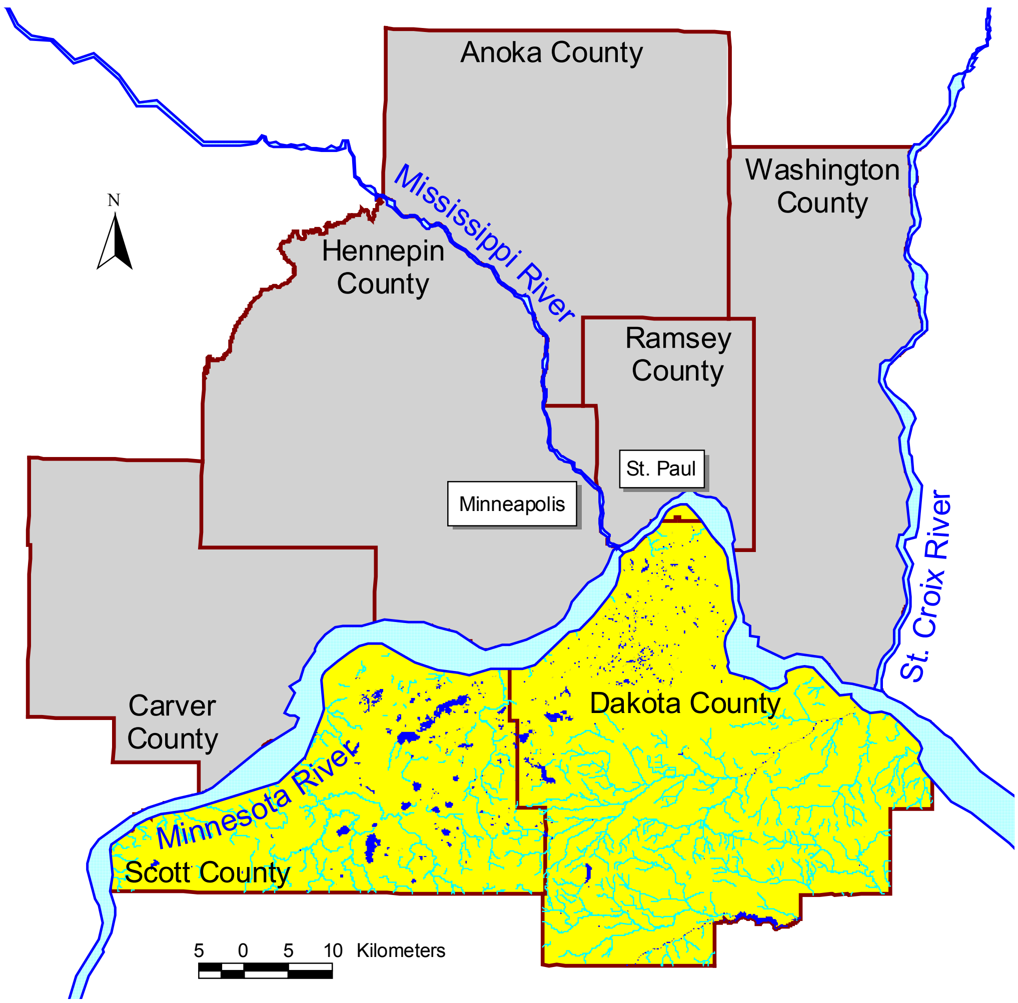
Metropolitan Area Groundwater Model
Project Summary

South Province, Layers 2 and 3 Model

Version 1.01, May 2001

Douglas D. Hansen and John K. Seaberg



Minnesota Pollution Control Agency

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Introduction

This document summarizes the development and construction of one module of the Metropolitan Area Groundwater Model (Metro Model). The Metro Model is actually comprised of four different regional groundwater flow models for the seven-county Twin Cities metropolitan area (Figure 1).

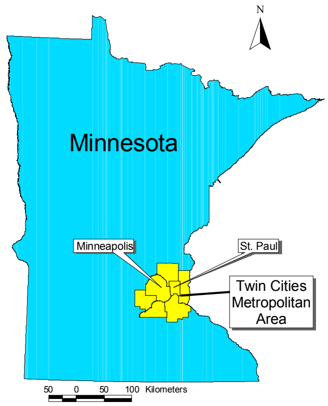

Figure 1 – Metro Model Index Map

One of the models is for the lower portion of the aquifer system representing the Franconia-Ironton-Galesville Aquifer (Layer 4), and the Mt. Simon-Hinckley Aquifer (Layer 5), and encompasses the entire metro area.

The upper portion of the aquifer system has been divided into three hydrologic provinces separated by the Mississippi, Minnesota, and St. Croix Rivers, as shown in Figure 2. These rivers are believed to serve as hydrologic boundaries for the upper three aquifers. The Northeast and Northwest Province models are for Layers 1 (Glacial Drift Aquifer), 2 (St. Peter Sandstone Aquifer), and 3 (Prairie du Chien/Jordan Aquifer). The South Province model approaches the aquifer system differently by modeling the Glacial Drift and St. Peter Sandstone as one aquifer and the Prairie du Chien/Jordan Aquifer. The St. Peter Sandstone is not modeled as a separate aquifer, because it does not occur consistently throughout this province.

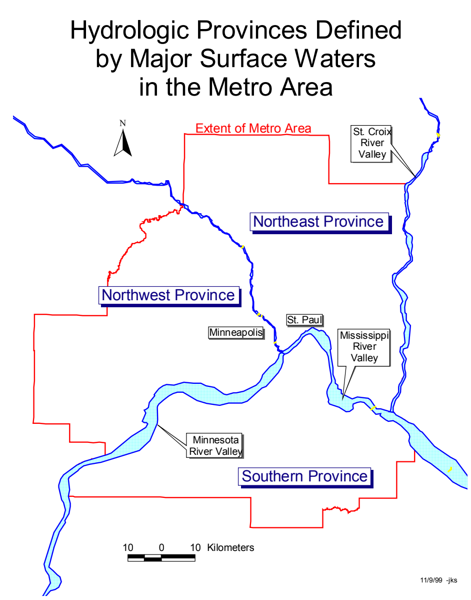

Figure 2 – Hydrologic Provinces

This report summarizes the development, construction, and revisions (Version 1.01) of the South Province steady-state model for the upper two layers. This includes an area comprised mainly of Scott and Dakota Counties. To provide consistency with the other models the Prairie du Chien/Jordan Aquifer is Layer 3 in this model. The Glacial Drift/St. Peter Sandstone Aquifer is Layer 2 and Layer 1 does not represent any aquifer, it is a 'place holder' allowing the model to be used for scenarios requiring differentiation of one of the modeled aquifers into two distinct aquifers.

This summary has been prepared to provide the user with the basic information required to understand and use the South Province Model. A full documentation log (over 95 pages) chronicling the construction and development of this module of the Metro Model is contained in three documents that are available on request. Also, more detailed information regarding the overall conceptual model may be found in the general report titled Overview of the Twin Cities Metropolitan Groundwater Model, which discusses development of the conceptual model and its application to the Multi-Layer Analytic Element Model (MLAEM), the software used for development of the model. Review of and familiarity with this report provides a more complete context in which to read this summary for the South Province. Refer to that document for more complete descriptions of the conceptual model and its implementation in MLAEM.

The development, construction, and revision of the South Province are presented in this document, starting with a summary of the upper hydrostratigraphic units, along with global parameters used in the model. A discussion regarding the construction of the polygon mesh used to simulate infiltration and leakage and how it is tied in to the hydrogeology follow this. The construction phase of the model is completed with a presentation of how surface waters and aquifer inhomogeneities are represented in the model. Revisions occur throughout this document, and reflect the adjustments that were necessary to incorporate changes to global aquifer parameters. A discussion of calibration targets and procedures naturally follows, in which water levels and water budget information were used to tie the model to measured conditions. The final portion of this report presents the actual model datasets that are available for use.

Conceptual Model

Hydrostratigraphy

As stated, the South Province model contains the two uppermost aquifer layers. Leaky layers representing aquitards separate these layer aquifers. For reasons that will be discussed later, flow between layers is not explicitly modeled as leaky flow that is determined by the model on the basis of intrinsic hydraulic properties of the aquitard. Instead, the regional Metro Model represents flow between aquifer layers by specifying the actual flux or leakage rates, which are adjusted during calibration procedures. A brief description of the hydrostratigraphic units is provided in this section. Table 1 summarizes the global aquifer parameters used in model construction. The derivation of these parameters is discussed in the Overview of the Twin Cities Metropolitan Groundwater Model.

Layer 1. This model does not contain a layer 1, as mentioned previously.

Layer 2. This layer represents a buried aquifer comprised of unconsolidated glacial materials and St. Peter Sandstone, where present, throughout the model domain. Groundwater recharge occurs at the top of this layer through infiltration. Water losses from this aquifer occur through discharge to surface water bodies and leakage to the underlying aquifer. The base elevation of this aquifer is globally set to 190 m MSL, and thickness to 70 m. The global hydraulic conductivity value is 6 m/day and the porosity is 0.3.

Changing the global aquifer parameters is the basis for the revision of the South Province Model. It became evident since the release of Version 1.0 that the St. Peter Sandstone, its thickness, and hydraulic properties were necessary for understanding regional flow in the material overlying Layer 3, the Prairie du Chien-Jordan Aquifer.

Leaky Layer 2. This leaky layer represents the lower-most unit(s) with vertical hydraulic resistance underlying the lower-most glacial drift aquifer or St. Peter Sandstone. It represents the effects of glacial till and/or the base of the St. Peter Sandstone. As mentioned previously, the St. Peter Sandstone geologic unit does not occur consistently enough to develop as a separate aquifer in this regional scale model as illustrated in Figure 3 below. It does not appear as an inhomogeneity either, but its presence was considered in the development of the polygon mesh, which defines vertical leakage.

Layer 3. Layer 3 represents groundwater flow in the Prairie du Chien-Jordan Aquifer, and treats both formations as one hydrostratigraphic unit of variable areal extent (Figure 3, below). Recharge to this aquifer occurs as leakage from overlying bedrock units and also from the glacial drift where the formation subcrops beneath it. Discharge occurs to surface water bodies, primarily the major river systems that physically dissect the aquifer. The base of this aquifer is the St. Lawrence Formation, a regional confining unit that generally allows only negligible leakage to lower aquifers. However, where buried bedrock valleys have cut through the Prairie du Chien-Jordan formations and in southwestern Scott County where the Prairie du Chien-Jordan formations are absent, the St. Lawrence Formation may be eroded and allow greater leakage between upper and lower aquifers. This requires the model to take into account leakage through the bottom of layer 3. The assigned global base elevation is 120 m MSL with a thickness of 60 m. The global value for hydraulic conductivity is 12 m/day and the porosity is 0.090.

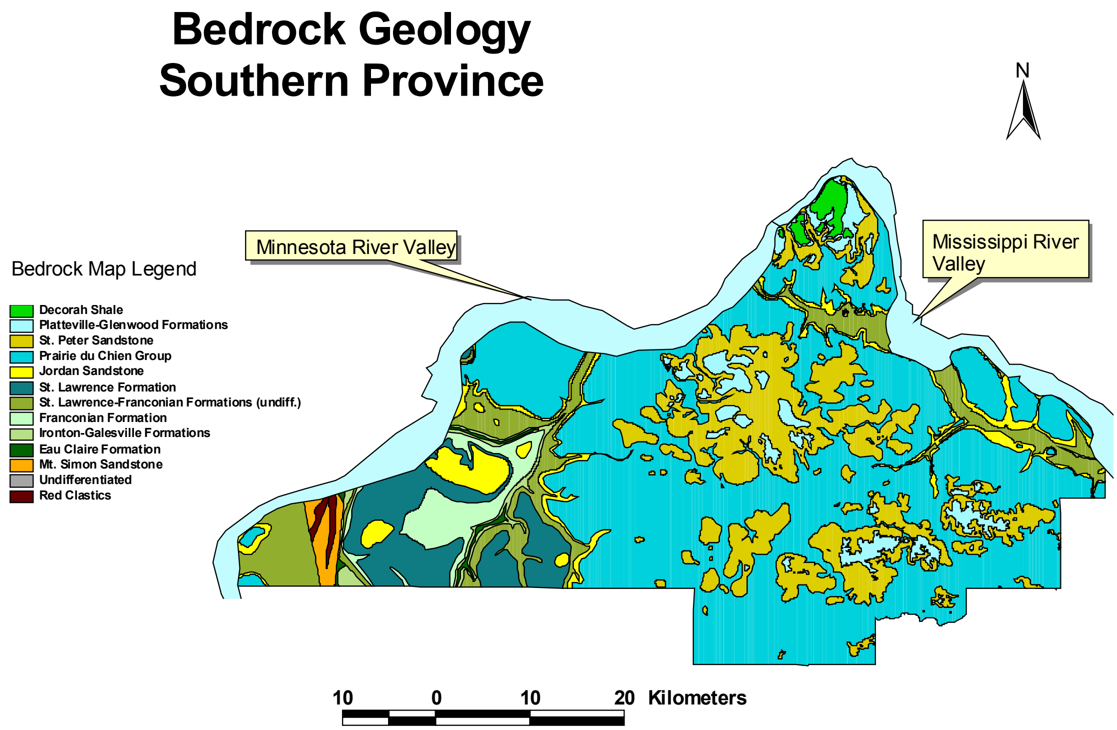

Figure 3 – Bedrock Geology of the South Province

Table 1

Global Aquifer Parameters, South Province Layers 2 and 3
Version 1.01

Model Layer	Aquifer	Base Elevation (m MSL)	Thickness (m)	Hydraulic Conductivity (m/day)	Porosity
Layer 2	Glacial Drift	190	70	6	0.30
Layer 3	Prairie du Chien-Jordan Aquifer	120	60	12	0.09

Implementation. Because the model is constructed using MLAEM, the aquifers are treated as extending infinitely, when they are actually of very limited extent. However, boundaries are imposed on the system by modeling the major rivers, which act as hydrologic boundaries to the system. Since the actual bedrock layers have variable limited extents, there are areas in the model where the aquifer is erroneously represented as present within a layer. Depending on the location and on the application of the model, this either may be of no consequence, or may require site-specific customization to model the system and to ensure a proper water balance.

The regional model uses only groundwater recharge and leakage rates to maintain the water balance for inter-aquifer flow. Site-specific models will require replacement of these given-strength elements in the area of interest with leaky areal elements that separate the aquifer layers. This will allow the model to properly respond to inter-aquifer stresses, such as pumping, that are imposed on the finite water balance of the system.

Recharge and Discharge Zones

Groundwater recharge for the top two aquifers in the South Province occurs throughout the interior, and is assumed to originate from infiltration into the glacial drift aquifer or as upward leakage from lower geologic units. The use of upward leakage is a departure from the method of proportional distribution of infiltrated water from above as described in the Overview of the Twin Cities Metropolitan Groundwater Model. The reason for using upward leakage came as a result of the heterogeneity of the aquifer materials that exist throughout the province; coupled with much larger buried bedrock valleys than are found in the other two provinces. These buried bedrock valleys are incised through Layer 3 and may promote upward leakage from lower aquifers. In addition, the bedrock geologic structure of southwestern Scott County is complicated and the Prairie du Chien-Jordan formations are for the most part absent, yet exist in the far field to the south. This exposes lower aquifers, which may contribute leakage to upper units. Therefore, manual calibration procedures were employed following automated calibration procedures to provide further improvement of the model fit to measured conditions

Discharge of groundwater from Layers 2 and 3 is assumed to occur via leakage to underlying units, discharge to surface waters, and discharge to the Mississippi and Minnesota River valleys, which serve as major discharge zones for both aquifer layers. Additionally, there is a net loss of groundwater owing to extraction from pumping wells. These wells are not explicitly included in this regional scale model. It is assumed their combined discharge effect is reflected in the leakage rates, which were calibrated to measured head data of the County Well Index (CWI).

Model Development and Construction

Polygon Development

Polygons are used to represent infiltration rates and inter-aquifer leakage in MLAEM. There are three different types of variable strength areal elements (VARELs) in MLAEM; each associated with different types of input parameters:

1) **Given-strength** elements are constructed by specifying the actual infiltration or leakage rate for the specified polygon;
2) **Leaky** elements, that separate aquifers specify only the hydraulic resistance (aquitard thickness divided by its vertical hydraulic conductivity); and
3) **Resistance** elements, which have head value (e.g., a surface water elevation), as well as a hydraulic resistance (e.g., of a lakebed) specified.

We have chosen to use given-strength VARELs to simulate inter-aquifer flow since it provides the most computationally expedient means to simulate water throughput on a regional basis. The given-strength VARELs will necessitate replacement with leaky or resistance VARELs in order to build local models that can effectively simulate inter-aquifer responses to stresses placed on the system.

Development of the polygon mesh for the South Province will be described very briefly here. Polygon construction is based largely on the theory that infiltration to the top of a layered aquifer system will be distributed to the various layers proportional to their transmissivity values in steady-state conditions. This means that any change in hydraulic properties, such as transmissivity or hydraulic resistance, in any of the layers will result in changes in the leakage distribution to all the layers of the system. The polygon mesh that is used to represent various leakage rates must be used to represent all the separating layers between aquifers and all the changes to parameters. This results in the use of a cookie-cutter approach to propagate the mesh throughout all the aquifer separating layers.

The geologic complexity in the South Province resulted in the development of a polygon mesh that also considers the effect of erosion of bedrock surfaces and the heterogeneity of drift and valley fill materials. Interpretive license was required to develop a relatively simple regional mesh out of a highly heterogeneous system. The final polygon mesh for the South Province is shown on the following pages overlying the various Geographic Information System (GIS) geologic coverages used in its construction. Discussion will be minimal since it is more useful to examine the mesh in context of the hydrogeology.

Figure 4 shows the major surface waters of the South Province that were considered in the development of the polygon mesh. No large lakes occur in this province in contrast to the other two provinces. Instead, an area of closed basin lakes near the Interstate 35 corridor in Burnsville, Minnesota was identified as a possible area of focused recharge and divided into two polygons with different given strength leakage rates. Prior Lake lying just west of this focused recharge zone is contained within other polygons representing a buried bedrock valley and is therefore not represented as a separate polygon.

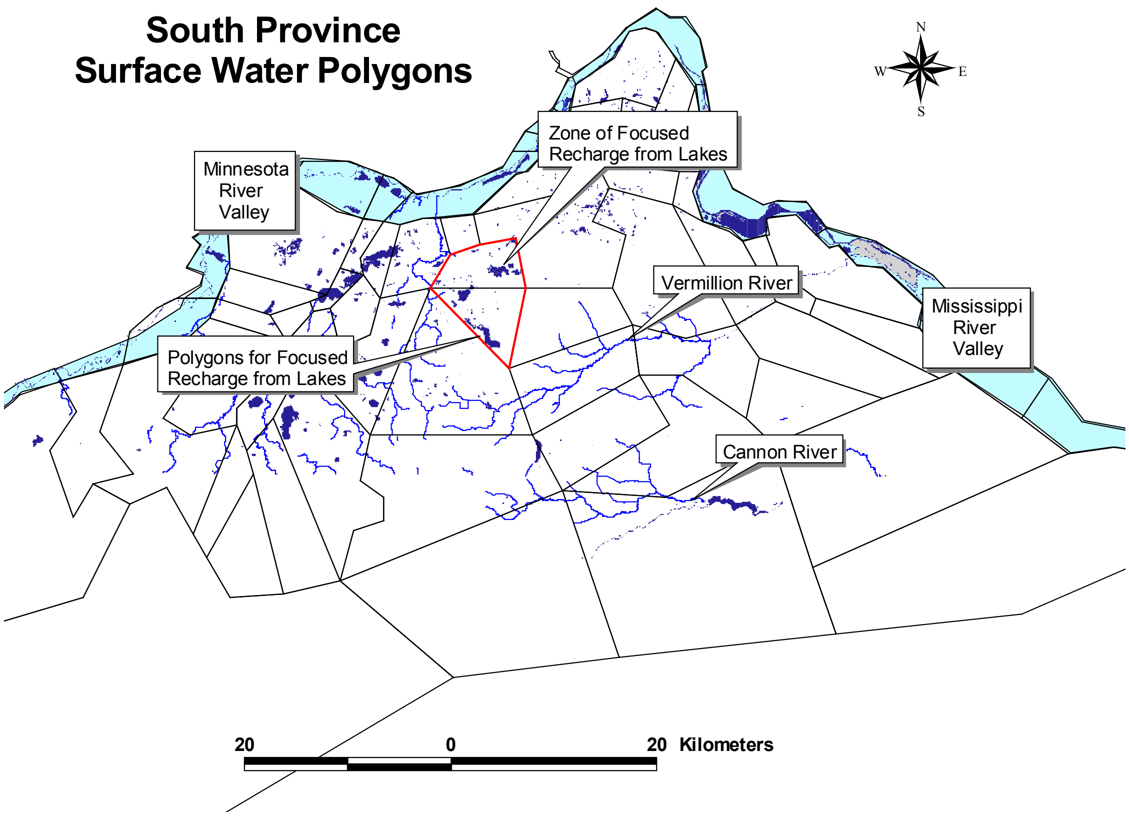

Figure 4 – South Province Surface Waters and Polygon Layout

Metro Model staffs have applied automated database querying and geostatistical techniques to produce sand content maps of the Quaternary glacial drift for different elevation horizon intervals. A detailed description of the procedures used can be found in the Overview of the Twin Cities Metropolitan Groundwater Model. The sand content maps for the four elevation intervals (Interval 1 at 280 – 300 m MSL, Interval 2 at 260 – 280 m MSL, Interval 3 at 240 - 260 m MSL, and Interval 4 at 220 – 240 m MSL) are shown in Figure 5. The naming convention for the intervals is similar to that used for Metro Model aquifer layers: number 1 is at the top of the sequence, and number 4 is at the bottom. Note that blank areas in the figures occur where either the interval's elevation is above the ground surface or below the bedrock surface.

A potential user of the Metro Model will benefit by being mindful of how the polygon mesh relates to all hydrogeologic features. Many polygon sides are defined by large surface water bodies (Figure 4) or changes in bedrock geology (Figure 7), but many were constructed to represent major regional differences in the sand content of glacial materials, either surficial or buried. Note that, although major changes in drift composition are generally depicted by polygon sides, smaller-scale inhomogeneities are not as likely to be defined. Local refinement of this mesh is expected to occur during the construction of site-specific models.

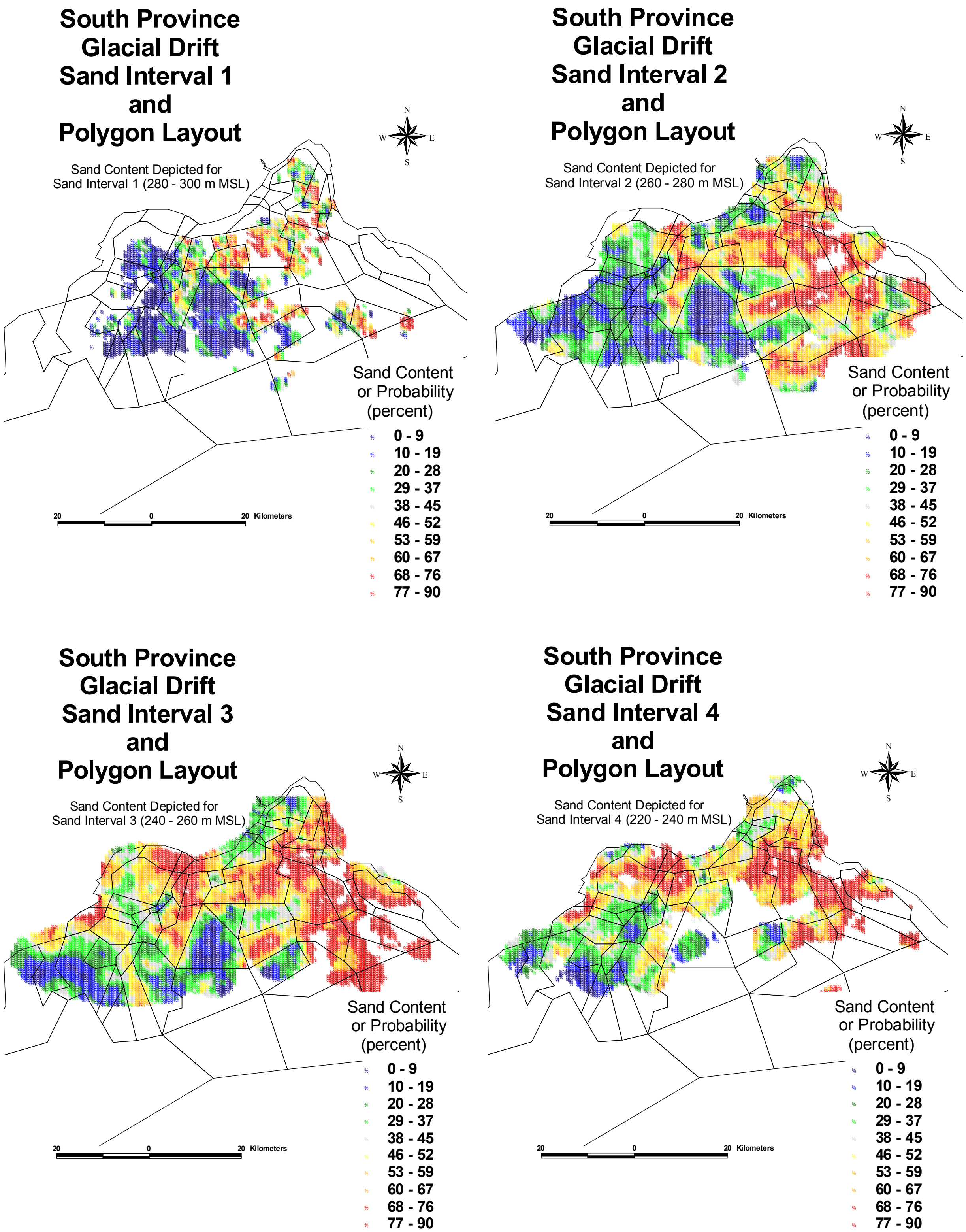

Figure 5 – South Province Sand Content of Glacial Drift Intervals 1, 2, 3, and 4

To help define differences in both surface infiltration and aquifer properties, two separate composite coverages were used as shown in Figure 6. The first represents the coverage of Sand Interval 1 overlying Sand Interval 2 that was used as a representation of the surficial glacial materials that impact overall infiltration rates. The second represents Sand Interval 3 overlying Sand Interval 4 as a representation of the nature of the glacial drift aquifer.

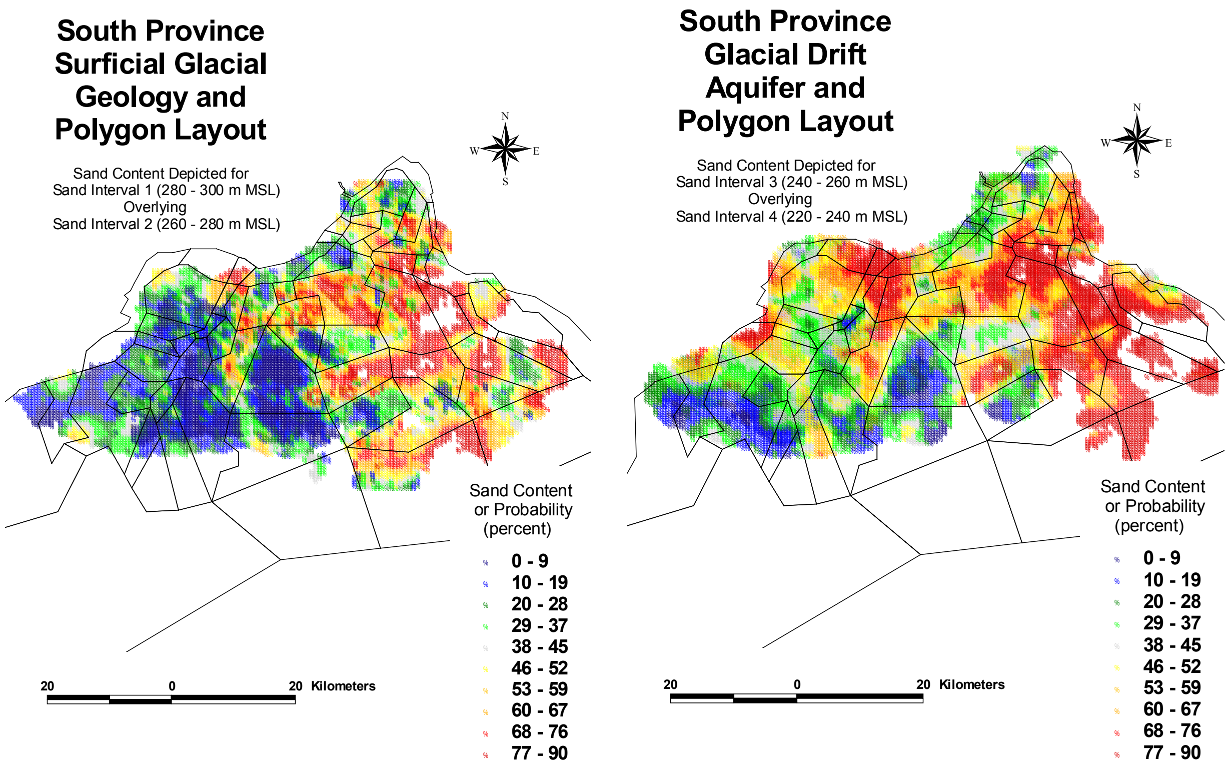

Figure 6 – Sand Content Composite Coverage of Surficial Drift Materials and Glacial Drift Aquifer

The polygon mesh overlies the bedrock geology coverage in Figure 7. Note the presence of a buried bedrock valley that begins in central Scott County, runs north into Hennepin County, then east into Dakota County and finally ends up beneath the Mississippi River valley along eastern Dakota County. This buried bedrock valley is incised as deep as the Eau Claire Formation in the west, where lower units rise, and as deep as the Franconia Formation in the east, thus cutting through both modeled aquifers.

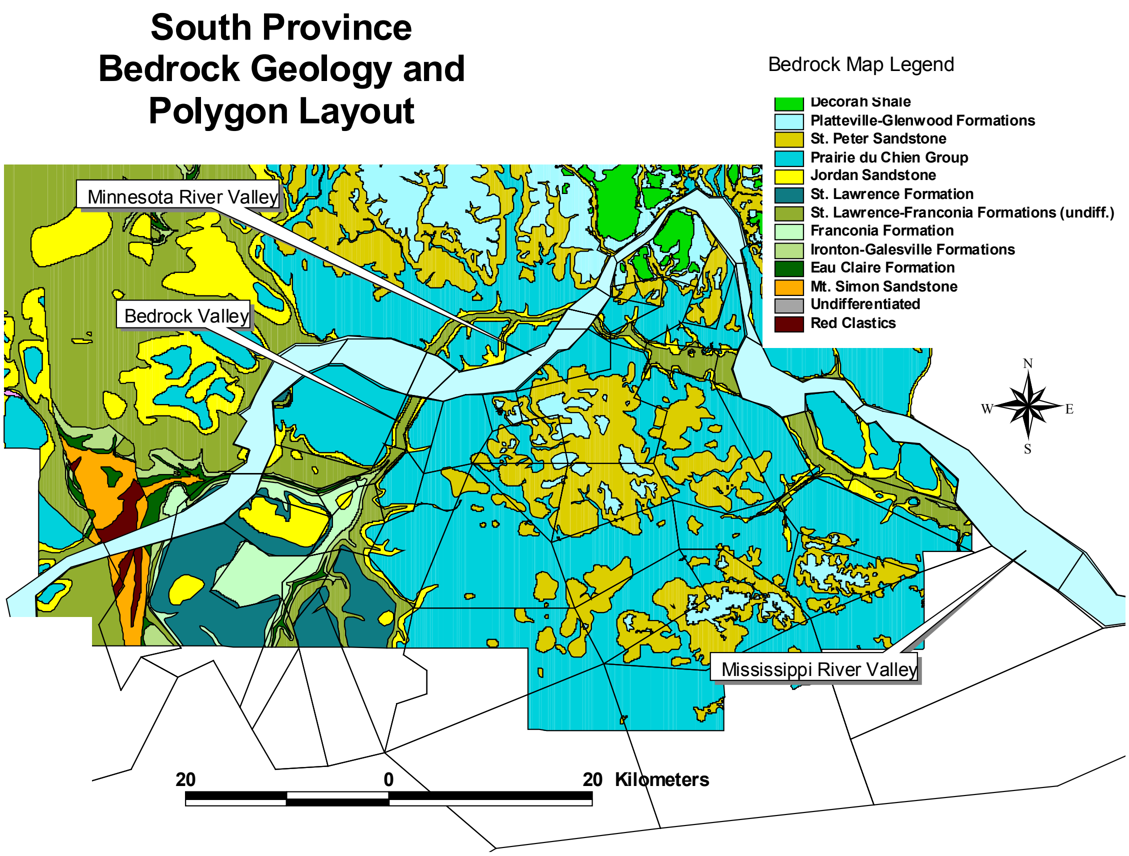

Figure 7 – South Province Bedrock Geology and Polygon Layout

Polygon Designation

In order to distinguish between the polygons that comprise the mesh as presented in the preceding pages, the individual polygons must be given unique designations. Three types of polygon naming conventions were used to name the polygons described, and are discussed in the following paragraphs. The first convention is a general one and covers standard infiltration and leakage polygons. The second naming convention deals with polygons that are defined by surface water bodies or that represent buried bedrock valleys. The third convention deals with the river polygons that border the province to the north, east, and west.

Unlike the Northeast Province model, this model contains no far field polygons. The southernmost row of infiltration-leakage polygons extends beyond the CWI calibration data sets in that direction and act as a far field. The model is bounded in the other directions by river polygons, which were used to induce flow toward the major discharge zones

The general naming convention used for standard infiltration and leakage polygons uses the following format:

[field 1][field 2]-[number]

Where:

field 1 — Is a single letter that represents which hydrologic province the model lies in. Because this document is describing a South Province model, the designation used in these files is almost exclusively indicative of the South Province. The letter prefixes are assigned as follows:

E	Northeast Province
S	South Province
W	Northwest Province

field 2 — Is generally represented by the first letter of the county name in which the polygon predominantly lays. This convention was used for the primary seven counties in the metropolitan area, and the letter designations are assigned as follows:

A	Anoka County
C	Carver County
D	Dakota County
H	Hennepin County
R	Ramsey County
S	Scott County
W	Washington County

A judgment call was made to assign the letter to polygons that straddle county boundaries. The southernmost tier of polygons in the South Province model lies for the most part in the next tier of counties south of Scott and Dakota Counties. They are from west to east, Le Sueur, Rice, and Goodhue Counties. Field 2 name designators will be:

LS	Le Sueur County
RI	Rice County
G	Goodhue County

number — This is the sequential number assigned to the polygons within each county. These numbers are generally assigned by starting in the northernmost part of the county and working southward.

Polygons not falling under the general category include those defined by lake features, buried bedrock valleys, and river polygons. These are covered in the following paragraphs:

Lake Features: The first letter prefix designates the hydrologic province where the surface water body is found—in this case that is an "S" for the South Province. The designation for the water body is then indicated in the remainder of the polygon name. In the South Province no specific surface water body is named. Instead the polygon names contain the word 'LAKES' in the second field followed by the sequential numbering format. A list of the polygons defining lake features in the South Province follows:

S-LAKES_1	North lakes
S-LAKES_2	South lakes

Buried Bedrock Valleys: Again, the "S" prefix designates the South Province. There are nine polygons representing the extent of buried bedrock valleys in the South Province outside of the Minnesota and Mississippi River valleys. They are listed as follows:

SS-BV_1	Northern portion of the Scott County buried bedrock valley next to the Minnesota River Valley
SS-BV_1S	Northern portion of the Scott County buried bedrock valley at the junction of the west and east forks
SS-BV_2	Western fork of the Scott County buried bedrock valley next to the Minnesota River Valley
SS-BV_2N	Western fork of the Scott County buried bedrock valley at the junction with the east fork
SS-BV_3	Northern portion of the eastern fork of the Scott County buried bedrock valley
SS-BV_4	Middle portion of the eastern fork of the Scott County buried bedrock valley
SS-BV_5	Southern portion of the eastern fork of the Scott County buried bedrock valley
SD-BV_1	Northern portion of the Dakota County buried bedrock valley between SD-BV_1W and SD-BV_1E
SD-BV_1W	Northern portion of the Dakota County buried bedrock valley next to the Minnesota River Valley
SD-BV_1E	Northern portion of the Dakota County buried bedrock valley that is adjacent to SD-BV_2
SD-BV_2	Northern portion of the Dakota County buried bedrock valley that is directly west of Spring Lake on the Mississippi River
SD-BV_3	Northern portion of the Dakota County buried bedrock valley that is directly south of Spring Lake on the Mississippi River

SD-BV_4	Southern portion of the Dakota County buried bedrock valley that is directly south of Spring Lake on the Mississippi River

River Polygons: The Minnesota and Mississippi River valleys are assumed to be major discharge zones for the two aquifers represented in this model and are therefore hydrologic boundaries. In Figure 7 one can see that the rivers intersect the buried bedrock valley and it was assumed for this model that they play a role in the leakage distribution of the province. Since the river valleys are also hydrologic boundaries for the other two provinces, the naming convention will not include a province designation and river polygons will be given more descriptive names. To locate the river polygons quickly their names will include city names or valley feature names included within the polygon.

The river polygons used in this model are listed below beginning downstream on both rivers.

MISSR_REDWING	Mississippi River near Redwing, MN.
MISSR_PRESCOTT	Mississippi River near Prescott, WI.
MISSR_SPRING_LAKE	Mississippi River near Spring Lake
MISSR_S_STPAUL	Mississippi River near south St. Paul
MISSR_ST_PETER-2	Mississippi River near downtown St. Paul that is in contact with the St. Peter Sandstone
MNR_JCTN	Minnesota River near junction with the Mississippi River
MNR_BV_1	Minnesota River intersection with buried bedrock valley at Dakota County
MNR_SAVAGE	Minnesota River near Savage, MN
MNR_BV_2	Minnesota River intersection with buried bedrock valley at Scott County
MNR_CHASKA	Minnesota River near Chaska, MN
MNR_JORDAN	Minnesota River near Jordan, MN
MNR_BELLEPLAINE	Minnesota River near Belle Plaine, MN

The polygon mesh with labels is presented in Figure 8 below.

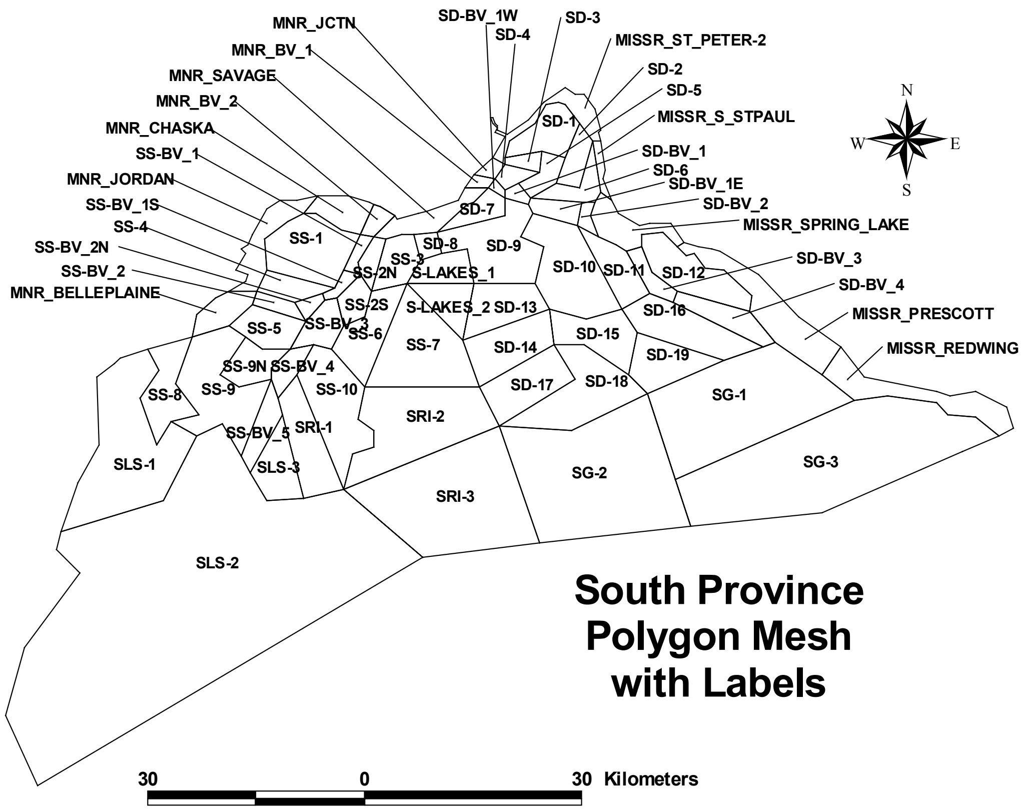

Figure 8 – Regional Polygon Mesh with Labels

The polygon mesh provides the framework for modeling the infiltration and leakage values, which are entered as given-strength flux. Assignment of the leakage values to individual polygons for each layer will be discussed below in the section labeled **Modeling of Leakage**.

Curvilinear Line-Sink Construction

Head-specified curvilinear line-sinks were used to represent hydrologic boundaries in both layers except along the lower Minnesota River in Layer 3. This feature is represented by a resistance linesink, which allows resistance to be varied along its length thus providing more control on leakage between the aquifer and the river, especially where the river crosses the buried bedrock valley (Figure 7). The reason for using a resistance line-sink in this area stems from additional information provided during an analysis of water use in northern Scott County. Past experimentation was conducted using different types of elements to represent the surface waters: head-specified line-sinks, resistance line-sinks, head- and resistance-specified (resistance) variable strength areal elements (VARELs), and resistance-specified (leaky) VARELs to vertically transmit flow between aquifers to the modeled boundary. We found that the head-specified line-sink was the most computationally efficient and also provided a good approximation of the boundary conditions for the regional models, even if they represented surface water bodies that are not in direct hydraulic communication with the aquifer.

Order and overspecification values for curvilinear line-sinks control model accuracy and optimization of the solution in a least squares sense in the vicinity of the element. In this model, the order of the curvilinear elements generally is set at 4, with an overspecification of 1.5 to 2. These values provide sufficient accuracy for the regional extent of this model. However, higher values were typically used for long curvilinear strings to maintain hydrologic control. Site-specific applications will necessitate increasing order and overspecification values on curvilinear elements in the area of interest—the respective default values of 6 and 4 assigned by MLAEM provide a good starting point for this type of detailed work.

The line-sinks in this model represent rivers, which are either the hydrologic boundaries of the model or lie in the interior of the province, where they are considered to have a hydrologic connection to the aquifer. Some also represent seepage faces of the aquifer that may daylight near the river valley.

One should note that the strings used to represent the Minnesota and Mississippi Rivers are placed near the center of the river valleys. This is a different approach than was used in the Northeast and Northwest Province models, where curvilinear line-sinks occur on the side of the river valley nearest the modeled province. The reason for moving these discharge zones away from the valley wall was done to simplify linking of this model to the lower two layer model, where the same curvilinear line-sinks could then be used. This places the seepage faces away from the bluff. Separate strings were not constructed because it was felt that consistent curvilinear string geometries should be used in both layers for regional simplification of the model. Site-specific applications might require modification of the seepage face geometry to better reflect natural conditions.

Use of curvilinear line-sinks in each aquifer layer are presented and illustrated in the following paragraphs.

Layer 2 Curvilinear Line-Sinks

Figure 9 illustrates the placement of the curvilinear line-sinks in Layer 2 of the South Province as well as the hydrography. The curvilinear line-sinks are used to represent significant regional river features. A comparison of the hydrography with the curvilinear line-sinks illustrates that the model is a simplification of reality. Clearly, site-specific modeling will require detailed work to include features representing flow on a local basis.

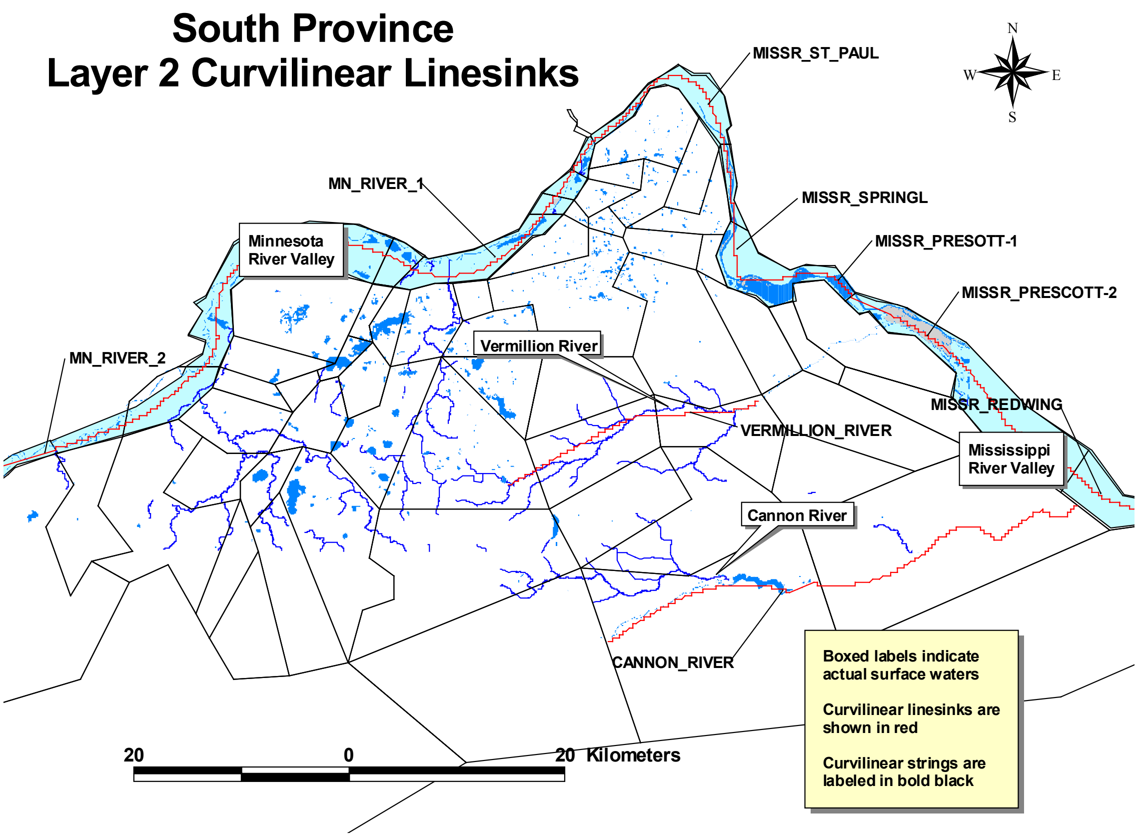

Figure 9 – South Province Layer 2 Curvilinear Line-Sinks

Layer 3 Curvilinear Line-Sinks

Layer 3 includes an additional curvilinear line-sink besides those used in Layer 2 to represent the lower portion of the Credit River in northern Scott County. At this time there is considered to be a direct connection between the lower river reach and the Prairie du Chien – Jordan aquifer. As stated previously, the Prairie du Chien formation and Jordan Sandstone are missing in southwestern Scott County, but both reappear to the south of the province. As a result the Minnesota River was considered to be the hydrologic boundary for Layer 3 even through the area where it was eroded back from the river valley. Figure 10 below shows the curvilinear line-sinks used in Layer 3.

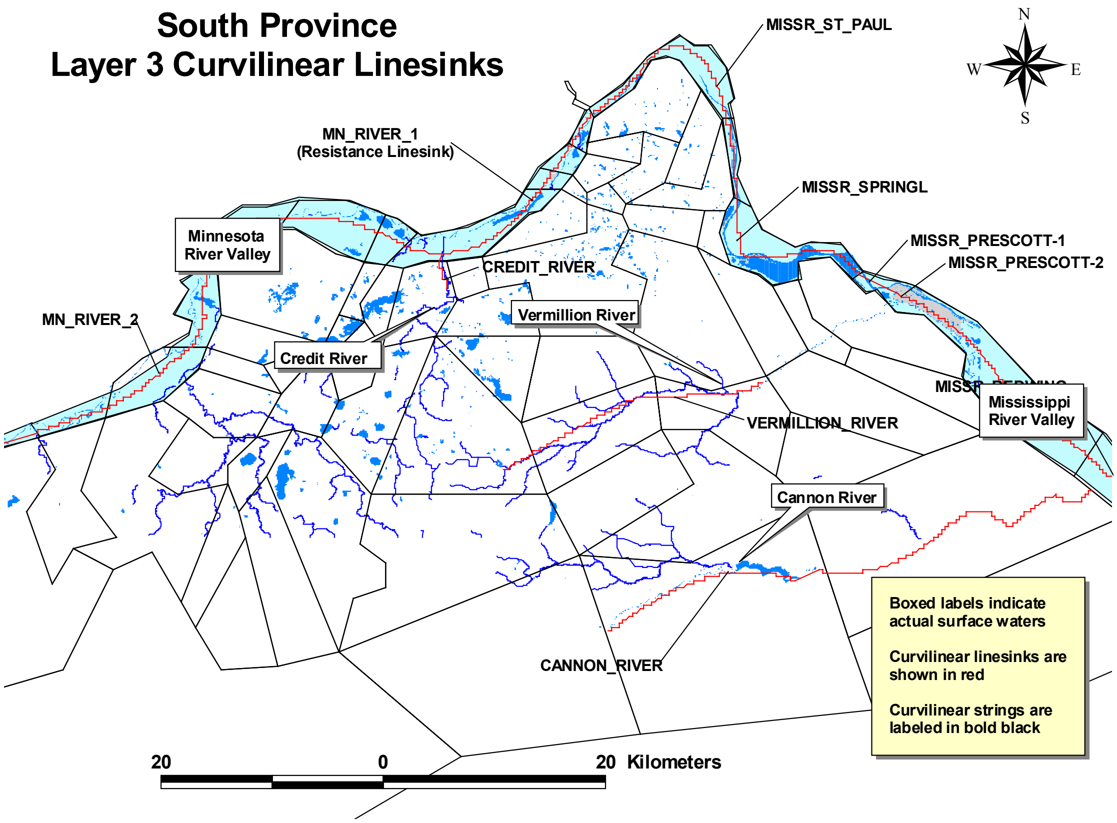

Figure 10 – South Province Layer 3 Curvilinear Line-Sinks

Inhomogeneity Placement

Inhomogeneities were used to represent large aquifer zones with hydraulic properties that differ significantly from those assigned globally in both layers of the South Province model. Each inhomogeneity is defined in the model by a polygon with associated changes in hydraulic properties. The change in global parameters and subsequent increase in detail that was required in the South Province has changed the number and size of inhomogeneities in both layers. No longer is there a large low sand content area in Layer 2, and additional refinement was carried out in old valleys incised into the bedrock surface. Figure 11 identifies the two portions of a large buried bedrock valley used for creating inhomogeneities in Layer 2 and presents the geometry used to define them (outlined in bold red). Inhomogeneity polygons for Layer 3 are subsets of the polygon geometries used in Layer 2, and are described in the appropriate sections below.

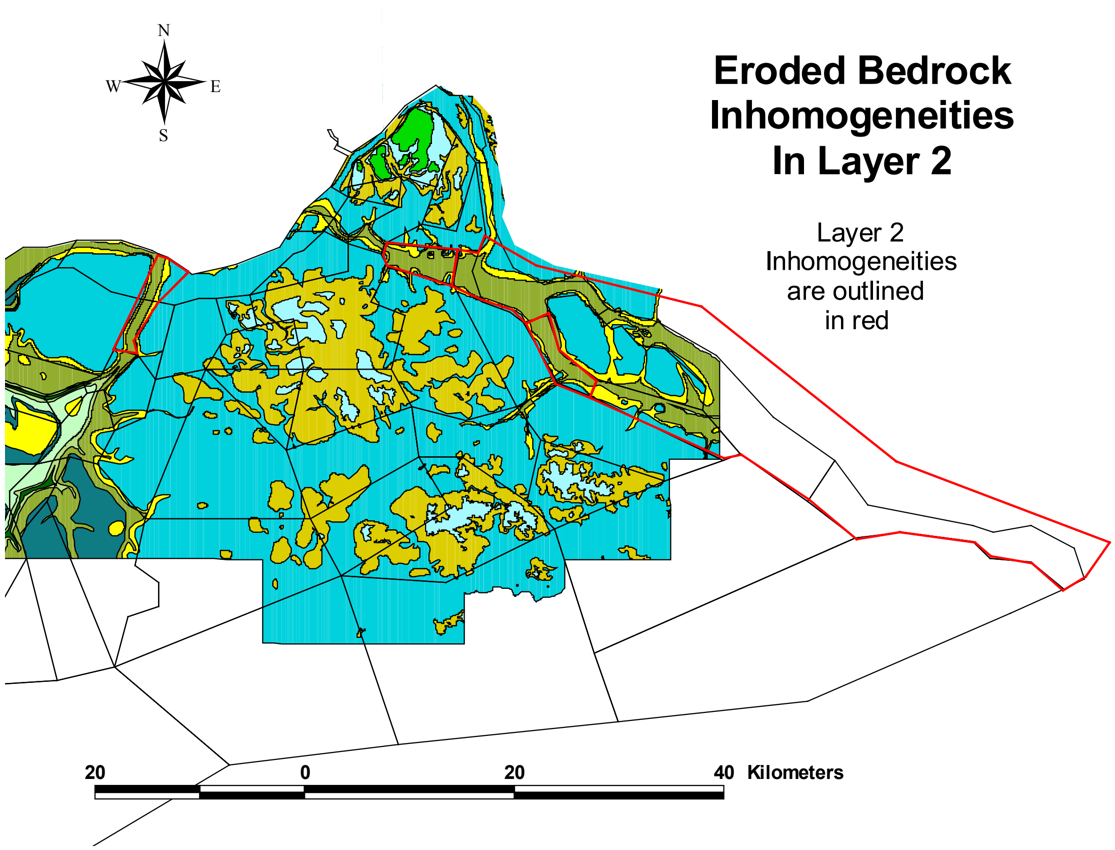

Figure 11 – Eroded Bedrock Inhomogeneities in Layer 2

Analytic elements called "doublets", defined by line segments, coincide with the inhomogeneity polygon sides, and are used to mathematically impose a continuous head across the inhomogeneity boundary. Order and overspecification values for doublets control model accuracy and optimization of head values in a least squares sense on either side of the doublet. In this model, the order is generally specified as 3 or 6, with an overspecification of 2 or 4. These values provide sufficient accuracy for the regional extent of this model. However, higher values are typically used for long doublet segments to maintain hydrologic control. Site-specific applications will necessitate increasing order and overspecification values on the doublets in the area of interest—the respective default values of 6 and 4 assigned by MLAEM provide a good starting point for this type of detailed work.

The inhomogeneities used in each layer for the South Province are described in the following paragraphs.

Layer 2 Inhomogeneities

The significant change in this version of the South Province Model was to include the St. Peter Sandstone with the buried glacial drift material as one aquifer. This has decreased the global hydraulic conductivity of Layer 2 from 21 m/day to 6 m/day, corroborating early work on this revision that indicates a good regional calibration with this global value. Additionally, the global hydraulic conductivity value for St. Peter Sandstone was estimated at 3.3 m/day, and the glacial drift at 21 m/day, so a value of 6 m/day reflects an intermediate value for the two units when they are combined as a single aquifer. The base elevation was lowered to 190 meters and the thickness of Layer 2 was increased from 40 meters to 70 meters to remove the large separation between layers.

Five inhomogeneities of higher hydraulic conductivity and two with lower hydraulic conductivity were constructed in Layer 2. The four inhomogeneities shown in Figure 11 are associated with buried bedrock valleys and have hydraulic conductivity values ranging from 20 to 90 m/day. The thickness was increased to 70 meters by lowering the base elevation to 190 meters. The base elevation of 190 meters is the same as the base elevation of the St. Peter Sandstone modeled aquifer in the Northeast and Northwest Provinces.

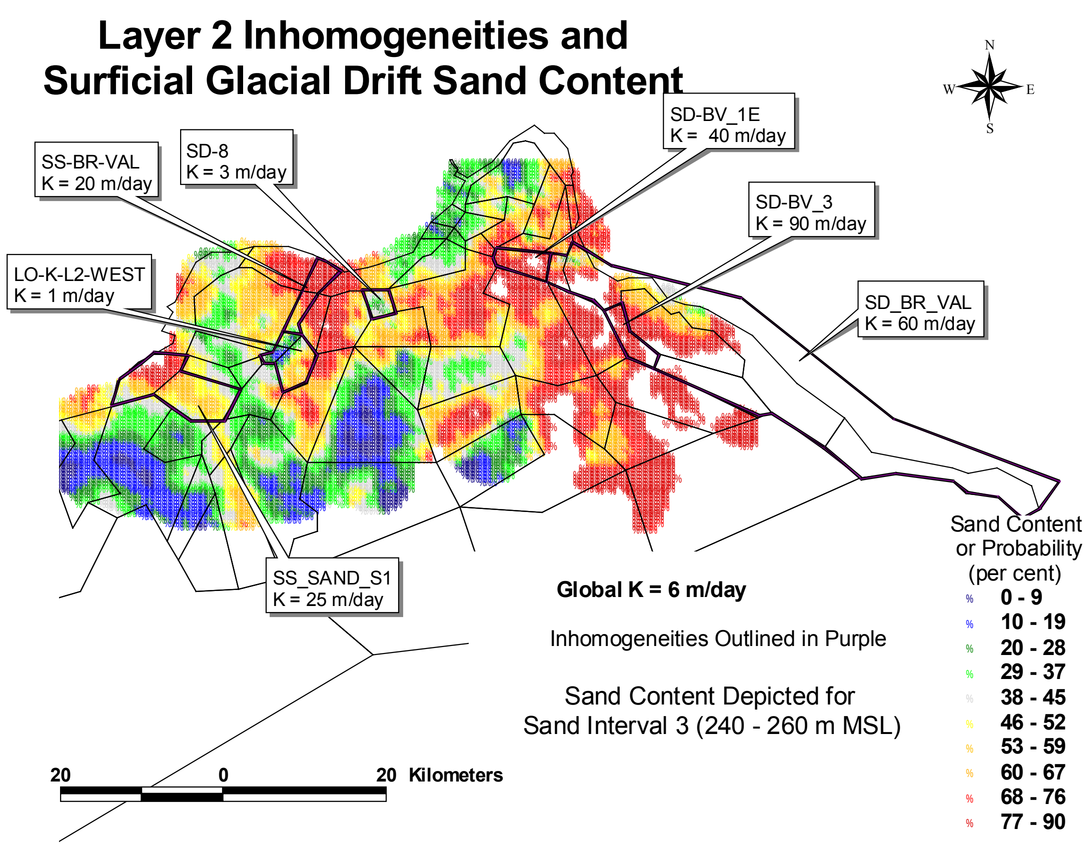

Figure 12 – Layer 2 Inhomogeneities and Surficial Glacial Drift Sand Content

Some inhomogeneities can encompass several of the given-strength polygons within the polygon mesh and, therefore, may differ from the polygons of the mesh. In Layer 2, four of the seven-inhomogeneity polygons encompass more than one polygon. These are illustrated in Figure 12 along with the sand content map of the surficial glacial drift materials.

Changing the global aquifer parameters has eliminated the large surficial till zone inhomogeneity (polygon SS_TILL1), found in Version 1.0, which had a hydraulic conductivity of 6 m/day. The hydraulic conductivity of the smaller inhomogeneity associated with polygon SD-8 was reduced to 3 m/day, and a second inhomogeneity with a hydraulic conductivity of 1 m/d was constructed, as a result of the calibration process, in a zone that occupies part of a buried bedrock valley. It was named LO-K-WEST-2, and coincides with a low sand content area. A third inhomogeneity called SS_SAND_S1 is associated with a high sand content zone in intervals 3 (240 – 260 m MSL) and 4 (220 – 240 m MSL). The buried bedrock valleys constitute the remaining four inhomogeneities (polygons SS-BR-VAL, SD-BV_1E, SD-BV_3, and SD_BR_VAL) with hydraulic conductivity values of 20, 40, 90, and 60 m/day assigned, respectively. The thickness and base elevations of all the inhomogeneities coincide with the base of Layer 2. These are also illustrated in Figure 13, which shows the sand content of the glacial drift at depth. Overall, the figures indicate that these zones contain a high percentage of sand. Ultimately, their inclusion and final geometry were shaped largely by calibration procedures.

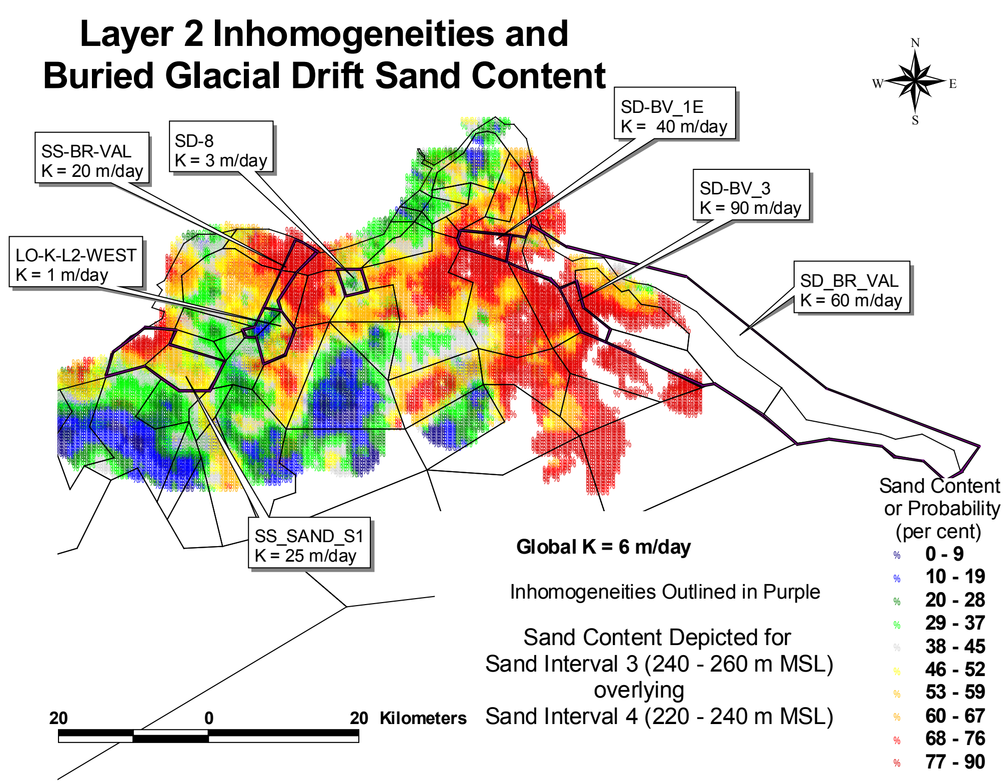

Figure 13 – Layer 2 Inhomogeneities and Buried Glacial Drift Sand Content

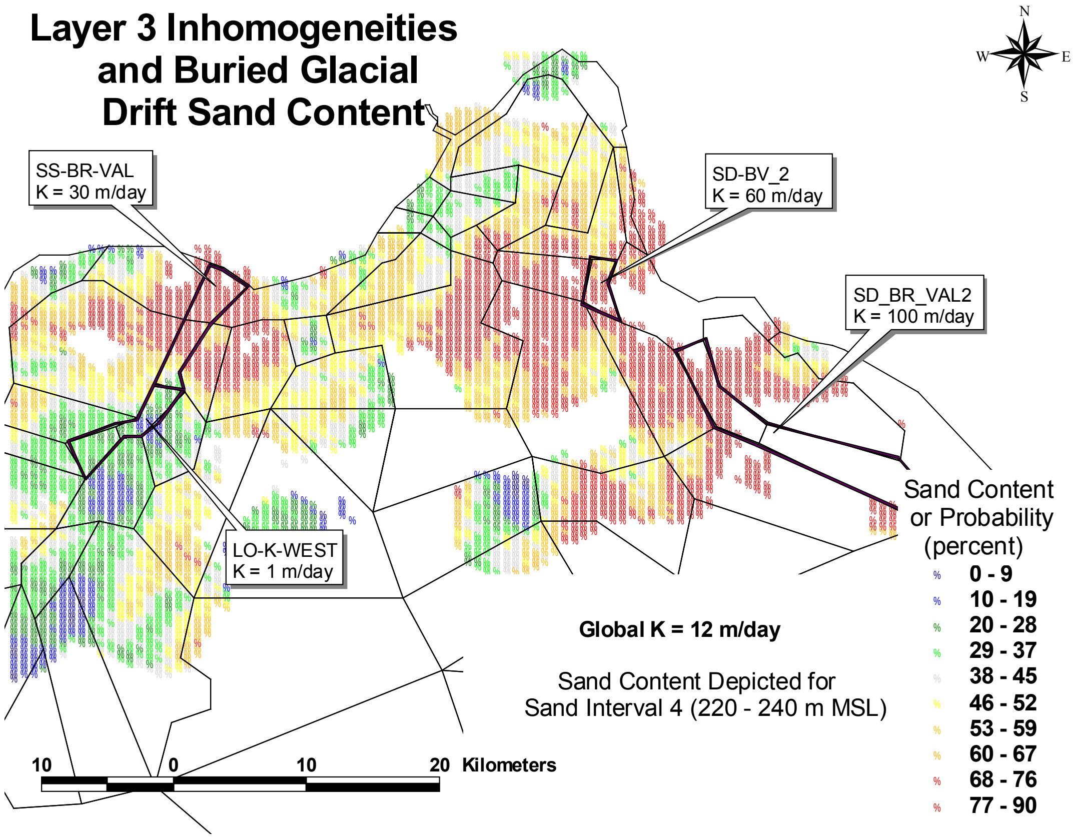

Figure 14 – Layer 3 Inhomogeneities with Buried Glacial Drift Sand Content

Layer 3 Inhomogeneities

Layer 3 contains four inhomogeneities representing changes in hydraulic conductivity within portions of the buried bedrock valley as shown in Figure 14. It illustrates the placement of inhomogeneities superimposed over the sand content map from the lowest horizon (220 to 240 m MSL) of the buried drift aquifer to provide a sense of the types of material likely to occur within the valleys at the elevation of Layer 3. The global value for hydraulic conductivity in Layer 3 is 12 m/day. The hydraulic conductivity values within the inhomogeneities is 1 m/day in polygon LO-K-WEST, 30 m/day in polygon SS-BR-VAL, 60 m/day in polygon SD-BV_2, and 100 m/day in polygon SD_BR_VAL2. These values were determined through the calibration process. In addition, except for the hydraulic conductivity in LO-K-WEST, these values may receive support from the sand content maps in Figure 14, which indicate an overall increase in sand content in the glacial drift aquifer (at depth) compared to the surficial glacial drift. As with Layer 2, the geometry and assignment of hydraulic parameters to the Layer 3 inhomogeneity resulted in large part from manual calibration procedures to measured water levels.

Model Adjustment and Calibration

The upper two aquifer layers of the South Province model were calibrated primarily by adjusting the input elevations of curvilinear line-sinks, placement of hydraulic conductivity inhomogeneities, and the infiltration rates of the polygons. This portion of the model presents special challenges that arise from the influence of the structural geology of the bedrock units. The base elevations of these units, as well as the overlying glacial drift aquifer, occur above the water level of the adjoining major discharge zones in some areas. Curvilinear line-sinks are used to represent seepage faces in these zones. However, in the absence of a distinct physical manifestation of discharge from each layer, elevations that are representative of the seepage face can be difficult to determine. Changes to the input elevations will likely occur as better information is collected, prompting further changes to leakage rates. Additionally, local-scale modeling may require changes to the geometry of the curvilinear line-sinks to better represent site-specific conditions.

After input heads were assigned to the curvilinear line-sinks and inhomogeneities were inserted, the infiltration rates to the polygon elements were adjusted to achieve a best fit to the measured head points. This was an iterative procedure that involved adjustments to the input heads throughout the process. Leakage rates were adjusted using both manual calibration procedures and PEST, an automated model calibration program. The most recent round of calibration was conducted using manual procedures.

Modeling of Leakage

The final infiltration rates used in the model are presented in Table 2 below (South Province Leakage Inputs, Version 1.01). Note that the negative values refer to downward leakage, and that a negative net value indicates a gain of water to the aquifer from that polygon, following MLAEM's convention of data input. This is seen both in Table 2 and in the figures that plot the net leakage rates for each polygon. However, this convention is dropped in the discussions of infiltration and leakage presented here, so that leakage and infiltration rates will not be referred to as negative. These values were determined through manual adjustment and calibration procedures, in conjunction with manually adjusting the input heads on the curvilinear line-sinks. PEST could be used to attempt to improve the fit to measured heads by adjusting the leakage values. However, the current leakage rates should suffice until more detailed modeling is conducted for the South Province. Such modeling could entail changes to hydraulic properties and boundary heads. Further adjustments to leakage would be most beneficial after the other parameters have been better defined.

Table 2
South Province Leakage Inputs
Version 1.01

POLYGON	Layer 2 Top (Total Infiltration) (m/day)	Layer 2 Top (Total Infiltration) (in/year)	Layer 2 Bottom (m/day)	Layer 2 Net (Top-Bottom) (m/day)	Layer 2 Net (Top-Bottom) (in/year)	Layer 3 Top (m/day)	Layer 3 Bottom (m/day)	Layer 3 Net (Top-Bottom) (m/day)	Layer 3 Net (Top-Bottom) (in/year)
SS-1	-1.12E-05	-0.16	-4.20E-06	-7.00E-06	-0.101	-4.20E-06	-4.10E-06	-1.00E-07	-0.001
SS-2N	-1.49E-03	-21.34	-8.55E-04	-6.30E-04	-9.05	-8.55E-04	-5.20E-06	-8.50E-04	-12.21
SS-2S	-2.83E-04	-4.07	-4.02E-05	-2.43E-04	-3.49	-4.02E-05	-5.20E-06	-3.50E-05	-0.50
SS-3	-9.64E-04	-13.85	-6.85E-04	-2.78E-04	-4.00	-6.85E-04	-5.20E-06	-6.80E-04	-9.77
SS-4	9.99E-06	0.14	-6.00E-05	7.00E-05	1.01	-6.00E-05	-1.00E-04	4.00E-05	0.57
SS-5	-1.00E-07	0.00	-4.10E-04	4.10E-04	5.89	-4.10E-04	-3.01E-05	-3.80E-04	-5.46
SS-6	-1.00E-07	0.00	-7.52E-05	7.51E-05	1.08	-7.52E-05	-5.20E-06	-7.00E-05	-1.01
SS-7	-1.05E-04	-1.51	-3.52E-05	-7.00E-05	-1.01	-3.52E-05	-5.20E-06	-3.00E-05	-0.43
SS-8	-8.05E-05	-1.16	-6.81E-04	6.00E-04	8.62	-6.81E-04	-8.01E-04	1.20E-04	1.72
SS-9	-1.14E-03	-16.37	-6.89E-04	-4.50E-04	-6.47	-6.89E-04	-1.39E-04	-5.50E-04	-7.90
SS-9N	-2.16E-04	-3.11	-6.20E-06	-2.10E-04	-3.02	-6.20E-06	-6.10E-06	-1.00E-07	-0.001
SS-10	-4.20E-04	-6.04	-2.80E-04	-1.40E-04	-2.01	-2.80E-04	-8.01E-05	-2.00E-04	-2.87
SS-BV_1	-5.50E-04	-7.91	-5.50E-04	-1.00E-07	-0.001	-5.50E-04	-2.00E-04	-3.50E-04	-5.03
SS-BV_1S	-3.70E-04	-5.32	-7.60E-04	3.90E-04	5.61	-7.60E-04	-2.00E-04	-5.60E-04	-8.05
SS-BV_2	-1.00E-07	0.00	-2.80E-04	2.80E-04	4.02	-2.80E-04	-1.40E-04	-1.40E-04	-2.01
SS-BV_2N	-1.47E-04	-2.11	-1.40E-04	-7.00E-06	-0.10	-1.40E-04	-1.40E-04	0.00E+00	0.00
SS-BV_3	-5.20E-04	-7.47	-1.00E-04	-4.20E-04	-6.04	-1.00E-04	-3.01E-05	-7.00E-05	-1.01
SS-BV_4	-2.64E-04	-3.80	-5.41E-05	-2.10E-04	-3.02	-5.41E-05	-3.01E-05	-2.40E-05	-0.34
SS-BV_5	-1.00E-07	0.00	-4.43E-04	4.43E-04	6.36	-4.43E-04	1.17E-04	-5.60E-04	-8.05
S-LAKES_1	-1.80E-03	-25.80	-1.41E-03	-3.90E-04	-5.60	-1.41E-03	-5.20E-06	-1.40E-03	-20.12
S-LAKES_2	-6.65E-04	-9.56	-2.15E-04	-4.50E-04	-6.47	-2.15E-04	-5.20E-06	-2.10E-04	-3.02
SD-1	-7.26E-04	-10.43	-5.04E-04	-2.22E-04	-3.18	-5.04E-04	-4.10E-06	-5.00E-04	-7.19
SD-2	-3.04E-04	-4.37	-7.41E-05	-2.30E-04	-3.31	-7.41E-05	-4.10E-06	-7.00E-05	-1.01
SD-3	-5.49E-04	-7.89	-4.29E-04	-1.20E-04	-1.72	-4.29E-04	-4.10E-06	-4.25E-04	-6.11
SD-4	-4.24E-04	-6.09	-4.24E-04	0.00E+00	0.00	-4.24E-04	-4.10E-06	-4.20E-04	-6.04
SD-5	-1.12E-03	-16.13	-8.44E-04	-2.78E-04	-4.00	-8.44E-04	-4.10E-06	-8.40E-04	-12.07
SD-6	-7.48E-04	-10.75	-3.98E-04	-3.50E-04	-5.03	-3.98E-04	-4.10E-06	-3.94E-04	-5.66
SD-7	-2.87E-04	-4.13	-8.41E-04	5.54E-04	7.96	-8.41E-04	-5.20E-06	-8.36E-04	-12.02
SD-8	-9.10E-04	-13.08	-7.35E-04	-1.75E-04	-2.51	-7.35E-04	-5.20E-06	-7.30E-04	-10.49
SD-9	-5.65E-04	-8.12	-3.55E-04	-2.10E-04	-3.02	-3.55E-04	-5.20E-06	-3.50E-04	-5.03
SD-10	-9.77E-04	-14.04	-5.25E-04	-4.52E-04	-6.50	-5.25E-04	-5.20E-06	-5.20E-04	-7.47
SD-11	-7.02E-05	-1.01	-3.52E-05	-3.50E-05	-0.50	-3.52E-05	-5.20E-06	-3.00E-05	-0.43
SD-12	-6.50E-04	-9.34	-2.00E-04	-4.50E-04	-6.47	-2.00E-04	-2.00E-07	-2.00E-04	-2.87
SD-13	-3.20E-04	-4.60	-1.80E-04	-1.40E-04	-2.01	-1.80E-04	-5.20E-06	-1.75E-04	-2.51
SD-14	-5.82E-05	-0.84	-6.52E-05	7.00E-06	0.10	-6.52E-05	-5.20E-06	-6.00E-05	-0.86
SD-15	-1.40E-04	-2.01	-1.05E-04	-3.50E-05	-0.50	-1.05E-04	-5.20E-06	-1.00E-04	-1.44
SD-16	-9.02E-05	-1.30	-5.52E-05	-3.50E-05	-0.50	-5.52E-05	-5.20E-06	-5.00E-05	-0.72
SD-17	-4.22E-05	-0.61	-3.52E-05	-7.00E-06	-0.10	-3.52E-05	-5.20E-06	-3.00E-05	-0.43
SD-18	-5.15E-04	-7.40	-3.05E-04	-2.10E-04	-3.02	-3.05E-04	-5.20E-06	-3.00E-04	-4.31
SD-19	-1.06E-03	-15.16	-7.05E-04	-3.50E-04	-5.03	-7.05E-04	-5.20E-06	-7.00E-04	-10.06
SD-BV_1	-1.35E-04	-1.94	-1.00E-04	-3.50E-05	-0.50	-1.00E-04	-2.00E-04	1.00E-04	1.44
SD-BV_1W	2.15E-04	3.09	-1.00E-04	3.15E-04	4.53	-1.00E-04	-2.00E-04	1.00E-04	1.44
SD-BV_1E	-6.90E-04	-9.92	-2.00E-04	-4.90E-04	-7.04	-2.00E-04	-2.00E-04	-1.00E-07	-0.001
SD-BV_2	-1.00E-07	0.00	-6.10E-04	6.10E-04	8.77	-6.10E-04	-4.00E-04	-2.10E-04	-3.02
SD-BV_3	-6.91E-05	-0.99	9.00E-07	-7.00E-05	-1.01	9.00E-07	-1.10E-06	2.00E-06	0.03
SD-BV_4	-3.51E-05	-0.50	1.40E-04	-1.75E-04	-2.51	1.40E-04	-1.10E-06	1.41E-04	2.03
SLS-1	-2.67E-05	-0.38	-2.57E-05	-1.00E-06	-0.01	-2.57E-05	-2.62E-05	5.00E-07	0.01
SLS-2	-2.21E-05	-0.32	-1.71E-05	-5.00E-06	-0.07	-1.71E-05	-2.10E-06	-1.50E-05	-0.22
SLS-3	-6.14E-05	-0.88	-1.14E-05	-5.00E-05	-0.72	-1.14E-05	-4.14E-05	3.00E-05	0.43
SRI-1	-1.76E-04	-2.53	-1.41E-04	-3.50E-05	-0.50	-1.41E-04	-4.14E-05	-1.00E-04	-1.44
SRI-2	-1.75E-04	-2.52	-1.25E-04	-5.00E-05	-0.72	-1.25E-04	-5.20E-06	-1.20E-04	-1.72
SRI-3	-4.65E-04	-6.68	-2.55E-04	-2.10E-04	-3.02	-2.55E-04	-5.20E-06	-2.50E-04	-3.59
SG-1	-1.09E-03	-15.61	-8.86E-04	-2.00E-04	-2.87	-8.86E-04	-1.86E-04	-7.00E-04	-10.06
SG-2	-7.02E-05	-1.01	-3.52E-05	-3.50E-05	-0.50	-3.52E-05	-5.20E-06	-3.00E-05	-0.43
SG-3	-5.38E-04	-7.72	-4.88E-04	-5.00E-05	-0.72	-4.88E-04	-3.48E-04	-1.39E-04	-2.00
MISSR_REDWING	4.97E-05	0.71	4.97E-05	0.00E+00	0.00	4.97E-05	-3.00E-07	5.00E-05	0.72
MISSR_PRESCOTT	4.98E-05	0.72	4.98E-05	0.00E+00	0.00	4.98E-05	-2.00E-07	5.00E-05	0.72
MISSR_SPRING_LAKE	4.98E-05	0.72	4.98E-05	0.00E+00	0.00	4.98E-05	-2.00E-07	5.00E-05	0.72
MISSR_S_STPAUL	5.90E-06	0.08	5.90E-06	0.00E+00	0.00	5.90E-06	-4.10E-06	1.00E-05	0.14
MISSR_ST_PETER-2	5.90E-06	0.08	5.90E-06	0.00E+00	0.00	5.90E-06	-4.10E-06	1.00E-05	0.14
MNR_JCTN	5.90E-06	0.08	5.90E-06	0.00E+00	0.00	5.90E-06	-4.10E-06	1.00E-05	0.14
MNR_BV_1	8.83E-05	1.27	-1.90E-04	2.78E-04	4.00	-1.90E-04	-2.00E-04	1.00E-05	0.14
MNR_SAVAGE	4.80E-06	0.07	4.80E-06	0.00E+00	0.00	4.80E-06	-5.20E-06	1.00E-05	0.14
MNR_BV_2	-4.51E-05	-0.65	-4.95E-04	4.50E-04	6.47	-4.95E-04	-5.00E-04	5.00E-06	0.07
MNR_CHASKA	2.96E-04	4.25	2.96E-04	0.00E+00	0.00	2.96E-04	-4.10E-06	3.00E-04	4.31
MNR_JORDAN	8.98E-05	1.29	8.98E-05	0.00E+00	0.00	8.98E-05	-6.02E-05	1.50E-04	2.16
MNR_BELLEPLAINE	-1.00E-07	0.00	-1.00E-04	1.00E-04	1.44	-1.00E-04	-3.01E-05	-7.00E-05	-1.01

Total system infiltration rates are plotted (inches/year) for each polygon on Figure 15 at both regional and metropolitan area scales. Net leakage rates for each aquifer layer will be presented in a similar fashion later as part of this discussion. The most notable value perhaps is that for polygon, S-LAKES_1, which is 25.8 inches/year. As seen in the Table 2 and Figure 15 below, 20+ inches/year of leakage is distributed to both Layers 2 and 3. Infiltration rates this high could only be justified if the lakes are located in closed watersheds with no surface water outlet or one that is very limited. Indeed the lakes in this area are situated in closed basins. Hence, the 25.8 inches/year infiltration rate used for polygon, S-LAKES_1 is plausible, and currently offered as the technical approach to calibrate to heads in the glacial drift and Prairie du Chien-Jordan aquifers in the area.

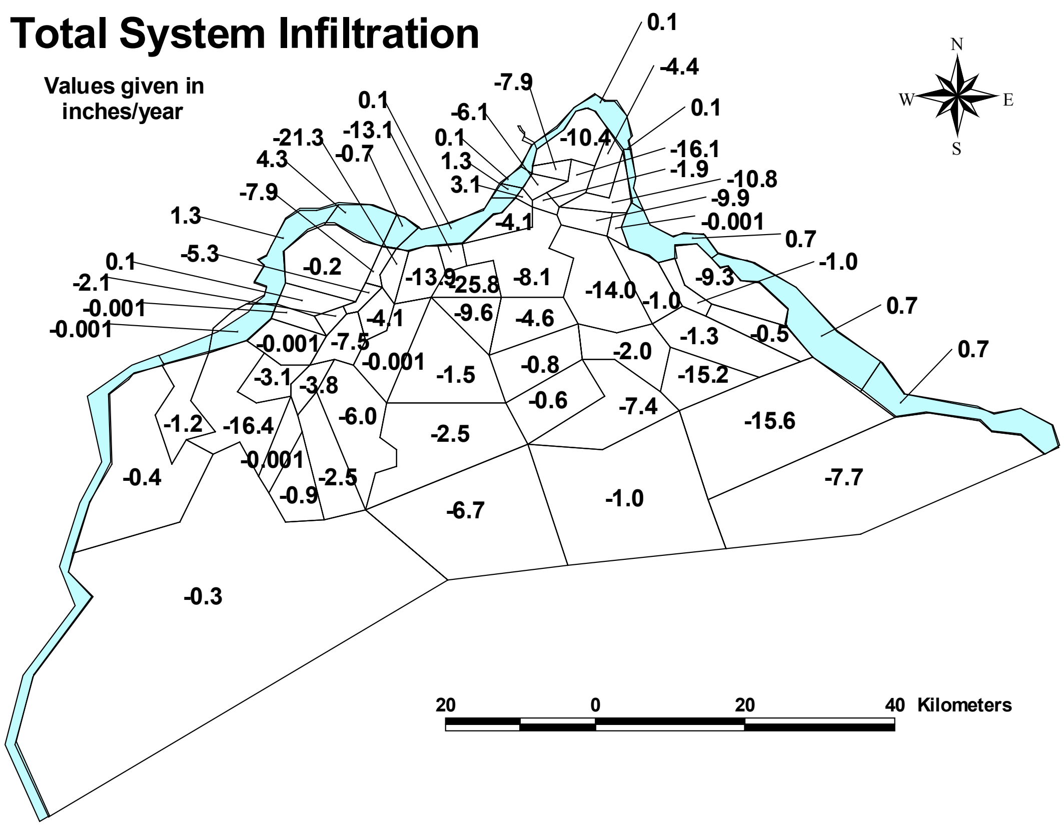

Figure 15 – Total System Infiltration Rates

Polygon SS-2N nearby to S-LAKES_1 has an infiltration rate of 21.3 inches/year. It represents a high sand content area in Layer 2 and the eroded edge of the Prairie du Chien-Jordan adjacent to a buried bedrock valley in Layer 3. 9 inches/year is needed in Layer 2 and 12 inches/year in Layer 3, and maybe indicative of pumping in the area that is not accounted for in the regional model.

Note also that some polygons have positive total infiltration values in Table 2 and Figure 15. As mentioned previously, this indicates an upward leakage following MLAEM's convention of data input. This does not necessarily mean that water is actually exiting at the surface in the real world, but would point to areas where local models should consider pumping as a means of discharge or leakage to lower aquifers must be considered. Excluding S-LAKES_1 and SS-2N, the total system infiltration rates for polygons within the metropolitan area range from less than 1 inch/year to 16.4 inches/year. Values for polygons representing the bedrock valleys and surrounding areas have the greatest variability. The river polygons are the least sensitive, having little affect on adjacent polygons and generally show an upward leakage pattern. Bedrock valleys least affect the central portion of the model and leakage values their range from 0.6 to 7.4 inches/year. Much of this area can be characterized as a glaciated landscape of interrupted drainage in the west, leaving very few surface water drainage features on glacial terrane that transforms to an outwash plain of high sand content overlying near surface bedrock and having more surface water drainage features. Note that areas through which the Vermillion River flows have less total infiltration. Higher infiltration values will need to be re-evaluated as further work is conducted in the area to better understand the water throughput of the system.

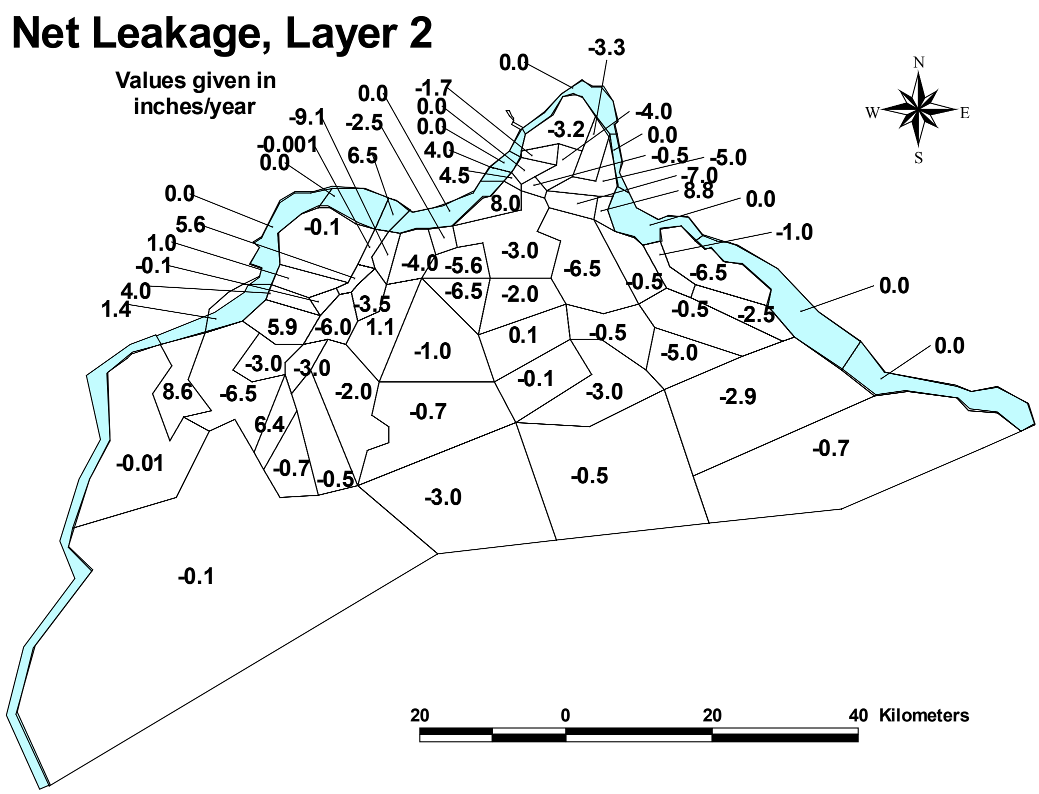

Figure 16 – Net Leakage to Layer 2

The distribution of net leakage to Layer 2 on a polygon-by-polygon basis is presented in Figure 16. Notice that some polygons have higher positive net values than shown in Figure 15. The positive value is a net loss of water from the layer and may represent additional leakage to lower layers. The lower global hydraulic conductivity in Layer 2 requires less overall net leakage and has eliminated the double digit leakage found in the South Province Model Version 1.0.

Net infiltration rates to Layer 3, the Prairie du Chien-Jordan aquifer, are presented in Figure 17. Except for S-LAKES_1 with a value of 20.1 inches/year and SS-2N with a value of 12.2 inches /year as previously discussed, the maximum value is 12.1 inches/year, which occurs in polygon SD-5. Polygon SD-5 represents an area of Prairie du Chien – Jordan aquifer that is not covered by bedrock, while surrounding areas to the west, north, and south have a covering of St. Peter Sandstone. This may concentrate leakage to Layer 3 in an eroded zone.

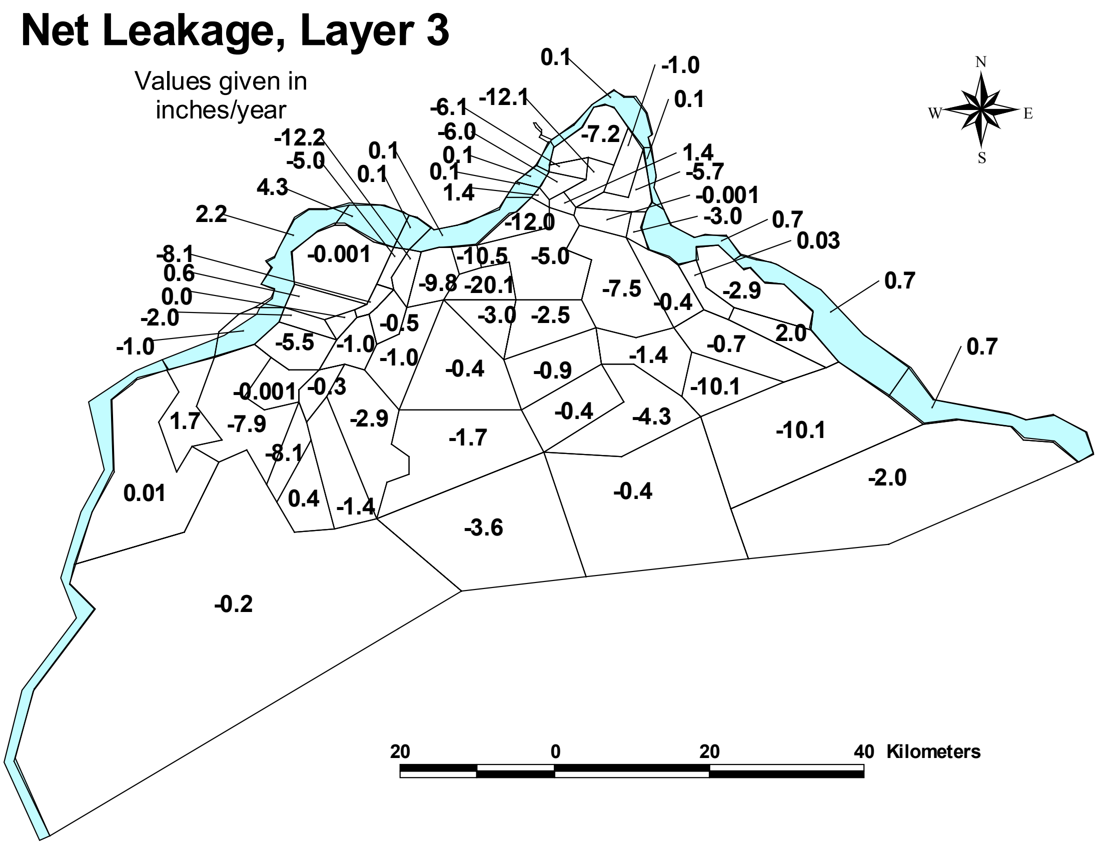

Figure 17 – Net Leakage to Layer 3

Polygon SS-9 is an area of Layer 3 that is void of the Prairie du Chien Group, and contains only a small "island" of Jordan Sandstone. The only calibration target in this area was a single head value, which may not reflect conditions well.

As additional work is conducted on the model and as new information and data are gathered, these infiltration rates will be re-evaluated to determine whether they represent natural conditions. Changes to the conceptual model and to the infiltration values will undoubtedly change, as more information becomes available.

Model Results

Comparison to Measured Heads

This section presents the most current calibration results and modeled head contours of the South Province model of Layers 2 and 3. The descriptive statistics of the mean absolute difference (of computed minus measured heads) are presented in the Table 3. The calibration and head contour plots for Layers 2 and 3 are presented on the pages following the statistics of mean absolute differences.

Table 3
Descriptive Statistics for Mean Absolute Difference Values

	Layer 2	Layer 3
Mean	3.64	3.52
Standard Error	0.11	0.09
Median	2.91	2.94
Mode	0.32	2.38
Standard Deviation	3.00	2.78
Sample Variance	8.97	7.71
Kurtosis	1.84	1.84
Skewness	1.27	1.26
Range	17.90	16.67
Minimum	0.004	0.01
Maximum	17.91	16.68
Sum	2933	3164
Count	805	900
Confidence Level(95.0%)	0.21	0.18

The inclusion of the St. Peter Sandstone in Layer 2 is based on the assumption that there is a continuous potentiometric surface between the sandstone and the overlying Quaternary materials throughout most of the South Province. The exception is in the northern portion of Dakota County, where significant bedrock units separate the St. Peter Sandstone from overlying glacial drift deposits. Inspection of static water levels contained in the County Well Index (CWI) in this area for wells screened separately in the St. Peter Sandstone and Quaternary materials show head differences as high as 60 meters. Thus, it is assumed the static water levels for Quaternary materials in this area reflect a perched condition.

Based on the assumption that these two units are hydraulically connected, and that a continuous potentiometric surface exists between the different geologic materials, a new calibration data set was constructed for Layer 2. This data set contains wells screened in either the St. Peter Sandstone or Quaternary deposits, and includes well unique numbers and information on the aquifer where the well screen is located. The new calibration data set is called **s2_cal1.dat** and is available with the new data input files.

The Quaternary calibration wells are both water table and buried drift wells, and are somewhat clustered along and inside the buried bedrock valleys. It is not certain at this time whether a differentiation should be made between these two types of wells. No clear evidence would indicate that on a regional scale, the water table and buried drift measured heads are different. Local scale models of the buried drift aquifer should consider separating the two types of wells.

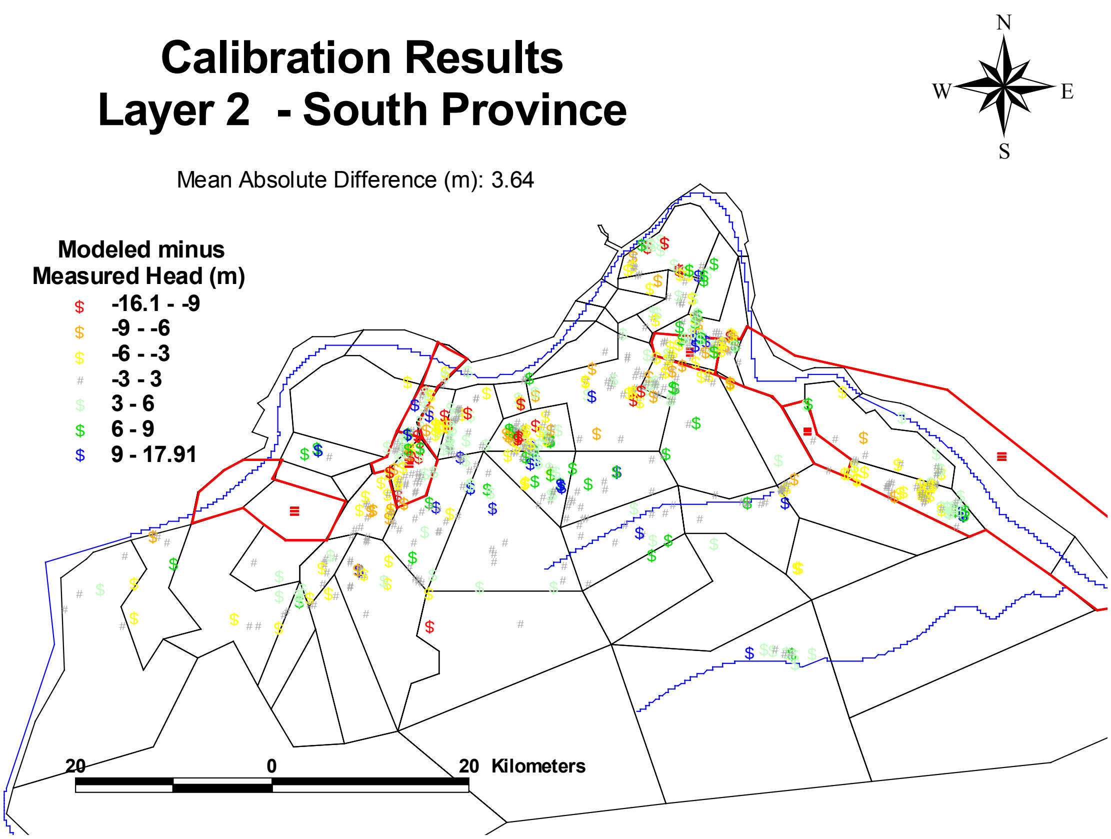

Figure 18 – Layer 2 Calibration Plot

The modeled head contours shown in Figure 19 are presented in English units of feet above Mean Sea Level (MSL). As expected, these contours show that the major discharge zones are the Minnesota and Mississippi River valleys, with lesser discharge to secondary rivers.

Note also, that the zone of highest heads occurs in the south central portion of the model, farthest from the major discharge rivers. This reflects the lower transmissivity of the regional system in this area, which would retain water, creating higher heads than in the surrounding sandier zones.

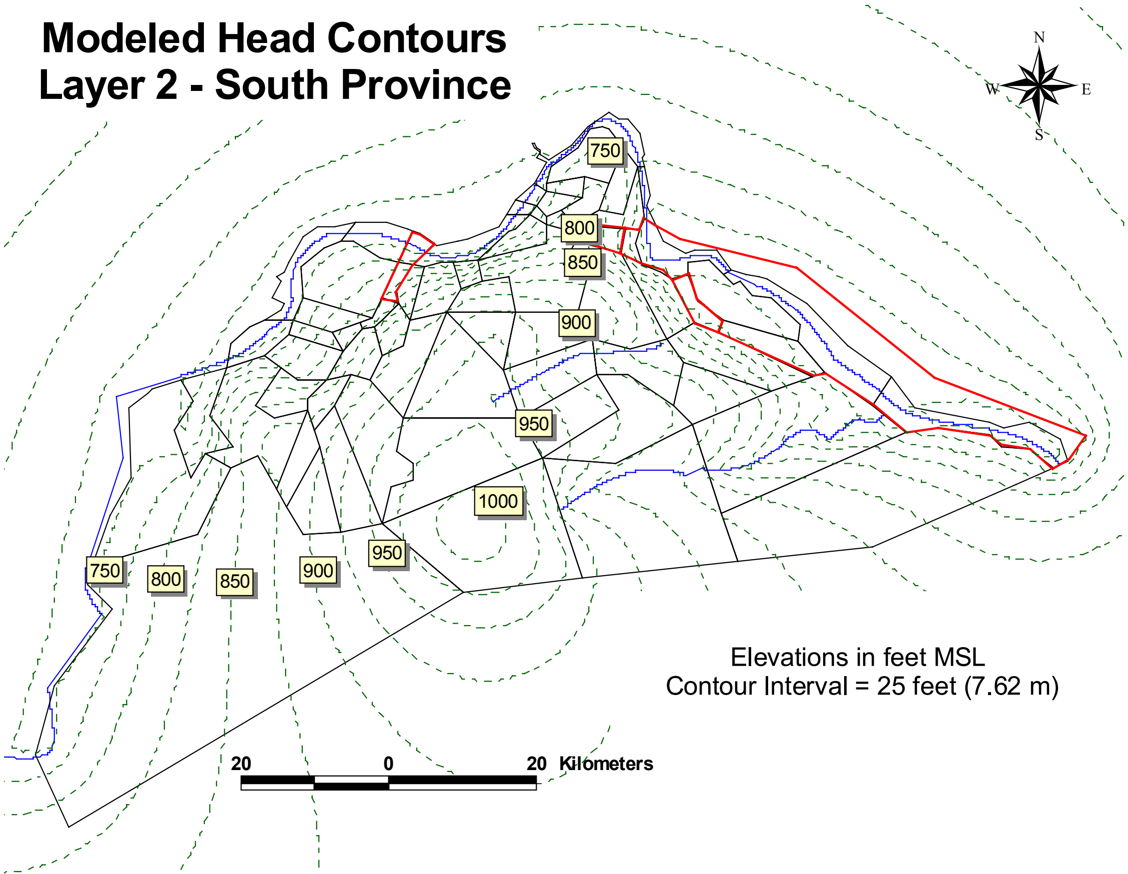

Figure 19 – Layer 2 Piezometric Contours

The latest calibration and modeled head contour plots for Layer 3 are presented in Figures 20 and 21. The mean absolute difference of modeled minus measured heads for Layer 3 was 3.52 m (Table 3). The calibration data points are well distributed over the model except in southwestern Scott County, where the Prairie du Chien – Jordan aquifer is eroded away. Inspection of the calibration plot shows no clusters of modeled heads that are either too high or too low. The targeted ± 3 meters difference between modeled and measured heads is well distributed among wells throughout the province.

The modeled head contours shown in Figure 21 indicate that the major discharge zones for Layer 3 are the Minnesota and Mississippi River valleys, with a zone of highest contours underlying the high head zone in Layer 2. In a saturated system this would be the case, as high heads above would encourage leakage downward.

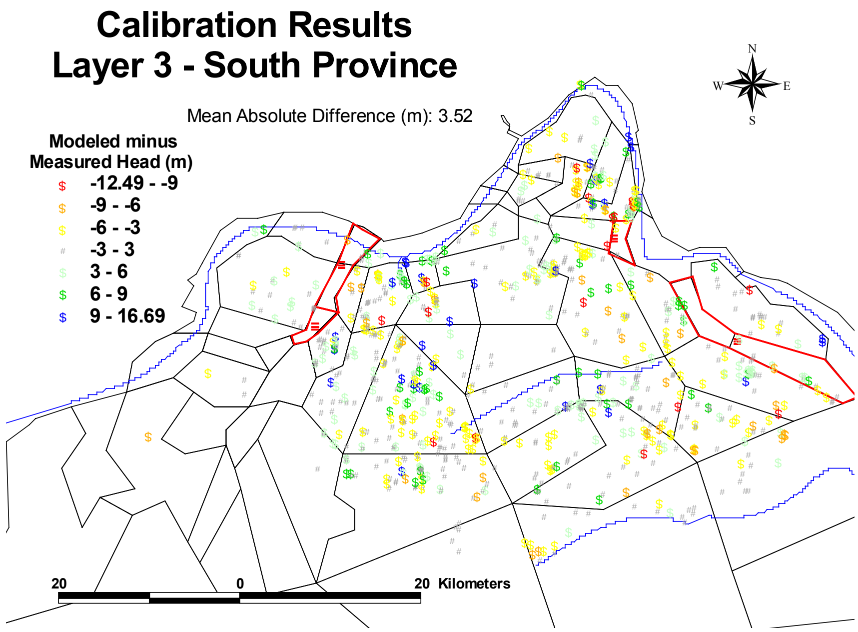

Figure 20 – Layer 3 Calibration Plot

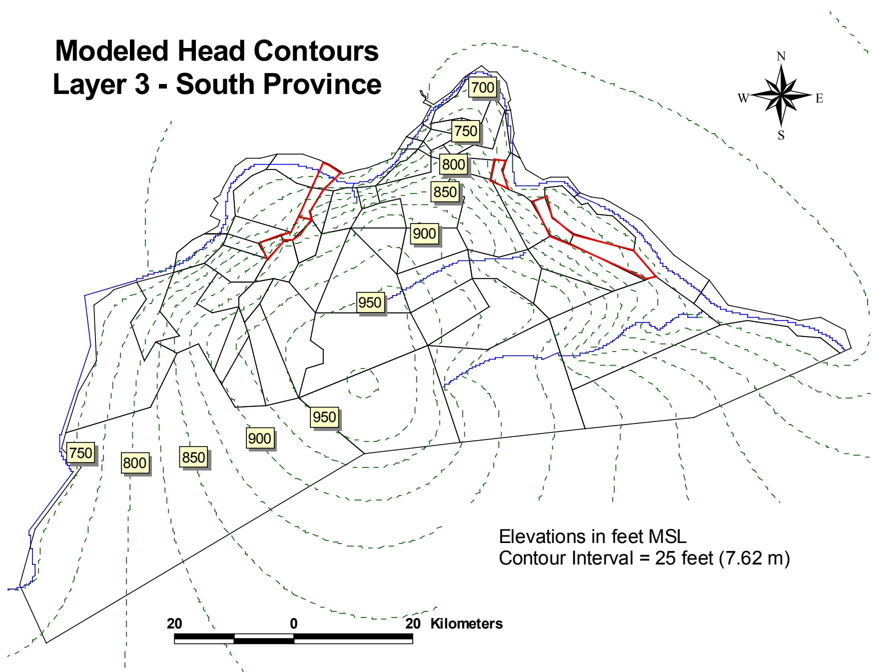

Figure 21 – Layer 3 Piezometric Contours

Comparison to Discharge Estimates

Efforts to fit the model to measured heads are a necessary part of the calibration process, but it does not however, ensure the water balance is correct. In addition to calibration to head values, it is important that the water throughput in the model compares favorably with that of the actual system, where measured. Presently, we do not have much data on aquifer discharge rates to surface water bodies. Further complicating this issue in the South Province is the structural geology constraints on the system, that render simple flat-lying layer-cake stratigraphy models of the aquifer system to be of little use. The geometry of the seepage faces that serve as discharge zones is likely quite complicated, and does not lend itself well to measuring the actual discharge of groundwater. Although more stream discharge data are becoming available, the only information we had to work with at the time of this analysis were discharge data for tributary streams and rivers to the Minnesota and Mississippi Rivers.

Table 4 presents a summary of the analysis of the discharge data for the lower portions of the Credit and Vermillion Rivers, and for the Cannon River. Groundwater discharge estimates for the lower Credit River were made from stream flow measurements made by Metropolitan Council and this agency in February of 1999. Stream flow data for the Vermillion and Cannon Rivers came from the historical flow data records of the United States Geological Survey (USGS) and Metropolitan Council data. Average flow measurements were determined from 7-day monthly minimum values for the month of September in the years 1994 to 1997 for the Vermillion River. The minimum flows for February in the years 1992 to 1997 were used for the Cannon River. Estimates of groundwater discharge per meter of stream length were made from this data and are presented below in Table 4.

Table 4
South Province
Groundwater Discharge Estimates for Tributary Streams to the Minnesota and Mississippi Rivers

Stream Name	Curvilinear String Name	Average Total Discharge (cms)	Average Total Discharge (cmd)	Estimated Stream Length (m)	Discharge per meter Stream Length (cms/m)	Discharge per meter Stream Length (cmd/m)
Credit River	Credit_River	0.085	7315	4470	1.89E-05	1.64
Vermillion River	Vermillion_River	0.724	62540	23880	3.03E-05	2.62
Cannon River	Cannon_River	2.175	187897	32710	6.65E-05	5.74

The modeled discharges are presented in Table 5 for each individual line-sink in both aquifer layers. The computed discharge values for each string is presented in the first two columns. String lengths are in the next column. The next two columns provide the discharge per unit length for each string, and the sum total discharge from both layers is presented in the far-right column. The model discharge results show a good match for the Credit, Cannon, and Vermillion Rivers.

The results for the Credit River indicate that groundwater discharge to this river from Layer 3 provides all of the estimated discharge shown in Table 4. This is acceptable based upon the assumption that this portion of the river is connected to the underlying bedrock aquifer, Layer 3.

The model results for the Cannon River in Table 5 are less than the estimated groundwater discharge in Table 4, which may include too many tributary additions to flow creating a higher estimate than what actually enters the river from the groundwater. It is also possible that too much water is entering the river from the far field in the south. Additional knowledge of the river flow will be required for detailed study in this area.

Table 5
Version 1.01

Modeled Discharge to Curvilinear Linesinks
South Province

Curvilinear String	Modeled Discharge to String (cmd)		Approx. String Length (m)	Discharge per Unit Length (cmd/m)		Total Discharge per Length (cmd/m)
	Layer 2	Layer 3		Layer 2	Layer 3	
MN_RIVER_1	8.82E+04	1.88E+05	56345	1.57	3.34	4.90
MN_RIVER_2	3.23E+04	9.98E+04	46423	0.70	2.15	2.85
MN_RIVER_3	3.79E+04	4.34E+04	52873	0.72	0.82	1.54
MISSR_ST_PAUL	1.50E+04	5.28E+04	18841	0.80	2.80	3.60
MISSR_SPRINGL	8.43E+04	9.66E+04	25123	3.35	3.85	7.20
MISSR_PRESCOTT-1	1.04E+04	1.70E+04	4012	2.59	4.23	6.82
MISSR_PRESCOTT-2	5.81E+04	6.90E+04	23230	2.50	2.97	5.47
MISSR_REDWING	4.44E+04	7.52E+04	27883	1.59	2.70	4.29
VERMILLION_RIVER	2.33E+04	1.61E+04	25387	0.92	0.63	1.55
CANNON_RIVER	1.13E+05	2.48E+05	98166	1.15	2.53	3.68
CREDIT_RIVER	NA	3.59E+03	3197	NA	1.12	1.12

NA: Not Applicable

Head Differences and Resistance

Although the current given-strength approach to modeling leakage on a regional basis allows for water to move vertically through the aquifer system, it does not permit simulation of the interactions that occur between aquifers. For example, the effects of pumping in one aquifer will not induce greater leakage from another aquifer with this approach. This type of simulation can be achieved by replacing given-strength VARELS with leaky VARELS. In a real system, flow between aquifers is driven by the head difference between them. However, the given-strength approach does not constrain the model in such a way that groundwater necessarily flows from higher head to lower head between aquifers.

Leakage between aquifers in this version of the South Province is generally downward, but there are instances where upward leakage is prescribed. For the most part upward leakage occurs in the river polygons, but is not restricted to them. The presence in this province of large buried bedrock valleys and areas with shallow drift coverage over bedrock has lead to specifying upward leakage values in some of these zones. Figure 22 shows the location of upward leakage in the polygon mesh between Layers 2 and 3. As shown in Table 2, upward (positive) leakage occurs also at the top of Layer 2. This does not necessarily mean that water is being released to the surface in these polygons. It is possible the water is lost through pumping that is not accounted for in this model.

Plotting the head difference between layers at specific grid points allows one to check on consistency between the sign of the head difference and the specified leakage direction. Zones where the model head difference and leakage direction are not congruent are indicators of possible problem areas within the model. Evaluation of the head differences provides a good internal check for the model.

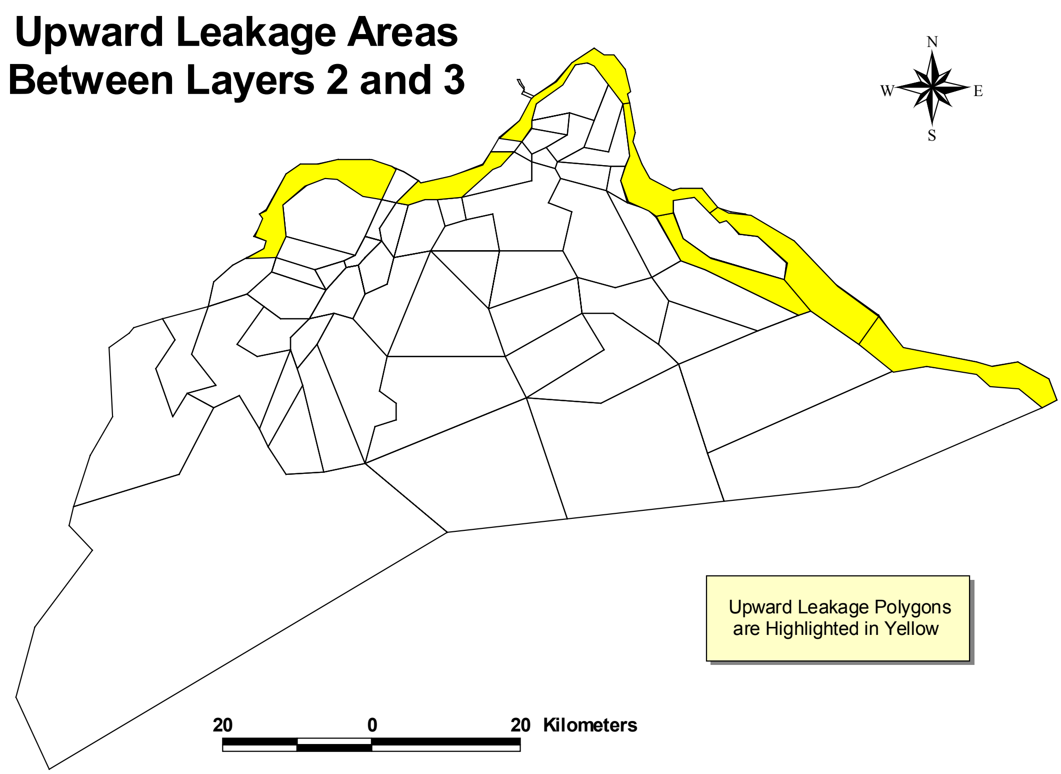

Figure 22 – Upward Leakage Areas Between Layers 2 and 3

A grid has been constructed at a density that readily allows depiction of the head differences, which is plotted in Figure 23 using a color scheme that was chosen to indicate positive (downward) differences in head between aquifer layers (greater than 3 m), and negative (upward) differences in head (less than –3 m). Head differences implying downward leakage are represented by the pale green to dark blue color scheme, and head differences that would imply upward leakage are represented by the yellow to red color scheme. Increasing color intensity indicates increasing magnitude in the head differences. The gray color represents zones of relatively small head difference (+/-3 m). Zones represented by gray are not considered to be problematic, because the model does not generally represent an accuracy level much better than +/-3 m on a regional scale. Additionally, modifications made to the model for site-specific applications can be used to better match field conditions than is possible on a regional basis.

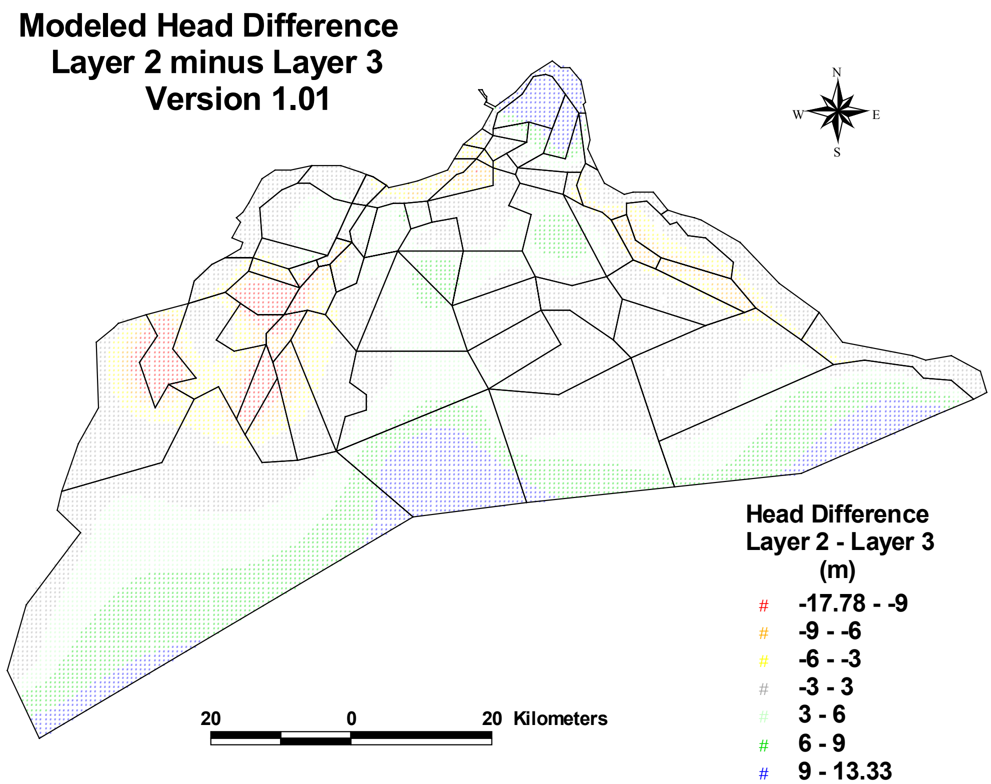

Figure 23 – Modeled Head Difference Layer 2 minus Layer 3

Head differences shown in Figure 23 would be expected to fall in the yellow to red zone in areas coinciding with the yellow polygons presented in Figure 22, and in the green to blue or gray ranges elsewhere. This may be seen in the model along its eastern boundary in the Mississippi River valley. The northern portion of the Mississippi River valley and the lower Minnesota River valley have head differences that are inconsistent with the leakage direction. This area has few or no calibration wells in Layer 2, which makes it difficult to determine whether a correct head is being modeled in that layer. The same may be said in the area of polygon SS-1 in northwestern Scott County, where calibration data for Layer 2 is nonexistent.

The yellow to red zone in southwestern Scott County is in an area where the Prairie du Chien–Jordan aquifer is missing, so the data do not really indicate a head difference between the glacial drift aquifer and the Prairie du Chien–Jordan aquifer. The structural geology of this area and the elevation changes occurring in the lower aquifers (Franconia-Ironton-Galesville and Mt. Simon-Hinckley) must also be considered.

This is also true when the hydraulic resistance between Layers 2 and 3 is plotted as shown in Figure 24. Resistance in this case refers to the resistance to vertical flow between aquifers and is calculated by dividing the modeled head differences shown in Figure 23 by the given leakage rates. Resistance values in this figure might be useful for providing starting values of resistance for localized model applications, but discretion should be exercised in using them. Note that the gray shades represent areas where a negative resistance was calculated, because the modeled head difference between Layers 2 and 3 was a negative value indicating a vertical upward gradient. The regional nature of the model does not permit the accurate modeling of heads on a local basis. Hence, the vertical upward gradients could be indicated where the differences in head are less than the error of the model. Additionally, hydrogeologic complexity not included in the model would further decrease the reliability of the resistance estimates.

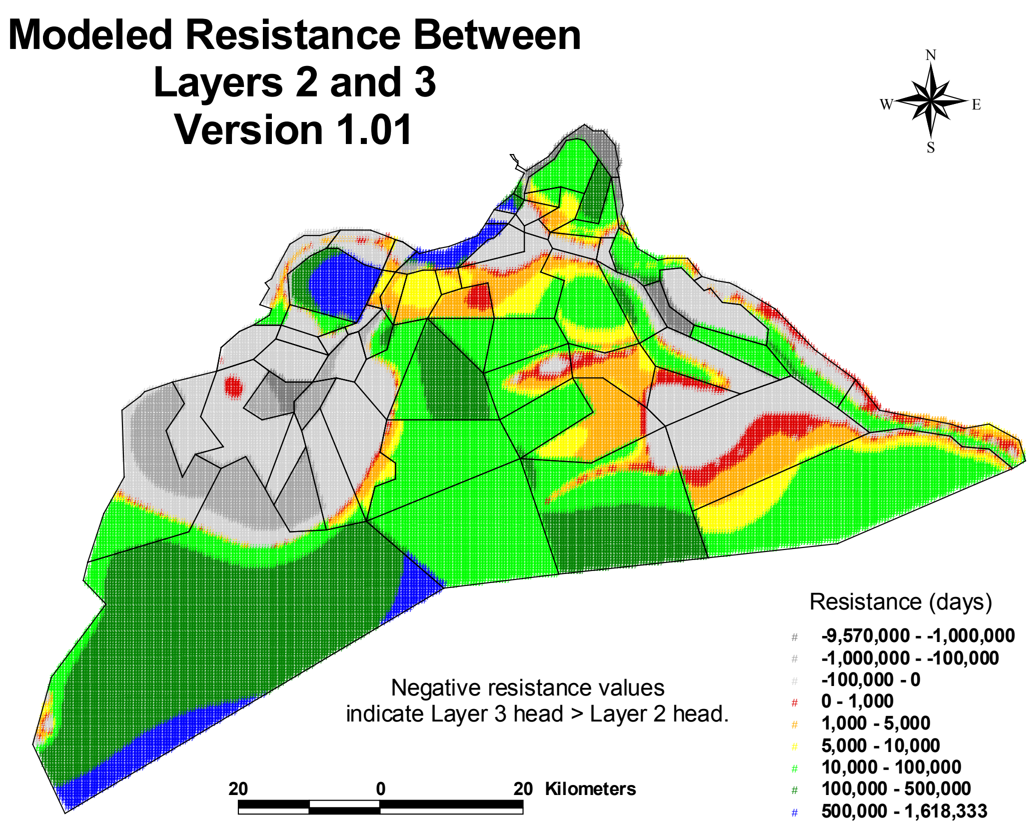

Figure 24 – Modeled Resistance Between Layers 2 and 3

Figures 23 and 24 serve as internal checks on the consistency of the South Province model, and help indicate potential problem areas. As additional data and resources become available, the model can be improved to help reduce the uncertainty and resolve internal inconsistencies. The results of this analysis should be used in site-specific modeling so that leakage and modeled head differences are consistent with each other.

Data Files, Version 1.01

A brief description of the data files that comprise the South Province model for Layers 2 and 3 is presented below. A list of other relevant supporting files such as high capacity pumping wells and regional head calibration datasets is found after the model datasets. All of these files can be downloaded from the Metro Model web page.

General Model Datasets:

s_setup1.dat	Commands to MLAEM software, and specification of graphical window.
s_aq1.dat	Global aquifer parameters for Layers 2 and 3.
s_poly1.dat	Polygon mesh for South Province, including both infiltration and inhomogeneity polygons.
s_msr_cu1.dat	Curvilinear strings for Mississippi River and associated seepage faces.
s_mnr_cu1.dat	Curvilinear strings for Minnesota River and associated seepage faces.
s_msc_cu1.dat	Curvilinear strings for Credit, Vermillion, and Cannon Rivers.

Quaternary/St. Peter Aquifer—Layer 2 Datasets

s2_ntop1.dat	Infiltration rates for polygons on top of Layer 2; can be considered the total infiltration for the two-layer aquifer system.
s2_msr1.dat	Boundary conditions (elevation heads) for relevant portions of Mississippi River.
s2_mnr1.dat	Boundary conditions (elevation heads) for Minnesota River and associated seepage faces.
s2_msc1.dat	Boundary conditions (elevation heads) for Vermillion and Cannon Rivers.
s2_inh1.dat	Hydraulic parameters and doublets for the Layer 2 inhomogeneities.
s2_nbot1.dat	Leakage out of bottom of Layer 2 specified for each polygon—same as leakage into the top of Layer 3.

Prairie du Chien-Jordan Aquifer—Layer 3 Datasets

s3_ntop1.dat	Leakage into top of Layer 3 specified for each polygon—same as leakage out of the bottom of Layer 2.
s3_msr1.dat	Boundary conditions (elevation heads) for relevant portions of the Mississippi River and associated seepage faces.
s3_mnr1.dat	Boundary conditions (elevation heads) for Minnesota River and associated seepage faces.
s3_msc1.dat	Boundary conditions (elevation heads) for Credit, Vermillion, and Cannon Rivers.
s3_inh1.dat	Hydraulic parameters and doublets for the Layer 3 inhomogeneities.
s3_nbot1.dat	Leakage out of bottom of Layer 3 specified for each polygon.

Call File for South Province Layers 2 and 3 Model

calls1.dat	Version 1.01 call file dataset for the South Province Layers 2 and 3; calls the model datasets described above.

The files described above are all that are needed to run the South Province model of Layers 2 and 3. However, some additional files presented below may be of use in the modeling process. High capacity well discharge data and head calibration datasets are discussed separately below.

High Capacity Well Discharge

Datasets with high-capacity discharge data were constructed from the DNR's groundwater appropriations database known as the State Water Use Data System (SWUDS) for the 1998-pumping year. Datasets for other years can be constructed on request. These datasets are to be entered separately. Version 1.01 of the model already includes these discharges intrinsically in the infiltration rates on a regional basis. The files are split up according to model layer:

s2_qswud1.dat	High capacity pumping well discharge in the Glacial Drift/St. Peter Sandstone Aquifer taken from the 1998 SWUDS database; for use in Layer 2.
s3_qswud1.dat	High capacity pumping well discharge in the Prairie du Chien-Jordan Aquifer taken from the 1998 SWUDS database; for use in Layer 3.

Regional Calibration Datasets

Calibration datasets that were constructed to calibrate the model on a regional basis are included below. As described in the Overview of the Twin Cities Metropolitan Groundwater Model, these data were geostatistically winnowed from the CWI database to provide head calibration targets over a very large area. As such, these data can only be appropriately applied to regional model development and calibration. Site-specific data are necessary for calibrating the locally refined model. The datasets are separated according to model layer:

s2_cal1.dat	Head calibration dataset for Layer 2, developed from measured static water levels in the Glacial Drift/St. Peter Sandstone Aquifer.
s3_cal1.dat	Head calibration dataset for Layer 3, developed from measured static water levels in the Prairie du Chien-Jordan Aquifer.

Application and Use of the Metro Model

The South Province portion of the Metro Model for Layers 2 and 3 has been presented as a starting point for constructing models on a more local scale. A regional system has been developed that will require modification to local scale models for two reasons. First, on a regional basis, the model will not provide a correct coarse representation of the flow system in all areas. Use of all available data on a more local basis will help lead to a better representation. Second, local detail will need to be incorporated to properly simulate local groundwater flow conditions.

Model elements themselves will require modification and/or replacement for more site-specific modeling. For example, order and overspecification values will likely need to be increased on both curvilinear elements and doublets in the area of interest to provide sufficient control to model the groundwater system. Also, multi-aquifer systems will require replacement of given-strength areal elements with leaky elements, which can actually propagate hydraulic interactions between aquifers. Additionally, control point placement is critical to properly simulate leakage effects between aquifers. Metro Model staff can provide guidance for applications of the model.

Changes and improvements are expected to the model. They will be periodically posted on this web site. To ensure that you are using the latest version of the Metro Model, be sure to frequently check it. The version currently posted is 1.01. The version number for future releases will be incrementally increased and will readily allow users to determine if they are using the most current version available.