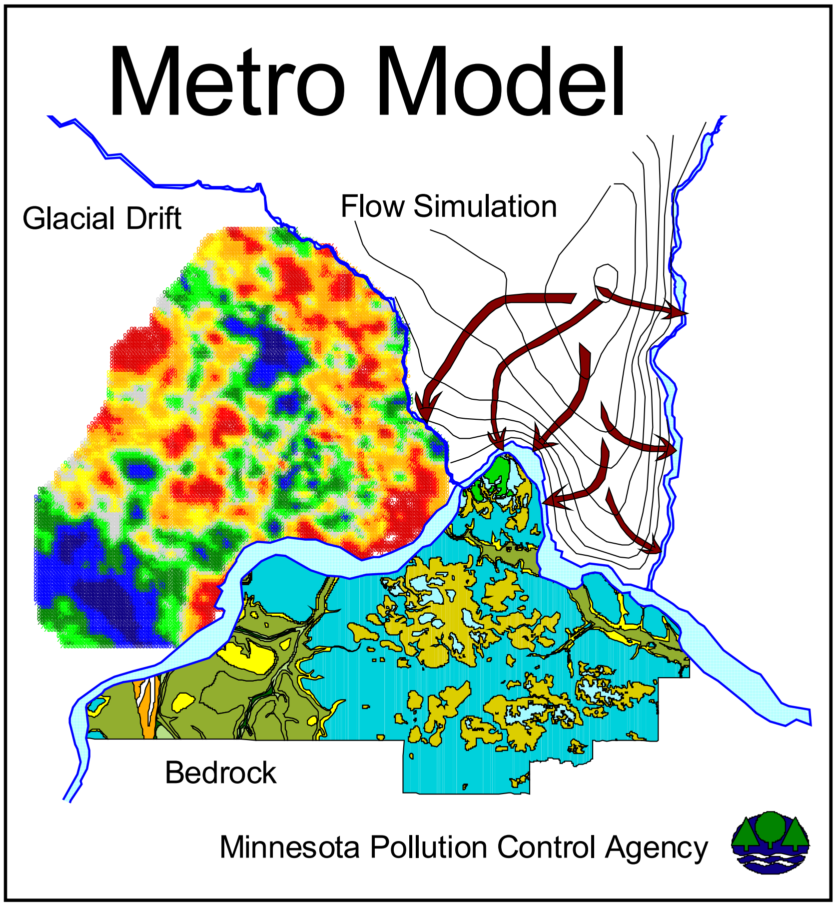
Metropolitan Area Groundwater Model
Project Summary

Overview of the Twin Cities Metropolitan Groundwater Model

Version 1.00, July 2000

John K. Seaberg



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Introduction

Objective

This report presents an overview of the development of the Twin Cities Metropolitan Groundwater Model (Metro Model), a computer model that simulates regional groundwater flow in the seven-county Twin Cities metropolitan area (Figure 1). This area includes Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, and Washington Counties. The Metro Model has been developed by staff from the Minnesota Pollution Control Agency (MPCA). The computer model is based on the analytic element method and simulates multi-aquifer groundwater flow. It is available for use as a management tool to groundwater scientists working in both the public and private sectors to aid in management decisions affecting groundwater. MPCA staff are applying it to problems of groundwater contamination, but it was developed with additional objectives in mind, to ensure that it has the broadest utility among all groundwater scientists. It is hoped that the

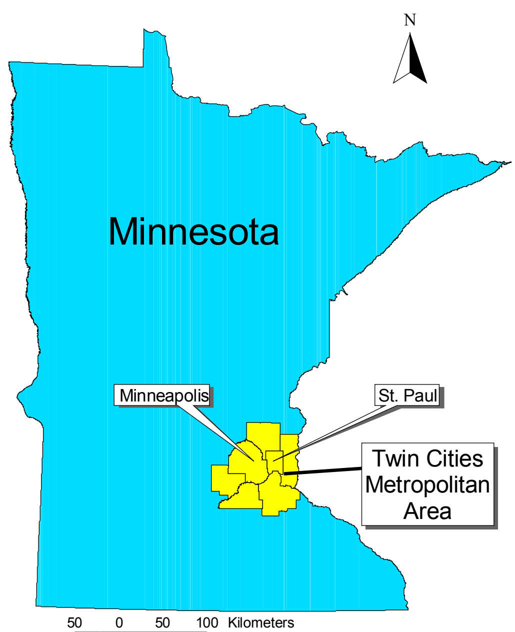

Figure 1. Metro Model Location Map

Metro Model and its supporting data will assist planners, government agencies, private consultants, and the people of Minnesota in protecting their groundwater resources

> **Important Note:** The Metro Model is a *regional* groundwater flow model that provides the regional context of groundwater flow in the metropolitan area. It can be an effective tool when modified to mindfully include local site-specific conditions. Using it "right out of the box" is very unlikely to provide an adequate representation of local flow conditions. Application of the Metro Model necessarily requires that end-users insert local detail into the model to conduct site-specific modeling. By serving as the starting point for site-specific models, the Metro Model provides added value to a project because a local model may be constructed with less time and money than would otherwise be required. Additionally, it may permit the user to spend more time developing the site-specific model since the context of regional flow is already provided. Moreover, the end product may be more technically robust, because the local detail is added against the regional backdrop that the Metro Model provides.

This document provides an overview of the Metro Model, its supporting databases, and the conceptual model on which it is based. As will be discussed, the Metro Model is actually comprised of four separate models that are capable of being linked. Separate project summaries, prepared for each of these four models, can be obtained from the project web site. This report is to be used with the project summary that is provided with each of the four model components of the Metro Model.

This report presents the first release version of the Metro Model available for widespread distribution, known as Metro Model Version 1.00. Future model revisions will be reflected by incremental increases in the version number, which will readily allow users to determine the most current version available. Resources permitting, revisions to the Metro Model will occur in response to increased knowledge and improved understanding of hydrogeologic flow systems. Our understanding of the groundwater systems is expected to improve as 1) existing data and information are collected, analyzed, and integrated; 2) new information becomes available and is incorporated; and 3) information from sub-regional and local applications of the Metro Model is captured. Judicious use of the information contained in this document is necessary. Be aware that, because the regional hydrogeologic system is being considered, the information presented here is not intended to represent site-specific conditions for local sites.

Feedback and Project Contacts

While this report provides background information for users of the model, it also serves as a springboard for receiving critical feedback that is essential for ensuring a level of quality that can only be achieved through peer review. The survival of this project depends on how relevant it is to the work of groundwater professionals. Therefore, reviewers are cheerfully invited to share feedback, ideas, and criticisms on any aspect of the project at *any* time. Project staff really want to know what is working and what isn't. If you have feedback to offer the Metro Model team, would like more information, or think that the Metro model project team can provide you with resources you need for your project, please contact one of the following individuals:

John Seaberg (651) 296.0550
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Project resource: Hydrogeology, conceptual model, Geographic Information Systems (GIS), and model development, calibration, and application.

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Project resource: Engineering applications, conceptual model, GIS, and model development, calibration, and application.

Also, we invite you to share your feedback and thoughts with management charged with project oversight, and ultimately its fate. Concerns and feedback can be given to the overseeing supervisor:

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Organizational and funding changes may impact the degree to which Metro Model staff may assist parties interested in project resources. But project staff will try their utmost to promptly and effectively respond to requests of customers, given the support and resources to do so.

Users' Advisory Workgroup

Metro Model staff work on a cooperative basis with interested governmental and private-sector parties from outside the MPCA, including government scientists, private consultants, and industrial representatives. As potential users of the model, these parties represent a Users' Advisory Workgroup for the model, providing valuable input into its development. This group consists of approximately 30 professionals who meet on a periodic basis to be apprised of progress and to give input on development of the Metro Model. This group is essential in providing critical technical review as well as guidance on the direction of model development and administration. The Metro Model would not have reached the current state without the dedicated support of the members of the Advisory Workgroup. Metro Model staff intend to continue convening meetings of the Users' Advisory Workgroup provided that the resources are available to do so.

Previous Efforts

Previous large-scale modeling efforts in the metropolitan area include the United States Geological Survey's (USGS') application of a finite-difference program (Trescott, 1975; Trescott and Larson, 1976) to develop a flow model of the metropolitan area (Schoenberg, 1990), which was subsequently converted to run using MODFLOW (Lindgren, 1996), and most recently converted to run on the GMS MODFLOW software package developed by EMS-I (http://www.ems-i.com/gms/index.html). Additionally, a model using the older version of MLAEM that employed quadrilateral areal elements was constructed by a private consultant to evaluate the suitability of potential landfill sites in one of the counties (Strack et al., 1989). USGS also produced a groundwater model to evaluate the effects of water withdrawals from the Mississippi River by the Minneapolis Water Works on the underlying groundwater flow systems (Lindgren, 1990).

More recently, some counties within the metropolitan area have begun development of countywide groundwater flow models using analytic elements. Hennepin Conservation District prepared a model for bedrock aquifers using an older version of MLAEM (Piegat, 1998). A model using MLAEM (again, an older version) was developed for Dakota County (Barr Engineering Company, 1995). The Ramsey Soil and Water Conservation District contracted with a consultant to construct a multi-layer groundwater flow model of the Ramsey County area using GMS MODFLOW (Barr Engineering Company, 1999a).

There have also been some significant miscellaneous models that have been developed to address groundwater management problems. One such model is a MLAEM model (with quadrilateral elements) of the Savage Fen area (Barr Engineering Company, 1994) prepared for the City of Savage. An early application of analytic element modeling was for a quarry on Grey Cloud Island in the southern metropolitan area (O.D.L. Strack, 1989). This model was later used to guide development of an analytic element model for the City of Inver Grove Heights (Strack et al., 1995).

The Minnesota Department of Health (MDH) has been active in recent years in developing regional and sub-regional groundwater flow models for use in wellhead protection. One such model is for Scott and Dakota Counties (Barr Engineering Company, 1999b). This model was constructed by using GMS MODFLOW, supported in large part by the databases, conceptual model, and layout of the Metro Model. Additionally, three MDH models are currently undergoing development by private contractors, using the Metro Model as their starting base. These are 1) a Prairie du Chien-Jordan model of the Northeast Province (MDH, 1999a), 2) a Franconia-Ironton-

Galesville and Mt. Simon-Hinckley model for Anoka County (MDH, 1999b), and 3) the deep Quaternary Anoka Sand Plain aquifer in Anoka County (MDH, 1999c).

Coordinate System and Units

The model is based on a Cartesian coordinate system (flat-plane ***x, y***-coordinates). This is appropriate, provided that the area of interest is small enough so that the curvature of the earth does not cause significant distortion of the coordinates within the modeled area. A Cartesian coordinate system is appropriate for the Metro Model since it is limited to a relatively small geographic area.

The Cartesian coordinate system chosen for the Metro Model is Universal Transverse Mercator (UTM), Zone 15, using the NAD83 datum. The UTM coordinate system has units of meters and introduces a minimal amount of distortion to the projected Cartesian coordinate system. No distortion is introduced to the system in the ***y***-direction (north-south) and a maximum distortion of 0.1 percent in the east-west direction is introduced across the entire state. Metric units are preferable since they are likely to become universal in this country. Additionally, the use of meters will result in lower numerical values than the English system for representing distances, which will be computationally more expedient. Note that conversions of coordinates between state plane, UTM, and latitude/longitude can be readily accomplished through the use of GIS software. Elevations and contour intervals of model output may be chosen to represent feet so that comparisons can be made to existing data in the English system (FSS units).

Geographic Information Systems

Model development, as well as model output, is handled largely in a Geographic Information Systems (GIS) environment. Specifically, the Metro Model team uses ArcView, a proprietary GIS software package that has gained wide acceptance within Minnesota. Data and information that the Metro Model team displays within a GIS environment include bedrock geology, sand content of glacial drift, bedrock topography, thicknesses and surface elevations of the tops of selected bedrock layers, and model outputs including head calibration plots and piezometric surfaces. The GIS environment allows ready comparison of different location-oriented databases and coverages. For example, well and pumping test locations with hydraulic conductivity values may be superimposed on displays of geology or piezometric surfaces.

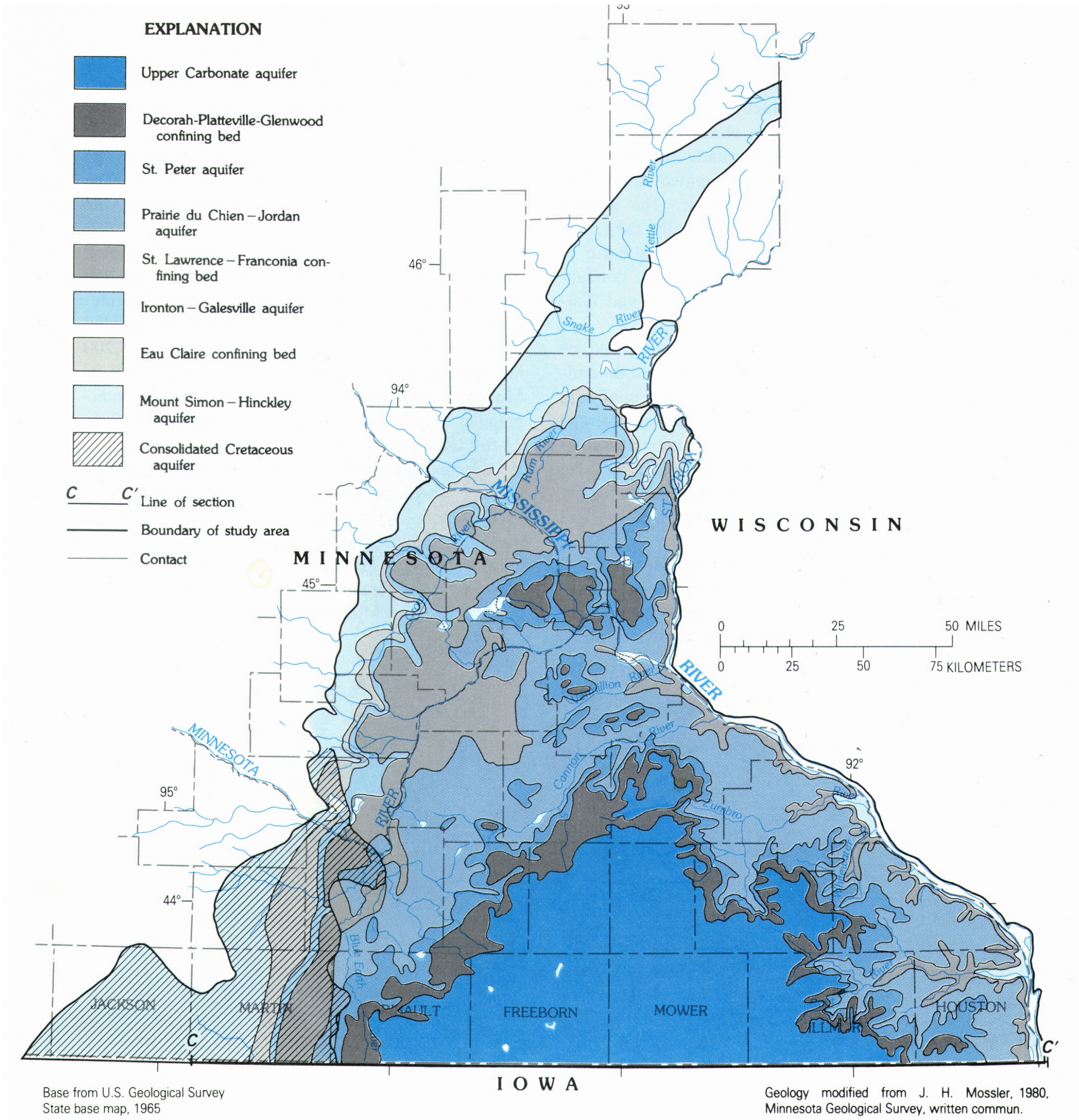
Background

Regional Geology

Geology in the Twin Cities metropolitan area is comprised of surficial unconsolidated glacial and alluvial sediments, overlying a thick sequence of Paleozoic sedimentary rocks, which in turn overlie the Hinckley Sandstone and its underlying formations. The Paleozoic strata are deposited in what is known as the Hollandale Embayment, a southerly-plunging synclinorium, developed over part of an older syncline (Delin and Woodward, 1984).

The Paleozoic sequence overlies older Proterozoic formations. Regionally, the Proterozoic rocks are comprised of a thick sequence of Keweenawan Basalts that are overlain by a thick sequence of detrital red clastic sedimentary rocks (Craddock, 1972). The uppermost Proterozoic sedimentary rock unit is the Hinckley Sandstone.

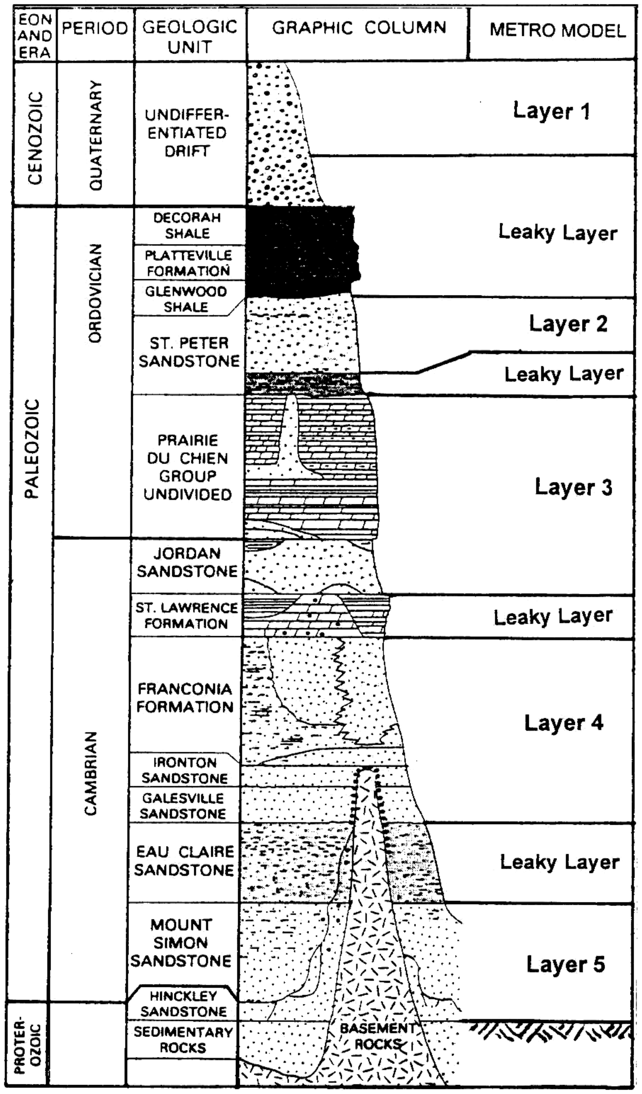
The Paleozoic strata were deposited during marine transgressions and regressions. The Paleozoic sequence above the Hinckley Sandstone begins with the Cambrian Mt. Simon Sandstone, and ends, in the Twin Cities metropolitan area, with the uppermost Ordovician Decorah Shale. The northwest border of the Hollandale Embayment is marked by the extent of the Paleozoic strata, which subcrop from approximately the Duluth area in the northeast stretching to the southwestern portion of the state. This zone passes through central Wright and Sherburne Counties, northwest of the metropolitan area, as illustrated in the simplified regional map of major hydrostratigraphic bedrock units in Figure 2 taken from Delin and Woodward (1984). The Paleozoic marine transgressions were bounded in the north by the transcontinental arch, resulting in near-shore high energy environments, dominated by coarser clastic deposits. Consequently, the Paleozoic formations up to the Jordan Sandstone tend to be more permeable near the northern portion of the metropolitan area. As a result, some formations generally regarded as confining units are used for groundwater production in the northern portion of the metropolitan area, and show reduced vertical hydraulic resistances. Secondary permeabilities attributed to fracturing and weathering of exposed bedrock prior to glacial cover further increase the overall hydraulic conductivity of these formations.



After Figure 2.4-1 of Delin and Woodward (1984)

Figure 2. Bedrock Geology of the Hollandale Embayment

Figure 3 is a stratigraphic column illustrating the sedimentary geology of the Twin Cities metropolitan area. Ignoring for the moment the assignment of Metro Model hydrostratigraphic layers (far right), which will be discussed in the section titled “Conceptual Model”, the bedrock units range from pre-Cambrian clastic sediments to the Ordovician Decorah Shale. A large gap in the geologic time record is represented by Quaternary age glacial drift deposits that rest unconformably on the subcropping bedrock units, the youngest of which is Ordovician in age, deposited over 430 millions years ago.



After Figure 2.21 of Delin and Woodward (1984)

Figure 3. Hydrostratigraphic Column and Conceptual Model

Reactivation of Proterozoic faults during Paleozoic time created secondary features within the Hollandale Embayment, including, most prominently, the Twin Cities Structural Basin, which is approximately centered beneath the Twin Cities metropolitan area (Delin and Woodward, 1984). To illustrate this structural feature, a north-south and an east-west transect are schematically plotted on Figure 4, showing the location of the geologic cross-sections through the metropolitan area that are schematically displayed in Figure 5. The erosional surface of the Paleozoic formations within the basin indicates that the subcropping formations become increasingly older in age (lower stratigraphically) moving concentrically out away from the center of the Twin Cities structural basin towards the northeast, north, and northwest, to the outer extent of the subcropping Hinckley Sandstone. Lower aquifers are recharged in this zone where they subcrop beneath the glacial drift. Because of the basin structure, stratigraphically younger aquifers have recharge zones closer to the center of the basin. Recharge zones for successively older aquifers move concentrically outward away from the basin center in the westerly and northerly directions.

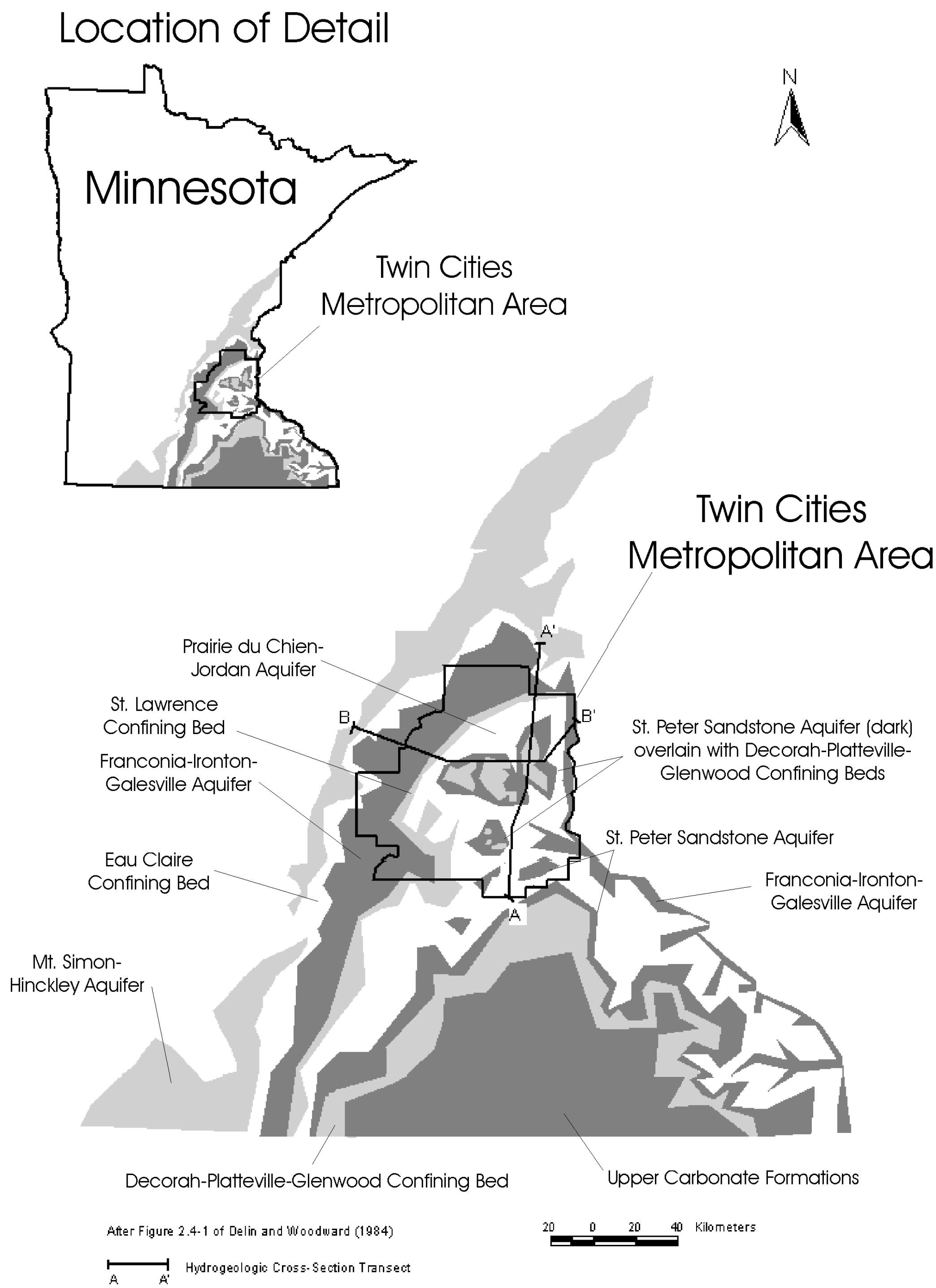
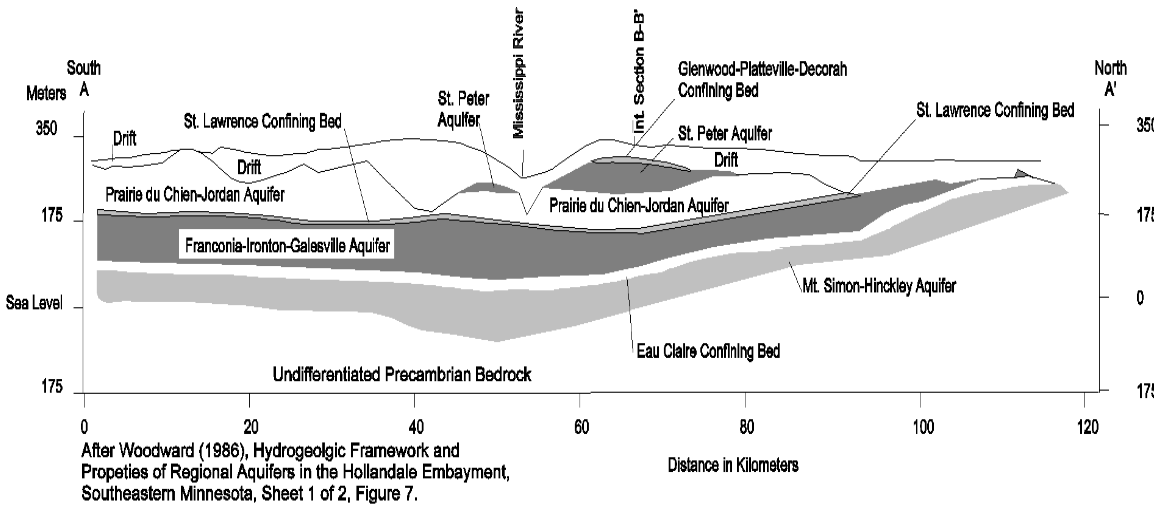
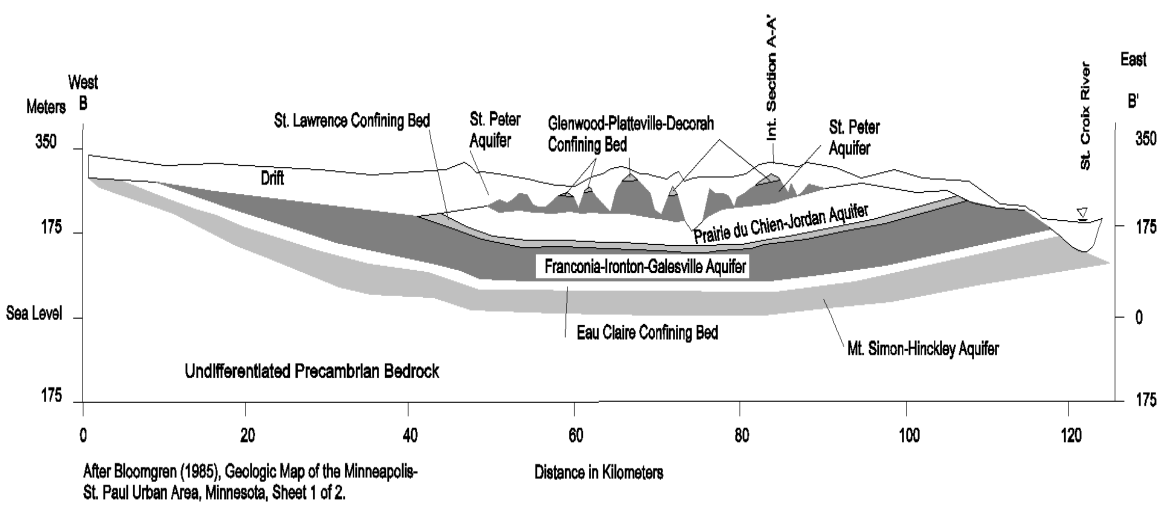


Figure 4. Location of Transects Through the Twin Cities Structural Basin



Cross-Section A – A'



Cross-Section B – B'

Figure 5. Cross-Sections Through the Twin Cities Structural Basin

The Paleozoic rocks have an erosional surface that includes several valleys cutting through the rock units. Some of the valleys are completely filled with Quaternary glacial materials, and others, although filled with alluvium, continue to serve as valleys for present-day rivers. The unconsolidated material overlying the bedrock surface of the Paleozoic units is comprised mostly of glacial drift deposited during different glacial advances with some alluvium in modern valleys.

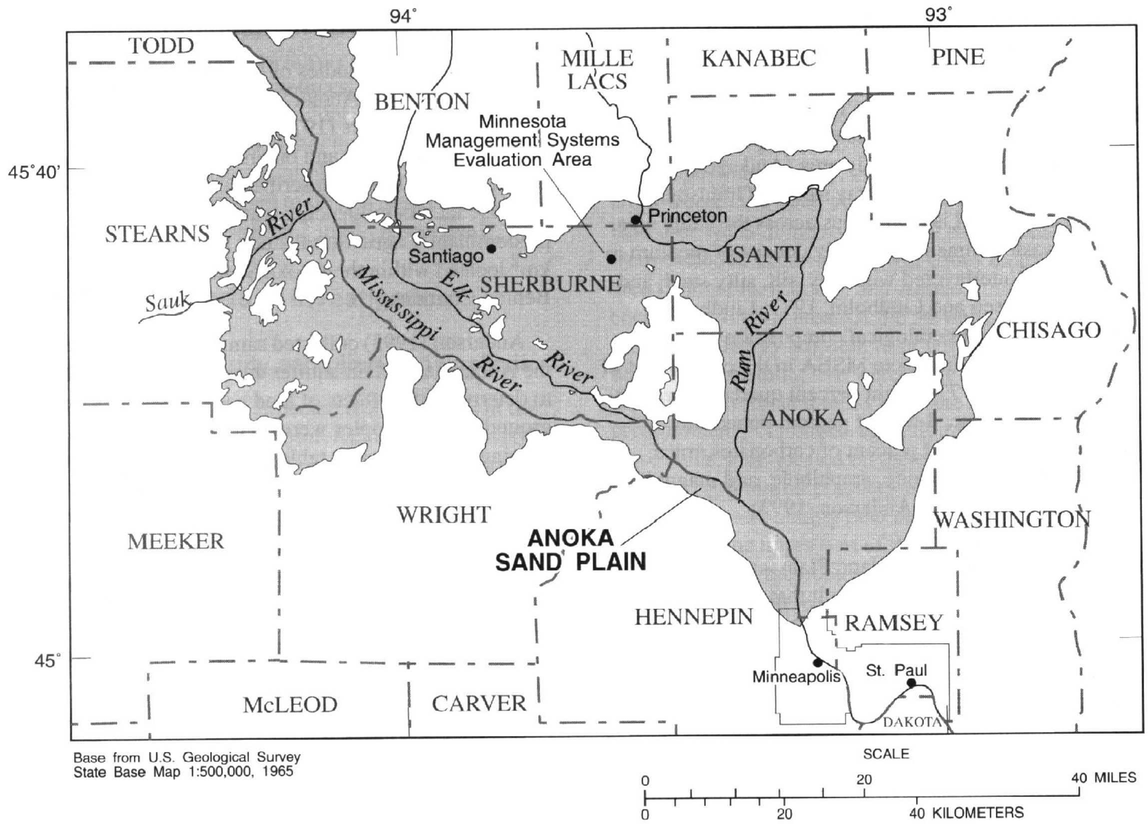
Glacial Hydrogeology

Unconsolidated Quaternary glacial deposits dominate the near-surface geology in the metropolitan area. Glacial sediments include relatively impermeable glacial tills and deposits of highly permeable outwash and ice-contact stratified drift, such as eskers, kames, and tunnel valley fans. Additionally, alluvium, generally confined to river valleys, is comprised of relatively permeable sands and gravels and relatively impermeable overbank type deposits. Much of the alluvium was deposited under glacial meltwater conditions. The glacial drift in the metropolitan area ranges from highly heterogeneous terrane, undifferentiated with no mappable units present, to zones showing significant continuous units that can be mapped over large areas. The approach taken to model groundwater flow in the glacial drift materials is described further in the discussion of Global Model Inputs for Layer 1 under the section titled “Model Development and Input Parameters”.

Although the fill material in buried bedrock valleys can be highly heterogeneous, and can include till deposits, some general observations can be applied with caution. If the pre-existing valley drained in the direction towards the glacier margin, meltwater would likely fill the depression forming a proglacial ice-dammed lake, favoring the deposition of fine and relatively impermeable lacustrine sediments. If, instead, the valley drained away from the glacier, it would provide a natural channel that could convey glacial meltwater. Such a valley is more likely to be filled with coarse permeable outwash/alluvium deposits.

A hydrogeologically important Quaternary unit that is present in the northern portion of the metropolitan area is the Anoka Sand Plain as shown in Figure 6 (from Landon and Delin, 1995). It is largely contiguous, extending to the north and northwest from the metropolitan area. In the absence of highly productive bedrock aquifers near the ground surface, the Anoka Sand Plain Aquifer is widely used as a groundwater resource.

Two outwash sand units comprise the Anoka Sand Plain (Anderson, 1993). The lower unit is comprised of red sands derived from the Superior lobe of glaciation. It is absent in the western third of the Anoka Sand Plain and occurs only discontinuously in the eastern two-thirds. The upper sand unit is comprised of gray outwash sands of Des Moines sublobe provenance. Both gray and red till units typically underlie the outwash units. However, on the basis of tritium data, Kanivetsky and Rumynin (1993) conclude that the Anoka Sand Plain behaves hydraulically as one unit and that the basal tills do not effectively impede infiltration.



After Figure 1 of Landon and Delin (1995)

Figure 6. Location of the Anoka Sand Plain

Bedrock Hydrogeology

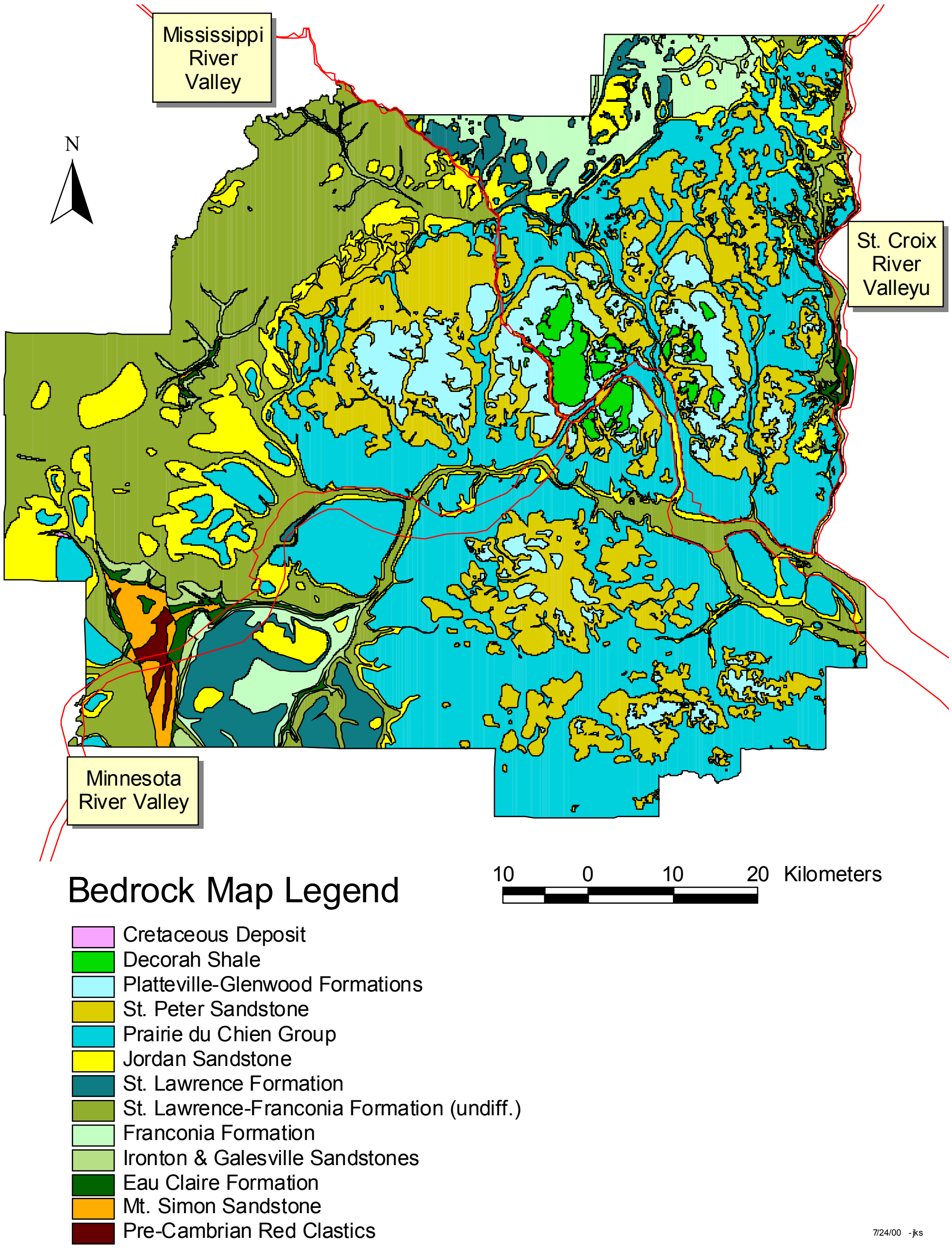
This section summarizes the hydrogeology of the sedimentary bedrock units in the Twin Cities metropolitan area, starting with the uppermost units and moving downward (down-section). The areal extent of these units is illustrated in Figure 7, a bedrock map of the seven-county Twin Cities metropolitan area that was provided by the Minnesota Geological Survey (MGS) (Mossler and Tipping, 2000). Please refer to this figure in the following descriptions about the various geologic units in this section.

Decorah Shale. The uppermost bedrock unit in the metropolitan area is the Decorah Shale, a bluish-green to bluish-gray blocky shale, with beds of fossiliferous limestone occurring throughout the unit. The formation is typically weathered and heavily broken up, owing to surface exposure prior to the deposition of glacial materials on top. The Decorah Shale occurs in thickness up to 29 meters (95 feet). Although it provides high hydraulic resistance to vertical flow, it is very discontinuous, covering only 91 square kilometers (25 square miles) of the entire 7,800-square kilometer (3,000-square mile) seven-county metropolitan area, as determined from the geologic coverage provided by Mossler and Tipping (2000).

Platteville Limestone. Underlying the Decorah Shale is the Platteville Limestone, a dark gray hard dolomitic limestone and dolomite that can be divided into five members in the metropolitan area: the Carimona, Magnolia, Hidden Falls, Mifflin, and Pecatonica members. Its maximum total thickness is estimated to be 9 meters (30 feet) (`Webers, 1972) to 11 meters (35 feet) (Norvitch and others, 1973). Although the Platteville Limestone is more extensive than the Decorah Shale, it still only covers about 540 square kilometers (210 square miles) in the seven-county metropolitan area (Mossler and Tipping, 2000). The Platteville Limestone serves as an aquifer in relatively few places, and will generally not be treated as an aquifer in the Metro Model. Groundwater within the Platteville Limestone is perched in places above the Glenwood Shale, likely the result of pumping in the Prairie du Chien-Jordan Aquifer inducing drawdown in the St. Peter Sandstone, which underlies the Glenwood Shale.

Glenwood Shale. The Glenwood Shale is a thin (generally less than 1.5 meters, or 5 feet, thick) soft bluish gray to bluish green shale that acts as a confining bed. It is continuous within the Paleozoic sequence, which has since been significantly eroded. It contains a thin layer (2.5 – 15 centimeters thick) of bentonite that is not continuous, but provides most of the vertical hydraulic resistance where present. Since the Glenwood Shale erodes so easily it is only found where the Platteville Limestone is present to protect it. Therefore, it encompasses the same area as the Platteville Limestone (540 square kilometers) in the metropolitan area

St. Peter Sandstone. Underlying the Glenwood Shale is the St. Peter Sandstone, a fine- to medium-grained, well-sorted, white to buff quartz sandstone occupying approximately 1,760 square kilometers (680 square miles) of the seven-county metropolitan area, as determined from Mossler and Tipping (2000). It is greater than 45 meters (150 feet) thick in the northern part of Ramsey County. Figure 7 illustrates the regional extent of the St. Peter Sandstone. The St. Peter Sandstone and the Paleozoic formations that overlie it in the metropolitan area are not continuously present moving to the south towards the Hollandale Embayment. This is because erosion of the Twin Cities structural basin has isolated these formations from the rest of the Hollandale Embayment.



After Mossler and Tipping (2000)

Figure 7. Metropolitan Area Bedrock Geology

Groundwater within the St. Peter Sandstone can be confined or unconfined. As stated previously, phreatic conditions are believed to be induced by heavy pumping in the underlying Prairie du Chien-Jordan Aquifer. Additionally, such conditions will likely exist in the St. Peter Sandstone near the valleys that dissect it, causing the groundwater to discharge through a seepage face. Siltstones and shales in the basal portion of the formation constitute a significant confining unit that occurs discontinuously over a large portion of the metropolitan area. In general, the confining properties are most significant in Hennepin and Ramsey Counties, where the confining zone is the thickest. It thins and disappears in Washington and Dakota Counties.

Prairie du Chien-Jordan Aquifer. The Prairie du Chien-Jordan Aquifer, which underlies the St. Peter Sandstone, is the most productive aquifer in the Twin Cities metropolitan area, supplying in general about 80 percent of the groundwater pumped, and 50 percent of all water used in the metropolitan area. The Jordan Sandstone occupies over 4,700 square kilometers (1,820 square miles) of the seven-county metropolitan area and the Prairie du Chien Group 3,950 square kilometers (1,520 square miles) as determined from Mossler and Tipping (2000) and illustrated on Figure 7. It is comprised of two formations that have been traditionally lumped together as a single hydrostratigraphic unit: 1) the Prairie du Chien Group, which is up to 76 meters (250 feet) thick and comprised of, in descending order, the following units: the Shakopee Dolomite, a karstified dolomite that is generally isotropic, the New Richmond Sandstone, and the Oneota Dolomite, which is anisotropic; and 2) the Jordan Sandstone, a white to yellowish fine- to coarse-grained sandstone exceeding 30 meters (100 feet) in thickness.

Different flow regimes occur in each formation. Flow in the Prairie du Chien Group is dominated by secondary porosity, owing to the occurrence of fractures, joints, and solution cavities. However, flow within the Jordan Sandstone is dominated by porous media flow. The two formations have been traditionally lumped together as one aquifer on the assumption that they are hydraulically well connected, which was supported by some field evidence that included lack of consistent head differences between the formations and the pumping responses between them. However, the degree of hydraulic connection between the two formations has been the subject of recent investigations by MGS personnel. Mounting evidence suggests significant hydraulic separation may occur between the formations, particularly in areas where the Prairie du Chien group is overlain by younger bedrock units, which help to preserve the structural integrity of the formations. Therefore, these formations might require treatment as separate aquifers for local applications. Water levels within the heavily pumped Prairie du Chien-Jordan aquifer are greatly affected by daily pumping cycles.

St. Lawrence Formation. The St. Lawrence Formation is a dolomitic siltstone up to 20 meters (65 feet) thick that is present below the Jordan Sandstone (Norvitch and others, 1973; Jirsa and others, 1986). It is a confining layer where it is overlain by the Jordan Sandstone. However, where the Jordan Sandstone is not present, weathering and fracturing of the St. Lawrence Formation may increase its permeability and allow it to transmit significant amounts of water to the underlying Franconia Formation. This is especially true north of the metropolitan area where a relatively high-energy environment favored the deposition of more clastic sediments with higher primary permeabilities than to the south. The St. Lawrence Formation subcrops below glacial drift away from the center of the Twin Cities structural basin in Scott and Carver Counties and northwest of the metropolitan area where it is more permeable. The St. Lawrence Formation underlies almost all of the 7,800 square kilometers (3,000 square miles) encompassed by the seven-county metropolitan area.

Franconia Formation. The Franconia Formation, a fine-grained sandstone containing glauconitic silts, is present beneath the St. Lawrence Formation and may exceed 61 meters (200 feet) in thickness (Norvitch and others, 1973). It underlies most of the seven-county metropolitan area. Although not generally regarded as an aquifer by itself, the Franconia Formation can produce 54 to 109 cubic meters per day (cmd) (10 to 20 gallons per minute (gpm)), generally where it is fractured, in a manner similar to that of the St. Lawrence Formation. It is typically used to produce water in areas outside the extent of the Prairie du Chien-Jordan aquifer. Wells in the Franconia Formation are also commonly open to the underlying Ironton and Galesville Sandstones. The Franconia Formation is sometimes considered together with the Ironton and Galesville Sandstones to comprise a single aquifer. In addition to being influenced by secondary fractures, the hydraulic characteristics in the Franconia Formation show considerable variability as a result of the depositional environment. The formation is dominated by fine sands and silts in the northern portion of the metropolitan area where deposition occurred more proximal to the ancient shoreline under a relatively high-energy environment. As a result, this formation contains up to 18 meters (60 feet) of clean sandstone in northern Washington and southern Anoka counties, coarsening toward the northern edge. This sandstone unit is known as the Mazomanie Member. Consequently, the Franconia Formation is more productive in the Anoka and Coon Rapids areas than the Mt. Simon-Hinckley Aquifer. Farther from the shoreline, in the vicinity of Scott and Carver Counties, the Franconia Formation is so carbonate-rich that at one time it was mapped as belonging to the Prairie du Chien Group.

Ironton and Galesville Sandstones. The Ironton Sandstone underlies the Franconia Formation, and is in turn underlain by the Galesville Sandstone. The Ironton Sandstone is a white medium- to fine-grained silty sandstone that may exceed 24 meters (80 feet) in thickness. It is in hydraulic connection with the underlying Galesville Sandstone, a yellow to white, medium- to coarse-grained poorly cemented sandstone approximately 6 meters (20 feet) thick (Miller, 1985). These two formations underlie almost all of the seven-county metropolitan area, and together comprise a significant aquifer, particularly where the Prairie du Chien-Jordan Aquifer is absent. Wells placed in this aquifer yield 218 cmd to 2180 cmd (40 gpm to 400 gpm) (Norvitch and others, 1973), and are sometimes open to other aquifers.

Eau Claire Formation. The Eau Claire Formation acts as an effective regional confining layer between the Galesville Sandstone and the underlying Mt. Simon-Hinckley Aquifer. It is up to 46 meters (150 feet) thick, and is comprised of siltstone and very fine sandstone, locally interbedded with shale (Norvitch and others, 1973). Its regional extent, shown in Figures 2, 4, and 7, encompasses most of the seven-county metropolitan area.

Mt. Simon-Hinckley Aquifer. The underlying Mt. Simon-Hinckley Aquifer is comprised of the Cambrian Mt. Simon Sandstone and the Proterozoic Hinckley Sandstone, which are separated by an unconformable contact. Refer to Figures 2, 4, and 7 to view the regional extent of these formations, which underlie almost all of the seven-county metropolitan area. Each formation can be as much as 61 meters (200 feet) thick (Norvitch and others, 1973). Both formations are typically medium- to coarse-grained sandstones, and together comprise the second major aquifer in the seven-county metropolitan area, supplying about 10 percent of the groundwater production. The base of the Hinckley Sandstone is assumed to represent an impermeable base for the Metro Model. Presently, flow in the Mt. Simon-Hinckley aquifer is not at steady state, as evidenced by the changing heads measured throughout the metropolitan area in the Minnesota Department of Natural Resources' (MDNR's) observation well network (MDNR, 2000a). Originally, groundwater flow within the metropolitan area was from the Mt. Simon-Hinckley Aquifer upward towards the Prairie du Chien-Jordan Aquifer. However, the vertical gradient has been reversed due to pumping that has resulted in drawdowns within the Mt. Simon-Hinckley Aquifer of up to 73 meters (240 feet).

Major Recharge and Discharge Zones

Recharge of groundwater to the aquifer systems in the metropolitan area ultimately originates from surface infiltration. Within the metropolitan area, surficial infiltration recharges the groundwater from the glacial drift materials downward at least to the Prairie du Chien-Jordan aquifer. Recharge to the lower aquifer systems beneath the Prairie du Chien-Jordan aquifer in the metropolitan area may not be as significant, owing to the high hydraulic resistance of the largely intact St. Lawrence and Eau Claire Formations that serve as aquitards. Moreover, the lower Franconia-Ironton-Galesville and Mt. Simon-Hinckley aquifers subcrop beneath glacial drift materials north and west of the metropolitan area (Figures 2, 4, and 5), where they receive significant amounts of recharge. The flow regimes of these lower aquifer systems have resulted in artesian conditions within the metropolitan area, at least prior to drawdown induced by pumping. Hydrogeology, head data, and preliminary results of our modeling efforts all indicate that these lower aquifers are recharged primarily where they subcrop, well outside the metropolitan area. This suggests that the flow regimes of these lower aquifers behave much differently from those for the upper aquifers down to the Prairie du Chien-Jordan Aquifer. Complicating this scenario is the presence of buried bedrock valleys that incise down to the Ironton and Galesville Sandstones. These bedrock valleys can serve as hydraulic apertures between aquifers, facilitating focused inter-aquifer flow.

Higher rates of recharge to the subcrop zones of the lower aquifers are believed to occur on the Anoka Sand Plain north of the Mississippi River than to the south where glacial tills predominate. Leakage from overlying layers also contributes to the water input of the lower aquifers. Additionally, the Mt. Simon-Hinckley aquifer may receive water from underlying formations, although this effect has been neither documented nor quantified.

Natural discharge from the aquifers occurs to surface water bodies. Discharge is also a consequence of groundwater extraction from wells. The surface water hydrography for the seven-county metropolitan area is illustrated on Figure 8. Groundwater from upper aquifer systems in local to intermediate flow regimes typically discharges to lakes and smaller streams. The hydraulic connection to smaller surface water bodies becomes more tenuous moving downward to lower aquifers. The deeper the aquifer, the more insulated it is from the surficial water bodies and the more likely it will discharge to a regional discharge zone, such as a major river.

The most significant discharge zones for groundwater in the metropolitan area are the Minnesota, Mississippi, and St. Croix Rivers (Figure 8). These major river systems serve as important regional discharge zones to all aquifers down to the Prairie du Chien-Jordan aquifer, as evidenced by head measurements. The interaction of these river systems with the lower aquifers, such as the Franconia-Ironton-Galesville and the Mt. Simon-Hinckley aquifers is not as clearly understood. However, erosion through the overlying strata has left subcrop zones of the Ironton-Galesville and the Mt. Simon-Hinckley aquifers beneath the St. Croix and Mississippi Rivers south of the metropolitan area. This information, coupled with head data, indicates that the aquifers discharge water to the rivers in these zones.

Lake Minnetonka is a significant surface water body situated within the St. Croix terminal moraine, in an area that is overlain with Des Moines lobe till. The thick mantle of till isolates most of Lake Minnetonka hydraulically from the underlying bedrock. However, the eastern third of the lake seems to be in communication with bedrock and may be considered a recharge area for bedrock aquifers.

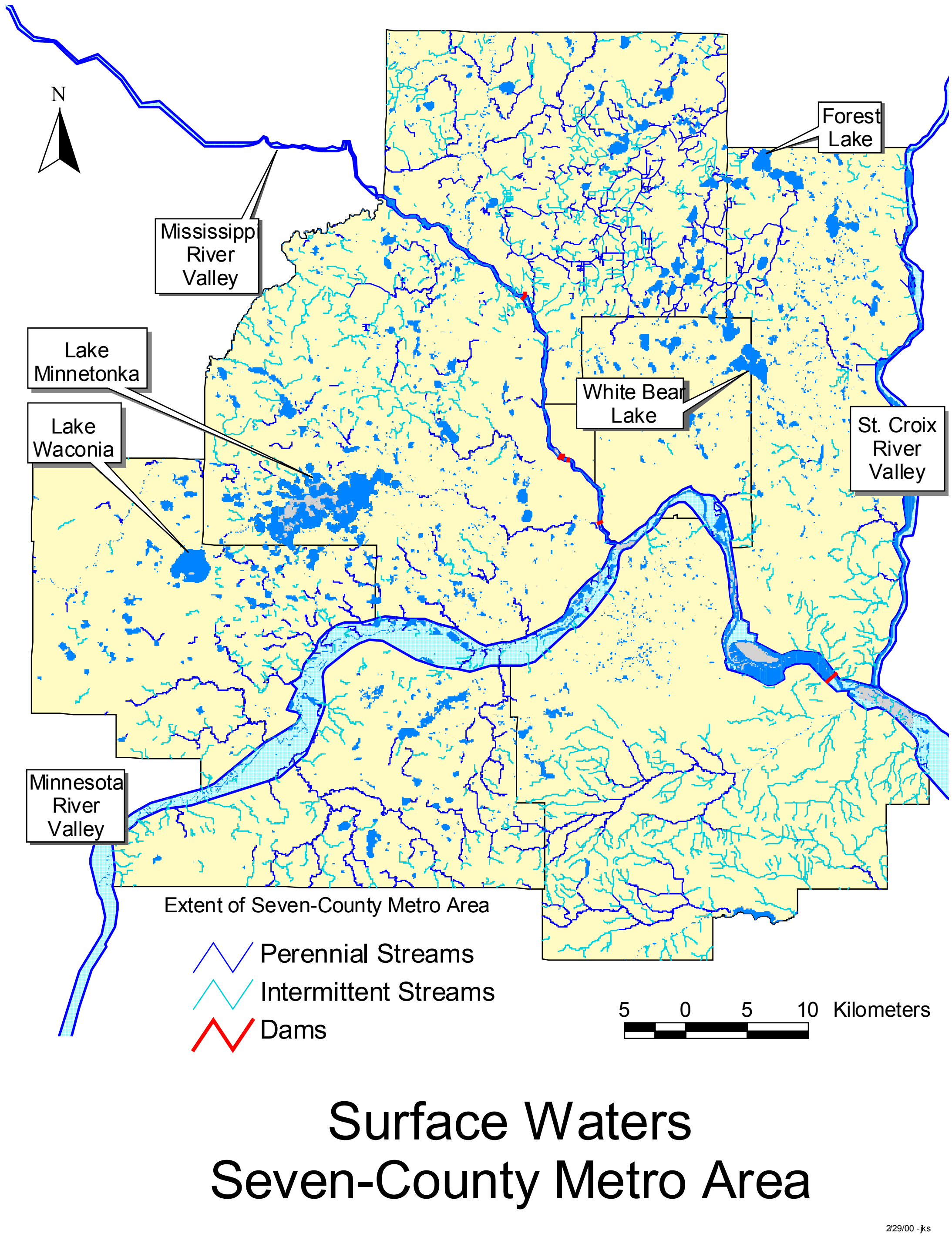


Figure 8. Metropolitan Area Hydrography

Model Approach

Software

Regional groundwater flow in the metropolitan area is being simulated using the analytic element method (O.D.L. Strack, 1989; Haitjema, 1995). Each analytic element is an analytic function that represents a particular feature in the aquifer, as discussed below under "Model Elements". The analytic element method is based on the superposition of such analytic functions. Distant hydrogeologic features are coarsely entered into the model to account for their effect on the area of interest. This part of the Metro Model is called the far-field and may encompass an area that extends from Duluth to the Iowa border in portions of the model. The degree of detail in the metropolitan area is much higher. Since the analytic element method is based on the superposition of analytic functions, it does not require the discretization of the model domain. This readily allows a user to add detail on a smaller scale for site-specific applications without having to re-discretize the model.

The software program specifically used to develop the Metro Model is the Multi-Layer Analytic Element Model program (MLAEM) developed by Professor Otto D.L. Strack of the Department of Civil Engineering of the University of Minnesota (O.E. Strack, 1992). Hydrostratigraphic units comprised of both bedrock and glacial drift units are included in the Metro Model. The model simulates three-dimensional groundwater movement. The subsurface is divided into water-bearing units that may be used for groundwater production (aquifers) that, in MLAEM, are separated by leaky layers. The Metro Model simulates regional interactions between aquifers, and is calibrated by comparison between measured and simulated heads and discharges.

Model Assumptions

The Metro Model is based on the following assumptions:

Steady-State. Flow in the aquifer is at steady-state conditions. This means that the model represents average conditions and does not account for temporal variations in aquifer stresses or changes in storage. Average or typical values of infiltration, surface water elevations, and pumping rates are used as inputs. Transient flow effects may be modeled in the future.

Dupuit-Forchheimer. The Dupuit-Forchheimer assumption for groundwater flow is adopted. This means that there is no vertical resistance to flow within an aquifer. Vertical head differences do not exist within the modeled aquifer, and vertical movement of groundwater is computed from continuity of flow (O.D.L. Strack, 1984).

Aquitards. Flow in aquitards or leaky layers is assumed to be vertical only. This assumption is valid whenever the hydraulic conductivity of the leaky layer is low compared to the hydraulic conductivity of the aquifer.

Wells. Pumping or injection wells within an aquifer are assumed to be fully penetrating.

Model Domain. The model domain extends to infinity, although the solution is only expected to be meaningful within the area of interest, where sufficient detail has been incorporated. Only real hydrogeologic boundaries are used, even if they are far from the area of interest. This eliminates a dependence on assumed or contrived boundaries.

Model Elements

The following is a list of analytic elements that have been used in the Metro Model during phases of its development. Note that not all elements presented are necessarily found in the latest version of the model, which has been modified to simulate regional flow conditions as efficiently as possible.

Head-Specified Curvilinear Line-Sinks. These elements are used to represent surface waters (rivers, lakes) that are in direct hydraulic connection with an aquifer. The line-sink element removes or injects water to the aquifer depending on the relation of the specified head to the head in the aquifer. These elements have also been used to represent streams that are not in direct hydraulic contact with the aquifer for the regional modeling. Experience from this project indicates that this approach provides satisfactory results, while being more computationally efficient for modeling regional groundwater flow.

Head- and Resistance-Specified Curvilinear Line-Sinks. Similar to head-specified line-sinks, these elements may discharge or recharge water to the aquifer, but they also incorporate a resistance value that represents the resistance to flow due to sediments at the bottom of the water body. These elements represent differences in head between the surface water and the aquifer.

Curvilinear Impermeable Walls. These features represent impermeable vertical walls within an aquifer layer that obstruct groundwater flow with curvilinear geometries. They have been used to represent vertical offset where normal faulting of an aquifer has occurred.

Given-Strength Area Elements. Given-strength area elements are areas bounded by a polygon for which a constant recharge or discharge rate is specified as a flux. These elements are used to model infiltration from precipitation and perched water bodies, as well as inter-aquifer leakage.

Head- and Resistance-Specified Area Elements. Also known as “resistance” elements, these elements are similar to resistance line-sinks in that values of head and resistance are entered. However, this type of element covers an area bounded by a polygon. The infiltration rate of the area element is computed by the model and varies over the element.

These elements are commonly used to model lakes and wide rivers, and can also simulate leakage from adjoining aquifers that are not explicitly modeled.

Leaky Area Elements. Leaky area elements are the same elements as the resistance area elements, except that they are used to model leakage between aquifers. Only a resistance value, which may vary over the element, is specified. Leakage may occur either upwards or downwards and vary over the area.

Wells. A well, or point sink, extracts water from or recharges water to an aquifer at a point. Currently, wells are modeled as fully penetrating and are specified for each aquifer. Multi-aquifer well elements are also available for inclusion in the model, as well as well areal elements (WARELs), which permit modeling of focused leakage induced near pumping wells.

Line Doublet. Line doublets are used to model jumps in aquifer properties: a combination of jumps in hydraulic conductivity, thickness, or base elevation of the aquifer. Areas with different aquifer properties are bounded by polygons and are referred to as inhomogeneities. If a transmissivity inhomogeneity is being modeled, the value should generally vary by a factor of five to ten times. Assuming that the hydraulic resistance of leaky layers adjoining the aquifer is relatively constant, the hydraulic conductivity between adjacent doublets within the aquifer ideally should be stepped up or down by a factor of two.

Variable Strength Area Elements. The three types of area elements discussed above were implemented in the Metro Model as variable strength area elements that are bounded by polygons (O.D.L. Strack, 1997; Strack and Janković, 1999). Variable strength areal elements are also referred to as VARELs for short. Parameter values of given-strength infiltration, head, or resistance to vertical flow are entered only at select points. For variable fields of input head or resistance values, Aquitard points, which may lie inside or outside the polygon boundary, are used in MLAEM. The Aquitard points provide the "known" inputs that are used as the basis for interpolating over the VAREL. If the parameter varies spatially, a number of Aquitard points may be entered and MLAEM interpolates between them such that the parameter varies continuously. The actual interpolated value of head and/or resistance is imposed on the model at another type of point, known as a basis or control point. If the value within a VAREL is constant, the values of head and resistance can be defined over the entire VAREL with only a single control point. Given-strength flux values can only be defined for a polygon using control points—Aquitard points are not currently supported to specify this input.

The leakage is computed at a number of control points for elements of unknown strength (leaky and resistance VARELs) and varies continuously between them. The value of the resistance and/or head (necessary to compute the leakage) is obtained by the model through the Aquitard data. Infiltration rates vary in a similar fashion for given-strength elements. Although head and resistance values may be specified directly at individual control points, the specification of parameter values through Aquitard points creates flexibility: model inputs may be revised using Aquitard points without necessarily having to change control points where the leakage is computed.

Conceptual Model

Description

A conceptual model of the groundwater flow is generally expressed in words as a set of assumptions (Bear and Verruijt, 1990). These assumptions include identification of the system's geometry, boundary conditions, type of flow, composition of the system, aquifer recharge and discharge zones, and hydraulic properties of the media. These assumptions represent a simplified perception of the hydrogeologic system intended to meet the objectives of the modeling effort by including only the features that are relevant to the questions being answered. Data and information used in the development of the conceptual model are approached from two fronts: 1) the hydrogeology is evaluated to identify features and processes likely to have a significant impact on the groundwater flow system; and 2) hydraulic head data are evaluated to ascertain indirectly the nature of interaction between hydrostratigraphic units and to help identify "hidden" hydrogeologic features that impact flow.

The hydrogeologic conceptual model has been developed from information derived from meetings held with local groundwater scientists representing both the public and private sectors, and from sundry literature sources. The conceptual model and the Metro Model will continue to evolve as additional information becomes available and as understandings of the system evolve. Application of multiple working hypotheses and flexibility in the development of the conceptual and computer models will enable the team to develop the most technically defensible interpretation and robust understanding of the groundwater system with the information at hand.

Use of MLAEM requires that the hydrostratigraphic layers be divided into aquifers and leaky layers. Assignment of units to either of these two categories requires that they fulfill appropriate criteria.

The criteria to be fulfilled to assign one or more geologic units to an aquifer may include one or more of the following:

- The unit(s) is sufficiently identifiable between boring logs to determine its extent;
- Piezometric head is consistent between the top and the bottom of the unit;
- Lateral groundwater flow is much more significant than vertical groundwater flow;
- The piezometric head is significantly different from that of overlying or underlying units; and
- Other evidence, such as pumping tests, indicates good vertical hydraulic connection throughout the entire aquifer.

The criteria for determining which units should be represented as leaky layers may include one or more of the following:

- The unit(s) is not used as a significant source of groundwater;
- Piezometric heads vary strongly from the top of the unit(s) to the bottom, indicating a strong vertical component of flow through it; and
- The hydraulic conductivity is significantly lower than that of the over- and underlying aquifers.

The current conceptual model consists of five aquifer layers separated by four leaky layers. Additionally, water can enter the system through the top of the upper-most aquifer and through subcrop zones of the lower aquifers. Groundwater may be transmitted between aquifers through leaky layers. Groundwater is removed from the system through discharge to rivers and lakes, and the pumping of wells. The approach taken in the development of the conceptual model allows flexibility to represent local change, as will be discussed following the discussion of the conceptual model.

The extent and hydraulic boundaries of the aquifers are discussed in the following paragraphs. The hydraulic boundaries are controlled largely by the morphology of the Twin Cities structural basin, erosion of the structural basin as well as the erosion of significant bedrock valleys, the nature and extent of the overlying glacial drift materials, the location of rivers that serve as major discharge zones, and leakage effects from other aquifers. The erosion of the bedrock structural basin has resulted in a roughly concentric exposure of successively older units moving outwards from the Twin Cities toward the north, and west (Figures 2, 4, and 7). This pattern is not entirely duplicated moving to the south, since the Twin Cities structural basin represents part of the northerly extension of the Hollandale Embayment. Consequently, a significant portion of the recharge to the lower bedrock aquifers occurs through the overlying glacial drift north and west of the Twin Cities area. Therefore, the outermost recharge zone in the west and north is for the deepest aquifer--the Mt. Simon-Hinckley Aquifer. The recharge zones occur successively closer to the Twin Cities as the aquifers become stratigraphically younger. The aquifers and leaky layers that comprise the Metro Model are defined in the following paragraphs. Figures 2 and 7 illustrate the areal extent of the subcrop zones beneath the glacial unit(s), and the stratigraphic column in Figure 3 schematically illustrates the Metro Model aquifers and leaky layers that are discussed in the following paragraphs.

Layer 1. This layer represents an aquifer of unconsolidated glacial materials throughout the model domain. A simplistic representation of the Anoka Sand Plain has been included with this layer. Groundwater recharge occurs at the top of this layer through infiltration. Water losses from this aquifer are to surface water bodies and to the underlying aquifer via leakage.

Leaky Layer 1-2. This leaky layer represents the lower-most unit(s) with vertical hydraulic resistance underlying the lower-most glacial drift aquifer. This leaky layer represents the effects of one or more of the following: glacial till, Decorah Shale, Platteville Limestone, and the Glenwood Shale. Therefore, its location is dependent on the areal distribution of these units.

Layer 2. This layer represents groundwater flow through the St. Peter Sandstone. Most recharge to the St. Peter Sandstone aquifer is expected to come from overlying drift materials in areas where the overlying bedrock layers are absent, such as the Minneapolis and St. Paul areas, between Burnsville and Rosemount, and in buried bedrock valleys where the St. Peter Sandstone subcrops. As previously noted, erosion of the Twin Cities structural basin has left an isolated "island" of the St. Peter Sandstone and its overlying Paleozoic formations, separate from the rest of the Hollandale Embayment (Figure 2). This "island" has subsequently been dissected by erosional bedrock valleys as illustrated in the bedrock map of the metropolitan area (Figure 7). Discharge of groundwater from this layer occurs through leakage to underlying units, discharge to surface waters, and discharge from seepage faces where the formation is truncated by the erosion of valleys into or through the St. Peter Sandstone, particularly along the Mississippi River in the urban Twin Cities area.

Leaky Layer 2-3. This leaky layer represents the base of the St. Peter Sandstone, which provides significant vertical hydraulic resistance. This separating layer will be present where the St. Peter Sandstone is present throughout the Twin Cities area, and will have the greatest resistance in Hennepin and Ramsey Counties and the smallest resistance in Washington and Dakota counties where the basal confining layer thins out and disappears.

Layer 3. Layer 3 represents groundwater flow in the Prairie du Chien-Jordan Aquifer, and includes both formations as one hydrostratigraphic unit. Exposure of the Prairie du Chien-Jordan aquifer to the glacial drift occurs over a large portion of the metropolitan area. The outer zone follows an approximate line from roughly ten kilometers (six miles) west of the southeastern corner of Scott County northwesterly to Lake Waconia, continuing in an arc up to the northeast corner of Washington County. Except for the incisement of buried bedrock valleys, the aquifer within the Twin Cities structural basin extends continuously to the Hollandale Embayment to the south. The outer extent of the Prairie du Chien-Jordan aquifer extends to the southwest from the metropolitan area (Figure 2). Recharge to this aquifer occurs as leakage from overlying bedrock units and also from the glacial drift where the formation subcrops beneath it. It is possible that this aquifer locally receives water from underlying formations near heavy pumping centers, which would induce flow from below by reversing the vertical hydraulic gradients. This aquifer may lose a small amount of water through its bottom via leakage through the St. Lawrence Formation. Additionally, the Mississippi, Minnesota, and St. Croix Rivers serve as major discharge zones for this aquifer.

Leaky Layer 3-4. This layer represents the St. Lawrence Formation where it overlies the Franconia Formation. This formation subcrops beneath glacial drift along a rather wide band starting north of the metropolitan area, extending in a south-southwesterly direction (Figure 2). This confining layer can actually serve as a significant aquifer where directly overlain by glacial materials due to surficial weathering and fracturing processes prior to cover with glacial materials. This is especially true in the northern portion of its extent, where it also contains more permeable sediments. Leaky Layer 3 is also used to represent leakage from overlying glacial drift into the Franconia-Ironton-Galesville Aquifer, which occurs outside of the subcropping St. Lawrence Formation, west and north of the metropolitan area. The recharge rates to the Layer 4 subcrop zone may reflect infiltration through tight tills or permeable sands, such as the Anoka Sand Plain.

Layer 4. The Franconia-Ironton-Galesville Aquifer will be represented by Layer 4. The Franconia Formation is being included with the Ironton-Galesville Sandstones because piezometric data indicate similar heads between the two and because it can be a significant source of groundwater in certain areas. Recharge to this unit occurs where it subcrops beneath glacial drift along a thin irregular band to the north, west, and southwest of the metropolitan area. Additionally, under unstressed conditions, it may receive a relatively small contribution of water from the Prairie du Chien-Jordan aquifer via the St. Lawrence Formation. However, with pumping stresses, it is possible that it receives water from the Mt. Simon-Hinckley aquifer through the Eau Claire Formation as well. Additionally, the Franconia-Ironton-Galesville Aquifer likely discharges water to at least portions of the Mississippi, Minnesota, and St. Croix Rivers.

Leaky Layer 4-5. This layer represents the Eau Claire Formation, a significant regional confining layer, the outer extent of which is shown in Figure 2.

Layer 5. Layer 5 represents the Mt. Simon-Hinckley Aquifer, which receives recharge via glacial drift where the aquifer subcrops, in a band stretching from the Duluth area down through southwest Minnesota to the Iowa border (Figure 2). Additionally, the aquifer receives water that leaks through the overlying Eau Claire formation where it is not impacted by the pumping of the shallower aquifers. Discharge for this aquifer likely occurs via unconsolidated valley fill to at least portions of the St. Croix and the Mississippi Rivers.

Hydrologic Provinces and Sub-Models

As mentioned previously, the Metro Model is actually comprised of four different regional groundwater flow models for the seven-county Twin Cities metropolitan area. They have been modularly constructed to facilitate linking with each other should the need arise. One of the models encompasses the entire metropolitan area and simulates groundwater flow in the lower two aquifers. The remaining three models all simulate flow in the upper three aquifer layers but each for a different hydrologic province. The metropolitan area has been divided into three hydrologic provinces, separated by the Mississippi, Minnesota, and St. Croix Rivers, as shown in Figure 9. These rivers are assumed to serve as hydrologic boundaries for the upper three layers of the metro model.

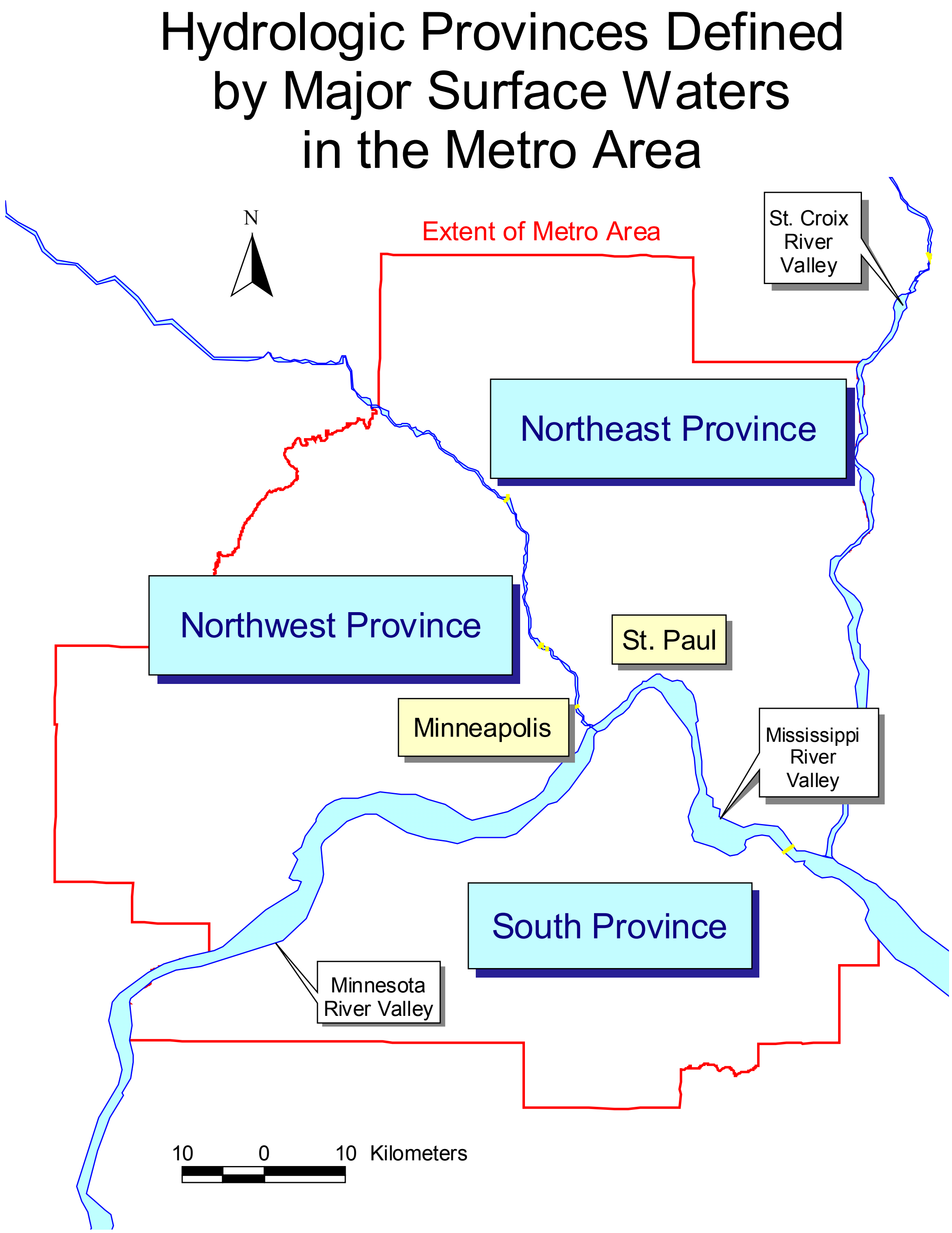


Figure 9. Hydrologic Provinces

The four model components are described here:

1. **Northeast Province, Layers 1, 2, and 3.** This model is for the Northeast Hydrologic Province, simply referred to as the Northeast Province, for Layers 1 (Glacial Drift Aquifer), 2 (St. Peter Sandstone Aquifer), and 3 (Prairie du Chien-Jordan Aquifer). It is comprised primarily of Anoka, Ramsey, and Washington Counties. More detailed discussion on the assignment of hydrostratigraphic units may be found in this report under the section titled "Conceptual Model".

2. **South Province, Layers 2 and 3.** This model is for the South Hydrologic Province for the Glacial Drift and Prairie du Chien-Jordan Aquifers. The St. Peter Sandstone is not explicitly modeled in the South Province, because it is not considered to be extensive enough to warrant modeling as a separate aquifer. Instead it is included with the glacial drift material and modeled as one aquifer that we have defined as Layer 2. Layer 1 remains an unused placeholder that could be used to further vertically discretize the aquifer system, should the need arise. The South Province is comprised primarily of Dakota and Scott Counties.

3. **Northwest Province, Layers 1, 2, and 3.** This model is for the Northwest Hydrologic Province for Layers 1, 2, and 3 as defined above. This province is comprised primarily of Carver and Hennepin Counties.

4. **Regional, Layers 4, and 5.** This model simulates multi-aquifer flow in Layers 4 (Franconia-Ironton-Galesville Aquifer) and 5 (Mt. Simon-Hinckley Aquifer) for the entire seven-county metropolitan area. The model itself extends far outside the metropolitan area to include regional effects. Again, refer to the section titled "Conceptual Model" for more detailed discussion on the assignment of hydrostratigraphic units.

Slight modification will be required to link an upper three-layer province model with the Layer 4 and 5 model if it is deemed necessary.

Model Area of Interest

The area of interest for which groundwater flow will be simulated in the Metro Model includes the entire seven-county Twin Cities metropolitan area, which encompasses approximately 7,800 square kilometers (3,000 square miles) as shown in Figures 1 and 9. An adequate representation of flow in this region requires the inclusion of features outside the area of interest that impact regional flow in the metropolitan area. These features include the subcrop zones of the lower aquifers to the north and west, and the St.Croix and Mississippi rivers to the east. In the south, each aquifer continues for a large distance; Layers 4 and 5 were discontinued beyond potentiometric highs near the Iowa border, and Layer 3 at the Cannon River in southern Minnesota.

Implementation of the Conceptual Model in MLAEM

The schematic illustration of hydrostratigraphic units as aquifer and leaky layers in the stratigraphic column (Figure 3) represents the flow system in cross-section. The computer model is based on this interpretive hydrostratigraphy as well as other information, including aquifer parameters, such as base elevations, thicknesses, hydraulic conductivity values, and hydraulic resistance values.

Vertical groundwater flow between layers was originally modeled with leaky elements representing aquitards between aquifers. However, this resulted in long computation times for the regional models. To decrease computation time, leaky layers were replaced with given strength fluxes to convey water between aquifers for the regional models. This approach has worked very well for the regional models. It also permits direct evaluation of leakage rates. However, site-specific modeling requires that these given-strength VARELs be replaced with the appropriate leaky or resistance VARELs in the area of interest. No leakage is modeled through the bottom of Layer 5.

One problem encountered in modeling the metropolitan area is that the Twin Cities structural basin introduces significant changes in the elevation within the aquifers. Since the deeper aquifers are largely confined, the base elevations of the aquifer are set at the minimum elevations at the center of the basin to ensure confined conditions. This assumes that each layer continues at the same elevation throughout the metropolitan area. Although this is a very simplistic representation, it is appropriate since head differences, rather than elevation differences, control flow under confined conditions, and the transmissivity values do not vary greatly over the metropolitan area. However, implementation of a stepped aquifer base would be a more accurate depiction of hydrogeologic conditions and would allow the confined/unconfined boundary to be modeled where it occurs.

Erosion of the bedrock surface and its subsequent cover with glacial drift has introduced complexity in the flow system that required attention in developing the Metro Model. Bedrock valleys, both buried and exposed, dissect the bedrock aquifers. The exposed valleys typically contain significant river systems that serve as major groundwater discharge zones. However, the valleys buried by glacial drift do not necessarily contain rivers. For exposed valleys, the base of an aquifer may lie above or below the level of the river. If the aquifer base is above the water level, the boundary will be modeled as a seepage face using a head-specified line-sink. Values for the input head are initially set to the base elevation of the aquifer at its erosional boundary, and then adjusted as part of the calibration procedure. If the aquifer base is below the water level, a head-specified element, possibly with hydraulic resistance, is used to represent the river in the aquifer. If a buried bedrock valley does not contain surface waters, the aquifers are modeled continuously across the valley. If a significant difference in hydraulic conductivity exists between the aquifer and the fill material, an inhomogeneity is specified to represent this difference. Additionally, changes in the given-strength infiltration and/or vertical resistance between model layers may be required to represent the interaction within the fill material.

Model Development and Input Parameters

Model Extent

To properly model the groundwater flow in the Metro Model, it was necessary to extend each layer far enough to include hydrogeologic effects that impact flow within the seven-county metropolitan area. These areas vary from layer to layer, depending on factors such as subcrop areas, which are important recharge zones, and the extent beyond the metropolitan area that groundwater flow is impacted by leakage to or from adjoining aquifers.

Hydrogeologic boundaries of the deeper layers may be hundreds of kilometers away. Hence, the question arises as to how far outside the metropolitan area to include features in and on top of the deeper layers. This distance depends on the characteristic length or leakage factor of the aquifer (λ, or lambda). The leakage factor is the square root of the product of the transmissivity of the aquifer and the hydraulic resistance of the separating leaky layer. The leakage factor has units of length, and is a measure of the spatial distribution of leakage to or from an aquifer (Kruseman and de Ridder, 1991). A large value of the leakage factor indicates that a given disturbance in an overlying aquifer influences flow in the underlying aquifer over a large distance and vice versa. As a rule of thumb, the effects in the underlying aquifer become negligible over a distance equal to three times the leakage factor (e.g. Verruijt, 1982). Therefore, in the absence of other hydrologic boundaries in the aquifer, such as rivers, the area elements were extended to a distance of approximately three times the leakage factor beyond the metropolitan area, based on our current understanding of the hydraulic parameters. Here, leakage through the leaky layer, in effect, serves as the hydraulic boundary for the aquifer. Features in the aquifer beyond this distance are not included, since their hydraulic effects within the metropolitan area will be obscured by leakage effects.

Base Elevations and Thickness

As previously mentioned, the model currently assigns global values of base elevations and unit thickness corresponding to the center of the Twin Cities structural basin, which represents the area of lowest base elevation of the bedrock units. A regional cross-section of the bedrock provided by Jirsa and others (1986) was used to establish the base of the Mt. Simon-Hinckley in the center of the basin along the Hennepin-Ramsey County line. Base elevations and thicknesses for the Prairie du Chien-Jordan (Layer 3) and St. Peter aquifers (Layer 2) were derived from the top of bedrock surfaces that were derived by Streitz (2000) using data from MGS (1999). The thicknesses of the underlying bedrock formations down through the Mt. Simon-Hinckley aquifer were assigned on the basis of the information obtained through the studies conducted on the Aquifer Thermal Energy Storage (ATES) project at the St. Paul campus of the University of Minnesota (Miller, 1984; Miller, 1985; Miller and Delin, 1994; and Walton and Hoyer, 1982). The base elevations of these older formations were assigned by keying the thicknesses determined at the ATES site to the base elevation of the Jordan Sandstone (or top of the St. Lawrence Formation) determined by Streitz (2000) using data from MGS (1999).

Actual base elevation and thickness values entered for the units are discussed below under "Global Model Inputs". This discussion is accompanied by figures illustrating the bedrock topography (after Mossler and Tipping (2000)) and the top surface elevations of the St. Peter, Prairie du Chien, Jordan, and St. Lawrence Formations, and the thicknesses of the St. Peter and Prairie du Chien-Jordan Aquifers (after Streitz (2000) using data from MGS (1999)). These figures will be helpful for establishing base elevations of aquifers on a sub-regional to local basis. Because of the great vertical relief effected by the Twin Cities structural basin on the Paleozoic bedrock units, site-specific modeling using the Metro Model will usually require the incorporation of this type of information to successfully adapt the Metro Model to local situations.

Inter-Aquifer Leakage

Measured hydraulic resistance values and leakage rates are typically difficult to obtain for both area elements and surface water bodies, yet they are important input parameters of a groundwater model. After deciding to model leakage with given-strength elements, the Metro Model team adopted a strategy for the initial assignment of leakage rates. The total infiltration rates to the entire aquifer system for the three province models were initially assigned to each VAREL polygon on the basis of literature, professional judgment and previous experience, and initial calibration efforts. The next step was to determine the vertical distribution of the leakage from this infiltration to the underlying aquifers for each of the polygons.

In theory, infiltration penetrating a homogeneous layered aquifer system under steady-state conditions will be distributed to each aquifer layer in proportion to its transmissivity (O.D.L. Strack, 1999). This is illustrated in the cross-sectional schematic in Figure 10, which shows that the total system transmissivity, T, is equal to the sum of transmissivity values for the individual aquifers (T1, T2, and T3, for Layers 1, 2, and 3, respectively). The total system infiltration, γ, is apportioned to the individual aquifers in proportion to the aquifers transmissivity relative to T, as indicated by the equations on the right for net leakage to each aquifer ($\gamma 1$, $\gamma 2$, and $\gamma 3$).

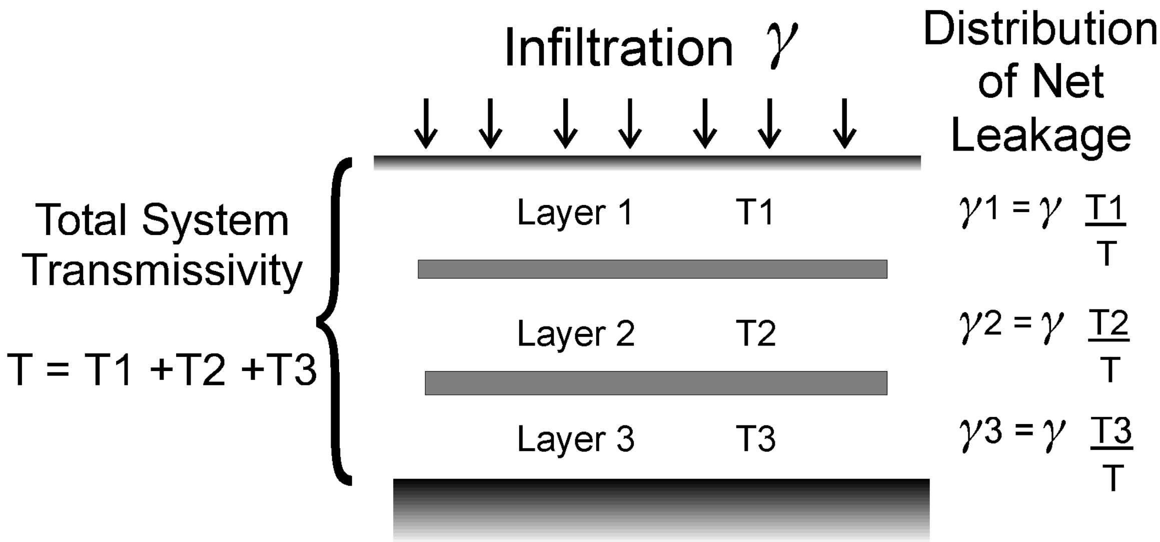


Figure 10. Leakage Distribution to a Homogeneous Layered System

However, natural aquifer systems are not homogeneous and a change in hydraulic properties of just one aquifer or leaky layer will change the distribution of leakage throughout the hydrostratigraphic column. This concept is illustrated in Figure 11, which displays essentially the same three-aquifer system cross-section shown in Figure 10, except that two inhomogeneities have been introduced. One inhomogeneity consists of a high hydraulic resistance inhomogeneity (High c) in the leaky layer separating Layers 1 and 2. The other inhomogeneity is a high hydraulic conductivity inhomogeneity (high K) in the Layer 3 aquifer. The red vertical dashed lines running through the entire hydrostratigraphic section represent boundaries between zones in which at least one of the hydrostratigraphic units has a different hydraulic property. These zones are labeled Zones 1 through 5. Note that Zone 3 represents an area of overlap between the two inhomogeneities.

Each zone represents an area, defined as a polygon in plan view, in which the total infiltration is distributed differently throughout the stratigraphic column compared to its neighbor. This means that even the homogeneous aquifer that is represented by Layer 2 will have different net leakage rates throughout its domain. These differences in leakage rates are attributable to inhomogeneities in other aquifers or leaky layers within that zone. To construct the polygon mesh to account for differences in leakage rates, these zones must intersect all aquifers and leaky layers in the hydrostratigraphic column. Therefore, a "cookie-cutter" approach was taken so that the same polygon mesh was used to define the separating layers between *all* aquifer layers to represent the differences in the vertical distribution of leakage throughout the layered system.

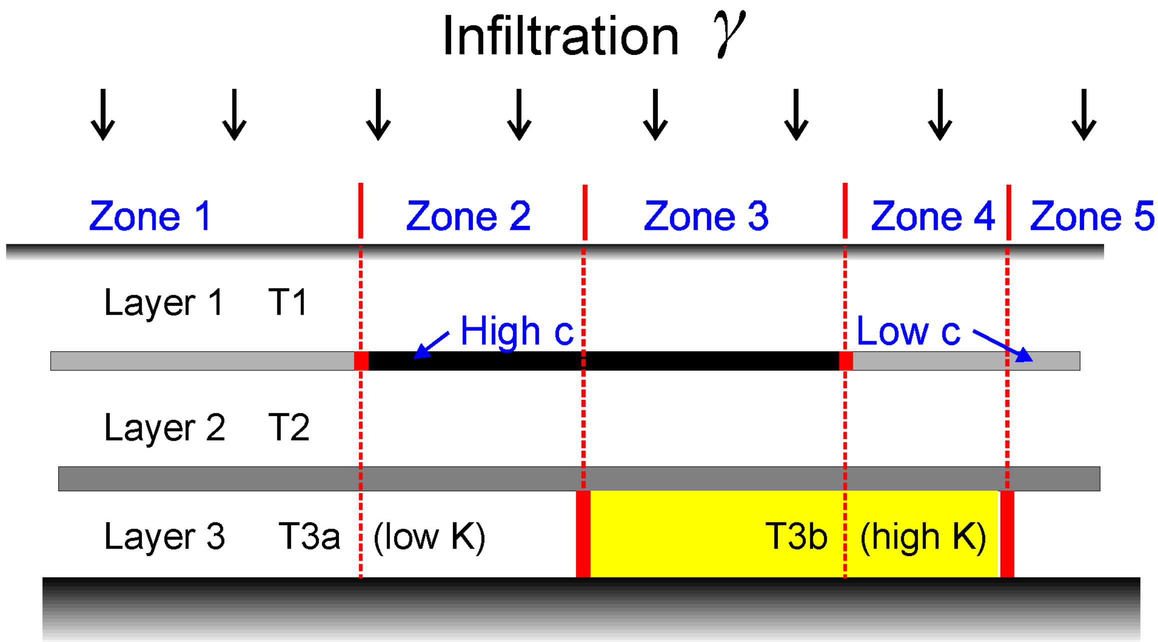


Figure 11. Leakage Distribution to a Layered System with Inhomogeneities

The polygon meshes used to simulate different leakage rates in the Metro Model were developed from GIS coverages of the various hydrostratigraphic units. Polygon boundaries were placed to coincide with major lithostratigraphic changes that would indicate the presence of inhomogeneities on a regional scale. The models have been constructed from given-strength elements located at both the top and bottom of each aquifer layer, except for bottom aquifers for which an impermeable base is assumed. The difference in the leakage rate between the top and bottom of an aquifer for each polygon represents the net infiltration rate, which under most circumstances represents a net gain of water.

The total system infiltration rate was initially distributed among the aquifers for each polygon by assigning a net infiltration rate that was proportional to the assigned transmissivity of each aquifer. Because the regional model cannot capture all the variations in hydraulic parameters, even if they were known, these net infiltration rates were subsequently adjusted during manual calibration procedures to provide a better fit to measured heads. These values will undergo continuous evaluation and comparison to all available data as the model is refined.

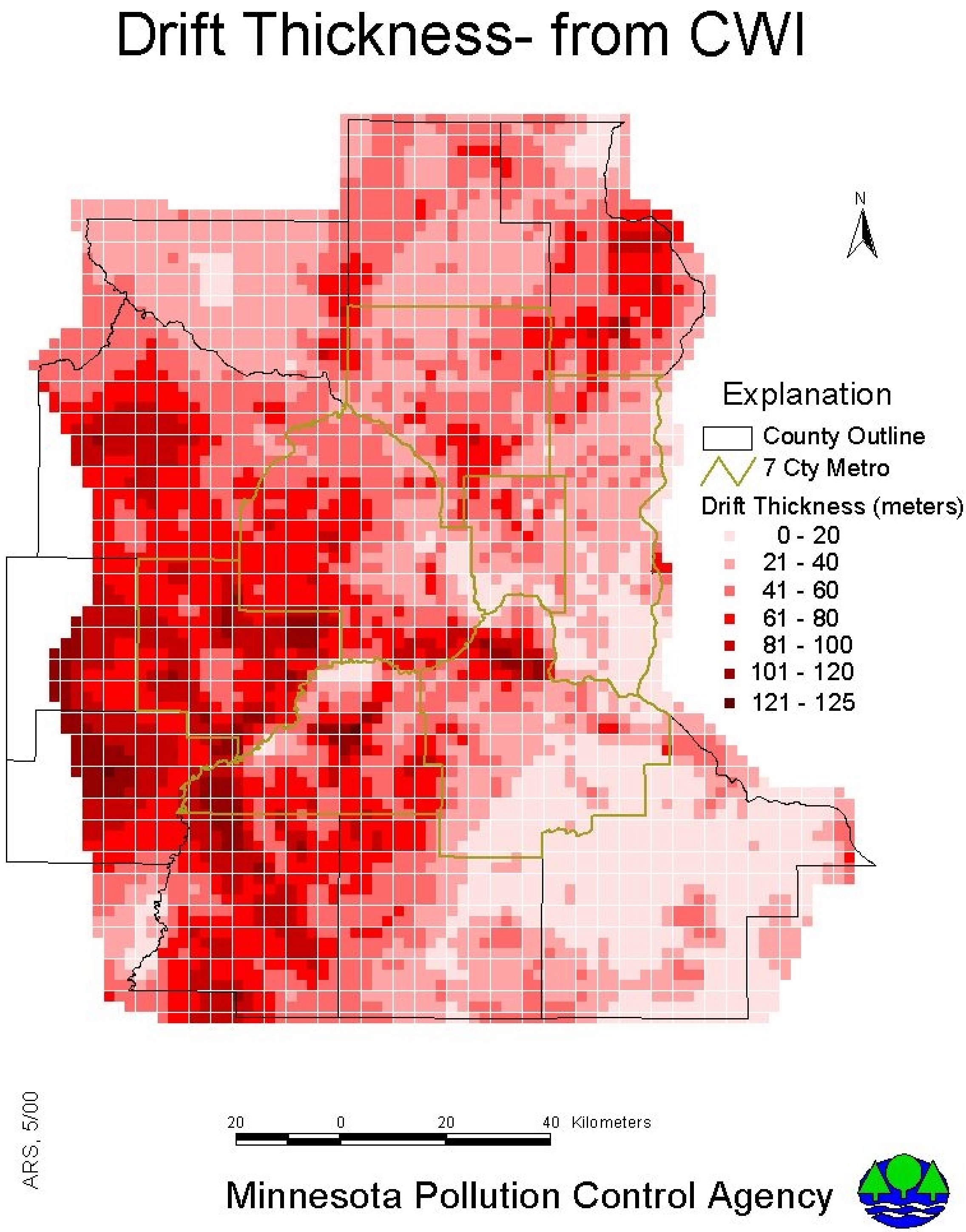
Global Model Inputs

General model setup and global parameters are discussed in the following paragraphs. The global model inputs are summarized in Table 1. Most of the supporting graphics are available in database or ArcView shapefile format on the Metro Model CD-ROM.. Note that the base elevation and thickness values defined for the leaky layers are not explicit model inputs, but are determined from the values entered for the aquifer layers themselves. Because the regional models are constructed using given-strength area elements, the thickness of the leaky layers do not become relevant until they are replaced with leaky area elements, at which point travel times through the aquitard will be proportional to its thickness.

Table 1. Globally Entered Hydraulic Parameters

Model Feature	Hydrostratigraphic Unit Represented	Base Elev. (m MSL)	Thick-ness (m)	Porosity	Horizontal Hydraulic Conductivity (m/day)
Layer 1	Glacial Drift	220	40	0.30	21
	Anoka Sand Plain	220	40	0.30	50
Leaky Layer 1-2	Glacial Drift, Decorah Shale, Platteville Limestone, and/or Glenwood Shale	219	1	--	--
Layer 2	St. Peter Sandstone	190	29	0.30	3.3
Leaky Layer 2-3	Basal St. Peter Sandstone	180	10	--	--
Layer 3	Prairie du Chien-Jordan Aquifer	120	60	0.09	12
Leaky Layer 3-4	St. Lawrence Formation	112	8	--	--
Layer 4	Franconia-Ironton-Galesville Aquifer	52	60	0.28	1.7
Leaky Layer 4-5	Eau Claire Formation	22	30	--	--
Layer 5	Mt. Simon-Hinckley Aquifer	-38	60	0.22	4.2

Layer 1. Glacial drift comprises a significant hydrostratigraphic unit in the Twin Cities metropolitan area. It is generally the first aquifer to be impacted by the release of contaminants to the subsurface. Therefore, its inclusion in the Metro Model is necessary to address surficial aquifer contamination. However, modeling groundwater flow through the drift can be very problematic, owing to the great complexity of the glacial drift materials. Figure 12 from Streitz (2000) presents a thickness map of the glacial drift in the seven-county metropolitan area. A phreatic surface is present in the drift throughout almost the entire area. Additionally, buried confined drift aquifers are also present in some areas.

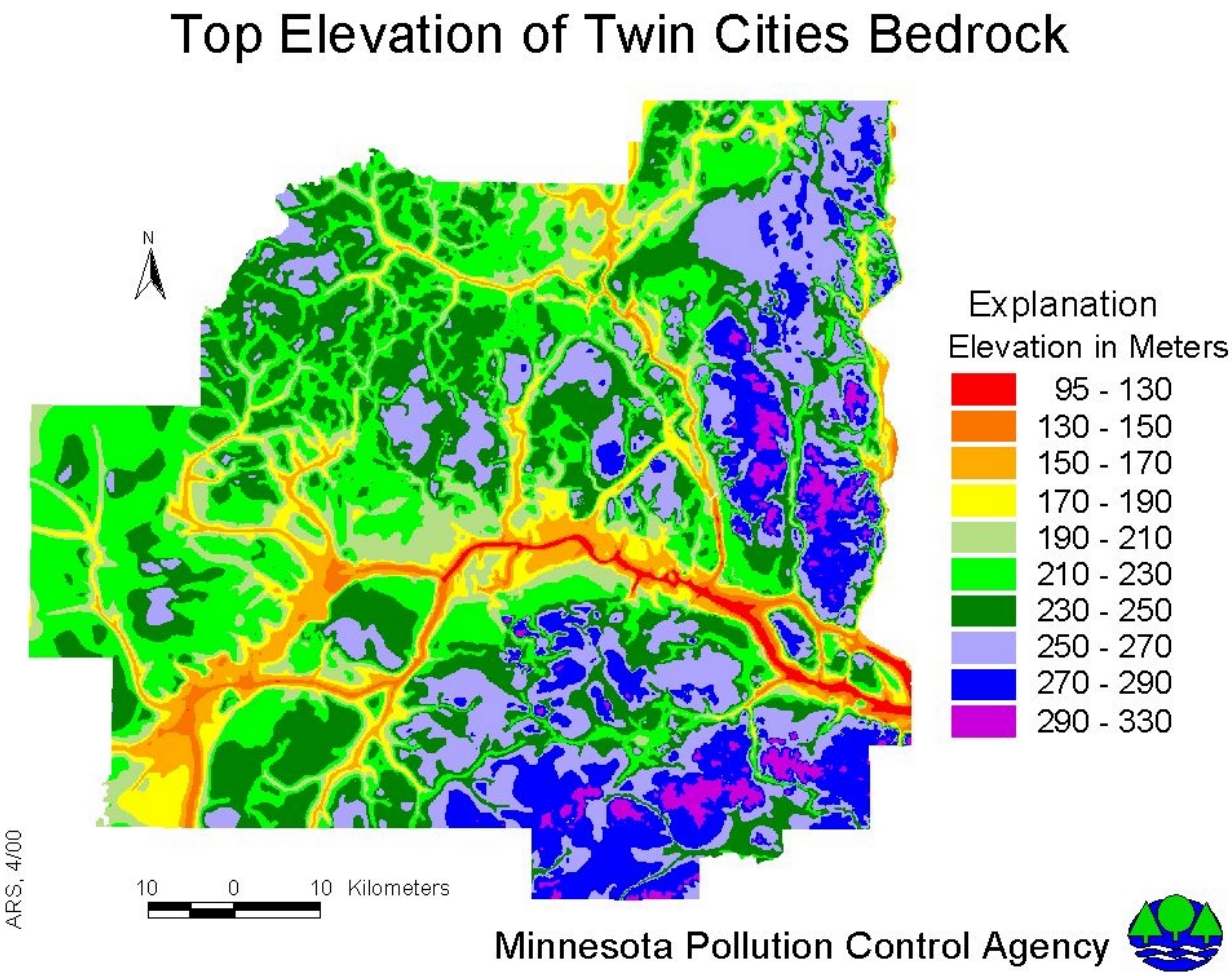


From Streitz (2000)

Figure 12. Metropolitan Area Glacial Drift Thickness

Different approaches were taken to develop a conceptual model of regional groundwater flow in the Quaternary glacial drift materials. Although considerable time was spent trying to relate glaciation episode, provenance, and depositional environments to regional groundwater flow within the drift materials, this approach was generally not found to be useful for constructing a conceptual model of regional flow within the drift materials. The team ultimately settled on an approach that relied on a geostatistical treatment of geologic data from well logs contained in the Minnesota County Well Index (CWI). This approach is covered in detail in the report titled "Preparation of Supporting Databases for the Metropolitan Area Groundwater Model" (Streitz, 2000). Application of this methodology produced maps showing gridded sand content, or probability of finding sand, for specified elevation horizons throughout the metropolitan area. These maps were used to develop the conceptual model and to define inhomogeneities that were constructed in the Layer 1 models. They have been prepared for each of the three individual hydrologic provinces. Therefore, they are not displayed here, but rather in the appropriate summary report for each province model for Layers 1, 2, and 3.

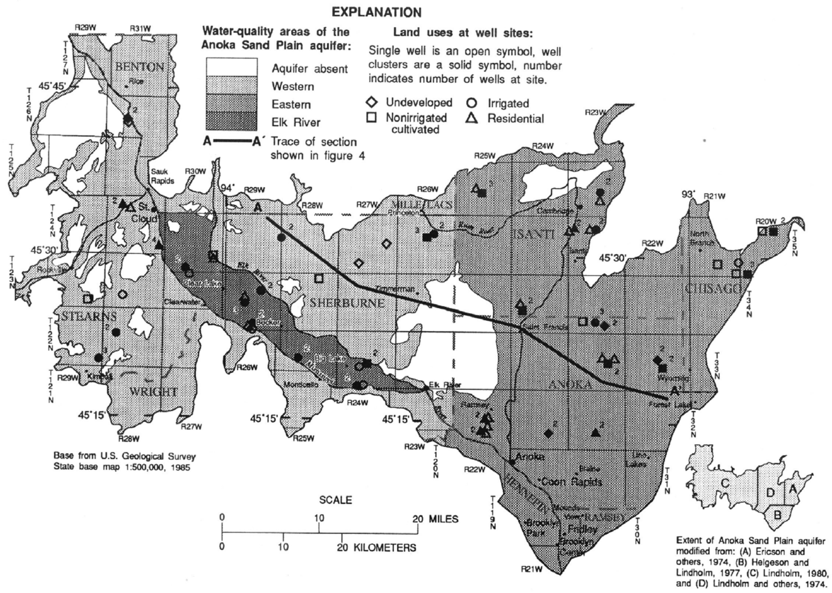
Referring to Table 1, the base elevation globally entered for Layer 1 is 220 m above mean sea level (MSL). This value was assigned to be consistent with the elevation and thickness values entered for the Paleozoic bedrock units so that the Layer 1 glacial drift aquifer overlies the bedrock hydrostratigraphic units. The base elevation of the glacial drift is highly variable of course, due in large part to the great variations in bedrock topography. Another factor is the presence of basal till material in some areas, which would be constitute part of the Layer 1-2 leaky layer rather than the Layer 1 aquifer. Bedrock topography of the metropolitan area is illustrated in Figure 13. Any site-specific modeling of Layer 1 will need to consider the actual bedrock surface elevation, as well as the characteristics of the drift material that overlies it.



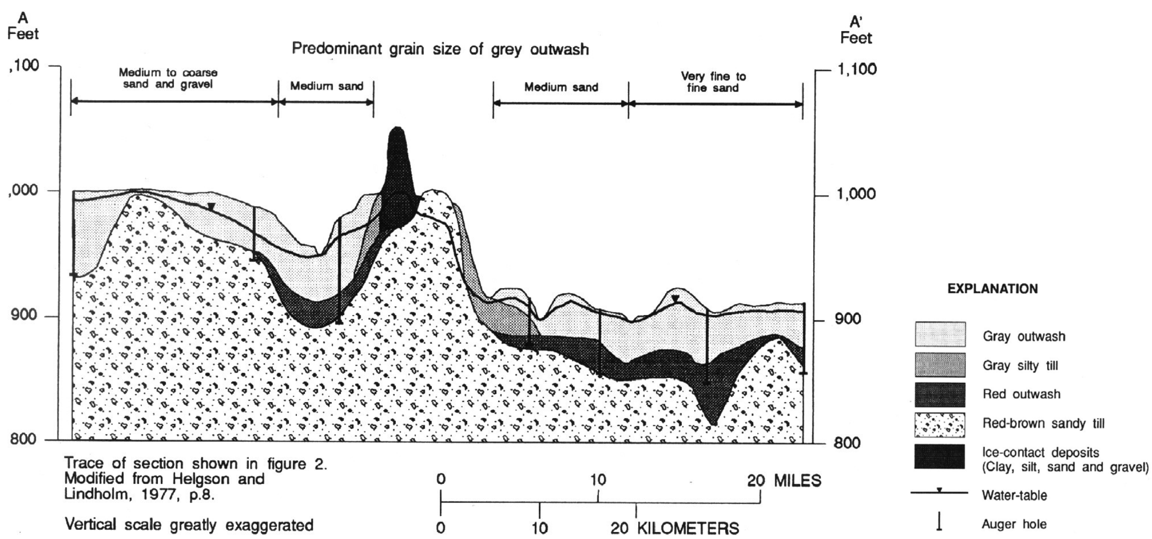
From Streitz (2000), after Mossler and Tipping (2000)

Figure 13. Metropolitan Area Bedrock Topography

The global hydraulic conductivity value of 21 m/day was derived from modeling work conducted by Hennepin Conservation District personnel (Piegat, 1998). The porosity value of 0.30 is assumed and can readily be modified using measured data. The Anoka Sand Plain comprises a large high-permeability inhomogeneity in Layer 1, which, because of its size, is included in Table 1. This feature extends significantly to the west and northwest of the metropolitan area. Delin and others (1994) found that the hydraulic conductivity of the Anoka Sand Plain near Princeton, Minnesota ranged from 36 to 77 m/day (units converted) with a mean value of 57 m/day based on chloride time of travel studies. Slug tests results ranged from 10 to 84 m/day with a mean value of 48 m/day. Additionally, an aquifer test yielded a K value of 240 m/day. Based on these results, a value of 50 m/day was chosen for the Anoka Sand Plain. See the following text regarding the global base elevation assigned for the Anoka Sand Plain.



After Figure 2 of Anderson (1993)



After Figure 4 of Anderson (1993)

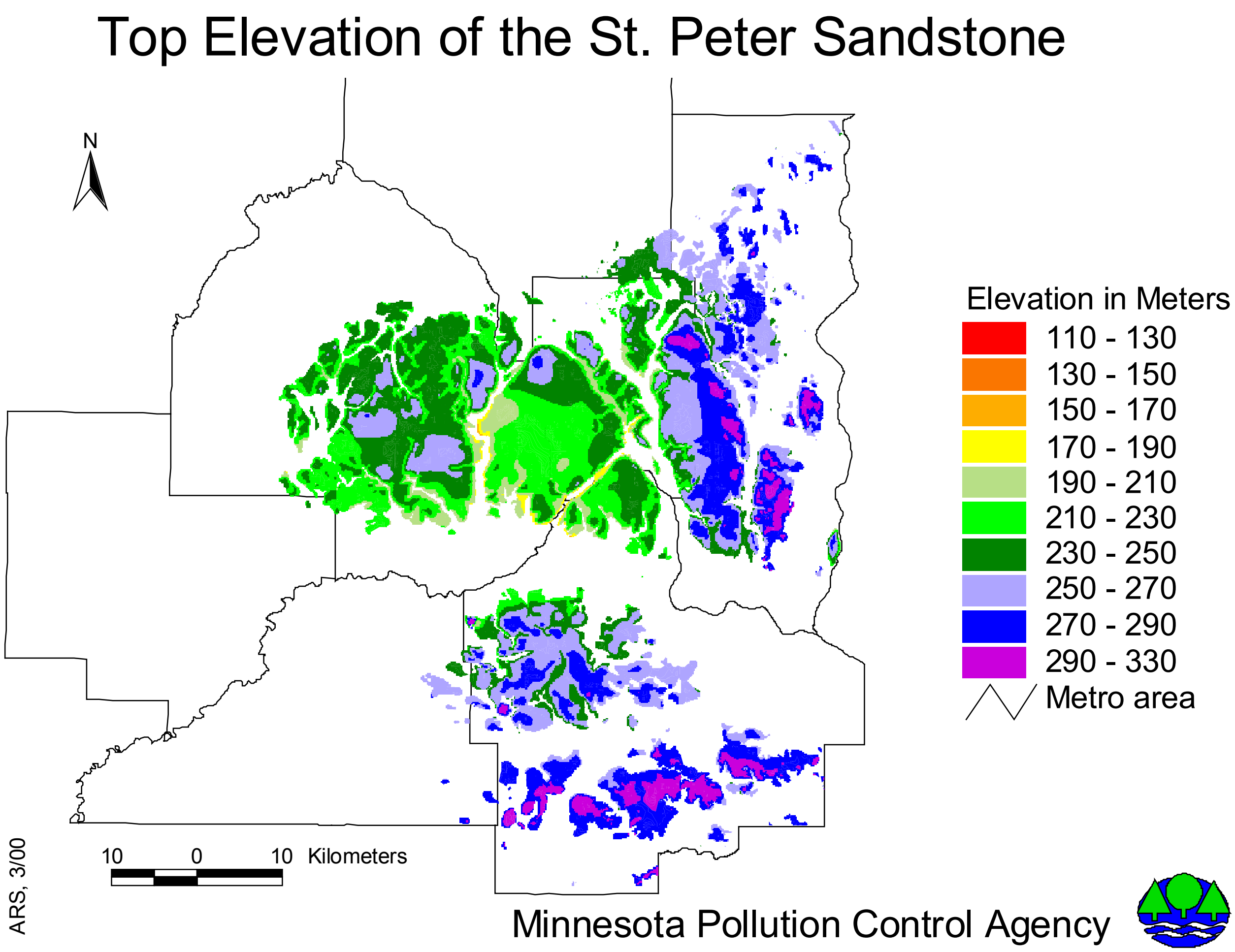
Figure 14. Anoka Sand Plain Base Elevation

Important note regarding the Anoka Sand Plain Aquifer: Following initial development and documentation of the Layer 1 model for the Northeast Province, team members decided that the base elevation for the Anoka Sand Plain inhomogeneity should be entered at a significantly higher elevation than the 220 m MSL listed in Table 1, which actually results in the simulation of confined conditions over much of the area. As illustrated by the cross-section in Figure 14, a base elevation of 220 m MSL (722 feet MSL) is significantly lower than the actual base of the sand unit. On the basis of this cross-section, a base elevation of 255 m MSL (837 feet MSL) for the Anoka Sand Plain inhomogeneity would be much more representative of conditions, especially in the eastern portion of the area, and would be lower than most surface water elevations in the area to permit their representation in the model.

Leaky Layer 1-2. Leaky Layer 1-2 represents properties of the aquitard separating the glacial drift and St. Peter Sandstone aquifer layers. It may be comprised of any of the following: glacial drift (especially till), Decorah Shale, Platteville Limestone, and/or Glenwood Shale. A thickness of 1 m was arbitrarily assigned to this unit. Site-specific modeling may require modification of base elevations and thicknesses to yield a more representative thickness. Polygons representing differences in infiltration rates due to the variable properties of this aquitard were designated using the sand content maps of the glacial drift materials to ascertain differences, and the GIS coverage of Paleozoic bedrock geology (Figure 7).

Layer 2. The top of Layer 2, representing the St. Peter Sandstone aquifer, is set at elevation 219 m MSL on the basis of the display, shown in Figure 15, produced by Streitz (2000) using gridded data from MGS (1999). This allows the 1-m thickness for Leaky Layer 1-2 below the base of Layer 1, as discussed in the preceding paragraphs. The figure indicates that the base of the St. Peter Sandstone in the center of the Twin Cities Basin is approximately 180 m MSL as discussed in the following subsection titled "Leaky Layer 2-3". This corresponds to the top surface of the Prairie du Chien Group, which also defines the base of the St. Peter Sandstone, where present. Assuming that the basal St. Peter Aquitard (see Leaky Layer 2-3 below) is 10 m thick, the base of the Layer 2 St. Peter Sandstone aquifer is at elevation 190 m MSL.

Therefore, Layer 2 has been assigned a global base elevation of 190 m MSL and a thickness of 29 m. The isopach map in Figure 16 illustrates the actual thickness of the St. Peter Sandstone. Local modeling will require the user to take actual base elevation and thickness values into account. The aquifer was assigned a hydraulic conductivity of 3.3 m/day, which falls within range of 0.05 - 8.2 m/day, and near the median of 3.8 m/day, as presented by Norvitch and others (1973). A porosity value of 0.30 was selected, and was taken from the high end of the range of 0.28 - 0.30 reported by Miller and Delin (1994) for the St. Peter Sandstone.



From Streitz (2000), after MGS (1999)

Figure 15. Elevation of Top of the St. Peter Sandstone

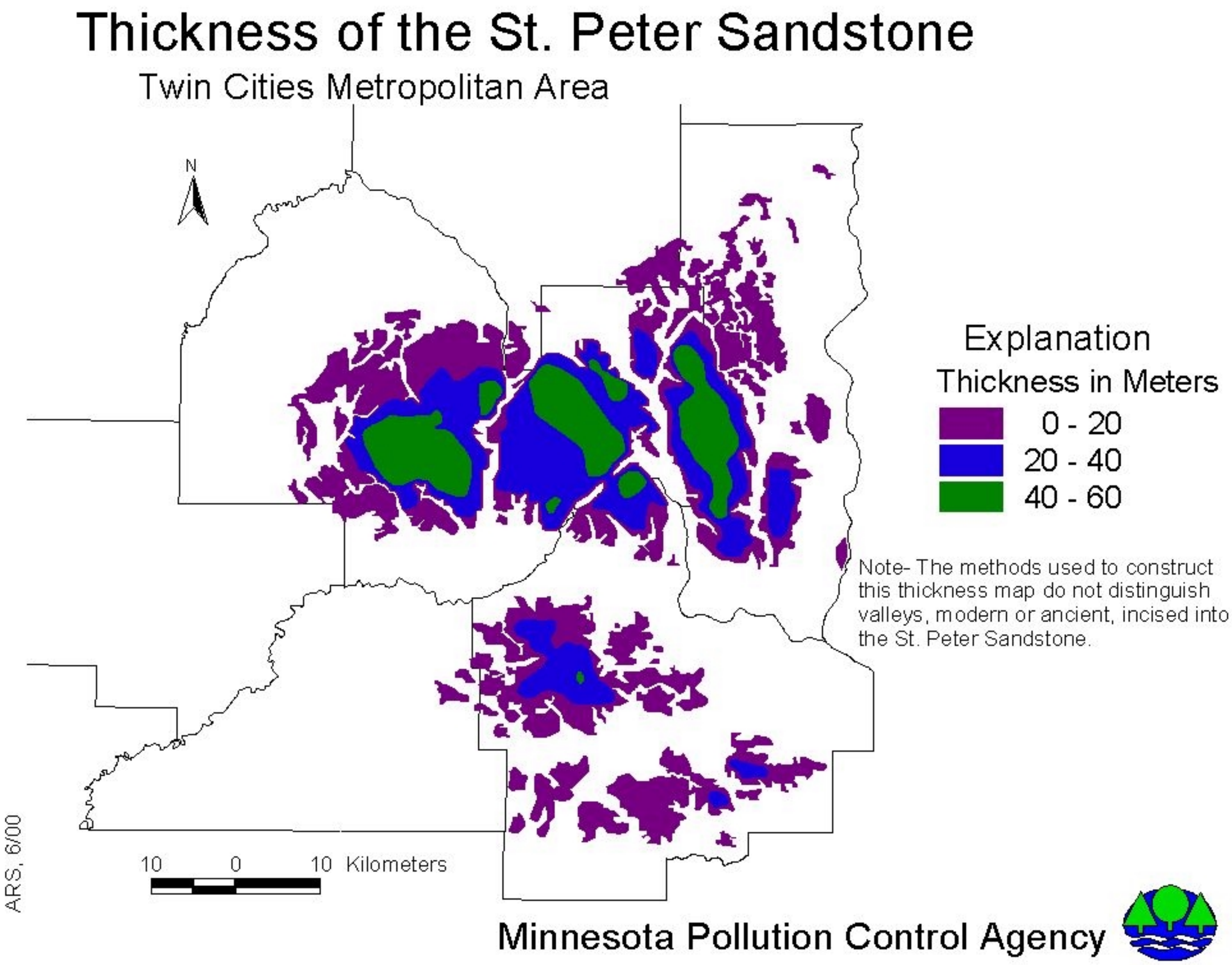
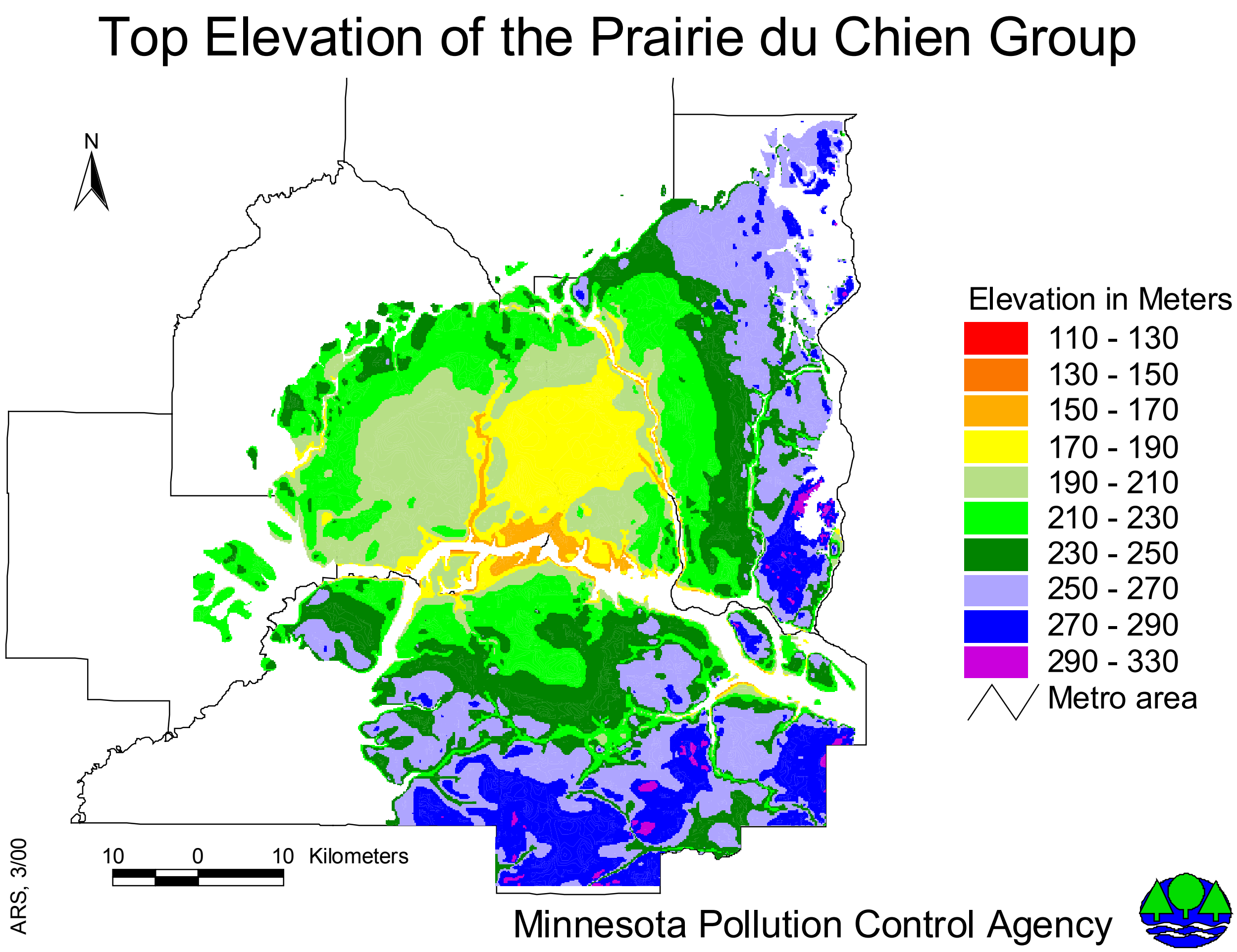


Figure 16. Isopach Map of the St. Peter Sandstone

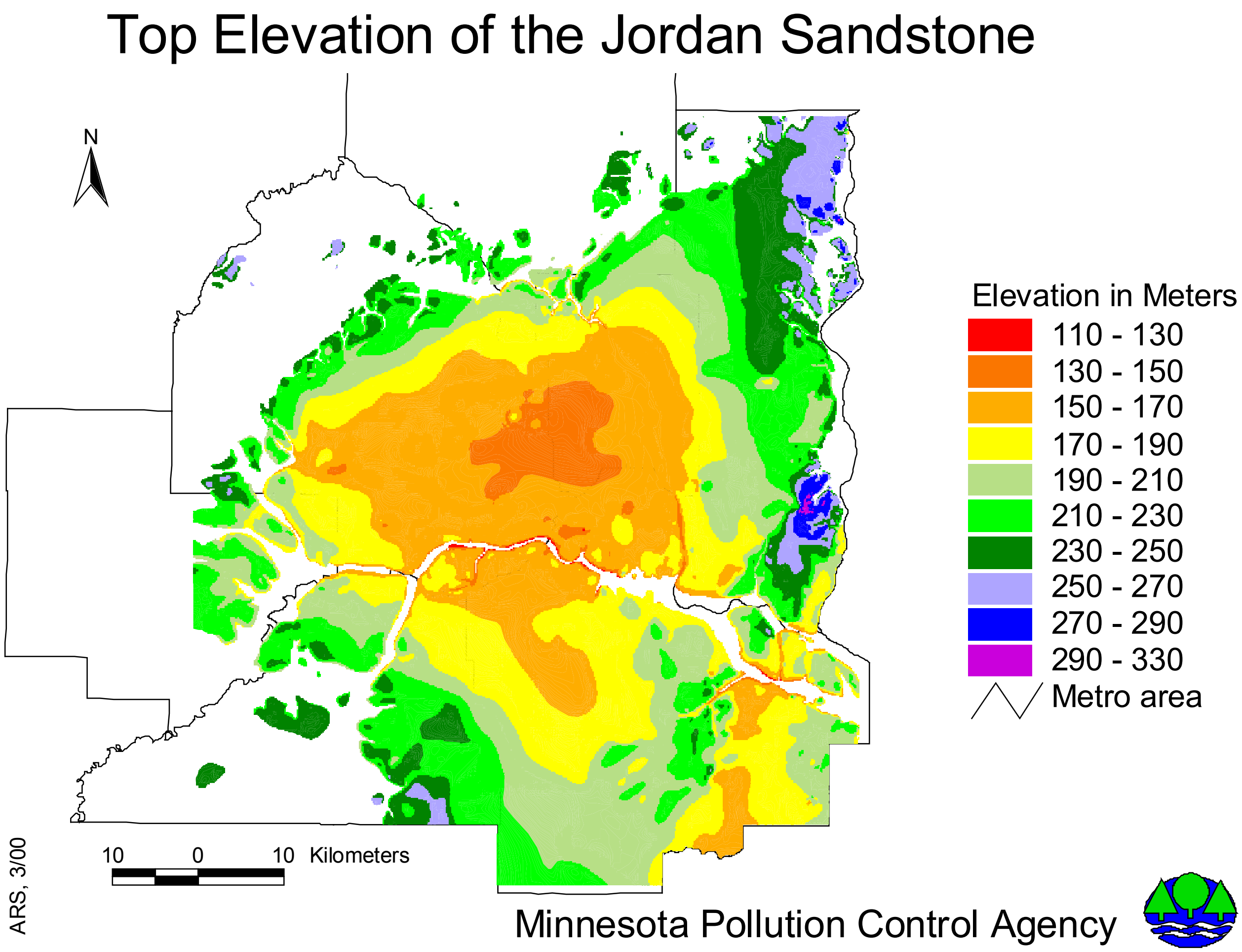
Leaky Layer 2-3. As mentioned in the discussion for Layer 2, this leaky layer represents hydraulic resistance to flow imposed by the basal St. Peter Sandstone. With its base elevation set at 180 m MSL, corresponding to the top of the Prairie du Chien Group, as shown in Figure 17 (from Streitz (2000) using data from MGS, (1999)), it has been assigned a thickness of 10 m.



From Streitz (2000), after MGS (1999)

Figure 17. Elevation of Top of the Prairie du Chien Group

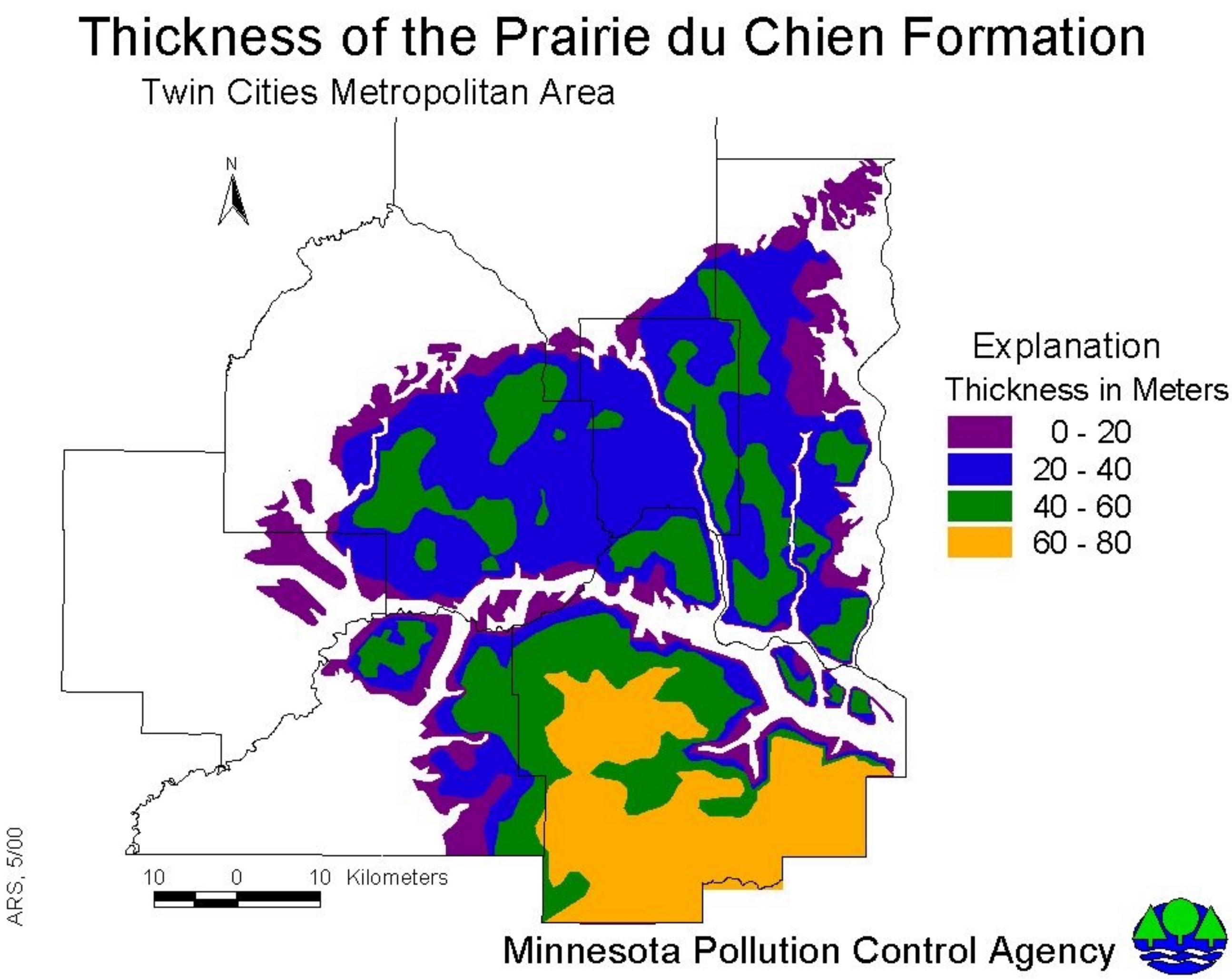
Layer 3. The Metro Model currently treats the Prairie du Chien Group and the Jordan Sandstone as one aquifer comprising Layer 3. Although evidence is building that suggests that these two aquifers may be separated by a resistant leaky layer over a significant portion of its area, lumping them together as one aquifer seems an appropriate treatment when conducting such a large-scale simulation as the Metro Model. Site-specific modeling projects may require subdividing this aquifer layer into two discrete bedrock units to permit proper groundwater flow simulation in situations requiring this vertical discretization. With this eventuality in mind, the elevation of the top of the Jordan sandstone is presented in Figure 18 to help users determine the contact between the Jordan Sandstone and the overlying Prairie du Chien Group.



From Streitz (2000), after MGS (1999)

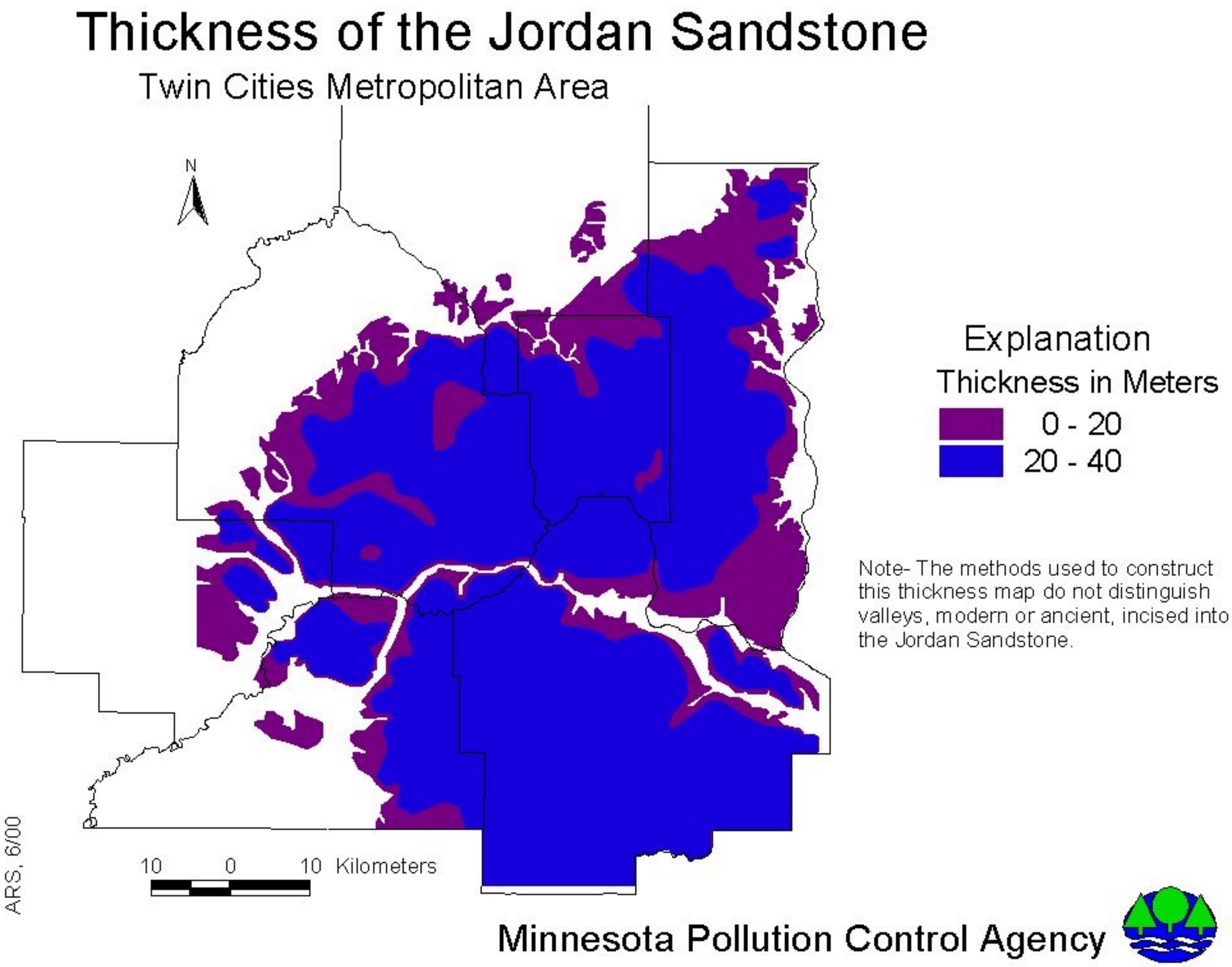
Figure 18. Elevation of Top of the Jordan Sandstone

To further assist interested users in treating the Prairie du Chien Group and the Jordan Sandstone as separate aquifers, isopach maps of each are presented in Figures 19 and 20, respectively. These coverages are available for use in an ArcView-ready shape-file format from the Metro Model Data CD-ROM.



From Streitz (2000)

Figure 19. Isopach Map of the Prairie du Chien Group



From Streitz (2000)

Figure 20. Isopach Map of the Jordan Sandstone

The Layer 3 (Prairie du Chien-Jordan aquifer) aquifer parameters are entered as constant values. The assigned global hydraulic conductivity value of 12 m/day (Table 1) was estimated from approximately 40 pumping test transmissivity values that were compiled by the U.S. Geological Survey (USGS) for the metropolitan area, and thickness values derived from Streitz (2000) using data from MGS (1999). Figure 21 shows the spatial distribution of the USGS' transmissivity values, and Figure 22 is an isopach map of the Prairie du Chien-Jordan aquifer. Individual hydraulic conductivity values were first estimated from the thickness and transmissivity values. After statistically eliminating 20 percent of the outlying hydraulic conductivity values, an arithmetic mean of 12 m/d was found. This is the value used for the global hydraulic conductivity of Layer 3.

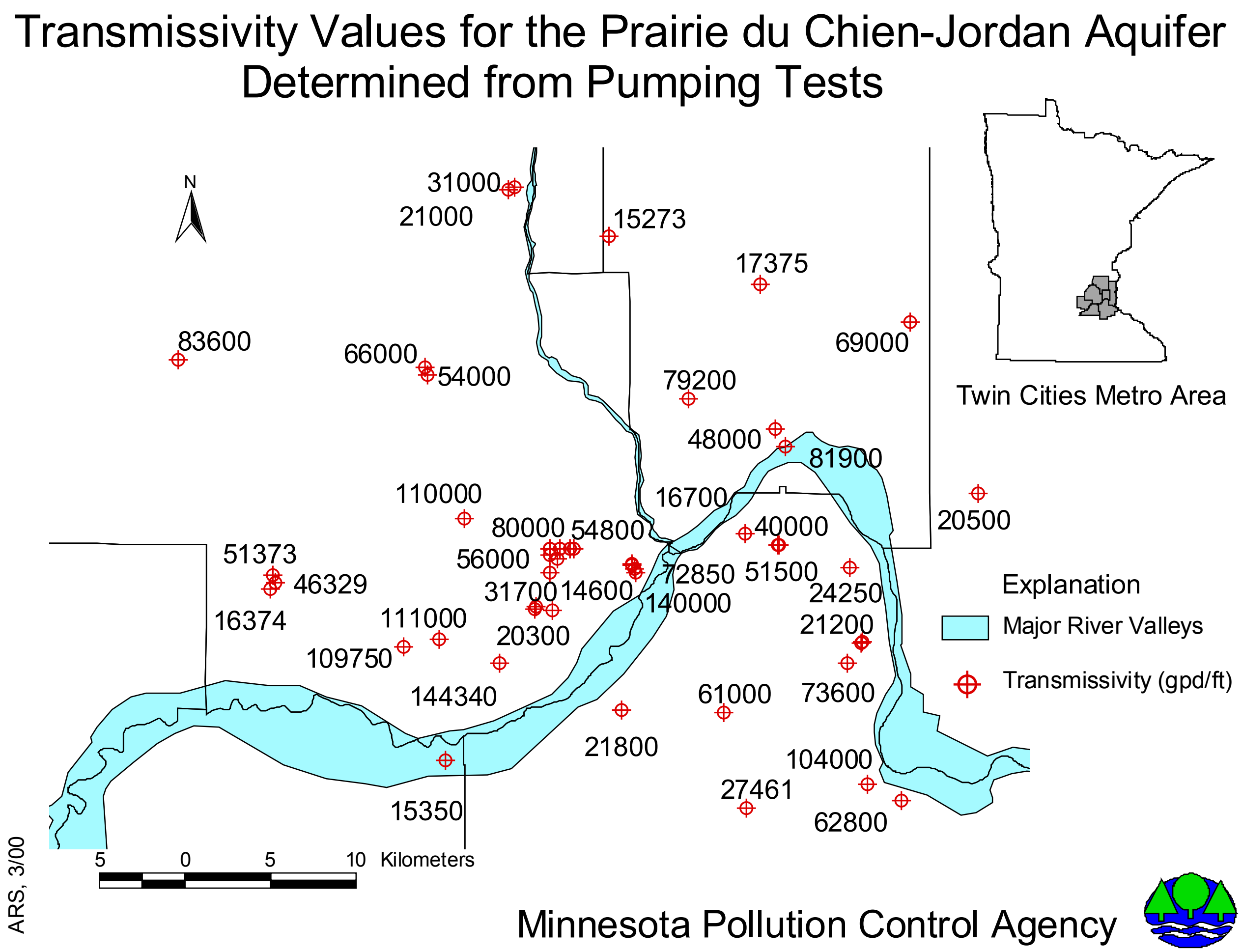
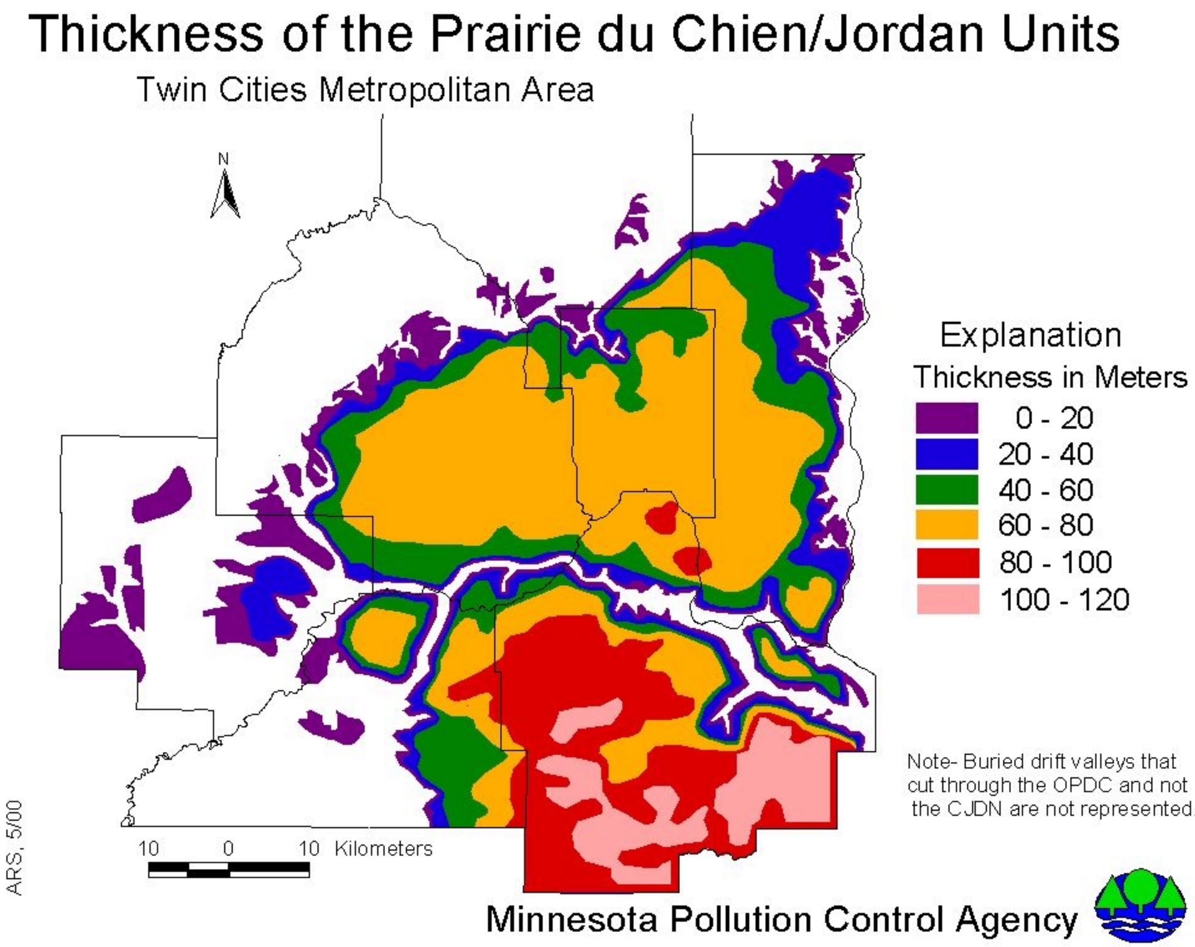


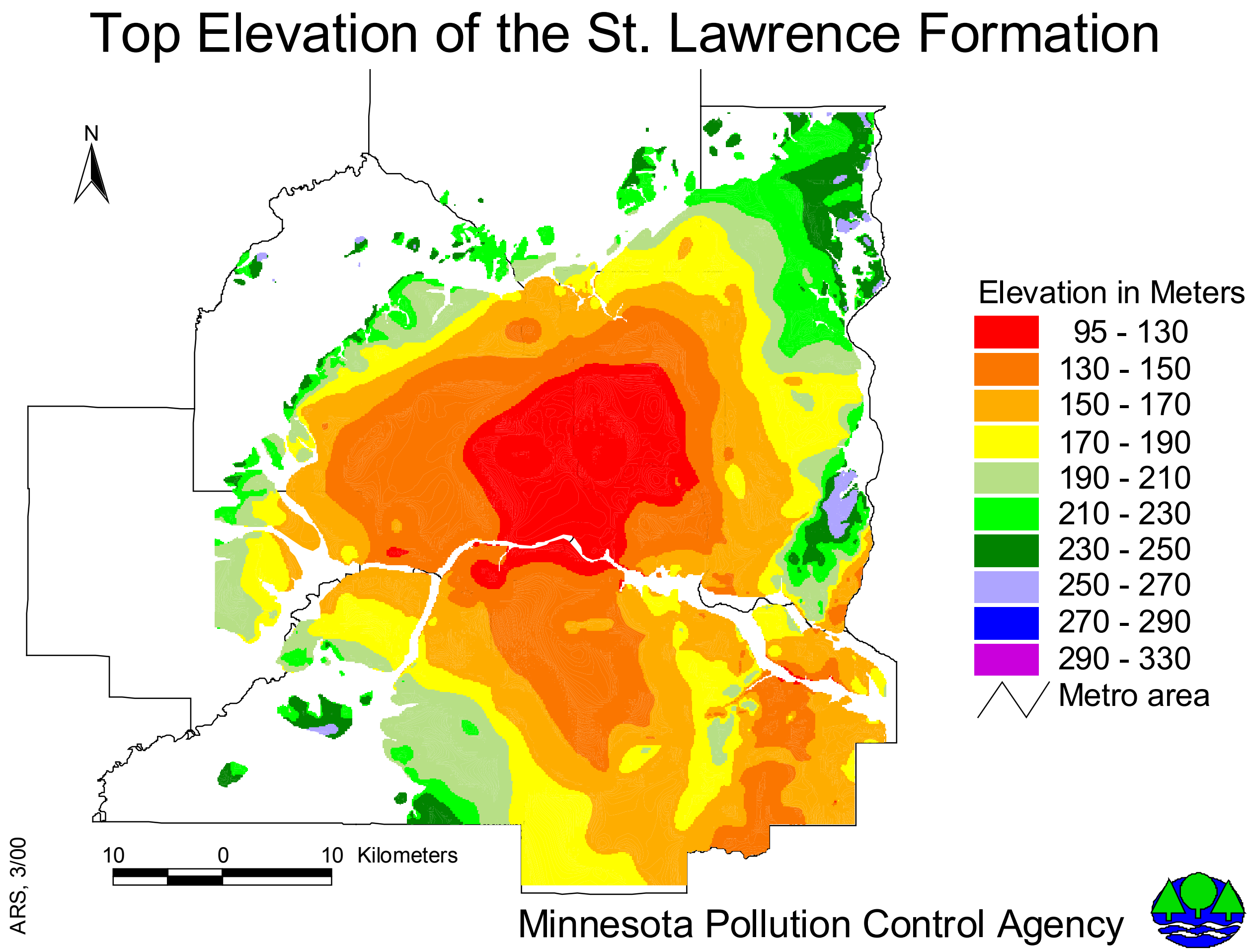
Figure 21. Transmissivity Values for the Prairie du Chien-Jordan Aquifer



From Streitz (2000)

Figure 22. Isopach Map of the Prairie du Chien-Jordan Aquifer

The base elevation and thickness for the Prairie du Chien-Jordan aquifer were established using the maps prepared by Streitz (2000) using data from MGS (1999). The base of the aquifer is currently set at elevation 120 m MSL corresponding to the top surface of the St. Lawrence Formation (Figure 23). Note that the lateral extent of the top surface of St. Lawrence Formation is shown to match exactly the extent of the Jordan Sandstone rather than the larger area it actually covers. This is because MGS estimated the top surface of the St. Lawrence Formation by subtracting an estimated thickness of Jordan Sandstone from its top elevation—the top of the St. Lawrence Formation cannot be estimated without the presence of the overlying Jordan Sandstone. The thickness of the Prairie du Chien-Jordan Aquifer is set to 60 m, corresponding to the general thickness at the center of the Twin Cities basin, as illustrated in Figure 22. The model uses an overall porosity value of 0.09. The source of this value could not be immediately found, and a recent shift in project resources does not permit pursuing this issue. However, Norvitch and others (1973) report a porosity value of 0.056 percent for the Prairie du Chien Group, and Reeder and others (1976) report values of 0.191 and 0.226 for the effective porosity of the St. Peter Sandstone and state that these values "are probably higher than the average". A weighted mean value of porosity was estimated for the combined Prairie du Chien and Jordan Formations, using assumed thickness values of 40 m and 30 m, respectively (see Figures 19 and 20), and the minimum porosity for the St. Peter Sandstone. The resulting value was 0.114, which compares favorably to the 0.09 value used in the Metro Model. Larson-Higdem and others (1975) estimated that infiltration values for this aquifer range from 0.21 to 0.84 mm/day (3 to 12 in/year). Leakage through the base of Layer 3 (through the St. Lawrence Formation aquitard) is assumed to be negligible for the Layer 1, 2, and 3 hydrologic province models.



From Streitz (2000), after MGS (1999)

Figure 23. Elevation of Top of the St. Lawrence Formation

Leaky Layer 3-4. This leaky layer represents the St. Lawrence Formation. It was measured to be 8 m thick at the ATES site (Miller and Delin, 1994). Its base elevation of 112 m MSL, which also corresponds to the top of Layer 4, was determined by subtracting this thickness from the base elevation of 120 m MSL for Layer 3. For future reference, Kanivetsky (1988) gives a range in vertical hydraulic conductivity values for this aquitard of 0.000079 to 0.00046 ft./day (0.000024 to 0.00014 m/day). A hydraulic resistance of the aquitard can be calculated by dividing the thickness of the unit by the vertical hydraulic conductivity. Using the 8 m thickness of the St. Lawrence Formation, the range of hydraulic resistance values becomes 57,000 to 330,000 days.

Layer 4. Layer 4 represents the Franconia-Ironton-Galesville aquifer. Its assigned global thickness of 60 m was derived from research at the ATES project (Miller, 1985). Subtraction of the thicknesses of the St. Lawrence, Franconia, Ironton, and Galesville Formations from the base of Layer 3 (120 m MSL) sets the base elevation of Layer 4 at 52 m MSL. The porosity value (0.28) was taken from the center of the range of average values (0.25 - 0.31) given by Miller and Delin (1994) for the ATES site. The horizontal hydraulic conductivity value used for Layer 4 was based on research conducted at the ATES site. A transmissivity value for the Franconia-Ironton-Galesville aquifer of 1100 $ft.^2$/day (Walton and Hoyer, 1982) was used with the 60 m thickness to yield a hydraulic conductivity of 1.7 m/day (5.6 ft./day) for Layer 4 of the model.

The St. Lawrence Formation and Franconia-Ironton-Galesville Sandstones subcrop beneath glacial drift to the north and west of the metropolitan area. Figures 2 and 4 illustrate this subcrop zone in plan view, and the cross-sections in Figure 5 illustrate how the aquifer subcrops beneath the drift. The St. Lawrence and Franconia Formations become more permeable in the subcrop zone as a result of weathering and fracturing that occurred when these formations were exposed at the surface prior to glaciation. For this reason the St. Lawrence aquitard subcrop zone was included as part of the subcrop zone for the Franconia-Ironton-Galesville aquifer in developing the model. Infiltration to this subcrop zone is believed to account for most the recharge to the aquifer.

Although infiltration to the subcrop zone is currently simulated by explicitly specifying the given-strength recharge rate, future work might require the use of resistance values for the overlying units, predominated mostly by sands of the Anoka Sand Plain and less permeable glacial till deposits. So for future reference, some initial starting point resistance values were estimated for the Anoka Sand Plain and predominantly glacial till terrane above the subcrop zones using methods developed by de Lange (1996) for calculating the feeding resistance to an aquifer. Resistance values for the Anoka Sand Plain and glacial till were estimated to be 2,000 and 700,000 days, respectively. The feeding resistance is a lumped parameter that represents the hydraulic resistance between the surface waters and the regional aquifer that is being modeled. The use of the feeding resistance provides a means to account for the hydraulic effects of the glacial drift material and the size and spacing of surface waters on recharge to the subcrop zones of the bedrock aquifers.

Leaky Layer 4-5. The Eau Claire Formation is represented by this layer, which has a global thickness of 30 m based on the ATES site data (Miller and Delin, 1994). Subtracting the 30 m from the base of Layer 4 (52) puts its base (or the top of Layer 5 aquifer) at elevation 22 m MSL.

Layer 5. Layer 5 (Mt. Simon-Hinckley Aquifer) was modeled using an approach similar to that used to model Layer 4. Layer 5 is separated from Layer 4 by the leaky layer representing the Eau Claire Formation. The base of Layer 5 was determined by subtracting its assigned thickness of 60 m, as reported by Miller and Delin (1994), from the base of the Eau Claire Formation (22 m MSL) to give an elevation of -38 m MSL. An assigned hydraulic conductivity of 4.2 m/day was used for the Mt. Simon-Hinckley aquifer in the model. This value was derived from a transmissivity value of 250 m^2/day and 60 m thickness presented by Miller & Delin (1994). This value is similar to that determined from the transmissivity presented by Norvitch and others (1973). They present an average transmissivity of 19,000 gpd/ft. (240 m^2/day); assuming a thickness of 60 m, the hydraulic conductivity is 4.0 m/day. Similarly, Schoenberg (1990) used a value of 15 ft./day (4.6 m/day) for the regional groundwater model developed by USGS. The porosity value of 0.22 represents the midpoint between mean values presented by Norvitch and others (1973) for the Mt. Simon Sandstone (0.23) and the Hinckley Sandstone (0.21).

Polygons representing differences in leakage to Layer 5 were constructed using information on the bedrock stratigraphy as well as the glacial drift geology. For example, different infiltration rates might be expected for areas overlain with the Eau Claire Formation versus those subcrop zones overlain by glacial drift materials. Further differences are expected in the subcrop zones of the Mt. Simon-Hinckley aquifer between areas overlain with till and areas overlain by the Anoka Sand Plain. Similar to the approach taken for Layer 4, the subcropping Eau Claire Formation was included with the subcropping Mt. Simon-Hinckley Aquifer since the Eau Claire Formation is expected to be more permeable owing to weathering and fracturing caused by surface exposure prior to glaciation. Infiltration through the subcrop zones is believed to account for most of the recharge to the Mt. Simon-Hinckley aquifer. Additionally, the polygon geometries are influenced by the geometries of the upper layer province models. This was done to permit ready linking of the province models to the lower aquifer model.

Application of the Layer 4 and 5 model will require that given-strength elements be replaced with leaky VAREL elements so that the effects of a disturbance, such as pumping, in one aquifer can be transmitted to adjoining aquifers. For future reference, some data regarding the vertical hydraulic resistance of the Eau Claire Formation found in literature are presented here. Walton (1991) provides a range of vertical hydraulic conductivity for the Eau Claire Formation of 7.4×10^{-6} to 1.0×10^{-3} ft./day, and Kanivetsky (1988) gives a range of $7. \times 10^{-7}$ to 4.6×10^{-6} ft./day. Assuming that the Eau Claire formation is 30 m (100 feet) thick as observed at the ATES Site (Miller and Delin, 1994), the Walton (1991) data yield hydraulic resistivities that range from 1.0×10^{5} to 1.4×10^{7} days, and the Kanivetsky (1998) data give a range of 2.2×10^{6} to 1.3×10^{8} days. A leakage factor of 50 km is estimated for the Mt. Simon-Hinckley aquifer using the leaky layer resistance value of 10^{7} days. The high value for the leakage factor, λ, (50 km) of the Mt. Simon-Hinckley aquifer required extending the area elements a large distance (approximately 120 km) to the south.

As with Layer 4, the subcrop zone for Layer 5 is covered by glacial drift—the Anoka Sand Plain immediately north of the metropolitan area, and terrane comprised predominantly of till to the north and south of the Anoka Sand Plain. Although this subcrop zone is currently modeled with given-strength elements, future work may require the use of resistance area elements to represent this zone. The initial hydraulic resistance values would be identical to those estimated for the subcrop zones of Layer 4, since they are based on the feeding resistances for the overlying drift aquifer that were calculated using the techniques developed by de Lange (1996). Therefore, starting values for the resistance to the subcrop zone beneath the Anoka Sand Plain would be 2,000 days, and the resistance for the subcrop zone to the south, which is dominated largely by till terrane, would be 700,000 days. The bottom of Layer 5 is modeled as impermeable.

Surface Waters

Surface water bodies are only added to the regional Metro Model to represent those features that appear to impact regional flow. The effects of numerous small surface water bodies, typically part of local groundwater flow regimes, are implicitly included in the infiltration or leakage rates. As previously stated, the Mississippi, Minnesota, and St. Croix Rivers are believed to serve as regional discharge zones for all aquifers down to at least the Prairie du Chien-Jordan Aquifer. The effects of these features on the lower aquifers become more subdued with increasing depth. Large lakes are included in the models, typically defining leakage polygons. Some lakes such as Lake Minnetonka or Big Marine Lake appear to have strong hydraulic connections to some of the bedrock aquifers. These features are discussed in detail in the reports for the individual Metro Model component models.

High-Capacity Pumping Wells

Pumping well discharges for all components of the Metro Model are entered on the basis of data from the MDNR State Water Use Data System (SWUDS) database for high-capacity permitted wells (MDNR, 2000b). This database includes only wells with discharges greater than either 10,000 gallons/day or 1,000,000 gallons/year. These data are available from Metro Model staff. Multi-aquifer wells have not yet been included in the model.

Calibration

Approach

Calibration is the process in which input parameters are adjusted so that computed model outputs match measured target values as closely as possible. Calibration is an iterative process that involves adjusting an input parameter, obtaining a solution, observing results, and then further adjusting the parameter. This process continues until the difference between computed output and measured values is minimized. Calibration can be a lengthy process if the computation times are large and/or several parameters are being adjusted. Calibration specifics are discussed individually in the reports for each of the model components.

The Metro Model has been calibrated using two types of calibration targets—measured water levels and stream discharges. Calibration to the head values was the primary means of calibration and model adjustment. The head values used were derived from geostatistically filtering static water level data from CWI (see Streitz, 2000), which has proved to be a good approach for calibrating the model on a regional basis. A large amount of geostatistically well-behaved data was found for the upper layers. Static water level data for the Mt. Simon-Hinckley Aquifer were sparse and highly variable. Calibration was conducted with the goal of producing output heads that were within 10 percent of the range of heads over the domain of interest. Areas within the model showing heads that do not fall within the calibration tolerance ranges indicate that the model is not properly representing the hydrogeological system. Further calibration will be of no use in such a situation until modifications are made to the model, based on hydrogeology.

Calibration to head values was conducted both manually and using a computer program called PEST, which is a model-independent nonlinear parameter estimator that was developed by Watermark Computing of Australia. PEST is set up to automatically run a specified modeling program, in this case MLAEM. It mathematically determines the best least-squares fit to the calibration targets, in this case head values, by adjusting specified model input values. PEST is generally applied after the problem has been defined and constrained with known or assumed input parameters. By helping the user to determine the sensitivity of the model to each adjustable parameter, PEST can achieve a best-fit calibration more quickly than manual procedures. Leakage rates for individual area element polygons were typically adjusted during the calibration process.

A short synopsis regarding the development of the head calibration datasets is presented in the following paragraphs. A detailed discussion of this work may be found in Streitz (2000). The first three layers of the Metro Model are broken into three separate hydrologic provinces, requiring nine different calibration datasets. The procedure to produce these datasets involved first searching through the CWI database for wells completed in the relevant aquifer, then separating the wells into the proper province using GIS tools. All the wells for a specific layer and province were then used to develop a variogram, a spatial statistical measure of the correlation of head elevation that can be used to estimate values on a grid or to identify and remove outliers. It is the latter function that is applied in the development of the calibration datasets. The idea is to remove unrepresentative well elevations from the dataset, those well elevations that are not in good spatial agreement (based on the variogram) with their neighbors. This is done through a process called cross-validation. The resulting dataset of statistically smoothed elevations produce a better calibration target for the regional groundwater model than an unprocessed dataset. The cross-validation process removes values appearing anomalous because they are either in error or reflect small-scale inhomogeneities. Neither situation would provide data that would be useful for calibrating the model on a regional basis.

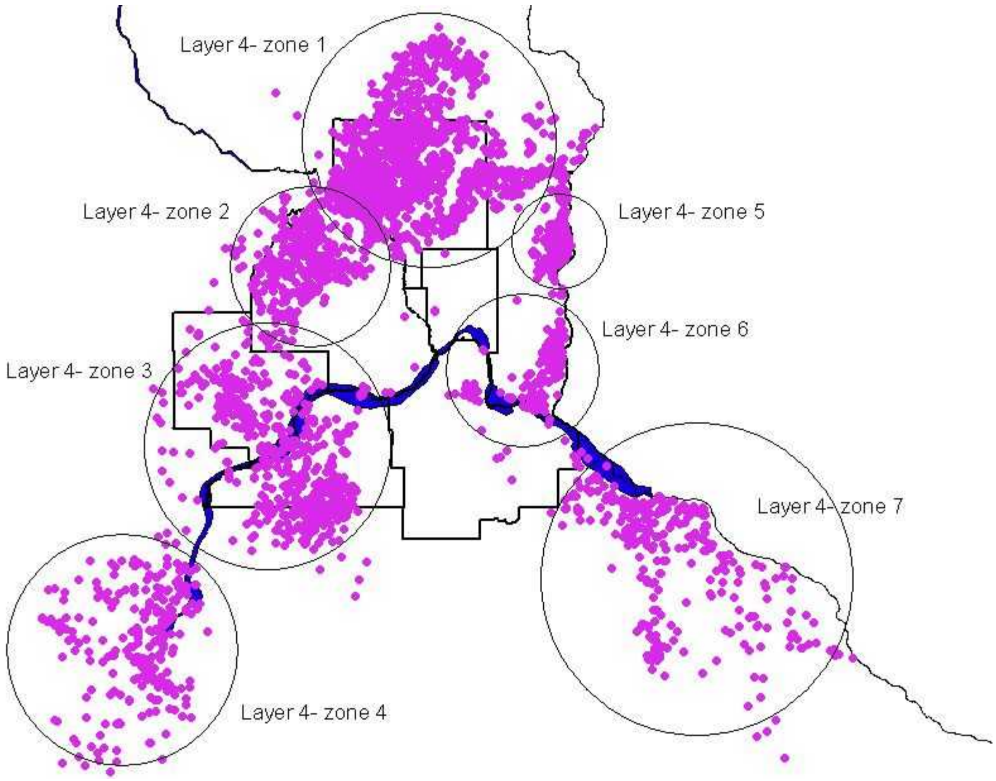
Layer 1. The Layer 1 Northeast Province had a total of 5900 entries in CWI, of which 1000 wells were randomly selected for cross-validation. This number of wells represents the limit imposed by the cross-validation software, but still constitutes a very large number of calibration points for our purposes. Following the procedure, wells are ranked according to the deviation of their groundwater elevation from the expected elevation as determined by their neighbors by the dataset's variogram. By trimming the dataset of the 10% of wells that show the greatest difference between observed and estimated head the most unrepresentative wells are removed from the calibration dataset. Therefore of the original 1000 wells, 900 were retained for use in calibration.

The Northwest Province started with 3700 Quaternary wells and the South Province had just over 1000 wells. Removing 10% from the randomly selected 1000, leaves 900 wells in each province's calibration datasets.

Layer 2. The final calibration datasets for the St. Peter Sandstone aquifer had 780 wells in the Northeast, 540 in the Northwest, and 275 wells in the South Province. In each case the final number of wells is 90% of the original, unprocessed dataset.

Layer 3. The final calibration datasets for the Prairie du Chien/Jordan Aquifer had 900 wells in the Northeast, 755 wells in the Northwest, and 900 wells in the South Province.

Layer 4. The process for producing calibration datasets for the wells screened exclusively in the Franconia-Ironton-Galesville Aquifer varied from the method used for the first three layers. Because the major metropolitan river systems are not the barriers to groundwater flow for this aquifer, the Layer 4 domain is not subdivided into hydrologic provinces. However, the wells that could be used for calibration are not well distributed spatially across the area, which violates one of the key assumptions for the use of spatial statistics (Figure 24). The wells stretch across the greater metropolitan area in a pattern resembling an upside down "V", with data clustered in roughly seven different groups. In order to apply the spatial tools it is necessary to split the larger dataset into discrete zones. For each zone variograms were developed and cross-validation was performed, resulting in seven subsets that comprise the head calibration dataset for Layer 4 as illustrated in Figure 24.



From Streitz (2000)

Figure 24. Location of Head Calibration Data Subsets for Layer 4

Layer 5. The calibration datasets for wells screened in the Mt. Simon-Hinckley Aquifer are based entirely on the MDNR's observation wells (MDNR, 2000a) as there are too few wells in CWI to provide the spatial distribution necessary for statistical analysis. Because the observation well network has multiple readings extending over several years, a different procedure was used to arrive at a representative value for each well. Data was filtered to concentrate on:

- The months of March, April and May—selected to avoid summer pumping; and
- An average of the years 1993 through 1998 were used to avoid dry or wet years, and to use the most recent data available.

Datasets were built using these constraints with ACCESS database software.

Stream discharge measurements and estimates based on hydrograph analyses were used to compare with computed stream discharges to evaluate the water balance of the Metro Model. Stream discharge data are relatively scarce. Metro Model personnel reduced much of the data through analysis of stream hydrographs. Discharge data for the major rivers (Mississippi, Minnesota, and St. Croix Rivers) are available, but measurement errors generally exceed the groundwater discharge contribution to flow between gauging stations. Discharge measurements for smaller streams were found to be useful, particularly in the lower reaches of tributaries to the major rivers, where the discharge rates are assumed to reflect discharge rates to the rivers. Other discharge data have become available since completion of version 1.00 of the Metro Model. Additionally, more stream hydrograph data are available for analysis to derive groundwater discharge rates. These data will be used in the future, as resources permit, to confirm and/or further calibrate the Metro Model.

Implementation and Availability

Using the approaches laid out in this report, the four components of the Metro Model have been constructed and are available for use. As previously stated, the four regional model components are **1)** Northwest Province, Layers 1, 2, and 3; **2)** Northeast Province, Layers 1, 2, and 3; **3)** South Province, Layers 2 and 3; and **4)** Regional, Layers 4 and 5. Separate documentation accompanies the datasets for each, summarizing model development, construction, and calibration. The datasets, as well as the documentation, are available for download from the Metro Model web site:

http://www.pca.state.mn.us/water/groundwater/metromodel.html

All four of these models currently simulate inter-aquifer leakage by explicitly entering given-strength flux. This approach simulates leakage well on a regional basis and greatly reduces computation time compared to the approach using leaky and resistance elements. However, local site-specific modeling will require substitution of these given-strength area elements with leaky or resistance elements in the area of interest to simulate inter-aquifer flow and groundwater-surface water interaction. This is necessary to ensure that stresses in one aquifer will properly propagate to other aquifers, and that surface water effects are properly simulated. This step constitutes one of the tasks required for adding the necessary site-specific detail to the Metro Model for application to a specific site.

Future Work

Any discussion of future work is contingent, of course, on the availability of resources. The following paragraphs have been prepared under the assumption that the project will survive and benefit from some level of continued support.

The Metro Model will be revised and improved as new data become available and as resources permit. New improvements in groundwater modeling techniques and software will also be used to enhance the Metro Model in the future. A very large percentage of the time and effort in building the Metro Model has been dedicated to collecting information and data and building the conceptual model. To make this resource available to as broad an audience as possible, the Metro Model team would like to cast the conceptual model in a format that would permit as many users as possible to access it regardless of the modeling approach and software used. For example, embedding the data as attributes in ArcView shape files would permit implementation of the Metro Model in other groundwater modeling software packages, such as Modflow.

Additionally, Metro Model staff will investigate the potential to implement the Metro Model in public domain software to facilitate a wider availability of the resource. Possibilities include Modflow and SPLIT, a public domain analytic element modeling code developed by Dr. Igor Jankovic at the University of Minnesota.

Other challenges that may be addressed as resources permit include: explicitly modeling aquifers as being limited in areal extent, resolving anomalous modeling results, better understanding the role played by buried bedrock valleys on the aquifer systems, and incorporating the highly variable elevation differences of the aquifers across the metropolitan area that result from the Twin Cities structural basin. Additionally, discharge and water balance data will be used to further constrain calibration of the Metro Model as the data become available.

Staff will be working to incorporate refinements to the Metro Model made during sub-regional and local modeling applications. For this reason, the Metro Model staff strongly urge users of the Metro Model to provide feedback on the model, and to supply them with supporting information, data, and documentation, and model refinements made in its site-specific applications. This will permit staff to leverage very limited resources to improve and refine the Metro Model in ways that would not be possible without such cooperation. Ultimately, all users will benefit from the collective input and cooperation that they provide to the project team.

With the completion of the first phase of the Metro Model, the team will be expanding their scope to include groundwater and modeling issues throughout greater Minnesota. As part of the Environmental Outcomes Division, the team is charged with serving as a resource to staff throughout the MPCA. Therefore, although the Metro Model will still be an essential part of the team's responsibility, the team will also be applying its resources to groundwater management problems in other areas throughout Minnesota.

Summary

The Metro Model has been developed as a coarse regional model that can be used as the starting point for the development of sub-regional to local site-specific models. Although it provides the regional context of flow, modifications that reflect the local conditions are imperative for the Metro Model to be effectively used. The conceptual model of groundwater flow consists of five aquifer layers and four leaky layers that separate them:

- **Layer 1:** Global glacial drift aquifer.
    - **Leaky Layer 1-2:** Leaky layer beneath lowest glacial aquifer; can represent glacial till, Decorah Shale, Platteville Limestone, and the Glenwood Shale.
- **Layer 2:** St. Peter Sandstone Aquifer.

  - **Leaky Layer 2-3:** Basal St. Peter Sandstone; silty, hydraulically resistant layer.

- **Layer 3:** Prairie du Chien-Jordan Aquifer.

  - **Leaky Layer 3-4:** St. Lawrence Formation

- **Layer 4:** Franconia-Ironton-Galesville Aquifer.

  - **Leaky Layer 4-5:** Eau Claire Formation.

- **Layer 5:** Mt. Simon-Hinckley Aquifer.

The Metro Model simulates multi-aquifer groundwater flow within the metropolitan area using MLAEM. The areal boundaries of the model are extended in each layer to include the hydrogeologic boundaries that impact flow in the metropolitan area. The erosionally dissected nature of the aquifer layers poses special problems for modeling the metropolitan area. Area elements are used to represent changes in vertical hydraulic resistance in the valley fill, and curvilinear line-sinks are used to represent the seepage face at the base of an aquifer lying at an elevation above an adjoining river. Inhomogeneities represent significant changes in hydraulic properties.

The Metro Model has been divided up into four separate models that it collectively refers to. The four separate models, listed below, have been constructed to permit ready linking if necessary:

1) Northwest Province, Layers 1, 2, and 3;
2) Northeast Province, Layers 1, 2, and 3;
3) South Province, Layers 2 and 3; and
4) Regional, Layers 4 and 5

The Metro Model simulates leakage between aquifers by explicitly entering the given-strength leakage rates, which were determined largely from calibration procedures. Geostatistically filtered head data from CWI was found to generally work well as model calibration targets on a regional basis. Additionally, water budget and stream discharge data were used as essential calibration targets in conjunction with the head data.

Future work on the Metro Model by this agency will be dependent upon its priority with respect to the goals of the agency. This work would include: continual improvement of the hydrogeologic conceptual model and its implementation in the Metro Model; evaluation of approaches to make the Metro Model available to a wider audience, such as the use of ArcView shape files with attributes that can be accessed by different modeling packages; and implementation of the Metro Model into public domain software packages.

Acknowledgments

The Metro Model was initially supported from 1995 through 1999 through a special allocation by the Minnesota Legislature as recommended by the Legislative Commission on Minnesota Resources, with additional support coming from the U.S. Environmental Protection Agency, and the MPCA. In July of 1999, the project was funded within the MPCA's Environmental Outcomes Division. Reorganization of this division in July of 2000 may alter the level of support to the Metro Model by the MPCA, since project staff will serve as a MPCA resource for groundwater and modeling issues in Greater Minnesota.

The work products provided through this project would not have been possible without the help and support of many individuals who have contributed to the Metro Model project since it began in 1995. The dedication and efforts of current project staff, Andrew Streitz and Doug Hansen, have been instrumental in development and construction of the Metro Model and its supporting databases and conceptual model. Special gratitude is extended to Don Jakes and Shelley Burman, early supporters of the project within MPCA and who provided supervisory oversight during the project's first five years. Former staff who have contributed technical inputs on the Metro Model include Hsu Yuan-Ming and Markell Lanpher. University of Minnesota staff who have provided valuable technical input and feedback include Professor Otto D.L. Strack, who wrote MLAEM and provided adjustments to the code as needs arose, Professor Randal Barnes, who provided valuable input on database and geostatistical treatment of data. Additionally, other personnel from the University of Minnesota who contributed to the project include Dr. Igor Janković, Erik Strack, Josh Curlee, Dr. Mark Bakker, and Brian Block. Dr. Wim de Lange of the Dutch Ministry of Transport, Public Works and Water Management provided invaluable assistance in the early stages of model development, and gave generously of his time to help project staff overcome difficult technical problems. Subcontractors to the project team provided valuable inputs to the project: University of Minnesota personnel (already listed) and Wim de Lange were instrumental in initial development of the Metro Model and pioneering new modeling techniques; Kelton Barr gave an independent review and critique of the project and helped apply the Metro Model to MPCA project sites; Steve Lorentz provided GIS, database, and graphics services; Greg Brick provided data he had collected on springs along the Mississippi River gorge within the Twin Cities; and MGS provided special geologic GIS coverages of selected Paleozoic formations within the metropolitan area. Personnel from the Twin Cities Metropolitan Council, Minnesota Department of Natural Resources, and the United States Geologic Survey were helpful in supplying essential information, data, and constructive suggestions for model development, construction, and calibration. Special thanks goes to the many members of the project Users' Advisory Workgroup, who selflessly gave of their time to read, listen, review, evaluate, and provide feedback on the Metro Model project. Their peer-review and feedback has immeasurably improved the work products of the Metro Model.

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