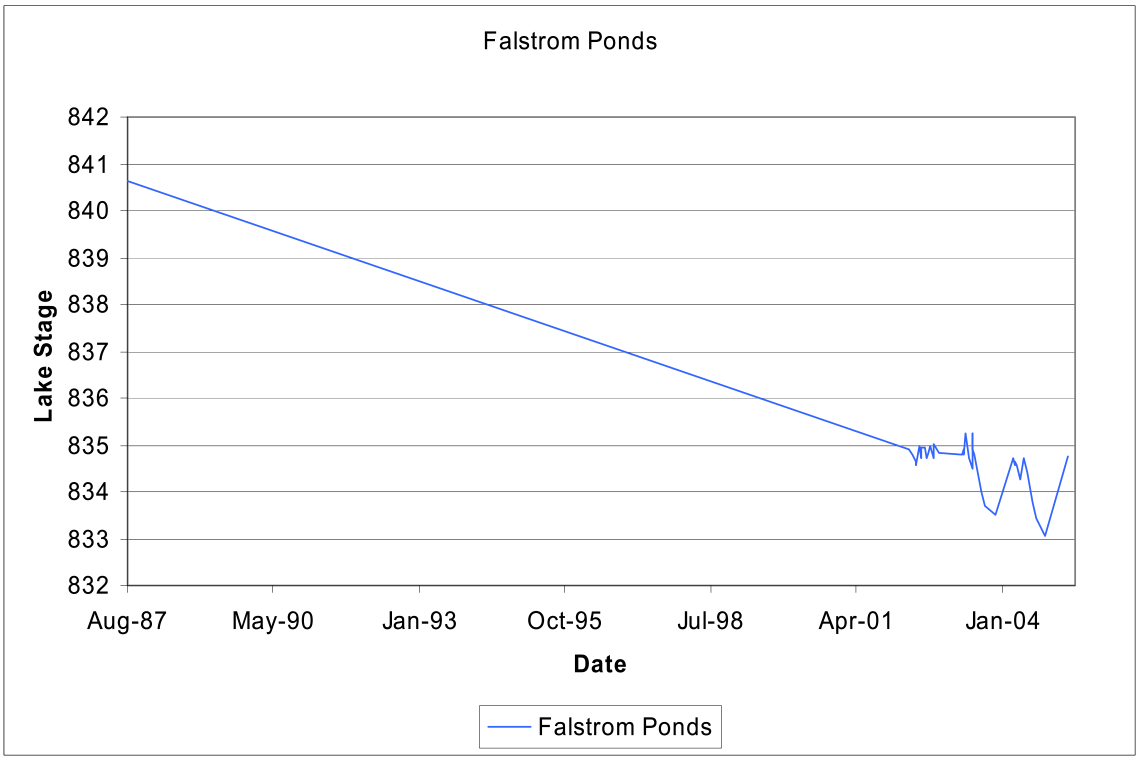

Wilmes Lake
905
904
903
902
901
900
899
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Wilmes Lake

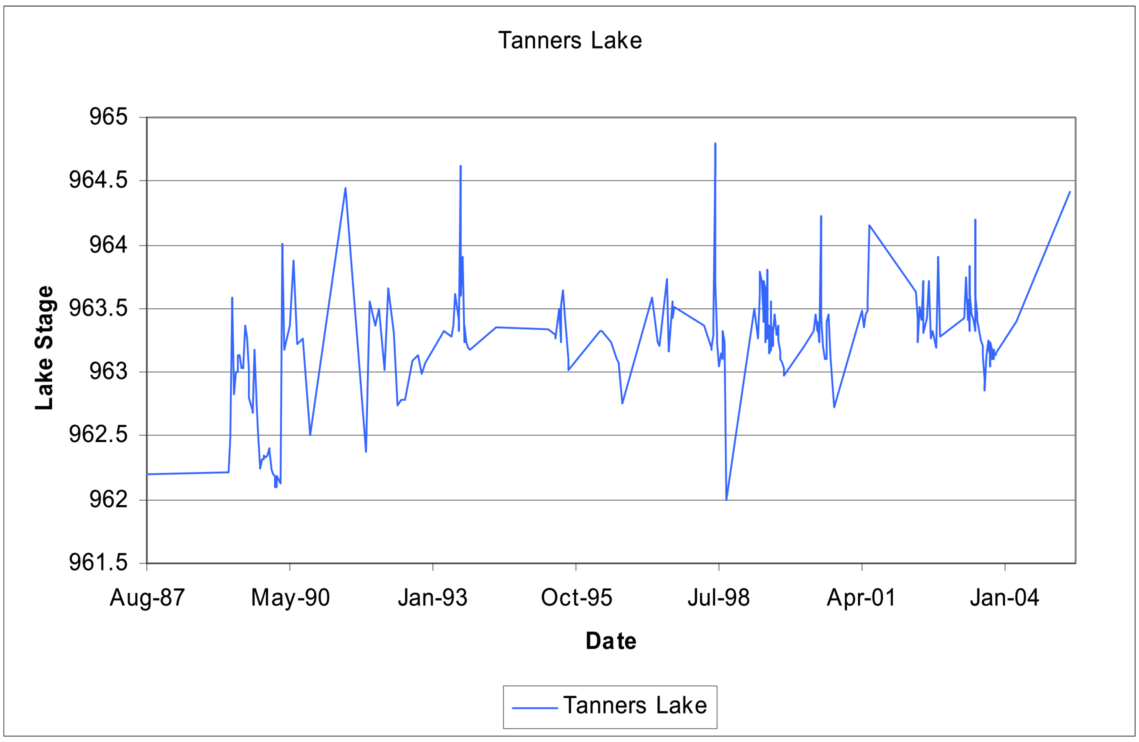

Shepard's Pond
1000
900
800
700
600
500
400
300
200
100
0
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Shepard's Pond

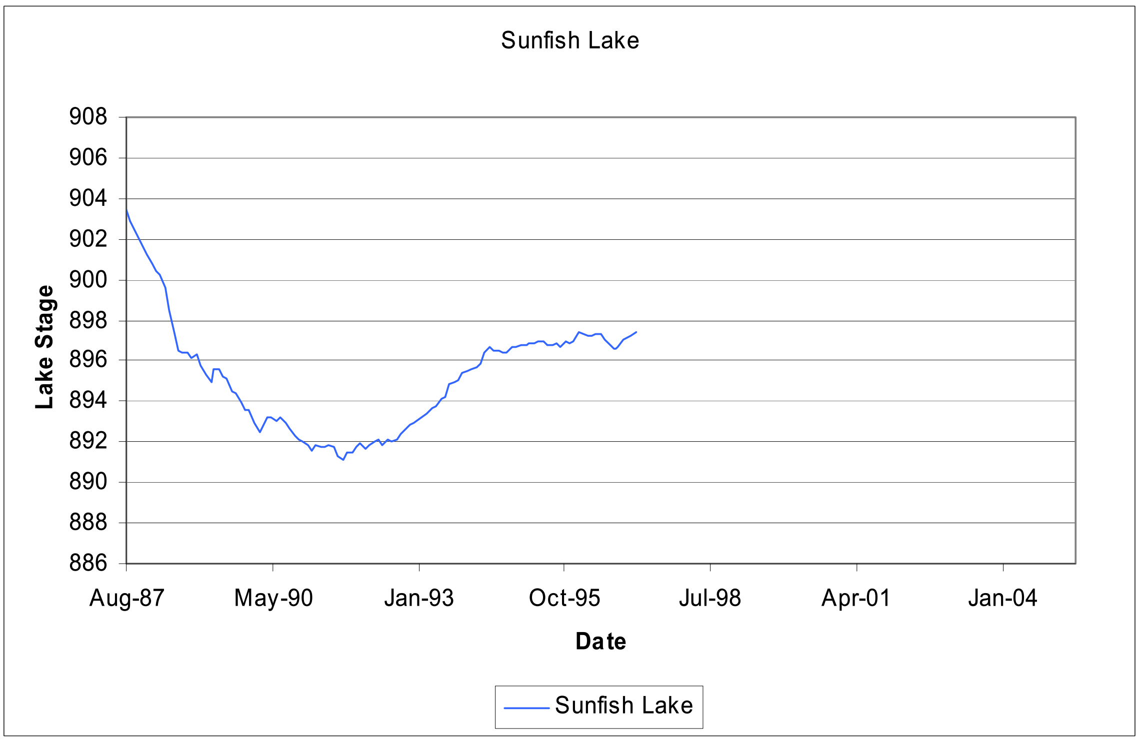

Goetschel Lake
892
891.5
891
890.5
890
889.5
889
888.5
888
887.5
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Goetschel Lake

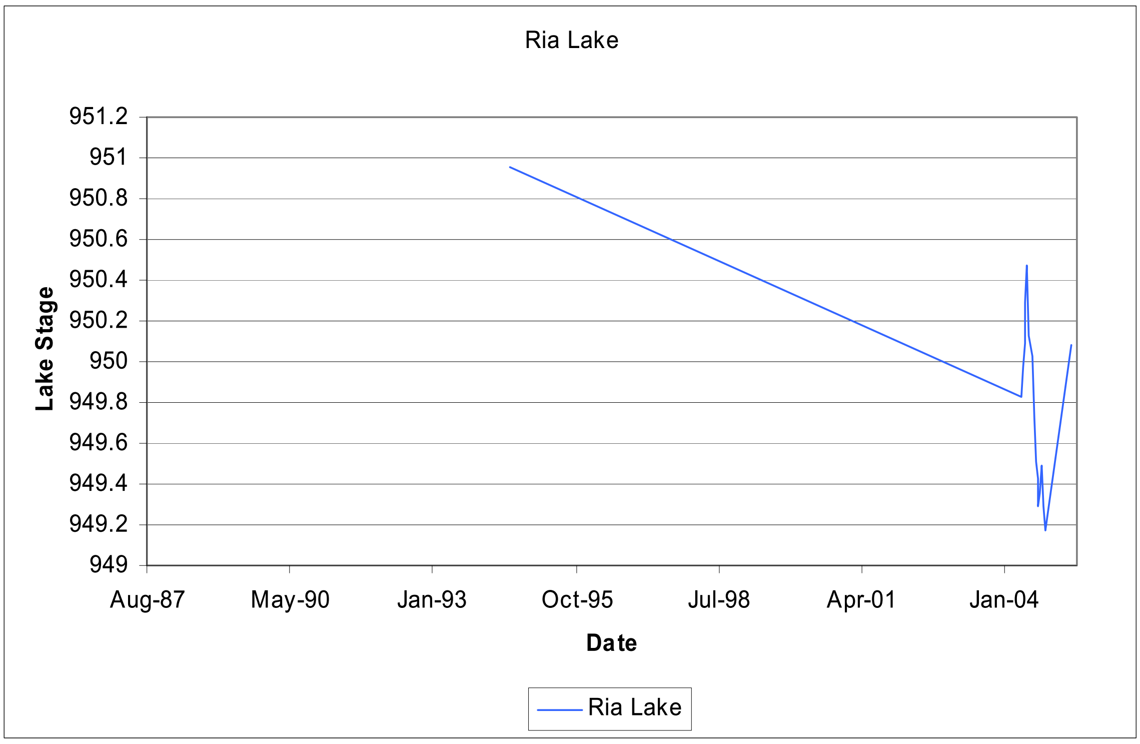

Bayl Lake
883.5
883
882.5
882
881.5
881
880.5
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Bayl Lake

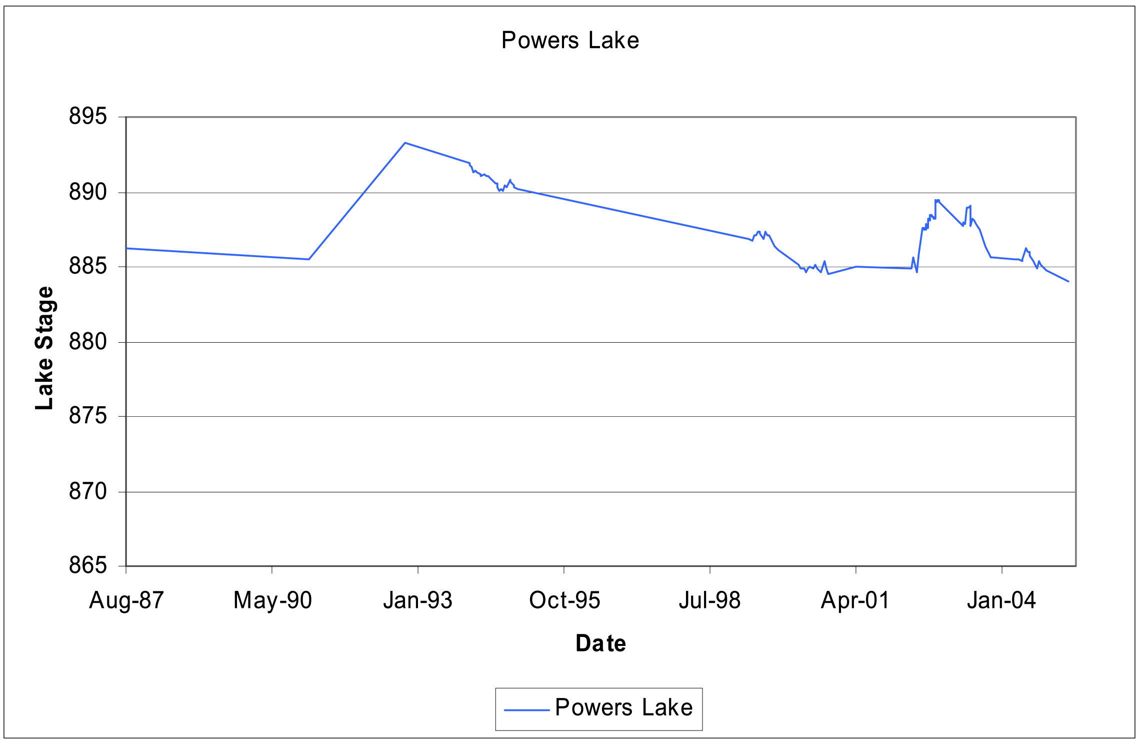

Bailey Lake
874
873
872
871
870
869
868
867
866
865
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Bailey Lake

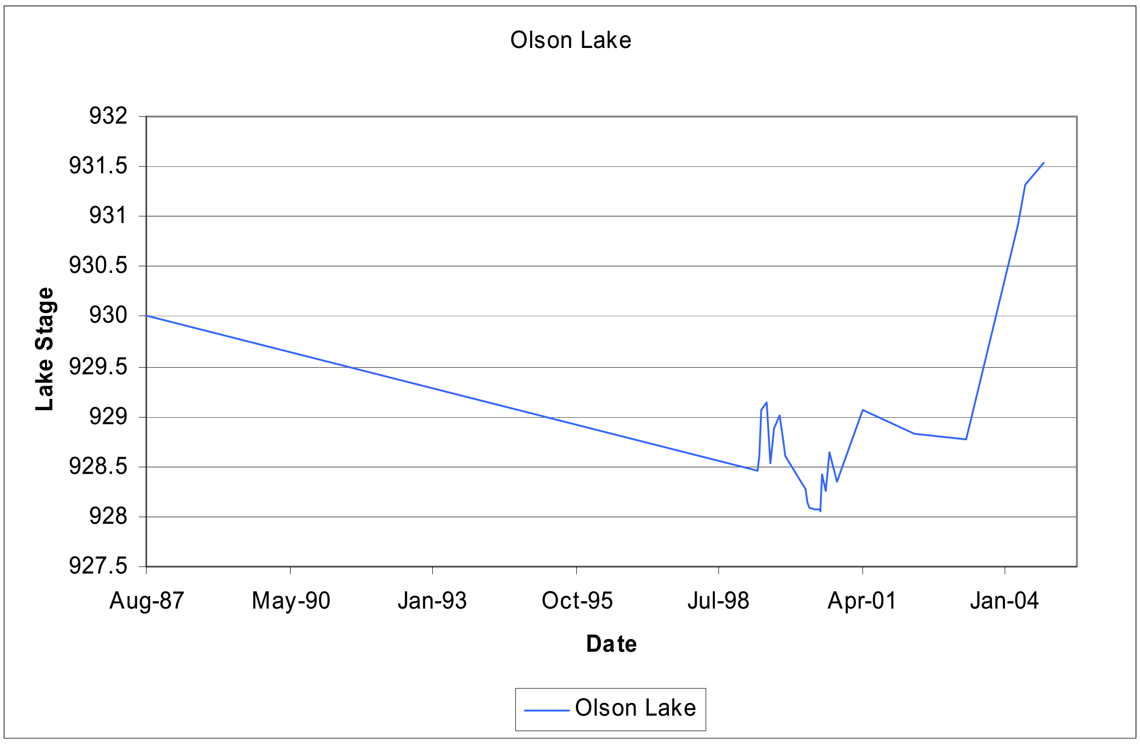

Falstrom Ponds
842
841
840
839
838
837
836
835
834
833
832
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Falstrom Ponds

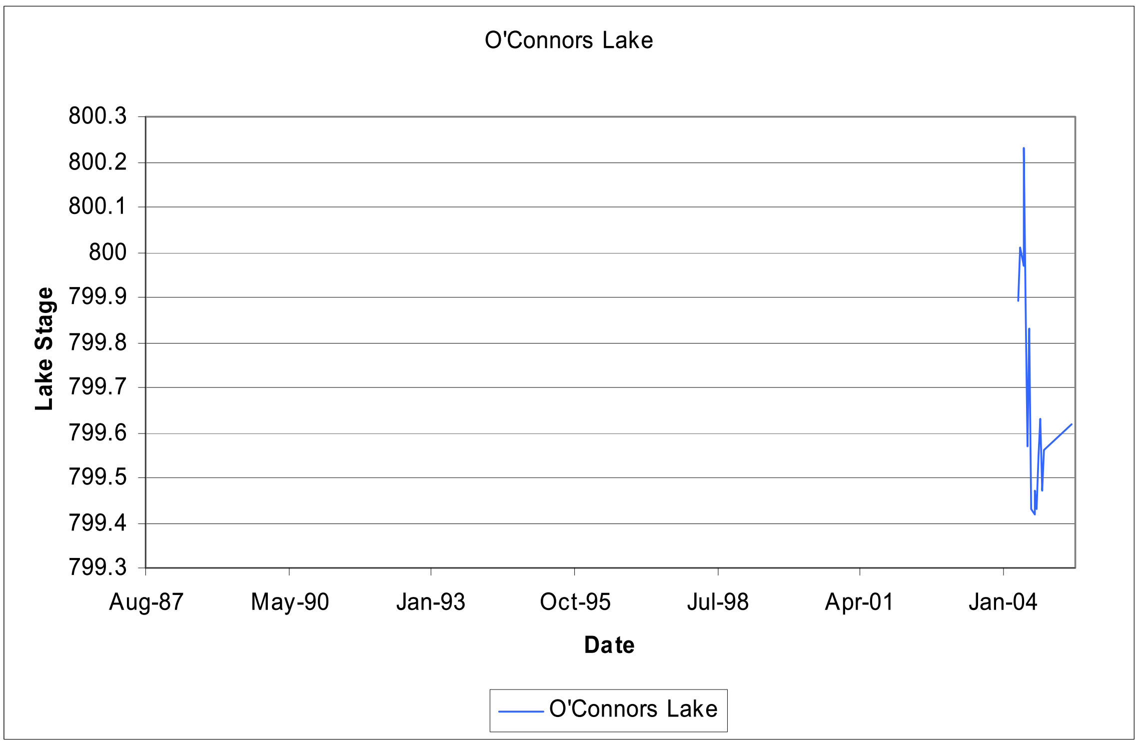

Tanners Lake
965
964.5
964
963.5
963
962.5
962
961.5
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Tanners Lake

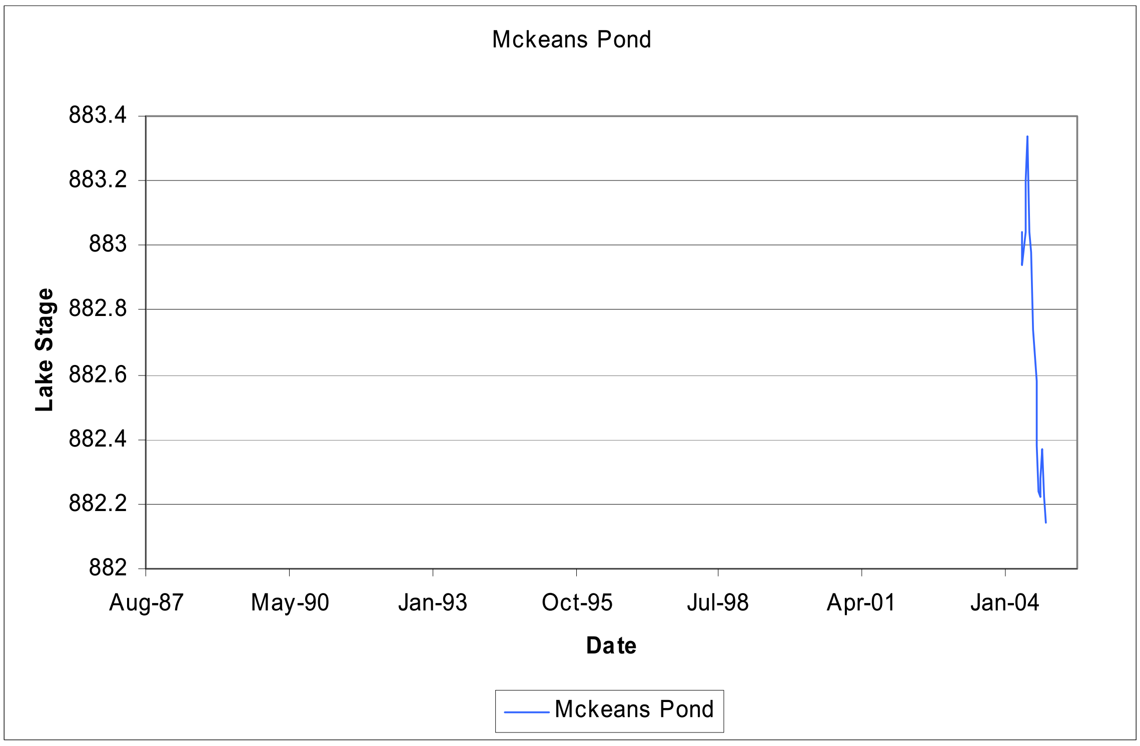

Sunfish Lake
908
906
904
902
900
898
896
894
892
890
888
886
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Sunfish Lake

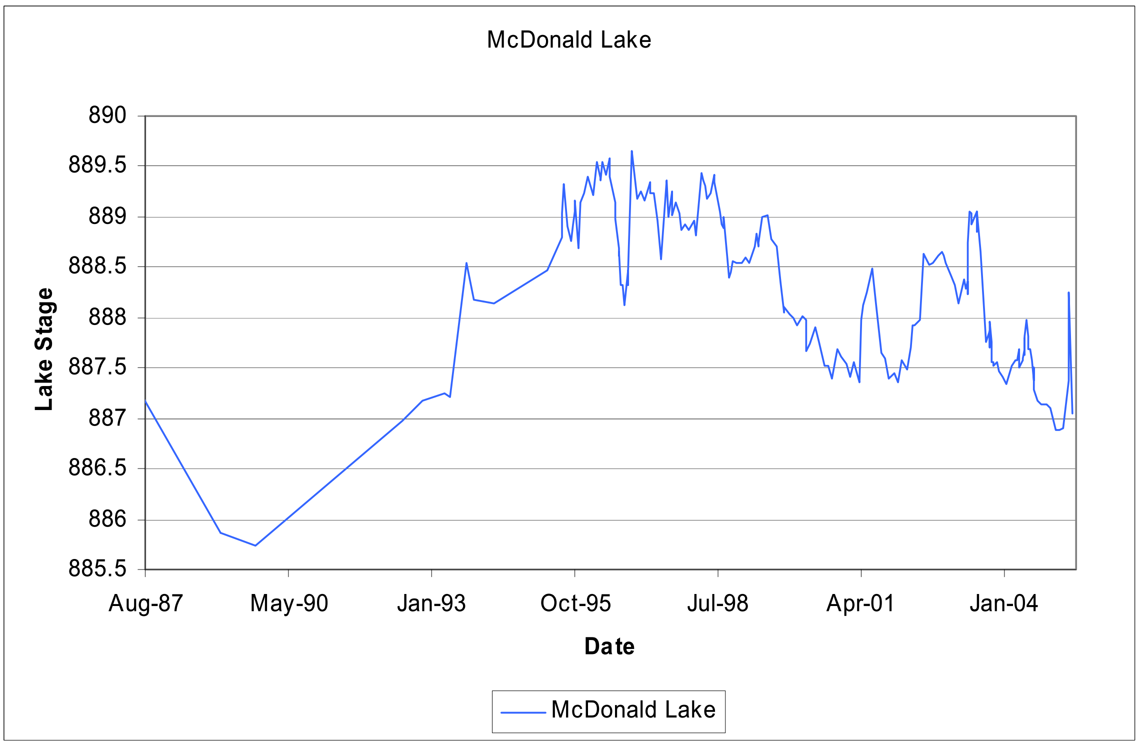

Ria Lake
Lake Stage
951.2
951
950.8
950.6
950.4
950.2
950
949.8
949.6
949.4
949.2
949
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Ria Lake

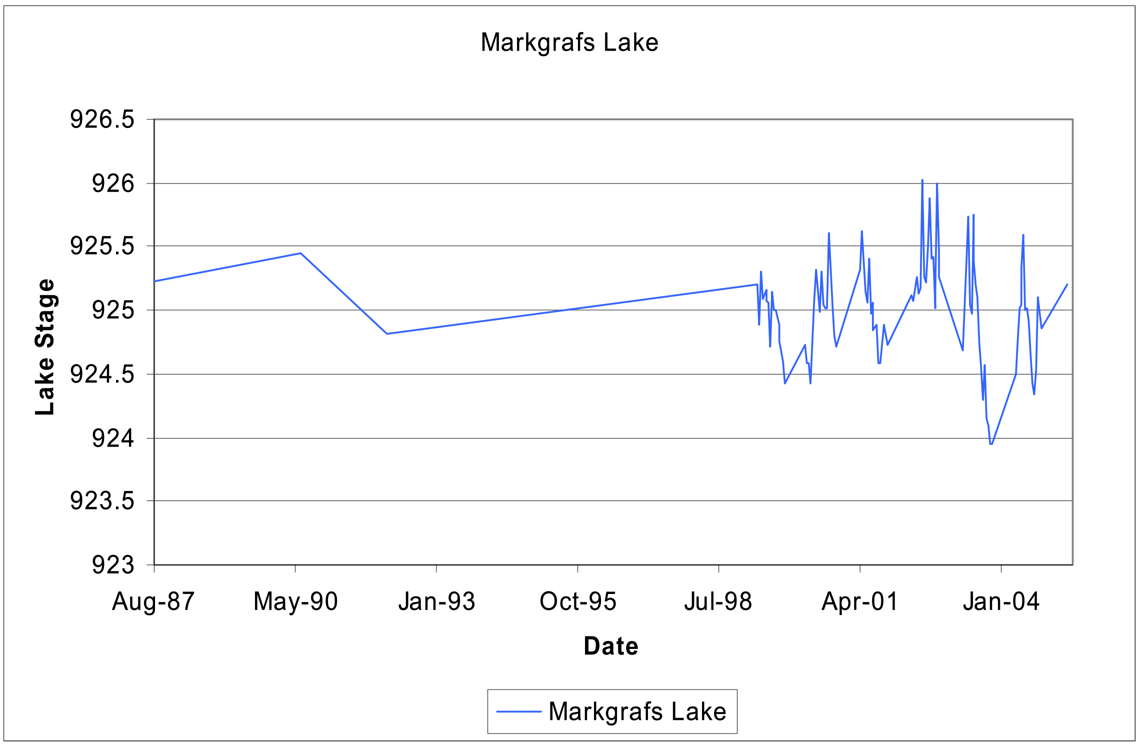

Powers Lake
Lake Stage
895
890
885
880
875
870
865
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Powers Lake

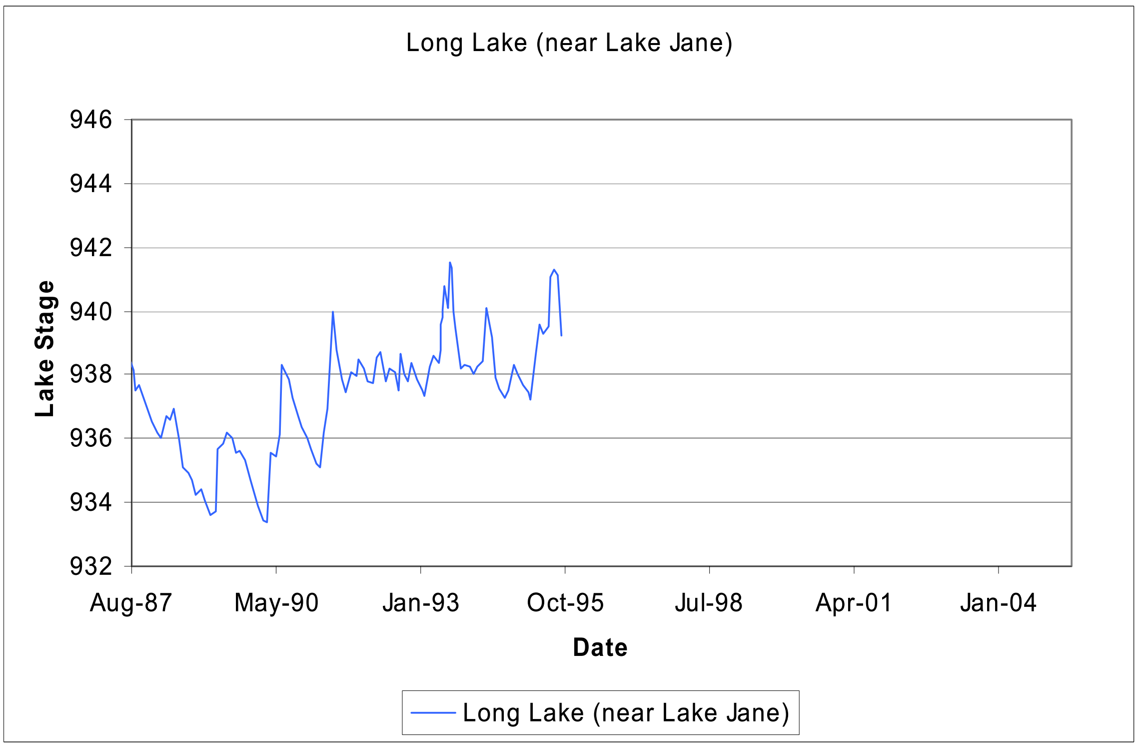

Olson Lake
932
931.5
931
930.5
930
929.5
929
928.5
928
927.5
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Olson Lake

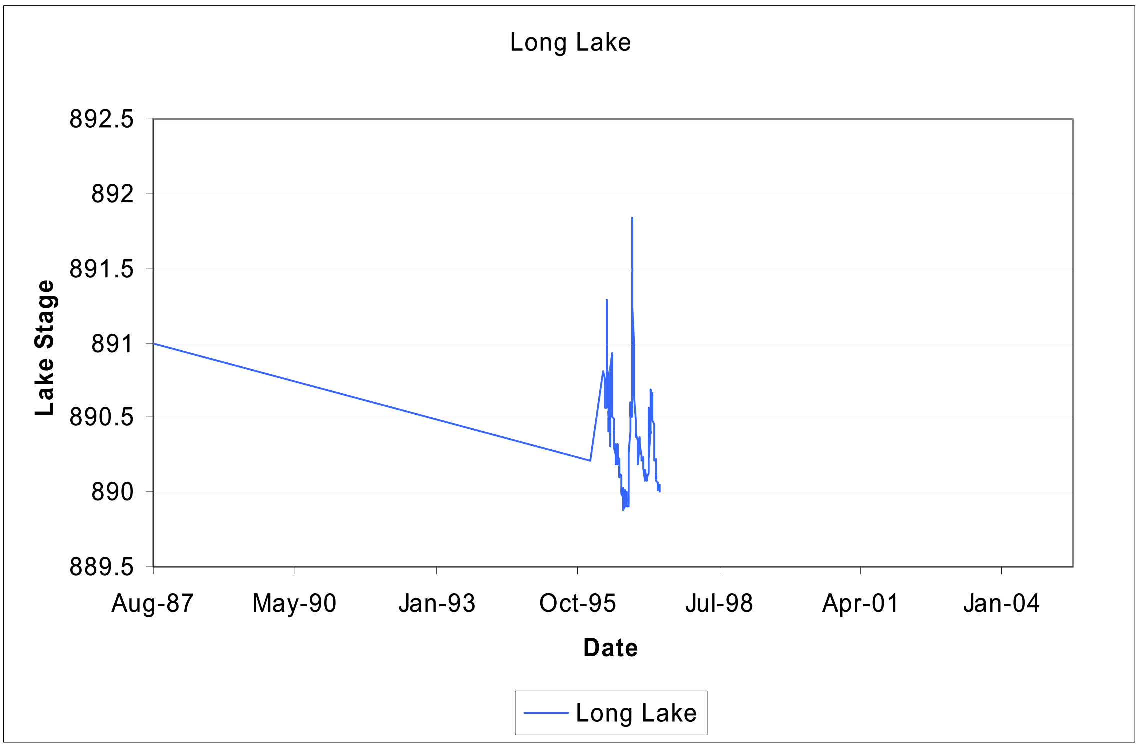

O'Connors Lake
800.3
800.2
800.1
800
799.9
799.8
799.7
799.6
799.5
799.4
799.3
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
O'Connors Lake

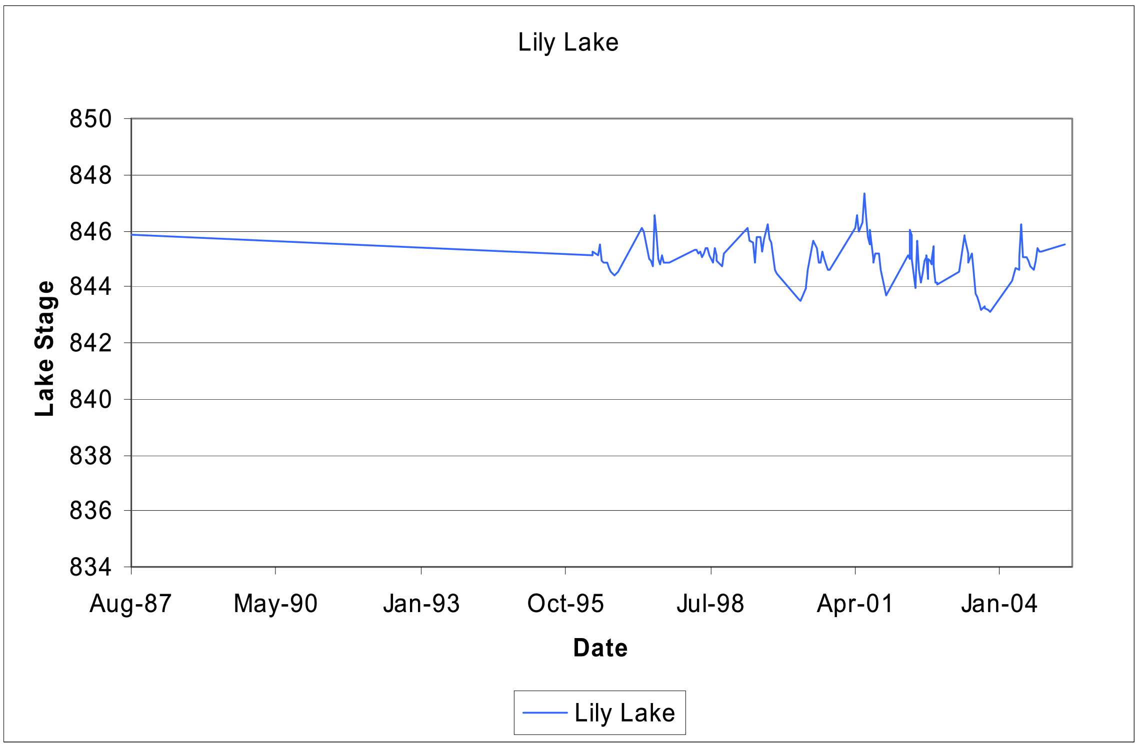

Mckeans Pond
Lake Stage
883.4
883.2
883
882.8
882.6
882.4
882.2
882
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Mckeans Pond

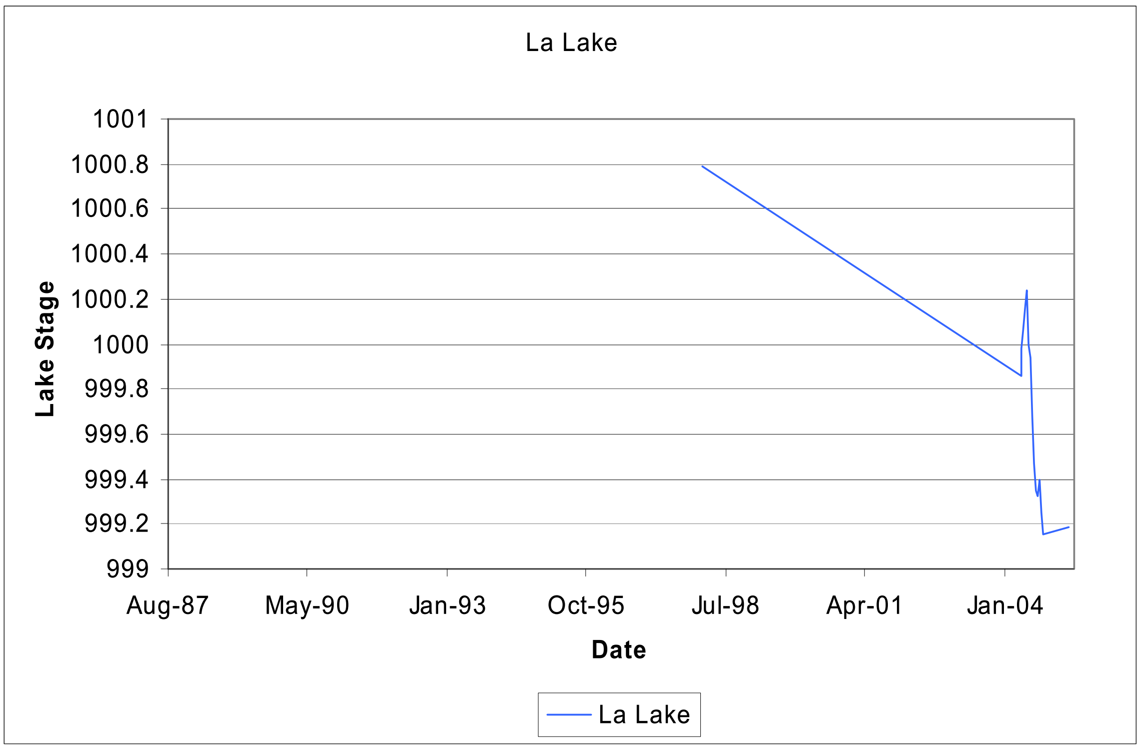

McDonald Lake
Lake Stage
890
889.5
889
888.5
888
887.5
887
886.5
886
885.5
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
McDonald Lake

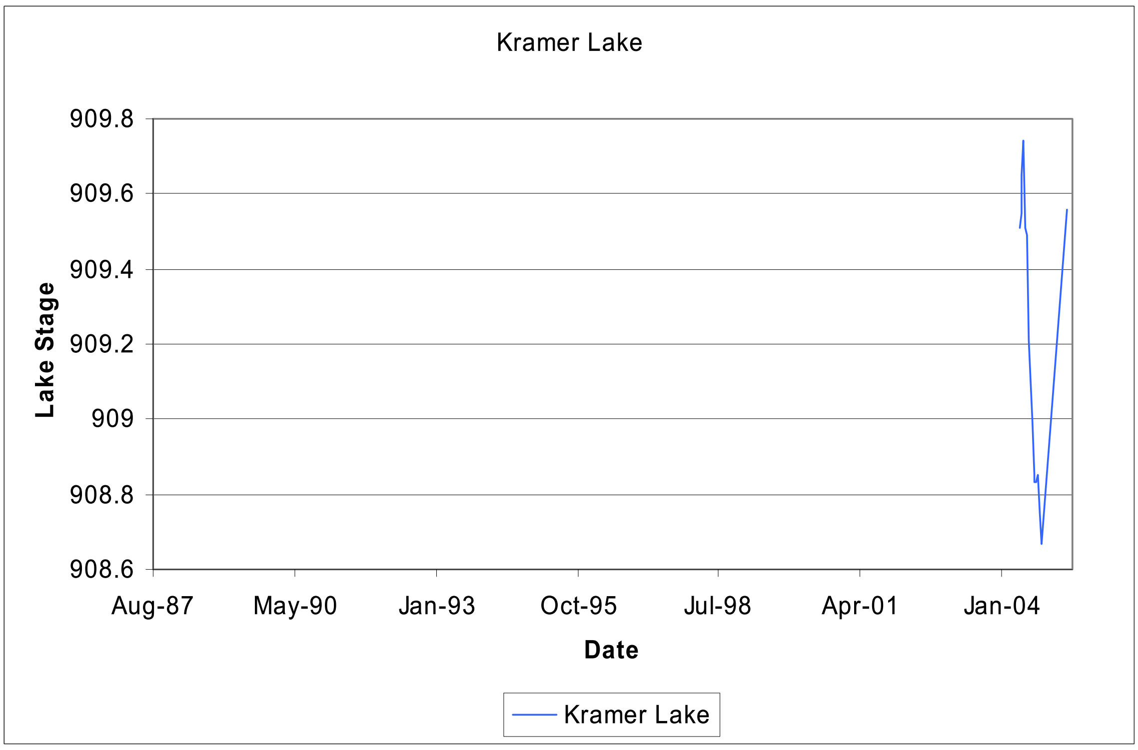

Markgrafs Lake
926.5
926
925.5
925
924.5
924
923.5
923
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Markgrafs Lake

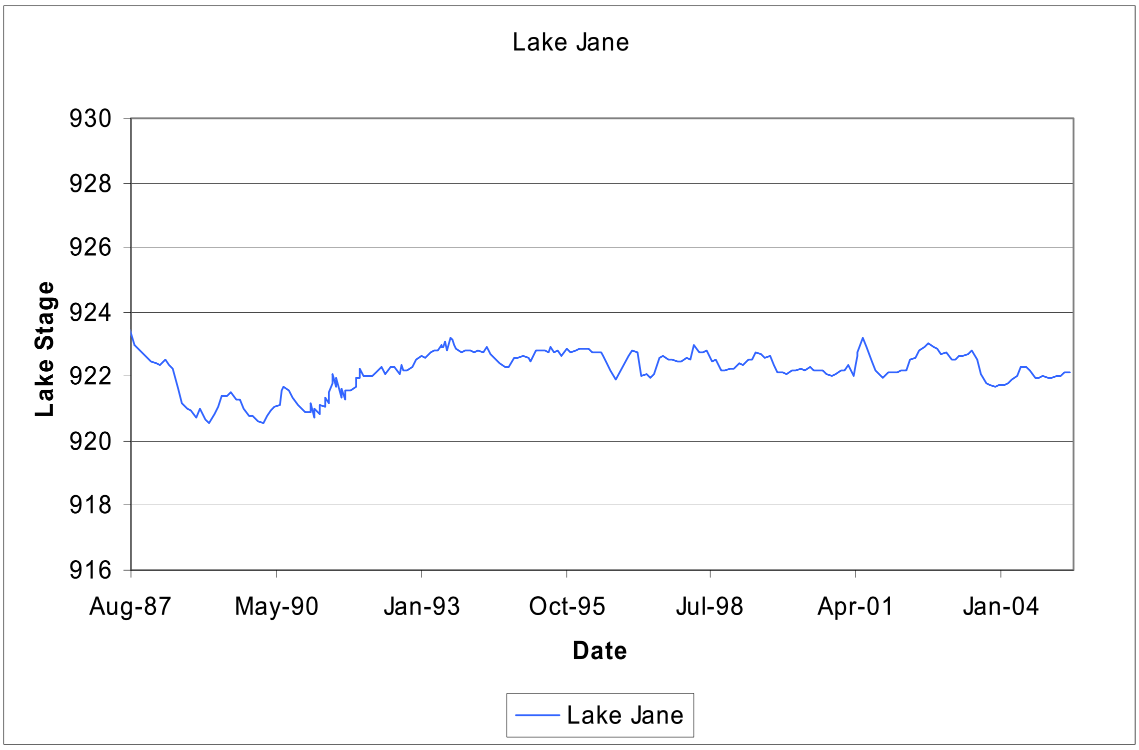

Long Lake (near Lake Jane)
946
944
942
940
938
936
934
932
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Long Lake (near Lake Jane)

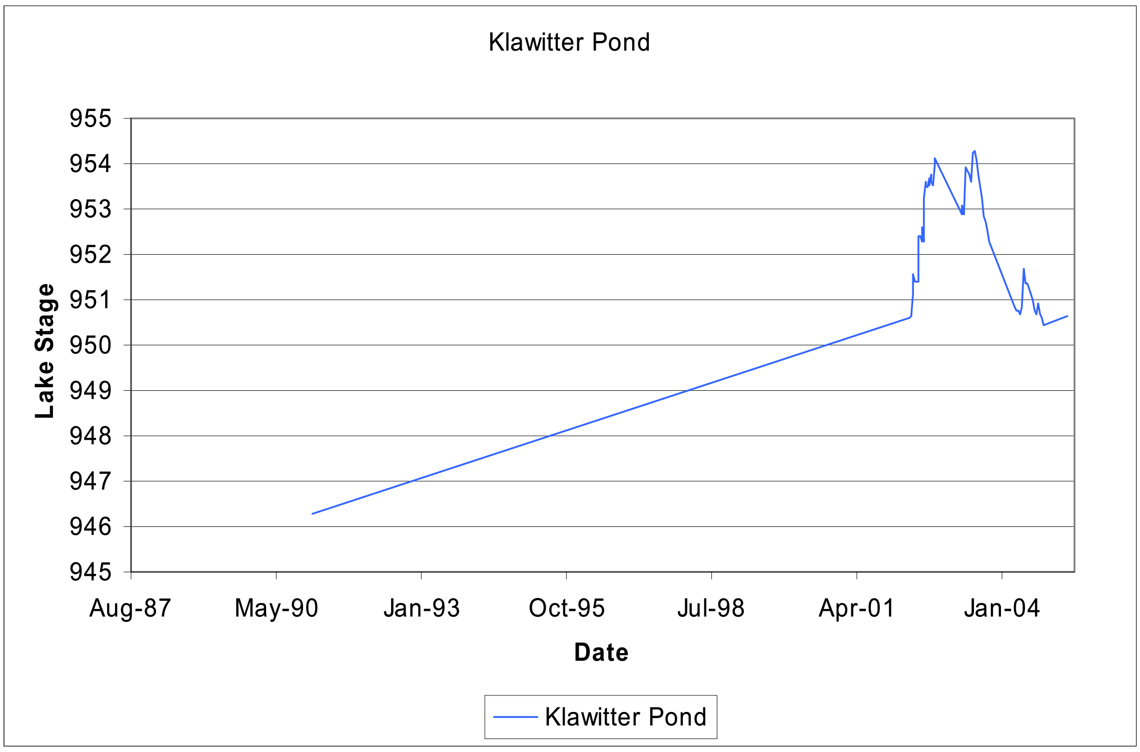

Long Lake
Lake Stage
892.5
892
891.5
891
890.5
890
889.5
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Long Lake

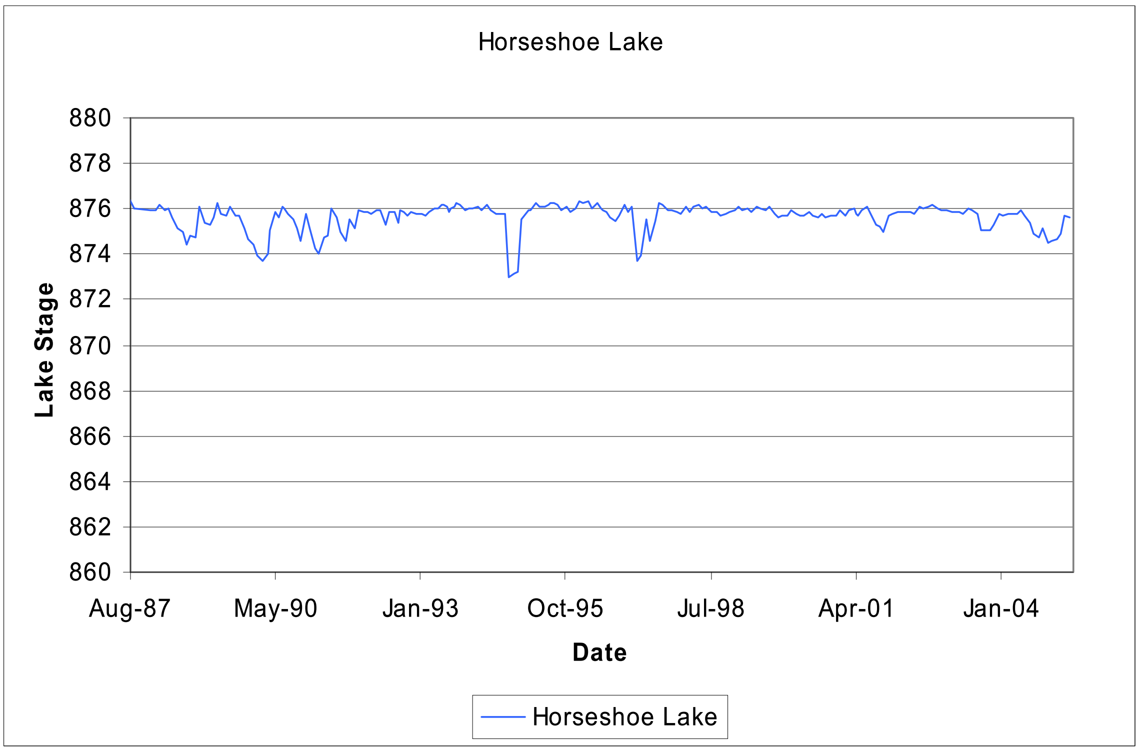

Lily Lake
Lake Stage
850
848
846
844
842
840
838
836
834
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Lily Lake

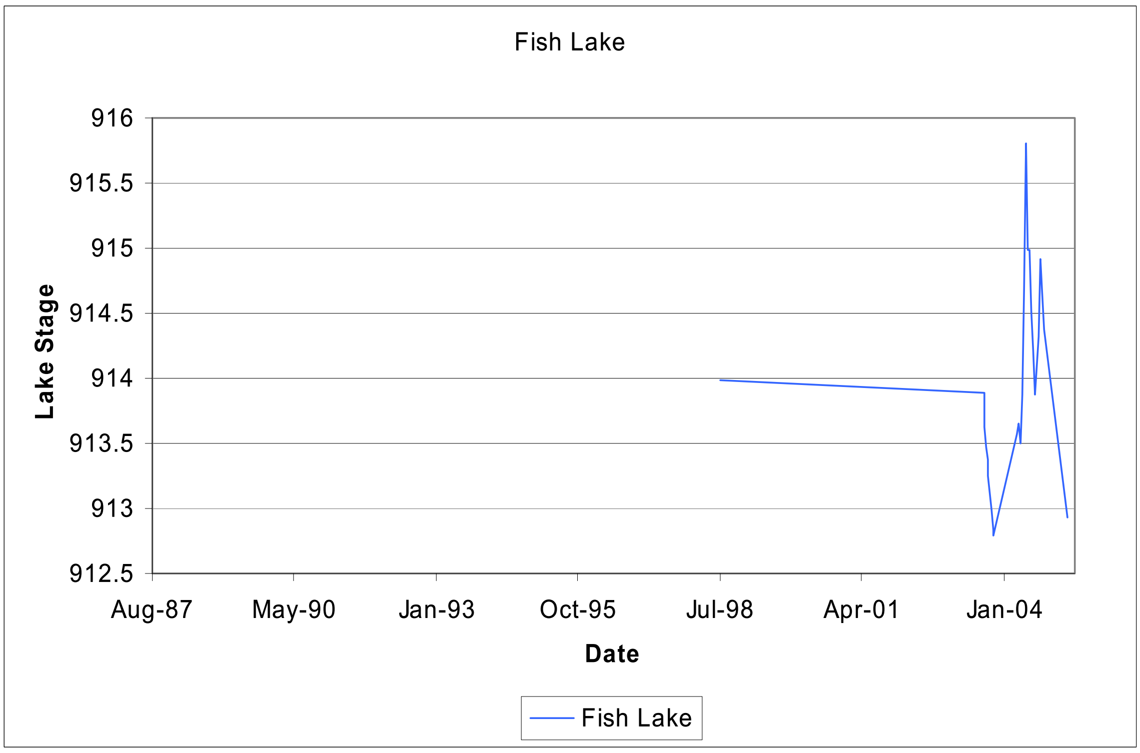

La Lake
Lake Stage
1001
1000.8
1000.6
1000.4
1000.2
1000
999.8
999.6
999.4
999.2
999
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
La Lake

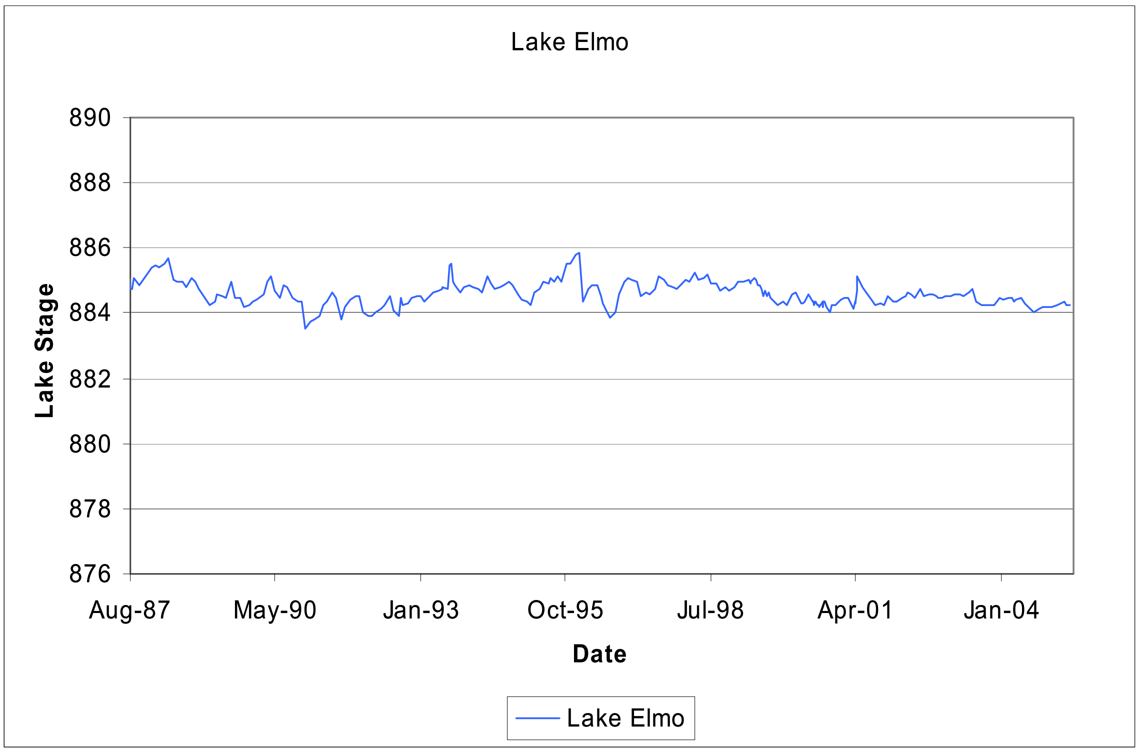

Kramer Lake
Lake Stage
909.8
909.6
909.4
909.2
909
908.8
908.6
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Kramer Lake

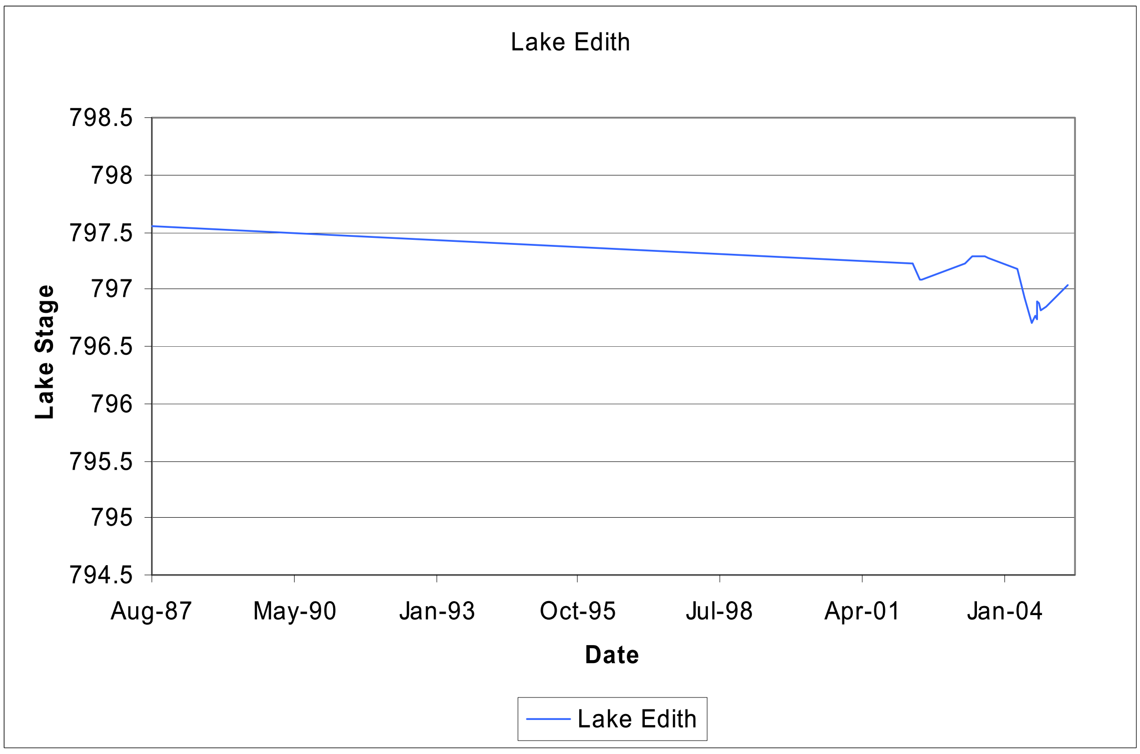

Lake Jane
930
928
926
924
922
920
918
916
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Lake Jane

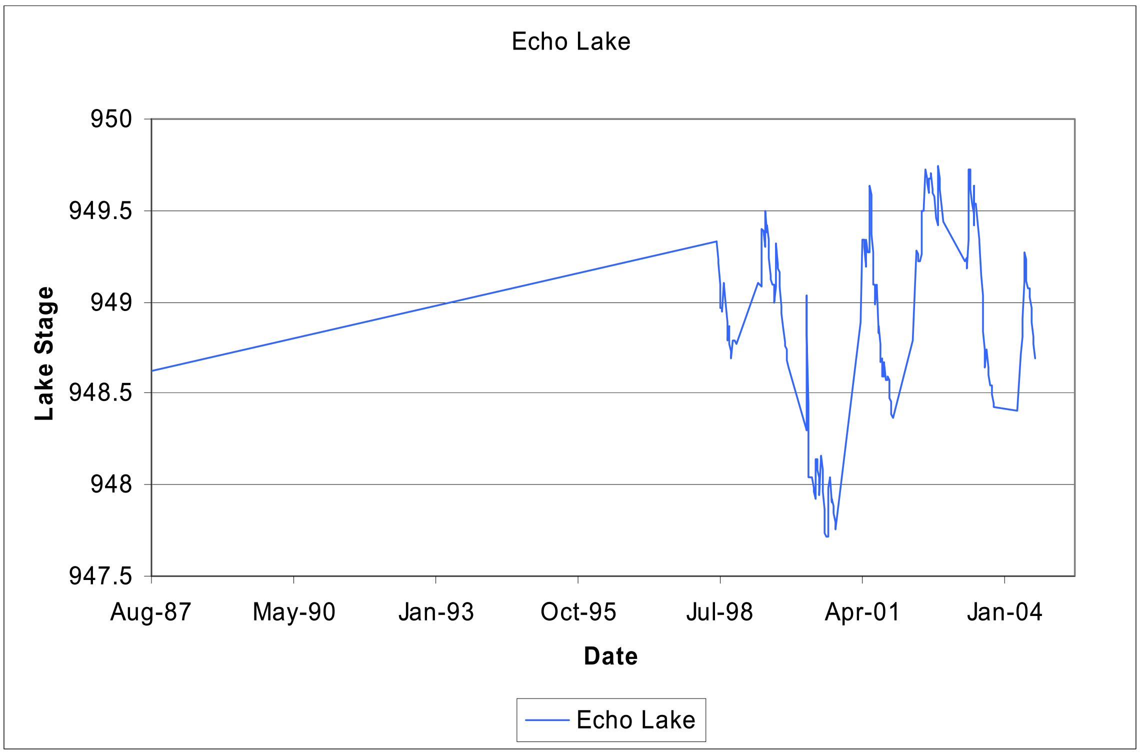

Klawitter Pond
955
954
953
952
951
950
949
948
947
946
945
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Klawitter Pond

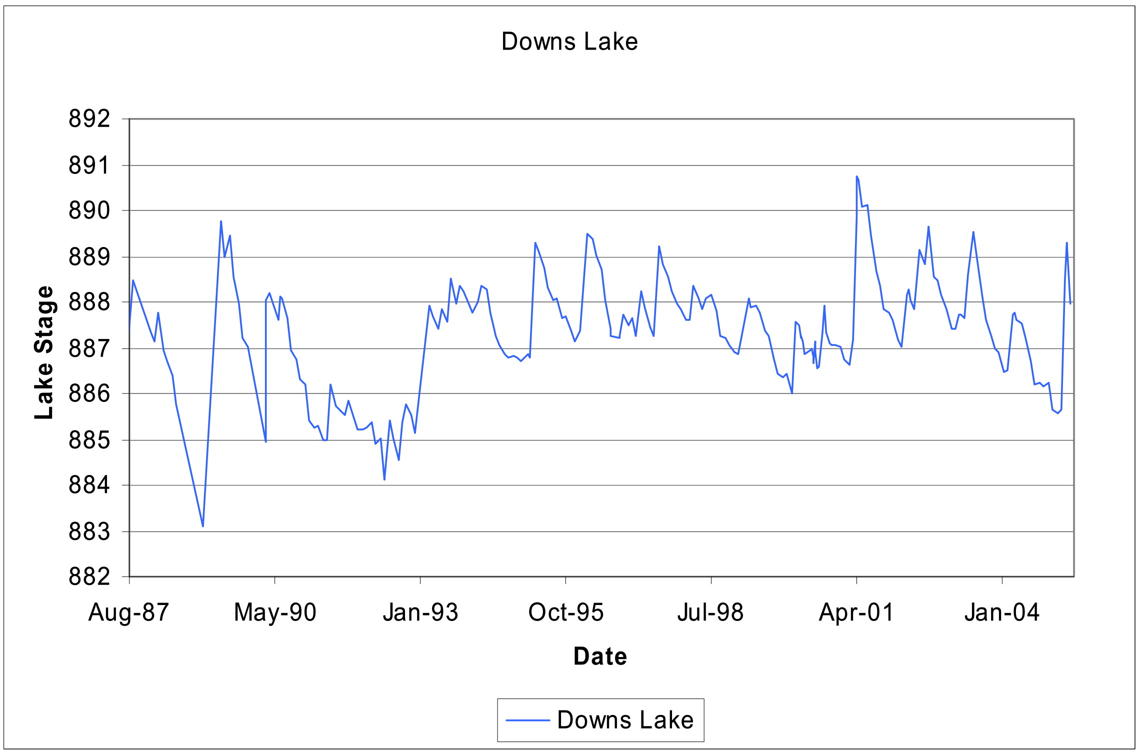

Horseshoe Lake
Lake Stage
880
878
876
874
872
870
868
866
864
862
860
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Horseshoe Lake

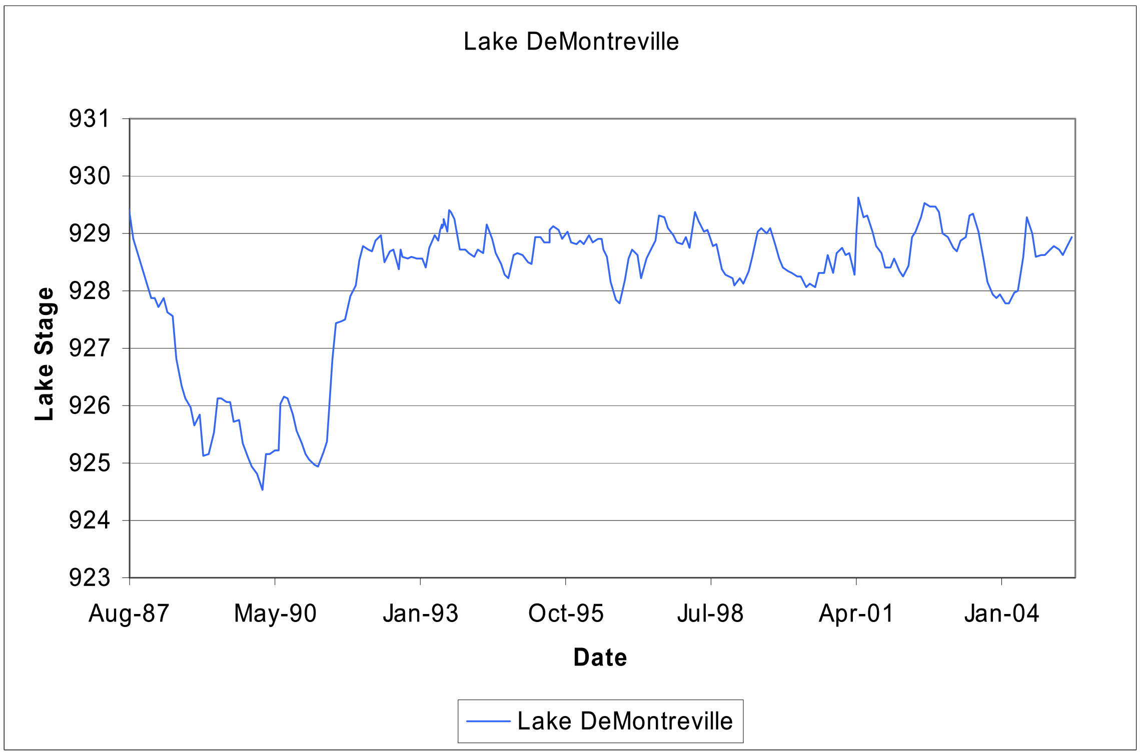

Fish Lake
Lake Stage
916
915.5
915
914.5
914
913.5
913
912.5
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Fish Lake

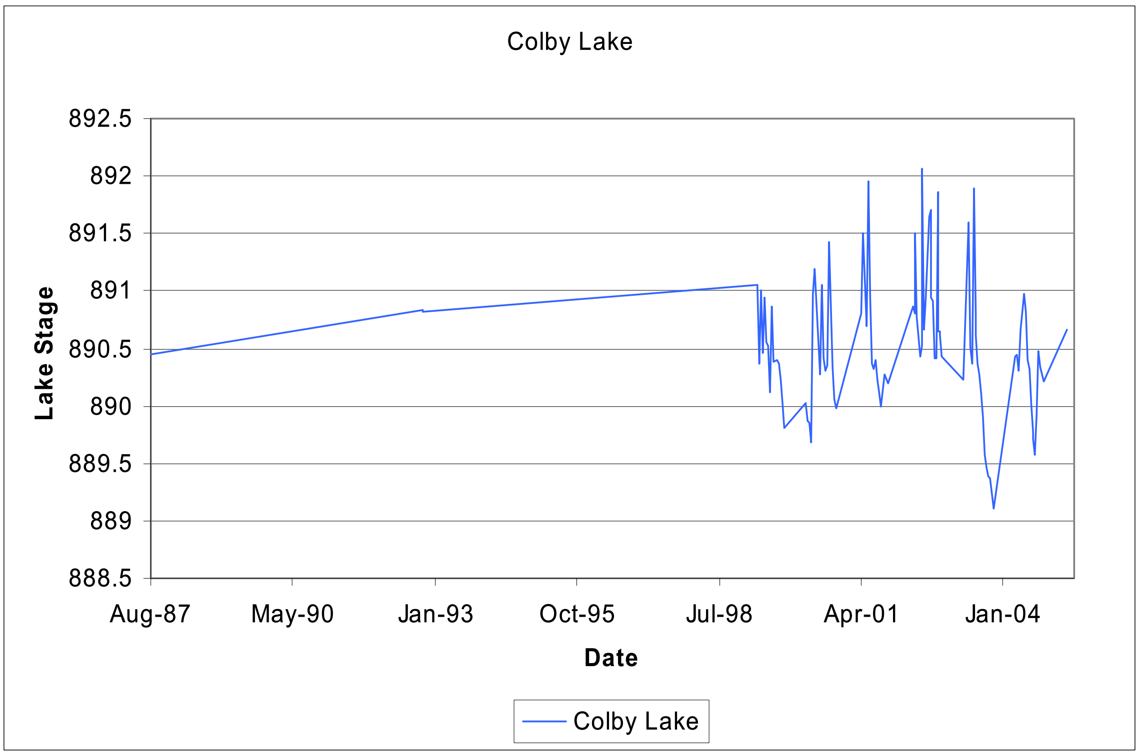

Lake Elmo
Lake Stage
890
888
886
884
882
880
878
876
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Lake Elmo


Lake Edith
Lake Stage
798.5
798
797.5
797
796.5
796
795.5
795
794.5
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Lake Edith


Echo Lake
950
949.5
949
948.5
948
947.5
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Echo Lake


Downs Lake
892
891
890
889
888
887
886
885
884
883
882
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Downs Lake


Lake DeMontreville
931
930
929
928
927
926
925
924
923
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Lake DeMontreville


Colby Lake
892.5
892
891.5
891
890.5
890
889.5
889
888.5
Lake Stage
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
Jan-04
Date
Colby Lake

Appendix D: Description of GIS Files

The following 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.

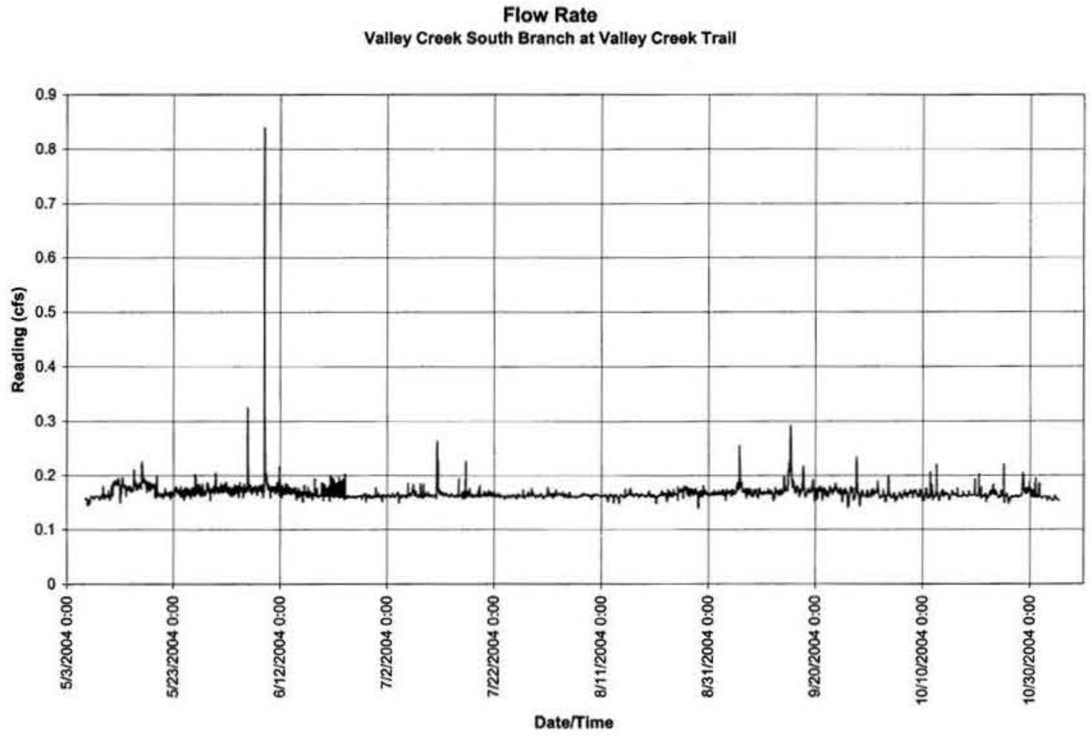
Directory	**File Name**	**File Type**	**File Type and Use**
root	Quarters	Shape - polygon	Quarter sections – UTM only
root	t-r-s	Shape - polygon	Township, Range, and Section Polygons – UTM only
Grid\utm83	Dep2w	Grid	Depth to water in feet
Grid\utm83	Soi_hyd	Grid	Soil hydrologic grouping (A, B, C, or D)
Grid\utm83	Top_ft	Grid	Top of bedrock (ft, MSL)
Maps	CountyBase.mxd	ArcGIS map file	Base map file of county
Maps	datatables.apr	ArcView apr file	Data tables
Maps	from_lcmr.apr	ArcView apr file	Plots from LCMR model
Maps	infiltration.apr	ArcView apr file	Infiltration data
Maps	mc-Geologic_topography.mxd	ArcGIS map file	Geology and topography data
Maps	mc-Geology.mxd	ArcGIS map file	Geology data
Maps	mc-Geology_Fault_Jordan_contours.mxd	ArcGIS map file	Faulting in Jordan data from MGS
Maps	md-	ArcGIS map file	Bedrock elevation data

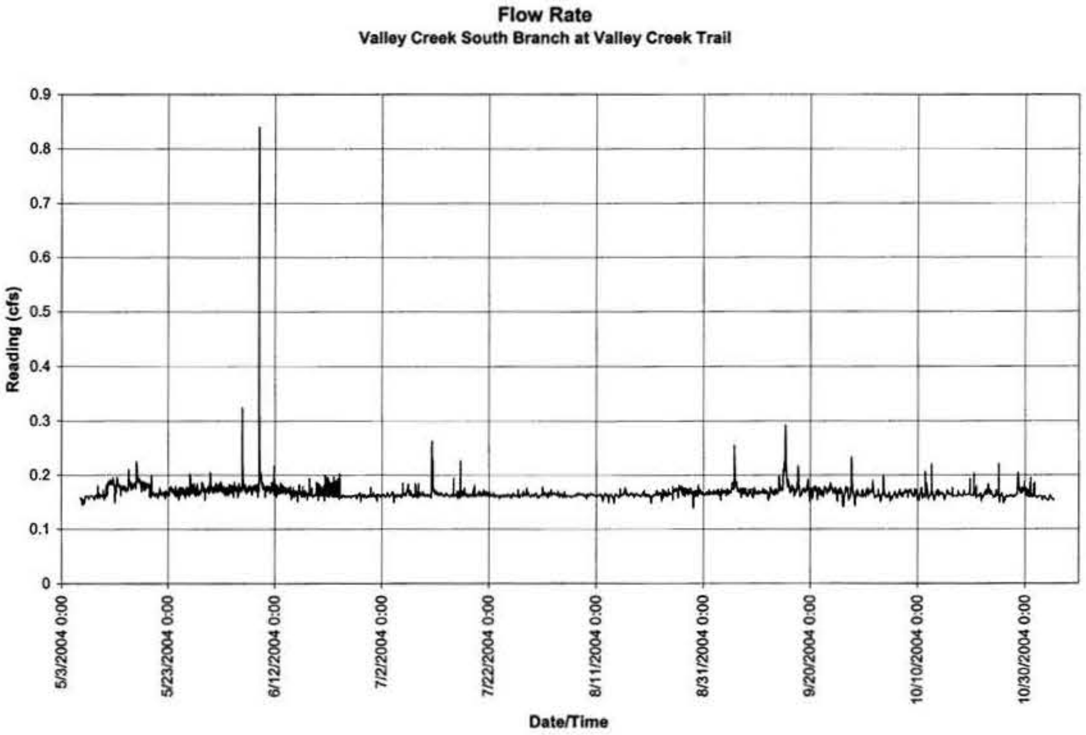
Directory	File Name	File Type	File Type and Use
	Bedrock_Elevtion_Geology.mxd		
Maps	md-Jordan_Contours.mxd	ArcGIS map file	Contours of top of Jordan
Maps	ms-Bedrock_Geology.mxd	ArcGIS map file	Bedrock geology
Maps	ms-Bedrock_Topology.mxd	ArcGIS map file	Bedrock topology
Maps	ms-Jordan_and_faultlines.mxd	ArcGIS map file	Fault lines and Jordan sandstone
Maps	ms-Linements.mxd	ArcGIS map file	Lineaments
Maps	sws-Gages.mxd	ArcGIS map file	Gage locations in study area
Maps	sws-Wells.mxd	ArcGIS map file	Wells in study area
Maps	WC_locations.mxd	ArcGIS map file	Water chemistry sampling locations in study area
Shapefile\UTM83\Base	masked_study_area	Shape file polygon	Study area with a donut opening for study area
Shapefile\UTM83\Base	study_area	Shape file polygon	Study area polygon
Shapefile\UTM83\Geology\mndnrdata\state\mn	lfrm_karstpt3	Shape file point	Karst features in study area (from DNR)
Shapefile\UTM83\Hydro	lakes_in_study_area_utm	Shape file polygon	Lakes in study area with rankings on type of groundwater interaction
Shapefile\UTM83\Hydro	lakes_with_mces_ranki	Shape file polygon	Lake quality rankings by MCES

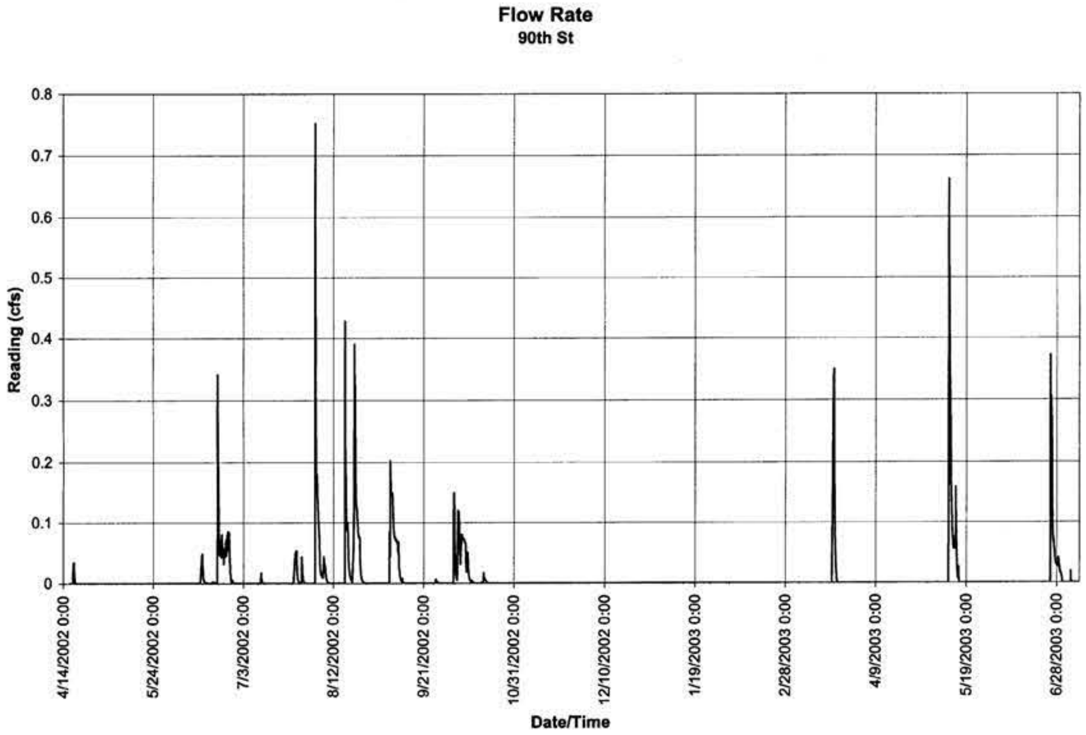
Directory	File Name	File Type	File Type and Use
	ngs		
Shapefile\UTM83\Hydro	swwd_infiltration_basins	Shape file polygon	Approximate polygon shapes of SWWD infiltration basins from EOR 2001 study
Shapefile\UTM83\infiltration	infiltration_in_year_utm	Shape file polygon	Infiltration (inches per year) for typical year – from LCMR study
Shapefile\UTM83\infiltration	infiltration_potential	Shape file point	Ranking of the infiltration potential of soils based on depth to groundwater, depth to bedrock, and hydrologic grouping
Shapefile\UTM83\infiltration	infiltration_potential_ranking	ArcView legend file	Legend file for infiltration_potential
Shapefile\UTM83\LandInfo	mbc_plant_comunities	Shape file polygon	Plant communities – from MNDN
Shapefile\UTM83\LandInfo	townships	Shape file polygon	Townships
Shapefile\UTM83\LandInfo	tw-rn-sec_utm	Shape file polygon	Sections
Shapefile\UTM83\LandInfo	updated_watershed_districts	Shape file polygon	Watershed Districts and WMO's, modified to include recent changes to SWWD
Shapefile\UTM83\Landmark	Wc_datalocations	Shape file point	Locations of data collected by WCD
shapefile\utm83\surf_capture_zones	creeks	Shape file polygon	10 and 100 year time of travel zones of contribution for creeks, as derived from the LCMR model
Shapefile\UTM83\Wells	dnr_ob_well	Shape file point	DNR observation well locations
Shapefile\UTM83\Wells	domestic_wells_cwi	Shape file point	Domestic wells in study area
Shapefile\UTM83\Wells	pdc_wells	Shape file	Prairie du Chien wells in study area

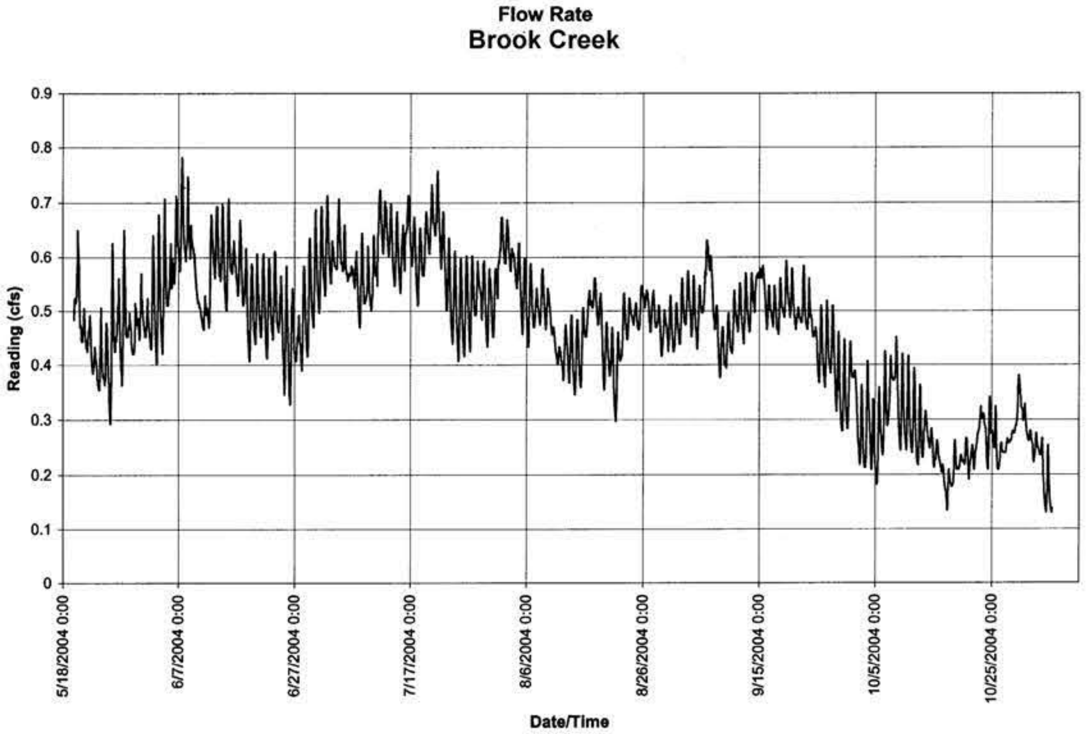
Directory	File Name	File Type	File Type and Use
		point	
Shapefile\UTM83\Wells	study_area_cwi	Shape file point	County Well Index data in study area
Shapefile\UTM83\Wells	st_peter_wells	Shape file point	St. Peter wells in study area
Shapefile\UTM83\Wells	wash_county_cwi	Shape file point	County Well Index data in Washington county
TabularData	flow_and_water_levels	Dbf file	Listing of flow and water level measuring points – from WCD
TabularData	Infiltration_potential.xls	Excel file	Spreadsheet of infiltration potential corresponding to the centers of quarter-quarter-quarter-quarter sections in study area
TabularData	WAshingtonCountyData.mdb	Database file	Database file from WCD
TabularData	TBLSITES	Shape file point	Point data of WCD sampling locations

Appendix E: Hydrographs of Stream Flows During 2004

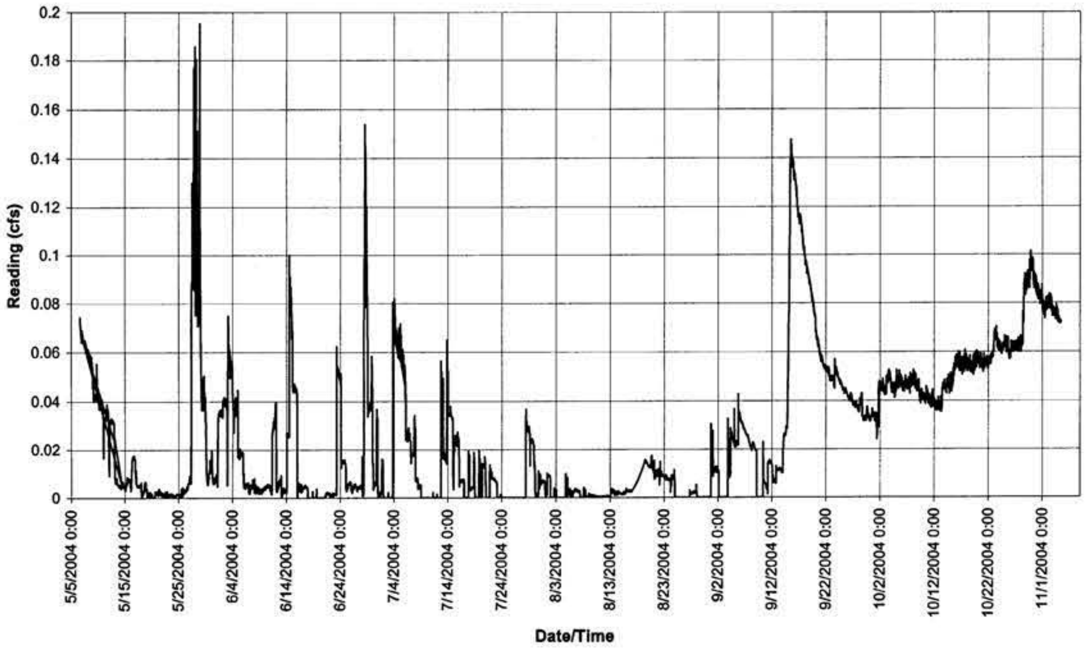




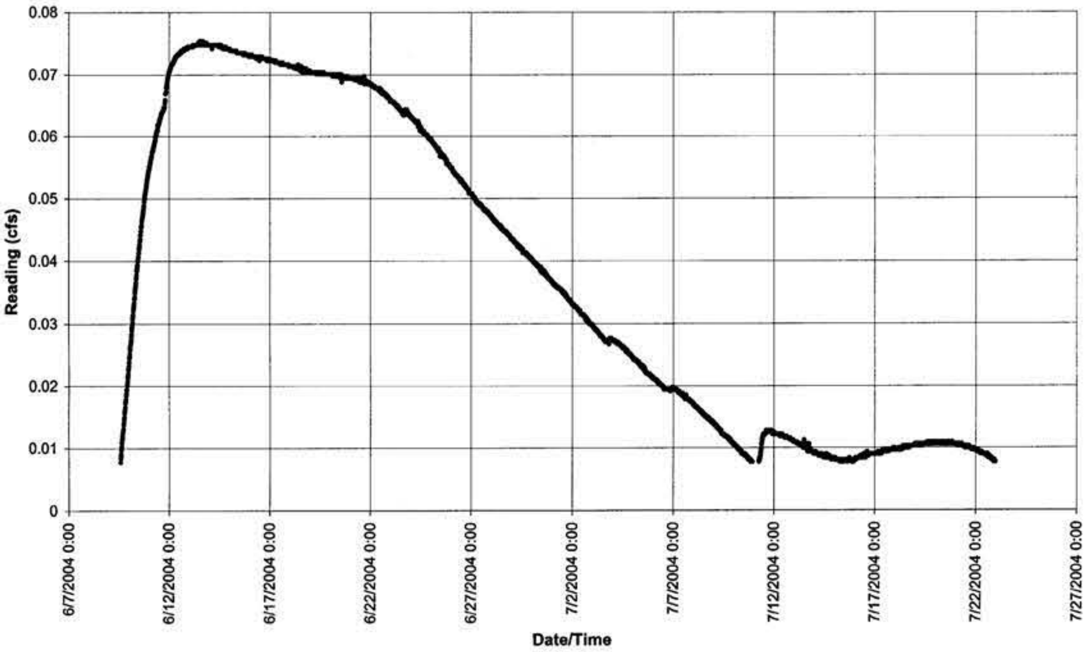

Flow Rate
90th St
Reading (cfs)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4/14/2002 0:00
5/24/2002 0:00
7/3/2002 0:00
8/12/2002 0:00
9/21/2002 0:00
10/31/2002 0:00
12/10/2002 0:00
1/19/2003 0:00
2/28/2003 0:00
4/9/2003 0:00
5/19/2003 0:00
6/28/2003 0:00
Date/Time

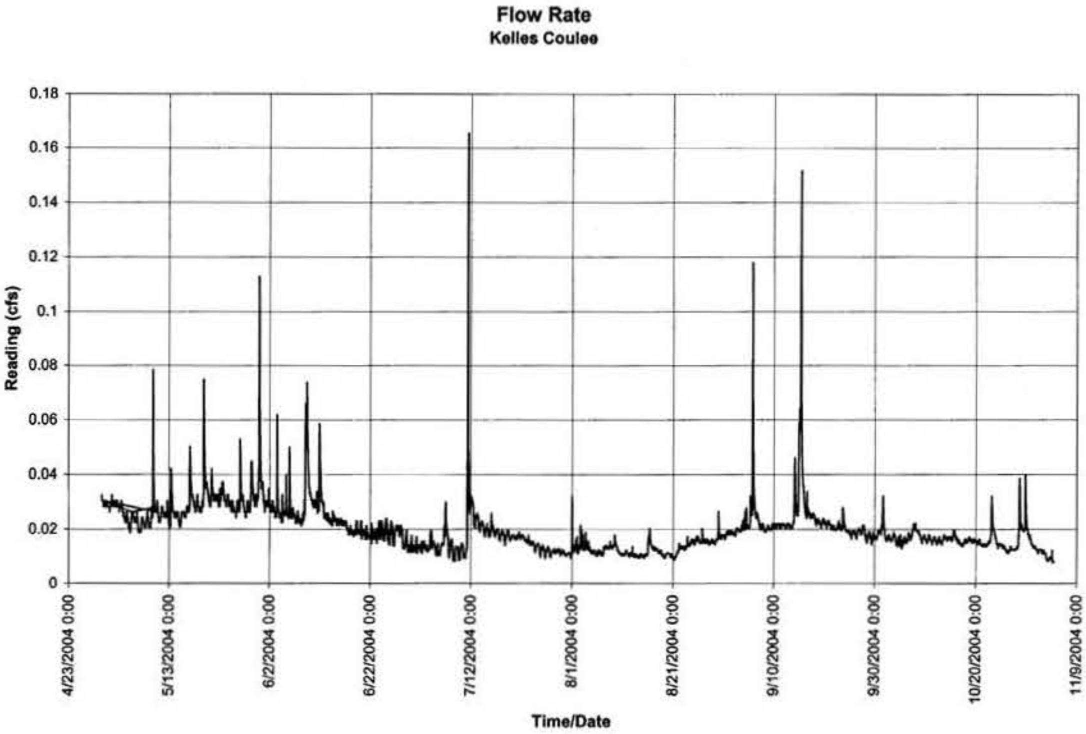

Flow Rate
Brook Creek
Reading (cfs)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5/18/2004 0:00
6/7/2004 0:00
6/27/2004 0:00
7/17/2004 0:00
8/6/2004 0:00
8/26/2004 0:00
9/15/2004 0:00
10/5/2004 0:00
10/25/2004 0:00
Date/Time

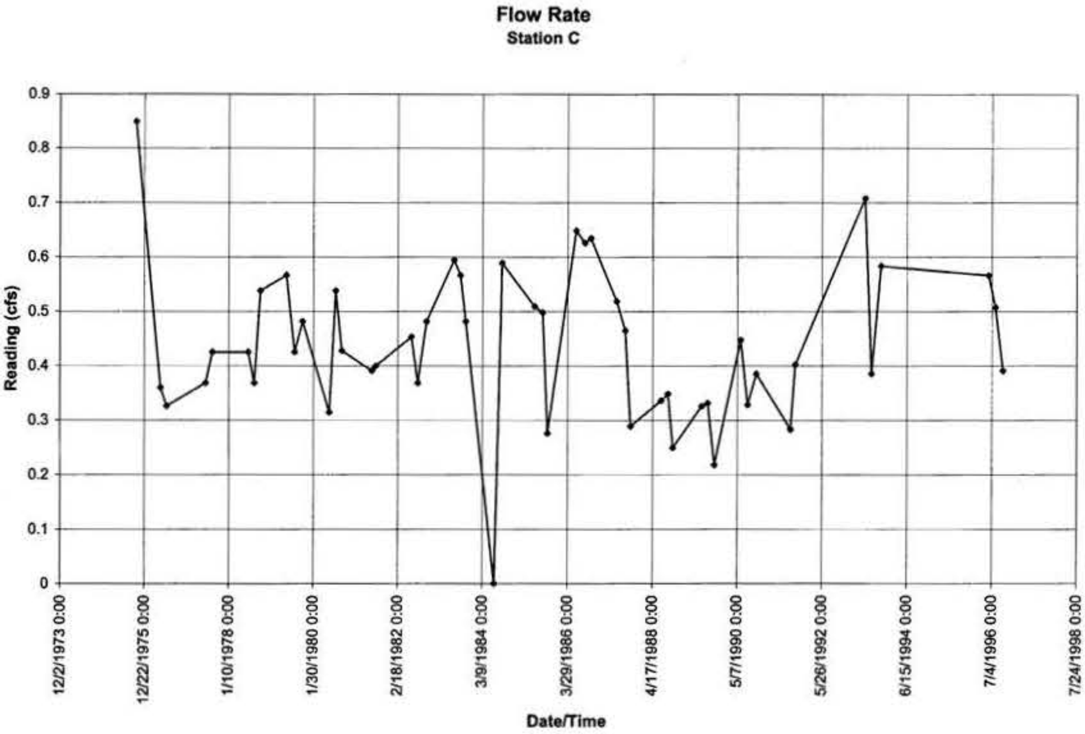
Flow Rate
Cottage Grove Ravine Park Lake Outlet



Flow Rate
Hwy 94 Rest Area Outlet




Flow Rate
Kelles Coulee
Reading (cfs)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
4/23/2004 0:00
5/13/2004 0:00
6/2/2004 0:00
6/22/2004 0:00
7/12/2004 0:00
8/1/2004 0:00
8/21/2004 0:00
9/10/2004 0:00
9/30/2004 0:00
10/20/2004 0:00
11/9/2004 0:00
Time/Date


Flow Rate
Station C
Reading (cfs)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12/2/1973 0:00
12/22/1975 0:00
1/10/1978 0:00
1/30/1980 0:00
2/18/1982 0:00
3/9/1984 0:00
3/29/1986 0:00
4/17/1988 0:00
5/7/1990 0:00
5/26/1992 0:00
6/15/1994 0:00
7/4/1996 0:00
7/24/1998 0:00
Date/Time

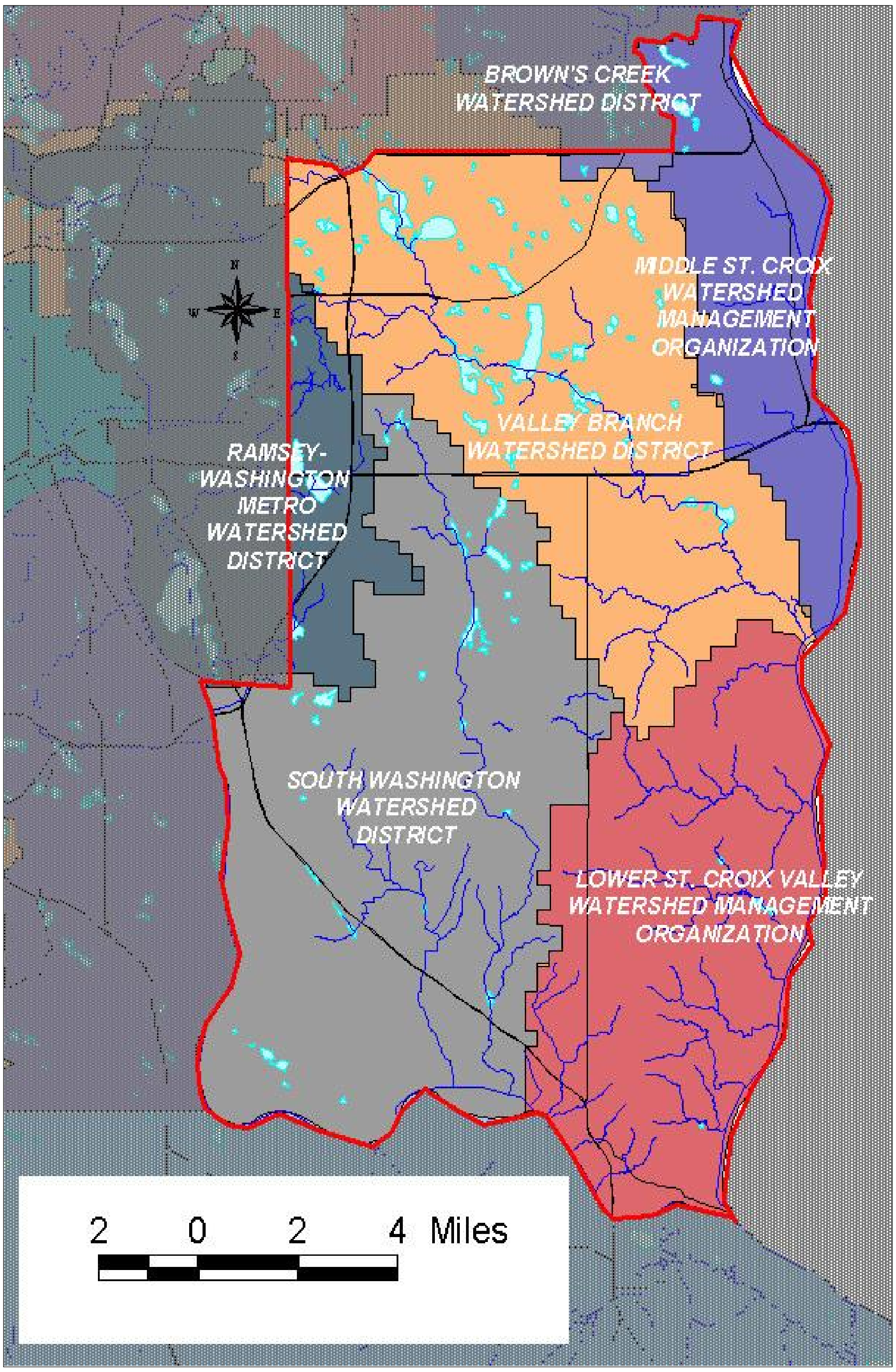


Figure 1

Location of Study Area and Watershed Districts/Management Organizations

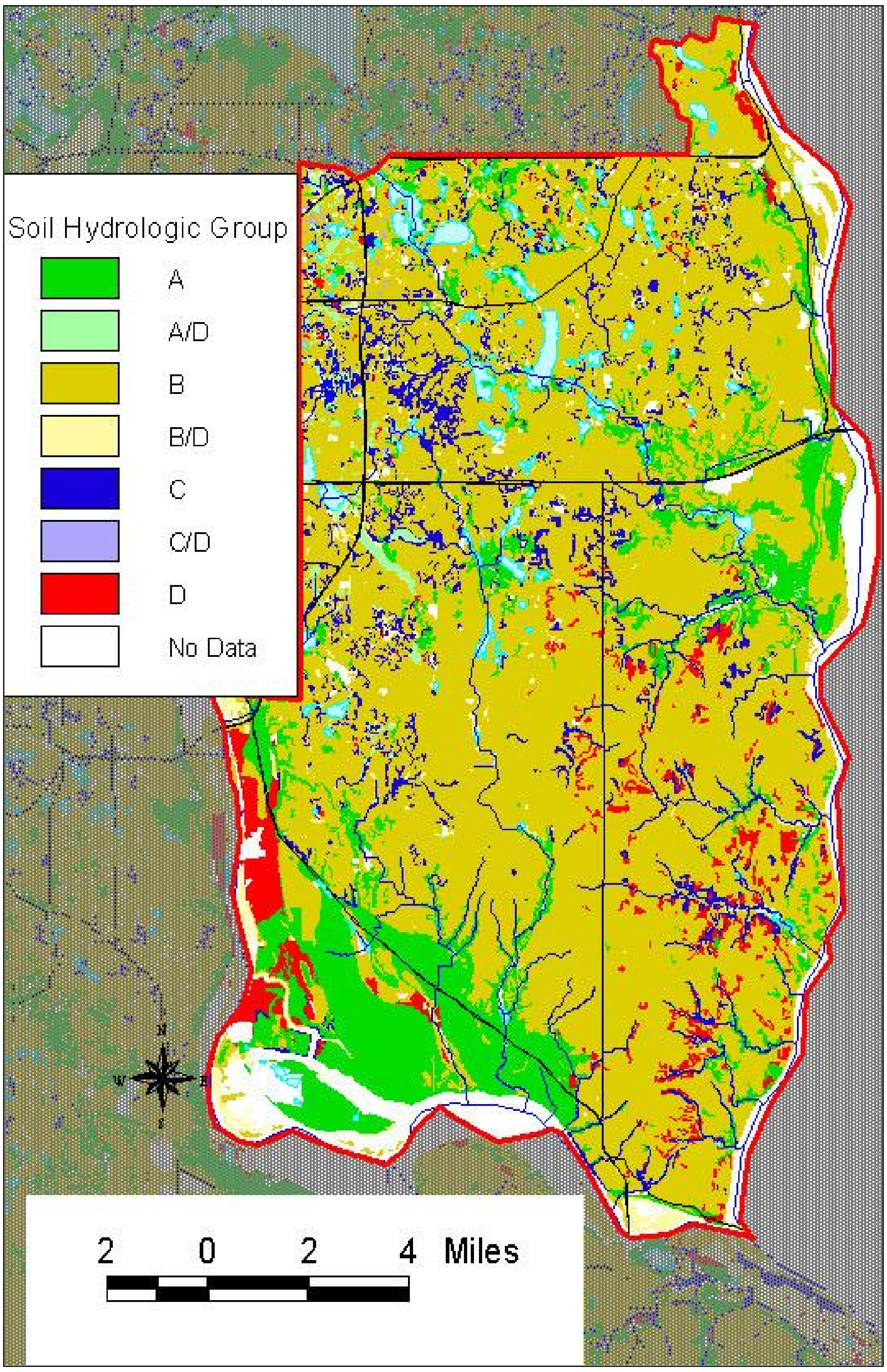


Figure 2

Soils Classified by Hydrologic Group

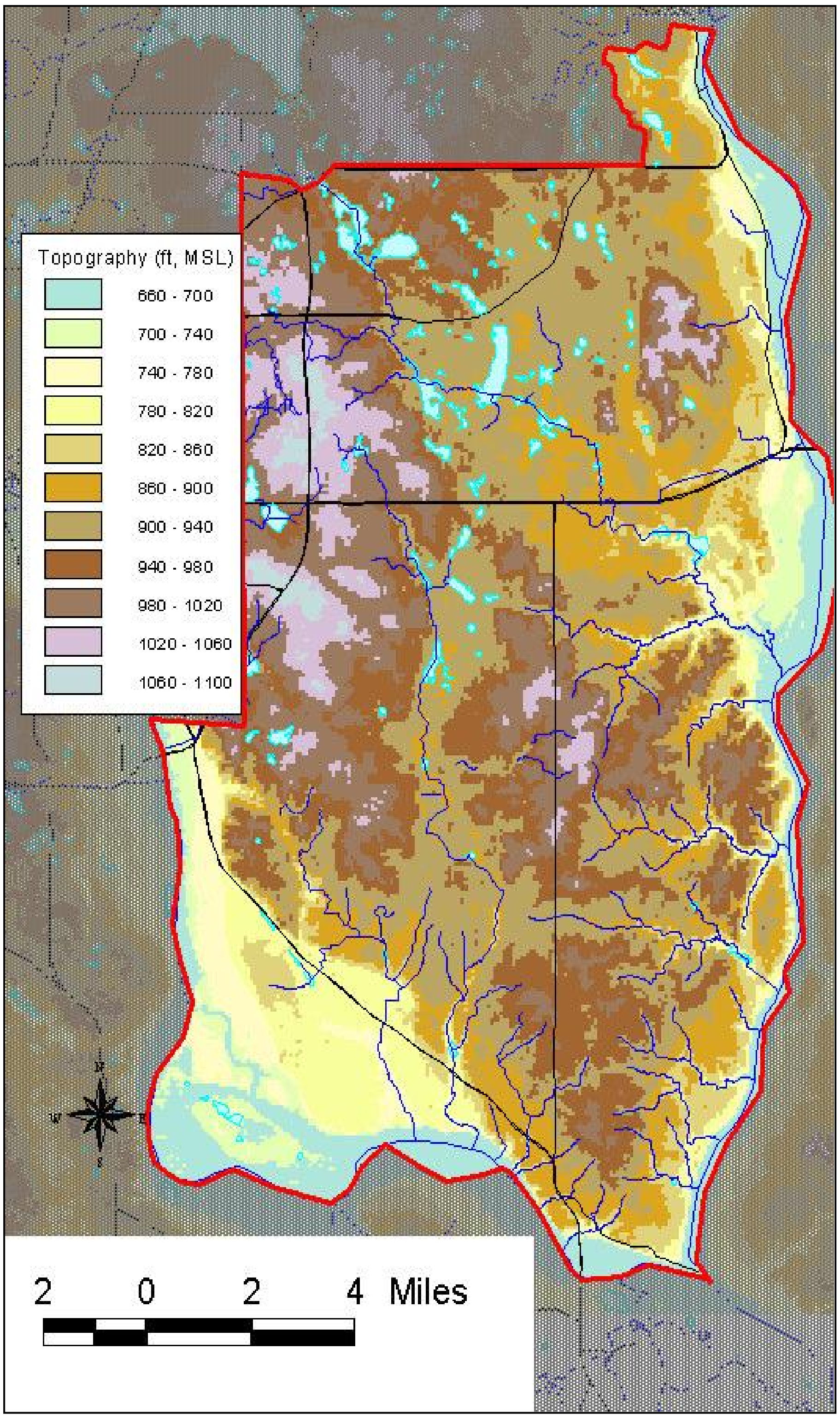
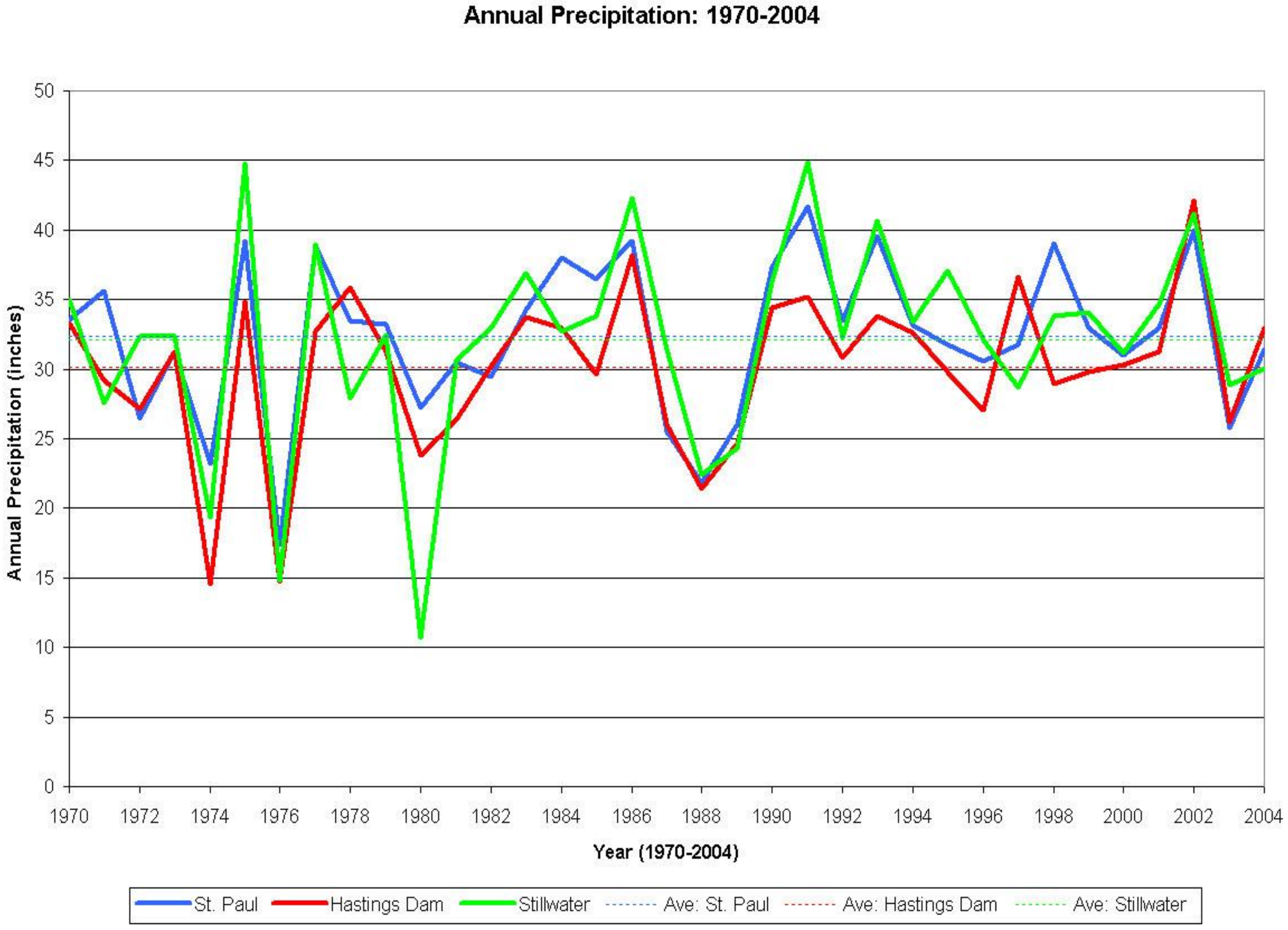


Figure 3

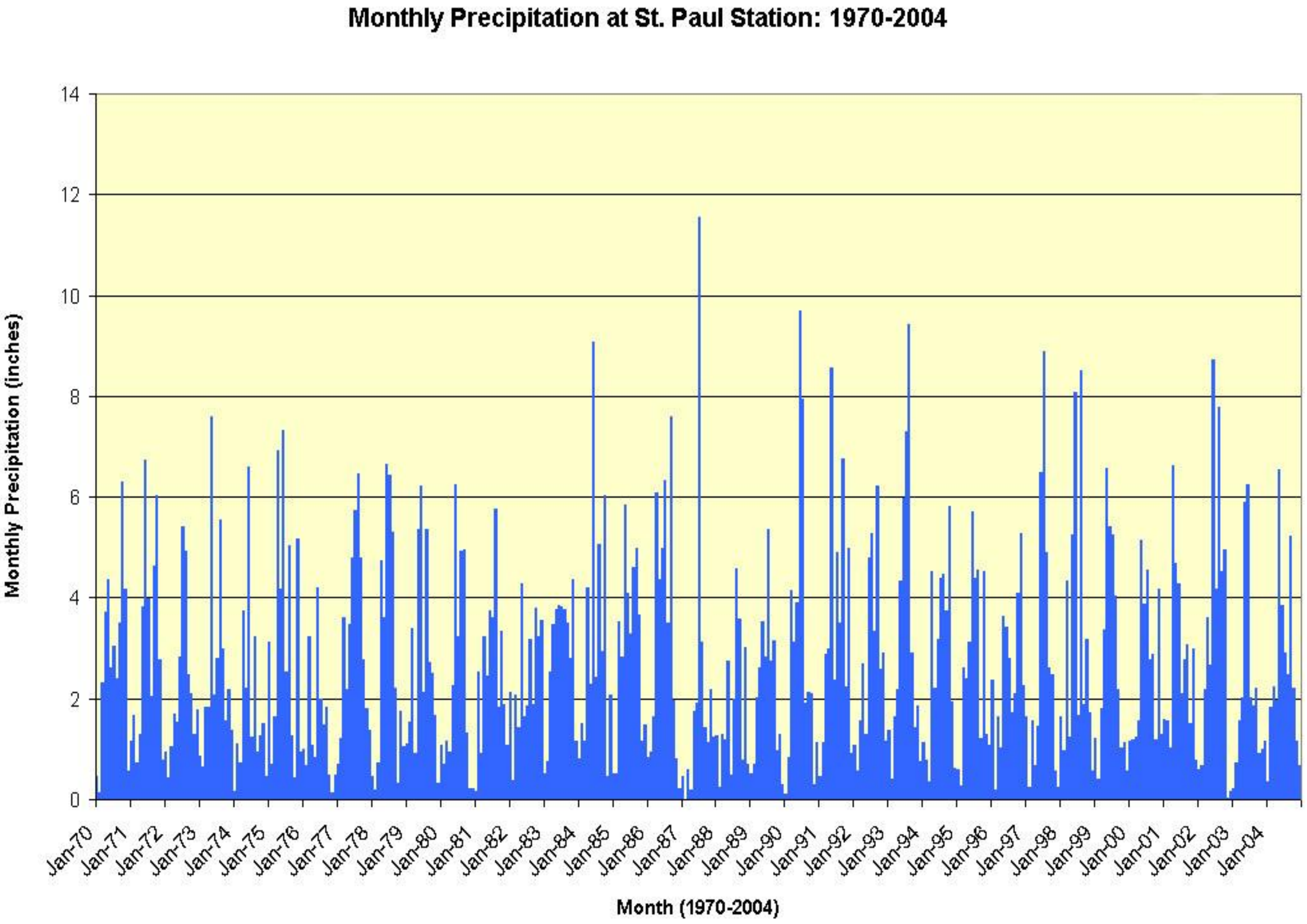
Ground-Surface Topography (feet, MSL)



Source: State Climatological Office

Figure 4

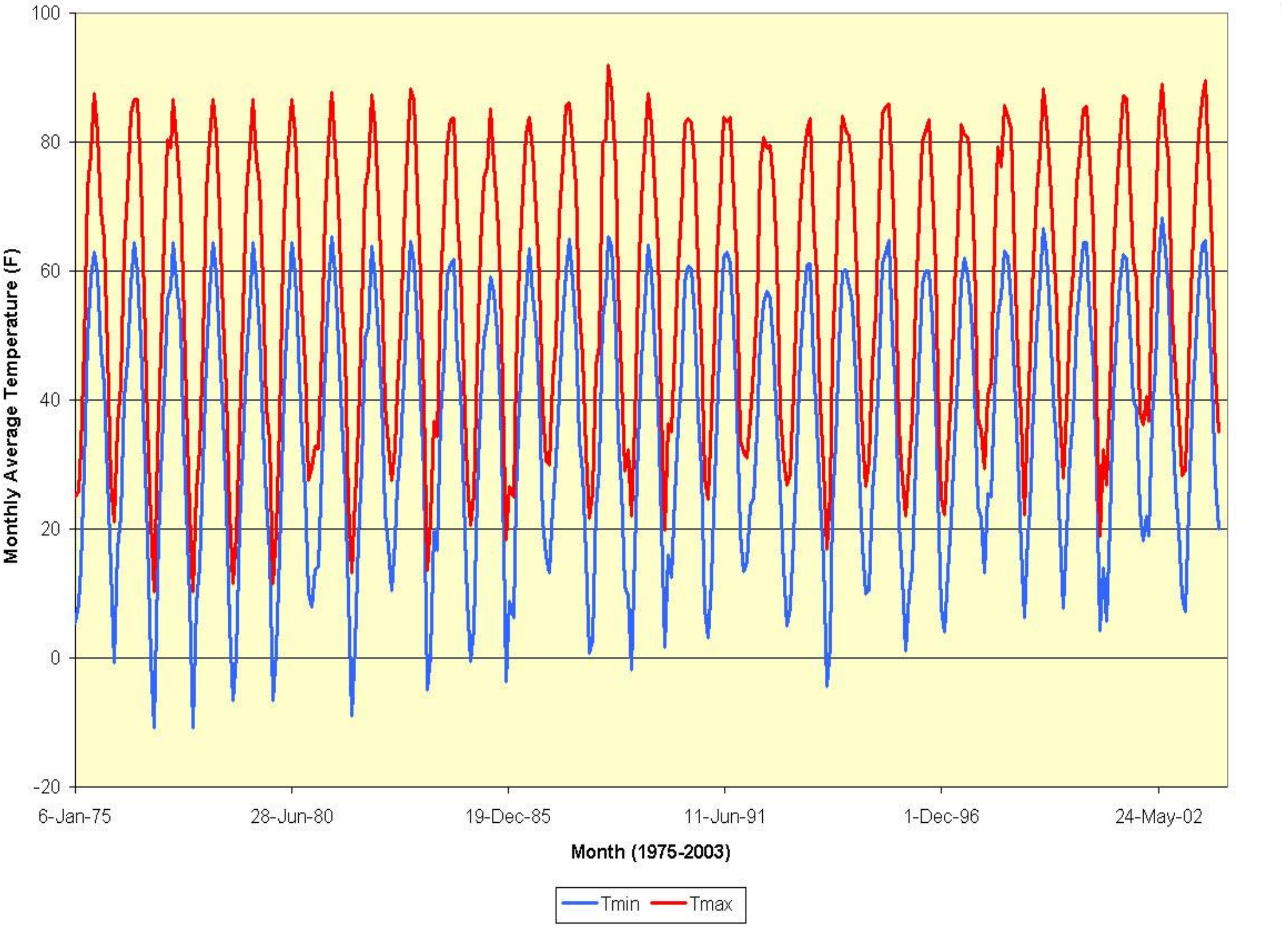
Annual Precipitation (inches) at Three Meteorological Stations in and Near Southern Washington County (1970-2004)



Source: State Climatological Office

Figure 5

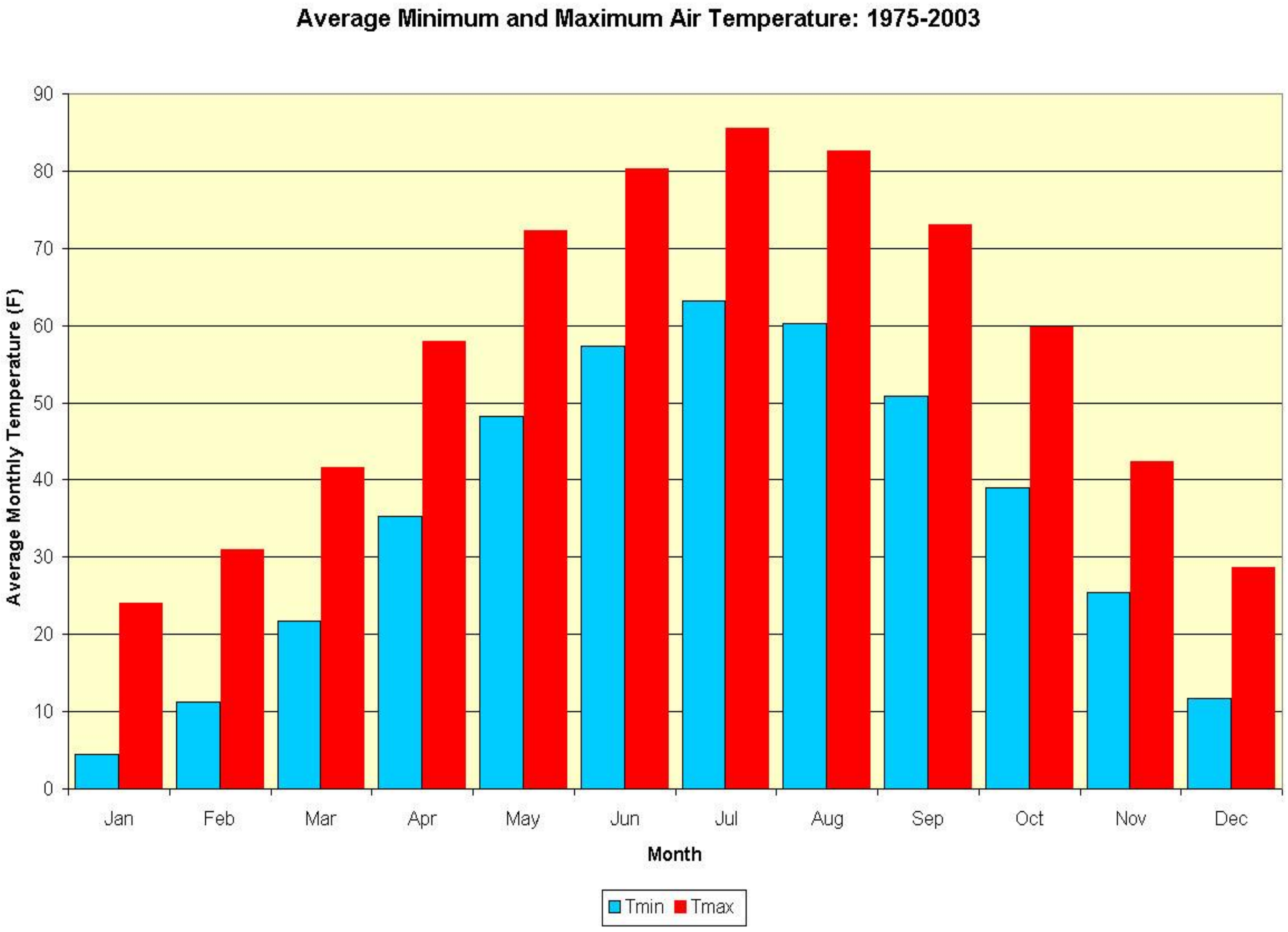
Monthly Precipitation (inches) at St. Paul (1970-2004)



Source: State Climatological Office

Figure 6

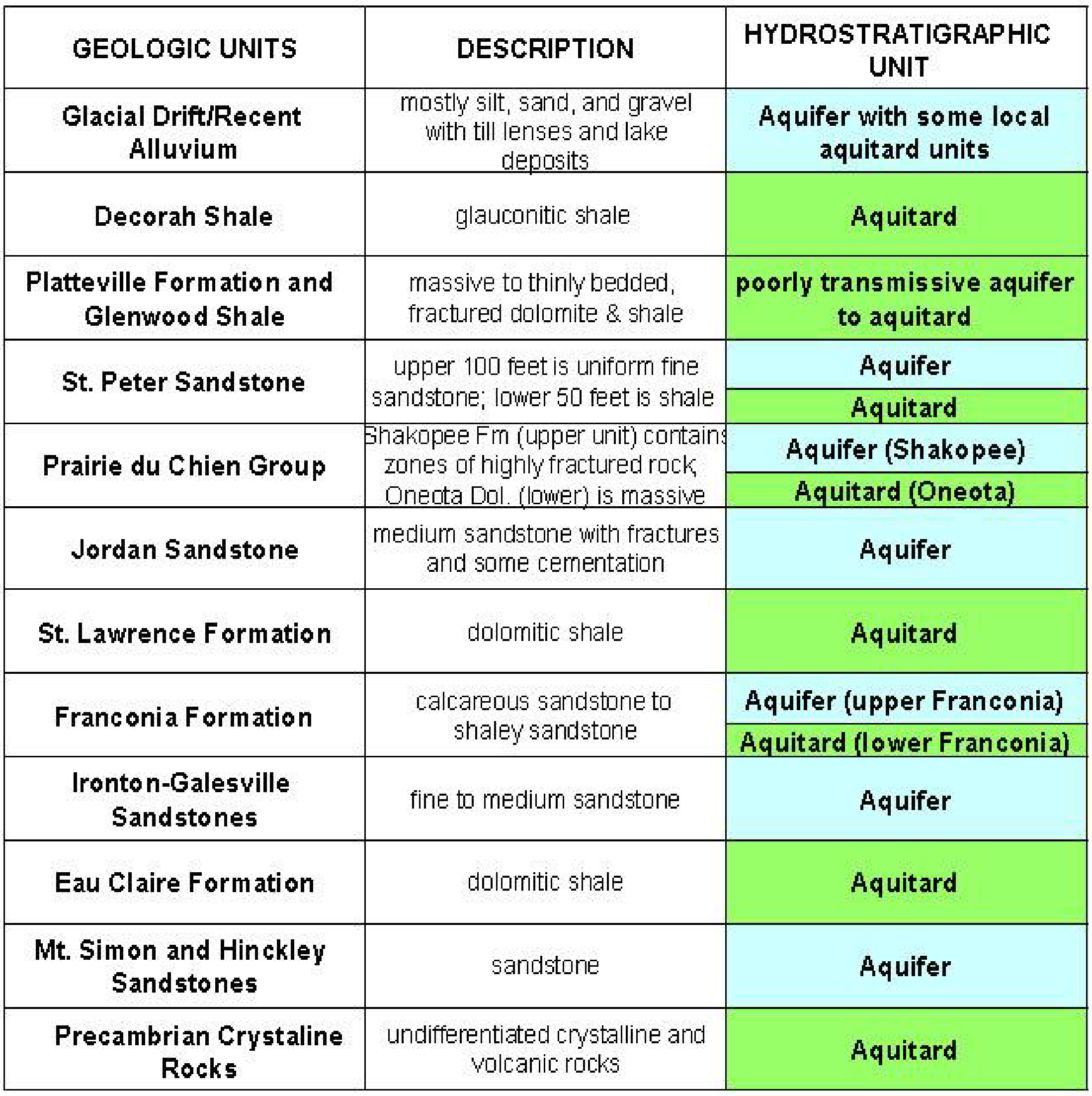
Monthly Maximum and Minimum Air Temperature (^{o}F) at St. Paul (1975-2003)



Source: State Climatological Office

Figure 7

Average Minimum and Maximum Air Temperature (^{o}F) by Month for Period 1975-2003



GEOLOGIC UNITS	DESCRIPTION	HYDROSTRATIGRAPHIC UNIT
Glacial Drift/Recent Alluvium	mostly silt, sand, and gravel with till lenses and lake deposits	Aquifer with some local aquitard units
Decorah Shale	glauconitic shale	Aquitard
Platteville Formation and Glenwood Shale	massive to thinly bedded, fractured dolomite & shale	poorly transmissive aquifer to aquitard
St. Peter Sandstone	upper 100 feet is uniform fine sandstone; lower 50 feet is shale	Aquifer Aquitard
Prairie du Chien Group	Shakopee Fm (upper unit) contains zones of highly fractured rock; Oneota Dol. (lower) is massive	Aquifer (Shakopee) Aquitard (Oneota)
Jordan Sandstone	medium sandstone with fractures and some cementation	Aquifer
St. Lawrence Formation	dolomitic shale	Aquitard
Franconia Formation	calcareous sandstone to shaley sandstone	Aquifer (upper Franconia) Aquitard (lower Franconia)
Ironton-Galesville Sandstones	fine to medium sandstone	Aquifer
Eau Claire Formation	dolomitic shale	Aquitard
Mt. Simon and Hinckley Sandstones	sandstone	Aquifer
Precambrian Crystaline Rocks	undifferentiated crystalline and volcanic rocks	Aquitard

Figure 8

Hydrostratigraphic Column of Southern Washington County

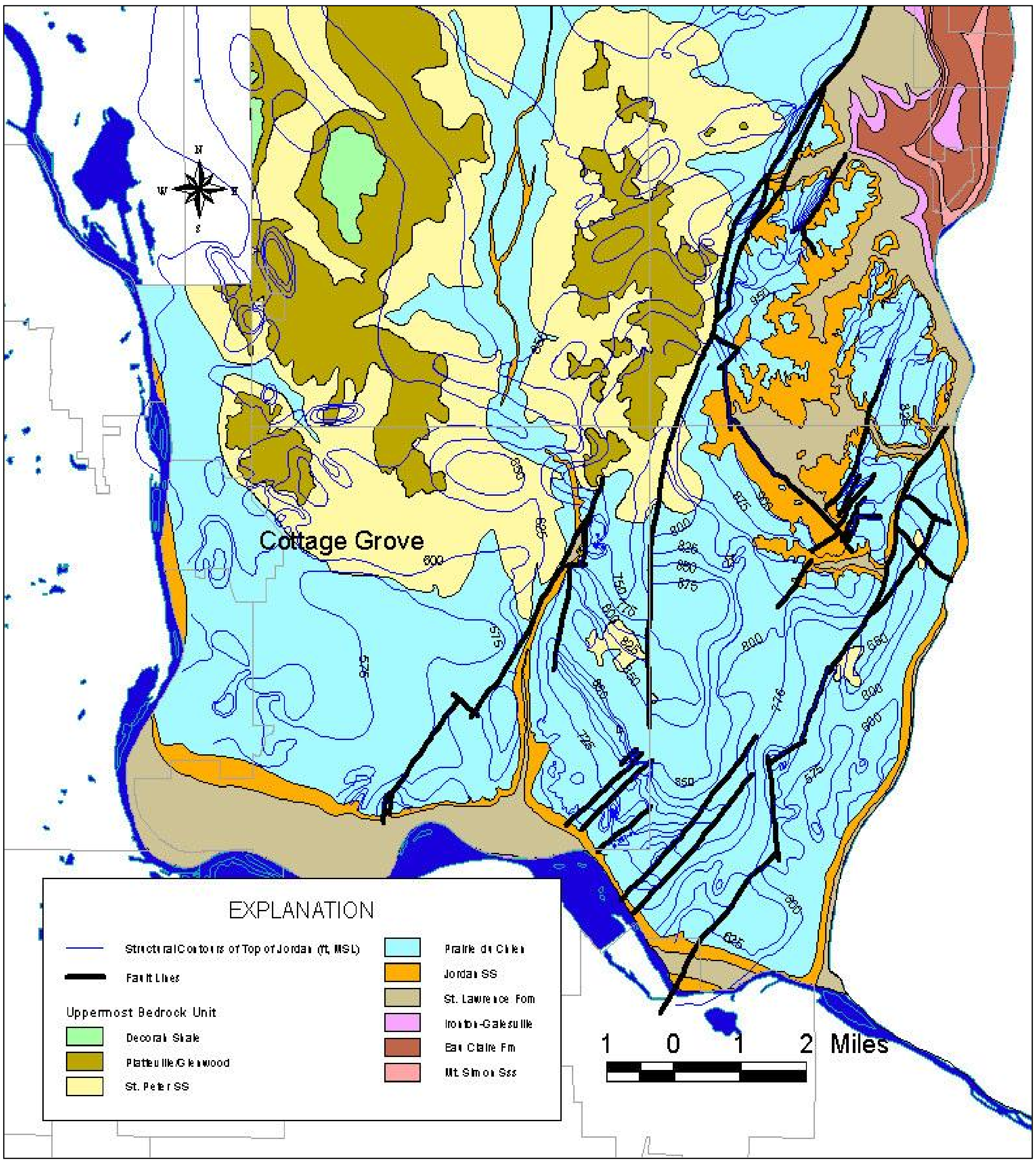


Figure 9

Location of Faults in Southern Washington County

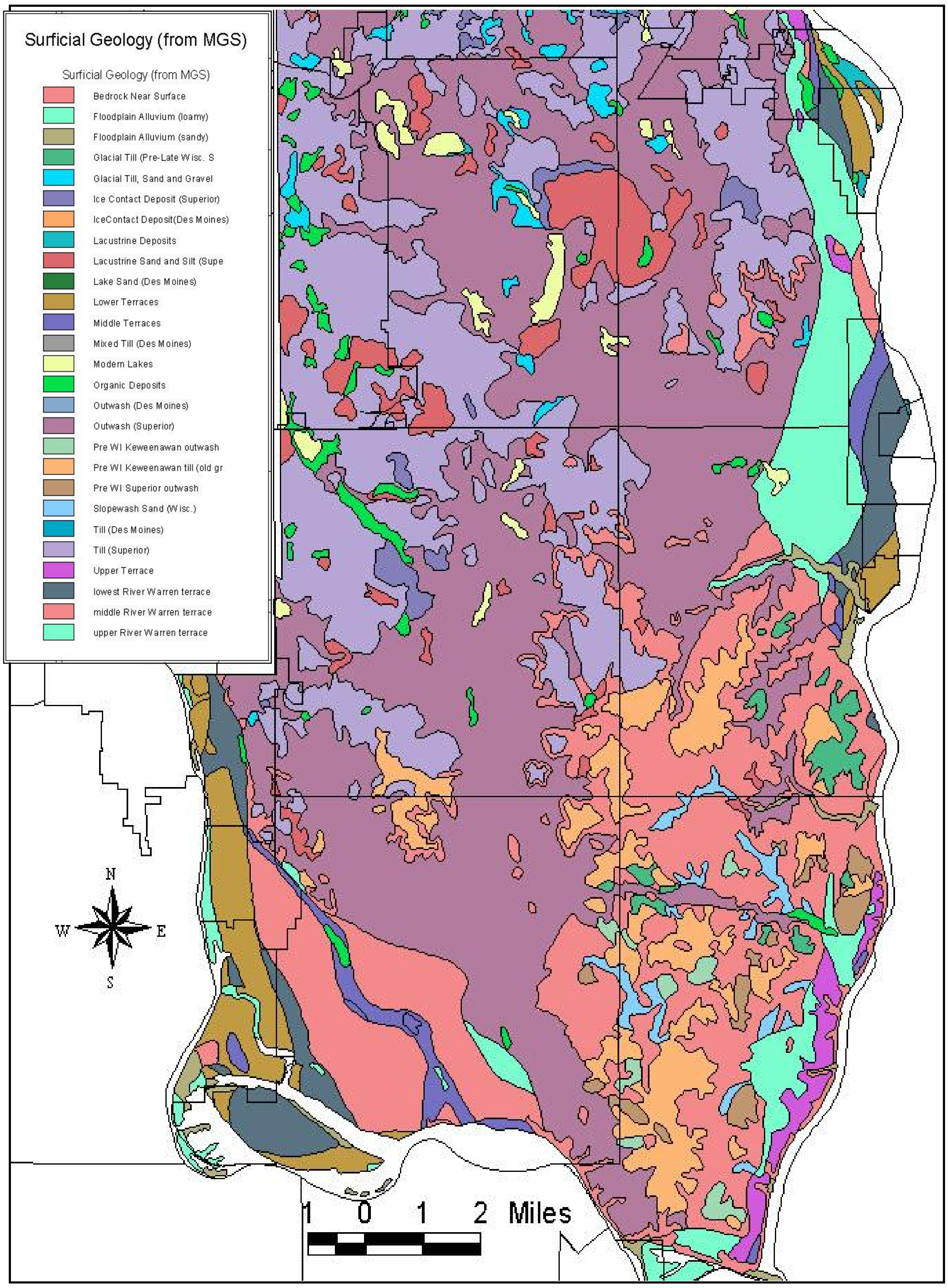
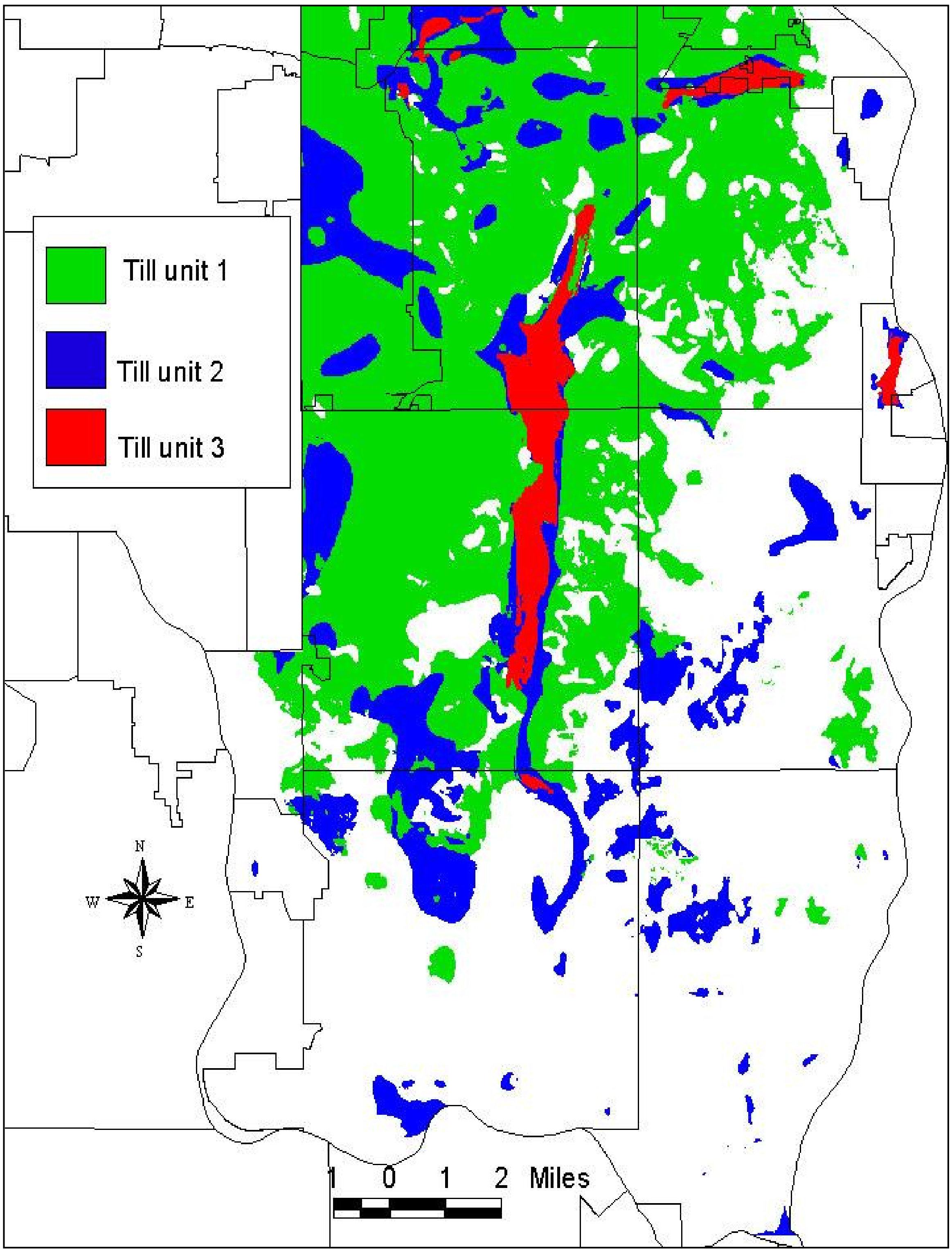


Figure 10

Surficial Geology of Southern Washington County



(adapted from MGS Grid Data)

Figure 11

Glacial Till Units in South Washington County

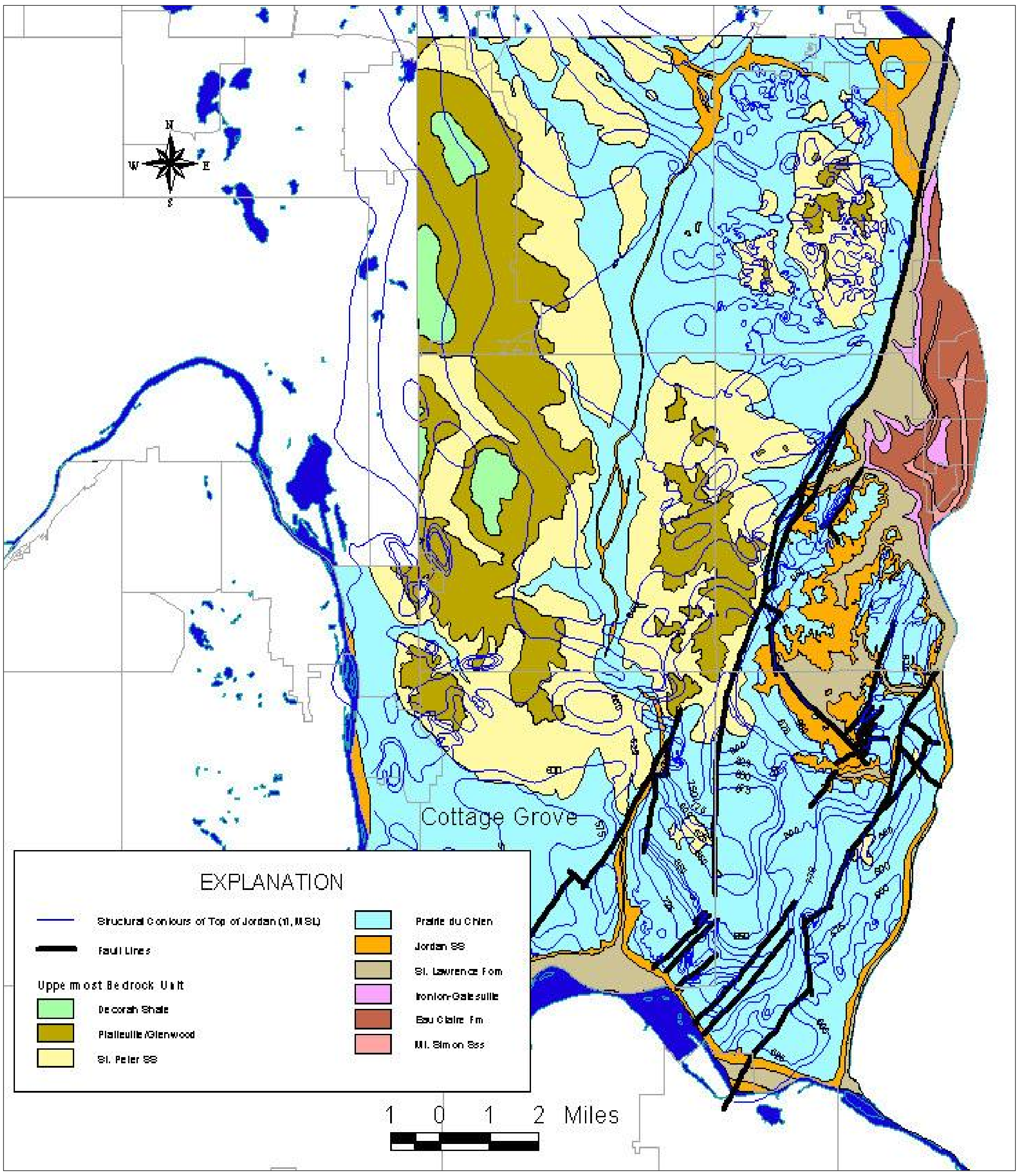


Figure 12

Uppermost Bedrock Units in Southern Washington County

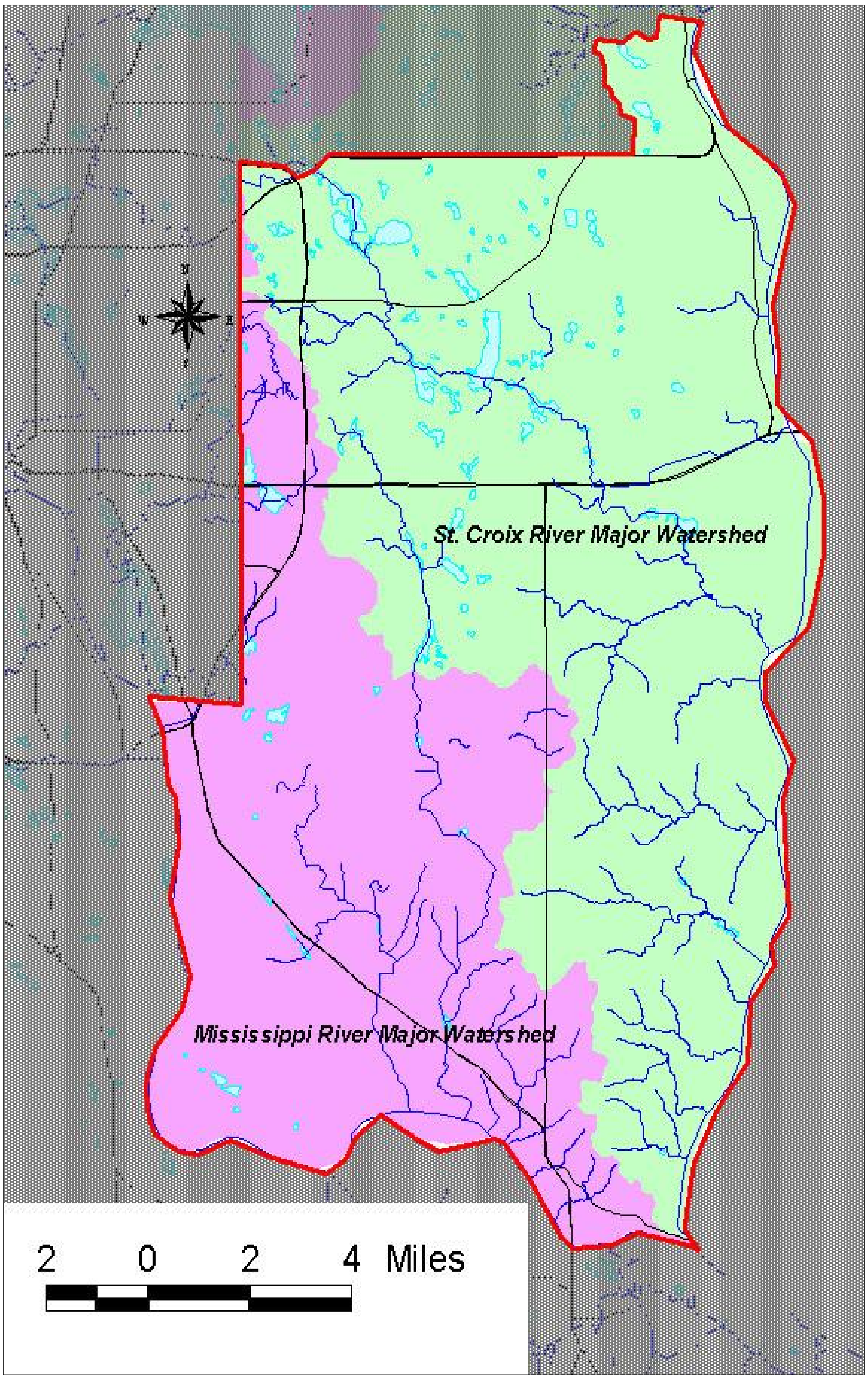
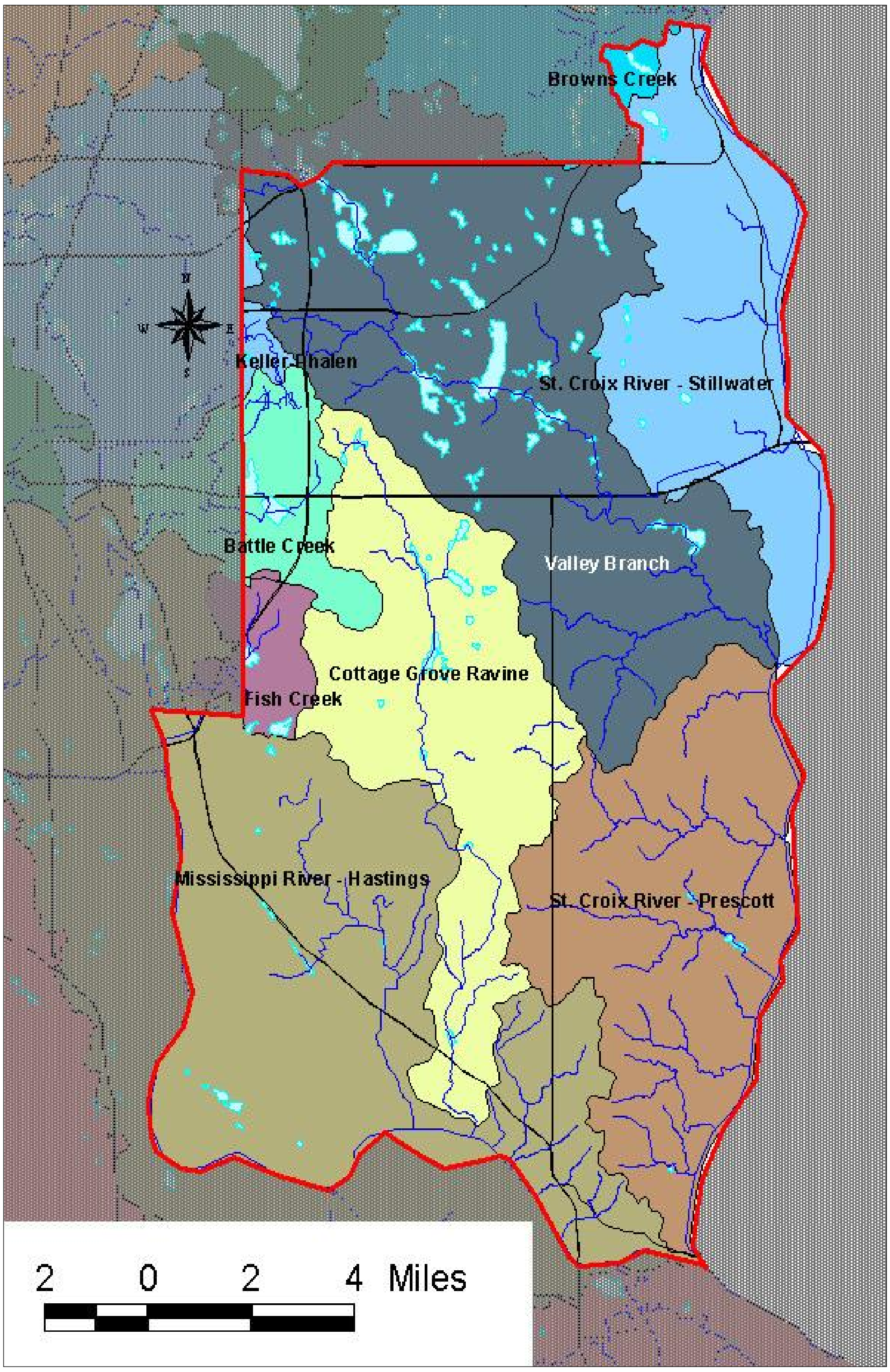


Figure 13

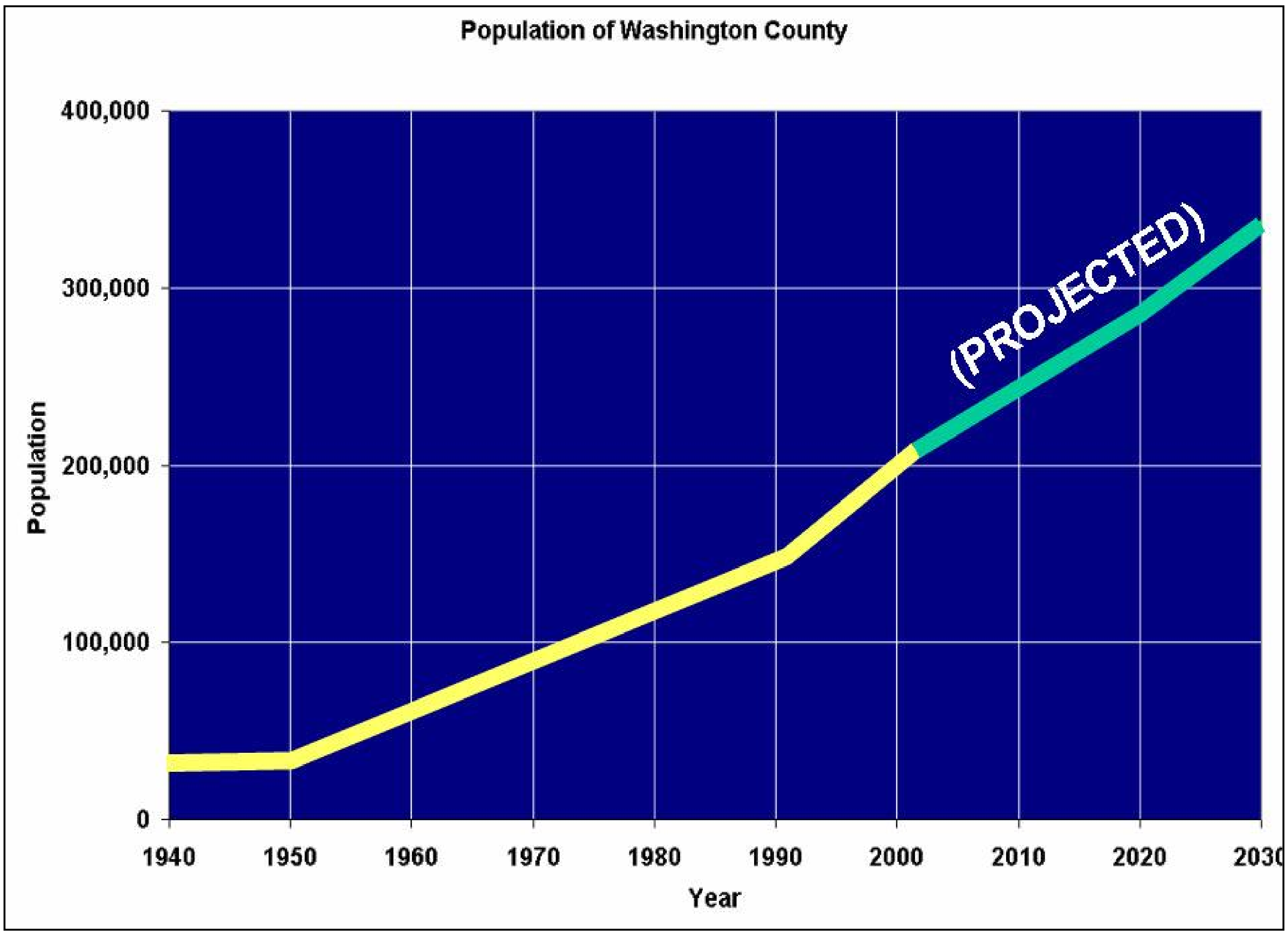
Major Watersheds in Southern Washington County



(from Metropolitan Council)

Figure 14

Secondary Watersheds in Southern Washington County



Source: U.S. Census Bureau and Washington County

Figure 15

Population of Washington County: Past and Projected

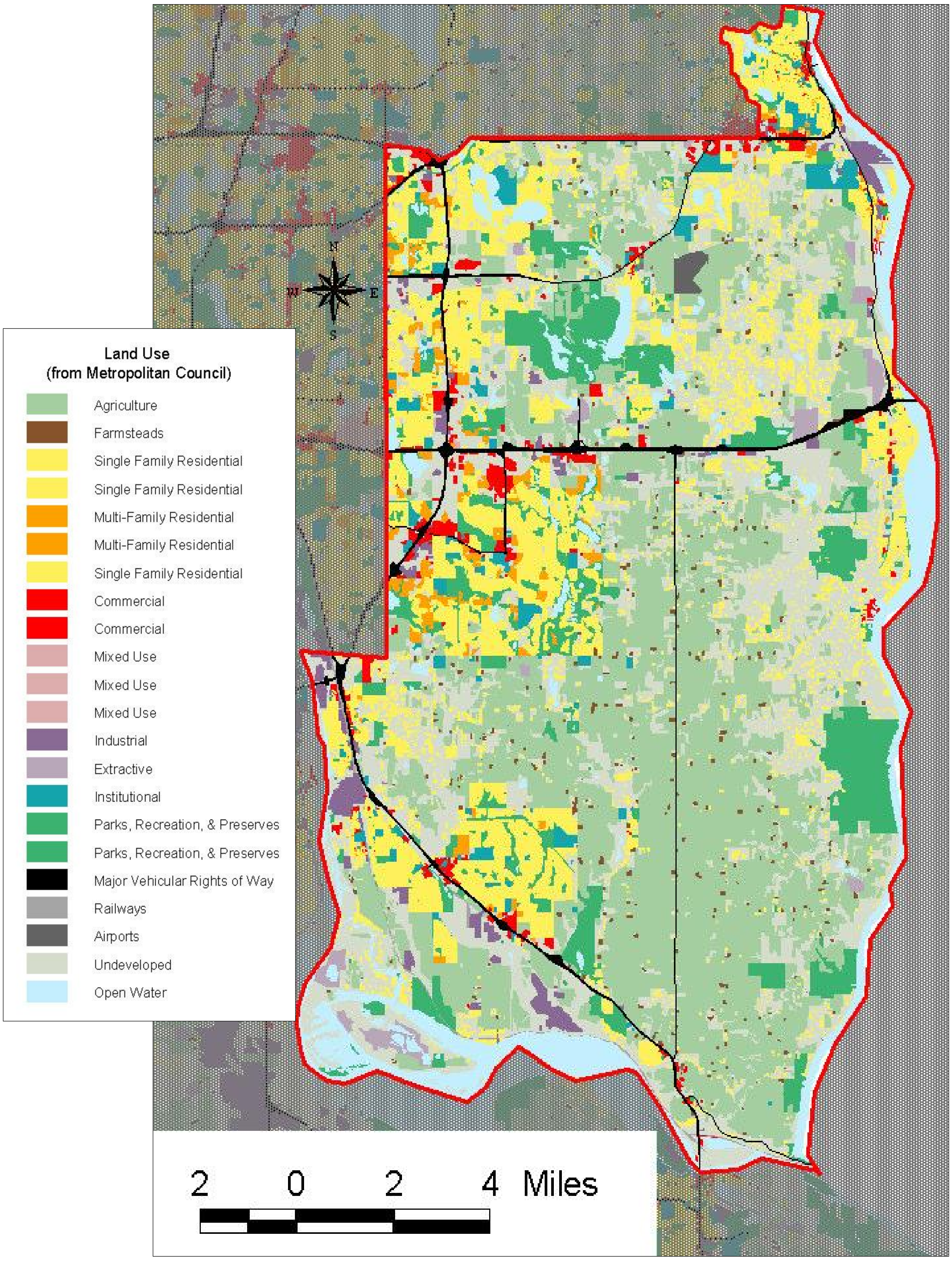


Figure 16

Land Use: Year 2000

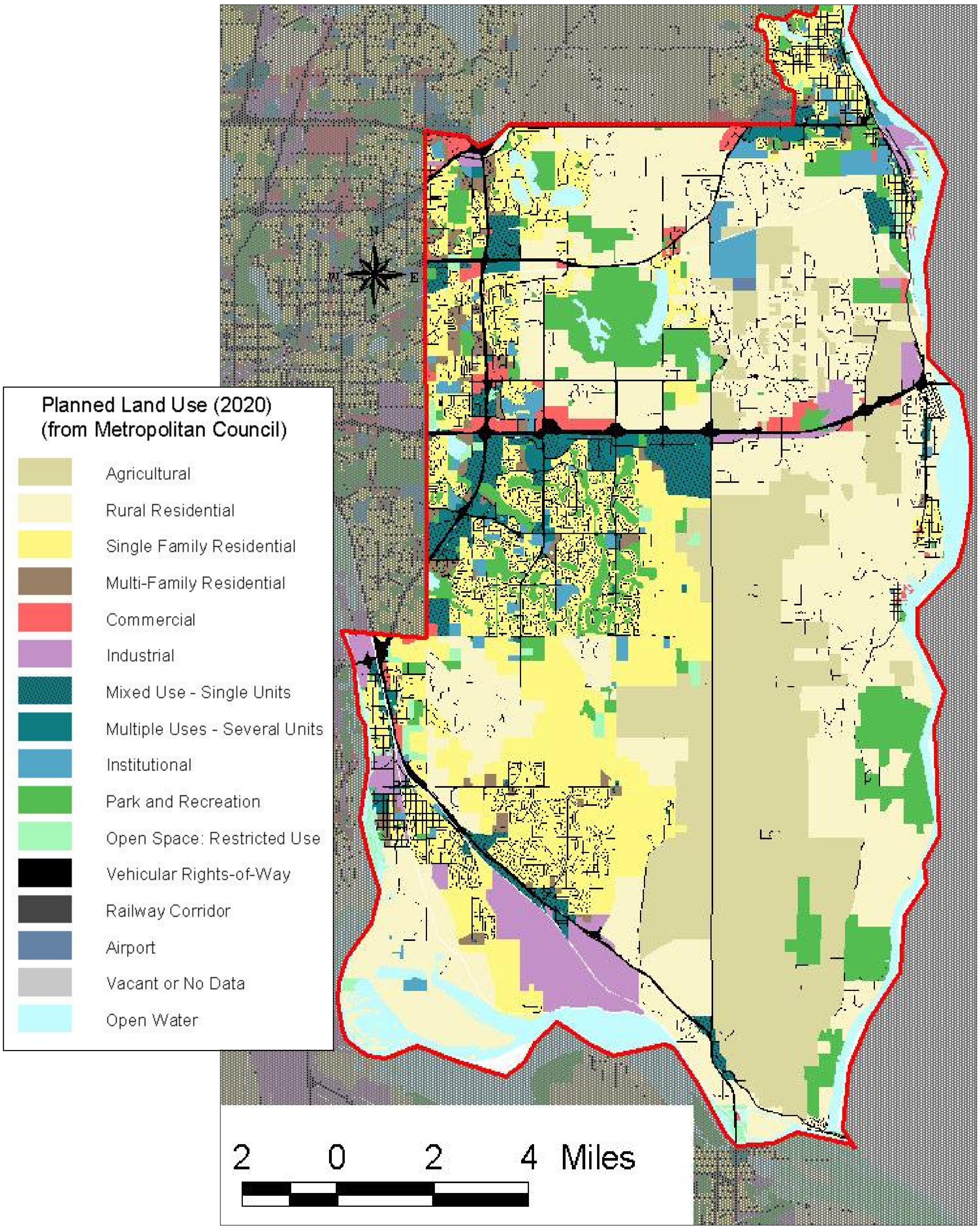


Figure 17

Planned Land Use: Year 2020

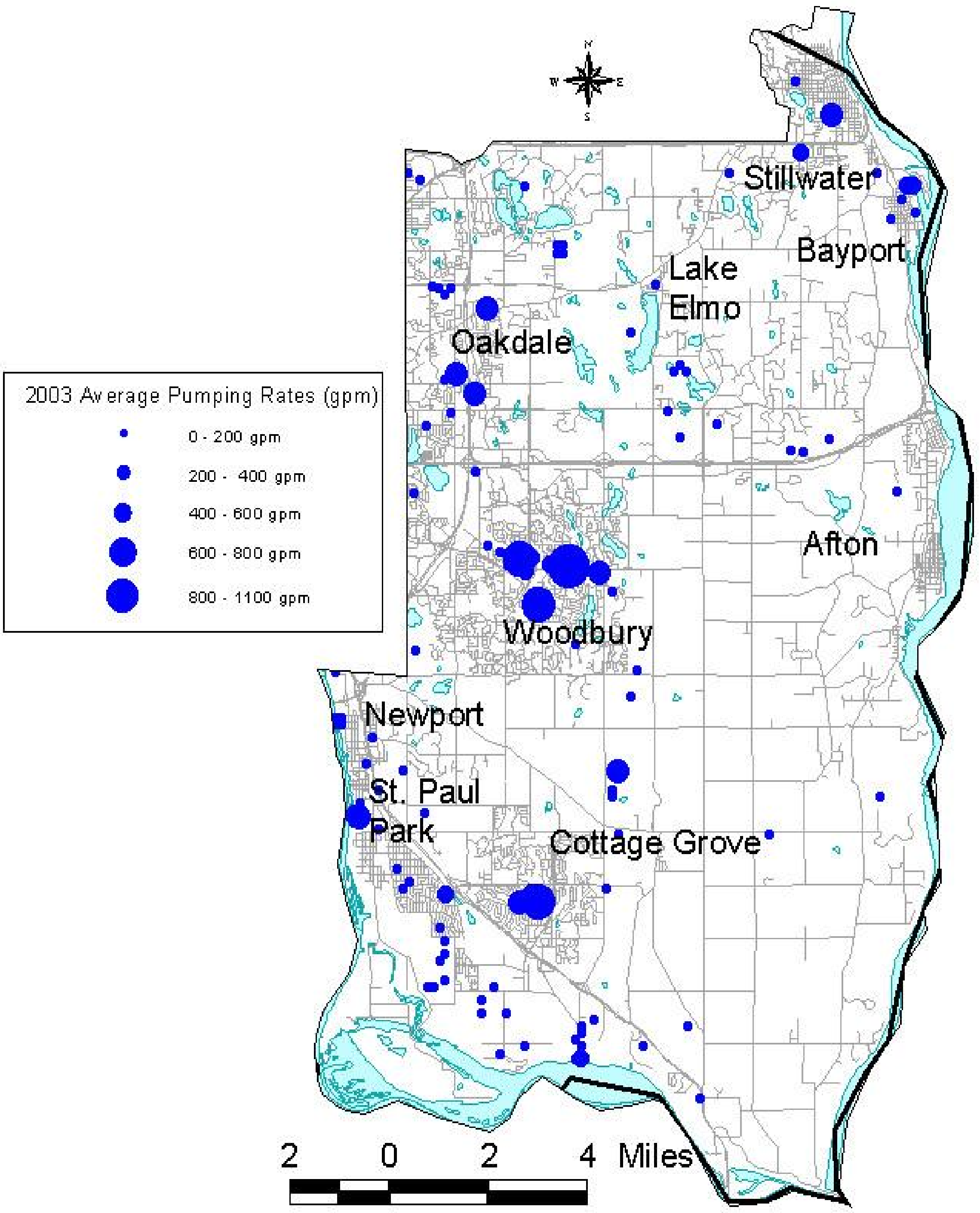


Figure 18

Average Annual Appropriated Groundwater Pumping in Southern Washington County for 2003

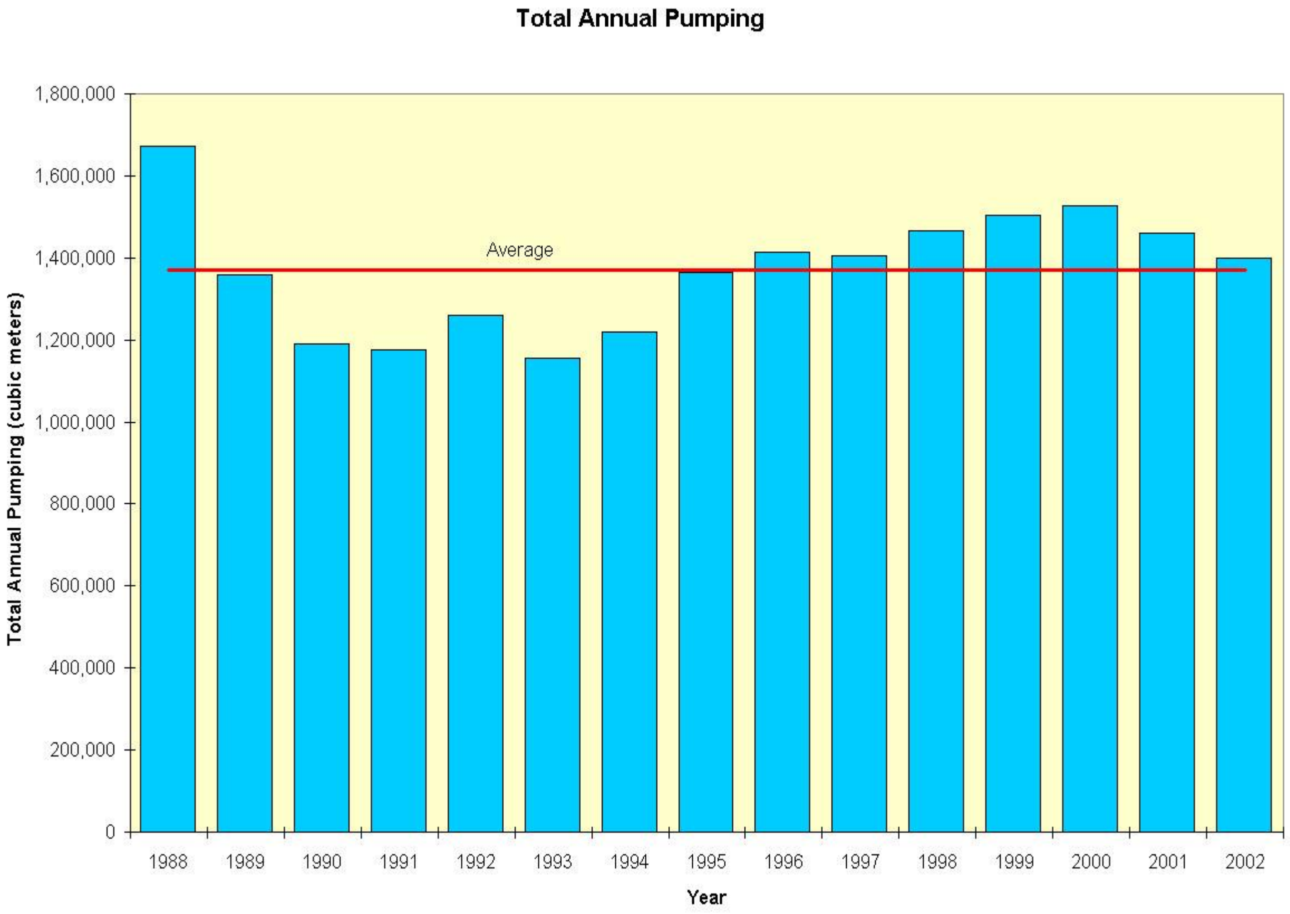


Figure 19

Annual Pumping in Southern Washington County: 1988-2002

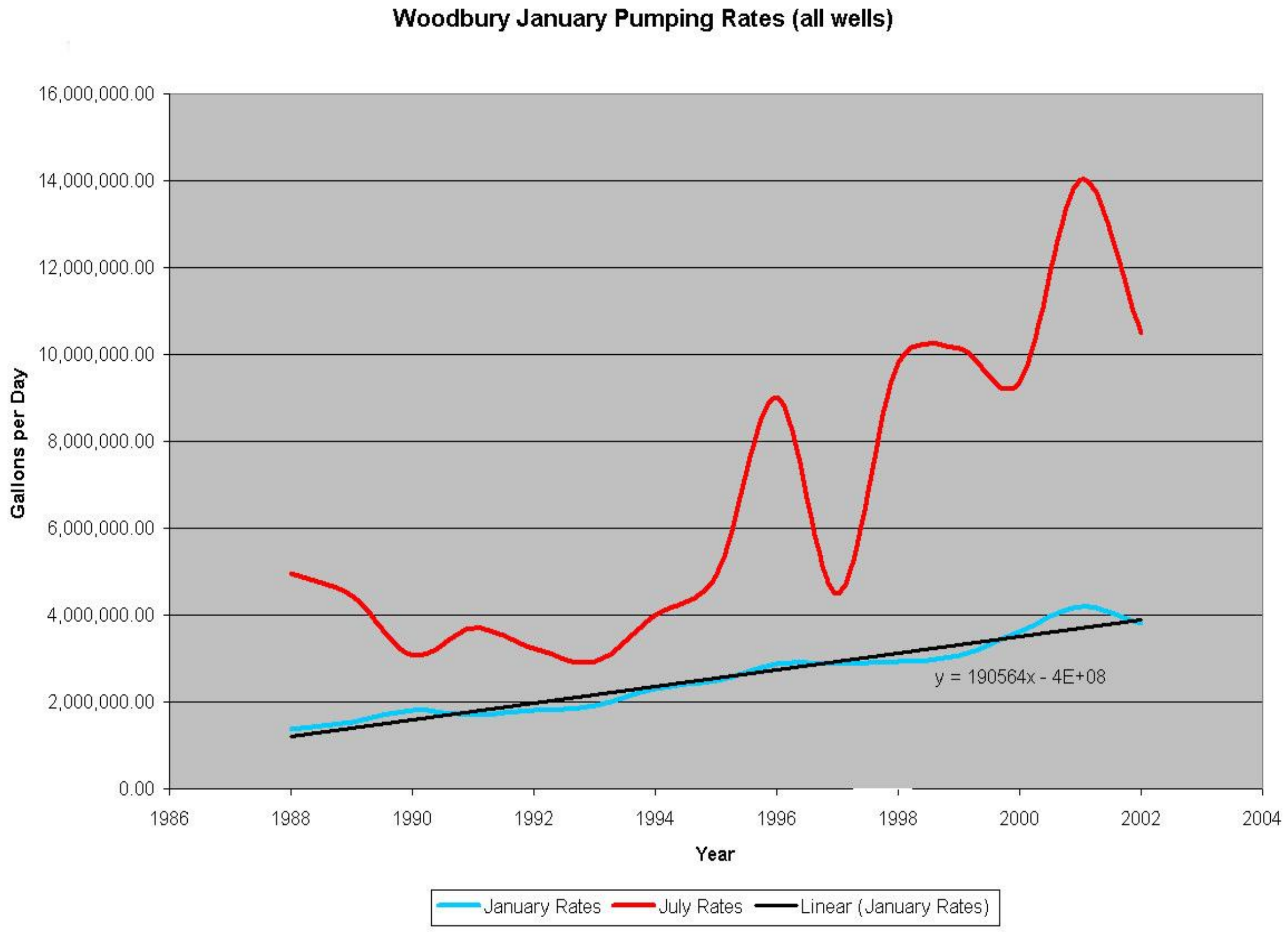


Figure 20

Comparison of January and July Pumping Rates for Woodbury: 1989-2002

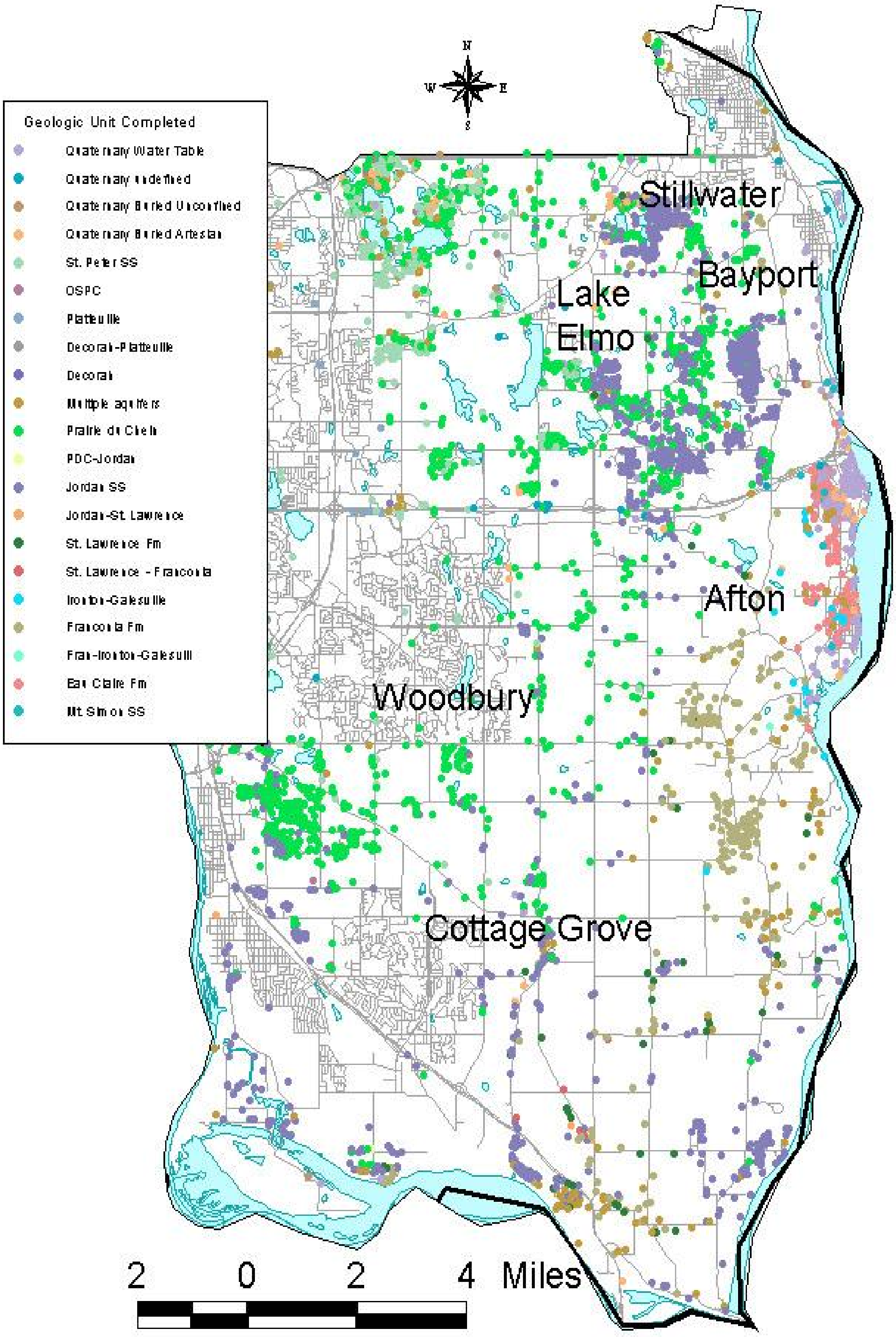


Figure 21

Domestic Wells Listed in County Well Index within Study Area

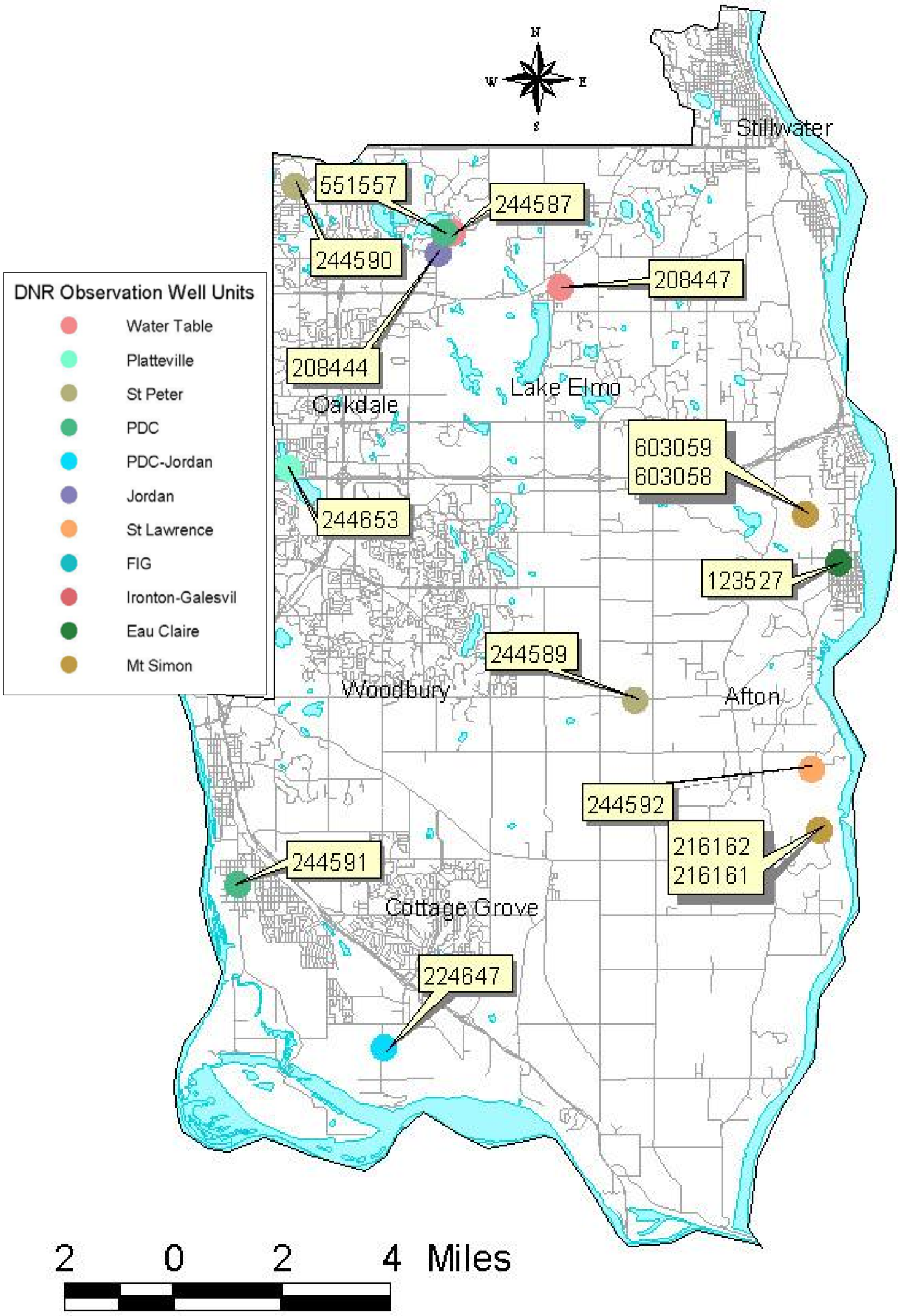
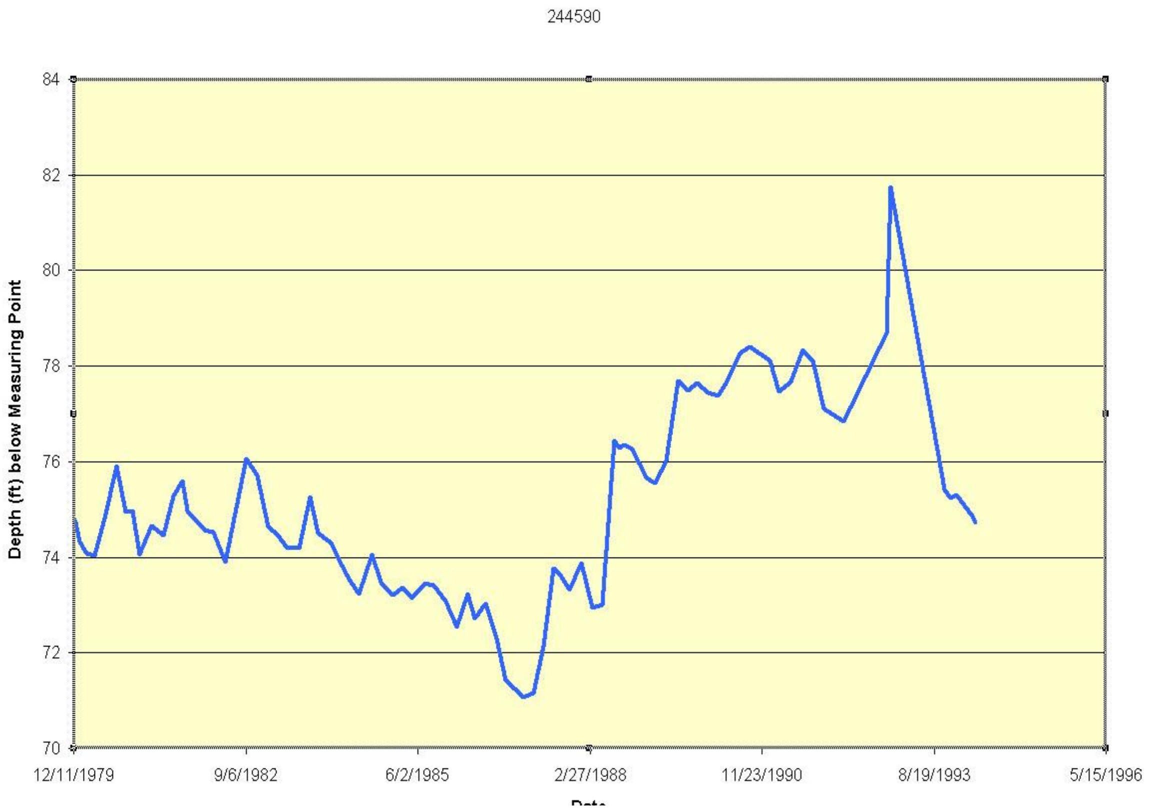


Figure 22

DNR Observation Wells in Study Areas

Figure 23

Water Level Fluctuations in DNR Observation Wells 208447 and 224647



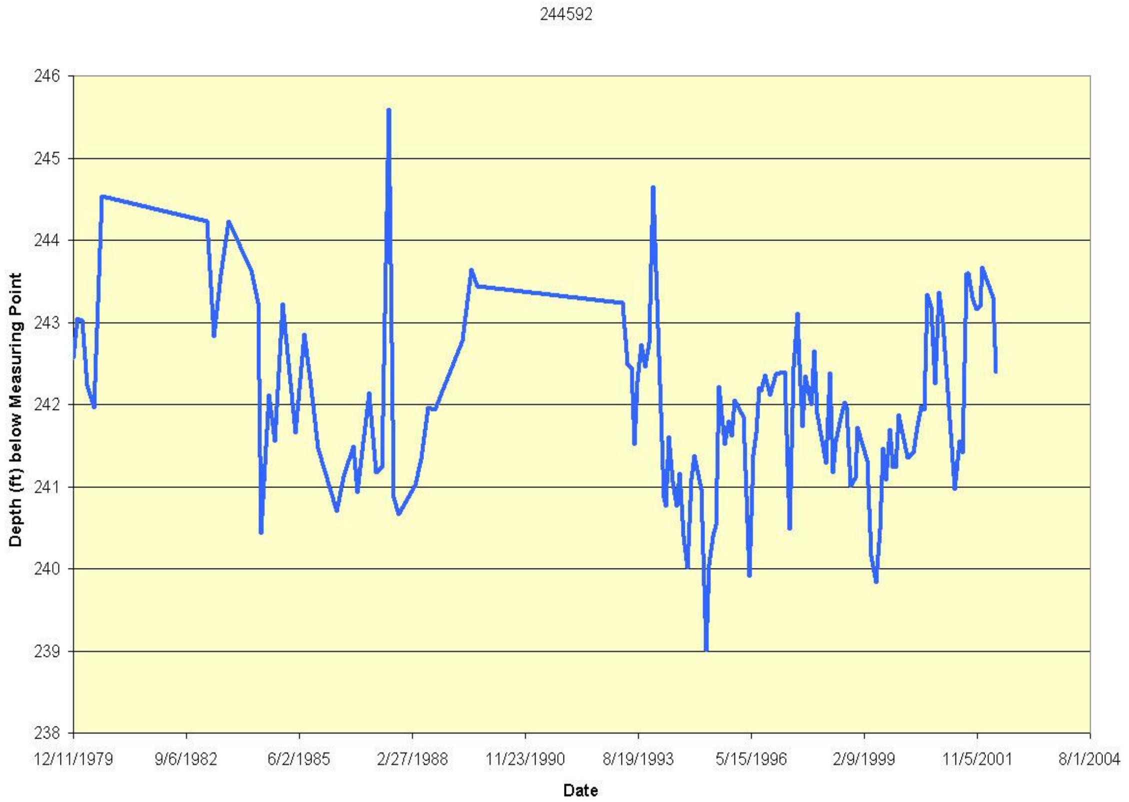


Figure 24

Water Level Fluctuations in DNR Observation Wells 244590 and 24592

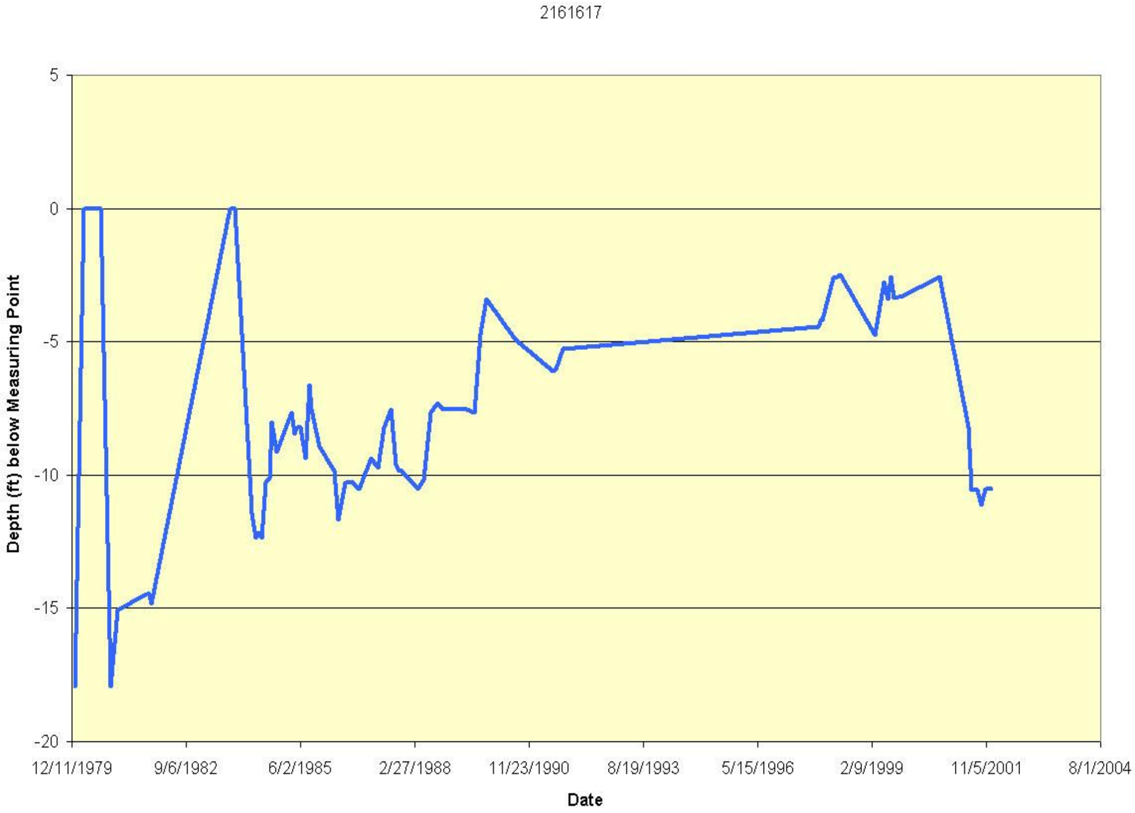


Figure 25

Water Level Fluctuations in DNR Observation Well 216161

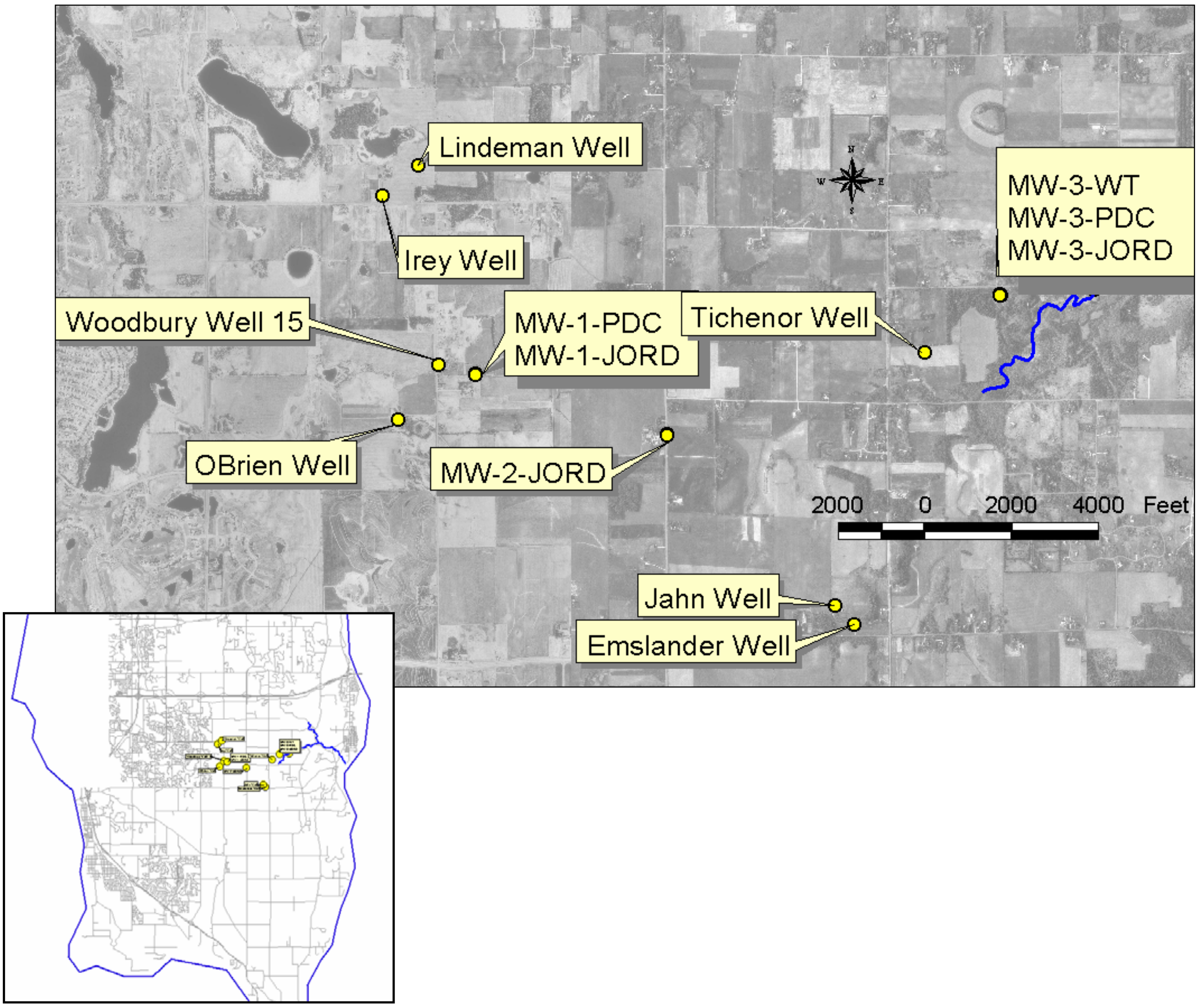


Figure 26

Location of Wells for Woodbury Well 15 Aquifer Tests

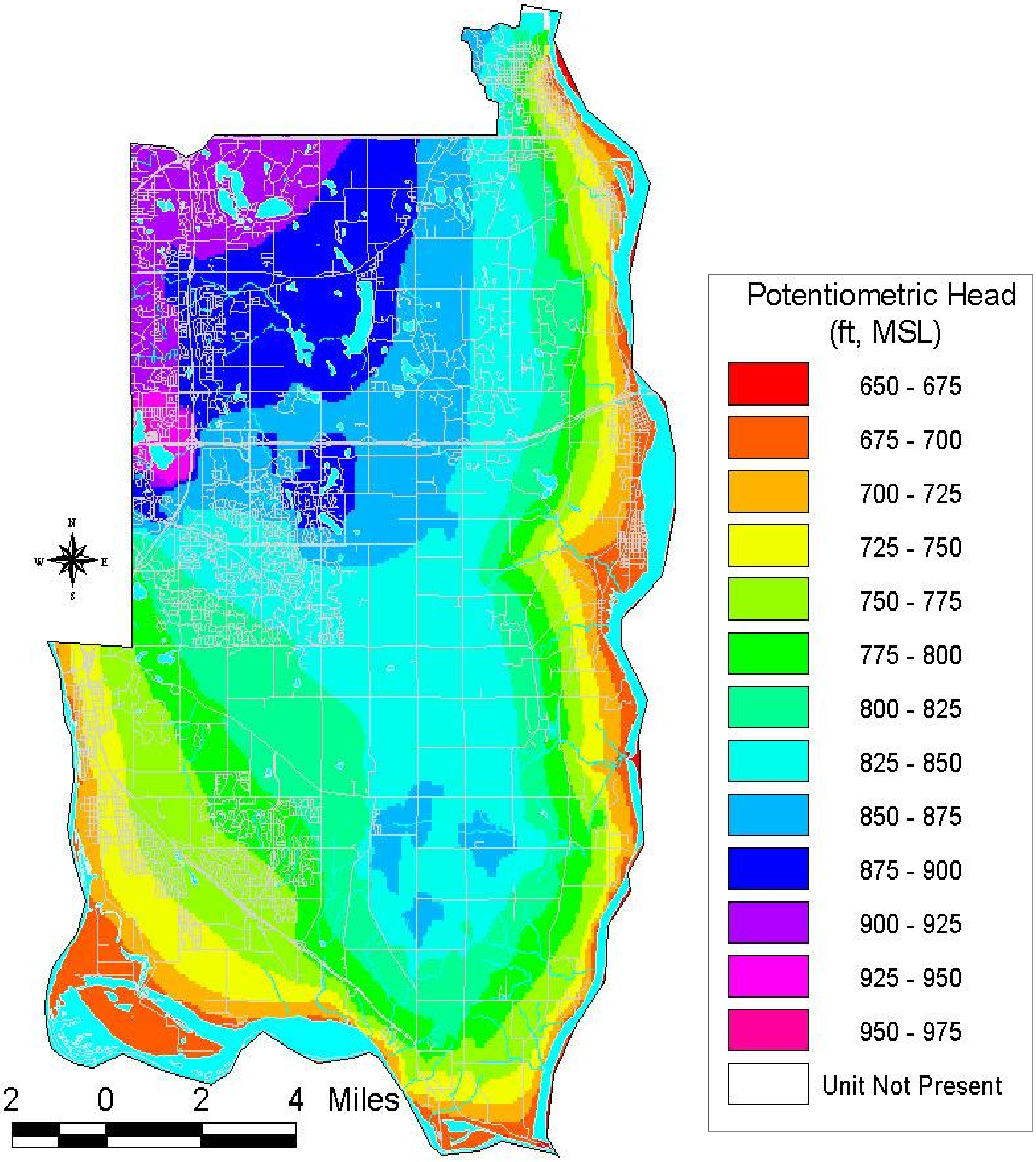


Figure 27

Water Table Elevation (feet, MSL)

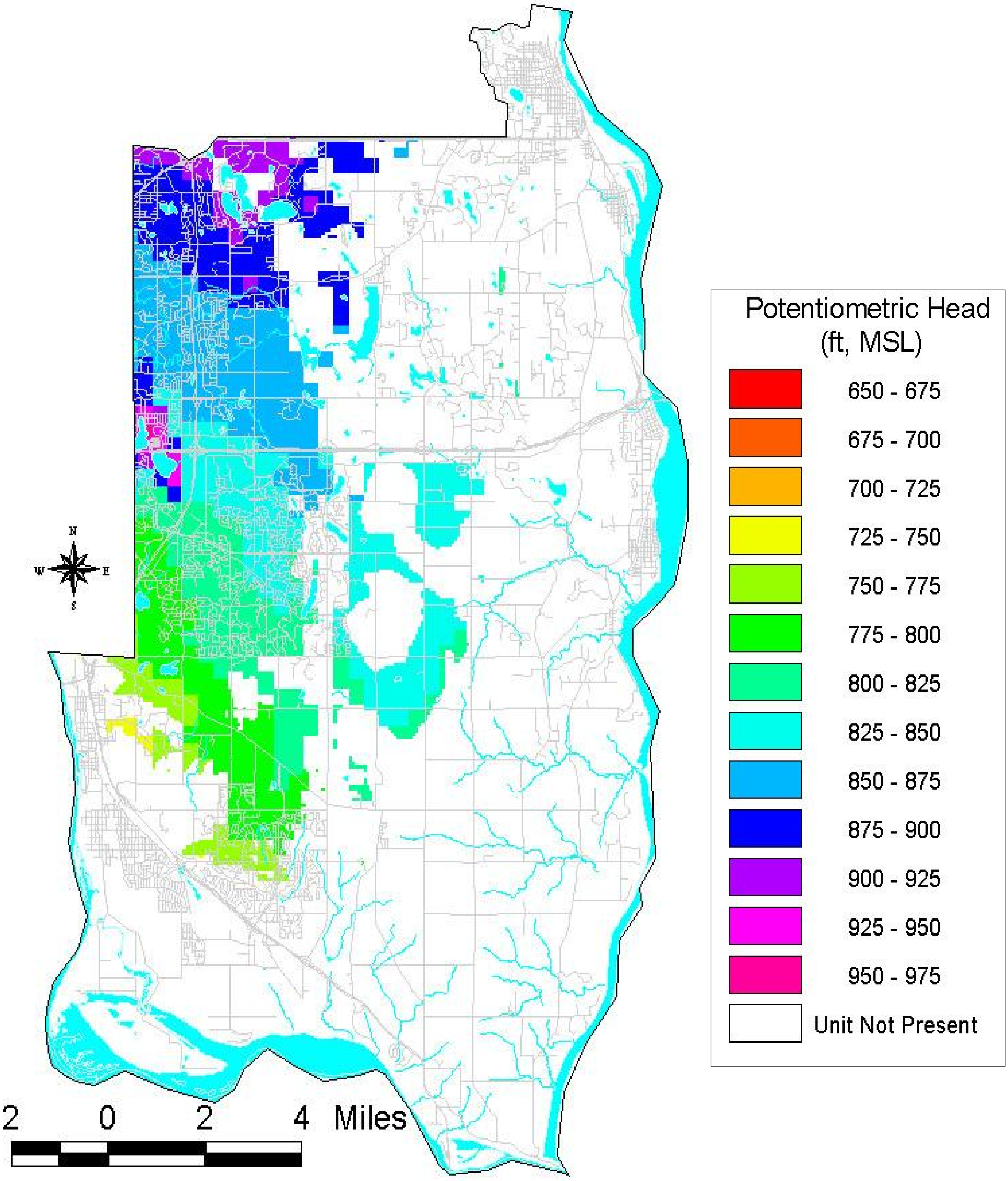


Figure 28

Potentiometric Surface of St. Peter Sandstone (feet, MSL)

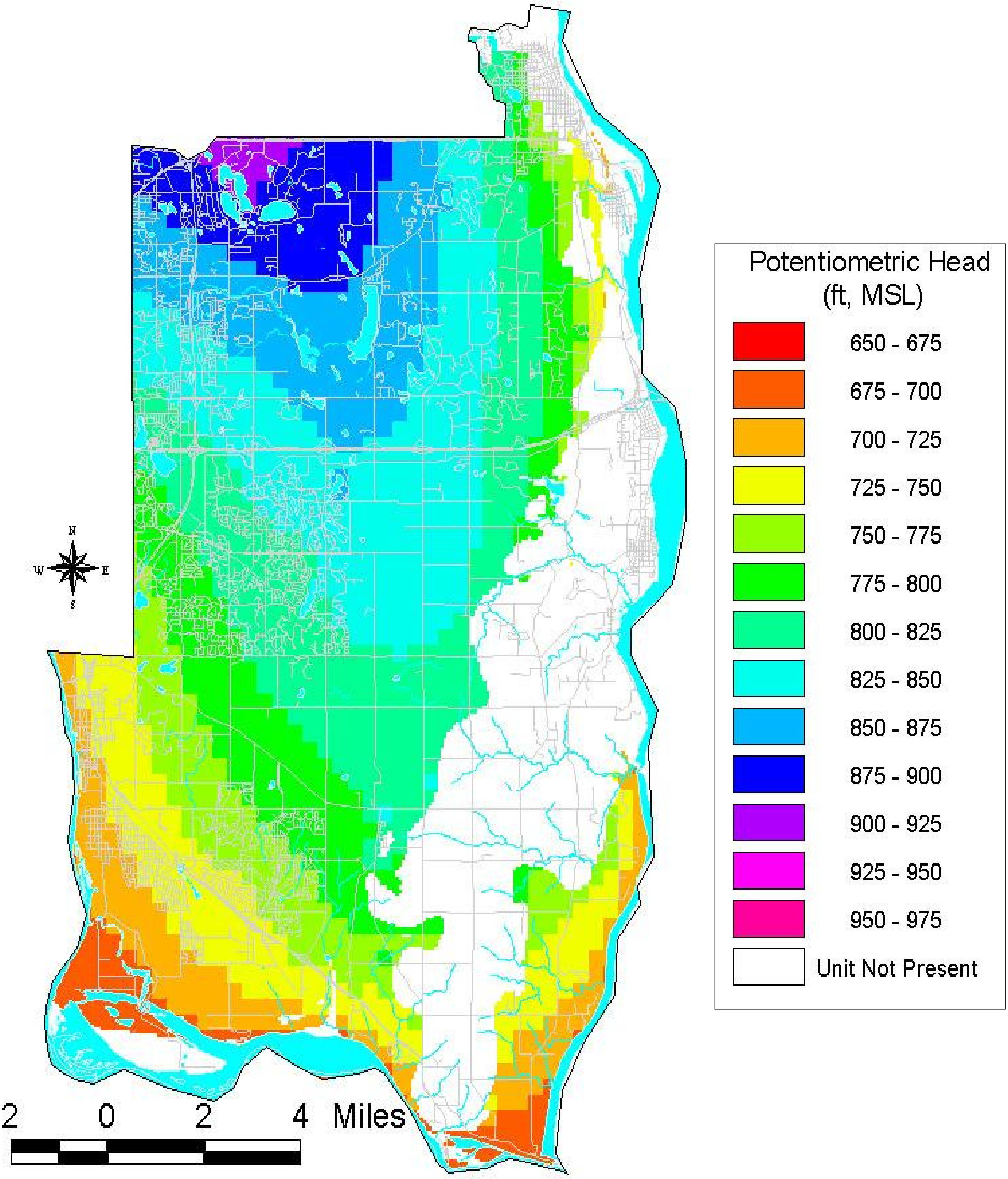


Figure 29

Potentiometric Surface of Shakopee Formation (ft, MSL)

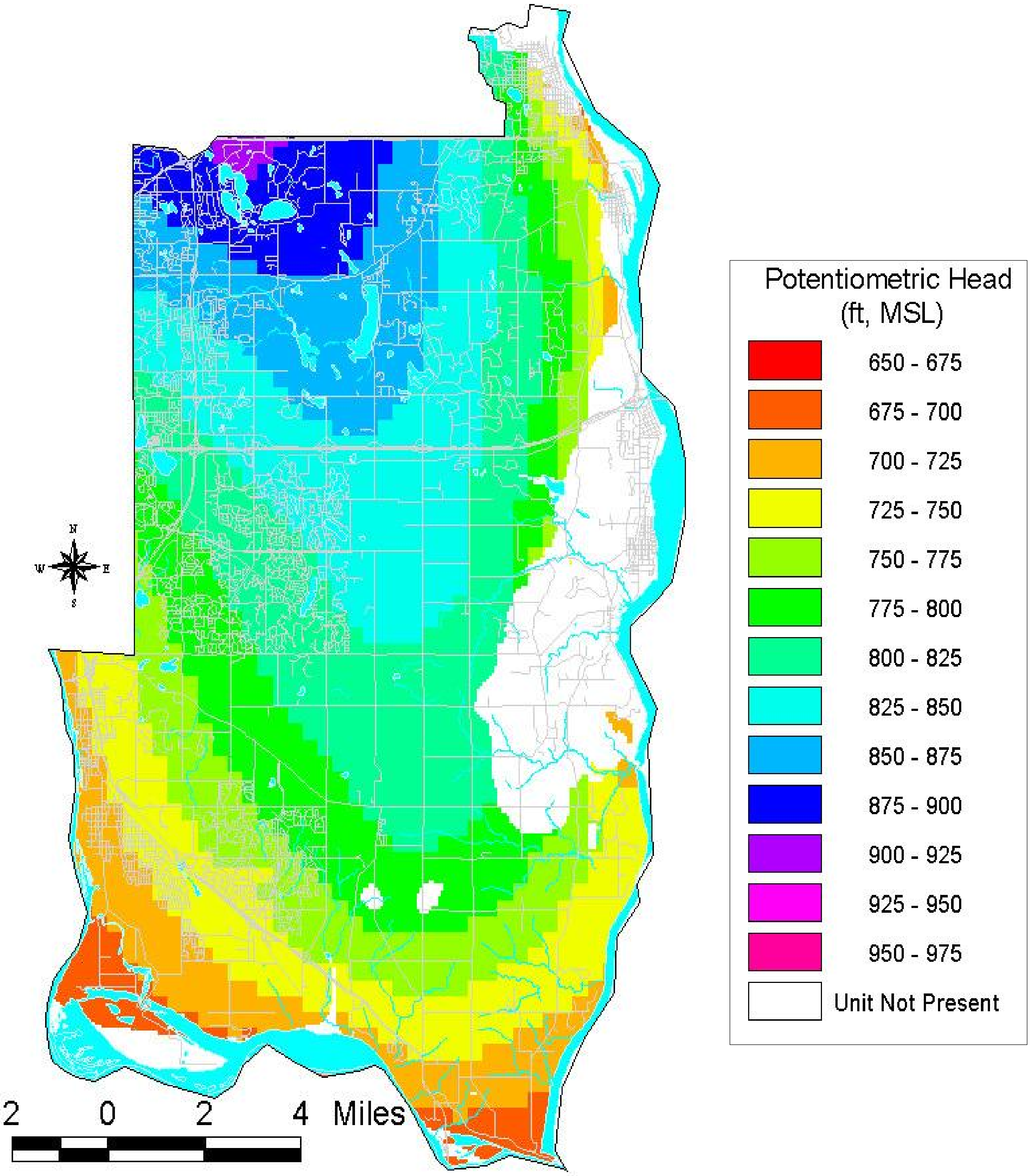


Figure 30

Potentiometric Surface of Jordan Sandstone (ft, MSL)

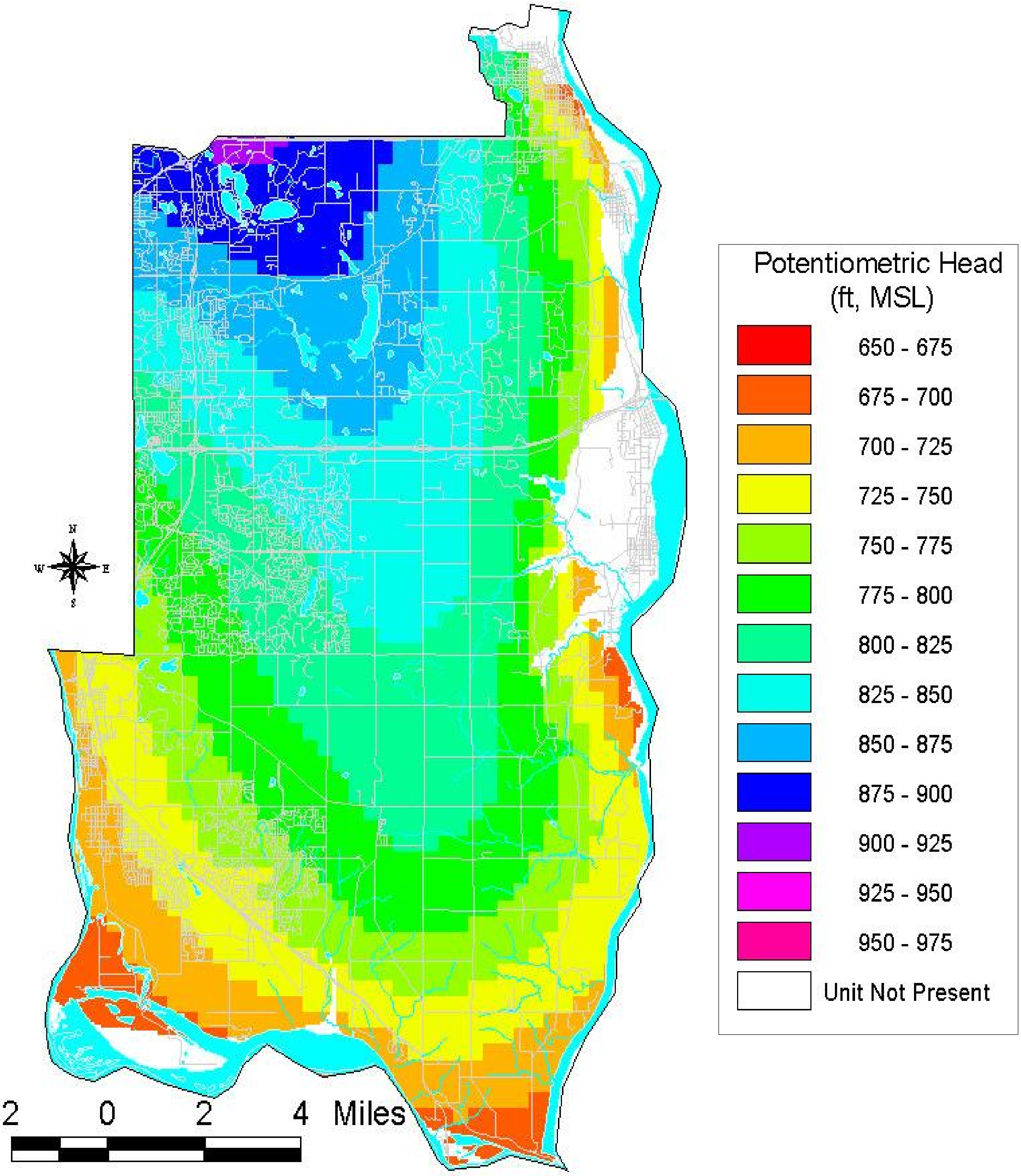
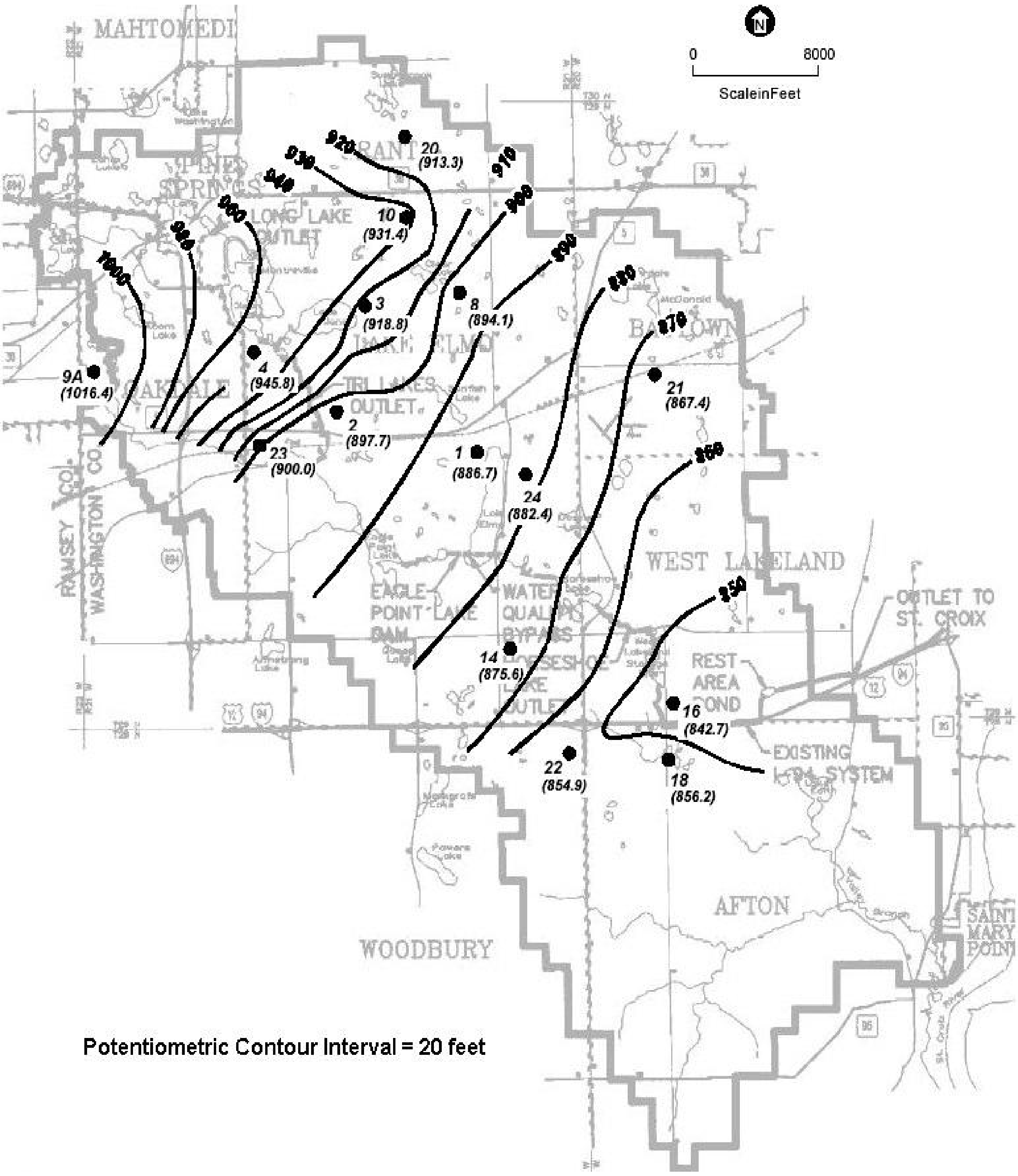


Figure 31

Potentiometric Surface of Franconia-Ironton-Galesville (ft, MSL)



Potentiometric Contour Interval = 20 feet

Figure 32

Contour Map of Shallow Groundwater in Valley Branch Watershed District: Average Elevations for 2002

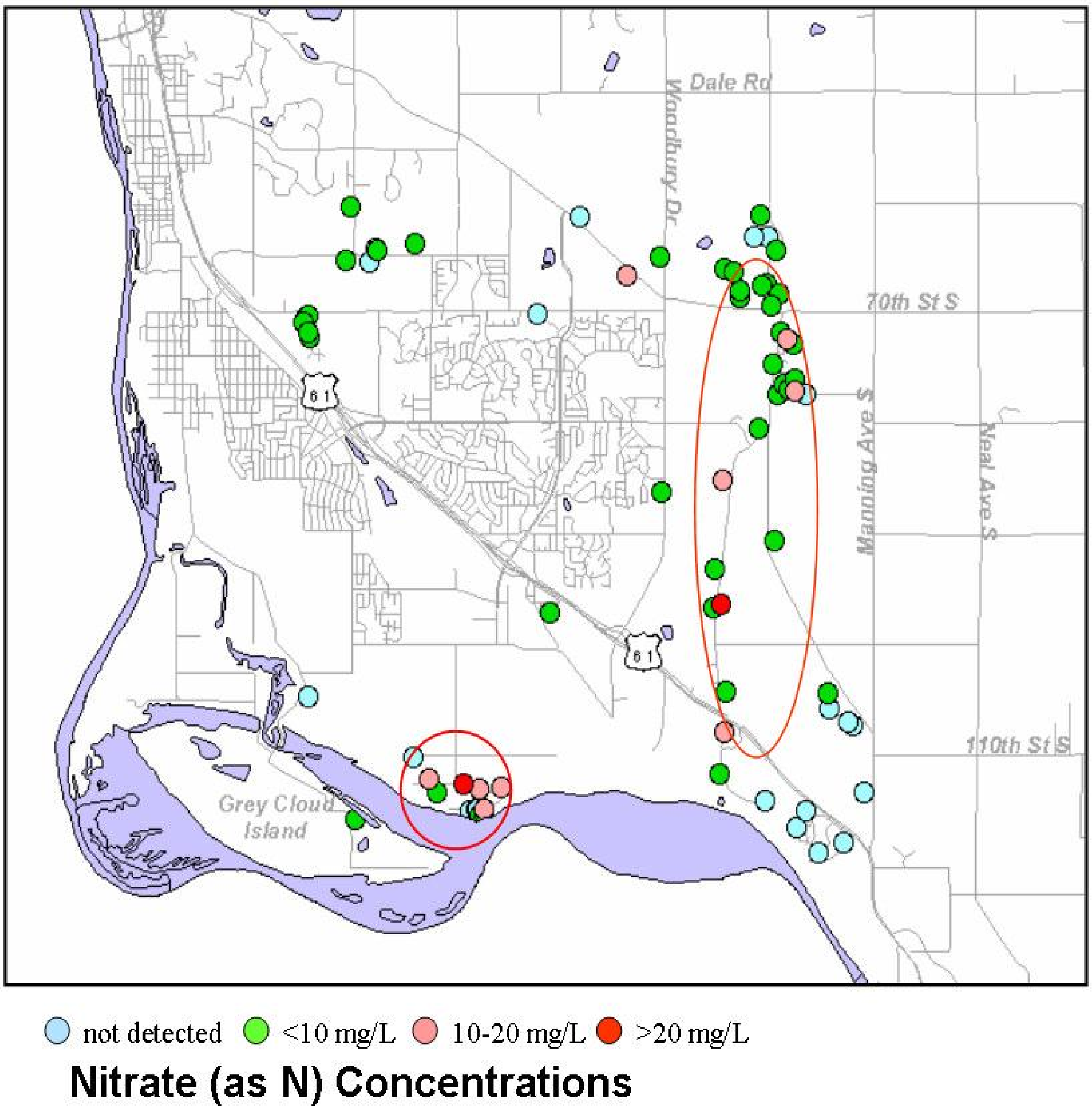


Figure 33

Nitrate Concentrations from MPCA Study of Cottage Grove Area

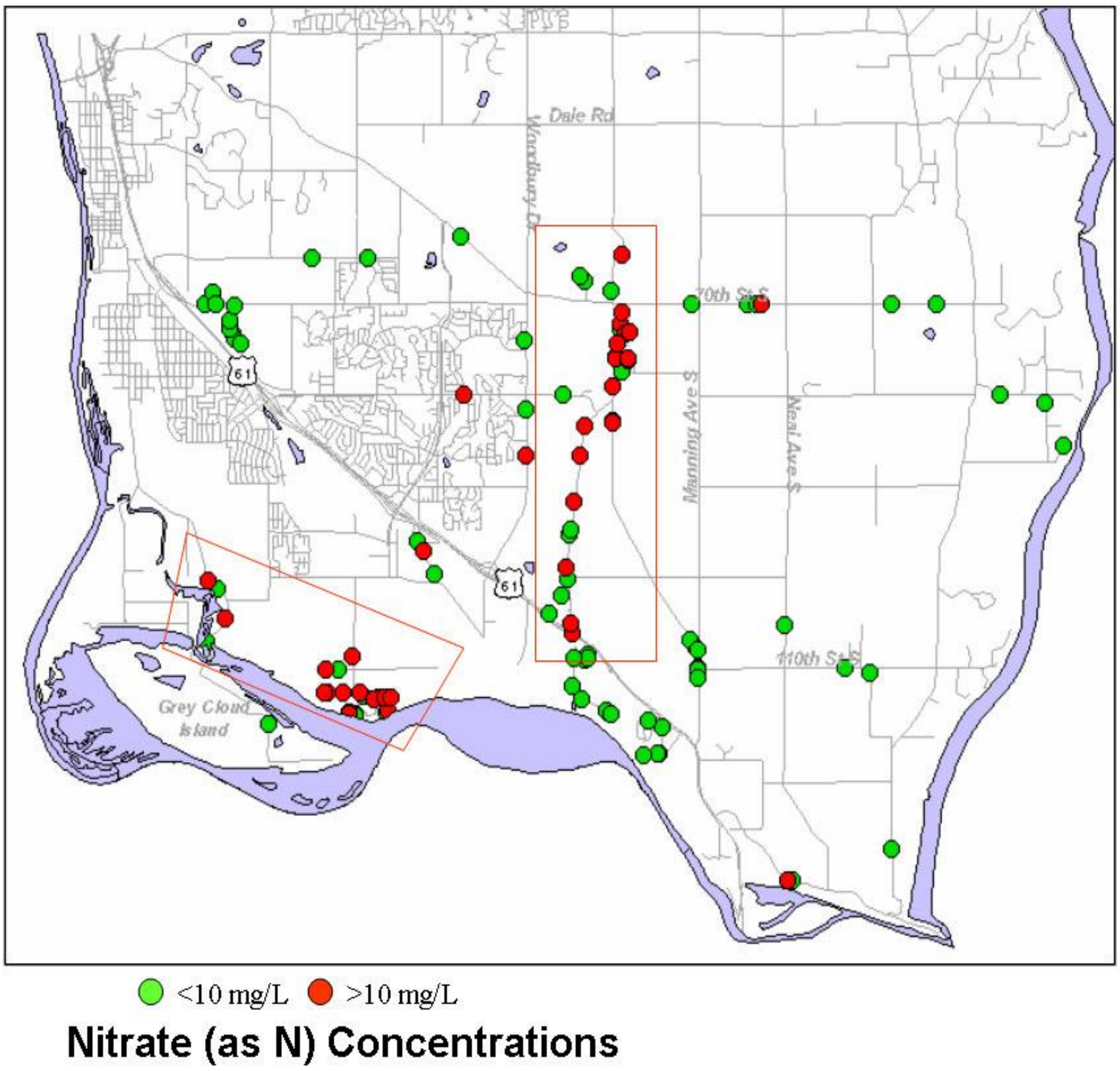


Figure 34

Nitrate Concentrations from Barr Nitrate Study

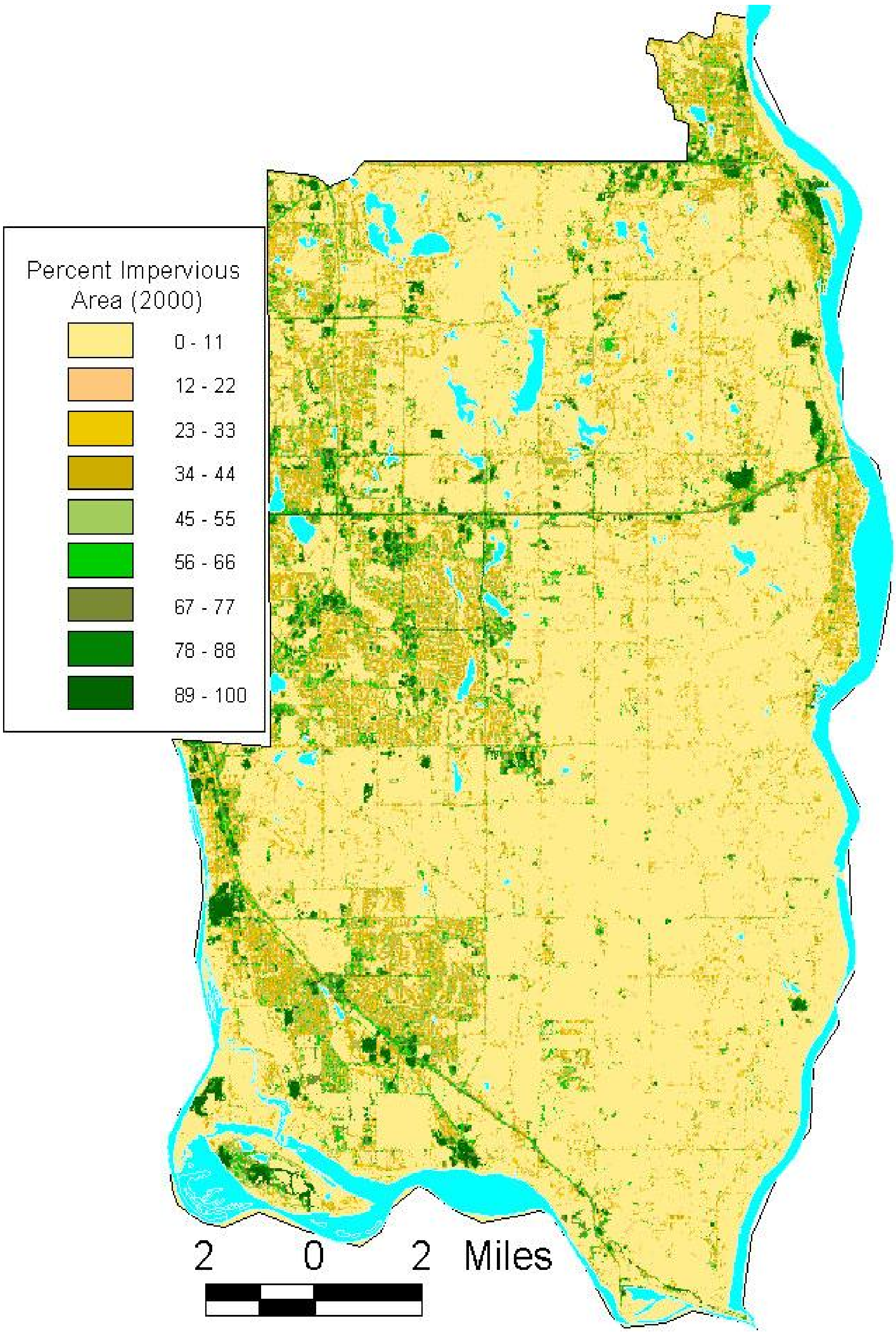
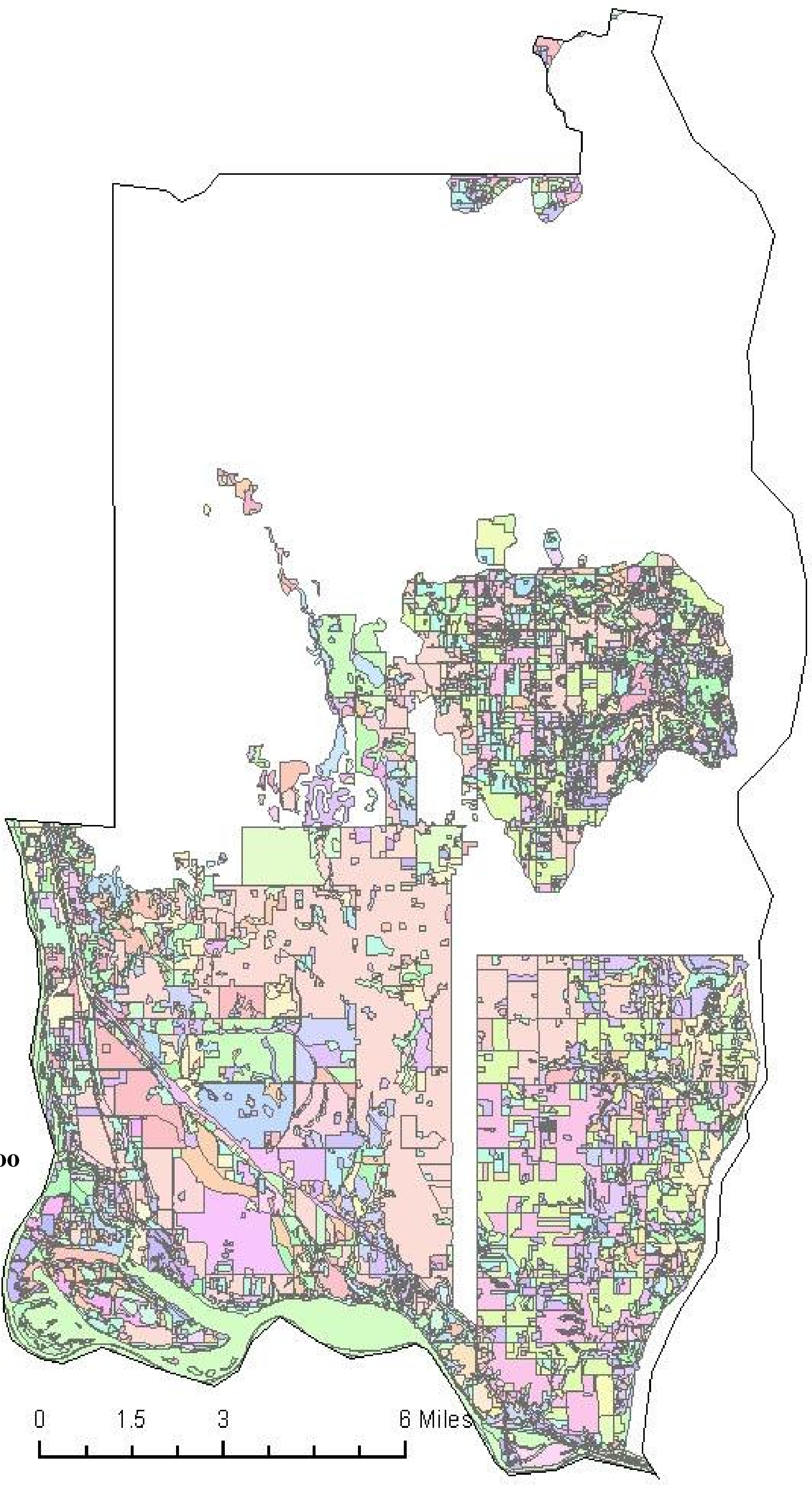


Figure 35

Estimate Percent of Impervious Area - 2000



(as of June 2005)

MLCCS Types too
numerous to
display in legend

Figure 36

MLCCS Coverage in Study Area

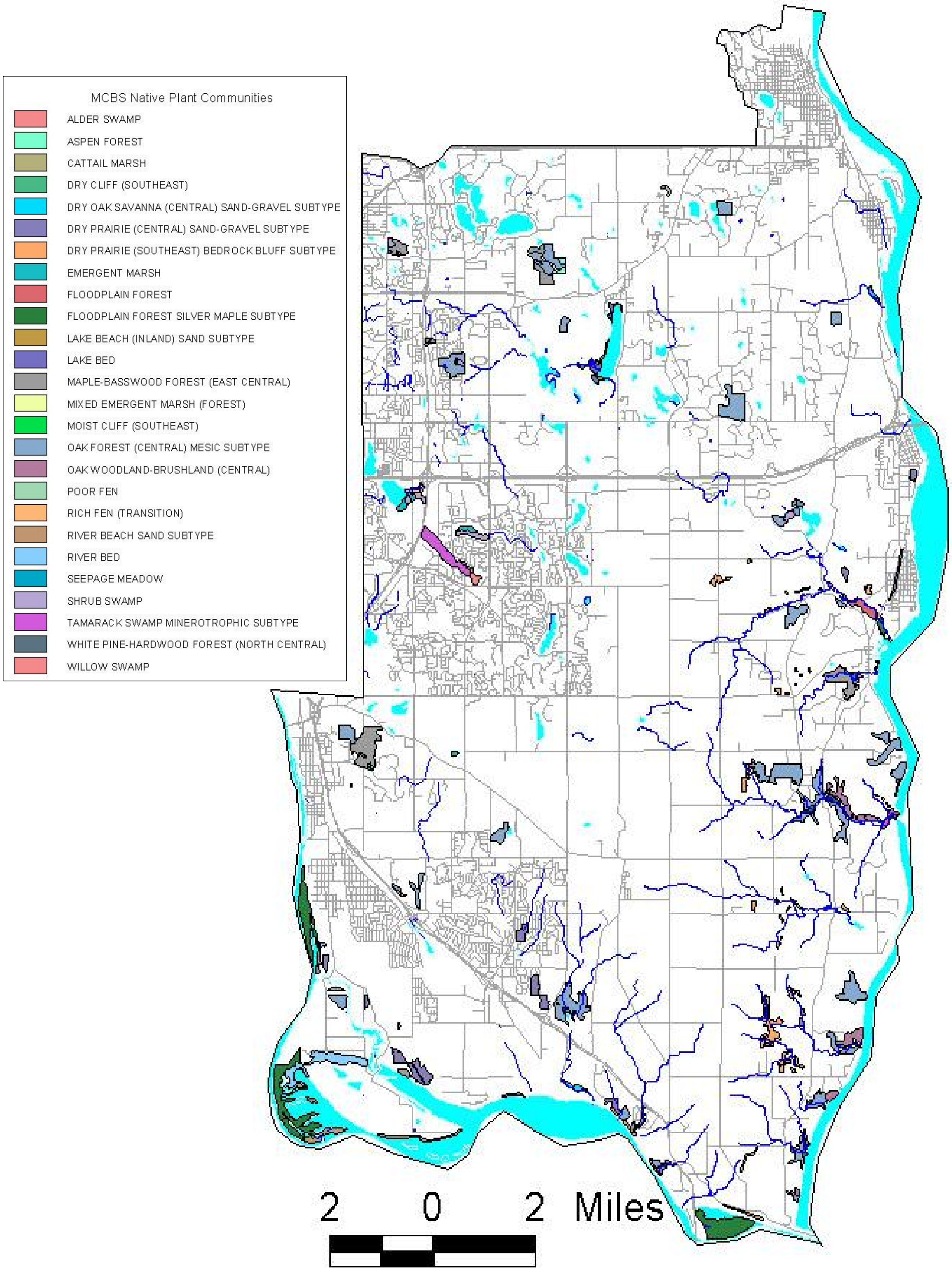


Figure 37

Minnesota County Biological Survey Native Plant Communities

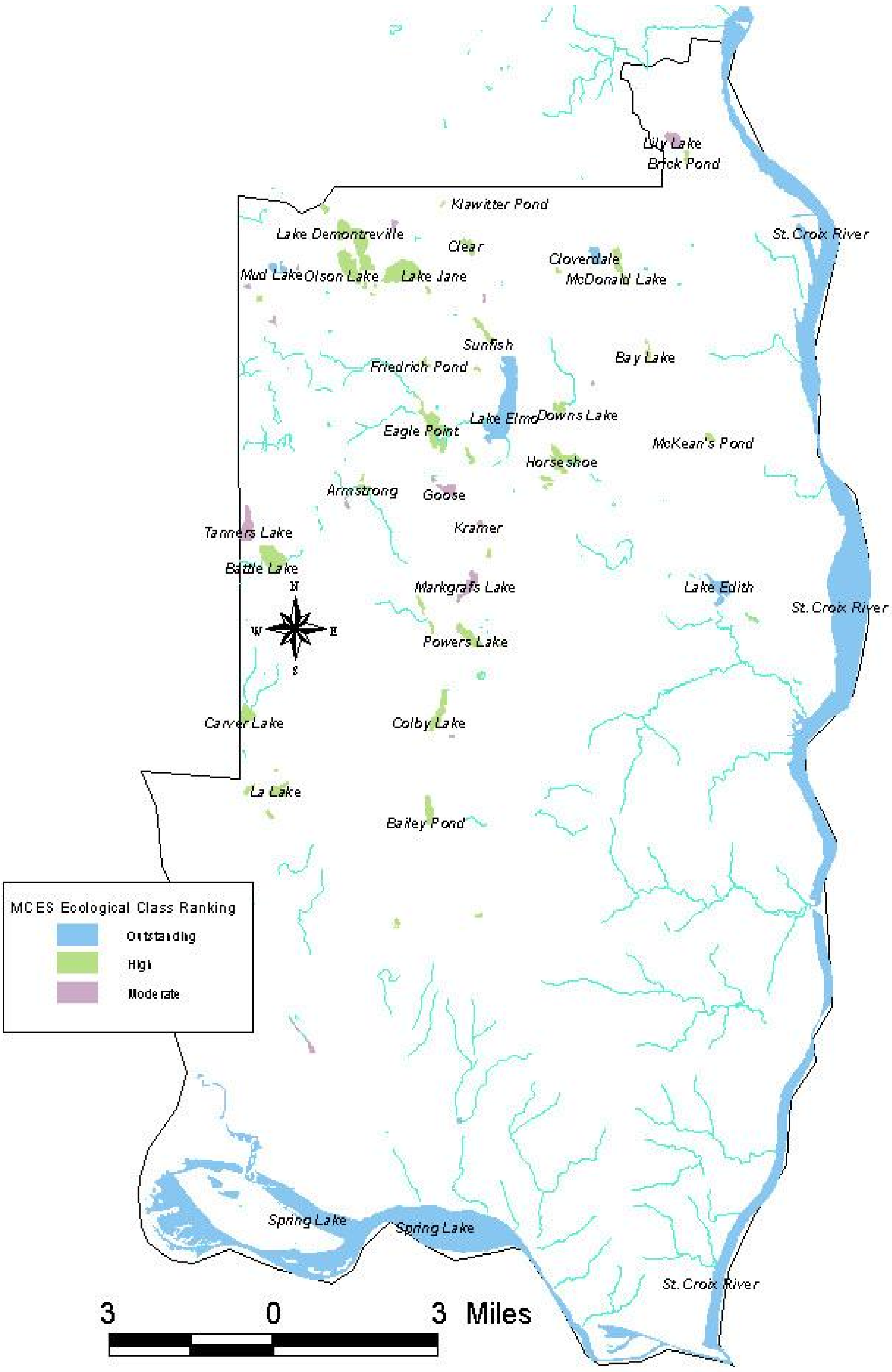


Figure 38

MCES Ecological Classification of Lakes

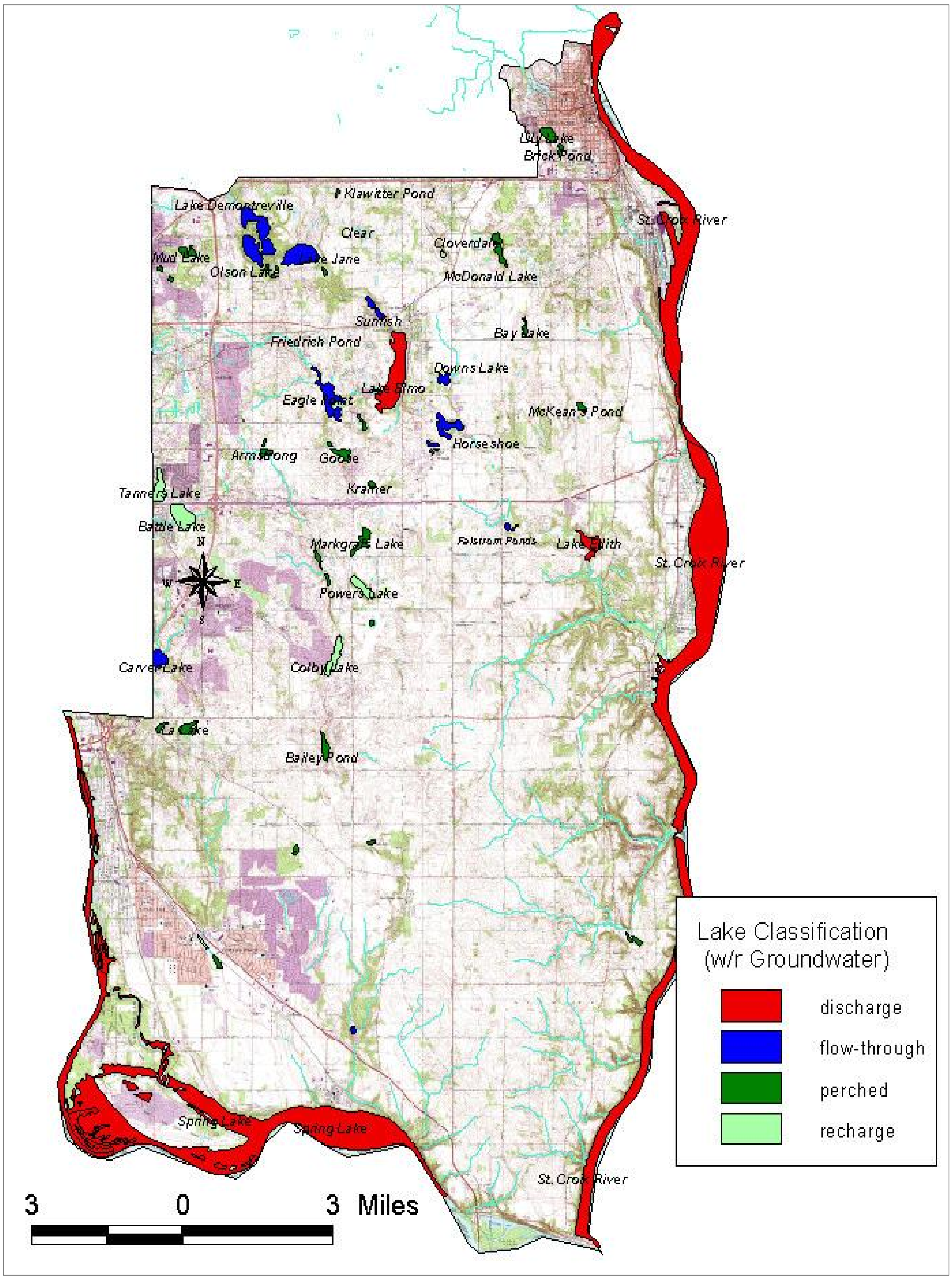
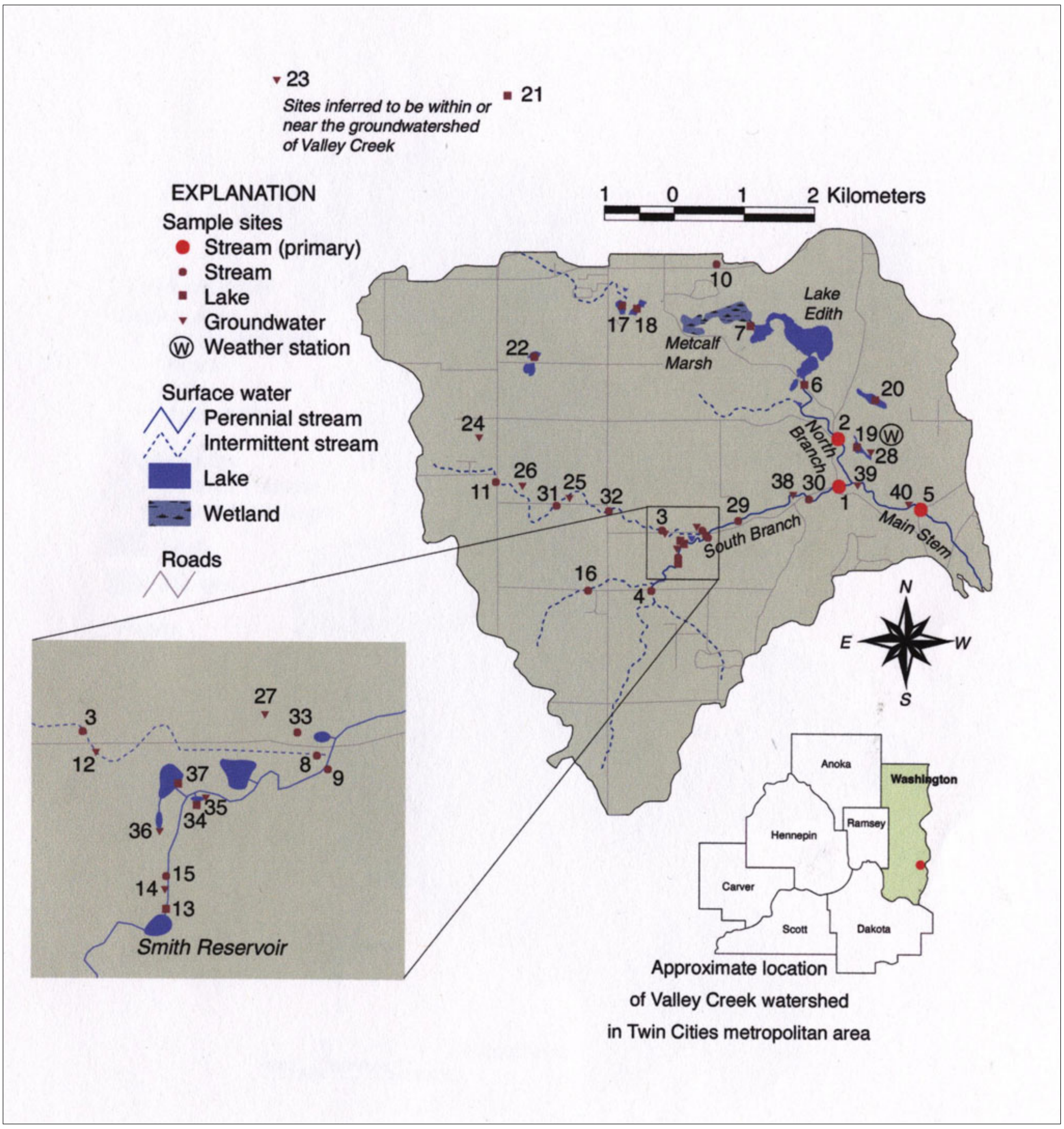


Figure 39

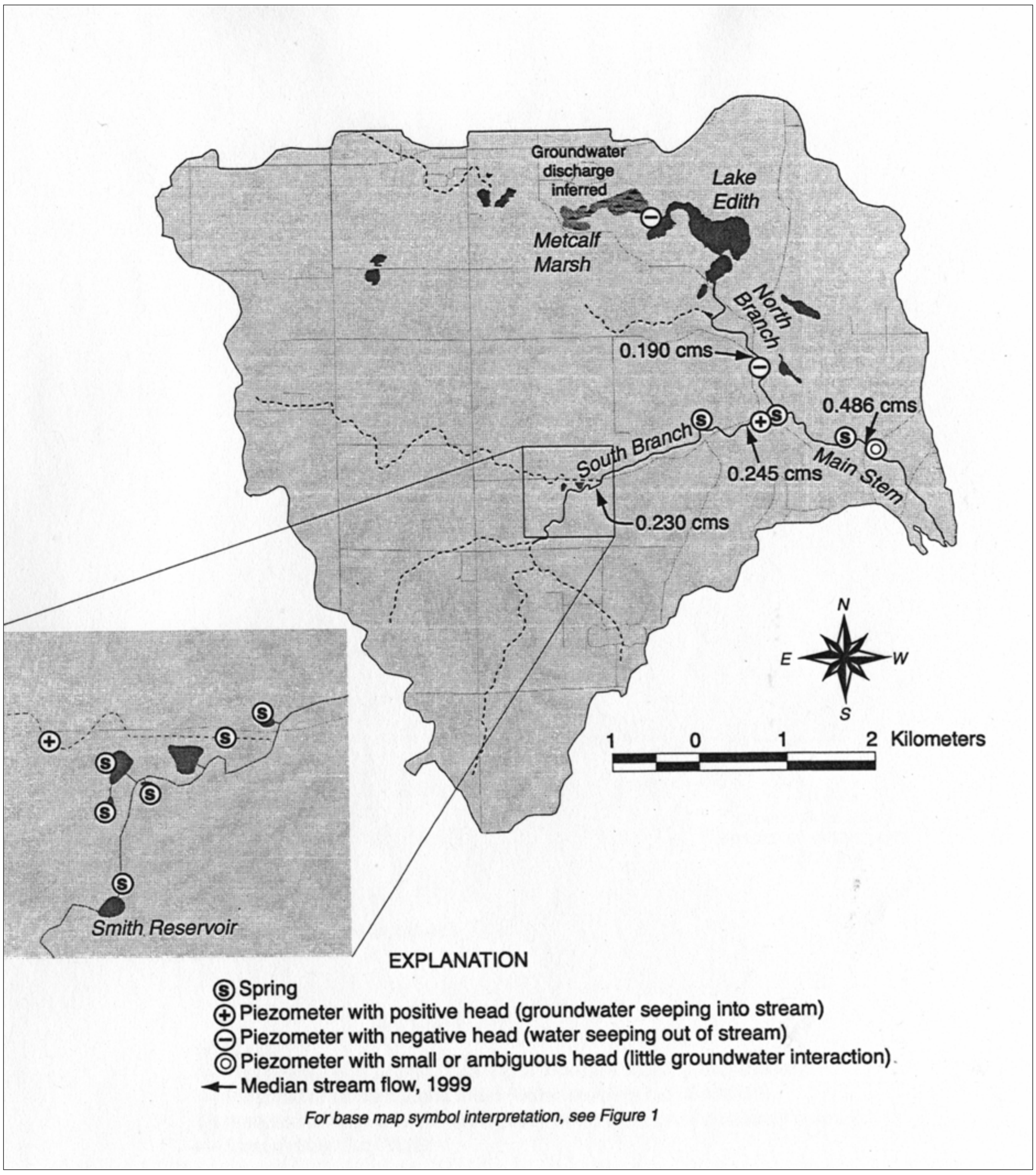
Lake Classification With Respect to Interaction with Groundwater



(from Almendinger, 2003)

Figure 40

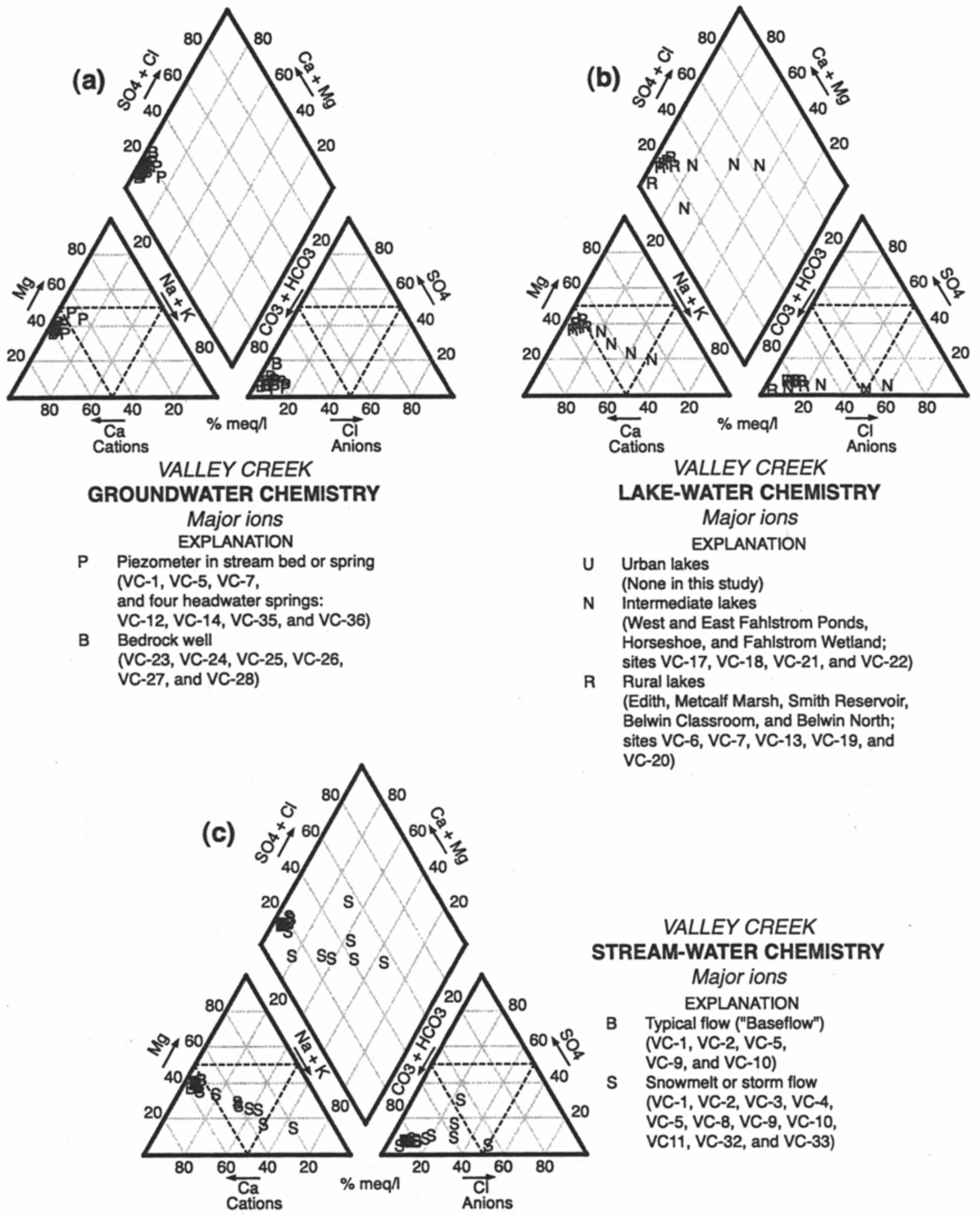
Location of Stream Gauging and Sampling Sites in the Science Museum of Minnesota Study of Valley Creek



(from Almendinger, 2003 – flows shown in cubic meters per second (cms))

Figure 41

Springs and Other Groundwater Interaction Features Along Valley Creek



(from Almendinger, 2003)

Figure 42

Piper Diagrams of Groundwater and Valley Creek Water

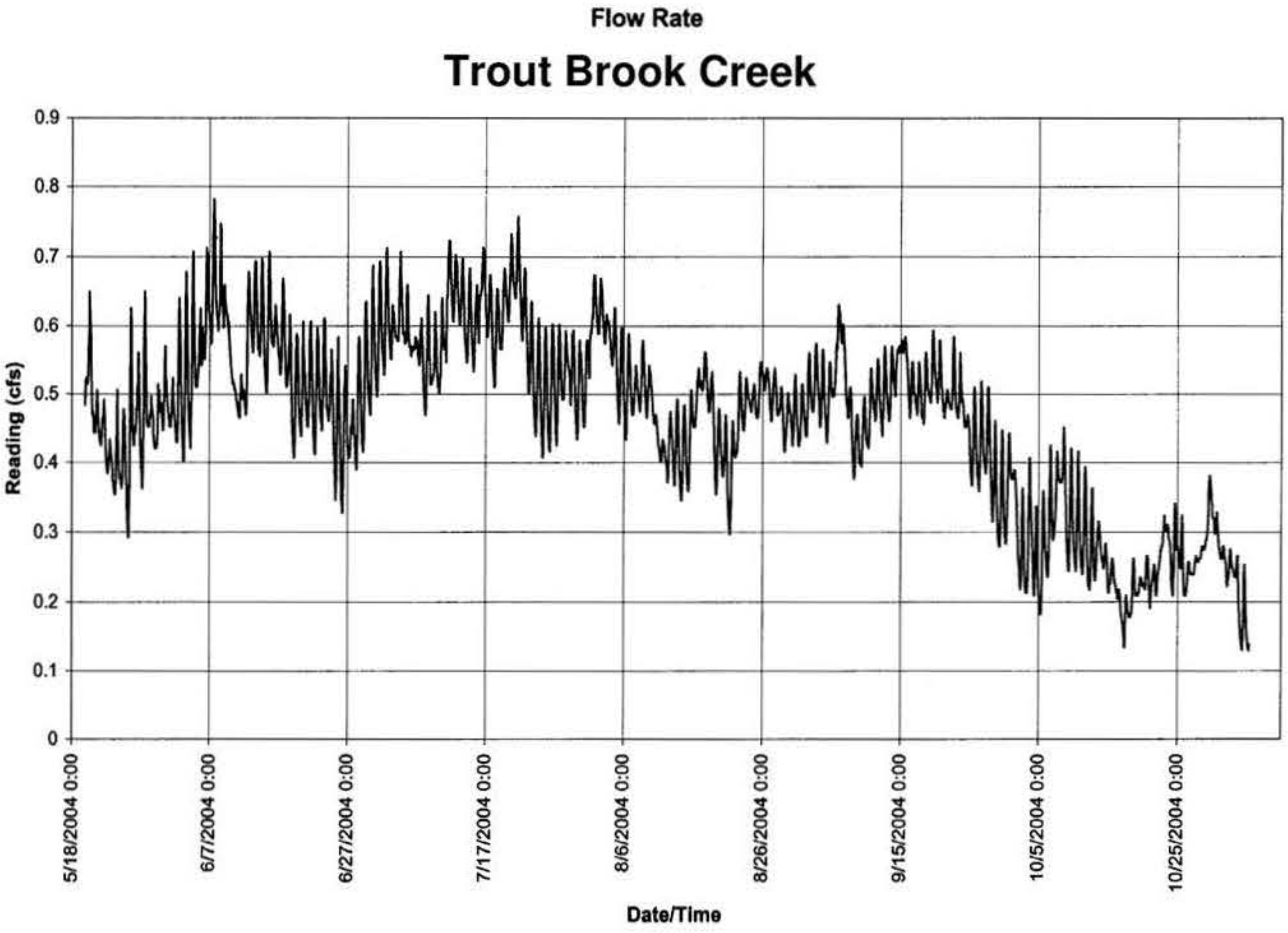
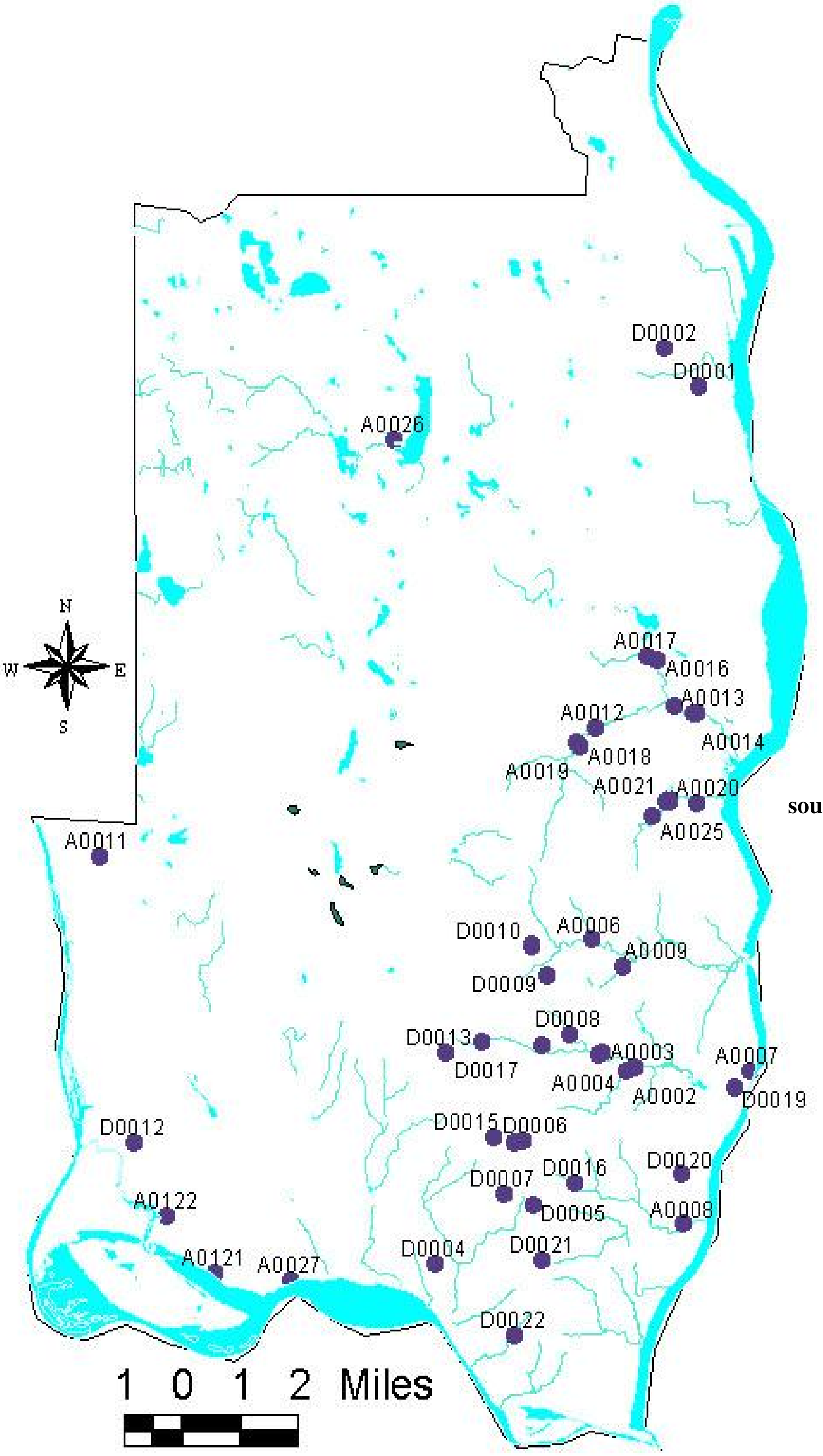


Figure 43

Hydrograph of Stream Flows in Trout Brook Creek



source: MDNR

Figure 44

Known Karst Features in Study Area

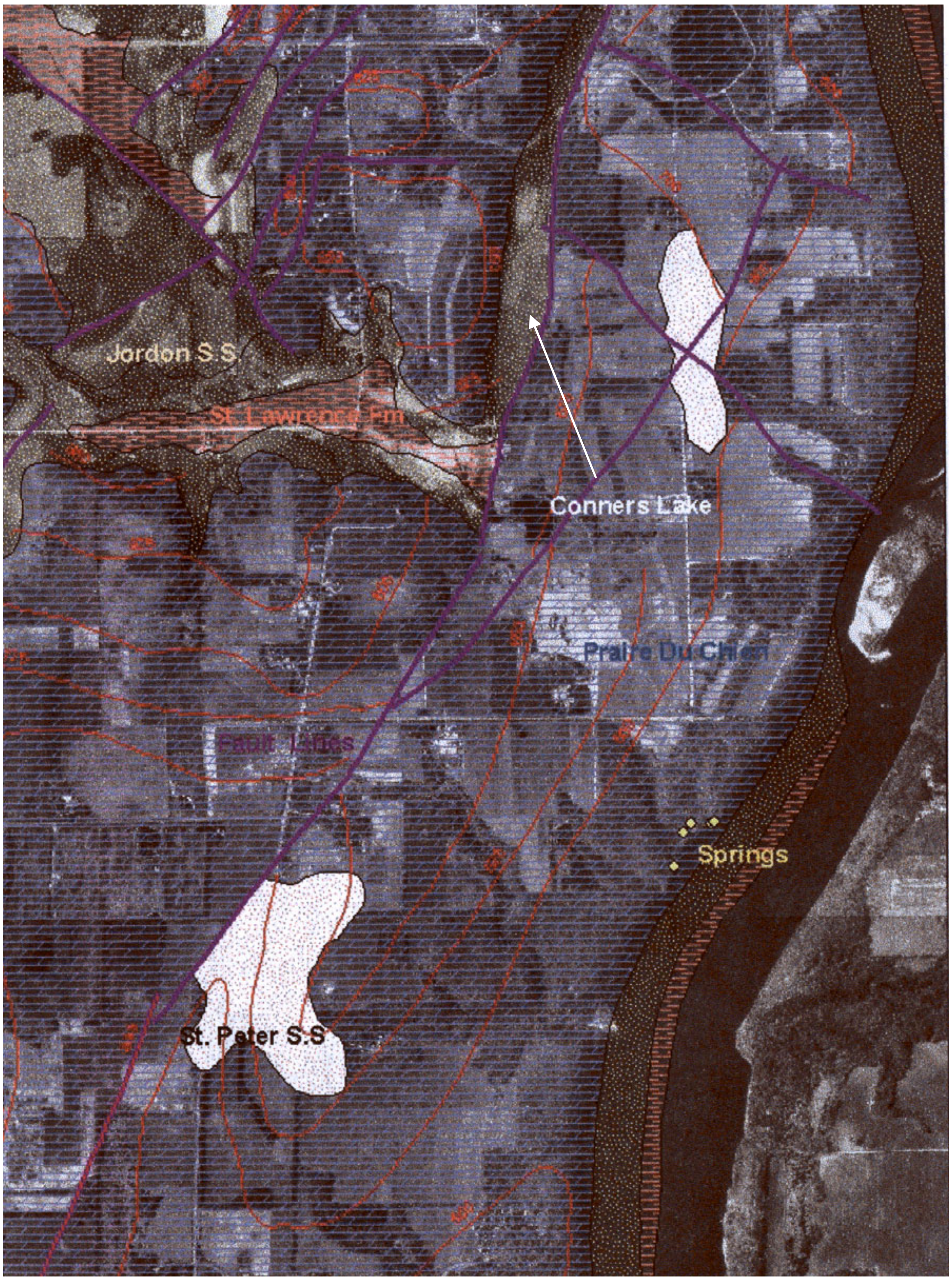
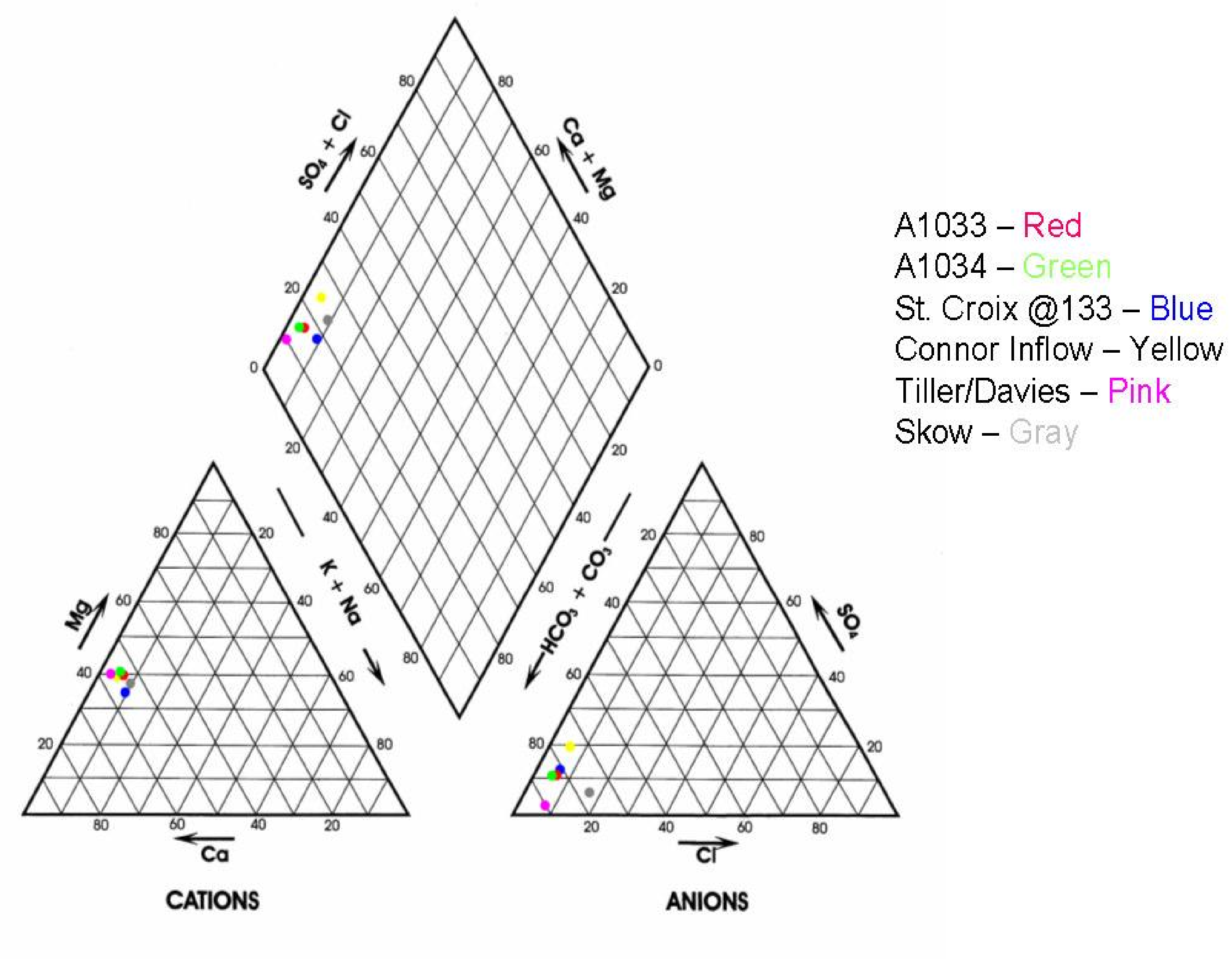


Figure 45

Location of Springs near O'Connors Lake (from Barry, 2003)



Data from Barry (2003)

Figure 46

Piper Diagram of O'Connors Lake Area Springs Samples

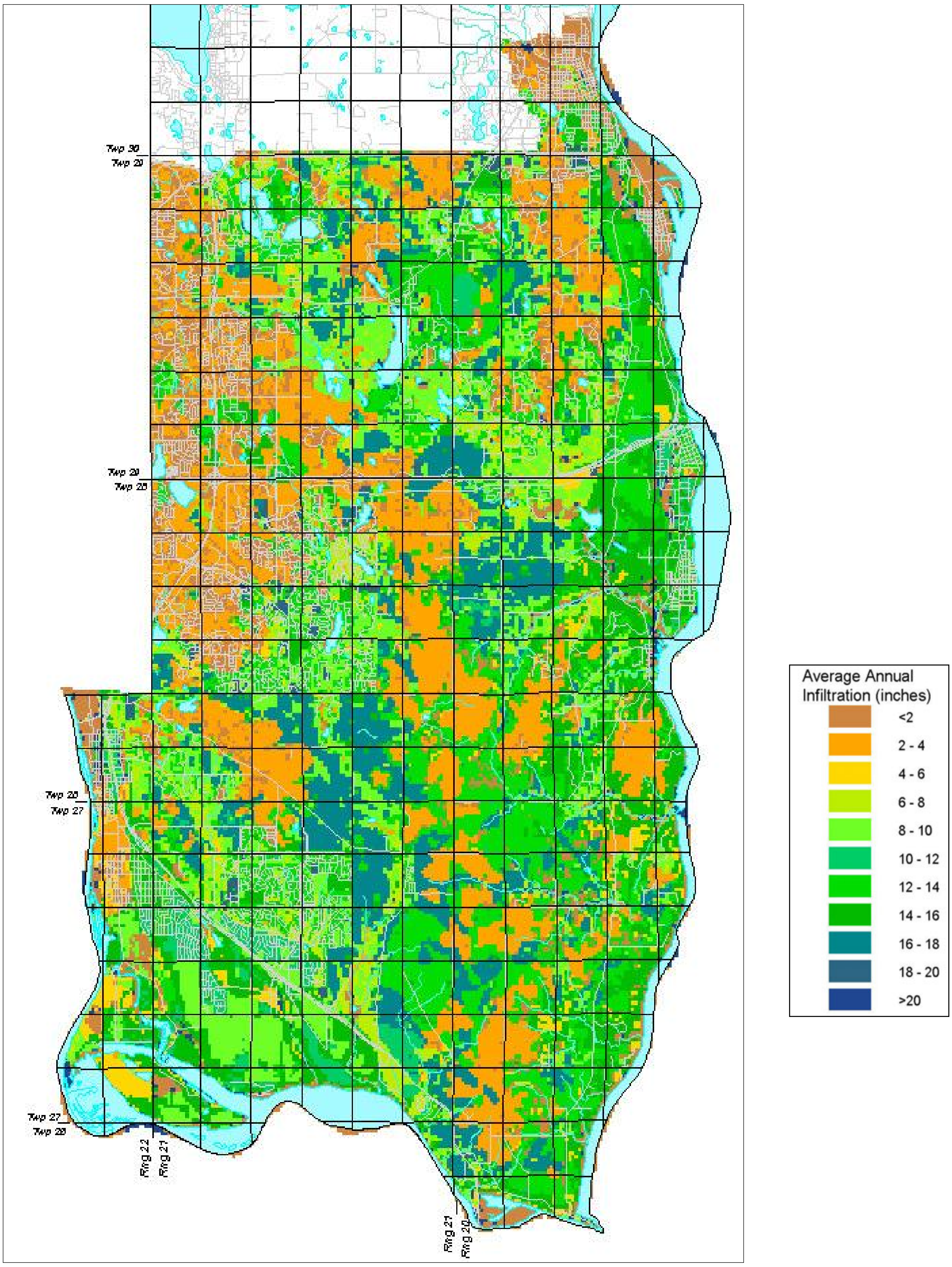
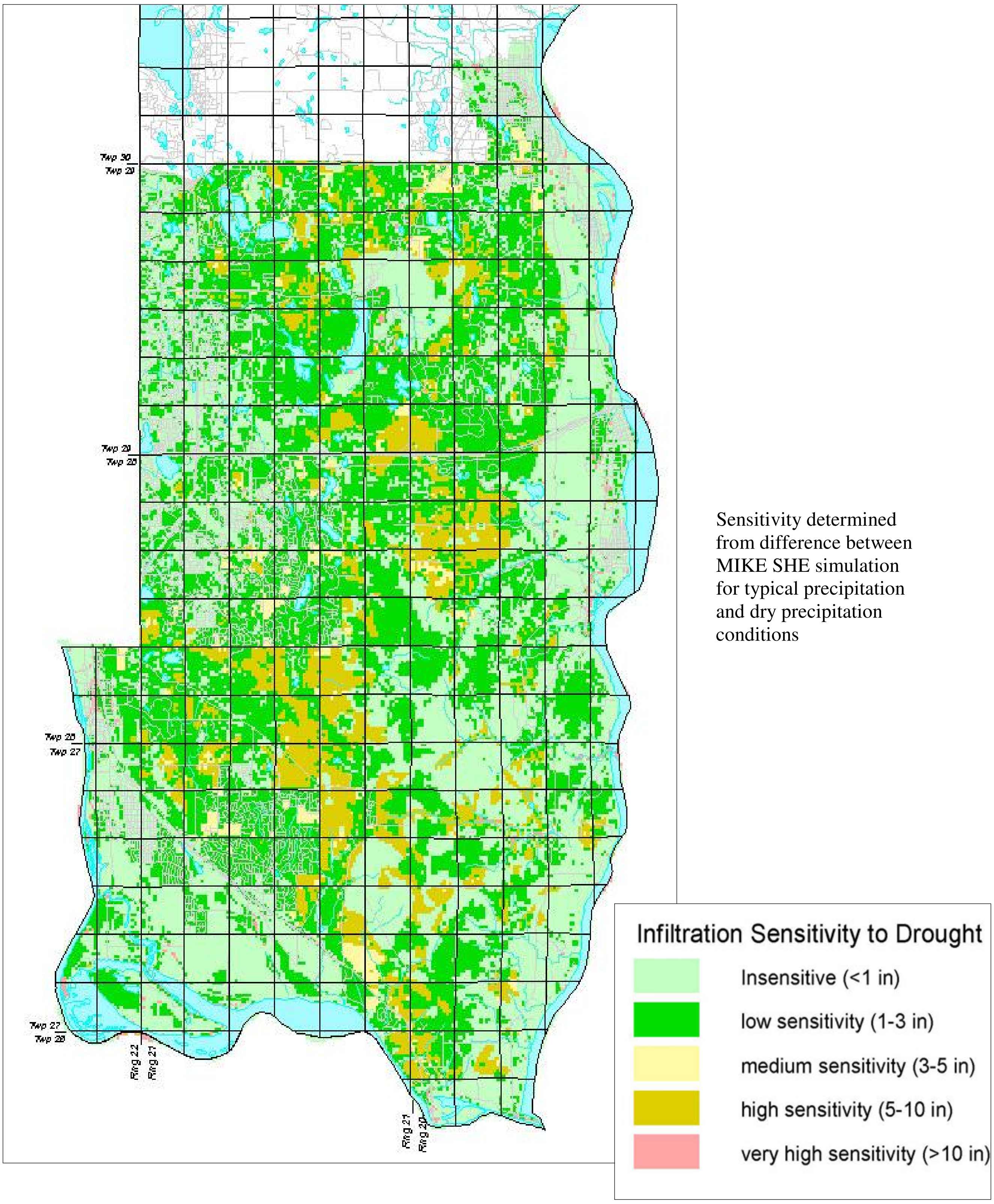


Figure 47

Estimated Annual Infiltration Rates (inches) for Typical Climatic Conditions



Sensitivity determined
from difference between
MIKE SHE simulation
for typical precipitation
and dry precipitation
conditions

Figure 48

Sensitivity of Infiltration to Drought Conditions

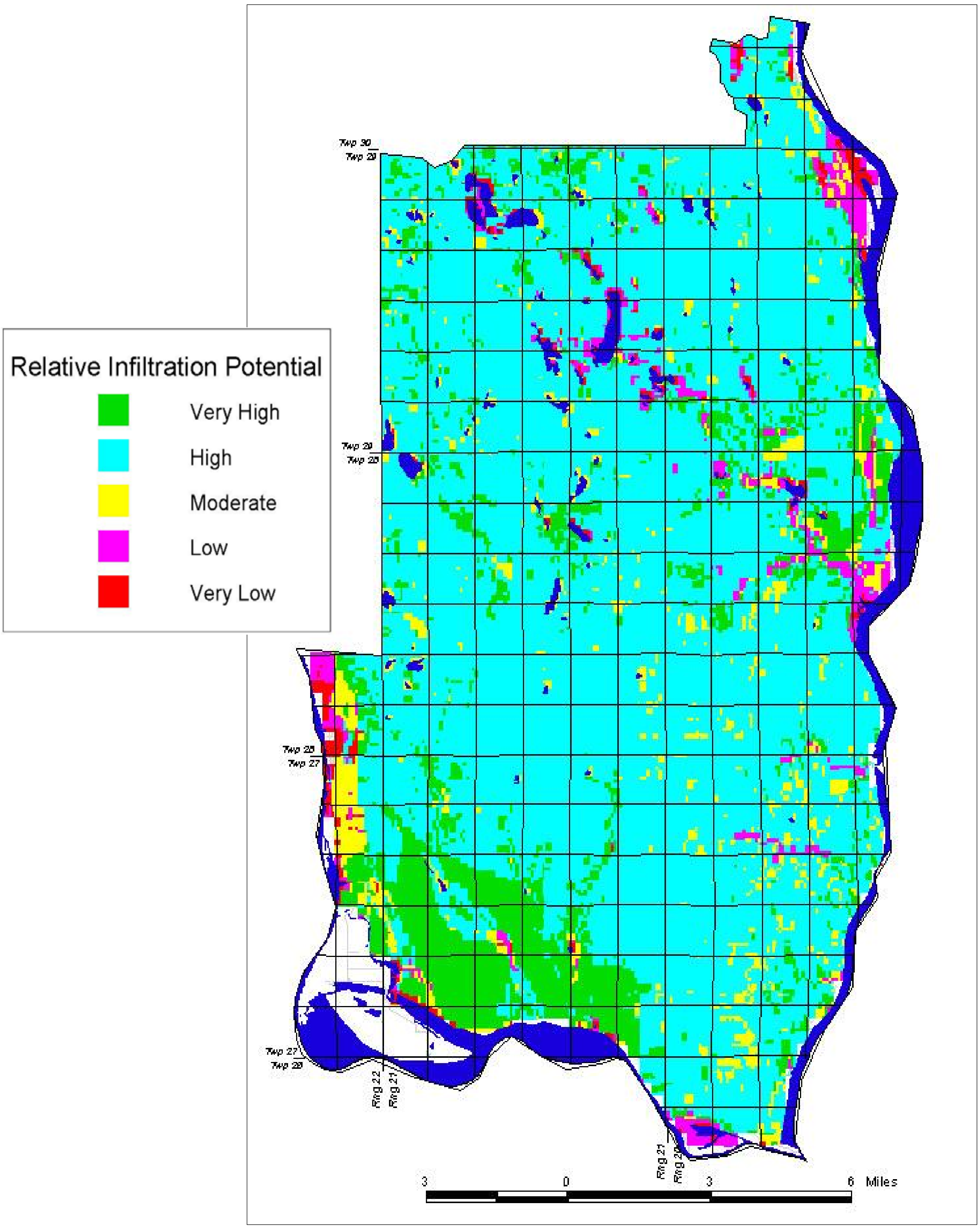


Figure 49

Relative Infiltration Potential

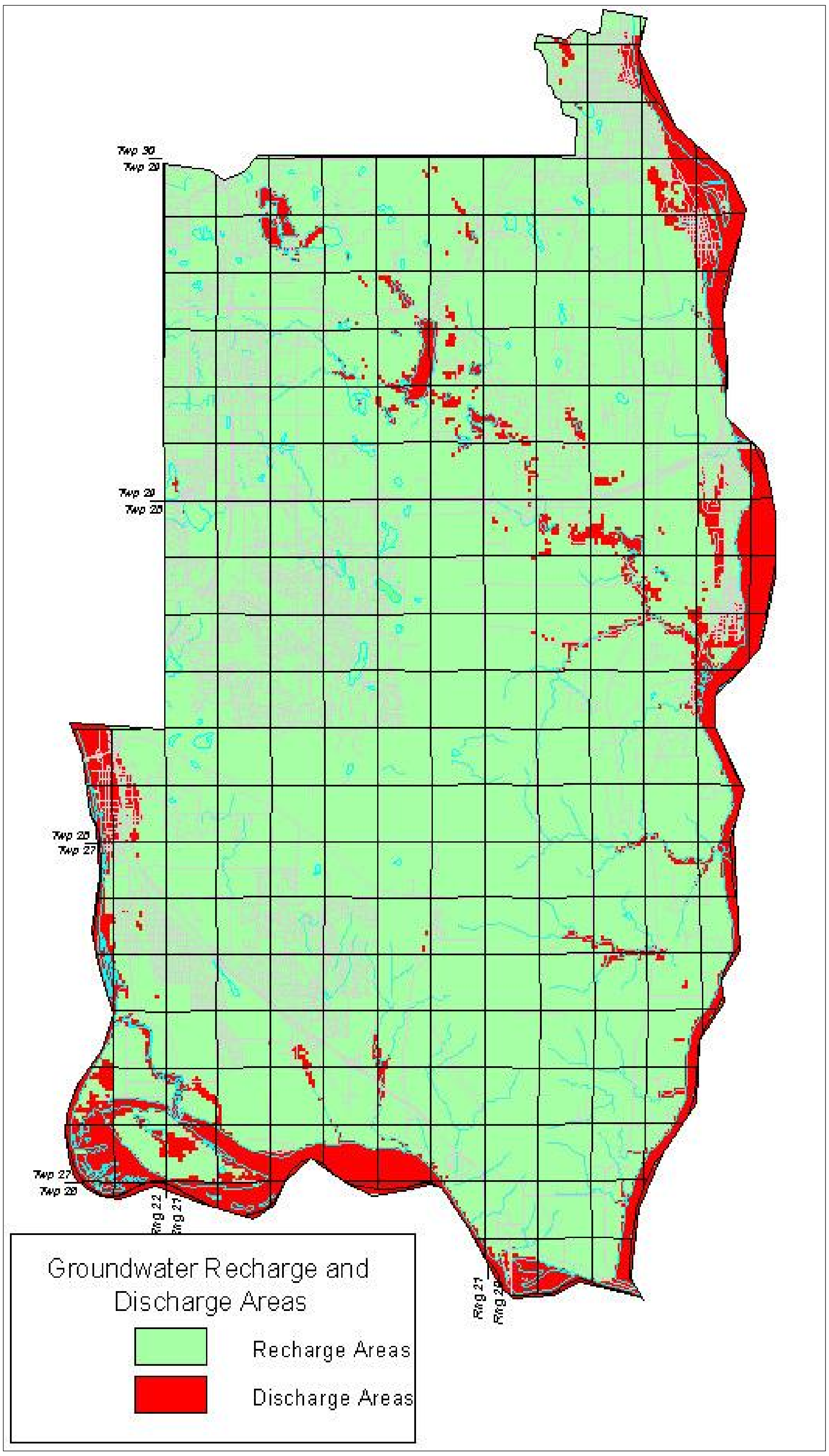


Figure 50

Groundwater Recharge and Discharge Areas

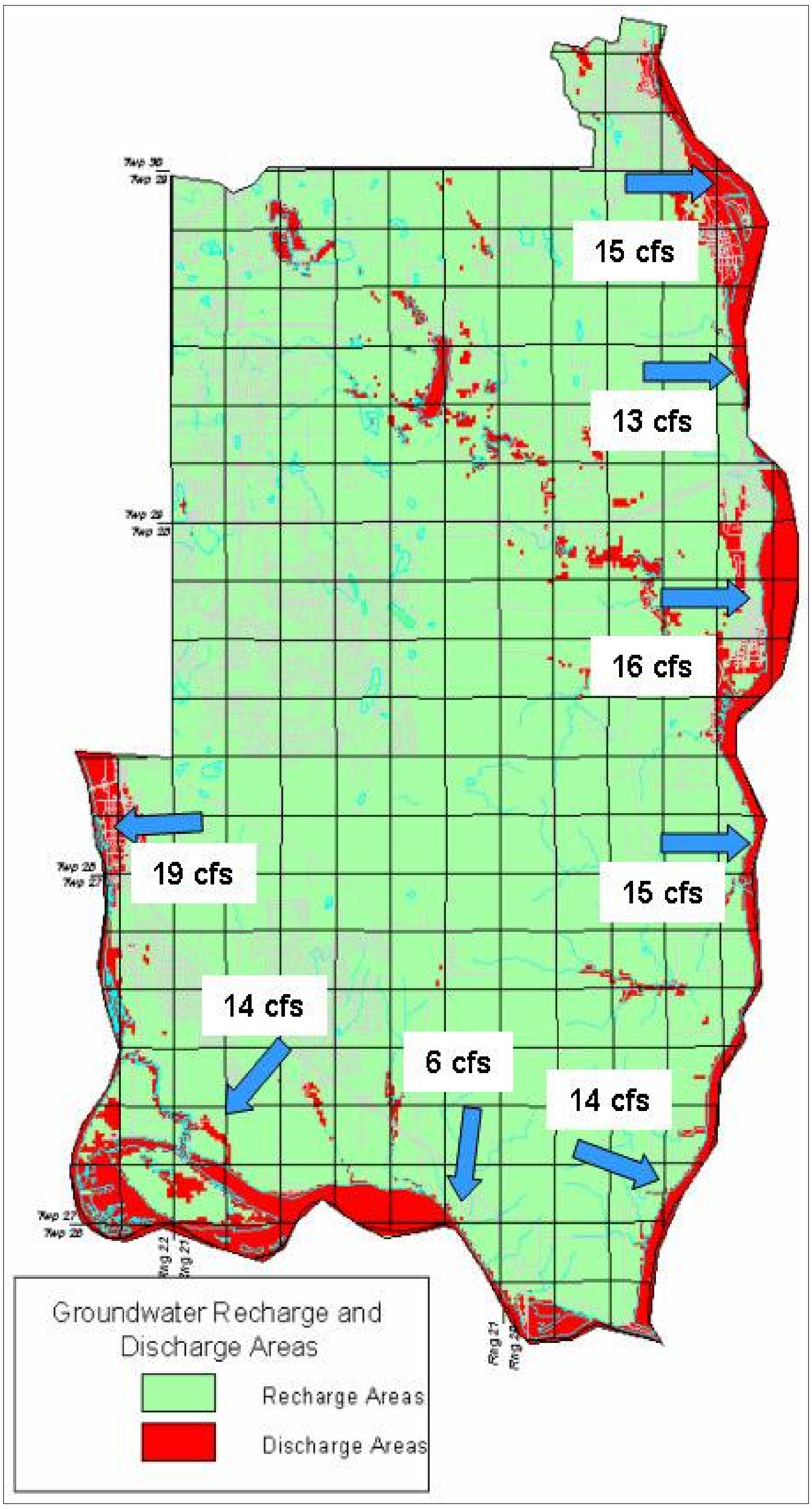
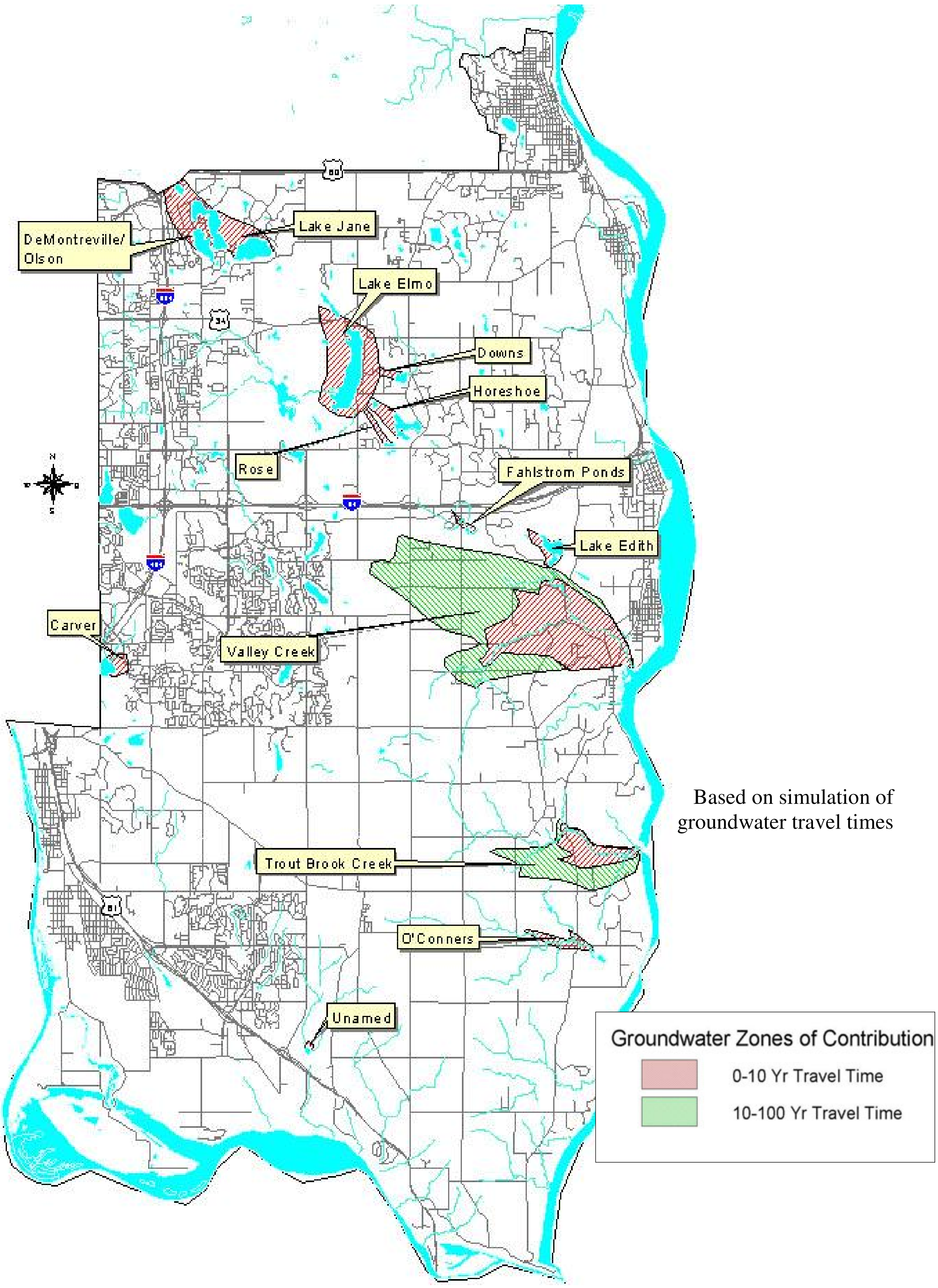


Figure 51

Distribution of Discharge to Mississippi and St. Croix Rivers



Based on simulation of groundwater travel times

Figure 52

Groundwater Zones of Contribution for Surface-Water Bodies Other Than Mississippi and St. Croix Rivers

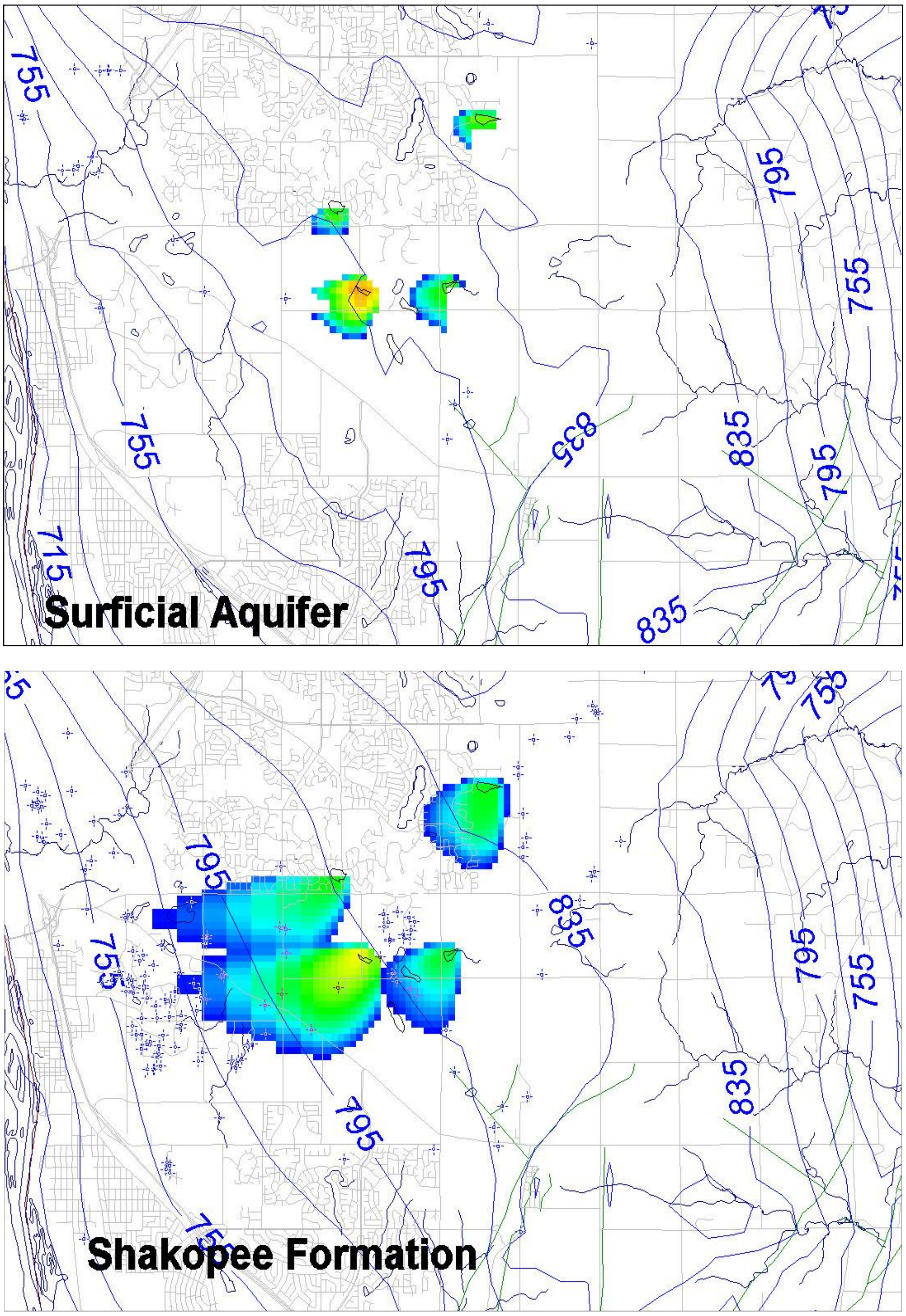


Figure 53

Simulation of Migration of Stormwater in Surficial Aquifer and Shakopee Formation after 10 Years

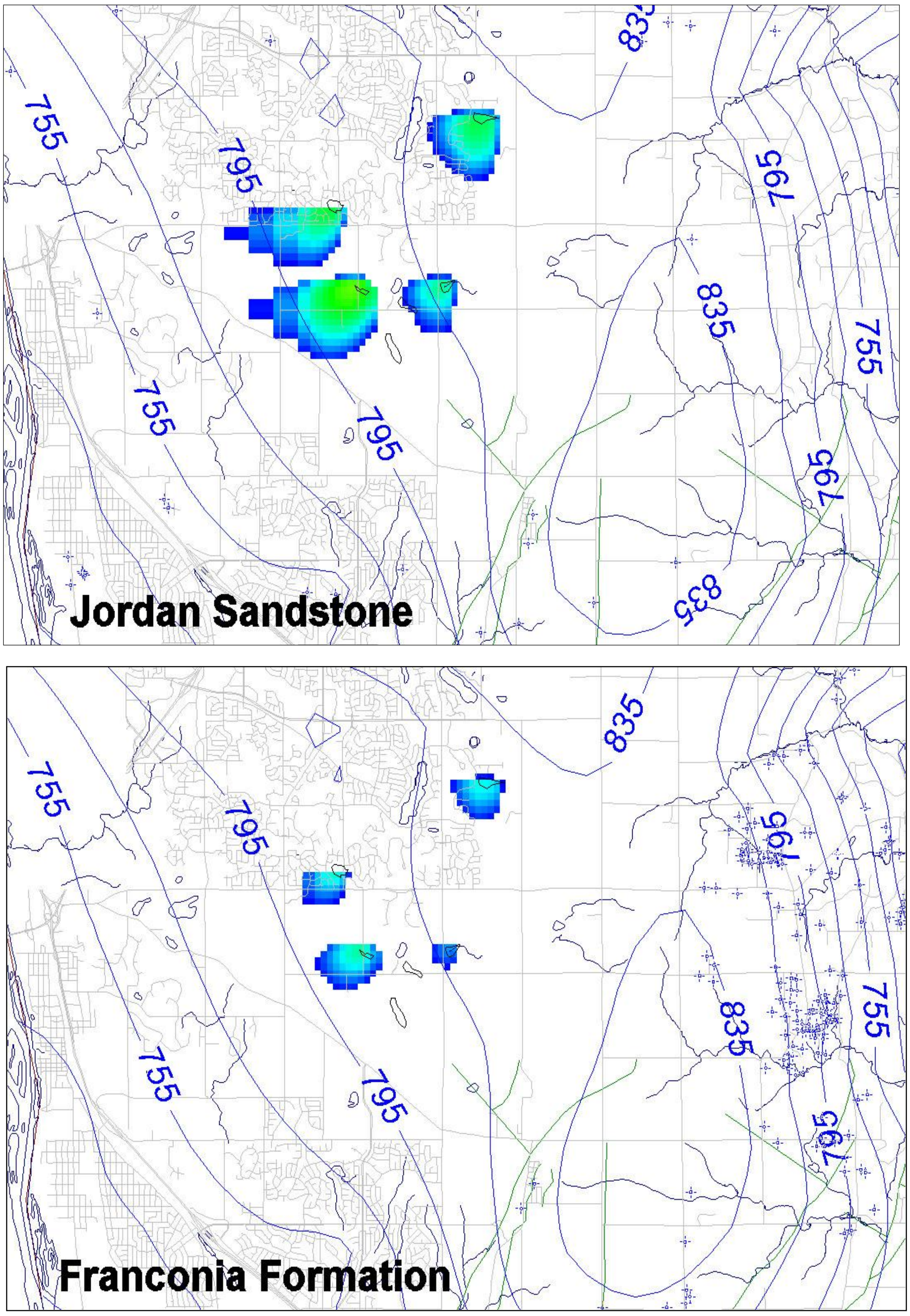
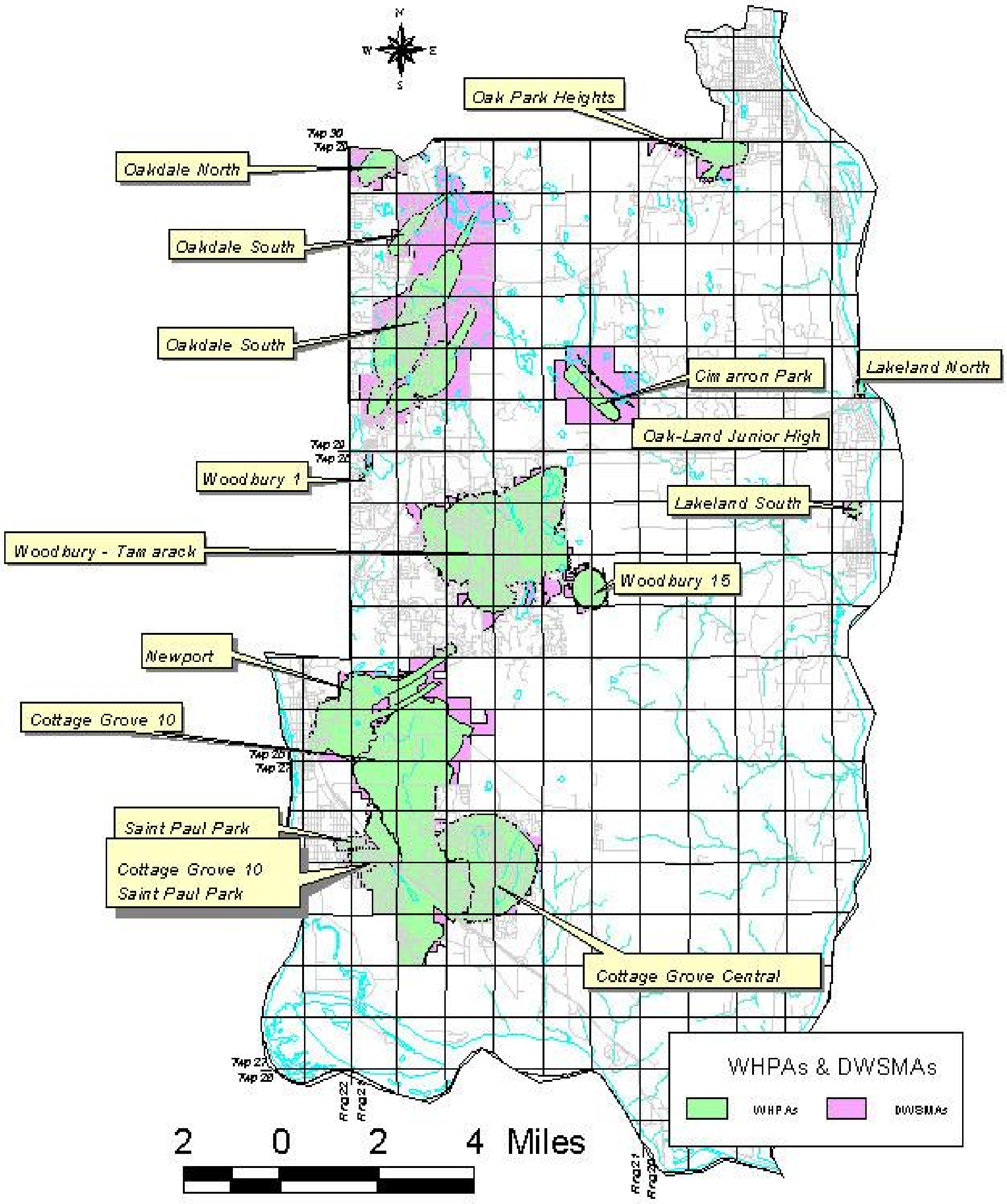


Figure 54

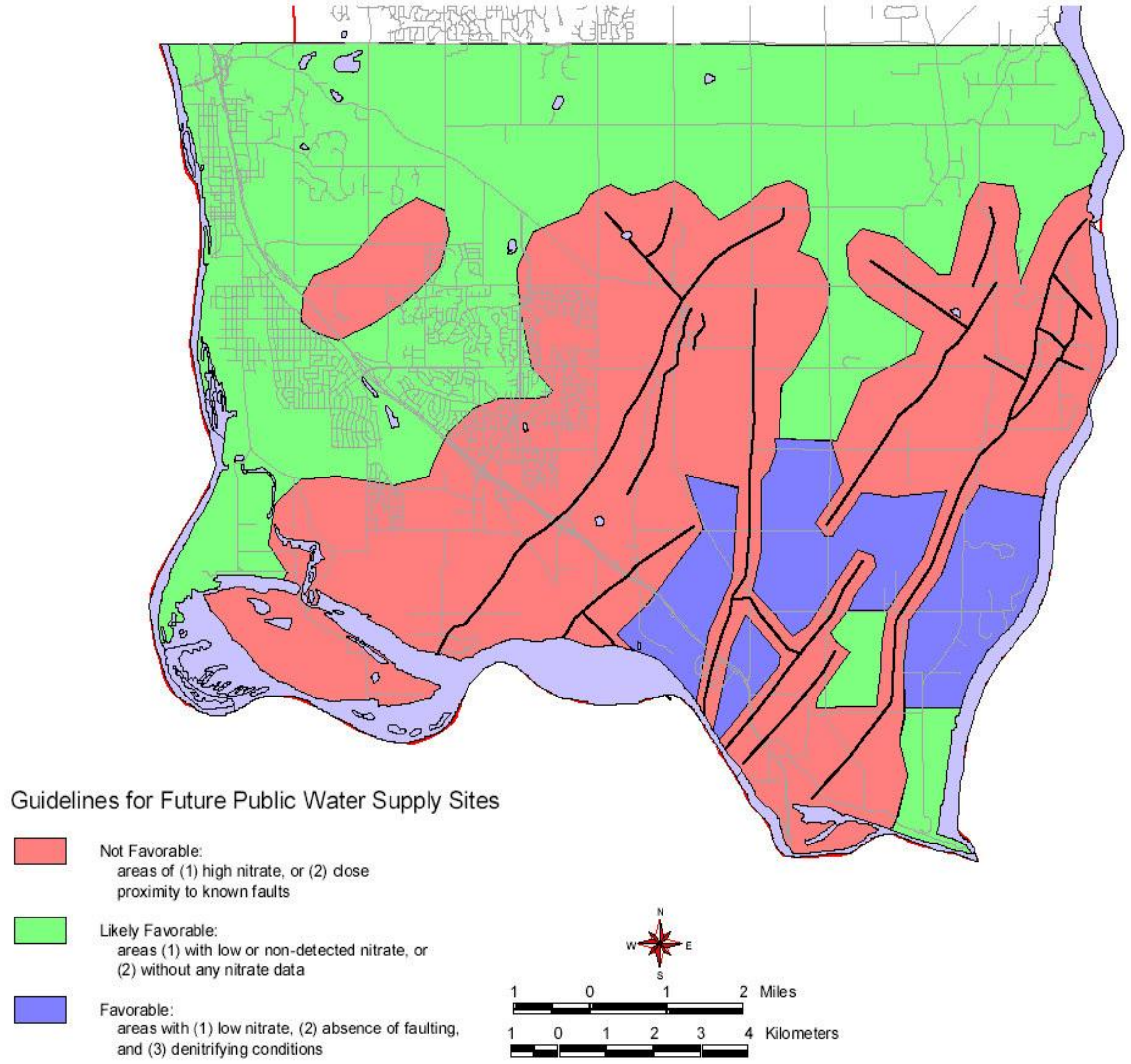
Simulation of Migration of Stormwater in Jordan Sandstone and Franconia Formation after 10 Years



Source: Minnesota Dept. of Health (Lake Elmo and Bayport WHPAs not available)

Figure 55

Wellhead Protection Areas and Drinking Water Source Management Areas



From Cottage Grove Area Nitrate Study (Barr Engineering Co., 2003)

Figure 56

Guidelines for Siting Future Public Water-Supply Wells in the Cottage Grove/Denmark Township Area for the Purpose of Minimizing Potential Exposures to Nitrate in Groundwater