Twin Cities Metropolitan Area Regional Groundwater Flow Model Version 2.00

Technical Report in Support of the Metropolitan Area Master Water Supply Plan

October 2009

Draft

Table of Contents

List of Tables

List of Figures

INTRODUCTION

PROJECT NEED

The 2005 Minnesota Legislature directed the Metropolitan Council to “carry out planning activities addressing the water supply needs of the metropolitan area” (Minnesota Statutes, Section 473.1565). Specifically, the Council is charged with developing a base of technical information for water supply planning decisions and to prepare a metropolitan area master water supply plan. The goal of these efforts is to guide sustainable water use in the Twin Cities metropolitan area. In order to address the legislature’s directive, the Council prepared a Metropolitan Area Master Water Supply Plan composed of a robust water availability analysis, the community profiles that ensuing from it, and the datasets that underlie it. These core pieces together constitute the Metropolitan Area Master Water Supply Plan.

Developing a modern regional groundwater flow model was determined to be the best approach to assess water supply availability under projected water demand conditions, and the resulting regional model serves as the foundation of the Metropolitan Area Master Water Supply Plan. Regional numerical groundwater flow modeling has been a component of Twin Cities metropolitan area water resource planning for decades. The United States Geological Survey developed a regional groundwater flow model in the late 1980’s with the purpose of testing possible effects of projected groundwater withdrawals from the Prairie du Chien-Jordan and drift aquifers in the Twin Cities metropolitan area The Minnesota Pollution Control Agency’s Twin Cities Metropolitan Groundwater Model Version 1.00 (Metro Model), developed in the 1990’s, was very successful in compiling hydrogeologic data into a single data repository, including the development of the base elevations of key bedrock aquifers and aquitard units and a cross-correlated calibration data set of groundwater level measurements. The Metro Model also laid out a conceptual model of the region’s groundwater flow system that is still in use today. In addition, several smaller-scale models have been developed over the last decade. They have been used for a wide variety of projects, including wellhead/source water protection, siting of new municipal wells, evaluation well interference effects, and addressing the impacts on trout streams and calcareous fens.

Use of existing local and sub-regional groundwater models was considered, but development of a new model was pursued because recent developments in modeling code and computing power have made it easier to accommodate greater spatial resolution and variable pumping conditions and to model substantial changes in the base elevation of aquifers. In addition, the long-term goal of intrinsically considering groundwater availability throughout the land use planning process warranted the construction of a new region-wide model that is more compatible with geographic information system (GIS) datasets and more portable between water supply planners in both the public and private sectors. Information from previous groundwater flow modeling efforts, particularly the Metro Model (Version

1.00), was used in the development of the new Metro Model (Version 2.00).

This tool is intended to be used to evaluate potential impacts of changes in groundwater withdrawals on water resources at the regional level. The model may also be refined to address more local problems. Model results are a substantial component of the water availability analysis supporting the Metropolitan Area Master Water Supply Plan.

GOALS & OBJECTIVES

The overarching purpose of this modeling effort is to create a groundwater flow model that allows land use and water utility planners across the metropolitan area to consider both groundwater availability and land use during their planning processes. Results of this process were used in the development and implementation of the Metropolitan Area Master Water Supply Plan.

The project was undertaken with the specific objectives of 1) integrating the best available hydrogeologic, land use, and water demand data into a regionally-consistent package; 2) developing consensus on a groundwater flow modeling approach and hydrogeologic conceptual model of the metropolitan area groundwater flow system; 3) constructing and calibrating a regional groundwater model; 4) developing model GIS coverages of new data; 5) develop a tool to predict conditions in all major metropolitan area aquifers and aquitards under a variety of demand and land use scenarios; and 6) providing public access to data and analysis tools for local assessments.

The Metropolitan Council has taken on the responsibility of constructing, maintaining and providing access to this new regional model to incorporate the salient characteristics of existing models and extend a uniform assessment method across the Twin Cities metropolitan area. This responsibility includes incorporating changes to previous conceptual hydrogeologic models resulting from continued hydrogeologic mapping and analyses, collecting and synthesizing field data for improved model calibration, and using widely accepted and portable modeling code.

GENERAL APPROACH

The Metropolitan Council contracted Barr Engineering Company to construct and calibrate a numerical groundwater flow model of the Twin Cities metropolitan Area; this process also included the development of a recharge model (Barr Engineering Company, 2007 and 2008). The project team included:

Chris Elvrum, Manager, Metropolitan Council Water Supply Planning
(651) 602-1066
Christopher.Elvrum@metc.state.mn.us
Project Resource: Project development, project management, and model application

Lanya Ross, Senior Environmental Scientist, Metropolitan Council Water Supply Planning (651) 602-1803 Lanya.Ross@metc.state.mn.us	
Project Resource:	Technical advisory committee coordination, Geographic Information Systems (GIS), and model application
Ray Wuolo, Vice President, Barr Engineering Company (612) 832-2696 rwuolo@barr.com	
Project Resource:	Hydrogeology, conceptual model, Geographic Information Systems (GIS), and model development, calibration and application
Evan Christianson, Hydrogeologist, Barr Engineering Company (612) 832-2957 echristianson@barr.com	
Project Resource:	Hydrogeology, conceptual model, Geographic Information Systems (GIS), and model development, calibration and application, Daily soil water balance model application

A technical advisory committee was convened to discuss data availability, the modeling approach, the hydrogeologic conceptual model, the calibration approach and the potential uses of the model. Representatives from the following organizations were present at the technical advisory meetings:

- Metropolitan Council (Chris Elvrum, Lanya Ross, Sara Smith)
- U.S. Geological Survey (Tim Cowdery, Geoff Delin, Jim Stark, Sue Langer, Chris Sanocki)
- Minnesota Pollution Control Agency (Andrew Streitz, Mindy Erickson, Sherri Kroening, Doug Hansen)
- Minnesota Geological Survey (Bob Tipping,)
- Minnesota Department of Natural Resources (Evan Drivas, Mike Liljegran)
- Minnesota Department of Health (Steve Robertson, Amal Djerrari)
- Minnesota Environmental Quality Board (Princesa VanBuren)
- Hennepin County (Joel Settles)
- Dakota County (Bill Olsen)
- Washington County (John Freitag)
- Scott County (Paul Nelson, Allen Frechette)
- University of Minnesota (Randal Barnes)
- Summit Envirosolutions (John Dustman, Brian Gulbranson)

- Short, Elliot, Hendrickson Inc. (Erik Anderson, Erik Tomlinson)
- Geomatrix (Beth Johnson)
- Bonestroo, Rosene, Anderlik & Associates (Mark Janovec, Mark Wallis)
- Emmons and Oliver Resources (Stu Grubb)
- Liesch Companies (Dave Lowell)
- Leggette, Brashears, and Graham Inc. (Dave Hume, John Oswald)

Meetings were held on: November 30, 2006; April 26, 2007; June 25, 2007; October 11, 2007; January 17, 2008, and June 18, 2008.

A technical subgroup was also convened to review model results in detail. Meetings were held on December 15, 2008 and February 9, 2009. Attendees included:

- Barr Engineering Company (Evan Christianson, Ray Wuolo)
- Metropolitan Council (Chris Elvrum, Lanya Ross)
- U.S. Geological Survey (Tim Cowdery)
- Minnesota Geological Survey (Bob Tipping)
- Minnesota Department of Natural Resources (Evan Drivas , Jeanette Leete)
- Minnesota Department of Health (Amal Djerrari)
- Dakota County (Bill Olsen)
- University of Minnesota (Randal Barnes)

Existing state and federal datasets were used as much as possible to improve consistency across the region. All of these data, along with model input and output files, were translated into GIS format if they were not already available in that format. Primary datasets include:

Organization	Dataset
Metropolitan Council	Land use mapping Stream discharge measurements Stream discharge low-flow estimates
Minnesota Department of Natural Resources	Groundwater appropriation data Lake levels Stream levels Stream discharge measurements Exchange rates between lakes and groundwater

Minnesota Department of Health	Minnesota County Well Index Aquifer test data
Minnesota Pollution Control Agency	Metro Model calibration targets Metro Model aquifer-property ranges
Minnesota Geological Survey	Geologic unit elevations and till layers
United States Geological Survey	Topography data Stream discharge measurements Stream discharge low-flow estimates Exchange rates between lakes and groundwater
United States Department of Agriculture: Natural Resources Conservation Service	Soil data
United States Department of Commerce: National Oceanic and Atmospheric Administration	Climate data

The Minnesota Pollution Control Agency's Metro Model Version 1.00 informed much of this modeling effort, including the general regional water budget, aquifer geometry, regional groundwater flow divides, and regional range of aquifer hydraulic properties. Changes to the Metro Model's conceptual model include the addition of model layers to explicitly model flow through both aquifers and aquitards, inclusion of new hydraulic conductivity zones within each model layer, and the use of the Daily Soil Water Balance method (Dripps and Bradbury, 2007) to estimate recharge to the groundwater system.

A modified version of the United States Geological Survey three dimensional finite-difference groundwater flow model MODFLOW-96 was employed through the graphical user interface Groundwater Vistas (Version 5.30 build 8). The model was calibrated to field values of hydraulic conductivity, aquifer head, and stream baseflow using the automated inverse optimization program PEST (Watermark Numerical Computing, 2005).

Model uncertainty derived from conceptual model assumptions of hydraulic conductivity variation was explored through the development and review of multiple models. Model sensitivity of the final model was analyzed, and the model was found to be most sensitive to river boundary conductance and horizontal hydraulic conductivity.

ACKNOWLEDGEMENTS The Metropolitan Council would like to thank the following individuals and organizations for their assistance with data on this project: Bob Tipping of the Minnesota Geological Survey, Steve Robertson and Amal Djerrari of the Minnesota Department of Health, Paul Juckem of the U. S. Geological Survey-Wisconsin Water Science Center, Tim Cowdery of the U.S. Geological Survey – Minnesota Water Science Center, Jeanette Leete and Evan Drivas of the Minnesota Department of Natural Resources, Jamie Schurbon of the Anoka Conservation District, Amy Herbert of the Bassett Creek Watershed Management Commission, Hilary Ziols of the Cannon River Watershed, Greg Aamodt of Carver County, Bill Olsen of Dakota County, Travis Bistodeau of the Dakota County Soil and Water Conservation District, Jennifer Olson of Emmons and Olivier Resources, Inc., Mark Janovec of Bonestroo, Inc., Udai Singh of the Minnehaha Creek Watershed District, Ned Phillips of the Rice Creek Watershed District, Ole Olmanson of the Shakopee Mdewakanton Sioux Community, Jim Almendinger of the St Croix Research Station, Travis Thiel of the Washington County Conservation District, and Randal Barnes of the University of Minnesota.

The Metropolitan Council also heartily thanks all those who participated through the technical advisory committee and the public review process.

Hydrogeologic Setting & Conceptual Model

STUDY AREA LOCATION

This regional groundwater flow modeling effort focuses on the 2,972 square mile seven-county Twin Cities metropolitan area located in east-central Minnesota and including Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, and Washington counties (Figure 1). In order to reduce artificial boundary effects at the edges of the seven-county metropolitan area, however, the model domain includes portions of adjacent counties including: Chisago, Goodhue, Isanti, LeSueur, McLeod, Rice, Sherburne, Sibley, and Wright counties in Minnesota; and Pierce, Polk, and St, Croix counties in Wisconsin.

GEOLOGIC SETTING

The geologic setting of the Twin Cities metropolitan area has been summarized in a multitude of reports. The reader is encouraged to review existing geologic maps and reports for more detailed information about local geology. ‘Bedrock Geology and Structure of the Seven-County Twin Cities Metropolitan Area, Minnesota’ (Mossler and Tipping 2000), ‘Hydrogeology of the Paleozoic Bedrock in Southeastern Minnesota’ (Runkel et al, 2003), ‘Geology in Support of Ground-water Management for the Twin Cities Metropolitan Area’ (Tipping, 2007), and ‘Paleozoic Stratigraphic Nomenclature for Minnesota’ (Mossler, 2008) are four recent reports that influenced conceptual model development, in addition to the ‘Metropolitan Area Groundwater Model Project Summary’ (Seaberg and Hansen, 2000). More general hydrogeologic information is available in other reports such as the 1992 U.S. Geological Survey ‘Ground Water Atlas of the United States: Iowa, Michigan, Minnesota, Wisconsin’ (Olcott, 1992).

A general description of the Twin Cities' geologic setting follows.

Geologic units underneath the Twin Cities metropolitan area fall into three broad categories: (1) Precambrian volcanic and crystalline rocks; (2) late-Precambrian through Ordovician sedimentary rocks; and (3) Quaternary and Tertiary unconsolidated deposits. The Precambrian volcanic and crystalline rocks generally are not considered major water-bearing units and are at a considerable depth below ground surface throughout most of the metro area. The late-Precambrian through Ordovician sedimentary rocks make up the major regional aquifers and aquitards in the metropolitan area, and include units such as the Mt. Simon Sandstone, the St. Lawrence Formation, and the Prairie du Chien Group (Figure 2a). The Quaternary unconsolidated deposits include glacial outwash, glacial till, and alluvial deposits (Figure 2b).

Groundwater flow through both bedrock and surficial units is shaped by the Twin Cities metropolitan area's geologic past. The Paleozoic sedimentary rock formations in this area were deposited in the Hollandale embayment, a depositional lowland that developed along the Middle Proterozoic Midcontinent rift system. Minor intermittent movements along the Midcontinent Rift during the Paleozoic era created numerous, small, gently folded synclines and anticlines, and faults. The Twin Cities basin and numerous smaller geologic structures like the Douglas, Pine and other faults are examples (Figure 3 and Figure 4). Continental glaciations during the Quaternary period covered earlier geologic features with a complex sequence of coarse and fine grained sediments, including multiple till layers, sand bodies, and lacustrine deposits. As a result, most of the Paleozoic bedrock that crops out in southeastern Minnesota is along major stream valleys or lies within the "driftless" area of extreme southeast Minnesota (Mossler, 2008; Tipping, 2007). These faulting, folding, and glacial processes have all influenced the development of bedrock erosional surfaces (Figure 5), including the creation of deep bedrock valleys and the complete removal of geologic units in some areas. Groundwater flow rates and directions are likewise influenced.

The hydrostratigraphic column in Figure 6 summarizes the bedrock characteristics of each geologic unit, presents reported ranges in hydraulic properties, illustrates the relationship between geologic units and major aquifers and aquitards in the Twin Cities area, and defines the regional groundwater flow model layers and model layer properties (Olcott, 1992; Runkel et al, 2003; Minnesota Pollution Control Agency, 2005).

AQUIFER PARAMETERS

The depositional environment and subsequent physical and chemical alteration of geologic units affect their hydraulic properties. The range in aquifer properties summarized in Figure 6 varies horizontally as well as vertically throughout the metropolitan area. This variation is apparent in data generated by various aquifer tests (Minnesota Department of Health, 2007a & b; Runkel et al, 2003, Runkel et al, 2004). Figure 7 illustrates measured horizontal variability in aquifer transmissivity, as determined through aquifer testing, across the Twin Cities metropolitan area. Figure 8 examines how hydraulic conductivity values vary with depth, generally supporting the conclusion that hydraulic conductivity decreases with depth. Where bedrock is only shallowly buried, weathering processes such as fracturing and secondary pore development are expected to enhance bulk aquifer hydraulic conductivity.

AQUIFER FLOW DIRECTIONS

Groundwater flows from zones of high piezometric head to zones of low piezometric head, which vary as a function of recharge, aquifer geometry, and hydraulic properties. It is generally understood, based on previous data collection and modeling, that regional groundwater flow in bedrock aquifers is from the edges of the Twin Cities metropolitan area toward the Minnesota, Mississippi, and St. Croix rivers (Olcott, 1992; Hansen and Seaberg, 2000a,b; Seaberg and Hansen 2000a,b) (Figure 9). However, pumping the Mt. Simon-Hinckley aquifer has resulted in a large cone of depression in the central metro area that diverts regional flow paths toward pumping wells.

Groundwater flow in surficial aquifers is understood to be more localized, although work characterizing flow patterns is still in early stages. Tipping (2007) presents geochemical evidence of very complex flow paths influenced by buried, inter-fingering sand bodies.

WATER BUDGET

The groundwater budget of the Twin Cities metropolitan area reflects the relationship between input and output of groundwater through the region. Input to the groundwater flow system ultimately results from infiltrating precipitation (recharge). Outputs include groundwater flow into surface water features and extraction from wells. These components of the groundwater budget control the volume of water in the flow system and are discussed in more detail below.

Climate

Daily temperature, precipitation, snowfall, and snowfall depth measurements have been made in the Twin Cities metropolitan area since 1884. Mean daily temperature and annual precipitation, as measured at the Minneapolis/St. Paul International Airport between 1971 and 2000, are 54.5 degrees Fahrenheit and 29.41 inches respectively (Minnesota Climatology Working Group, 2008a). Precipitation across the metropolitan area averages from approximately 28 to 33 inches per year (Minnesota Department of Natural Resources, 2008a). Climate conditions vary temporally (Figure 10) and spatially (Figure 11).

Recharge

The volume of precipitation and rate at which it infiltrates the Twin Cities metropolitan area groundwater flow system are important and difficult factors to quantify, and several local and state-wide studies have examined this problem. In the context of this groundwater flow model development, the United States Geological Survey (USGS) definition of recharge has been adopted: “entry into the saturated zone of water made available at the water-table surface”. Recharge is therefore a complicated function of local factors that include climate, land cover, topography, and soil characteristics. Existing methods of assessing recharge at local versus regional scales traditionally provide significantly different results. The U.S. Geological Survey recently compared results of regional approaches to multiple local-scale values in Minnesota and determined that a state-wide regional regression recharge (RRR) model provides reasonable estimates of average annual recharge across Minnesota. This method estimates that recharge in the Twin Cities metropolitan area ranges from approximately 3 to 9 inches per year (Figure 12) (Delin et al, 2007).

Various other estimates of average infiltration have been made in the Twin Cities area. Norvich et al. (1974) estimated that this rate is between 4 and 10 inches per year. Schoenberg (1990) estimated that annual recharge from precipitation is approximately 1.5 to 4.5 inches per year.

Recharge rates are generally accepted to be higher in the northern metropolitan area, particularly within the Anoka Sand Plain of Anoka County. Recharge rates tend to decline to the south and west where low-permeability glacial tills dominate and precipitation is less.

Baseflow to surface water

Aquifer systems of the Twin Cities metropolitan area, particularly surficial aquifers, are hydraulically connected to streams and other surface water features. In the Twin Cities area, groundwater flows toward the major discharge zones of the Mississippi, Minnesota, and St. Croix Rivers. Local discharge to the gaining portions of smaller streams and tributaries can take place within the surficial aquifers, but the effects on groundwater flow of these water bodies become negligible in deeper aquifers (Olcott, 1992). Schoenberg (1990) estimates that, on annual average, approximately 15 to 25 percent of total flow in streams results from groundwater discharge into streams. This interaction between groundwater and surface water features occurs year round, but it is most apparent and easier to quantify during winter months when runoff is small and baseflow conditions (i.e. the groundwater component of stream flow) typically account for most of the flow.

Various attempts have been made to estimate groundwater inflows into the large rivers in the Twin Cities metropolitan area by detailed gauging of river flows (Schoenberg, 1994; Payne, 1995). The most recent efforts were performed by the U.S. Geological Survey, which used sophisticated Doppler measurement techniques to calculate flows in the rivers at several cross sections. In principle, by subtracting the stream flows measured at an upstream section from the stream flows measured at a downstream section (and assuming no tributary inflows), the difference in stream flow should be attributable to base flow from groundwater. In smaller streams, this technique works reasonably well but in large streams, such as the Minnesota and Mississippi Rivers, the error in the measurement is nearly equal to or higher than the calculated groundwater inflows – rendering the calculated base flows highly suspect. However, baseflow estimates for these major rivers were used during model calibration to lend some control to on the model mass water-balance.

Where site specific baseflow measurements did not exist, late season low-flow data was used to approximate baseflow. The Metropolitan Council collected baseflow data from various federal, state, and local agencies monitoring streams within the model domain. The quality of this data varied considerably. Often just a few measurements in the late fall or winter were all that was available for an estimate of baseflow, and the range of those estimates was very large, often an order of magnitude. Of 234 stream sites identified as likely to receive some contribution from groundwater (Figure 13), 104 sites were monitored once or more between 1988 and 2007 for flow in December, January and/or February (Anoka Conservation District, 2007; Cannon River Watershed Partnership, 2007; Carver County, 2007; Dakota County Soil and Water Conservation District, 2007; Janovec, Mark, 2007; Minnesota Department of Natural Resources, 2007; Metropolitan Council, 2007; Minnehaha Creek Watershed District, 2007; Rice Creek Watershed District, 2007; Shakopee Mdewakanton Sioux Community, 2007; St. Croix Research Center, 2007; United States Geological Survey, 2007; EOR, 2007; Washington County Conservation District, 2007).

Groundwater Extraction from Wells

Wells provide the final major source of groundwater discharge in the Twin Cities metropolitan area. The Minnesota County Well Index contains records for over 50,000 wells and boreholes within the seven-county metropolitan area (Minnesota Department of Health, 2008). Only approximately 3,100 wells, however, pump enough water to require appropriation permits from the Minnesota Department of Natural Resources as high-capacity wells. Groundwater sources supply approximately 25% of the total reported high-capacity demand (consumptive and non-consumptive) in the Twin Cities metropolitan area. The average daily extraction of groundwater from high capacity wells during 1995-2005 was approximately 290 million gallons per day in the Twin Cities metropolitan area (Minnesota Department of Natural Resources, 2007).

The majority of groundwater extracted in the Twin Cities metropolitan area is used for municipal water supply (70%), although a significant amount is used for private uses such as industrial processing and irrigation. All non-municipal residential water demand is supplied by groundwater (Figure 14) (Minnesota Department of Natural Resources, 2007).

The Prairie du Chien Group and Jordan Sandstones are the primary groundwater sources used to meet total demand in the Twin Cities metropolitan area, followed by the Quaternary, the Franconia Formation and the Ironton-Galesville Sandstones, the Mt. Simon and Hinckley Sandstones, the St. Peter Sandstone, the Platteville Formation, and the St. Lawrence Formation (Figure 15) (Minnesota Department of Natural Resources, 2007).

CONCEPTUAL MODEL

Model Extent and Hydraulic and Physical Boundaries

The 4,913 square miles represented by this regional groundwater flow model include the seven Minnesota counties comprising the Twin Cities metropolitan area and portions of the following adjacent counties: Chisago, Goodhue, Isanti, LeSueur, McLeod, Rice, Sherburne, Sibley, and Wright counties in Minnesota; and Pierce, Polk, and St, Croix counties in Wisconsin (Figure 16).

The model domain was chosen to include the Twin Cities metropolitan area and to extend far enough beyond that area to limit the effects of artificial boundary conditions within the area of interest. To the east, the model extends into Wisconsin allowing for groundwater flow into the St. Croix River from the east to be accounted for. To the northwest, the model extends to the edge of the Mt. Simon-Hinckley aquifer. To the north, west, and south, the model extends an arbitrary amount to limit the effects of boundary conditions.

9 geologic units are explicitly included in the conceptual model (Figure 6). In general, the layer assignments are as follows:

Layer 1 – Quaternary deposits, Decorah Shale, Platteville Formation, and Glenwood Formation
Layer 2 – St. Peter Sandstone
Layer 3 – Prairie du Chien Group
Layer 4 – Jordan Sandstone
Layer 5 – St. Lawrence Formation
Layer 6 – Franconia Formation
Layer 7 – Ironton and Galesville Sandstone
Layer 8 – Eau Claire Formation
Layer 9 – Mt. Simon and Hinckley Sandstone

The hydrogeologic boundaries of the Twin Cities metropolitan area groundwater flow system extend beyond the seven-county metropolitan area. As noted previously, regional groundwater flow is generally toward the Mississippi, Minnesota, and St. Croix rivers. These regional hydraulic features act as boundaries on the regional flow system. The northwestern boundary of the Paleozoic bedrock aquifer system is located in Wright and Sherburne counties where the Mt. Simon-Hinckley aquifer thins and groundwater flow into the system is likely to be dominated by vertical recharge. The regional groundwater flow system is bounded on the south by a groundwater divide located in Goodhue, Rice, and LeSueur counties, which separates flow to the north into the Twin Cities area from flow to the south into Iowa (Figure 16).

MODEL DESIGN

MODEL CODES

The finite difference modeling code MODFLOW-96 (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) as implemented in the modeling package Groundwater Vistas (version 5.09 build 16) (Environmental Simulations, Inc., 2007) was used to model the groundwater flow.

MODFLOW-96 simulates three-dimensional, steady-state and transient groundwater flow (saturated) using finite-difference approximations of the differential equation of groundwater flow:

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

where:

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

W: sources and sinks

S_s: specific storage

h: hydraulic head

t: time

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

The model was run in a confined state to speed model convergence and avoid such problems as cells drying out (Environmental Simulations, Inc., 2007). All model cells above the water table were set as inactive, and the thickness of layer 1 was adjusted to represent only the saturated thickness. By making these adjustments, the difference between running the model as confined verses unconfined is minimal (D'Agnese et. al., 2002).

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

The VCONT parameter for the computation of leakance between model layers is computed automatically from values of vertical hydraulic conductivity, which are stored in a separate array (Environmental Simulations, Inc., 2004). Leakance for the uppermost saturated layer can vary as a function of saturated thickness of the unconfined layer.

The regional groundwater flow model implements MODFLOW using the graphical user interface Groundwater Vistas (Version 5.09 Build 16) (Environmental Simulations, Inc. 2007). Most model input parameters can be imported into Groundwater Vistas as Environmental Systems Research Institute, Inc. (ESRI) shapefiles.

The MODFLOW model was calibrated using the model-independent parameter estimation software PEST (version 11.4), a software program utilizing a series of automated inverse optimization procedures that minimize the difference between simulated results and real-world observations (Watermark Numerical Computing, 2005). PEST was not employed until traditional trial-and-error methods resulted in a reasonable (but not fully calibrated) modeling result.

RELATIONSHIP BETWEEN THE CONCEPTUAL AND NUMERICAL MODELS

Simplifying Assumptions

In the process of translating between conceptual and numerical models, some simplifications and assumptions were made. Similar to the Minnesota Pollution Control Agency’s Twin Cities Metropolitan Groundwater Model Version 1.00, this model considers the groundwater flow system of the Twin Cities metropolitan area under steady-state conditions. The model therefore represents long-term average conditions and does not account for temporal variation in aquifer stresses or changes in storage. Long-term average values of recharge, groundwater and surface water elevations, stream baseflows, and pumping rates are used as model inputs.

The choice to use MODFLOW (McDonald and Harbaugh, 1988) requires the conceptual model domain to be subdivided into a set of blocks; hydraulic properties within each block are therefore assumed to be uniform.

Unlike the Minnesota Pollution Control Agency’s Metro Model Version 1.00, this model domain does not extend to real hydrogeologic boundaries in all cases. The southern boundary of the model domain, for example, is defined by a constant head boundary. In this area, it is assumed that aquifer heads remain constant at elevations defined based on Minnesota County Well Index records and modeling results from the Metro Model Version 1.00.

Also, the numerical model does not represent geologic units in full detail. Not all geologic units were explicitly included. For example, complex sequences of Quaternary deposits were represented as a single unit. In addition, flow through the Decorah, Platteville, and Glenwood is grouped into layer 1 with the unconsolidated Quaternary deposits. This decision improves computational efficiency by limiting the number of model layers and reducing their complexity. Those units are unsaturated or perched in many areas, which MODFLOW struggles with. The definition of model layer elevations across buried bedrock valleys and faults also entailed some simplifying assumptions, described in more detail in the following section.

In regards to the hydraulic properties of regional bedrock aquifers, the model assumes that available aquifer test data adequately represents the transmissivity and hydraulic conductivity of each aquifer. Sand content is assumed to correlate to hydraulic conductivity in unconsolidated sediments.

It is also assumed that stress on the groundwater flow system due to pumping can be adequately represented by high-capacity well withdrawals documented by Minnesota Department of Natural Resources water appropriation permit records. The Minnesota Department of Natural Resources does not have regulatory authority over withdrawals from or records of low-capacity private wells, which are primarily used for domestic purposes. However, withdrawals from these low-capacity wells are assumed to be insignificant when compared to withdrawals from high-capacity wells.

Discretization and Measurement Units

As noted previously, MODFLOW uses the finite-difference approximation to solve the groundwater flow equation (McDonald and Harbaugh, 1988). In this model, the finite difference grid; each grid cell is 500 meters square. The thickness of each cell varies based on hydrostratigraphic unit thickness. Not all cells are part of the regional flow system; those which are not are defined as inactive in the final model. The details of the model discretization are summarized below.

Number Rows	280
Number Columns	264
Number Layers	9
Number Total Cells	665,280
Number Active Cells	417,793
Cell Size	500 x 500 meters
Length Units	Meters
Site Coordinates	UTM NAD 83, Zone 15N
Model Grid X Offset	405,775 meters
Model Grid Y Offset	4,909,982 meters
Time Units	Days

The nine model layers vary in elevation and thickness across the model (Figure 17). Model layers generally represent the major hydrostratigraphic units defined in Figure 6, although the Decorah, Platteville, and Glenwood are grouped with Quaternary deposits in model layer 1.

A model layer may represent more than one hydrostratigraphic unit. For example, in portions of southwestern Scott County and southern Carver County, faulting has uplifted the Mt. Simon sandstone enough to make it horizontally adjacent to the Eau Claire Formation. The Eau Claire Formation is Mt. Simon Sandstone is generally represented by model layer 9. In this area, however, the top and bottom elevations of model layer 8 were interpolated across the faulted zone and the hydraulic conductivity values of the model layer 8 within the fault zone was defined to represent the Mt. Simon. Faults in southern Washington and northeastern Dakota counties were handled differently due to their characterization as closely spaced step faults. In this area, model layer elevations were adjusted across the faulted zone and the hydraulic conductivity values of each layer represent only one hydrostratigraphic unit (model layer 4 represents only the Jordan Sandstone, for example). Figure 17 provides some illustration of how faults were handled and highlights some of the model complexity difficult to summarize in text.

A hydrostratigraphic unit such as the Quaternary is also represented by more than one layer in some areas. The Quaternary unit occupies more than one layer because some bedrock units, such as the St. Peter sandstone and Prairie du Chien group, do not extend over the entire model domain. Where these upper bedrock units are not present, the model layer associated with them is instead assigned to the Quaternary unit. For example, in areas where the Jordan Sandstone is the first bedrock unit present (i.e. the St. Peter Sandstone and Prairie Du Chien Group are not present) the Quaternary occupies model layers 1-3.

Model Properties

Groundwater Vistas defines several different properties that are represented in the model as either a matrix or in zones of equal value. Some of these parameters are hydraulic or transport properties, including hydraulic conductivity (x-, y-, and z-directions), storage coefficient, and layer bottom elevation. Other parameters include boundary conditions and initial conditions, including recharge and initial heads (Environmental Simulations, Inc., 2007).

Hydraulic Conductivity Zones

Within each model layer, different hydrostratigraphic units are represented by a range of hydraulic conductivity zone numbers (Table 1). Each hydraulic conductivity zone number is assigned, in turn, to a single hydraulic conductivity value. This scheme allows for the hydraulic conductivity of a single hydrostratigraphic unit to vary over the model domain. Allowing for more zones also creates more adjustable parameters during the model calibration.

The hydraulic conductivity zones for the Quaternary were manually delineated based on percent sand within the glacial drift (Figure 18). Percent sand was calculated based on the thickness of sand and gravel intervals, compared to total well depth, as reported in Minnesota County Well Index (CWI) logs. Large hydraulic conductivity zones were then further subdivided arbitrarily along county boundaries to allow for more room to adjust parameters during model calibration. Although layer 1 is a composite of Quaternary deposits, Decorah shale, Platteville formation, and Glenwood formation, only the sand content of the Quaternary deposits was considered when defining hydraulic conductivity zones.

Hydraulic conductivity zones for bedrock portions of each model layer were defined in the following manner. First, large zones were defined based on the geographic extent of the bedrock units (i.e. Jordan Sandstone, St. Lawrence Formation, etc.) assigned to each layer. Zones representing the bedrock units were then subdivided into two categories: areas where the geologic unit outcrops or subcrops beneath glacial sediments and areas where it is buried beneath other bedrock. Defining hydraulic conductivity zones in such a manner is done to try and replicate natural conditions where, presumably, the first bedrock unit is more weathered and/or fractured and has a higher hydraulic conductivity. Bedrock hydraulic conductivity zones were then broken down even further based on the locations of transmissivity targets obtained from pumping test data (Figure 19 through Figure 27).

A total of 424 hydraulic conductivity zones were defined and used during model calibration. The numbering scheme for the hydraulic conductivity zone numbers in Table 1.

Table 1. Model numbering scheme for hydraulic conductivity zones.

Zone Number*	Hydrostratigraphic Unit
1 - 99	Quaternary deposits, Decorah Shale, Platteville Formation, and Glenwood Formation
100 - 199	St. Peter Sandstone
200 - 299	Prairie Du Chien Group
300 - 399	Jordan Sandstone
400 - 499	St. Lawrence Formation
500 - 599	Franconia Formation
600 - 699	Ironton and Galesville Sandstones
700 - 799	Eau Claire Formation

800 - 899	Mt. Simon and Hinckley Sandstones
901	Precambrian Crystalline
902	High K (Quarry Footprints)

**Not all zone numbers are used in model*

Storage Coefficient

The model constructed for this study is a steady state model; hence, storage is not a model parameter. Storage terms are only necessary when simulating groundwater flow under transient conditions.

Base Elevation of Layers

The basal elevation of each model layer was defined using corresponding digital elevation models of the region's geologic units and Minnesota County Well Index data. The Minnesota Geological Survey has created several digital elevation models including the tops of the St. Peter Sandstone, Prairie du Chien Group, Jordan Sandstone, and St. Lawrence Formation within the seven county metropolitan area (Tipping and Mossler, 1996); the tops of the Eau Claire Formation, Ironton-Galesville Sandstone, Mt. Simon Sandstone, and Precambrian crystalline bedrock in the northwest metro area (Runkel et al., 2003); and the tops of the St. Peter Sandstone, Prairie Du Chien Group, Jordan Sandstone, St. Lawrence Formation, Franconia Formation, Ironton-Galesville Sandstone, Eau Claire Formation, and the Mt. Simon Sandstone in Scott County (Runkel and Tipping, 2006). In areas where digital elevation models had previously been developed by the Minnesota Geological Survey, it was assumed they are the best available information and no further work was necessary. In areas where the Minnesota Geological Survey did not develop digital elevation models for a hydrostratigraphic unit represented in the model, the Minnesota County Well Index was used to determine the elevation of the lithologic contacts. Data from Minnesota Geological Survey digital elevation models and Minnesota County Well Index lithologic contacts were then combined to form digital elevation models (300 m^2 grid cells) of hydrostratigraphic units that extend across the entire model domain in Minnesota.

The elevation of the top and bottom of the model layers generally corresponds with the digital elevation models of hydrostratigraphic formation contacts, although some simplifications were made in the process of defining the model layer elevations and hydraulic properties. Simplifications include:

- Allowing Quaternary deposits to occupy more than one model layer. Hydraulic conductivity zones were used to delineate bedrock units and Quaternary deposits within each model layer.
- Defining the upper elevation of Quaternary deposits based on land surface topography. The base elevation of Quaternary deposits was defined based on the elevation of the first underlying

bedrock unit.

- Interpolating model layers across the major river valleys where the upper bedrock units have been eroded away. For example, model layer elevations on the Minnesota side of the St. Croix and Mississippi rivers were extended consistently across the river valleys into Wisconsin. Where model layers are above ground surface in some areas. When the bottom elevation of a model cell is above the ground surface, the cell is defined as inactive and not included in model computation.
- Adjusting model layer hydraulic conductivity or elevation across fault zones. As described previously, model layers were adjusted in one of two ways across fault zones. In western Scott County and southern Carver County, layer elevations were interpolated across bedrock faults and changes in lithology across faults were defined using hydraulic conductivity zones within each layer. In Washington County, the hydrostratigraphic units remained in the same layers but the elevations of those layers were adjusted in a series of steps (Figure 17). This is a reasonable approach because the exact location of the faults, and their exact offset, is unknown.

Recharge

For this study, average 1975-2003 annual recharge was calculated independently of the groundwater model using a daily soil-water balance (SWB) model (Dripps and Bradbury, 2007). The model code is written in Visual Basic and requires Microsoft Excel 2000 to run. The SWB model calculates recharge using hydrologic soil group, land cover, available soil-moisture capacity, surface flow direction, initial soil moisture, and initial snow cover data based on methods similar to Thornthwaite (1948) and Thornthwaite and Mather (1957). The model uses a simple mass balance calculated at a daily time step as depicted in Figure 28:

recharge = precipitation – interception – runoff – evapotranspiration + antecedent soil moisture – total soil moisture storage capacity of the root zone

This recharge modeling process is described in detail in Appendix A.

For this study, 30 meter square grids of annual recharge were developed for 1975-2003 (Appendix A). The SWB method estimates that mean annual recharge in the Twin Cities metropolitan area is approximately 6 inches and ranges from zero to 18 inches, depending on soil characteristics, topography, and land cover (Figure 29).

The groundwater flow model incorporates the average annual recharge value over this time period; average calculated recharge within 500 x 500 meter model cells were used as a groundwater flow model input (Figure 30). During the model calibration process, recharge was adjusted uniformly over the model domain within a range defined by the minimum and maximum annual recharge calculated by the SWB model.

Initial Heads

Because the model was run as a fully confined, steady-state model, initial heads do not significantly affect the final model solution. For the first model run, an arbitrary value of 400 meters above mean sea level was applied across the model domain; initial heads were adjusted in subsequent iterations based on the previous solution. Following model calibration, initial heads are equivalent to final heads.

Boundary Conditions

The model incorporates regional flow boundaries in three ways: as constant head, constant flux, and mixed type boundary conditions (Environmental Simulations, Inc., 2007). In this model, specified flux boundary cells are represented using no-flow or wells. Rivers represent mixed-type boundary condition cells in the model.

Constant-Head

A constant head is a boundary where the head does not change during the simulation. Constant head boundaries were assigned to the eastern and southern edges of the model domain (Figure 31). A significant amount of groundwater flows into the model domain in these areas, and the constant head cells allow for such flow. Values for the constant head cells on the eastern edge of the model were derived from results of a groundwater flow model for Pierce, Polk, and St. Croix counties, Wisconsin, done by the U. S. Geological Survey (Juckem, 2007). Minnesota County Well Index static water level data and model files from the MPCA's Twin Cities Metropolitan Groundwater Model Version 1.00 (Metro Model) were used to establish head values for the constant head boundaries on the southern edge of the model.

No-Flow

A no-flow boundary is a special type of constant flux boundary, where flux equals zero. By default, all outer edges of the model grid are assumed to be no-flow. For example, areas outside the active model domain but within the finite-difference grid, were assigned as no-flow boundary cells and were not a part of the computation process (Figure 31). No-flow boundaries were also assigned to areas where hydrostratigraphic units yield negligible amounts of water to the system. For example, several model cells in the western model area were assigned as no-flow boundaries. A regionally insignificant amount of water is believed to flow into the model domain in this area, as flow through Quaternary deposits is believed to be mostly vertical and the primary bedrock units are thin or absent. The main exception to this rationale may be the Mt. Simon Sandstone, as flow in the Mt. Simon is potentially much different than in the upper bedrock units in that area. However, with such little data to support the selection of any other boundary type, the no-flow boundary along the western edge of the model extends through the Mt. Simon as wells as overlying model layers.

As noted earlier, the northern and northwestern limits of the active model domain reflect the thinning, and even pinching out, of bedrock aquifer units. The southwestern limit of the active model domain was defined based on the understanding that flow in that area is toward the Minnesota River; a roughly delineated flow path defines the edge of the active model domain in this area. Like portions of the western metro, a regionally insignificant amount of water is believed to flow horizontally into the model domain from these areas.

Finally, cells that were determined to be dry after initial calibration runs (i.e. the hydraulic head is below the bottom of the cell) were also set as inactive (no-flow) for subsequent calibration runs in order to reduce the computational time of the model. This condition occurred most often in model layer 1 (Figure 32).

High-Capacity Wells

The model incorporates wells as constant flux boundaries. Analytic elements were used to define wells, allowing the model to assign flow rates to a range of model layers and compute the flux for each layer based on the transmissivity of that layer (Environmental Simulations, Inc., 2007).

Wells for which there are water use permit records maintained by the Minnesota Department of Natural Resources through the State Water Use Data System (SWUDS) were included in this study. This dataset includes all public and private wells withdrawing more than 10,000 gallons of water per day, or 1 million gallons per year. Dewatering for the major quarries in the Twin Cities area was included in this dataset: Kraemer Quarry in northwest Dakota County, Larson Quarry in southwest Washington County, and Sheily Quarry in northeast Scott County. The average pumping rate from 1995 to 2005 was used for this study.

For a small number of these high-capacity wells, the aquifer source was unknown or not listed in SWUDS or the Minnesota County Well Index (CWI) databases. These wells were excluded from the model only if they are non-municipal wells pumping less than an average of 250 gallons per minute. Extra effort was made to obtain further information about all municipal wells and wells pumping more than 250 gallons per minute, if aquifer data was missing.

Many wells are screened across multiple hydrostratigraphic layers and are therefore assigned to multiple model layers. For these multi-aquifer wells, the pumping rate is applied to each layer based on the transmissivity of each layer at the location of the well. When running the model from Groundwater Vistas, this calculation is automatically performed when creating the MODFLOW files. However, during model calibration with PEST, this calculation must be performed separately (‘*distribute_pumping_by_T.py’,* described in Appendix B). Note that all pumping wells within the model are listed by the Minnesota Department of Natural Resources installation ID rather than the unique well number, because many records in SWUDS have no unique well number associated with them.

Rivers

Major rivers and streams and smaller designated trout streams and major lakes were included in the model and simulated using MOFLOW's River Package (Figure 33). Using the River Package allows model cells representing rivers to be defined as a special form of a head-dependent boundary condition, in which the model computes the difference in head between the boundary and the model cell where the boundary is defined. The head difference is then multiplied by a conductance term to get the amount of water flowing into or out of the aquifer.

An ESRI shapefile was created with each river and stream broken down into several reaches. The beginning and end of each reach, or line segment, was assigned a stage elevation based on either Minnesota Department of Natural Resources stream gage data (average stage) or based on 30 meter United States Geological Survey National Elevation Dataset (NED) digital elevation model data. Groundwater Vistas was used to interpolate between the endpoints of each reach to assign river stage values for model cells between the endpoints and to assign the river cell to the proper model layer based on the stage elevation (i.e. not all river cells are located within layer one of the model). River bed conductance values were assigned to each reach. The conductance values for the river reaches were adjusted during model calibration to match baseflow targets. Adjustment of conductance values was restricted to a range between 25 and 500,000 m^2/day. The following 33 rivers were included in the model:

- Apple River
- Assumption Creek
- Basset Creek
- Bevens Creek
- Browns Creek
- Cannon River
- Carver Creek
- Credit River
- Crow River
- Eagle Creek
- Elk River
- Elm Creek
- Kinnickinnic River
- Little Cannon River
- Minnehaha Creek
- Minnesota River
- Mississippi River
- N. Crow River
- Nine Mile Creek
- Old Mill Stream
- Pine Creek
- Purgatory Creek
- Rice Creek
- Riley Creek
- Rum River
- S. Branch Vermillion River
- Sand Creek
- St Croix River
- Sunrise River
- Trout Brook
- Valley Creek
- Vermillion River
- Willow River

Major lakes within the model domain were included in the model if they were larger than 50% of a model cell (each model cell is 500 meters square); lakes smaller than 50% of a model cell were not included. The stage elevation for each lake was set at either the average stage elevation as recorded in the Minnesota Department of Natural Resources lake database, or the elevation based on a 30 meter United States Geological Survey NED digital elevation model. The depth of the lake was set at the depth listed by the Minnesota Department of Natural Resources computer database of lake information (Lakes-DB). For many smaller lakes, where no depth information was available, depth was estimated at 5 meters. Lakes were grouped into 13 groups and a lakebed conductance value was assigned to each group. Lake bed conductance values were adjusted for each group during model calibration. Adjustment of conductance values was restricted to a range between 25 and 500,000 m^2/day on four lakes where groundwater-surface water interaction data had been collected (Long Lake, Square Lake, White Bear Lake, and Vadnais Lake) and in lakes and wetlands within the Minnesota River Valley. Lakebed conductance in all other lakes in the model was restricted to a range between 20.863 and 104.314 m^2/day. In perched lakes, lake conductance was set to vary within a range such that leakage is equivalent to between 6 and 30 in/year. 962 lakes were included in the model

Solvers and Convergence Criteria

The Link-AMG (LMG) solver (Mehl & Hill, 2001) was used exclusively during the calibration process. This technique for solving matrix equations was developed to link MODFLOW with the freeware algebraic multigrid (AMG) solver developed by the German National research Center for Information Technology. The LMG solver was selected because of its ability to converge on a solution must faster than the Preconditioned Conjugate-Gradient 1 (PCG2) solver (Hill, 1990). Details of the solver criteria are as follows:

Maximum iterations:	30
Maximum cycles per iteration:	25
Budget closure criterion:	0.000001
Maximum damping value:	1.0
Minimum damping value:	0.2

The PCG2 solver was used following model calibration for predictive simulations. Details of the solver criteria are as follows:

Maximum outer iterations:	100
Maximum inner iterations:	75
Head change criterion:	0.0001
Residual criterion for convergence:	0.1

Relaxation parameter:	0.97
Matrix preconditioning method:	Cholesky
Maximum bound on eigenvalue:	Set equal to 2
Damping factor:	1
Converge if criteria met for:	3 outer iterations

CALIBRATION TARGETS AND PROCEDURES

Following regional model construction, targets for calibrating the regional model were established. Calibration targets included hydraulic head, flux, transmissivity from pumping tests, and hydraulic conductivity anisotropy. During model calibration, recharge, horizontal and vertical hydraulic conductivity, riverbed conductance, and lakebed conductance parameters were adjusted.

After traditional trial-and-error methods resulted in a reasonable (but not fully calibrated) modeling result, the parameter estimation software PEST (Watermark Numerical Computing, 2005) was used to calibrate the model. Because model results (and hence, model calibration) are more sensitive to some parameters than others, using PEST involved making some choices on which parameters (e.g., hydraulic conductivity zones, riverbed conductance, etc.) would be allowed to vary, the maximum and minimum values in which the parameters' values could be varied, and initial estimates for the parameters' values. In an iterative process, the results of the PEST calibration were evaluated and changes were made to the model. Changes made included defining dry cells as inactive (no-flow) conditions, adjusting the thickness of layer 1 to limit the effects of modeling as confined, adjusting hydraulic conductivity zone distribution, and adjusting the lower and upper bounds for parameter values.

Hydraulic Head Calibration Targets

The primary source for hydraulic head calibration data was the Minnesota County Well Index (CWI). Minnesota Department of Natural Resources groundwater level monitoring program data was also used. This project relied on CWI static water level data that had been cross-validated during development of the Minnesota Pollution Control Agency's Metro Model (Streitz, 2003). For regions outside the seven-county metro area and for the deeper hydrostratigraphic units, Minnesota County Well Index data was cross-validated using the Pollution Control Agency's method before being incorporated into the final hydraulic head calibration dataset.

As was done for the Minnesota Pollution Control Agency's Metro Model, an exclusion zone of 100 meters was used around each observed value during the cross validation calculation. The largest 10 percent of the absolute residuals for each stratigraphic unit were considered to be outliers and removed from the dataset. A cutoff value of 10 percent was chosen in order to remain consistent with Minnesota Pollution Control Agency dataset. Data points for the Eau Claire Formation (Layer 8) and the Mount Simon – Hinckley Sandstone (Layer 9) were not cross validated because the data points were not well distributed throughout the model domain and there is an overall lack of data for these two units.

Data from the Minnesota County Well Index were also automatically excluded if the aquifer or the ground surface elevation was unknown. Data were also excluded if top and bottom screen elevations were missing in Quaternary wells. Because the Quaternary can span several model layers, knowledge of the screen elevation is required to assign water level observations to the correct layer.

Minnesota Department of Natural Resources groundwater observation wells were added as calibration targets; average 1995-2008 measured head was assigned as the target value. These targets were assigned greater weight than CWI static water level calibration targets in the calibration process, because the data represent the most accurate long-term average water level measurements available in the region.

On the east side of the St. Croix River, manually defined head targets were established to maintain a reasonable hydraulic head gradient. While the locations of these targets were arbitrary, the values used were obtained from a U.S. Geological Survey groundwater flow model for Pierce, Polk, and St. Croix counties, Wisconsin (Juckem, 2007). After initial model calibration runs, head targets assigned to cells determined to be dry were removed from the data set.

The final hydraulic head calibration dataset contains 14,680 head targets (Figure 34). These target head values generally represent water levels measured by drilling contractors during the time of well installation, and contain multiple sources of error. In general, head targets for regional modeling in Minnesota are typically assigned a likely error of at least ±20 feet (about ±6 meters).

Factors affecting the accuracy and precision of hydraulic head calibration targets include the following:

- Inaccurate water level measurement – drilling contractors may not have used precise measuring devices, especially for wells drilled decades ago.
- Inaccurate well location – many wells are identified only to the nearest quarter-quarter-quarter section, which may result in up to 600 feet of location error.
- Inaccurate well elevation – well elevations are typically estimated using 7.5-minute topographic maps. Standard practice assumes that elevations determined using topographic map contours have a measurement error of ½ the contour interval. Where topographic map contour intervals are 20 feet, measurement error is ±10 feet. Where well locations are inaccurate, elevation estimates have even greater error.

- Unstable water levels at the time of measurement – water levels are typically collected during or immediately after well installation or development and may not have reached equilibrium with the aquifer.
- Misidentification or incorrect assignment of hydrostratigraphic units in databases – the well may actually be screened in a different unit or in multiple units.
- Seasonal pumping affects on water levels – depending on where the well is located and at what time of year it was installed, the water level measured by the drilling contractor may have been affected by seasonal pumping.
- Long-term changes in water levels due to climate or growing demand - water levels are affected by season and year of installation; water levels from different wells typically represent the entire range of possible dates and times of the year and thus are a composite of many years of data.

It is not uncommon to find two nearby targets in the same aquifer with substantially different values. The cross validation techniques used in this study helps to reduce some of this discrepancy. Also, because this error is both widespread and generally random, the errors tend to be of lesser importance when many targets are used.

Flux Calibration Targets

Flux calibration targets were established for all rivers, streams, and lakes where sufficient data were available (Figure 35). Rivers and streams were broken down into reaches between stream gauges, which correspond to baseflow measurement sites. The baseflow contribution for each individual reach was then used as the calibration target. Stream segments unbounded by stream gauges were not assigned baseflow calibration targets, because net baseflow along that reach could not be calculated. Each target was weighted in inverse proportion to the flow. For example, the baseflow value for the Mississippi River has a much larger error associated with it than a smaller stream such as Valley Creek; hence, the target value for the Mississippi River had a much lower weight associated with it. Weighting of calibration targets also allows PEST to calculate the proper residual for baseflow targets. PEST does not consider the unit of the residual when calculating residuals, which results in unweighted residuals of baseflow being inherently much greater than unweighted residuals of head. Adjusting the weights allows for different calibration target types (i.e. head and baseflow) to be used concurrently, even though their units of measurement are not the same.

The final stream baseflow calibration dataset contains 35 baseflow targets. These target baseflow values generally represent 1988-2007 average late season stream flows, which were measured through a variety of programs and studies by surface water resource technicians as part of routine monitoring programs. Several factors contribute to inaccuracy in these baseflow target values; they should only be considered accurate within approximately an order of magnitude.

Factors affecting the accuracy and precision of these baseflow calibration targets include the following:

- Inaccurate discharge measurement – imprecise measuring devices or methods may have been used.
- Inaccurate stage/discharge relationship – changes in stream bed morphology may result in inaccurate stage/discharge relationships and, thus, inaccurate discharge estimates.
- Runoff contribution to stream flow at the time of measurement – estimates of baseflow may be inaccurate if surface water runoff is a significant component of total stream flow, which may happen if the measurement was made following a precipitation event.
- Long-term changes in stream flow due to climate – stream discharge is affected by climate and watershed characteristics. Measurements made during a particularly dry period will underestimate baseflow. A long-term record was used to minimize this effect.

Lake flux target values were established for four lakes where data regarding groundwater-surface water interaction was available: Long Lake, Square Lake, Vadnais Lake, and White Bear Lake. Like baseflow calibration targets, each target was weighted in inverse proportion to the flux. These target flux values represent data collected during site-specific studies (Mohring, 1986; Minnesota Department of Natural Resource, 1998; Ruhl, 1994; Menheer, 2005). Uncertainty in these values varies by study, and is largely addressed by conditions addressed in the discussion of baseflow calibration target error above.

Transmissivity Calibration Targets

Transmissivity values calculated as part of high-capacity well pumping tests were used as targets during the model calibration. This pumping test data, collected between 1959 and 2007 and submitted to the Minnesota Department of Health, were primarily collected for the purposes of assessing aquifer capacity for water supply development and wellhead protection.

A total of 98 transmissivity targets were used for model calibration (Figure 19 through Figure 27). The residual value of the transmissivity targets was calculated outside of the model using an external script (*‘transmissivity_calculation.py’,* described in Appendix B).

Transmissivity target values may contain multiple sources of error including:

- Inaccurate water level and pumping rate measurements – imprecise water level and pumping rate devices may have been used, particularly in aquifer tests conducted decades ago.

- Effects of neighboring pumping on water level measurements – water level measurements may reflect pumping affects from nearby wells in addition to the well being pumping for the aquifer test.
- Application of an inappropriate analytical method – all analytical methods incorporate a variety of assumptions regarding aquifer properties; error is introduced when these assumptions are not valid for the site.
- Use of professional judgment in selecting a representative value when multiple observation wells yield a range of results – the selection of data used in the analysis affects conclusions regarding transmissivity; different values will result from the use of data from observation wells versus pumping wells, data from multiple observation wells versus a single well, use of late-time versus early-time data, use of pumping versus recovery data, etc..

Anisotropy Calibration Targets

Hydraulic conductivity anisotropy targets were used to maintain a reasonable anisotropy ratio (K_x/K_z). It is widely accepted that horizontal hydraulic conductivity (K_x) is consistently greater than vertical hydraulic conductivity (K_z). However, this may not always be the case, particularly in highly fractured areas. Rather than specifying a fixed anisotropy ratio, both K_x and K_z were allowed to vary independently during model calibration. Vertical hydraulic conductivity was allowed to be greater than horizontal hydraulic conductivity; however, there was a penalty associated with doing so. In other words, for zones where K_z is greater than K_x, a high residual is given for the anisotropy target. For zones were K_z is less than K_x, a low residual (near zero) is given. Anisotropy residuals were calculated with an external script (‘*anisotropy_regularisation.py*’, described in Appendix B).

PEST Optimization Procedure

The primary purpose of automated inverse optimization is to minimize the differences, or residuals, between simulated conditions and observed (i.e. measured) conditions. For the steady-state regional model optimizations, this means minimizing the residual between the simulated hydraulic head and the observed head at the calibration target locations as well as between simulated baseflow and observed baseflow for river reaches. The sum of the squared weighted residuals for all targets is the ‘objective function’ that is to be minimized; the square of the residual is used because some residuals are negative and some are positive.

Only those parameters selected to vary in the optimization process are allowed to affect the resulting calibration. In the this model, there are 904 adjustable parameters including recharge, horizontal and vertical hydraulic conductivity zones, riverbed conductance reaches, and lakebed conductance groups.

As noted, recharge was adjusted as a calibration parameter. The initial recharge values assigned to the model were calculated using the SWB model discussed earlier in this report. During the calibration process, recharge was adjusted uniformly across the model using a scaling factor, or multiplier. The lower and upper limits of the recharge multiplier (0.2344 and 1.6719, respectively) were based on minimum and maximum average annual recharge values calculated using the SWB model for 1976-2003.

A total of 424 hydraulic conductivity zones were defined and used during model calibration. Within each zone, horizontal conductivity was assumed to be isotropic ($K_x = K_y$) and vertical anisotropy (K_x/K_z) was allowed to vary during model calibration. In total, there were 848 adjustable hydraulic conductivity parameters during model calibration – 424 horizontal conductivity parameters and 424 vertical hydraulic conductivity parameters. Lower and upper bounds were defined for each hydraulic conductivity zone to guide the model calibration process.

A total of 43 riverbed conductance reach parameters were adjusted during model calibration to match baseflow targets. Adjustment of conductance values was restricted to a range between 25 and 500,000 m^2/day. Lakes within the model were compiled into 12 groups and lakebed conductance was assigned to each group. The lakebed conductance of each group was adjusted during model calibration. Adjustment of conductance values was restricted to a range between 25 and 500,000 m^2/day on four lakes where groundwater-surface water interaction data had been collected (Long Lake, Square Lake, White Bear Lake, and Vadnais Lake) and in lakes and wetlands within the Minnesota River Valley. Lakebed conductance in all other lakes in the model was restricted to a range between 20.863 and 104.314 m^2/day. In perched lakes, lake conductance was set to vary within a range such that leakage is equivalent to between 6 and 30 in/year.

Some parameters are more correlated than others, and different combinations of some parameter values can produce nearly identical results. One outcome resulting from this situation is a non-unique optimized model. The more (and more varied) types of calibration targets used in model optimization, the more unique the optimized model will be. Placing constraints on the range in which a parameter can vary (i.e. upper and lower limits) may also assist in reducing non-uniqueness. However, placing too much constraint on parameter limits may hinder the optimization process due to the need to vary the parameter values over large ranges in order to assess the numerical derivative. Holding a parameter constant, adding prior knowledge, and tying parameter values to one another are other methods that may help reduce non-uniqueness.

The model was run in a confined state, which helped speed model convergence and avoid problems such as cells drying out (Environmental Simulations, Inc., 2007). All model cells above the water table were set as inactive, and the thickness of layer 1 was adjusted to represent only the saturated thickness. By making these adjustments, the difference between running the model as confined verses unconfined is minimal (D'Agnese et. al., 2002).

Singular value decomposition-assist (SVD-assist) was used during model calibration. SVD-assist allows for the full set of 904 parameters to be simplified into a more manageable and numerically stable set of parameters. For further implementation on SVD-assist, the reader is referred to the PEST user manual (Watermark Numerical Computing, 2005).

MODEL RESULTS

DATA FILES

Model input and output files are available for download from the Metropolitan Council's Water Supply Planning unit website at: http://www.metrocouncil.org/environment/WaterSupply/metrogroundwatermodeldatasets.htm. Appendix C contains a list and description of model files.

RECHARGE

As noted earlier, average 1975-2003 annual recharge was calculated independently of the groundwater model using a daily soil-water balance (SWB) model (Dripps and Bradbury, 2007). The resulting 500 x 500 meter grid distribution of average annual recharge was input into the model and adjusted uniformly over the model domain during model calibration. The optimized model adopted a recharge multiplier of 0.7120759. In other words, model calibration was achieved with recharge rates approximately 30% less than rates calculated using the SWB model.

AQUIFER PROPERTIES

The final hydraulic conductivity values assigned to each model layer are presented in Table 2 and Table 3 and Figure 36 through Figure 44. Mean hydraulic conductivity was calculated as the average value reported in each model cell representing each hydrostratigraphic unit.

Table 2. Horizontal hydraulic conductivity in calibrated regional groundwater flow model (Metro Model 2).

Unit	Mean K (m/day)	Minimum K (m/day)	Maximum K (m/day)
Quaternary	24.13	6.96	73.53
St. Peter	3.95	0.34	15.00
Prairie du Chien	12.78	1.64	50.00
Jordan	16.87	3.00	50.00
St. Lawrence	0.27	6.0×10^{-3}	2.00
Franconia	6.92	0.27	30.00
Ironton-Galesville	11.67	0.10	30.00
Eau Claire	6.9×10^{-3}	5.6×10^{-3}	0.10
Mt. Simon-Hinckley	3.63	0.10	10.00

Table 3. Vertical hydraulic conductivity in calibrated regional groundwater flow model (Metro Model 2).

Unit	Mean K (m/day)	Minimum K (m/day)	Maximum K (m/day)
Quaternary	14.24	6.42	26.71
St. Peter	1.53	5.0×10^{-4}	5.27
Prairie du Chien	1.53	1.0×10^{-2}	10.58
Jordan	2.20	5.0×10^{-2}	14.46
St. Lawrence	5.6×10^{-3}	3.0×10^{-5}	0.54
Franconia	0.65	3.0×10^{-4}	3.0
Ironton-Galesville	0.33	3.0×10^{-4}	2.48
Eau Claire	1.48×10^{-4}	0.00	1.0×10^{-3}
Mt. Simon-Hinckley	0.46	2.75×10^{-3}	4.29

COMPARISON TO MEASURED HEAD

Head calibration characteristics of the final optimized regional model are summarized in Table 4. A normalized root mean square (residual standard deviation divided by the observed range of head values) less than 10 percent is generally considered appropriate for a calibrated groundwater model. Three targets, located in model cells defined as no-flow boundaries, were not included in the calculation of calibration statistics because the model did not calculated hydraulic head in these cells. Two of the calibration targets are located east of the St. Croix River in Wisconsin; the third calibration target is located at the northwestern edge of the model.

Table 4. Hydraulic head calibration target statistics.

		Model Layer								
Calibration Statistic (meters)	**All**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Residual Mean	-1.36	0.73	0.31	-0.79	-0.99	-2.36	-2.58	-1.65	-2.64	-1.06
Residual Standard Deviation	6.25	5.98	7.15	6.62	6.16	5.25	5.52	5.52	6.70	7.54
Absolute Residual Mean	3.52	5.25	5.83	4.42	3.79	2.23	2.04	2.69	2.55	4.06
Minimum Residual	-51.99	-11.68	-23.28	-22.70	-29.83	-19.68	-29.67	-21.50	-51.99	-30.67
Maximum Residual	63.39	27.05	63.39	36.19	23.35	26.88	29.72	26.11	22.05	44.85
Observed Range in Head	140.15	89.89	123.07	111.30	110.32	101.81	102.10	98.45	114.91	112.56
Residual Std. Dev./Range	0.045	0.067	0.058	0.059	0.056	0.052	0.054	0.056	0.058	0.067

Figure 45 through Figure 53 compare simulated head values to observed head values for each model layer. Figure 54 through Figure 62 illustrate head residuals and hydraulic head contours for all nine model layers.

COMPARISON TO TRANSMISSIVITY

Calibration to transmissivity provided reasonable results (Figure 63), except in the vicinity of Belle Plaine Well 1, a Quaternary well, where modeled transmissivity is considerably lower than observed

VALUES

transmissivity. Poor model fit in this area may be due to the inability of sand content mapping to delineate high permeability features buried in thick till. Figure 64 compares simulated hydraulic conductivity values to observed hydraulic conductivity values for each geologic unit.

COMPARISON TO DISCHARGE ESTIMATES

Calibration to baseflow offered mixed results (Table 5, Figure 65). For some river reaches, simulated and observed baseflow values show favorable comparison. In other reaches, particularly along the Mississippi River, simulated and observed baseflow values are poorly correlated. Additionally, the model was not always able to match limited field data indicating groundwater discharge along certain stream reaches; instead, the model predicted groundwater infiltration in some portions of Basset Creek, Bevens Creek, Carver Creek, Credit River, Elm Creek, Minnehaha Creek, Valley Creek, and the Vermillion River. It is important to note that the error associated with field-measured values of baseflow is very high, particularly in large rivers such as the Mississippi, which must be considered when interpreting the validity of model results.

Table 5. Flux (baseflow) calibration target statistics.

Calibration Statistic	Value
Residual Mean	-219,427.89
Residual Standard Deviation	603,625.84
Absolute Residual Mean	242,293.46
Minimum Residual	NA
Maximum Residual	168,109.66
Observed Range in Head	NA
Residual Standard Deviation/Range	0.207

WATER BUDGET

Table 6 illustrates the calibrated model water balance. Water movement between model layers is illustrated in Figure 66 through Figure 73.

Table 6. Inputs and outputs to the regional groundwater flow model by layer.

Layer	Inflow						Outflow					
	Recharge	Rivers	Constant Head	Wells	Top	Bottom	Recharge	Rivers	Constant Head	Wells	Top	Bottom
1	2,439,382.43	1,309,253.91	98,687.95	0.00	0.00	1,380,417.37	0.00	1,616,342.34	20,842.91	33,683.71	0.00	3,556,873.55
2	696,420.26	138,724.75	90,553.33	0.00	3,556,873.55	2,131,449.72	0.00	1,295,255.08	13,044.29	29,510.94	1,380,417.37	3,895,794.90
3	579,856.42	376,899.69	170,583.57	0.00	3,895,794.90	2,380,252.34	0.00	931,545.25	39,878.32	324,823.58	2,131,449.72	3,975,688.61

4	131,803.51	127,307.61	120,725.44	0.00	3,975,688.61	1,849,957.75	0.00	562,616.91	22,361.56	489,420.66	2,380,252.34	2,750,832.06
5	98,649.80	36,082.50	64,546.57	0.00	2,750,832.06	1,774,917.49	0.00	436,332.38	19,579.26	44,272.51	1,849,957.75	2,374,887.07
6	59,319.87	975.30	160,276.55	0.00	2,374,887.07	1,174,366.94	0.00	436,721.87	28,938.56	82,123.86	1,774,917.49	1,447,123.74
7	9,367.55	10,061.92	301,425.07	0.00	1,447,123.74	490,540.16	0.00	529,907.45	44,545.30	42,018.45	1,174,366.94	467,680.98
8	520.17	0.00	142,888.84	0.00	467,680.98	167,988.50	0.00	2,196.68	15,135.04	5,613.31	490,540.16	265,593.18
9	0.00	0.00	19,010.05	0.00	265,593.18	0.00	0.00	0.00	6,496.07	110,118.36	167,988.50	0.00
Total	4,015,320.01	1,999,305.67	1,168,697.37	0.00	-	-	0.00	5,810,917.97	210,821.30	1,161,585.39	-	-

SENSITIVITY ANALYSIS

During the process of model calibration, several conceptual model assumptions regarding hydraulic conductivity were tested, including the relationship between sand content and hydraulic conductivity in Quaternary sediments, the impact of defining hydraulic conductivity in Quaternary sediments using zones versus model cells, the impact of defining uniform hydraulic conductivity for each hydrostratigraphic unit versus defining variable hydraulic conductivity within each hydrostratigraphic unit, and the impact of allowing vertical hydraulic conductivity to exceed horizontal hydraulic conductivity in large areas across the model domain in order to achieve a more optimized model.

Seven models were developed and optimized. All models relied on the same calibration targets, boundary conditions, pumping stresses, and initial heads and recharge rates. Model scenarios included:

1. "Quaternary by Zone Sand Content" – This is the model used by the Metropolitan Council for the development of the Twin Cities Metropolitan Area Master Water Supply Plan and described in detail in this report. The hydraulic conductivity of each hydraulic conductivity zone representing Quaternary deposits varies based on the representative percent sand within that zone. The hydraulic conductivity is based on a linear relationship between a maximum and minimum hydraulic conductivity (Figure 74). Maximum and minimum hydraulic conductivity were adjustable parameters during model calibration. The hydraulic conductivity of bedrock units was also defined using a zone-based approach.
2. "Quaternary by Cell Sand Content" – Like the "Quaternary by Zone Sand Content"

approach, the hydraulic conductivity of Quaternary deposits was varied based on representative percent sand. However, the hydraulic conductivity of each *model cell* representing the Quaternary was varied based on percent sand within that cell. The hydraulic conductivity of bedrock units was defined as described above.

3. "Base Case" – Hydraulic conductivity zones were used to define hydraulic conductivity for all hydrostratigraphic units in each model layer. Hydraulic conductivity values within all zones were allowed to vary freely during model calibration; Quaternary zones were unconstrained by sand content.
4. "Minimum Parameters 1" – Hydraulic conductivity zones for each hydrostratigraphic unit were tied together so that each unit had only two adjustable parameters, horizontal and vertical hydraulic conductivity. In other words, the hydraulic conductivity of each hydrostratigraphic unit was assumed to be uniform across that unit.
5. "Minimum Parameters 2" – Like the "Minimum Parameters 1" approach, this scenario employed a very simplified method of defining hydraulic conductivity. In this case, hydraulic conductivity zones for subcrop and buried portions of each hydrostratigraphic unit were tied together. In other words, the hydraulic conductivity of each hydrostratigraphic unit was assumed to be uniform across the buried portions of the unit and uniform across the exposed or subcropping portions of that unit; buried and subcrop areas were allowed to have hydraulic conductivity values that differed from one another.
6. "Base Case Fix Anisotropy" – Following the "Base Case" run, it was noted that several hydraulic conductivity zones had vertical hydraulic conductivity values greater than horizontal hydraulic conductivity values. For these zones, the vertical and horizontal hydraulic conductivity values were adjusted to be equal and the model was re-run.
7. "Minimum Parameters 1 Fix Anisotropy" – Following the "Minimum Parameters 1" run, it was noted that several hydraulic conductivity zones had vertical hydraulic conductivity values greater than horizontal hydraulic conductivity values. For these zones, the vertical and horizontal hydraulic conductivity values were adjusted to be equal and the model was re-run.

Appendix D contains summary figures illustrating maximum, mean, minimum, and range in head and horizontal hydraulic conductivity as determined by these seven models. Hydraulic head residuals for each model layer are summarized in Table 7.

Table 7. Hydraulic head residuals resulting from seven regional groundwater model scenarios employing different approaches to hydraulic conductivity delineation.

	Layer Head Residual								
Model Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Quaternary by Zone	38010.1	107405.9	119398.2	54262.4	43564.8	176921.0	20249.0	20376.2	20020.8
Quaternary by Cell	74187.2	145133.9	294997.2	108254.4	134339.7	278708.8	40343.1	30428.6	34348.6
Base Case	34494.3	78282.8	91526.2	49571.2	35953.8	121776.5	21660.3	20376.9	15453.2
Minimum Param. 1	96174.1	207029.2	176552.1	73669.6	48707.5	206543.6	39297.3	53659.9	46498.6
Minimum Param. 2	96655.8	209743.8	153296.1	64234.6	43098.1	172888.3	18953.9	26153.2	30458.1
Base Case Fix Anis	33437.9	78809.2	92352.4	49878.5	36198.4	121964.4	21703.4	20369.5	15445.3
Min Par 1 Fix Anis	97346.6	218768.1	179560.2	73703.5	48661.1	206324.0	39226.5	53607.4	46495.5

Within the “Quaternary by Zone Sand Content” model, relative parameter sensitivities provide a qualitative indication of where model parameter uncertainty may originate. Figure 75 illustrates the top 25 most sensitive adjustable parameters. Many of these parameters are bed conductance values for river boundary condition cells. This suggests that, in some cases, model uncertainty could be reduced by obtaining better estimates of lake bed conductance and stream baseflow. Other sensitive parameters include horizontal hydraulic conductivity values in portions of the Prairie du Chien Group, Jordan Sandstone, and Franconia Formation; calibration limits on Quaternary hydraulic conductivity zones; and multiplication factor applied to recharge during model calibration.

Selected calibration statistics were computed for six of the most sensitive “Quaternary by Zone Sand Content” model parameters. The differences in model-calculated sum of squared residuals and average head between model simulations show the model sensitivity to these adjustments (Figure 76).

MODEL UNCERTAINTY

Models are simplifications of reality; therefore, all models have inherent uncertainty imbedded within them. This uncertainty within the model will always lead to some uncertainty in any conclusions drawn from the model. Still, modeling is the best tool available to synthesize the myriad factors governing our regional groundwater flow system and to meet the challenge of impact prediction. Sources of uncertainty in the Metro Model 2 stem from:

- An incomplete understanding of the geologic conditions in the Twin Cities area, including the presence of undetected features (e.g., faults, changes in glacial deposits);
- An incomplete understanding of groundwater flow pathways and rates;
- Data gaps in groundwater levels (particularly for deeper aquifers);

- Accuracy in estimates of aquifers and aquitard hydraulic conductivity due to a small set of existing pumping tests;
- Undocumented or inaccurately reported groundwater withdrawals;
- Limited base-flow data for streams (particularly for the Mississippi River through Minneapolis and St. Paul);
- Limited or non-existent information on the permeability of lake bottoms;
- Limited or non-existent information on rate of flux between groundwater and surface water systems in wetlands and lakes;
- Incomplete and evolving understanding of how and where recharge through infiltration takes place;
- The necessary simplifications, lumping of conditions, and time-averaging of observations that is needed in order to build and calibrate a groundwater flow model;
- The need to exclude very detailed, site-specific hydrogeologic data in a regional model; and
- The conceptualization of groundwater flow on a regional basis for the purpose of this model (the evaluation of groundwater supply).

Continuing efforts will be made to reduce model uncertainty and increase model uniqueness through the implementation of the Twin Cities Metropolitan Area Master Water Supply Plan. The Metro Model 2 will be recalibrated, or optimized, as new data are obtained and new understandings of regional hydrogeology evolve. The following types of information are particularly likely to have an impact on reducing model uncertainty:

- Surface water-groundwater interaction data
    - Stream baseflow measured at multiple locations along the stream, not just at the mouth
    - Hydraulic properties (hydraulic conductivity) of stream and lake bed sediments
    - Seepage rates into or out of streams and lakes
- Better understanding of the water-transmitting characteristics of the glacial drift deposits
    - Region-wide, three-dimensional mapping of till and outwash deposits
    - Hydraulic properties (hydraulic conductivity, specific storage, storage coefficient) of these deposits
- Better understanding of the water-transmitting characteristics of all bedrock units
    - Hydraulic properties (hydraulic conductivity, specific storage, storage coefficient) of these units
- Additional head calibration data, such as that generated by additional observation wells and synoptic water level measurements

APPLICATION AND USE OF THE METRO MODEL 2

APPROPRIATE MODEL USE & LIMITATIONS

The process and resulting regional steady-state model presented in this report address the following objectives:

1) Integration of hydrogeologic, land use, and water demand data into a regionally-consistent package was achieved through the creation of GIS files and their inclusion in online mapping applications allowing users to download data for their own purposes. This package includes existing data as well as new GIS and Metro Model 2 files compiled for this project.
2) Access to this data was provided through the Metropolitan Council's MAPS website and the Water Supply Planning Unit's Metro Model 2 website. Periodic changes and improvements are expected to the model; they will be posted on the Metropolitan Council Water Supply Planning website.
3) Development of consensus on a groundwater flow modeling approach and hydrogeologic conceptual model was achieved through the coordination of a technical advisory committee of local groundwater experts and other interested parties, the Master Water Supply Plan public review process, and subsequent small group discussion and model revision. Technical advisory committee materials are available online at: www.metrocouncil.org/environment/WaterSupply/metrogroundwatermodelmeetingmaterials.html
4) Construction and calibration of a regional groundwater flow model was achieved through the process outlined in this report.
5) Prediction of potential future regional conditions in all major metropolitan area aquifers and aquitards under a variety of demand and land use scenarios was achieved through a process described in Appendix E.

The intended use of the Metro Model 2 is the regional evaluation of potential water resource and supply impacts resulting from changes in groundwater withdrawals. Conclusions drawn from this regional analysis, presented in Appendix E, are a substantial component of the water availability analysis supporting the Twin Cities Metropolitan Area Master Water Supply Plan. It is important to note that model results are intended simply to guide long-term resource protection strategies focused on resource monitoring and the subsequent establishment of resource protection thresholds. Model results are *not* intended to be used as triggers for water supply system development requirements.

Limitations in the model are acknowledged. The steady-state nature of the model does not allow for evaluation of seasonal change in aquifer water levels or stream baseflow; the model represents conditions only as they would appear under equilibrium, or long-term average conditions. The model grid cell size limits the model's ability to predict aquifer water levels precisely at a discrete point; the model calculates the average aquifer water level across each grid cell and is therefore unable to evaluate drawdown precisely at a specific well. The model represents lakes and rivers with MODFLOW's River package, which assumes a constant long-term average water level for these features; the model does not evaluate changes in lake and stream levels. Uncertainty present in the conceptual model and in calibration datasets limit the accuracy and precision of model calculations of groundwater level and flux, as described earlier in this report.

The model is most reliable when predicting likely future groundwater levels, given projected water demand - more so in bedrock than surficial aquifers. In contrast, predictions of future baseflow in streams are highly uncertain and should be verified through field data collection. The model may be used with some confidence, however, to evaluate the magnitude of stream baseflow change given different system conditions. This type of comparative analysis may be useful in informing certain data collection and management decisions.

Site-specific predictions should not be made with the regional model. For these problems, telescopic mesh refinement (TMR) should be employed to create a more detailed local model capable of estimating water levels with greater precision. Use of all available local information will lead to a better representation of the flow system. Model parameters likely require modification and/or replacement for more site-specific modeling.

FUTURE WORK

Through the model and Master Water Supply Plan development process, multiple directions for future work were identified. A need for periodic model recalibration was identified, ongoing evaluation of the conceptual model was suggested, several predictive model scenarios were proposed, and the need for an established process to update the model with information from local studies was identified.

Model Recalibration

Previous discussion of model uncertainty touched on the value of additional data for future model recalibrations. In order to improve the predictive accuracy of the model, several data collection and recalibration efforts were identified. Data needs include:

- Water-level measurements at existing municipal production and observation wells, taken at least monthly. Water-level measurements in wells open to the Franconia Formation and Ironton and Galesville Sandstones are particularly needed in the central metropolitan area, where most wells utilize the Prairie du Chien-Jordan Aquifer.
- Water-level measurements at new state observation wells. New wells in the Mt. Simon aquifer are needed, and nested observation wells across the region will be particularly valuable in providing information about the interaction between aquifers and vertical rates of flow through the groundwater flow system.

- Synoptic groundwater-level measurements, taken at least every 5 years.
- Aquifer test data. There is a particular need for aquifer test data in the Franconia Formation and Ironton and Galesville Sandstones in the southwestern and west-central part of the Twin Cities metropolitan area. Aquifer testing of Quaternary aquifers throughout the region is also needed.
- Surface water base-flow data. For model calibration, additional stream gauging data, particularly for low-flow conditions, is needed at upstream locations along tributaries to the Minnesota, Mississippi, and St. Croix Rivers. Regular late-season measurements of stream discharge at the head and mouth of tributary streams is necessary to estimate groundwater contribution along those tributaries within the Twin Cities metropolitan area.
- Lake- and stream-bed hydraulic properties. Local assessments of lake- and river- bed conductance are necessary throughout the region to better define relationships between the surface water and groundwater flow systems.
- Hydrogeologic mapping, particularly of unconsolidated sediments, is needed throughout the Twin Cities metropolitan area. Anoka and Carver counties will particularly benefit from the collection of updated hydrogeologic data. Detailed study of flow between bedrock and surficial aquifers in the vicinity of buried bedrock valleys is also needed.
- Recharge measurements. Field measurements are needed to verify model-predicted rates of infiltration below the root zone. Nested observation wells, open to surficial and bedrock aquifers, will be particularly valuable in understanding vertical groundwater flow rates through the region's layered aquifer system.

Recalibration of the model will be considered annually or as needed on a project specific basis. Because of the time required to conduct calibration, multiple calibration targets or changes to the model will be made prior to calibration. A single additional hydraulic head calibration target most likely does not warrant the time necessary to recalibrate the model. In general, new calibration targets that are associated with new hydraulic stresses offer the greatest opportunities for insight into model parameters. For example, groundwater elevations associated with the installation of a new high capacity well or base flow changes associated with significant changes in quarry dewatering could provide data that would affect the parameter selection (especially locally). Appendix F provides technical suggestions to assist the model calibration process.

Evaluation of the Conceptual Model

The conceptual model underpinning the Metro Model 2 should be reviewed and revised as new data and analyses lead to new understanding of the hydrogeologic system of the Twin Cities metropolitan area, and as the Metropolitan Council to addresses questions beyond the scope of the current model. For example:

- Modifying the Metro Model 2 to run transient simulations, in order to provide improved predictive capability to address impacts of summer peak demands and water conservation strategies.

- Revising the current model representation of surficial sediments as more detailed mapping of those sediments becomes available. Instead of representing surficial deposits as essentially a single model layer, perhaps additional model layers will be needed to more realistically represent the flow system.
- Representing the Franconia Formation as two model layers, based on recent work defining the Franconia Formation as both an aquifer and an aquitard.
- Changing Metro Model 2 boundaries, particularly no-flow boundaries, based on improved hydrogeologic mapping (already in progress in Carver and McLeod counties). Evaluating the effects of using a no-flow boundary versus a constant head boundary in the western and southern portions of the model may be worthwhile.
- Assessing model boundary conditions associated with the Mt. Simon Sandstone, particularly in the southwestern portion of the model where regional flow data is sparse.

Revision of the conceptual model will be considered as warranted by new data. This process is expected to require substantial resources to accomplish, in terms of both time and money. Active contribution by the technical advisory group will be needed over a period of years.

Predictive Model Scenarios

The Metropolitan Council intends to apply the Metro Model 2 to regional land use planning and regional water supply availability assessment through the development and presentation of several recharge and demand scenarios. Possible examples include:

- Applying all current Minnesota Department of Natural Resource permitted groundwater appropriation rates to the model in order to test the impacts of currently approved withdrawal rates on future aquifer conditions; permitted withdrawals are often much larger than actual use and the cumulative impact of permitted rates on the metropolitan area groundwater system has not been evaluated.
- Applying all future pumping to the Mt. Simon-Hinckley aquifer in order to test current Minnesota policy restricting use of that aquifer in the Twin Cities metropolitan area.
- Applying reduced demand to the model to reflect a variety of conservation measures in order to test the capacity of conservation requirements to improve water availability
- Appling all future pumping to each major aquifer in an iterative process to illuminate the implications of over-developing certain aquifers
- Applying projected land use changes to the SWB model in order to test impacts of change on recharge distribution and rate.
- Applying estimates of climate fluctuations to the model in order to test impacts of change on future aquifer conditions

Integrate Local Information

Ongoing implementation of the Twin Cities Metropolitan Area Master Water Supply Plan includes cooperation between local and regional entities. In order to maximize the value of water resource assessment and protection efforts, local and regional data collection and resource assessment activities should be reviewed and integrated wherever possible. Where local studies and the regional assessment contradict one another, issues must be resolved. A formal process to do this has not yet been established. As a first step, the Metropolitan Council intends to utilize existing regional groundwater work groups and to establish additional work groups to facilitate data sharing and discussion of local and regional water supply issues. More information is provided in the Twin Cities Metropolitan Area Master Water Supply Plan.

REFERENCES

Anoka County Conservation District. 2007. Stream Flow Data, accessed July 2007 at www.AnokaNaturalResources.com.

Barr Engineering Company. 2005. Integrating Groundwater and Surface Water Management: Southern Washington County, prepared for Washington County and the Washington Conservation District, accessed online http://www.co.washington.mn.us/client_files/documents/phe/ENV/ENV-GW-SWC.PDF on July 13 2007.

Barr Engineering Company. 2007. A Simple Daily Soil Water Balance (Draft). Submitted to the Metropolitan Council Environmental Services, May 2008.

Barr Engineering Company. 2008. Water Supply Availability Analysis: Report on Development of a Groundwater Flow Model of the Twin Cities Metropolitan Area (Draft). Submitted to the Metropolitan Council Environmental Services, May 2008.

Cannon River Watershed Partnership. 2007. Email summarizing 2001-2003 Cannon River flow data, From Beth Kallestad of Cannon River Watershed Partnership to Lanya Ross of Metropolitan Council, Dated December 20, 2007.

Carver County Watershed Management Organization (WMO). 2007. Email summarizing 1997-2006 Carver County flow data, From Greg Aamodt of Carver County to Lanya Ross of Metropolitan Council, Dated 7/7/2007.

D'Agnese, Frank A., O'Brien, Grady M., Faunt, Claudia C., Belcher, Wayne R., San Juan, Carma. 2002. A Three-Dimensional Numerical Model of Predevelopment Conditions in the Death Valley Regional Ground-Water Flow System, Nevada and California, U.S. Geological Survey Water-Resources Investigations Report 02-4102, 122 p.

Dakota County Soil and Water Conservation District. 2007. Email summarizing historical Vermillion River flow data, From Travis Bistodeau of Dakota County Soil and Water Conservation District to Lanya Ross of Metropolitan Council, Dated 6/15/2007.

Delin, G.N. and D.G. Woodward. 1984. Hydrogeologic Setting and the Potentiometric Surfaces of Regional Aquifers in the Hollandale Embayment, Southeastern Minnesota, 1970-80. U. S. Geological Survey Water Supply Paper 2219. 56 p.

Delin, Geoffrey N.; Healy, Richard W.; Lorenz, David L., and Nimmo, John R.. 2007. Comparison of local- to regional-scale estimates of ground-water recharge in Minnesota, USA; Journal of Hydrology, Issue 334, pages 231-249.

Dripps, W.R. and Bradbury, K.R.. 2007. A simple daily soil-water balance model for estimating the spatial and temporal distribution of ground-water recharge in temperate humid areas: Hydrogeology Journal, v. 15. p. 433-444.

Environmental Simulations, Inc.. 2007. Guide to using Groundwater Vistas, Version 5, Environmental Simulations Inc., 372 p.

Hansen, Douglas D. and Seaberg, John K.. 2000. Metropolitan Area Groundwater Model Project Summary: South Province, Layers 1, 2, and 3 Model (Version 1.00, July 2000).

Hansen, Douglas D. and Seaberg, John K.. 2000. Metropolitan Area Groundwater Model Project Summary: Lower Aquifers Model (Version 1.00, July 2000).

Harbaugh, A.W., and McDonald, M.G.. 1996. User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.

Hill, M.C.. 1990. Preconditioned Conjugate-Gradient 2 (PCG2), A Computer Program for Solving Ground-Water Flow Equations. U.S. Geological Survey Water-Resources Investigations Report 90-4048, Denver, Colorado, 43p.

Janovec, Mark. 2007. Email summarizing flow data, From Mark Janovec of Bonestroo to Lanya Ross of Metropolitan Council, Dated 6/11/2007.

Johnson, M.D., and H.D. Mooers. 1998. Ice-margin positions of the Superior lobe during Late Wisconsinan deglaciation. in Patterson, C.J., and H.E. Wright eds. Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49, p. 7-14.

Juckem, P.. 2007. Simulation of the Ground-Water-Flow System in Pierce, Polk, and St. Croix Counties, Wisconsin. Draft U. S. Geological Survey Scientific Investigations Report 2008-XXXX., 69 p.

McDonald, M.G., and A.W. Harbaugh. 1988. A Modular Three-Dimensional Finite-Difference Groundwater Flow Model, U.S. Geological Survey Techniques of Water Resource Investigations, TWRI 6-A1, 575 p.

Metropolitan Council. 2007. Report to the Minnesota State Legislature: Water Supply Planning in the Twin Cities Metropolitan Area, Publication No. 32-07-004, 52 p.

Mehl, S.W., and Hill, M.C., 2001, MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model - User Guide to the Link-AMG (LMG) Package for Solving Matrix Equations Using an Algebraic Multigrid Solver: U.S. Geological Survey Open-File Report 01-177, 33 p.

Menheer, Michael. 2005. Development of a Benthic-Flux Chamber for Measurement of Ground-Water Seepage Rates and Water Sampling for Mercury Analysis at the Sediment-Water Interface, U. S. Geological Survey Scientific Investigation Report 2004-5298, 20 p.

Metropolitan Council. 2007a. Water Supply Planning in the Twin Cities Metropolitan Area: Report to the 2007 Minnesota State Legislature, 53 p.

Metropolitan Council. 2007b. MCES Continuous Stream Monitoring Data, internal database of unpublished data summarizing stream flow in streams throughout the Twin Cities metropolitan area.

Minnehaha Creek Watershed District. 2007. Unpublished data summarizing stream flow in the Minnehaha Creek Watershed. September 27, 2007; From Udai Singh of Minnehaha Creek Watershed District to Lanya Ross of Metropolitan Council.

Minnesota Climatology Working Group. 2008a. Minneapolis/St. Paul Metro Area Climate Page, accessed at http://climate.umn.edu/doc/twin_cities/twin_cities.htm.

Minnesota Climatology Working Group. 2008b. Normal Precipitation Maps, accessed at http://climate.umn.edu/doc/historical/precip_norm.htm.

Minnesota Department of Health. 2007a. Email summarizing aquifer test data generated through municipal water supply planning. From Amal Djerrari of Minnesota Department of Health to Lanya Ross of Metropolitan Council. Dated 10/4/2007.

Minnesota Department of Health. 2007b. Email summarizing aquifer test data generated through municipal water supply planning, From Steve Robertson of Minnesota Department of Health to Lanya Ross of Metropolitan Council, Dated 10/3/2007.

Minnesota Department of Health. 2007c. Email summarizing Public Water Supply Inventory Report data. From Judy McDermott of Minnesota Department of Health to Lanya Ross of Metropolitan Council.

Dated 01/26/2007.

Minnesota Department of Health. 2008. Minnesota County Well Index, downloaded May 2008 from the Minnesota Geological Survey.

Minnesota Department of Natural Resources - Waters. 1998. Lake-Ground Water Interaction Study at White Bear Lake, Minnesota: Report to the Legislative Committee on Minnesota Resources, 92 p .

Minnesota Department of Natural Resources. 2007. Email summarizing the State Water Use Data System (SWUDS). From Sean Hunt of Minnesota Department of Natural Resources to Sara Bertelsen of Metropolitan Council. Dated 05/29/2008.

Minnesota Geological Survey. 2006. County Well Index, updated November 3, 2006.

Minnesota Department of Natural Resources. 2007. Minnesota Department of Natural Resources/Minnesota Pollution Control Agency Cooperative Stream Gaging Data. Accessed June 12, 2007 at http://www.dnr.state.mn.us/waters/csg/ index.html.

Minnesota Pollution Control Agency. 2005. Metropolitan Groundwater Model Informational Catalog, http://www.pca.state.mn.us/water/groundwater/huc/index.html, last reviewed January 18, 2005. Accessed July 2007.

Mohring, Eric. 1986. The Effects of Lake Level Lowering on Lake-Ground Water Interaction at School Section Lake, Stearns County, Minnesota, Minnesota Department of Natural Resource Division of Waters, 27 p.

Mossler, J.H., 2008, Paleozoic Stratigraphic Nomenclature for Minnesota, Minnesota Geological Survey Report of Investigations 65, ISSN 00769177, Published by University of Minnesota, St. Paul, MN, 84 p.

Mossler, J.H. and R.G. Tipping. 2000. Bedrock geology and structure of the seven-county Twin Cities metropolitan area, Minnesota. Miscellaneous Map Series M-104, Minnesota Geological Survey.

Mossler, J.H., Runkel, A.C., Bauer, E.J.. 2006. Subcrop of the St. Lawrence Formation in the seven-county Twin Cities Metropolitan Area, Minnesota: Minnesota Geological Survey Open File Report 06-05.

Novotny, E.V. and Stefan, H.G.. 2007. Stream Flow in Minnesota: Indicator of Climate Change, Journal of Hydrology, v. 334, Issues 3-4, pages 319-333.

Olcott, P.C.. 1992. Ground Water Atlas of the United States: Iowa, Michigan, Minnesota, Wisconsin, U.S. Geological Survey Hydrologic Atlas Report HA 730-J, accessed online at http://pubs.usgs.gov/ha/ha730/ch_j/index.html on July 15, 2007.

Payne, G. A.. 1995. Ground-Water Baseflow to the Upper Mississippi River Upstream of the Minneapolis-St. Paul area, Minnesota during July 1988. U. S. Geological Survey Open-File Report 94-478, 28 p.

Rice Creek Watershed District, 2007, Email summarizing historical Rice Creek Watershed stream flow data, From Ned Phillips of Rice Creek Watershed District to Lanya Ross of Metropolitan Council, Dated 6/13/2007.

Ruhl, J.F.. 1994. The Quality of Groundwater around Vadnais Lake an in Lambert Creek Watershed, and Interaction of Ground Water with Vadnais Lake, Ramsey County, Minnesota. U. S. Geological Survey Water-Resources Investigations Report 94-4062, 59 p.

Runkel, A.C., Tipping, R.G., Alexander Jr., E.C., Green, J.A., Mossler, J.H., Alexander, S.C.. 2003. Hydrogeology of the Paleozoic Bedrock in Southeastern Minnesota, Minnesota Geological Survey Report of Investigations 61, ISSN 0076-9177, Published by University of Minnesota, St. Paul, MN, 112 p.

Runkel, A.C., R.G. Tipping, and J.H. Mossler. 2003. Geology in support of groundwater management for the northwestern Twin Cities Metropolitan Area. Final report to the University of Minnesota and the Metropolitan Council, August 27, 2003.

Runkel, A.C. and R.G. Tipping. 2006. Bedrock topography, depth to bedrock, and bedrock geology models, Plate 5 in Geologic atlas of Scott County, Minnesota. D.R. Setterholm (ed.). Minnesota Geological Survey, county atlas series, atlas C-17. 6plts

Runkel, A.C., J.H. Mossler, R.G. Tipping, and E.J. Bauer. 2006. A hydrogeologic and mapping investigation of the St. Lawrence Formation in the Twin Cities Metropolitan Area. Minnesota Geological Survey Open File Report 06-04.

Schoenberg, M. E. and G. B. Mitton. 1990. Monthly Mean Discharge at and between Selected Streamflow-Gaging Stations along the Mississippi, Minnesota, and St. Croix Rivers, 1932-87. U. S. Geological Survey Open-File Report 90-186, 36 p.

Schoenberg, M. E.. 1994. Effects of Present and Projected Ground-Water Withdrawals on the Twin Cities Aquifer System, Minnesota. U. S. Geological Survey Water Resources Investigations Report 90-4001, 165 p.

Seaberg, John K., and Hansen, Douglas D.. 2000. Metropolitan Area Groundwater Model Project Summary: Northwest Province, Layers 1, 2, and 3 Model (Version 1.00, July 2000)

Seaberg, John K., and Hansen, Douglas D.. 2000. Metropolitan Area Groundwater Model Project Summary: Northeast Province, Layers 1, 2, and 3 Model (Version 1.00, July 2000)

Shakopee Mdewakanton Sioux Community. 2007. Email summarizing historical Boiling Springs flow data, From Ole Olmanson of Shakopee Mdewakanton Sioux Community to Lanya Ross of Metropolitan Council, Dated 7/27/2007.

St. Croix Research Center. 2007. Email summarizing historical St. Croix River tributary flow data, From Jim Almendinger of St. Croix Watershed Research Center to Lanya Ross of Metropolitan Council, Dated 6/1/2007.

Streitz, A.R. 2003. Preparation of supporting databases for the Metropolitan Area Groundwater Model, Version 1.00. http://www.pca.state.mn.us/water/groundwater/mm-datareport.pdf. 45 p.

Thorleifson, Harvey L., Editor. 2008. Potential Capacity for Geologic Carbon Sequestration in the Midcontinent Rift System in Minnesota: A report prepared in fulfillment of the requirements of Minnesota Legislative Session 85 Bill S. F. 2096, Minnesota Open File Report OFR-08-01, University of Minnesota, St. Paul.

Tipping, R.G. and Mossler, J.H. 1996. Digital elevation models for the tops of the St. Peter Sandstone, Prairie du Chien Group, Jordan Sandstone and St. Lawrence/St. Lawrence-Franconia Formations within the seven-county metropolitan area: Minnesota Geological Survey, unpublished manuscript maps, scale 1:100,000, four digital files.

Tipping, R.G.. 2007. Geology in Support of Ground-water Management for the Twin Cities Metropolitan Area, unpublished Minnesota Geological Survey report to the Metropolitan Council.

Thornthwaite C.W. 1948. An approach toward a rational classification of climate. Geog. Rev. 38: no.1, 55-94.

Thornthwaite C.W. and J.R. Mather. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Publications in Climatology. 10: no. 3

United States Geological Survey. 2007. Real-Time Data for Minnesota_Streamflow, accessed June 2007 through the National Water Information System Web Interface at http://waterdata.usgs.gov/mn/nwis/current/?type=flow

Vermillion River Groundwater Report/EOR. 2007. Email summarizing Vermillion River flow data, From Jennifer Olson of EOR to Lanya Ross of Metropolitan Council, Dated 6/7/2007.

Washington County Conservation District. 2007. Email summarizing Washington County Conservation District stream flow data, From Travis Thiel of Washington County Conservation District to Lanya Ross of Metropolitan Council, Dated 8/15/2007.

Watermark Numerical Computing. 2005. PEST: Model-Independent Parameter Estimation. User Manual. 5th edition.