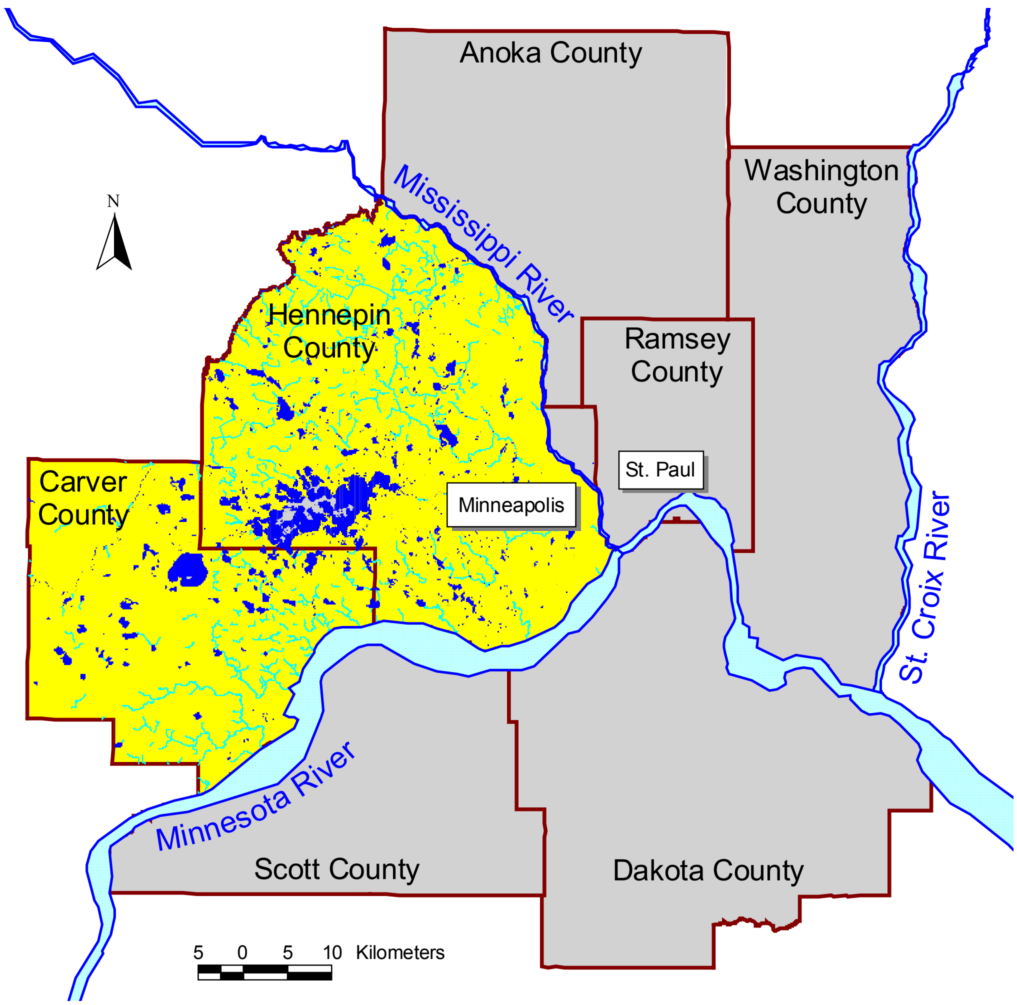
Metropolitan Area Groundwater Model
Project Summary

Northwest Province, Layers 1, 2, and 3 Model

Version 1.00, July 2000

John K. Seaberg and Douglas D. Hansen



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).

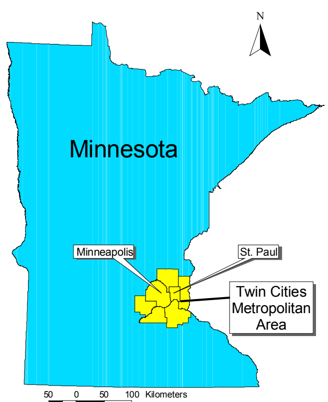


Figure 1. Metro Model Index Map

One of the models is for Layers 4 (Franconia-Ironton-Galesville Aquifer), and 5 (Mt. Simon-Hinckley Aquifer), and encompasses the entire metro area. The remaining models are for Layers 1 (Glacial Drift Aquifer), 2 (St. Peter Sandstone Aquifer), and 3 (Prairie du Chien-Jordan Aquifer). The metro area has been divided into three hydrologic provinces for these upper aquifer layers, 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 layers.

This report presents a summary of development and construction for the Northwest Province steady-state model of the upper three layers. The model area of interest includes an area comprised mainly of Hennepin and Carver Counties.

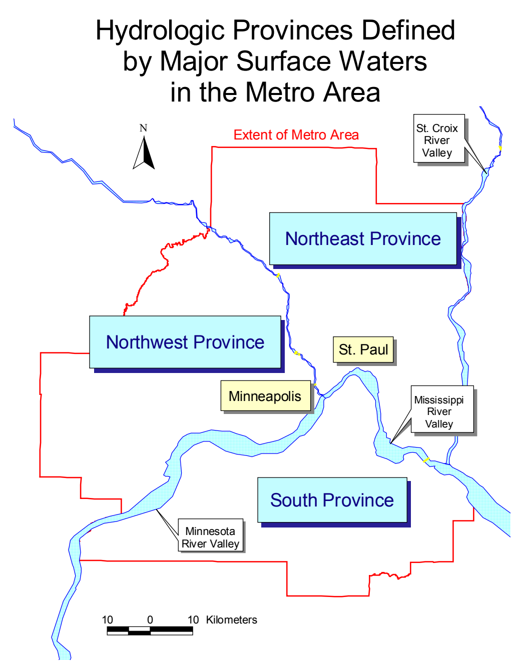


Figure 2. Hydrologic Provinces

This summary has been prepared to provide the user with the basic information required to understand and use the Northwest Province Model. A full documentation log, comprised of earlier hand-written logbooks and more recent work in electronic format (over 30 pages) chronicling the construction and development of this module of the Metro Model, may be inspected 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 (Seaberg. 2000), 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 Northwest Province. Refer to that document for more complete descriptions of the conceptual model and its implementation in MLAEM.

The development and construction of the Northwest Province are presented in this document, starting with a summary of the upper hydrostratigraphic units, along with global parameters used in the model. This is followed by a discussion regarding the construction of the polygon mesh used to simulate infiltration and leakage, and how it is tied in to the hydrogeology. The construction phase of the model is completed with a presentation of how surface waters and aquifer inhomogeneities are represented in the model. 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 Northwest Province model contains the three uppermost aquifer layers. Leaky layers representing aquitards separate these aquifer layers. For reasons that will be discussed later, the regional model does not simulate leaky flow as an output parameter 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 (Seaberg, 2000).

Layer 1. This layer represents a buried aquifer comprised of unconsolidated glacial materials 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 220 meters (m) above mean sea level (MSL), and thickness to 40 m. The global hydraulic conductivity value is 21 m/day and the porosity is 0.30.

Leaky Layer 1. 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.

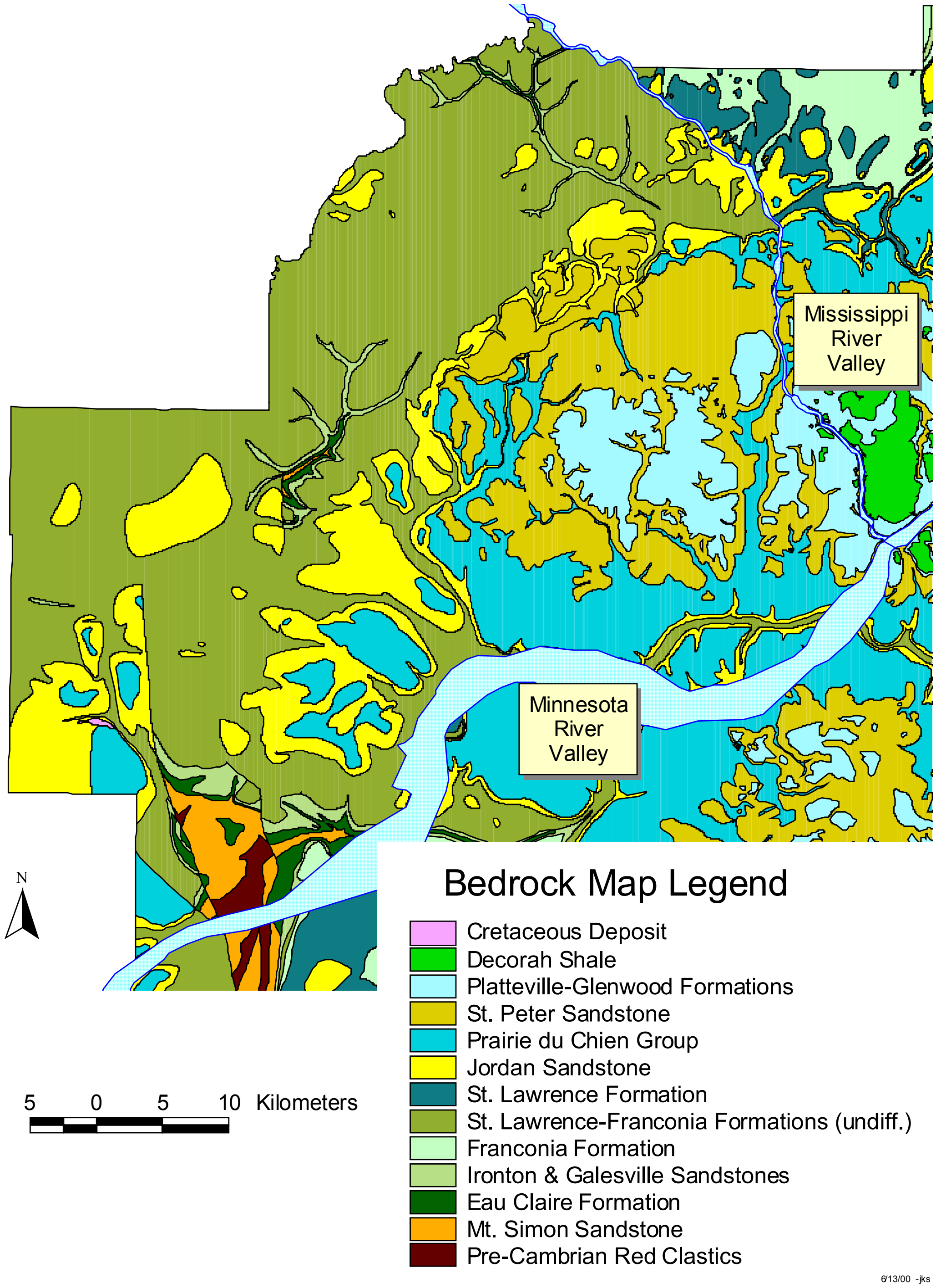
Layer 2. The St. Peter Sandstone, represented by Layer 2 in the Metro Model, occurs discontinuously in the Northwest Province, owing to post-depositional erosion as illustrated in Figure 3 below. It occurs as the first bedrock in some areas, but is overlain by the Platteville and Glenwood Formations in others, portions of which are sparsely overlain by the Decorah Shale only in the far eastern portion of the Northwest Province. Recharge rates to this aquifer are influenced by, among other things, the hydraulic properties of the overlying units, which can range from very permeable glacial outwash materials to the tight shale and limestone formations. Layer 2 has been assigned a global hydraulic conductivity value of 3.3 m/day, a porosity of 0.30, with a base elevation of 190 m MSL and a thickness of 29 m.

Leaky Layer 2. This leaky layer represents the base of the St. Peter Sandstone, which may provide significant vertical hydraulic resistance.

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 (both shown in Figure 3). 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 we are assuming represents an impermeable base for the model of Layers 1, 2, and 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.

Table 1
Global Aquifer Parameters, Northwest Province Layers 1, 2, and 3
Version 1.00

Model Layer	Aquifer	Base Elevation (m MSL)	Thickness (m)	Hydraulic Conductivity (m/day)	Porosity
Layer 1	Glacial Drift	220	40	21	0.30
Layer 2	St. Peter Sandstone	190	29	3.3	0.30
Layer 3	Prairie du Chien-Jordan Aquifer	120	60	12	0.09



After Mossler and Tipping (2000)

Figure 3. Bedrock Geology, Northwest Province

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 three layers in the Northwest Province occurs throughout the interior, originating from infiltration into the glacial drift aquifer. As described in Seaberg (2000), the infiltrated water is generally apportioned to the underlying aquifer units proportional to their transmissivities. This ratio method was applied to initial attempts at modeling the layered system and the automated calibration procedures that followed. However, because we cannot account for all existing heterogeneity, this method cannot be expected to produce a well-calibrated model in all areas when it is based on the assumption of homogeneous media. 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 1 and 2 occurs via 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. Water is assumed to discharge from Layer 3 to the Mississippi and Minnesota River valleys, which serve as major discharge zones for all three aquifer layers. Additionally, there is a net loss of groundwater owing to extraction from pumping wells.

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 (eg. of a lake bed) 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 Northwest 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. Therefore, the polygon mesh that is used to represent various leakage rates must be used to represent all the separating layers between aquifers. A cookie-cutter approach is used to propagate the mesh throughout all the aquifer separating layers.

Geologic complexity in the Northwest Province poses challenges in developing a polygon mesh, and requires interpretive license to develop a relatively simple regional mesh out of a highly heterogeneous system. The final polygon mesh for the Northwest Province is shown on the following pages overlying the various Geographic Information System (GIS) geologic coverages used in its construction. Discussion is minimal since it is more useful to examine the mesh in context of the hydrogeology.

Figure 4 shows the major surface waters of the Northwest Province and includes the final polygon mesh. The Crow, Mississippi, and Minnesota Rivers form the major hydraulic boundaries for the model. Other major surface waters, include Lakes Waconia and Minnetonka.

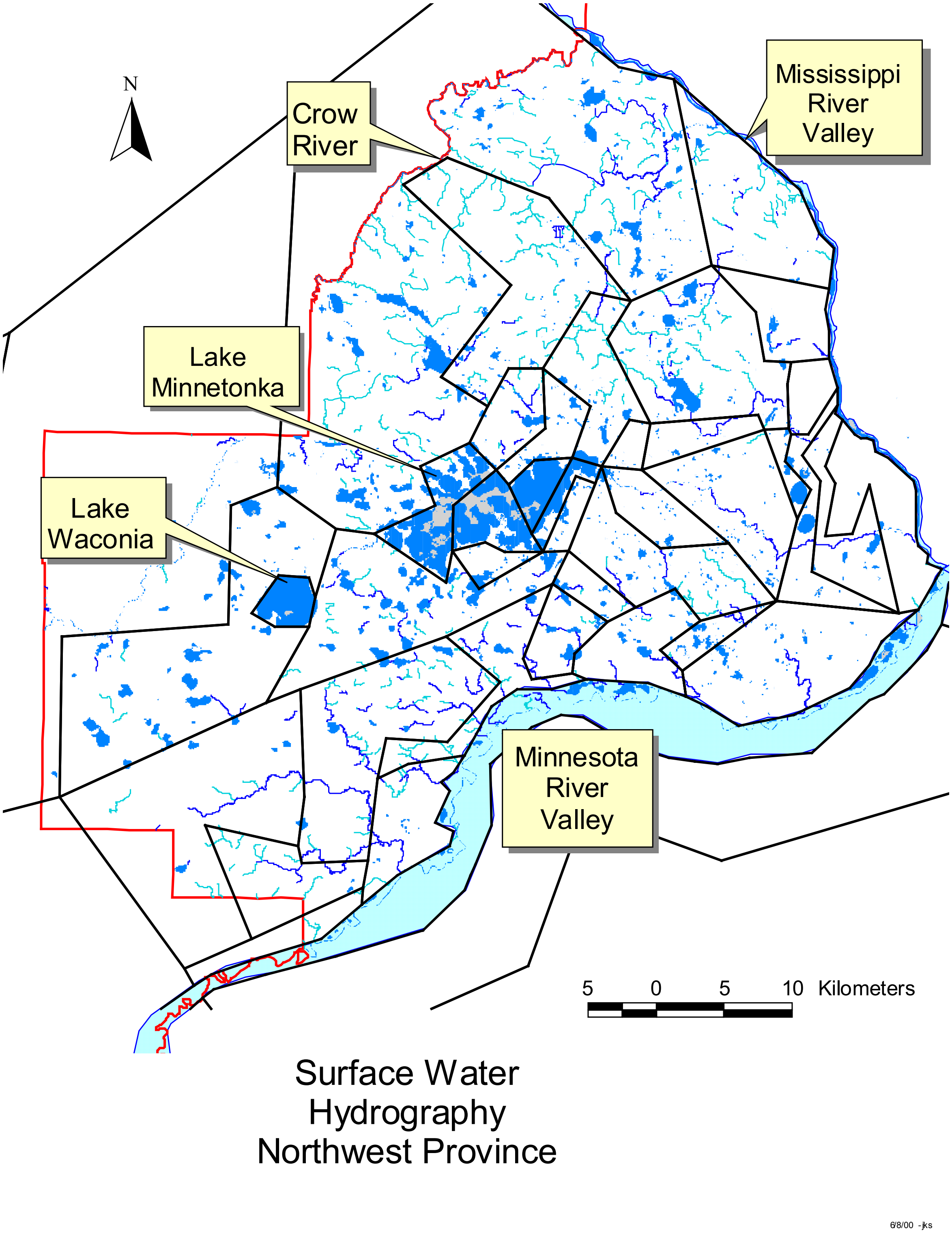
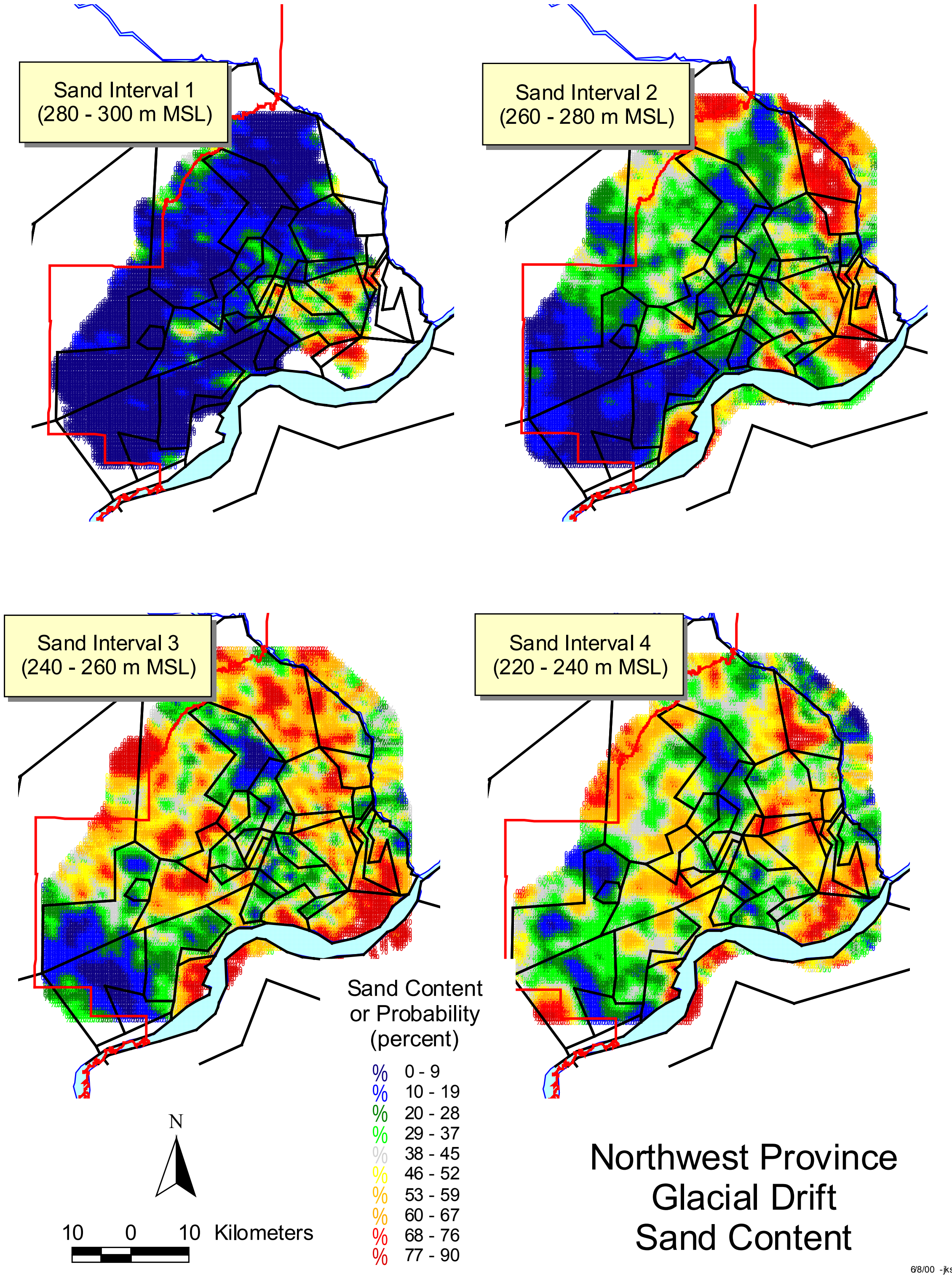


Figure 4. Northwest Province Surface Waters and Polygon Layout



After Streitz (2000)

Figure 5. Northwest Province Sand Content of Glacial Drift Intervals 1, 2, 3, and 4

Metro Model staff 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 report titled "Preparation of Supporting Databases for the Metropolitan Area Groundwater Model" (Streitz, 2000). 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 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, but many were constructed to represent major regional differences in the sand content of glacial materials, either surficial or buried. Note that, although polygon sides generally depict major changes in drift composition, 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.

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.

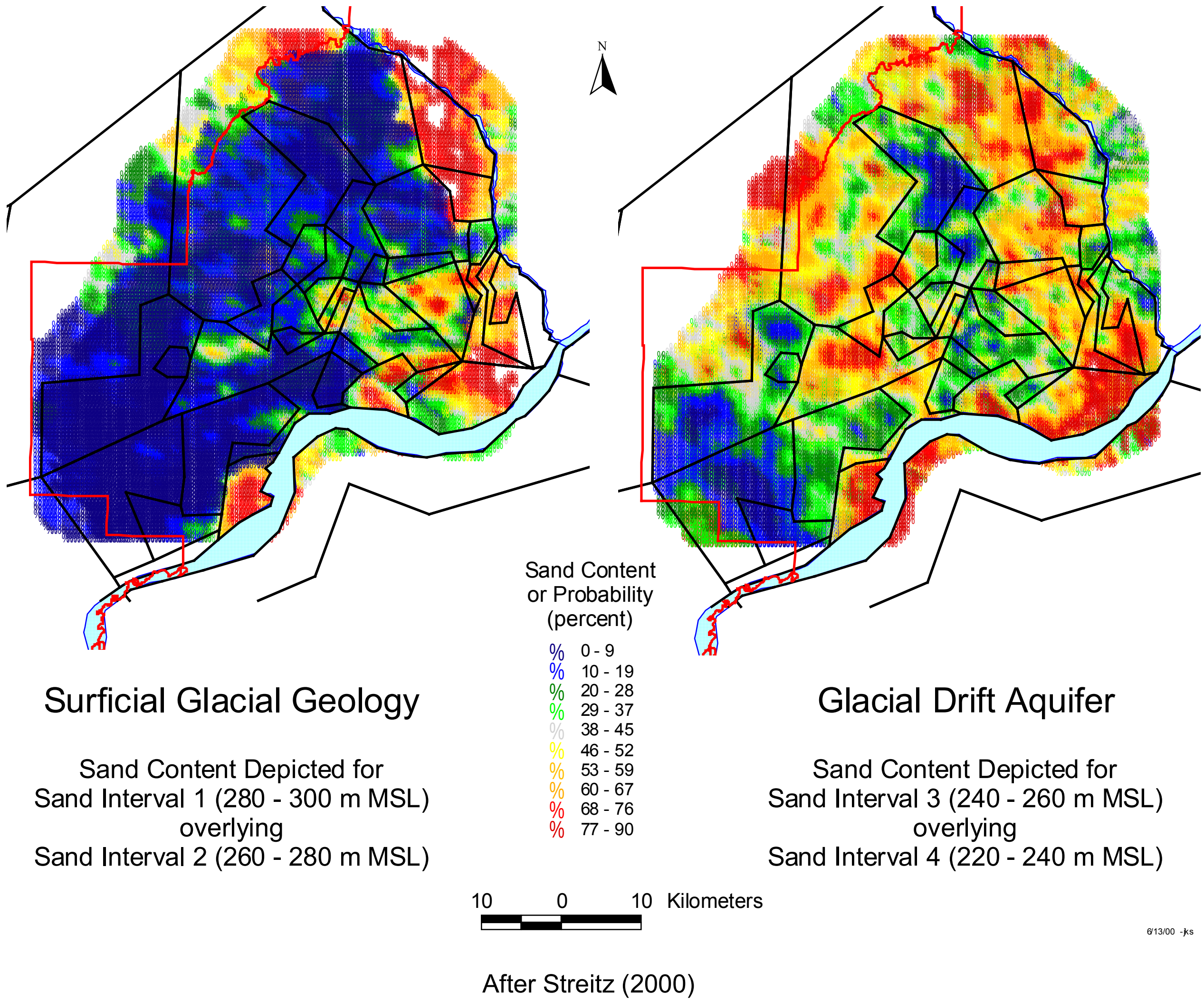
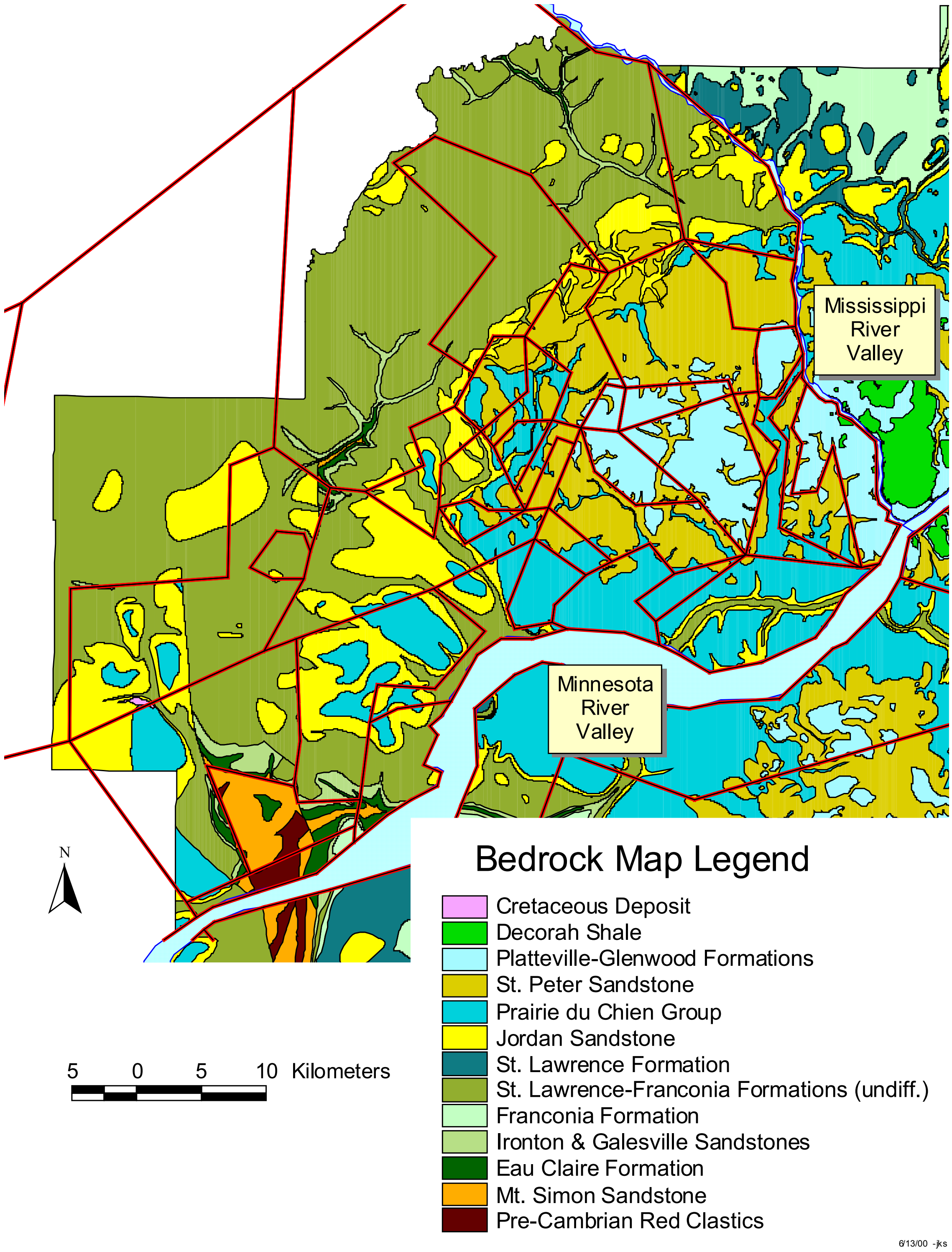


Figure 6. Sand Content Composite Coverages of Surficial Drift Materials and Glacial Drift Aquifer

The polygon mesh overlies the bedrock geology coverage in Figure 7. Note that major regional changes in lithology are reflected in the placement of the coarse polygon boundaries.



Geology after Mossler and Tipping (2000)

Figure 7. Northwest Province Bedrock Geology and Polygon Layout

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. Two 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 large surface water bodies, or that represent far-field conditions.

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 Northwest Province model, the designation used in these files is almost exclusively indicative of the Northwest Province. The letter prefixes are assigned as follows:

- E — Northeast Province
- S — Southern Province
- W — Northwest Province

field 2 — Is generally represented by the first letter of the county name in which the polygon predominantly lies. 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

Designations for Carver and Hennepin Counties predominate in the Northwest Province. A judgment call was made to assign the letter to polygons that straddle county boundaries.

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 large surface water bodies and buried bedrock valleys, and those that represent far-field conditions. These are covered in the following paragraphs:

Surface Water Bodies: The first letter prefix designates the hydrologic province where the surface water body is found—in this case that is a "W" for the Northwest Province. The name of the water body is then indicated in the remainder of the polygon name. A list of the polygons defined by and named after surface water bodies in the Northwest Province follows:

W-L_Waconia	Lake Waconia
W-L_Minnetonka-1	Lake Minnetonka—western portion
W-L_Minnetonka-2	Lake Minnetonka—central portion
W-L_Minnetonka-3	Lake Minnetonka—east-central portion
W-L_Minnetonka-4	Lake Minnetonka—eastern portion

Far-Field Features: Polygons falling within the Northwest Province hydrologic boundaries follow the general naming convention described for standard infiltration and leakage polygons described above.

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

Where:	field 1	Designates the hydrologic province—"W" is used here to indicate it belongs to a Northwest Province model.
	field 2	Is "FF", indicating "far-field".
	number	Is the sequential number assigned to each of these polygons.

The geometry of these polygons is determined in part by the areal extent of lower hydrostratigraphic units, which will help facilitate linking the upper layers with the lower layers, should the need arise.

The polygon mesh with labels is presented in Figures 8 and 9 below. Figure 8 emphasizes the regional layout, and Figure 9 focuses on the seven-county metropolitan area.

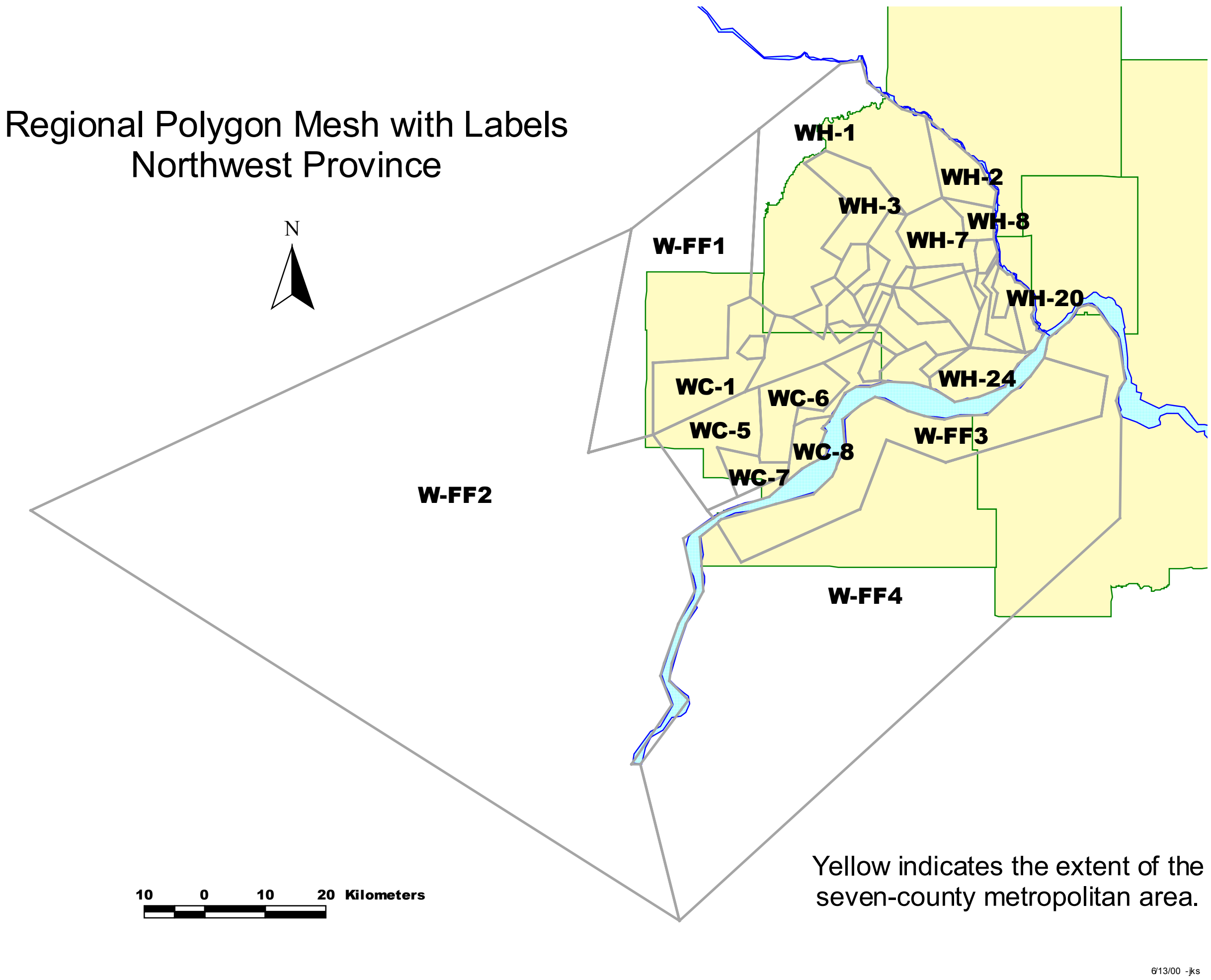


Figure 8. Regional Polygon Mesh with Labels

Figure 9. Polygon Mesh with Labels, Metro Area

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 subsection labeled **Modeling of Leakage** under **Model Adjustment and Calibration**.

Curvilinear Line-Sink Construction

Head-specified curvilinear line-sinks were used to represent hydrologic boundaries in all three layers. 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.

Figures 10 and 11 illustrate the placement of the curvilinear line-sinks in the Northwest Province. The curvilinear line-sinks are used to represent rivers that constitute the most significant regional features in the model. Because the same rivers are used as regional boundary features in Layers 1, 2, and 3, and are represented by curvilinear line-sinks, Figures 10 and 11 apply to all three layers. Figure 10 shows the far-field regional layout of the curvilinear line-sinks as well as the hydrography within the metropolitan area. The Minnesota River constitutes the most prominent far-field feature in the model, represented by string **Upper_Minnesota_R** and serves to constrain flow southwest of the metropolitan area without much additional computational burden. 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 11 illustrates the curvilinear line-sinks used in the metropolitan area. Note that the Crow River is represented using one curvilinear string, while the Mississippi and Minnesota Rivers are broken into multiple strings. Curvilinear strings **W_MissR_St_Peter-1** and **W_MissR_St_Peter-2** correspond to erosional exposures of the St. Peter Sandstone near the rivers. String **MinnR_Coarse_South** was placed along the south wall of the Minnesota River valley to intercept water from the south to permit separation of discharge from the north for comparison to measured data for groundwater discharge to the Minnesota River valley from the Northwest Province.

Some of the line-sinks represent surface waters, while others represent seepage faces of the aquifer that may daylight near the river valley. An example of this would be Layer 1 curvilinear line-sinks that represent discharge to the Mississippi and Minnesota River valleys. Starting at St. Anthony Falls, these curvilinear elements follow the bluff line down to Fort Snelling and around to the west up the Minnesota River valley. The glacial drift, sitting on top of the bedrock formations, is generally not in direct hydraulic connection with the Mississippi or Minnesota Rivers. Head values assigned to these line-sinks represent seepage faces, and were first assigned to correspond to the topographic elevations of the bluff line. They were then manually adjusted to provide the best fit to head calibration targets. The distance between the seepage face and the river may be greater than that represented by the line-sinks, which follow the valley edges, especially for those formations that do not extend all the way to the valley edge. However, we chose to use consistent curvilinear string geometries throughout all three layers to keep the regional simulation as simple as possible. Site-specific applications might require modification of the seepage face geometry to better reflect natural conditions.

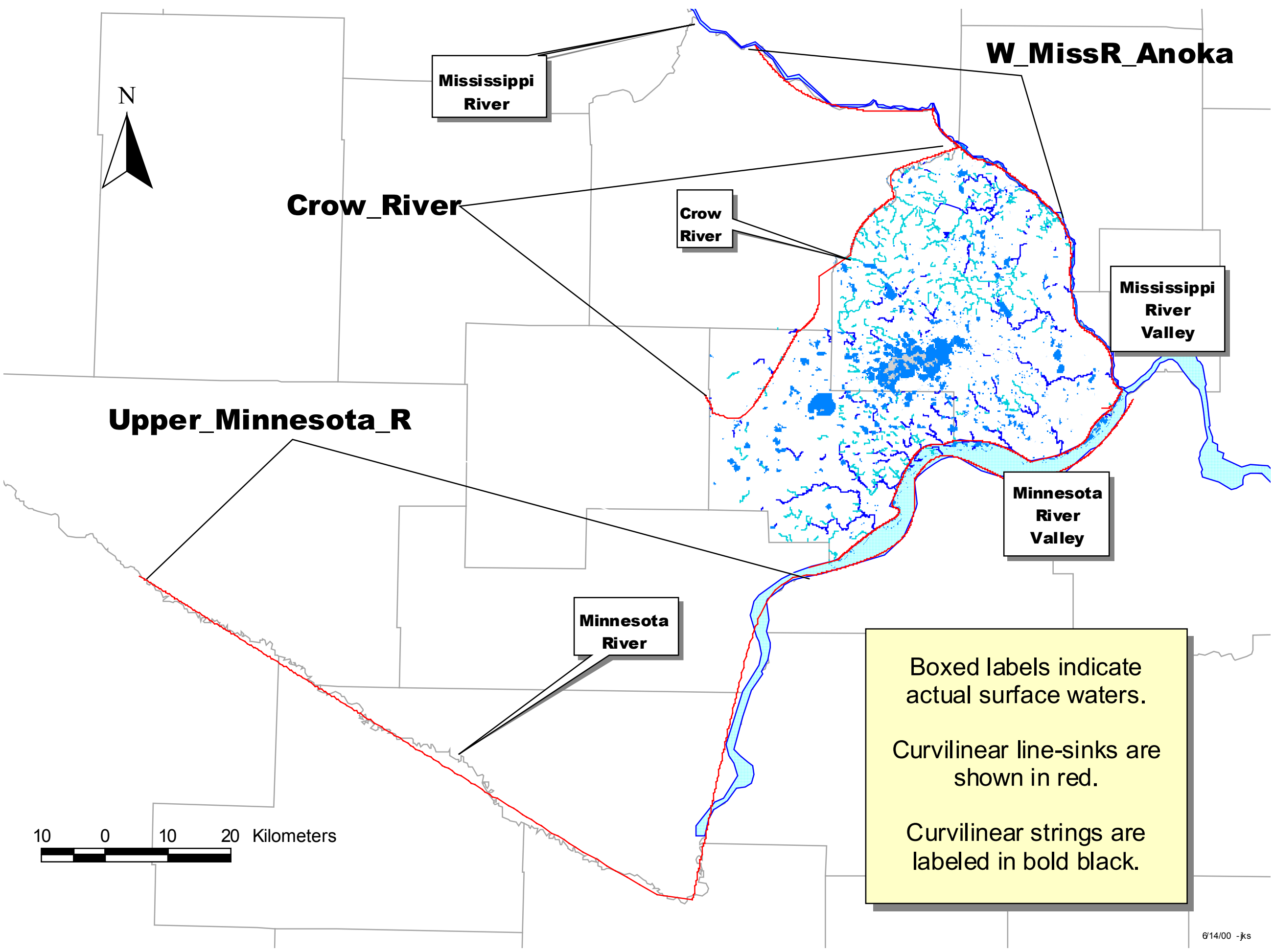


Figure 10. Northwest Province Curvilinear Line-sinks, Regional

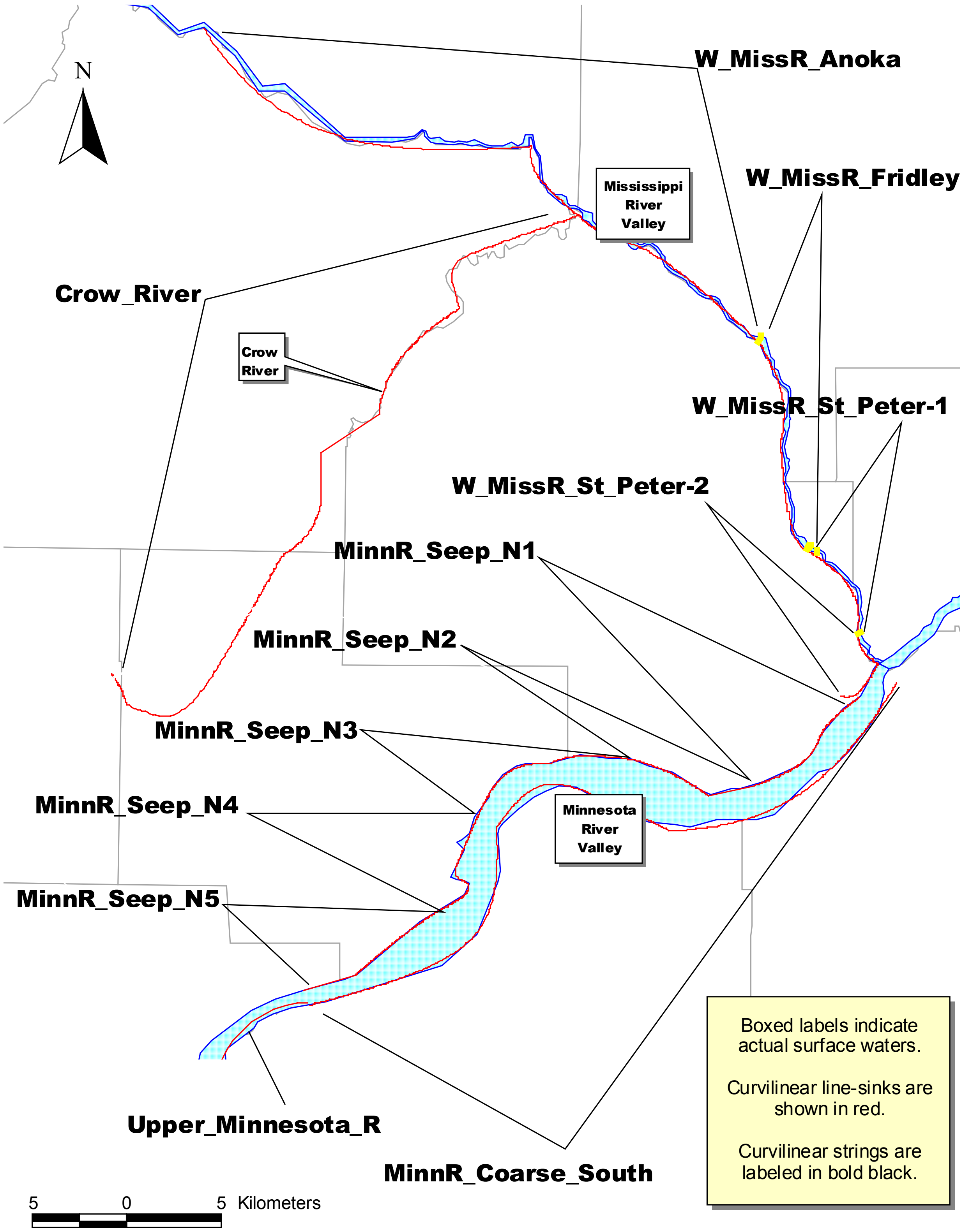


Figure 11. Northwest Province Curvilinear Line-sinks, Metropolitan Area

The Mississippi River is in contact with the St. Peter Sandstone from immediately below St. Anthony Falls dam in Minneapolis, continuing downstream below the Ford Dam, all the way to the confluence with the Minnesota River. From here, string **W_MissR_St_Peter-2** wraps around to the west to follow roughly the bluffline and extent of the St. Peter Sandstone. Elevations specified for the line-sink along this stretch in Layer 2 reflect the elevations of the pools between the Ford and Hastings dam (dams illustrated in yellow), and between the St. Anthony Falls and Ford dams. Because few data were available for determining the elevations, they were assigned using best judgment, and are considered subject to change on the basis of improved data.

Inhomogeneity Placement

Inhomogeneities were used to represent large aquifer zones with hydraulic properties that differ significantly from those assigned globally in all three layers of the Northwest Province model. Each inhomogeneity is defined in the model by a polygon with associated changes in hydraulic properties. The only inhomogeneities included in the Northwest Province model are in Layer 1. These inhomogeneities represent large areas of relatively low hydraulic conductivity that were defined using the sand content maps of the unconsolidated glacial drift.

The inhomogeneities are illustrated in Figure 12 along with the sand content maps of the unconsolidated glacial drift for Intervals 3 (240 –260 m MSL) and 4 (220 – 240 m MSL). Recalling from Table 1 that the base elevation of Layer 1 is set at 220 m MSL and its thickness is 40 m, Intervals 3 and 4 correspond to this horizon, 220 – 260 m MSL. Two inhomogeneities are defined with the polygons labeled **Low_K-1** and **Low_K-2** (Figure 12), and have been assigned a hydraulic conductivity value of 6 m/day, contrasting with the global value of 21 m/day. The polygon geometries defining the inhomogeneities roughly follow the 40-percent sand cutoff, and coincide most closely with Interval 3, although there is also rough agreement with the sand content map of Interval 4. Ultimately, their inclusion and final geometry were shaped largely by calibration procedures.

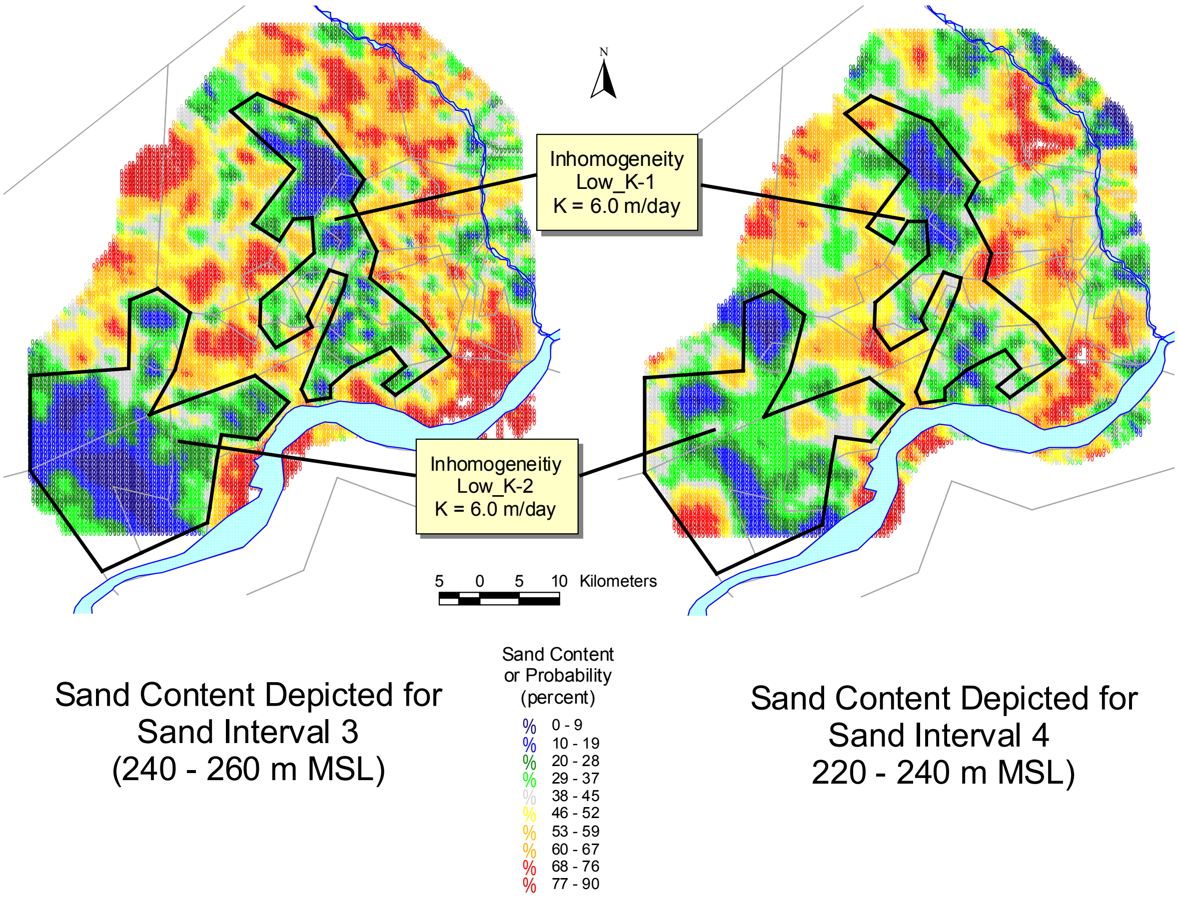


Figure 12. Layer 1 Aquifer Sand Content and Inhomogeneities

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, 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 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.

Model Adjustment and Calibration

The upper three aquifer layers of the Northwest Province model were calibrated primarily by adjusting the input elevations of curvilinear line-sinks, placement of hydraulic conductivity inhomogeneities (Layer 1 only), 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 (Northwest Province Leakage Inputs, Version 1.00). 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 Northwest 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.

This section starts with a general discussion of total system infiltration rates for each polygon. This is followed by a discussion of the net leakage to each of the individual aquifer layers. Because the discussion will refer to rates associated with individual polygons, please refer to Figures 8 (p. 14) and 9 (p. 15) for layouts displaying labeled polygons at the regional and metropolitan scales, respectively. Infiltration, leakage, and net leakage values may be read from Table 2. Additionally, net leakage values may be read directly from the figures that accompany the text.

Table 2
Northwest Province Leakage Inputs
Version 1.00

	Layer 1					Layer 2				Layer 3	
	Top (Total Infiltration)		Bottom	Net (Top - Bottom)		Top	Bottom	Net (Top - Bottom)		Top (same as net)	
POLYGON	(m/day)	(in/year)	(m/day)	(m/day)	(in/year)	(m/day)	(m/day)	(m/day)	(in/year)	(m/day)	(in/year)
WH-1	-3.83E-04	-5.5	-2.09E-04	-1.74E-04	-2.5	-2.09E-04	-1.74E-04	-3.50E-05	-0.5	-1.74E-04	-2.5
WH-2	-5.58E-04	-8.0	-2.45E-04	-3.13E-04	-4.5	-2.45E-04	-2.17E-04	-2.80E-05	-0.4	-2.17E-04	-3.1
WH-3	-6.54E-05	-0.9	-5.15E-05	-1.39E-05	-0.2	-5.15E-05	-4.87E-05	-2.80E-06	0.0	-4.87E-05	-0.7
WH-4	-1.09E-05	-0.2	-7.38E-06	-3.52E-06	-0.1	-7.38E-06	-6.96E-06	-4.20E-07	0.0	-6.96E-06	-0.1
WH-5	-2.37E-05	-0.3	-1.67E-05	-7.00E-06	-0.1	-1.67E-05	-1.39E-05	-2.80E-06	0.0	-1.39E-05	-0.2
WH-6	-2.33E-04	-3.3	-1.08E-04	-1.25E-04	-1.8	-1.08E-04	-1.04E-04	-4.00E-06	-0.1	-1.04E-04	-1.5
WH-7	-5.89E-05	-0.8	-2.83E-05	-3.06E-05	-0.4	-2.83E-05	-2.62E-05	-2.10E-06	0.0	-2.62E-05	-0.4
WH-8	-4.55E-04	-6.5	-2.25E-04	-2.30E-04	-3.3	-2.25E-04	-1.97E-04	-2.80E-05	-0.4	-1.97E-04	-2.8
WH-9	1.25E-04	1.8	1.25E-04	0.00E+00	0.0	1.25E-04	1.04E-04	2.06E-05	0.3	1.04E-04	1.5
WH-10	-9.74E-04	-14.0	-6.26E-04	-3.48E-04	-5.0	-6.26E-04	-5.22E-04	-1.04E-04	-1.5	-5.22E-04	-7.5
WH-11	-5.98E-04	-8.6	-2.50E-04	-3.48E-04	-5.0	-2.50E-04	-2.44E-04	-6.00E-06	-0.1	-2.44E-04	-3.5
WH-12	-2.59E-04	-3.7	-1.54E-04	-1.05E-04	-1.5	-1.54E-04	-1.04E-04	-5.00E-05	-0.7	-1.04E-04	-1.5
WH-13	-4.91E-04	-7.1	-2.30E-04	-2.61E-04	-3.8	-2.30E-04	-2.09E-04	-2.10E-05	-0.3	-2.09E-04	-3.0
WH-14	-8.52E-04	-12.2	-5.74E-04	-2.78E-04	-4.0	-5.74E-04	-5.57E-04	-1.70E-05	-0.2	-5.57E-04	-8.0
WH-15	-1.77E-04	-2.5	-7.31E-05	-1.04E-04	-1.5	-7.31E-05	-2.78E-05	-4.53E-05	-0.7	-2.78E-05	-0.4
WH-16	-3.13E-04	-4.5	-1.39E-04	-1.74E-04	-2.5	-1.39E-04	-1.04E-04	-3.50E-05	-0.5	-1.04E-04	-1.5
WH-17	-2.09E-05	-0.3	-1.60E-05	-4.90E-06	-0.1	-1.60E-05	-1.39E-05	-2.10E-06	0.0	-1.39E-05	-0.2
WH-18	-5.39E-04	-7.7	-2.96E-04	-2.43E-04	-3.5	-2.96E-04	-2.09E-04	-8.70E-05	-1.3	-2.09E-04	-3.0
WH-19	-8.91E-04	-12.8	-5.78E-04	-3.13E-04	-4.5	-5.78E-04	-4.04E-04	-1.74E-04	-2.5	-4.04E-04	-5.8
WH-20	-6.09E-04	-8.8	-4.00E-04	-2.09E-04	-3.0	-4.00E-04	-3.48E-04	-5.20E-05	-0.7	-3.48E-04	-5.0
WH-21	-6.92E-04	-9.9	-5.39E-04	-1.53E-04	-2.2	-5.39E-04	-4.52E-04	-8.70E-05	-1.3	-4.52E-04	-6.5
WH-22	4.21E-04	6.0	1.57E-04	2.64E-04	3.8	1.57E-04	2.96E-04	-1.39E-04	-2.0	2.96E-04	4.3
WH-23	-2.92E-04	-4.2	-2.09E-04	-8.30E-05	-1.2	-2.09E-04	-1.74E-04	-3.50E-05	-0.5	-1.74E-04	-2.5
WH-24	-5.57E-04	-8.0	-3.31E-04	-2.26E-04	-3.2	-3.31E-04	-2.44E-04	-8.70E-05	-1.3	-2.44E-04	-3.5
WC-1	-6.76E-05	-1.0	-5.37E-05	-1.39E-05	-0.2	-5.37E-05	-4.75E-05	-6.20E-06	-0.1	-4.75E-05	-0.7
WC-2	-1.57E-04	-2.3	-1.29E-04	-2.80E-05	-0.4	-1.29E-04	-1.22E-04	-7.00E-06	-0.1	-1.22E-04	-1.8
WC-3	-9.50E-04	-13.7	-6.09E-04	-3.41E-04	-4.9	-6.09E-04	-5.57E-04	-5.20E-05	-0.7	-5.57E-04	-8.0
WC-4	-9.81E-04	-14.1	-7.72E-04	-2.09E-04	-3.0	-7.72E-04	-6.82E-04	-9.00E-05	-1.3	-6.82E-04	-9.8
WC-5	-1.66E-04	-2.4	-1.45E-04	-2.10E-05	-0.3	-1.45E-04	-1.39E-04	-6.00E-06	-0.1	-1.39E-04	-2.0
WC-6	-5.86E-05	-0.8	-5.37E-05	-4.90E-06	-0.1	-5.37E-05	-4.75E-05	-6.20E-06	-0.1	-4.75E-05	-0.7
WC-7	-1.66E-04	-2.4	-1.45E-04	-2.10E-05	-0.3	-1.45E-04	-1.39E-04	-6.00E-06	-0.1	-1.39E-04	-2.0
WC-8	-4.53E-04	-6.5	-4.52E-04	-1.00E-06	0.0	-4.52E-04	-4.18E-04	-3.40E-05	-0.5	-4.18E-04	-6.0
WC-9	-1.63E-05	-0.2	-7.93E-06	-8.37E-06	-0.1	-7.93E-06	-7.02E-06	-9.10E-07	0.0	-7.02E-06	-0.1
W-L_MINNETONKA-1	6.92E-04	9.9	2.74E-04	4.18E-04	6.0	2.74E-04	2.42E-04	3.20E-05	0.5	2.42E-04	3.5
W-L_MINNETONKA-2	-9.19E-05	-1.3	-7.10E-05	-2.09E-05	-0.3	-7.10E-05	-6.26E-05	-8.40E-06	-0.1	-6.26E-05	-0.9
W-L_MINNETONKA-3	-2.24E-04	-3.2	-1.73E-04	-5.10E-05	-0.7	-1.73E-04	-1.52E-04	-2.10E-05	-0.3	-1.52E-04	-2.2
W-L_MINNETONKA-4	-5.90E-04	-8.5	-2.83E-04	-3.07E-04	-4.4	-2.83E-04	-2.63E-04	-2.00E-05	-0.3	-2.63E-04	-3.8
W-L_WACONIA	7.96E-04	11.4	3.79E-04	4.17E-04	6.0	3.79E-04	3.48E-04	3.10E-05	0.4	3.48E-04	5.0
W-FF1	-2.35E-04	-3.4	-7.88E-05	-1.56E-04	-2.2	-7.88E-05	-6.96E-05	-9.20E-06	-0.1	-6.96E-05	-1.0
W-FF2	-1.63E-05	-0.2	-7.93E-06	-8.37E-06	-0.1	-7.93E-06	-7.02E-06	-9.10E-07	0.0	-7.02E-06	-0.1
W-FF3	-3.45E-04	-5.0	-1.72E-04	-1.73E-04	-2.5	-1.72E-04	-1.51E-04	-2.10E-05	-0.3	-1.51E-04	-2.2
W-FF4	-3.81E-06	-0.1	-1.72E-06	-2.09E-06	0.0	-1.72E-06	-1.51E-06	-2.10E-07	0.0	-1.51E-06	0.0

Note in Table 2 that the model inputs in units of m/day are provided along with total infiltration and net rates for each layer in units of inches/year, to allow for more ready comparison with the rates given in literature. As currently set up, the total system infiltration enters the model through the top of Layer 1. The given-strength leakage approach is based on the assumption that the water leaving the bottom of one aquifer is identical to the water entering the top of the underlying aquifer, with no loss of water via the separating layer. Hence, the leakage rates for water leaving the bottom of Layer 1 are identical to the rates entering the top of Layer 2, just as the rates for the bottom of Layer 2 are identical to those for the top of Layer 3. Although net leakage rates are not specified in this model, they are listed to provide a sense of the water throughput for each layer. Refer to the Overview of the Twin Cities Metropolitan Groundwater Model (Seaberg, 2000) for a more detailed description on application of the given-strength leakage approach.

Total system infiltration rates are plotted (inches/year) for each polygon of the Northwest Province on Figure 13 at both regional and metropolitan area scales. These values represent the total infiltration rate at the top of Layer 1 that feeds the entire layered aquifer system. The values for individual polygons range from –14.1 inches/year to 11.4 inches/year. The positive values represent a total net extraction from the aquifer system, and are seen in polygons **WH-22**, **W-L_MINNETONKA-1**, and **W-L_WACONIA**, the latter two representing the western Lake Minnetonka and Lake Waconia, respectively. This indicates that net discharge is occurring from the aquifer system into Lake Waconia and western Lake Minnetonka. Moreover, discharge is occurring from all three aquifer layers, as will be discussed further below. This discharge phenomenon has not yet been independently confirmed with field data. Further analysis of the water budget of the lakes would help resolve whether these areas actually serve as discharge zones for the aquifers. Net extraction of water from polygon **WH-22,** which adjoins the Minnesota River valley, may not be so readily explained. Total extraction of water from Layers 1 and 3 exceed the net recharge rate to Layer 2 from this polygon, representing a physical system that is difficult to account for. This anomaly likely results from poorly defined boundary conditions (especially heads at the Minnesota River valley), the limited extent of the aquifers (eg., the St. Peter Sandstone is almost absent within this polygon, undefined inhomogeneneities, and/or lack of head calibration data for Layers 1 and 2. Further work conducted for local-scale modeling may help to resolve these issues.

Net infiltration to the layered aquifer system was simulated for the remainder of the polygons in the Northwest Province, ranging from 0.1 inch/year (far-field polygon **W-FF4**) to 14.1 inches/year (polygon **WC-4**). Eleven of the polygons have total infiltration rates that exceed 8.0 inches/year (**WH-2**, **-10**, **-11**, **-14**, **-19**, **-20**, **-21**, & **-24**; **WC-3**, **-4**, and **W-L_Minnetonka-4**). On a regional basis, these polygons tend to lie adjacent to or near the major discharge zones of the Mississippi and Minnesota Rivers (Figure 13), possibly symptomatic of artificially low boundary heads for these rivers. If the boundary heads are too low, the infiltration rates may be increased during calibration procedures to match observed head values that would otherwise be “held down” near these artificially low head boundaries. Infiltration rates and boundary head inputs will need to be re-evaluated as further work is conducted in the area to better understand the water mass balance of the system and refine the model.

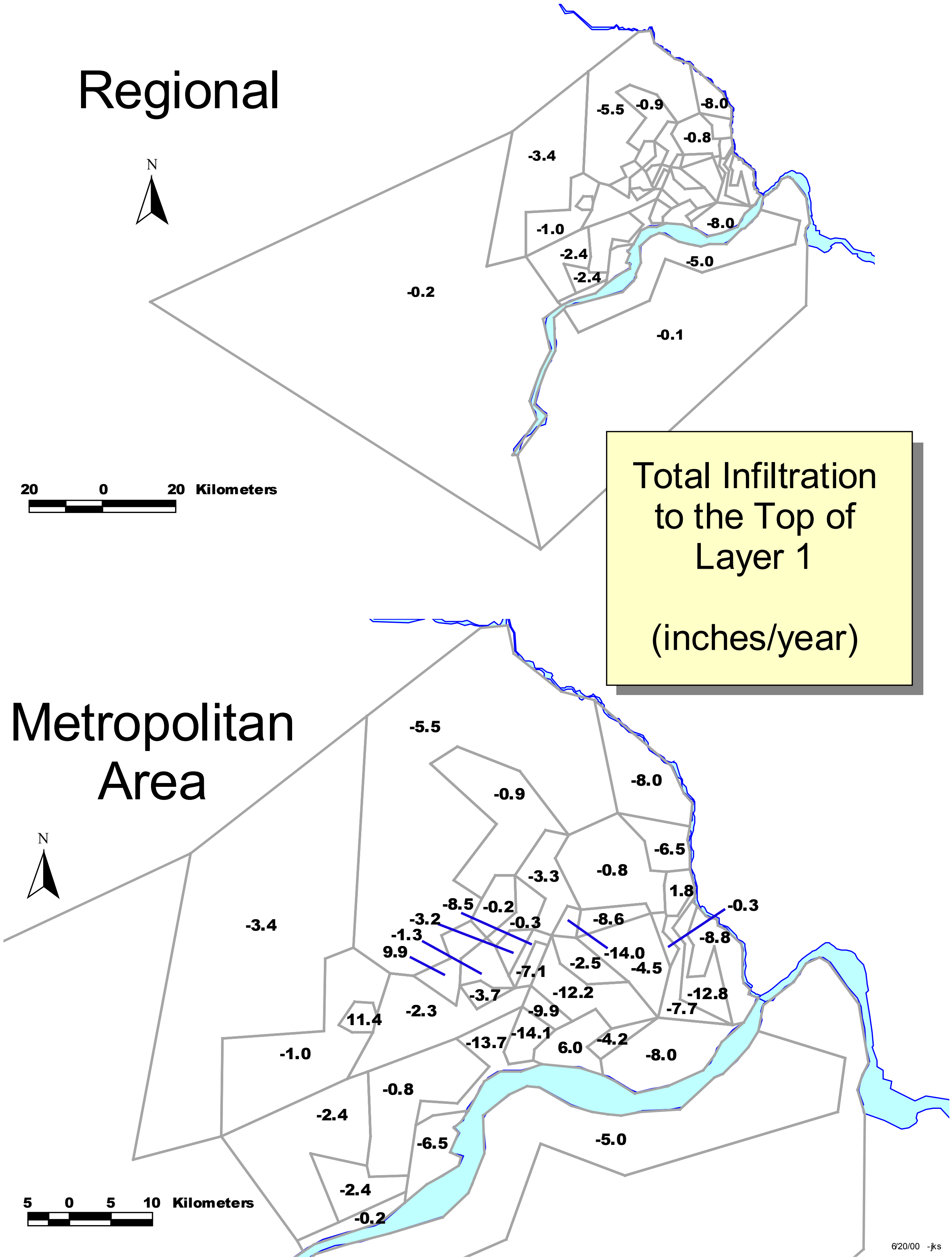


Figure 13. Total System Infiltration Rates—Regional and Metro Scales

The distribution of net leakage to Layer 1 on a polygon-by-polygon basis is presented in Figure 14 at both regional and metropolitan scales. Extraction of water, indicated by positive net leakage values, mimics the same pattern seen for total system infiltration, occurring in polygons **WH-22**, **W-L_MINNETONKA-1**, and **W-L_WACONIA**. As stated above, this simulation may reflect actual aquifer discharge to western Lake Minnetonka and Lake Waconia. A water budget analysis of these lakes would be useful to confirm or refute this, and would help in model calibration. The net extraction of 3.8 inches/year from polygon **WH-22** is not congruent with our conceptual model. This value, determined during calibration procedures, may reflect discharge conditions near the Minnesota River valley, and/or may result from the lack of head calibration targets in the area. Local applications of the model in this area will require modification based on a better understanding of the local hydrogeology to produce a technically sound simulation.

The rate of net leakage or recharge to Layer 1 ranges from less than 0.05 inches/year, as indicated by –0.0 on Figure 14, to 5.0 inches/year. With the exception of Lake Waconia, the net recharge through the polygons encompassing the Layer 1 inhomogeneity **Low_K-2** is low, with a maximum rate of 0.3 inches/year. Elsewhere in the Northwest Province, no major patterns in the distribution of net leakage are readily apparent.

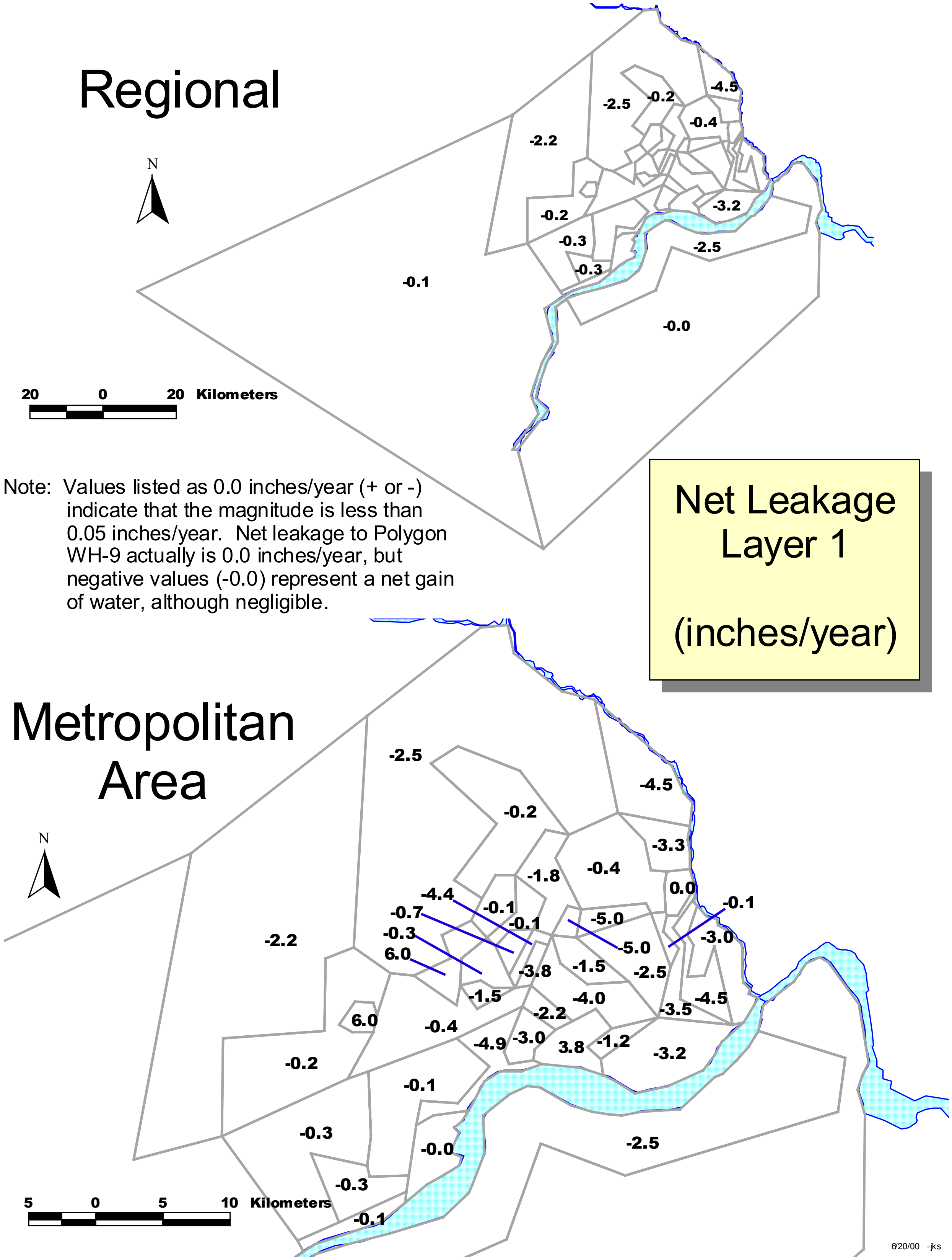


Figure 14. Net Leakage to Layer 1—Regional and Metro Scales

Figure 15 illustrates the net infiltration rates for Layer 2 at both regional and metro scales. In general the net rates for Layer 2 are substantially lower than those for Layers 1 and 3. This is consistent with the theory that distribution of infiltration to a multi-layered system will occur in proportion to the transmissivity of each layer. The transmissivity value of the St. Peter Sandstone is much lower than the values for the glacial drift and Prairie du Chien-Jordan Aquifers, so it would be expected to generally have lower net infiltration rates.

As observed for Layer 1, extraction of water from Layer 2 occurs in polygons **W-L_MINNETONKA-1**, and **W-L_WACONIA**, suggesting discharge from this aquifer layer into Lake Waconia and western Lake Minnetonka. As stated above, this simulation may reflect actual aquifer discharge to western Lake Minnetonka and Lake Waconia. However, the St. Peter Sandstone is actually absent beneath these polygons. Because MLAEM represents aquifers as having infinite areal domains, Layer 2 is still present in this area within the model. Current resources do not permit project staff to construct a more representative depiction of hydrostratigraphy in this area. Local modeling of groundwater here will require that consideration be given to the relationship of the model layers to the hydrostratigraphy. Hydrostratigraphy, modeling objectives, and constraints of MLAEM will determine how the model is locally applied. For example, Layer 2 might be used to represent a lower horizon of glacial drift in the area instead of the St. Peter Sandstone.

Polygon **WH-9** also has a positive net leakage, indicating extraction of water from that polygon. Again, because this result is not consistent with our conceptual model of groundwater flow, local modeling efforts will need to rely heavily on incorporation of site-specific data and information for the model. The cause of groundwater extraction in this area might be influenced by discharge to the Mississippi River, the presence of nearby head changes at dams, and/or the lack of head calibration targets in the area.

Elsewhere in the Northwest Province, the rate of net leakage or recharge to Layer 2 ranges from less than 0.05 inches/year (–0.0 on Figure 15) to 2.5 inches/year. With the exception of polygon **WH-10** (1.5 inches/year), the highest values for net infiltration in Layer 2 tend to be concentrated near the lowermost reach of the Minnesota River valley, as evidenced by the net leakage rates to polygons **WC-4** (1.3 inches/year), **WH-18** (1.3 inches/year), **-19** (2.5 inches/year), **-21** (1.3 inches/year), **-22** (2.0 inches/year), and **-24** (1.3 inches/year). This may indicate that the boundary head entered for the St. Peter Sandstone at the lower portion of the Minnesota River valley is too low. Further investigation is required to better understand the boundary conditions and leakage rates for this area of the model. Any local applications in this area will need to critically evaluate and include additional information and data in the model.

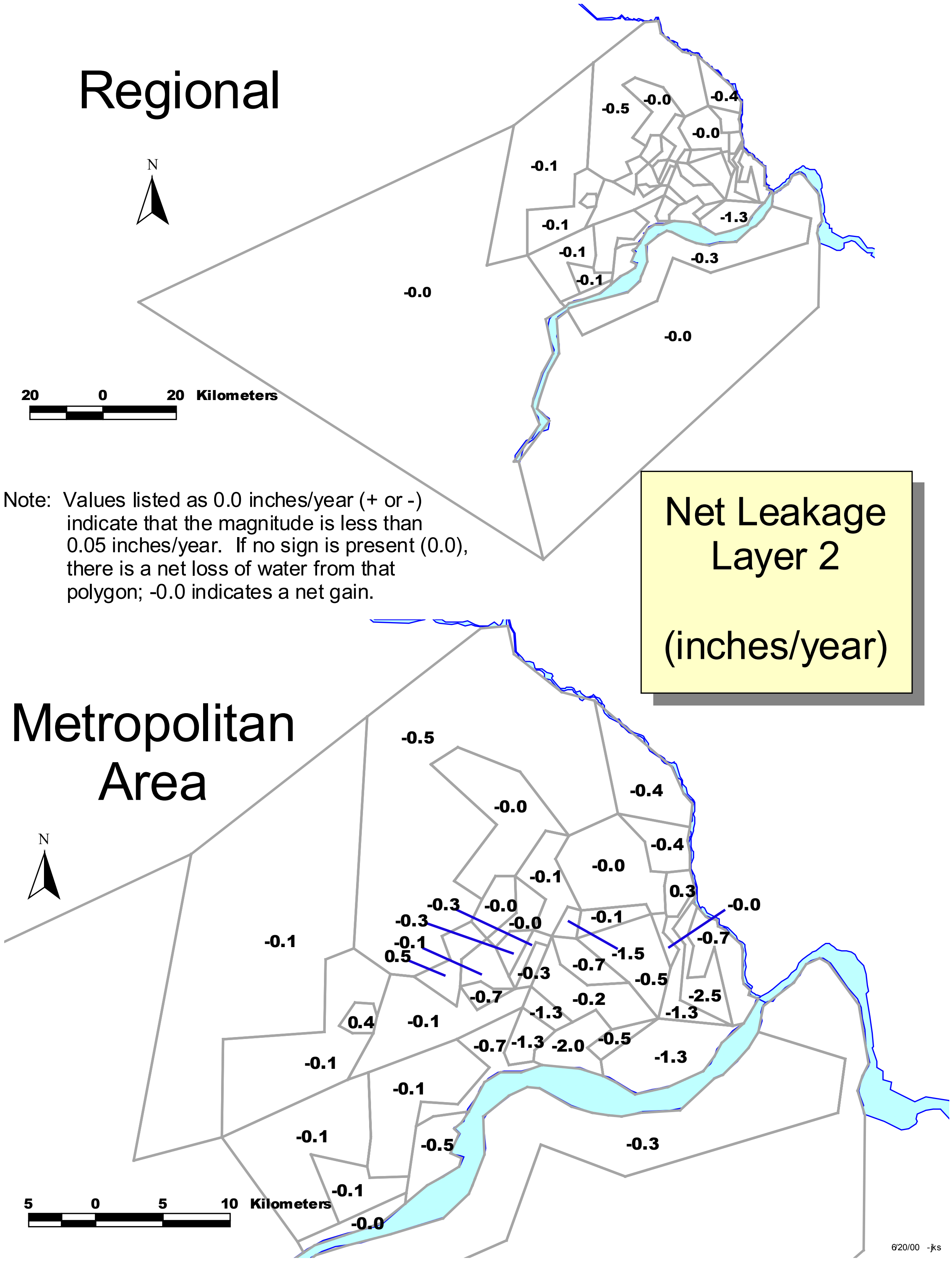
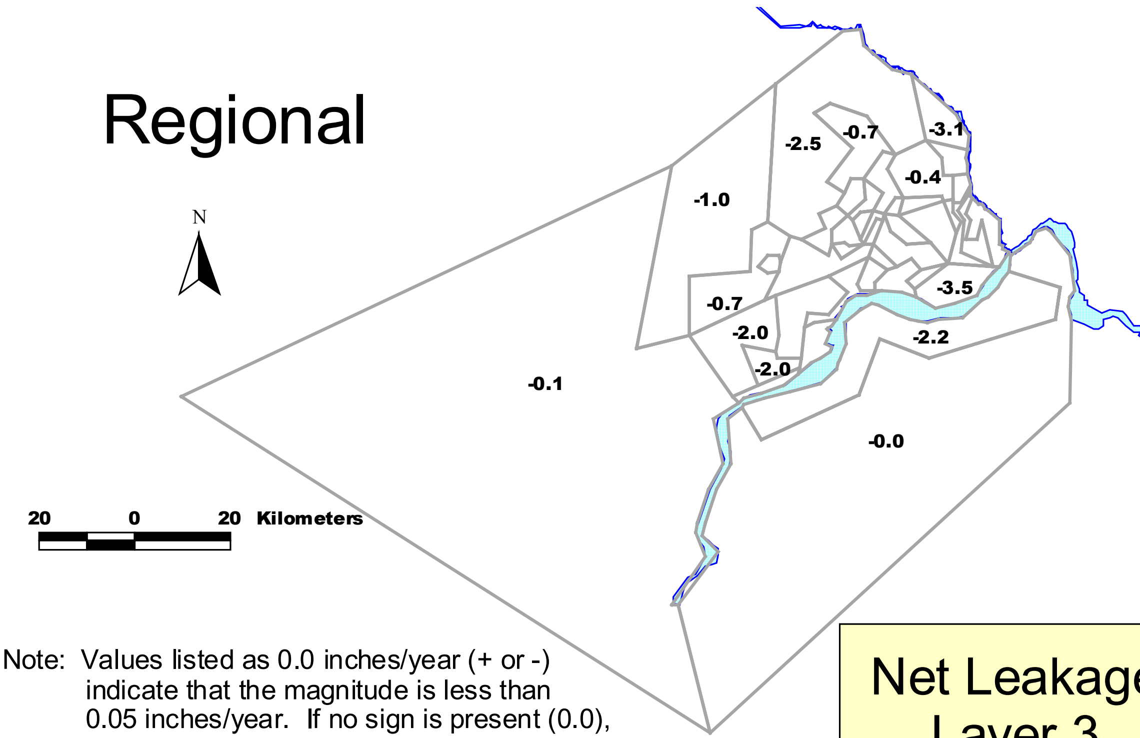


Figure 15. Net Leakage to Layer 2—Regional and Metro Scales

Net infiltration rates to Layer 3, the Prairie du Chien-Jordan aquifer, are presented in Figure 16. As observed for Layers 1 and 2, extraction of water from Layer 3 occurs in polygons **W-L_MINNETONKA-1** and **W-L_WACONIA**, suggesting discharge to the associated lakes. The Prairie du Chien-Jordan Aquifer is absent beneath polygon **W-L_WACONIA**, and only patchy and laterally discontinuous beneath polygon **W-L_MINNETONKA-1**. Refer to the discussion above on Layer 2, regarding similar hydrogeologic circumstances, for implications on site-specific modeling in the area. Polygons **WH-9** and **–22** also show net losses of water from Layer 3 (1.5 and 4.3 inches/year, respectively), which, as discussed above for Layers 1 and 2, does not conform to our understanding of groundwater flow. Even more striking is the contrast in extraction values from these two polygons compared to the net leakage values representing recharge to nearby polygons. These two polygons have rates as high as 9.8 inches/year, without any hydrogeologic evidence to support such phenomena. Therefore, application of the Metro Model in these two areas warrants particular attention to ensure conditions in these two areas are properly simulated. This will entail the use of site-specific data to produce a simulation of groundwater flow that adequately represents the hydrogeologic conditions.

Within the Northwest Province, net recharge rates to the Layer 3 aquifer range from 0.1 to 9.8 inches/year. High net leakage rates near the Minnesota River (Polygons **WC-3**, **-4**, and **–8**, and **WH-14** and **–21**) may again indicate that boundary heads entered for portions of the Minnesota River are too low. Further investigation is required to better define the head conditions within the Minnesota River valley. Changes to these values in the model will result in changes to leakage rates.

As additional work is conducted on the model and as new information and data are gathered, infiltration and leakage rates for all three layers will be re-evaluated to determine how well they represent natural conditions. Changes to the conceptual model and to the infiltration values will undoubtedly change as more information becomes available regarding boundary conditions and hydraulic characteristics. In the meantime, users of the model will need to exercise caution when applying it to local problems. As stated, certain areas are not well represented by the model, and local applications in these areas will require the user to better represent natural conditions prior to its usage.



Note: Values listed as 0.0 inches/year (+ or -) indicate that the magnitude is less than 0.05 inches/year. If no sign is present (0.0), there is a net loss of water from that polygon; -0.0 indicates a net gain.

Net Leakage Layer 3

(inches/year)

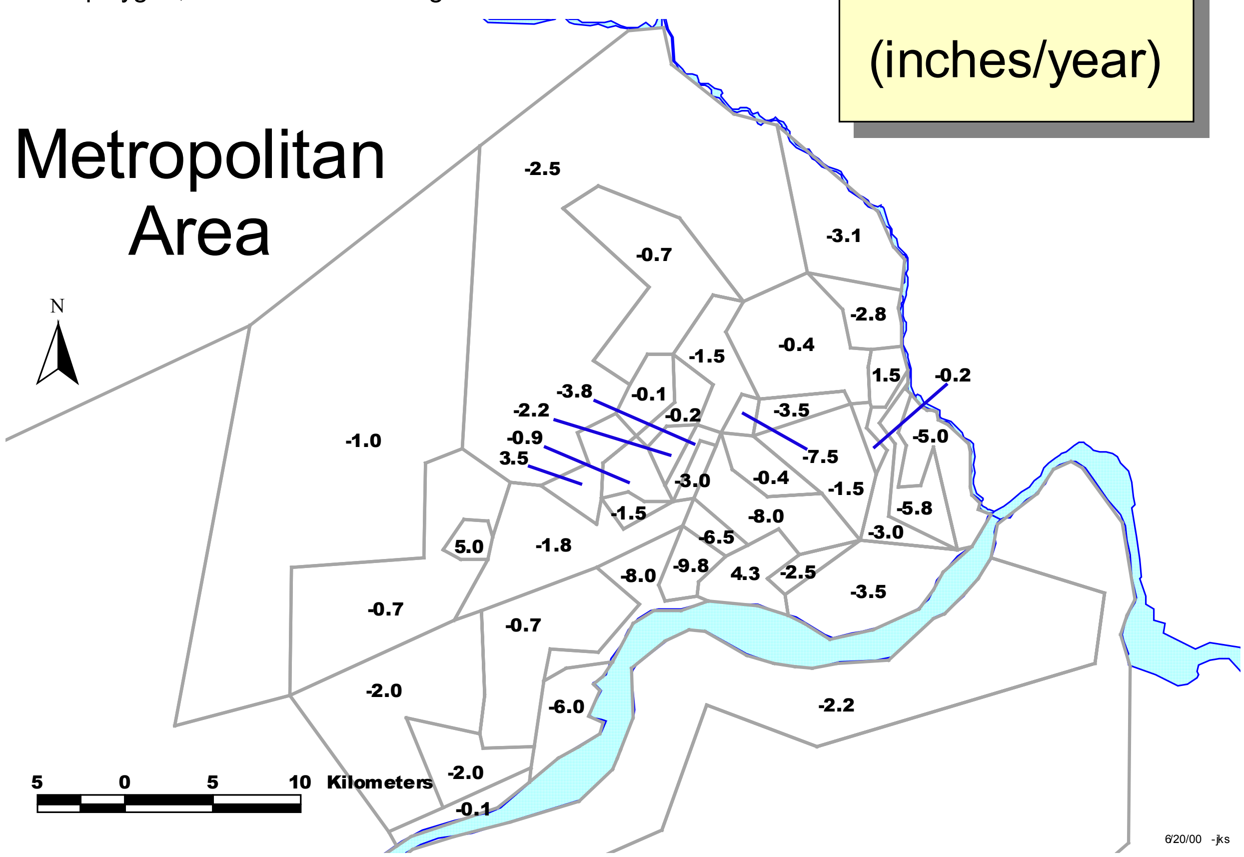


Figure 16. Net Leakage to Layer 3—Regional and Metro Scales

Model Results

Comparison to Measured Heads

This section presents the most current calibration results of the Northwest Province model of Layers 1, 2, and 3. The descriptive statistics of the mean absolute difference (of computed minus measured heads) are presented in Table 3. The calibration plots and modeled piezometric surfaces for Layers 1, 2 and 3 are presented on the pages following the statistics of mean absolute differences. The modeled head contours are presented in feet MSL to allow ready comparison with previously published data and results that have been produced in units of feet. Plots in metric units can be readily produced on request.

Table 3
Descriptive Statistics for Mean Absolute Difference Values
Northwest Province
(Modeled – Measured Heads in m)

Parameter	Layer 1	Layer 2	Layer 3
Mean	3.10	3.14	3.26
Standard Error	0.09	0.11	0.09
Median	2.38	2.46	2.57
Mode	0.22	--	0.41
Standard Deviation	2.69	2.57	2.59
Sample Variance	7.24	6.58	6.72
Kurtosis	3.29	0.77	1.51
Skewness	1.53	1.07	1.24
Range	17.86	13.51	15.35
Minimum	0.01	0.00	0.00
Maximum	17.86	13.51	15.35
Sum	2792.55	1706.86	2458.11
Count	900	544	754

The mean absolute difference between the measured and modeled heads for Layer 1 was 3.10 m (Table 3 and Figure 17). The Layer 1 calibration plot and modeled head contour map are shown in Figures 17 and 18, respectively. Inspection of the calibration plot reveals two areas, both near the Minnesota River valley, that are not particularly well represented by the computed heads of the model. One area, encompassed by polygon **WC-8** (Figure 9) near Chaska, has a cluster of wells indicating that the model simulates heads that are too high. Because this area lies close to the boundary condition imposed the Minnesota River valley linesink, and net recharge to this polygon is negligible (Table 2 and Figure 14), the most likely source of error is the assignment of an input head that is too high to represent actual conditions. Determination of the head values for seepage faces is difficult without field inspection, so it is not surprising that some of the assigned head values may not represent natural conditions well. Better definition of local seepage face head conditions will help resolve this anomaly.

The other area showing a poor calibration is in Bloomington in the vicinity of polygon **WH-24**. Again, a cluster of modeled heads that are too high to adequately represent conditions is observed. Recall from the bedrock map in Figure 7 that a portion of a very significant buried bedrock valley is found beneath this polygon but is not accounted for. Earlier efforts in modeling included a high hydraulic conductivity inhomogeneity to represent what are presumed to be highly permeable valley fills. Inclusion of this feature lowered the modeled heads in the area by reducing the hydraulic resistance between the wells and the Minnesota River valley seepage faces. However, this feature was removed since it represents a localized condition and increases the computational burden. Any future localized applications of the model in this area will likely want to account for hydraulic influence of the bedrock valley.

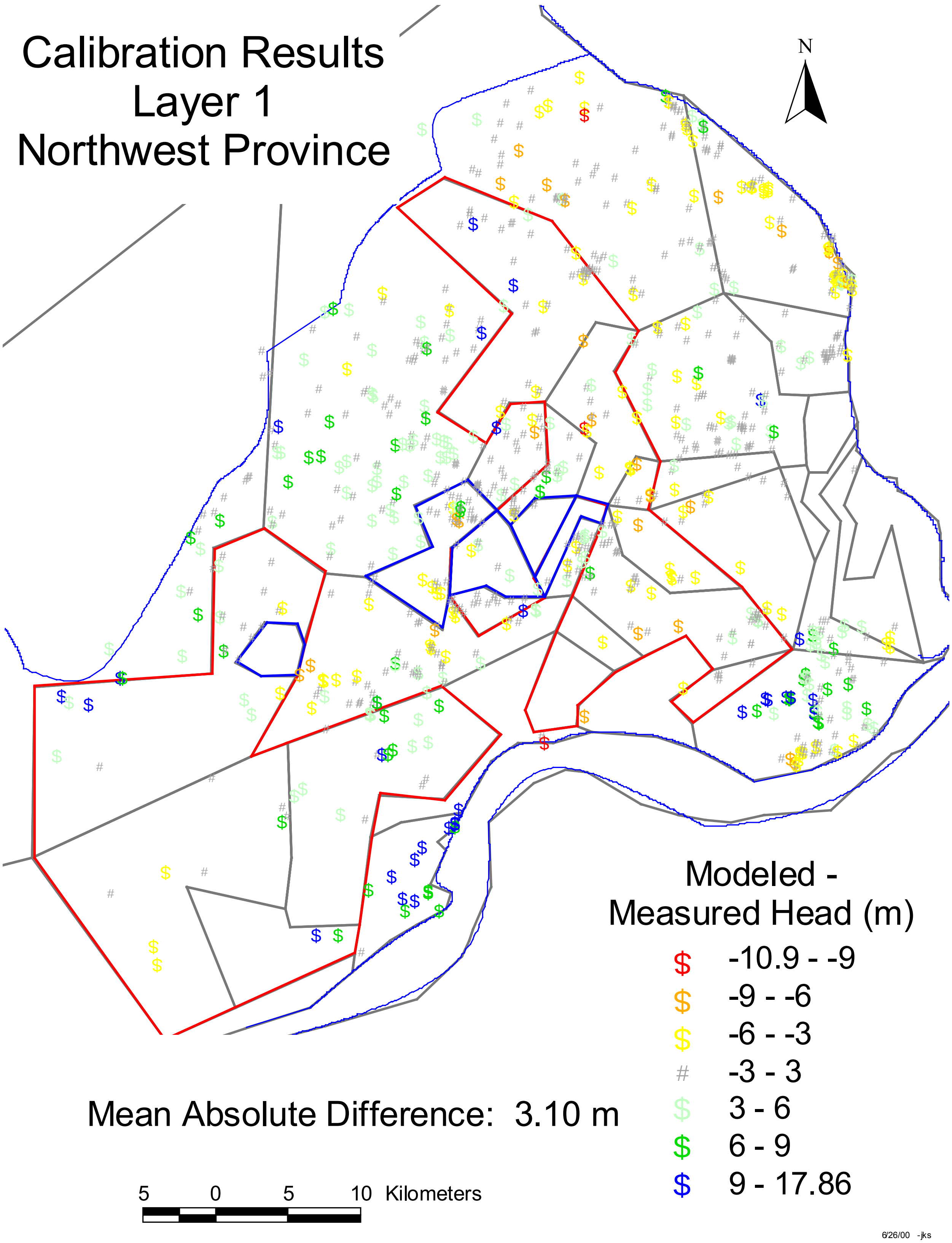


Figure 17. Layer 1 Calibration Plot

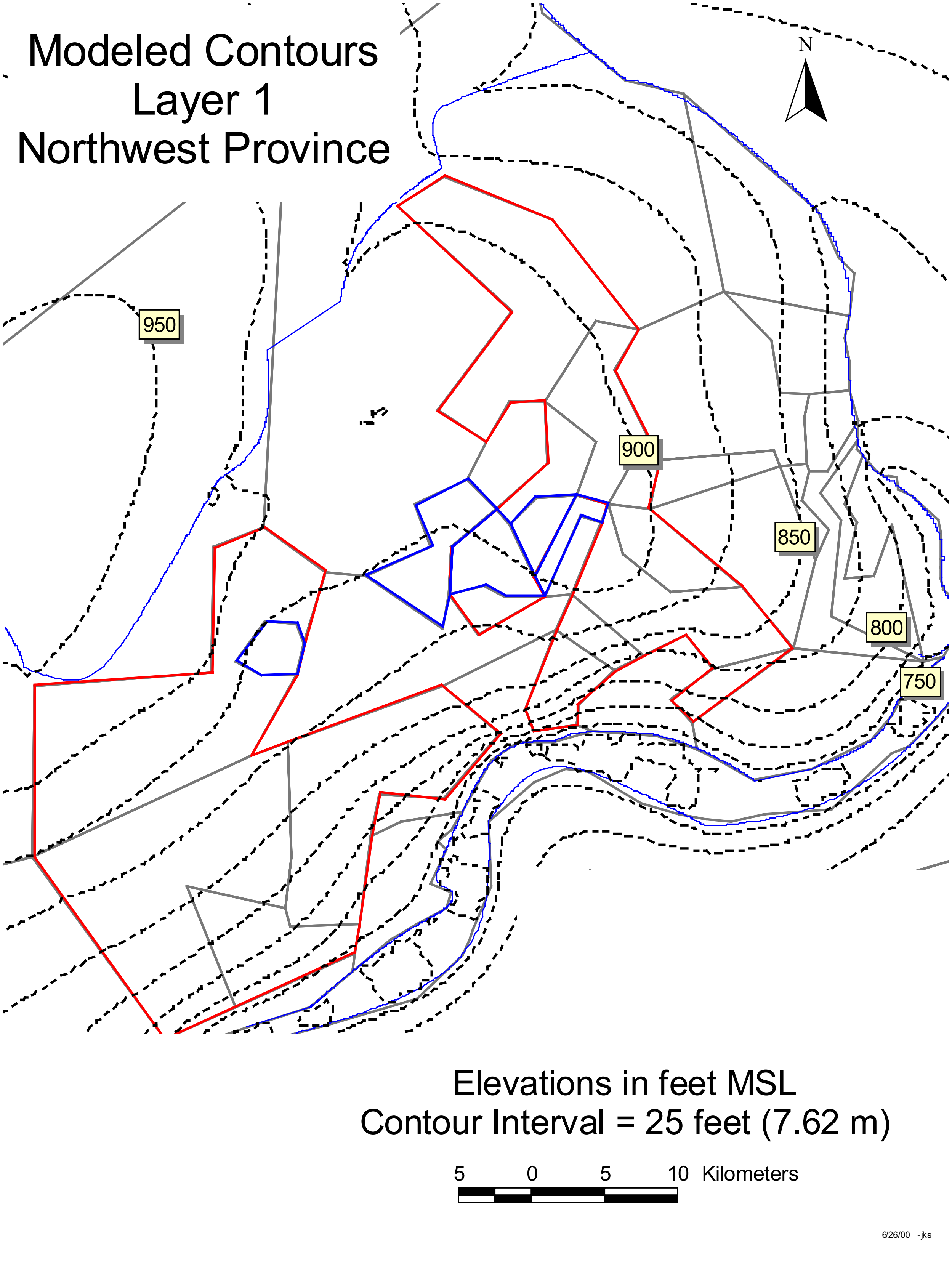


Figure 18. Layer 1 Modeled Piezometric Contours

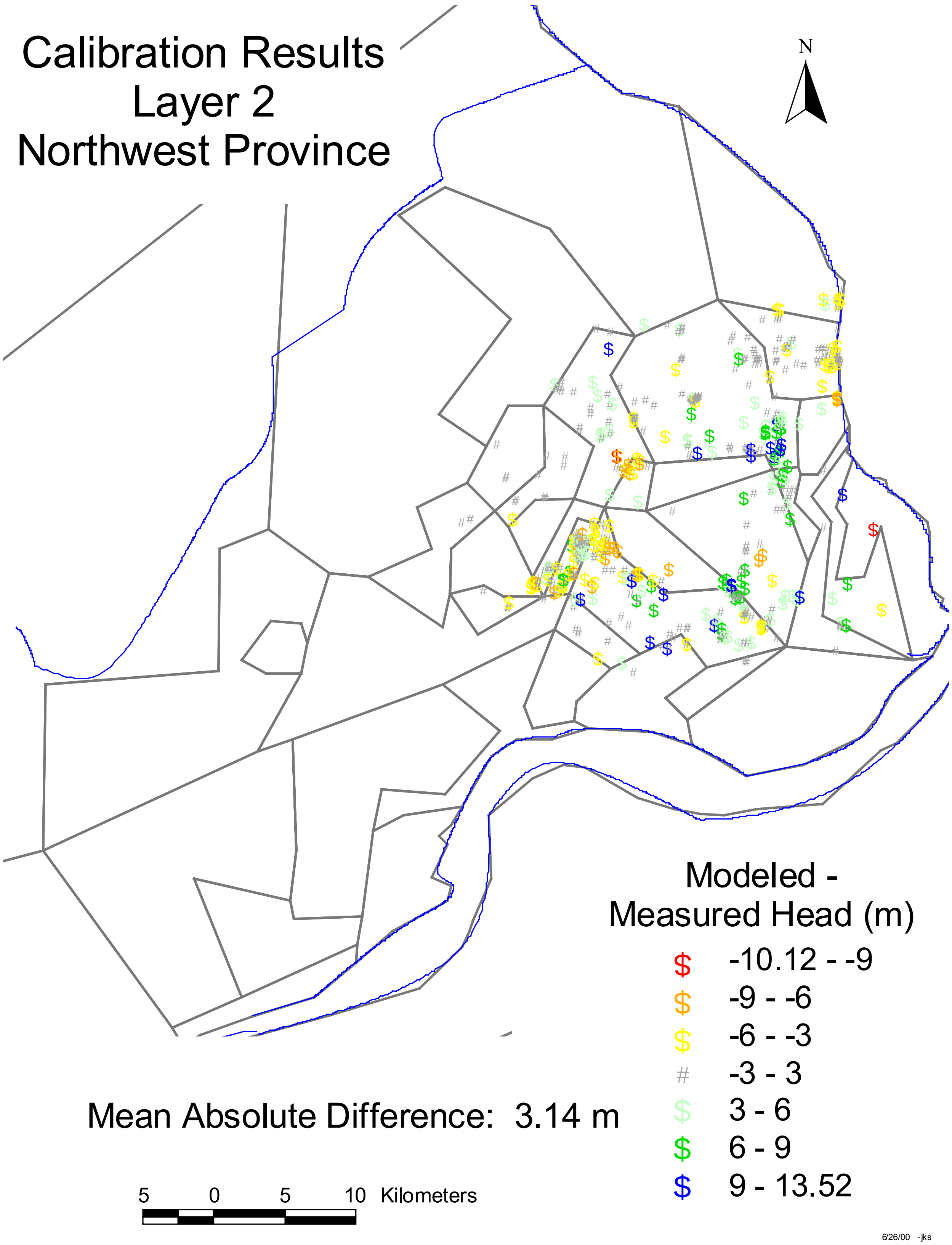


Figure 19. Layer 2 Calibration Plot

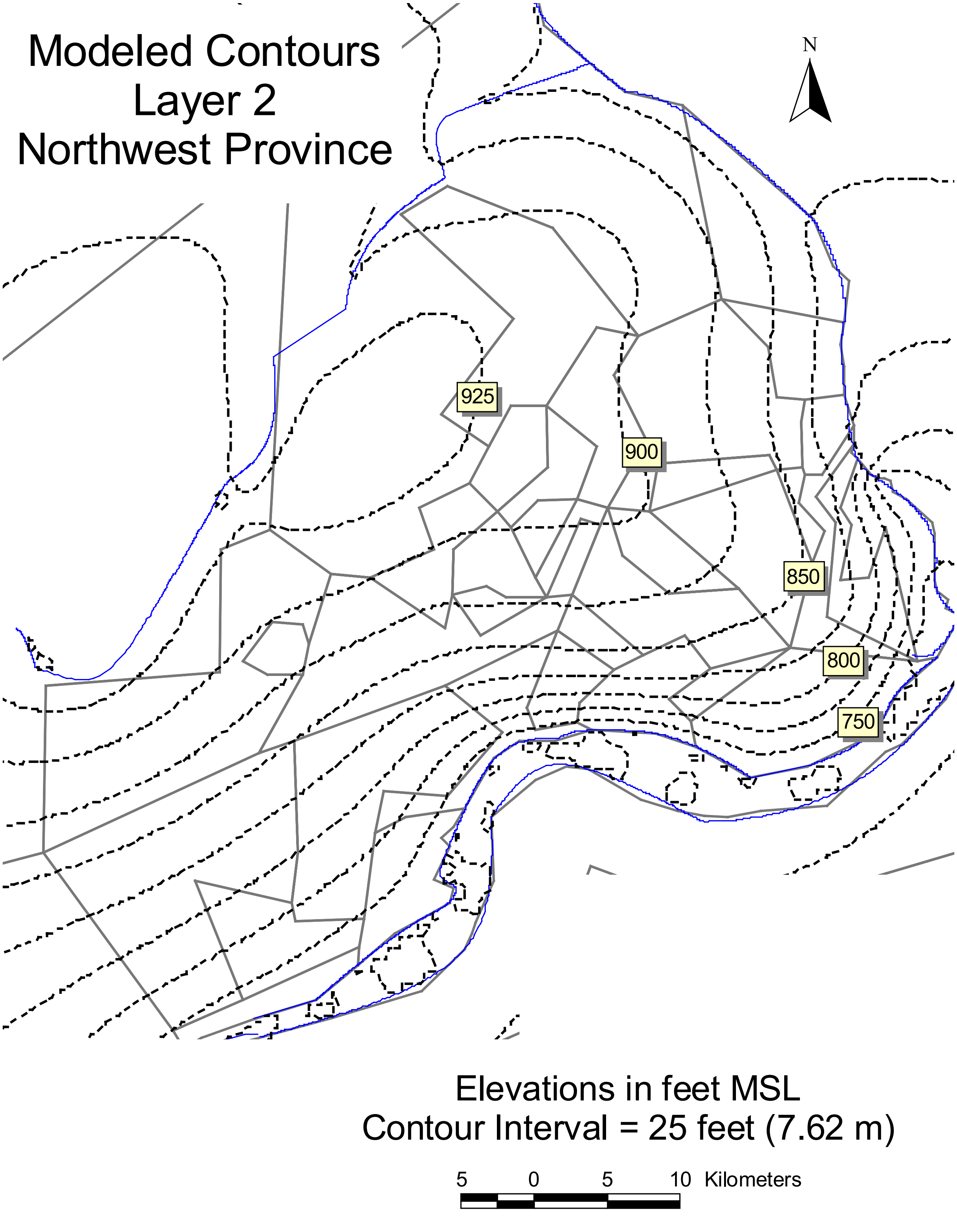


Figure 20. Layer 2 Modeled Piezometric Contours

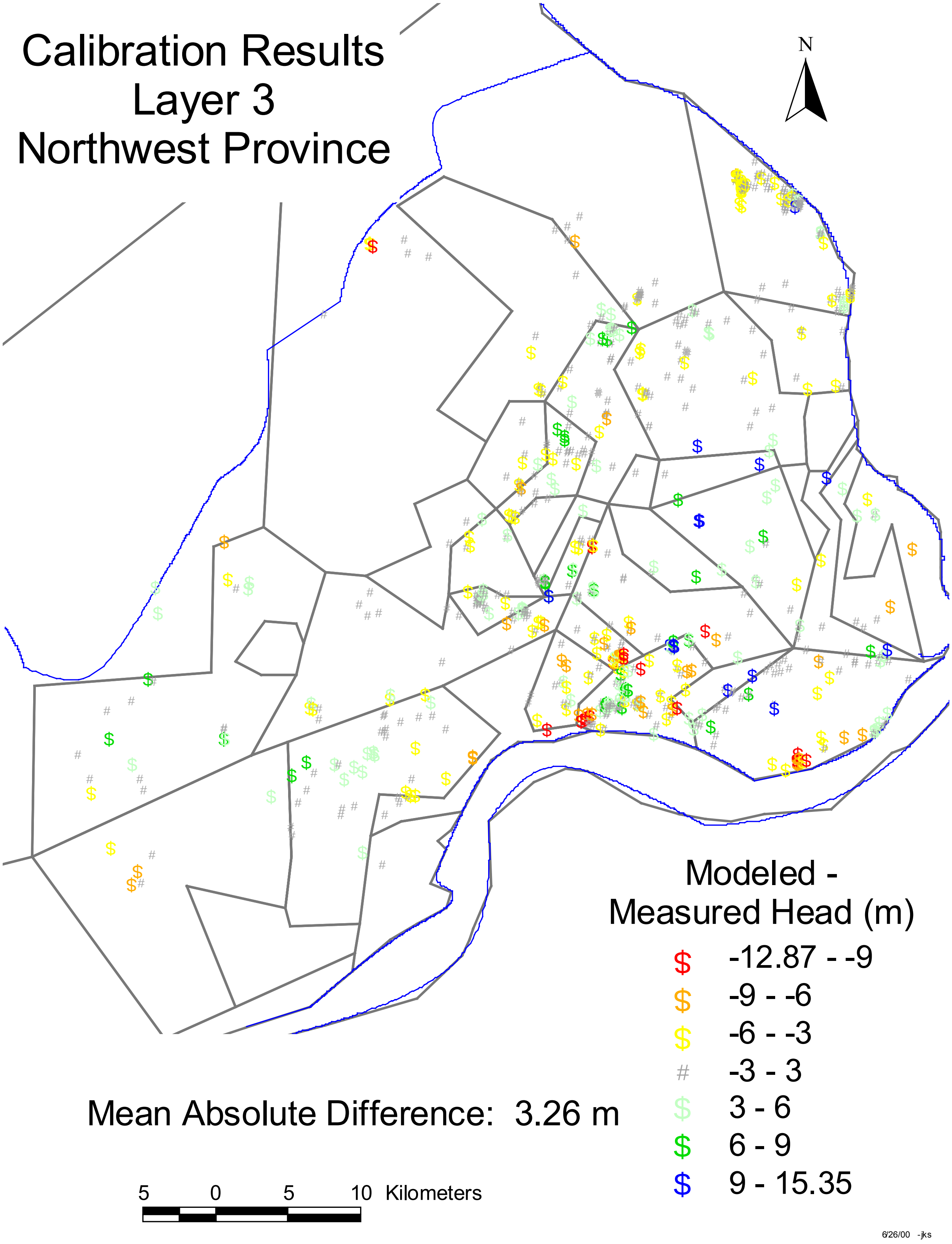


Figure 21. Layer 3 Calibration Plot

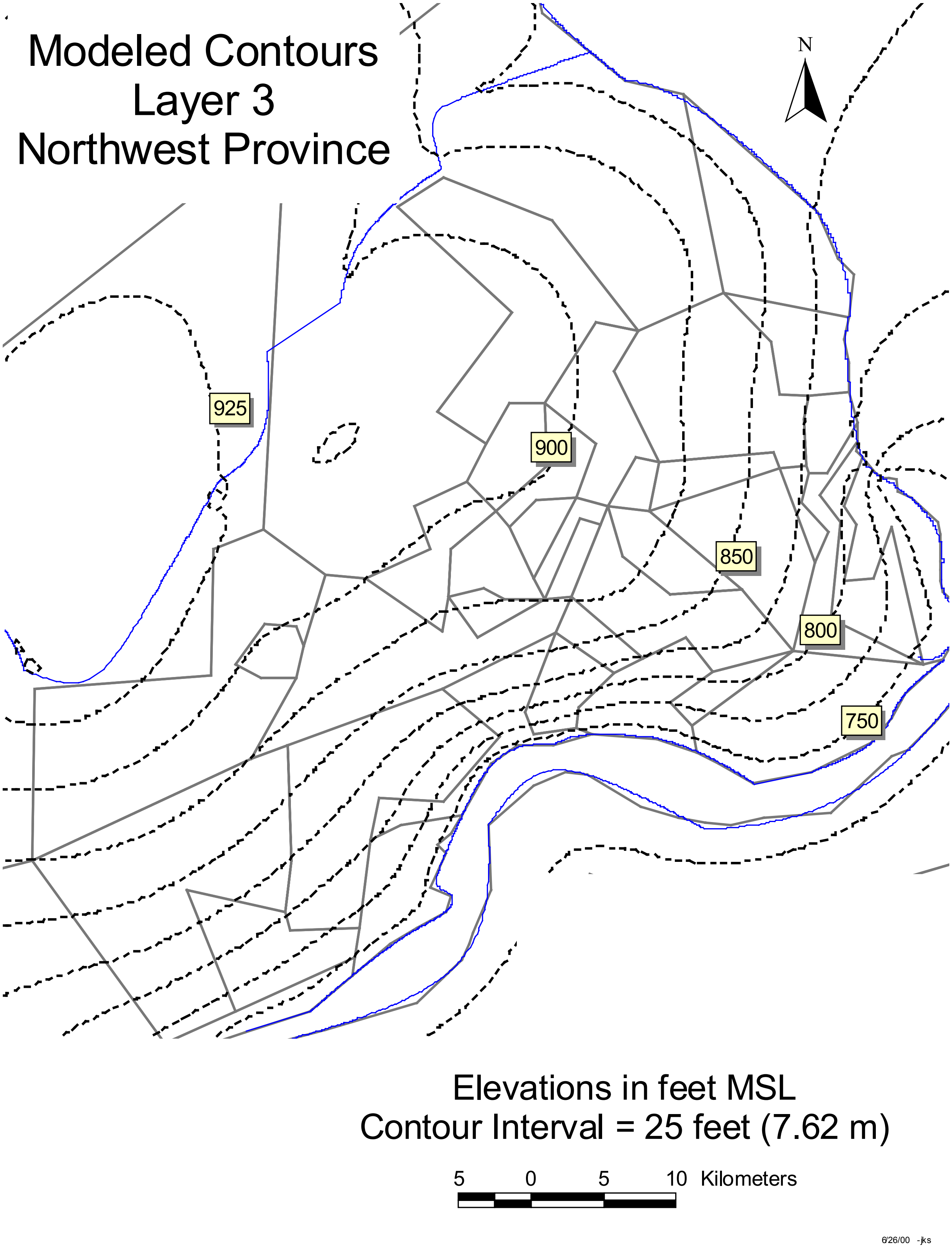


Figure 22. Layer 3 Modeled Piezometric Contours

Figures 19 and 20 illustrate the calibration plot and modeled piezometric surface, respectively, for Layer 2. The mean absolute difference of modeled minus measured heads for Layer 2 was 3.14 m (Table 3), indicating a similar fit to measured heads in the Layer 1 model. The area for which calibration points are present is significantly smaller than for Layers 1 or 3 due to the limited areal extent of the St. Peter Sandstone in the metropolitan area. No striking clusters or anomalies are present in the calibration plot for Layer 2.

The Layer 3 model had a value for the absolute mean difference between modeled and measured heads of 3.26 m. The calibration plot and modeled piezometric surface for Layer 3 are presented in Figures 21 and 22, respectively. Inspection of the calibration plot shows that a wide range of variability exists, and that, in general, no significant trends or clusters are readily discernible. A possible exception to this is the presence of a zone of calibration points where the model produced low heads along the Minnesota River valley in Bloomington in the area encompassed by polygon **WH-24**. Possible causes of this "dry" zone in the model may include assignment of unrepresentative boundary heads for the Minnesota River, system heterogeneity, and local pumping effects. Local modeling in this area will require better representation of the hydrogeology in the model input parameters.

Comparison to Measured Discharges

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. Additionally, the complexity of structural geology and geomorphology in the Northwest Province further complicate the hydrogeologic conceptual model, resulting in difficulties in associating the source or sources of groundwater to field discharge measurements. Also, 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 two tributary streams to the Minnesota River—Carver and Nine Mile Creeks. The data were provided by personnel from the Metropolitan Council and analyzed by project staff. Following reduction and analysis of the data, the focus was placed on the lower reaches of the streams near the Minnesota River. When the streams were individually placed in the model, the modeled discharges did not consistently provide favorable comparisons to the measured results. This is because the streams are very localized features that were placed in a regional model. Without refining the local hydrogeologic conditions in the vicinity of the streams, the model cannot be expected to produce representative discharges. However, since discharge from the lower portions of the streams is very near the Minnesota River valley, these rates are assumed to reflect groundwater discharge to the

Minnesota River valley. Therefore, the discharge values from the lower reaches of Carver and Nine Mile Creeks are used to compare against model discharges to the Minnesota River valley linesinks.

Table 4 presents a summary of the analysis of the discharge data for the lower portions of Carver and Nine Mile Creeks. The discharge rates are quite consistent between the two creeks, ranging from 1.2 m^3/day-m to 1.7 m^3/day-m for Carver Creek, and 0.5 m^3/day-m to 1.7 m^3/day-m for Nine Mile Creek. The mean of all values for both creeks is 1.3 m^3/day-m. These values are compared against the discharge computed for the northern side of the Minnesota River valley for the Northwest Province model. Hydrogeologic complexity does not allow us to determine the relative contributions of the separate aquifers to the discharge of these streams. If the hydraulic connection between the lower reaches of the creeks and the lower aquifers is attenuated or absent, the summed modeled discharge for all three layers from the Northwest Province to the Minnesota River would be expected to exceed the measured discharge. Therefore, comparisons of the measured discharge rates will be made to the Minnesota River linesinks for the total composite discharge of all three layers, as well as individual aquifer layers.

Table 4
Summary of Discharge Data to Lower Reaches of Carver and Nine Mile Creeks

		Measured Stream Discharge	
Location	Time of Occurrence*	m^3/sec*m stream	m^3/day*m stream
Carver Creek	**23-Feb-99**	1.43E-05	1.2
	September	1.46E-05	1.3
	October	1.84E-05	1.6
	November	1.92E-05	1.7
Nine Mile Creek	**23-Feb-99**	5.28E-06	0.5
	September	1.42E-05	1.2
	October	1.50E-05	1.3
	November	1.96E-05	1.7

* Values other than February 23, 1999 are mean values for the years 1989 through 1996.

The computed discharges from the Northwest Province model are presented in Table 5 for each individual line-sink in each of the three aquifer layers. The curvilinear string name is presented in the first column, followed by the string lengths, estimated using Arcview, in the second column. The discharge values for each string, computed using MLAEM, in each of the three layers are presented in the next three columns. The next three columns provide the discharge per unit length for each string, again for each of the three layers. The sum total discharge from all three layers is presented in the far-right column. As additional data become available, comparisons to the modeled results will be made, and the model will be adjusted accordingly.

Although modeled discharge data are presented for all Northwest Province curvilinear line-sinks in Table 5, our current focus is on strings **MinnR_Seep_N1** through **MinnR_Seep_N5**, since they provide the modeled discharge to the Minnesota River valley. Mean discharge rates, weighted to string length, were calculated for the entire length encompassed by these five strings for each aquifer layer as well as the composite total for all three aquifers.

Table 5
Modeled Discharge to Curvilinear Line-Sinks
Northwest Province

Curvilinear String	Approximate Length (m)	Computed Stream Discharges (m^3/day) Layer 1	Layer 2	Layer 3	(m^3/day*m stream) Layer 1	Layer 2	Layer 3	Total
Crow_River	68000	1.15E+05	1.03E+04	4.80E+04	1.7	0.2	0.7	2.5
W_MissR_Anoka	60000	7.01E+04	8.36E+03	2.36E+04	1.2	0.1	0.4	1.7
W_MissR_Fridley	19000	5.28E+04	2.97E+03	6.18E+03	2.8	0.2	0.3	3.3
W_MissR_St_Peter-1	9900	3.95E+04	9.61E+03	8.48E+04	4.0	1.0	8.6	13.5
W_MissR_St_Peter-2	7200	1.23E+04	1.33E+04	1.22E+04	1.7	1.9	1.7	5.3
MinnR_Seep_N1	12300	2.22E+04	2.73E+03	2.30E+04	1.8	0.2	1.9	3.9
MinnR_Seep_N2	11400	1.64E+04	7.81E+03	2.77E+04	1.4	0.7	2.4	4.5
MinnR_Seep_N3	16000	3.70E+04	1.47E+04	8.78E+04	2.3	0.9	5.5	8.7
MinnR_Seep_N4	10000	6.43E+03	2.42E+03	2.19E+04	0.6	0.2	2.2	3.1
MinnR_Seep_N5	13800	6.45E+03	3.73E+03	3.60E+04	0.5	0.3	2.6	3.3
MinnR-Coarse-South	68000	1.05E+05	1.20E+04	8.14E+04	1.5	0.2	1.2	2.9
Upper_Minnesota_R	160000	1.80E+05	2.20E+04	1.17E+05	1.1	0.1	0.7	2.0

Results are generally consistent for the Minnesota River strings **MinnR_Seep_N1** through **MinnR_Seep_N5** within each aquifer layer. The discharge rates in Layer 1 range from 0.5 m^3/day-m to 1.8 m^3/day-m, with a weighted mean of 1.4 m^3/day-m, comparing favorably to the measured mean of 1.3 m^3/day-m. The discharge rates for Layer 2 are considerably less, ranging from 0.2 m^3/day-m to 0.9 m^3/day-m, with a weighted mean of 0.5 m^3/day-m. The summing of these rates, representing discharge from the top two aquifers, still yields values that comfortably compare to the measured values. However, the computed discharge to the Minnesota River in Layer 3 is higher, ranging from 2.2 m^3/day-m to 5.5 m^3/day-m, with a weighted mean of 3.0 m^3/day-m. These Layer 3 rates by themselves exceed the measured rates.

If the measured discharge rates truly reflect discharge from all three aquifers, comparisons should be made to the computed total discharge. The computed total discharge rates represent maximum values for comparison to the measured discharge values. The composite total of discharge from all three layers ranges from 3.3 m^3/day-m to 8.7 m^3/day-m, with a weighted mean of 5.0 m^3/day-m. This total discharge exceeds the measured rates (maximum of 1.7 m^3/day-m, and mean of 1.3 m^3/day-m). However, even under this worst case scenario, the maximum rates are easily within an order of magnitude of the measured rates, with the weighted mean representing a four-fold increase over the measured mean. This represents a reasonable agreement between the model and field measurements. Additionally, other factors introduce sources of variability to the field measurements. Two such factors that would contribute to lower measured discharge values are 1) partial penetration—the streams may not actually receive water from all three aquifer layers; and 2) groundwater pumping that has not been accounted for, which would reduce the amount of water reaching the streams. Also, the orientation of the tributary creeks are more closely aligned with the groundwater flow direction than the Minnesota River valley walls, which are essentially perpendicular to flow. Therefore, variations in the amount of water captured per unit stream length could be a function of this difference in geometry. Also, the expected variability of a natural system will introduce complexity that will not be reflected in the model, resulting in differences in discharge rates.

Inspection of Table 5 indicates discharge rates to be generally consistent within all three aquifer layers. The discharge rates associated with the Minnesota River valley line-sinks, which compare well with field data, are similar to the others in the model. Because no great variability exists within the model, major differences in the discharge rates are not expected. Therefore, the consistency in the recharge rates in each layer boosts confidence that discharge rates throughout the regional model and, hence, the regional water balance, are reasonable.

High Capacity Well Discharge

Following the calibration procedures in which leakage rates were adjusted to fit the model to calibration targets of measured heads and discharge measurements, pumping discharge rates of high capacity wells were entered in the model for the 1995 pumping season. These discharge rates were taken from the Minnesota DNR's groundwater appropriations database, known as the State Water Use Data System (SWUDS) (MDNR, 2000). The purpose for adding the well extraction rates was to evaluate their effect on the flow systems and to determine how best to include them in applications of the model.

The high capacity pumping dataset was constructed using SWUDS wells essentially from Hennepin and Carver Counties, with the exception of pumping wells in Hennepin County on the east side of the Mississippi River that were removed from the datasets for Layers 2 (six wells) and 3 (five wells). Also, the Layer 1 high capacity dataset includes pumping from wells to the west of the Northwest Province that were inadvertently included. Current resources do not permit removal of these wells, especially considering that they exert no significant impact on Layer 1 heads within the Northwest Province, since the Crow River serves as a solid hydraulic boundary. Input of pumping data into Layer 1 included pumping occurring from all aquifer horizons of the Quaternary Glacial Drift Aquifer, including the water table, even though the model is calibrated to head data collected from only buried drift. Layer 3 pumping data includes extraction from wells that are screened in the Prairie du Chien Group, the Jordan Sandstone, as well as both formations together. Also note that the locations of SWUDS wells may be coincident with the head calibration points. Heads measured in SWUDS wells are not likely to reflect the head within the aquifer while the wells are pumping. Therefore, future work on the model should include removal from the calibration dataset of those wells that are part of the SWUDS database, for regional calibration of the model with the inclusion of high capacity pumping wells.

The addition of the pumping wells to the model affected each layer differently. The mean absolute difference values between modeled and measured heads are given in Table 6 for both the pumped and unpumped conditions. Because the model was already calibrated by adjusting leakage rates before the addition of the high-capacity pumping wells, the mean absolute difference would be expected to increase since the extraction of water from these wells was already intrinsically accounted for in the leakage rates that were used. The more significant the extraction rate is for a layer, the greater the mean absolute difference will be for pumped conditions.

Table 6 indicates an insignificant decrease in the mean absolute difference in Layer 2 (0.01 m) with the addition of the 1995 SWUDS pumping data for the Northwest Province—not a surprising result, given that only two pumping wells were entered for the St. Peter Sandstone. However, large differences occur with the addition of pumping reported in the 1995 SWUDS database for Layers 1 and 3. The mean absolute difference between computed and measured values increased from 3.10 m to 11.39 m for Layer 1 and from 3.26 m to 9.86 m for Layer 3 with the addition of the pumping wells. This is also illustrated in the calibration plots presented below.

Table 6

Mean Absolute Difference Values
(in meters)

	Layer 1	Layer 2	Layer 3
Without High Capacity Wells	3.10	3.14	3.26
With High Capacity Wells	11.39	3.13	9.86

Calibration plots for Layers 1, 2, and 3 with the discharge from SWUDS wells are presented in Figures 23, 24, and 25, respectively. A comparison of the calibration plot for Layer 2 to the non-pumped conditions (Figure 19) shows little noticeable difference in the calibration plots, consistent with the small difference between the mean absolute values. As previously stated, little change was expected since only two pumping wells were entered.

The greatest response to the addition of the high-capacity production wells occurred in Layers 1 and 3, evidenced by the increase in the mean absolute differences of at least 6 meters, and inspection of the calibration plots that include pumping (Figures 23 and 25, respectively) and those that do not (Figures 17 and 21, respectively). The addition of the pumping wells has significantly dried out the aquifers . This indicates that the pumping effects of the high-capacity wells in both the Glacial Drift and Prairie du Chien-Jordan Aquifers, while very significant, are already reflected in the leakage rates of Northwest Province prior to their inclusion in the model.

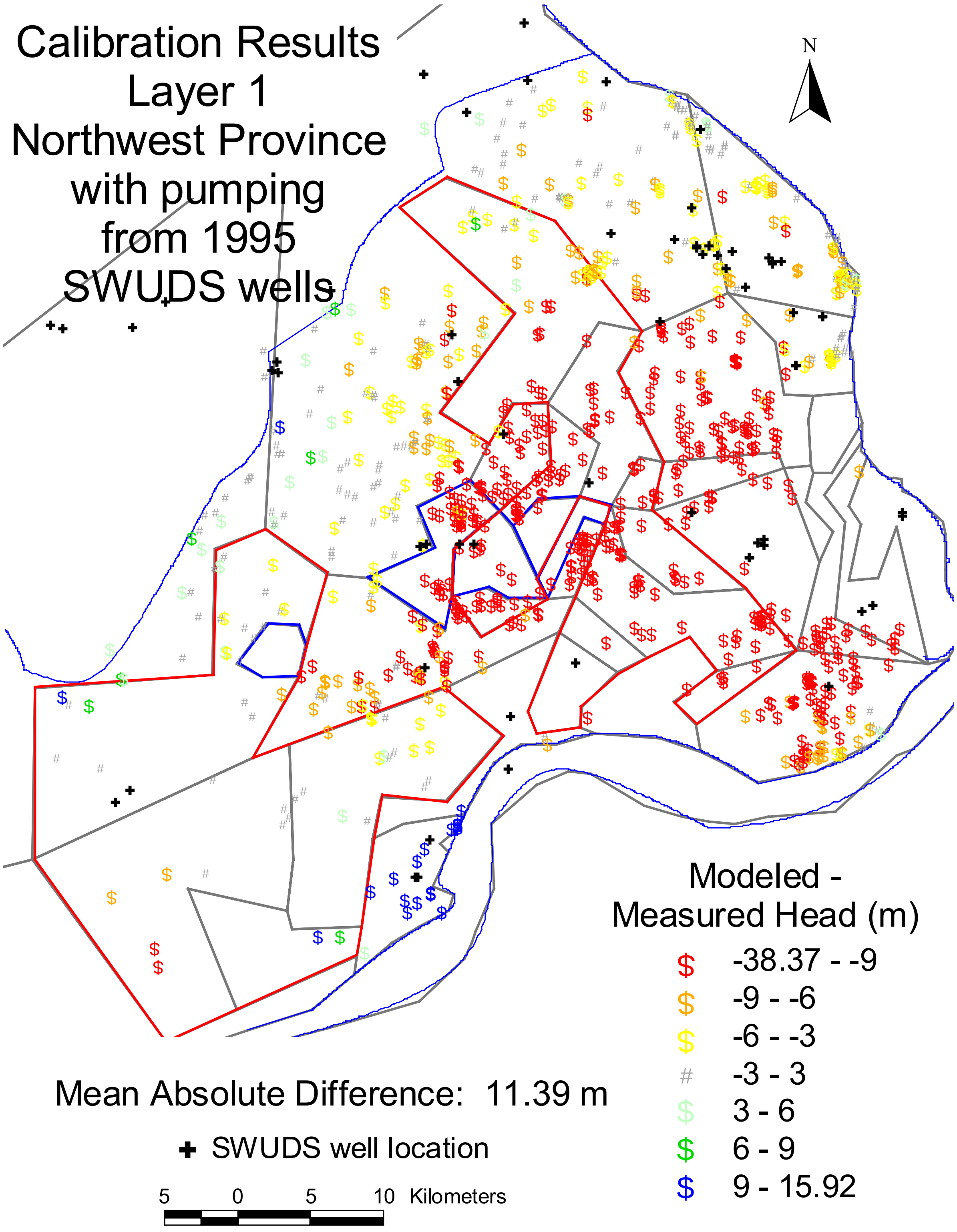


Figure 23. Calibration Plot for Layer 1 with High Capacity Pumping.

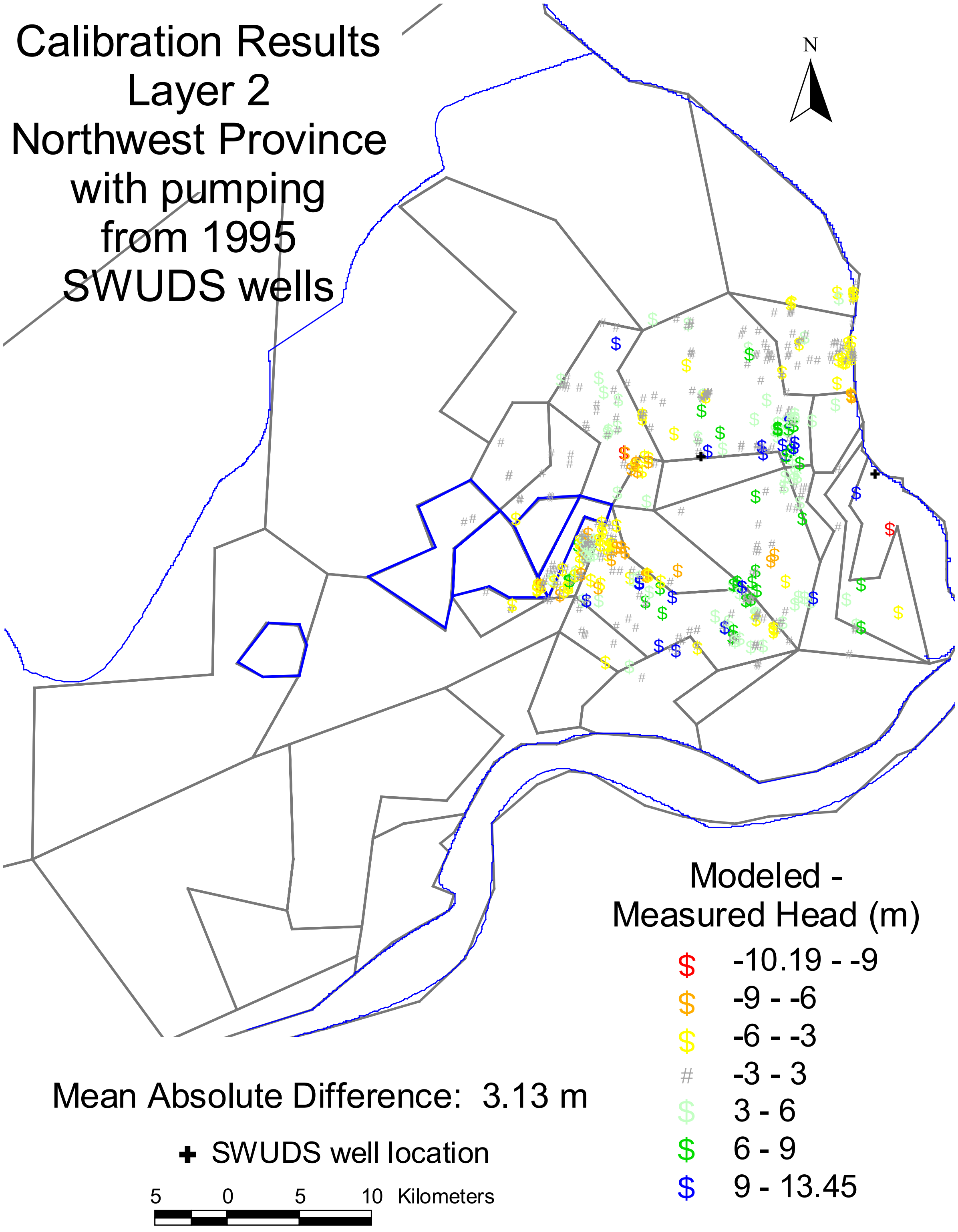


Figure 24. Calibration Plot for Layer 2 with High Capacity Pumping

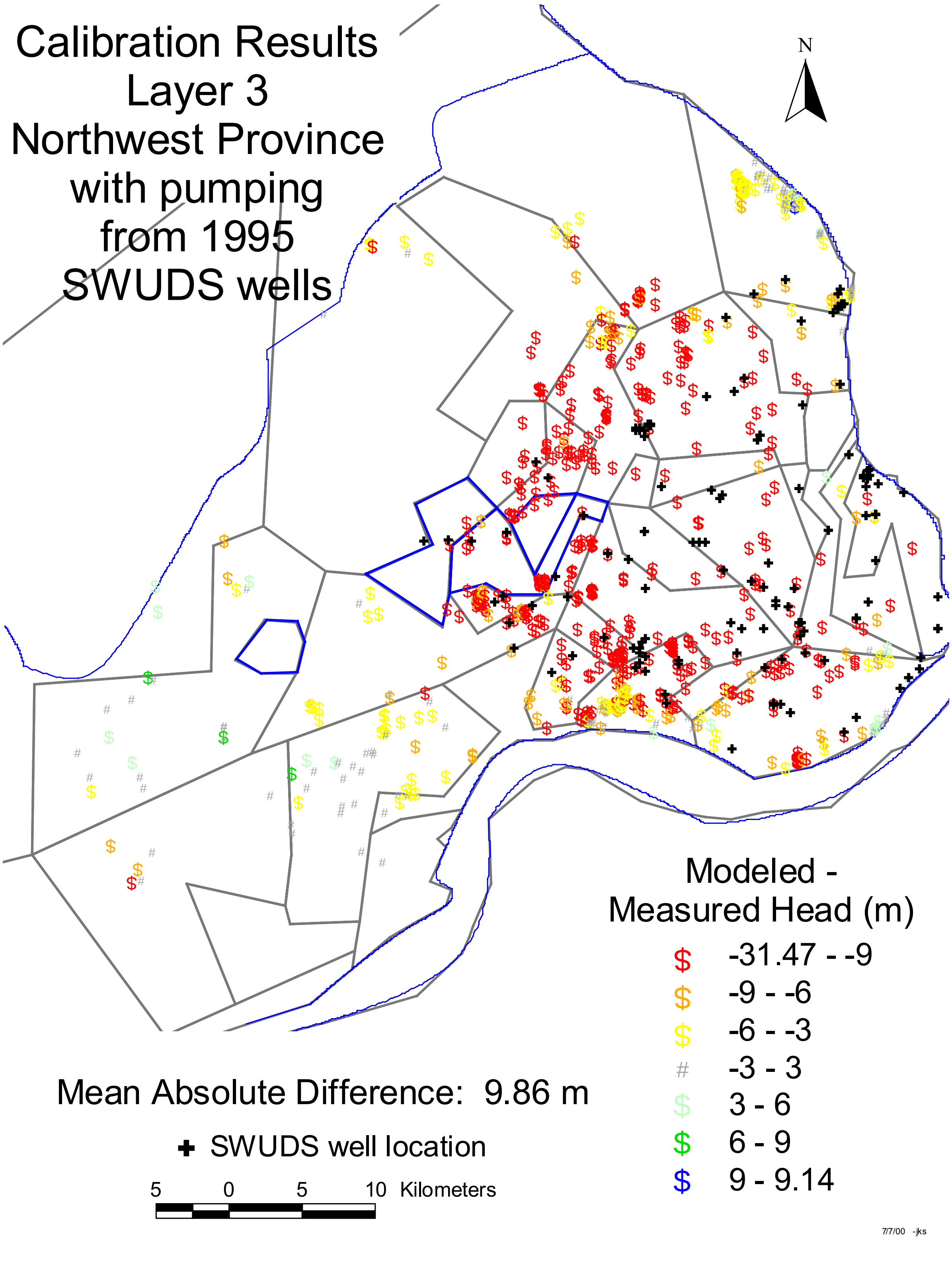


Figure 25. Calibration Plot for Layer 3 with High Capacity Pumping

In general, pumping extraction is already reflected in the leakage rates that were determined before adding in the high capacity pumping wells. Regional flow and leakage conditions can be better simulated by using these leakage values without explicitly adding the pumped wells. However, pumping wells will be required locally for site-specific models in the area of interest to reflect local flow conditions. Ideally, the model would be calibrated again with the inclusion of the high capacity pumping wells by adjusting the leakage rates. This would entail a careful and detailed examination of high capacity well data, and most likely should view pumping data over a period of years. In the meantime, a local model scenario that starts with this regional model could include pumping wells placed around the areas of interest along with leaky and/or resistance elements that would replace the given strength elements that are found between aquifer layers. Current resources do not yet permit further exploration of modeling with the inclusion of the pumping wells. Therefore, local modeling should be conducted by 1) including the high capacity pumping wells in the area of interest, 2) adjusting the leakage values locally to recalibrate the model, 3) replacing these given-strength leakage values between aquifers with leaky elements, and 4) proceeding with the local model development.

Head Differences—an Internal Consistency Check

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 using the model with the given-strength approach to leakage. This type of simulation can be achieved by replacing given-strength VARELs with leaky VARELs. In a real aquifer 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 in the Northwest Province has been prescribed as downward in most of the polygons. This implies, in a natural system, that heads decrease moving downward through the aquifer system. Zones within the model that have a vertical upward gradient are not congruent with the direction of groundwater flow. Identification of these zones can serve as an indicator of problem areas within the model. Evaluation of the head differences provides a good internal consistency check for the model.

A grid of modeled head values for each aquifer was constructed at a density that readily allows graphical depiction of the head differences between aquifers. Gridded differences in head between aquifers were plotted in the following two figures 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 of head difference, while the gray color-coding represents zones of relatively small head difference (+/- 3 m). Zones represented by gray are not considered to be problematic, even if upward leakage is implied 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 26 illustrates a grid of head difference between Layers 1 and 2 in the metropolitan area and implies that leakage driven by head differences would be either downward or neutral except for the three areas depicted in yellow and orange. This is reasonably consistent with the specified flow directions. The gray area, predominating the northern portion of the Northwest Province, indicates that the head difference is less than 3 m, representing relatively neutral conditions. This head difference, although small, may be positive, suggesting a vertical downward gradient between Layers 1 and 2, or negative, indicating a vertical upward gradient. Moving towards the confluence of the Mississippi and Minnesota Rivers in the southeast, the head differences are indicative of conditions representing downward flow, with intensity increasing towards the river. This is attributable to the difference in boundary condition elevations for the two aquifers at the rivers—Layer 1 represents seepage face conditions along the bluffline, and Layer 2 represents the surface water level in this zone. The other main area showing the greatest vertical downward gradient occurs mostly in Carver County, and roughly coincides with the low hydraulic conductivity inhomogeneity there. It seems reasonable that significant vertical downward gradients would be present in glacial drift materials where till terrane predominates. Although the Layer 2 St. Peter Sandstone is essentially absent in this area, boundary conditions in Layer 2 that are similar to those in Layer 1, would likely produce a similar head distribution resulting in the strong downward vertical gradient indicated in Figure 26.

Three areas have head differences exceeding 3 m that would suggest upward leakage, all lying roughly within Hennepin County (Figure 26). However, the Layer 2 St. Peter Sandstone aquifer is essentially absent in these areas, so the data do not really indicate a head difference between the glacial drift aquifer and the St. Peter Sandstone aquifer. Unless Layer 2 in these areas is to be used as a subdivision of the glacial drift aquifer for site-specific modeling, it is hard to attach meaning to the head differences where the Layer 2 aquifer is absent.

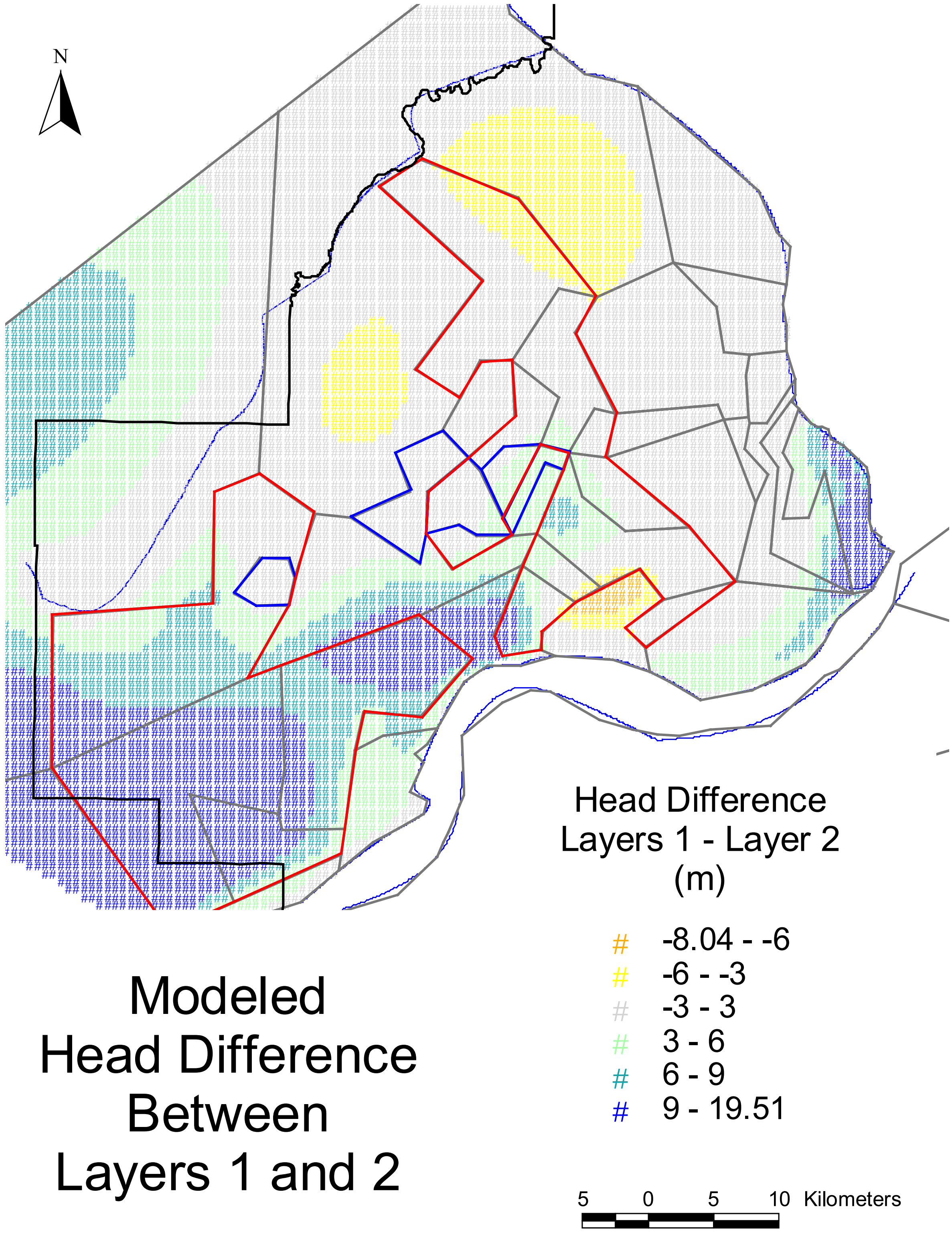


Figure 26. Grid of Modeled Head Difference
Layer 1 – Layer 2

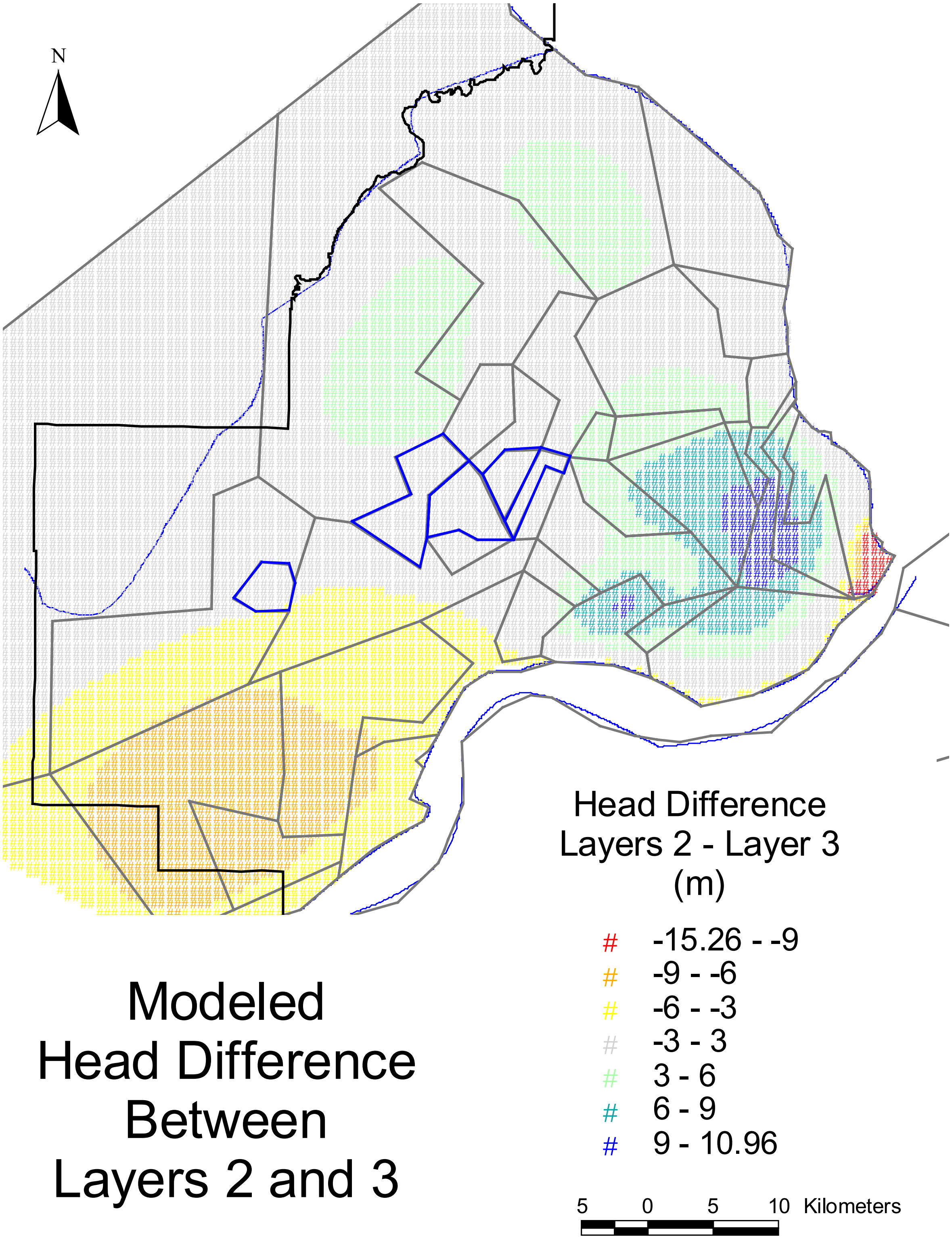


Figure 27. Grid of Modeled Head Difference
Layer 2 – Layer 3

The grid of head difference between Layers 2 and 3 is illustrated in Figure 27, and indicates fairly neutral differences (+/- 3 m) throughout much of the Northwest Province. Head differences indicating vertical downward leakage between the two layers are especially prominent in the southeastern portion of the Northwest Province, likely an artifact of heavy pumping within the Prairie du Chien-Jordan Aquifer being reflected in the head calibration dataset in this area. Two zones of vertical upward gradients are seen—one in the southwestern portion, predominantly in Carver County, and one near the confluence of the Mississippi and Minnesota Rivers. The southwestern zone occurs in an area where the St. Peter Sandstone and most of the Prairie du Chien-Jordan Aquifer are absent so the data do not really indicate a head difference between the St. Peter Sandstone and Prairie du Chien-Jordan Aquifers. The more intense vertical upward gradient seen near the confluence of the Mississippi and Minnesota Rivers is the consequence of the boundary heads assigned for each aquifer—Layer 3 input heads representing confined conditions, are higher than the assigned seepage face elevation. Care needs to be exercised to appropriately apply the Metro Model in these areas.

The plots of head differences above were constructed as an internal check on the consistency of the Northwest Province model of Layers 1, 2, and 3, and to indicate potential problem areas. Future investigation, necessary to better characterize the nature of groundwater flow in the area, should help confirm or refute the findings from the analysis of modeled head differences and help to resolve internal inconsistencies. These factors might include interactions between aquifers, inhomogeneities, areal extent of aquifers, as well as other complexities. Site-specific modeling efforts should be conducted in the context of this analysis so that leakage and modeled head differences are consistent with each other.

Estimated Hydraulic Resistance

Site-specific applications of the Metro Model that require accounting for the interactions between aquifers will require that given-strength areal elements be replaced with leaky elements between aquifers. Hydraulic resistance values, equivalent to the aquitard thickness divided by its vertical hydraulic conductivity, are assigned to leaky areal elements. The hydraulic resistance may be defined by the following equation:

$$c = \frac{(\phi_2 - \phi_1)}{\gamma}$$

where:
- c = hydraulic resistance of the aquitard
- ϕ_1 = head in the aquifer above the aquitard
- ϕ_2 = head in the aquifer below the aquitard
- γ = leakage through the aquitard

Since the model computes heads for each of the aquifer layers, and the leakage is specified as given-strength values for each aquitard, or separating layer, values of hydraulic resistance can be readily computed using the model. Figures 28 and 29 present grids of hydraulic resistance computed from these values between Layers 1 and 2 and between Layers 2 and 3, respectively. These figures might be useful for providing starting values of resistance for localized applications of the Northwest Province model. However, discretion should be exercised in using them. Note that the gray stippled zones represent areas where the vertical gradient is upward—refer to the head differences in Figures 26 and 27 to determine the magnitude of the head differences. Because these zones are not consistent with the prescribed downward leakage through the aquitards, resistance values cannot be calculated. The regional nature of the model does not permit the accurate modeling of heads on a localized basis. Hence, vertical upward gradients could be readily 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. For example, the plots imply continuous coverage of the aquitard across the domain of the entire Northwest Province. However, the St. Peter Sandstone and Prairie du Chien-Jordan aquifers have limited areal extents.

Despite the limitations of applying these estimates of hydraulic resistance to aquitards, these values may still be of some use if applied with caution. Although the plots do not provide a continuous field of resistance across the Northwest Province, they can provide some initial estimates where present. These values would serve as a starting point for local scale models, and would likely undergo modification during model construction and calibration procedures.

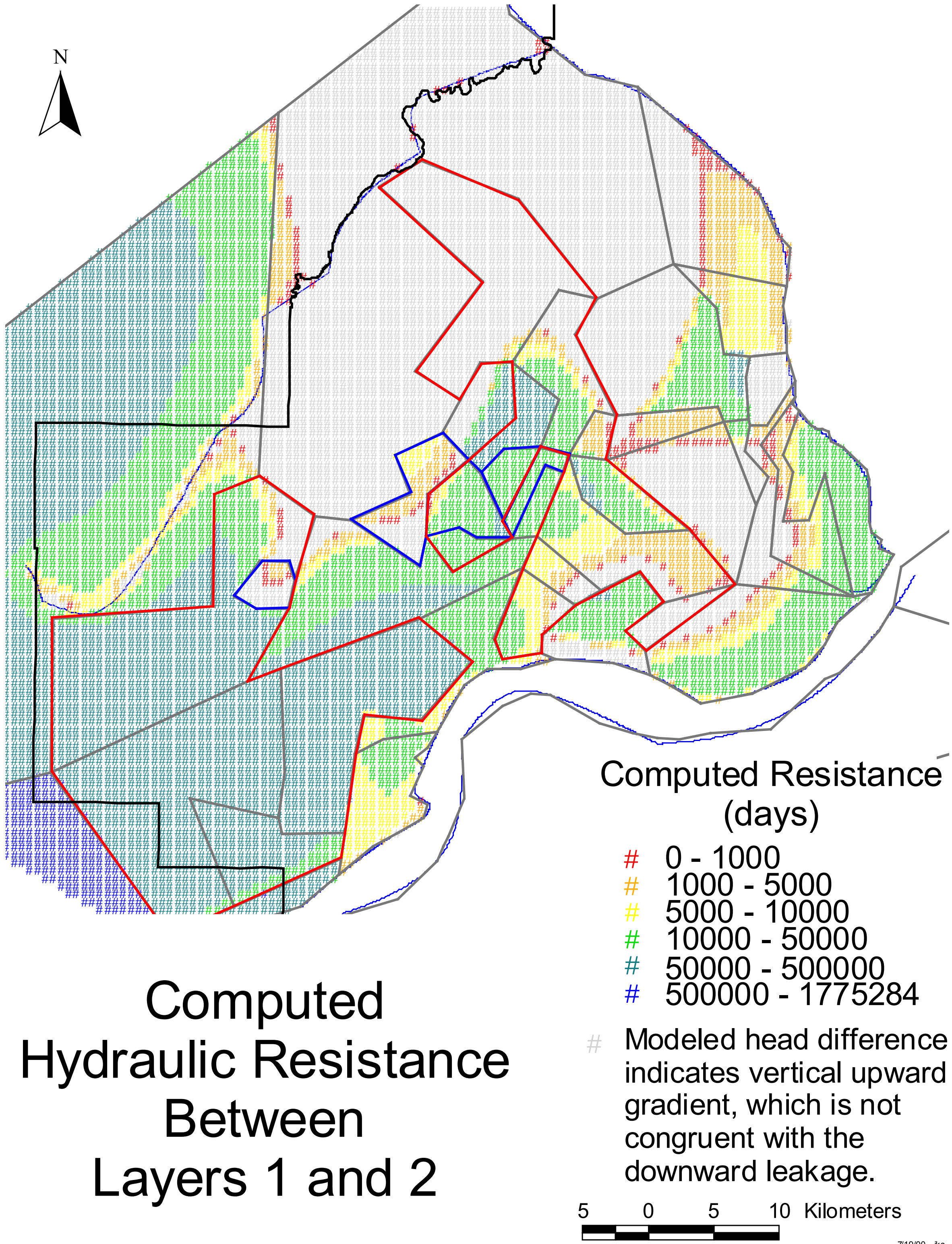


Figure 28. Grid of Hydraulic Resistance Between Layers 1 and 2

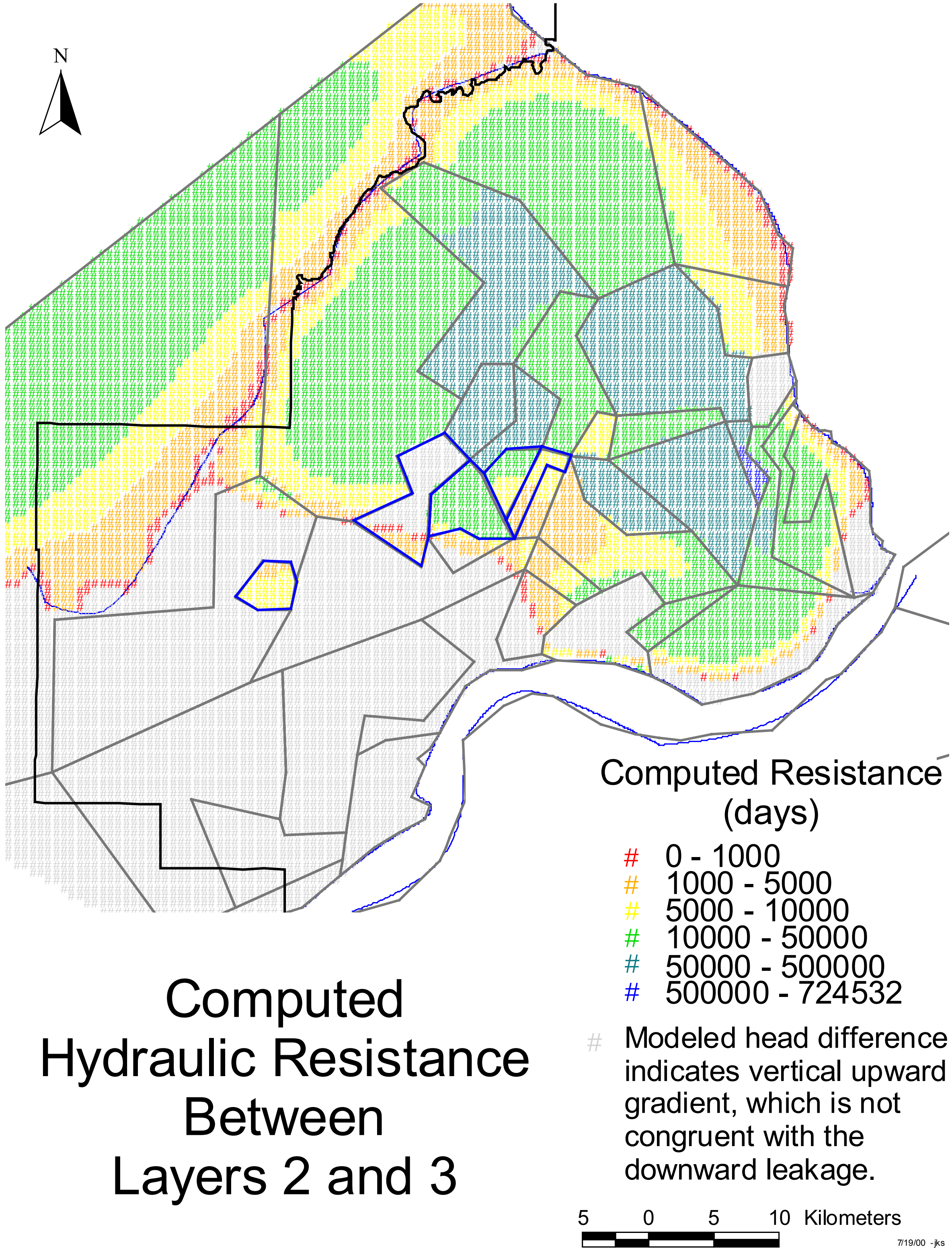


Figure 29. Grid of Hydraulic Resistance Between Layers 2 and 3

Data Files, Version 1.00

A brief description of the data files that comprise the Northwest Province model (Version 1.00, July 2000) for Layers 1, 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 (www.pca.state.mn.us/water/groundwater/metromodel.html).

General Model Datasets:

w_setup.dat	Commands to MLAEM software, and specification of graphical window.
w_aq.dat	Global aquifer parameters for Layers 1, 2, and 3.
polyriv.dat	Polygons defining the Mississippi, Minnesota, and St. Croix River valleys.
w_poly.dat	Polygon mesh for Northwest Province, including both infiltration and inhomogeneity polygons.
w_crr_cu.dat	Curvilinear strings for Crow River.
w_msr_cu.dat	Curvilinear strings for Mississippi River and associated seepage faces.
w_mnr_cu.dat	Curvilinear strings for Minnesota River.

Quaternary Aquifer—Layer 1 Datasets

w1_ntop.dat	Infiltration rates for polygons on top of Layer 1; can be considered the total infiltration for the entire three-layer aquifer system.
w1_msr.dat	Boundary conditions (elevation heads) for relevant portions of the Mississippi River and associated seepage faces.
w1_mnr.dat	Boundary conditions (elevation heads) for relevant portions of the Minnesota River and associated seepage faces.
w1_crr.dat	Boundary conditions (elevation heads) for Crow River.
w1_inh.dat	Hydraulic parameters and doublets for the two inhomogeneities (Low_K-1 and –2) representing less permeable glacial drift.
w1_nbot.dat	Leakage out of bottom of Layer 1 specified for each polygon—same as leakage into the top of Layer 2.

St. Peter Sandstone Aquifer—Layer 2 Datasets

w2_ntop.dat	Leakage into top of Layer 2 specified for each polygon—same as leakage out of the bottom of Layer 1.
w2_msr.dat	Boundary conditions (elevation heads) for relevant portions of Mississippi River.
w2_mnr.dat	Boundary conditions (elevation heads) for relevant portions of Minnesota River.
w2_crr.dat	Boundary conditions (elevation heads) for Crow River.

w2_nbot.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

w3_ntop.dat	Leakage into top of Layer 3 specified for each polygon—same as leakage out of the bottom of Layer 2.
w3_msr.dat	Boundary conditions (elevation heads) for relevant portions of the Mississippi River.
w3_mnr.dat	Boundary conditions (elevation heads) for relevant portions of the Minnesota River.
w3_crr.dat	Boundary conditions (elevation heads) for Crow River.

Call File for Northwest Province Layers 1, 2, and 3 Model

callnw.dat	Version 1.00 call file dataset for the Northwest Province Layers 1, 2, and 3; calls the model datasets described above.

The files described above are all that are needed to run the Northwest Province model of Layers 1, 2, and 3. However, some additional files presented below may be of use to the modeler. 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 MDNR's SWUDS groundwater appropriations database (MDNR, 2000) for the 1995 pumping year. Datasets for other years can be constructed on request. These datasets are to be entered separately. As previously mentioned, Version 1.00 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:

w1qswd95.dat	High capacity pumping well discharge in the Glacial Drift Aquifer taken from the 1995 SWUDS database, averaged over the entire year; for use in Layer 1.
w2qswd95.dat	High capacity pumping well discharge in the St. Peter Sandstone Aquifer taken from the 1995 SWUDS database, averaged over the entire year; for use in Layer 2.
w3qswd95.dat	High capacity pumping well discharge in the Prairie du Chien-Jordan Aquifer taken from the 1995 SWUDS database, averaged over the entire year; 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 (Seaberg, 2000), these data were geostatistically winnowed from 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 regional calibration datasets are split up according to model layer:

w1_cal2.dat	Head calibration dataset for Layer 1, developed from measured static water levels in the buried Glacial Drift Aquifer.
w2_cal2.dat	Head calibration dataset for Layer 2, developed from measured static water levels in the St. Peter Sandstone Aquifer.
w3_cal2.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 Northwest Province portion of the Metro Model for Layers 1, 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 1.00. 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.

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