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Development of a Transient Version of the Northeast Metro Lakes Groundwater-flow (NMLG) Model - with Simulation and Calibration from 1980 through 2016

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List of Acronyms

3D	Three-dimensional
CN	Runoff Curve Number
DEM	Digital Elevation Model
gSSURGO	Gridded Soil Survey Geographic Database
GUI	Graphical User Interface
MGS	Minnesota Geological Survey
MM3	Metro Model 3
MNDNR	Minnesota Department of Natural Resources
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow Model
NLCD	National Land Cover Database
NMLG	Northeast Metro Lakes Groundwater-flow Model
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
PEST	Parameter ESTimation & Uncertainty Analysis Software
OPCJ	Prairie-du-Chien-Jordan
SCS	Soil Conservation Service
SIR	Scientific Investigations Report
SWB	Soil-Water-Balance Model
TCMA	Minneapolis-St. Paul Twin Cities Metropolitan Area
[MODFLOW]-LAK	Lake package for MODFLOW
[MODFLOW]-MNW	Multi-Node, Drawdown-Limited Well package for MODFLOW
[MODFLOW]-NWT	Newton-Raphson formulation package for MODFLOW
[MODFLOW]-RIV	River package for MODFLOW
[MODFLOW]-RCH	Recharge package for MODFLOW
[MODFLOW]-SFR	Stream-Flow Routing package for MODFLOW
[MODFLOW]-UZF	Unsaturated-Zone Flow package for MODFLOW
[MODFLOW]-WEL	Well package for MODFLOW

UMN	University of Minnesota
USGS	United States Geological Survey
WBL	White Bear Lake

Executive Summary

This report details the development, calibration, and illustrative application of a transient model of groundwater and surface water conditions within the area designated by Minnesota Department of Natural Resources (MNDNR) as the North and East Metro Groundwater Management Area in the Twin Cities. The model, referred to as the transient Northeast Metro Lakes Groundwater-flow model (NMLG model) can simulate groundwater and surface water conditions throughout the area under varying conditions, including changes in rainfall, evaporation, and groundwater pumping. Simulations completed under varying conditions, referred to as scenarios, can be used to inform decisions about future groundwater management actions.

Why Develop a Model?

The North and East Groundwater Management Area has experienced periodic rises and declines in both groundwater levels and lake levels. The major factors that cause groundwater levels and lake levels to rise and fall are changes in rainfall, evaporation, and groundwater pumping. How much each of these factors affect groundwater and lake levels over time depends on the patterns and rates of rainfall and evaporation and the magnitude, location and timing of pumping. The NMLG model was developed to help understand and meet the challenges of sustainable groundwater use throughout the North and East Groundwater Management Area. The NMLG model can be used to simulate actual historical conditions (historical model), or to project potential future conditions. The historical model can also be used to simulate groundwater and lake levels in the past that might have resulted if some of the factors listed above – such as pumping, or rainfall, or evaporation – had been different.

Some Demonstration Scenarios

Of particular and immediate interest to the application of the NMLG model are the concerns raised about low water levels that were experienced by White Bear Lake in recent years. A series of hypothetical scenarios was developed to illustrate how the NMLG model can be used to support resource management decisions. The NMLG model was used to simulate historical conditions surrounding and including White Bear Lake under a variety of alternate assumptions regarding groundwater use (i.e., pumping), which are referred to as alternate scenarios. These simulations help estimate the likely relative impact of the different factors on groundwater and lake levels, thereby helping to support resource management decisions. The specific scenarios evaluated with the NMLG to-date are as follows:

First, a small number of model runs was made in which all historical pumping rates for all pumping permits that include at least one well within a five-mile radius of White Bear Lake was reduced either by 25%, 50%, 75% or set to zero (effectively, turned off) to estimate the effect on White Bear Lake of the pumping that is associated with all permits simultaneously.

Second, a large number of model runs was made in which historical pumping rates for each pumping permit that includes at least one well within a five-mile radius of White Bear Lake was individually set to zero (effectively, turned off) to estimate the independent, relative, effect of the pumping associated with each individual permit on White Bear Lake volumes and levels.

Third, a single model run was made in which groundwater pumping associated with summertime residential irrigation was eliminated (effectively, turned off).

Initial Observations

First, the multi-permit scenarios collectively suggest that groundwater pumping within about five miles of White Bear Lake may, in aggregate, affect levels in White Bear Lake by as much or more than half a foot in some years. The effect of pumping is more pronounced during years of low net precipitation (i.e., recharge) and when lake stages are already below typical levels. Secondly, the elimination of pumping associated with each permit individually illustrates the proportionally larger effects of pumping associated with some permits versus others on lake levels. The relative proportions of these effects are related strongly to the rates of pumping, the distance of the pumping from the lake, and the aquifer(s) from which the water is pumped. And thirdly, the calculations suggest that eliminating summertime domestic irrigation would have a very limited effect on lake levels of less than about inch in any year.

The simulated scenarios illustrate how the transient NMLG model can be used to help understand and evaluate alternate resource management options, with conditions in the vicinity of White Bear Lake serving as an example. However, a much wider range of scenarios could be developed to evaluate other resource management options, including augmenting levels in White Bear Lake with imported surface water or groundwater; adjusting the level of the lake outlet control structure; or implementing alternate storm-water management practices within and beyond the surface water catchment of the lake.

Using the Model More Widely

Although the simulated scenarios emphasize conditions in and around White Bear Lake, they demonstrate how the transient NMLG model might be used to evaluate potential alternate water management scenarios further afield from the lake. As such, the transient NMLG model represents the most comprehensive compilation and numerical representation of data and information that are relevant to evaluating conditions and making water resource management decisions in the North and East Groundwater Management Area northeast metro area.

A Few Technical Details

The transient NMLG model was developed using the MODFLOW-NWT (Niswonger et al., 2011) groundwater and surface water flow simulator. Six major regional lakes are represented in the model using the MODLFLOW Lake (LAK) package, enabling changes in volume and lake level to be simulated explicitly; and groundwater recharge, components of overland flow into certain lakes, and other components of the water budget were estimated using the Soil Water Balance (SWB) model (Smith and Westenbrook, 2015). The development of this transient model builds directly upon an initial steady-state NMLG model that was developed by the United States Geological Survey (USGS)(Jones et al., 2017). Indeed, the transient NMLG model incorporates the vast majority of the features and capabilities of the steady-state model. The transient NMLG model, however, simulates time-varying conditions from 1980 through 2016.

Two versions of the transient NMLG model have been developed as described in this report: the first of these, referred to as the annual stress period version, simulates conditions on an annual-average basis. This version executes quickly and can be used to efficiently facilitate calibration, and make long-term calculations and assessments on an annual-average basis. The second version, referred to as the triannual version, is identical to the annual version except that it simulates conditions on a rolling four-month average that generally distinguishes between the typical periods of high, low and moderate pumping and groundwater recharge throughout any given year. The triannual version requires substantially longer to execute than the annual version, but by representing these three periods it simulates change with greater frequency and amplitude and should be used for higher-precision simulations where peaks in amplitude are important.

The transient NMLG model was calibrated to time-varying groundwater and lake level measurements throughout the period 1980 through 2016, although emphasis was placed on the period 1988 through 2016 for which there are detailed and reliable records. Using recent changes in levels at White Bear Lake as an example, hypothetical historical scenarios were simulated to illustrate how the transient NMLG model can be used to contrast the likely relative impact of groundwater pumping throughout the North and East Metro Groundwater Management Area, and might be used to develop focused mitigation strategies to minimize undesirable impacts. The report provides recommendations for subsequent work and additional capabilities from which the transient NMLG model would benefit, with emphasis on supporting these and other resource management analyses.

REPORT

Section 1
Introduction

1.1 Background

As documented by the Metropolitan Council (2013) among others, groundwater is the source of drinking water for about three-quarters of the people living in the Twin Cities metropolitan area (Figure 1-1). In addition to providing a critical drinking water resource, groundwater also discharges into and feeds many lakes and rivers supporting those ecosystems and associated recreational activities; and groundwater is also extracted for other purposes including industrial, agricultural, and aquifer remediation and restoration from contamination.

Groundwater in the Twin Cities metropolitan area resides within a sequence of aquifer units comprised from the land-surface downward of the following: complex, unconsolidated quaternary sediments comprising sands silts and gravels; the St. Peter Sandstone aquifer; the Prairie-du-Chien-Jordan (OPCJ) aquifer, comprising a combination of consolidated carbonate and sandstone facies; the Tunnel City-Wonewoc aquifer (formerly known as the Franconia-Ironton-Galesville aquifer), comprising a combination of consolidated carbonate and sandstone facies; and lastly the Mt. Simon-Hinckley aquifer, comprised predominantly of consolidated sandstone. Figure 1-2 depicts the generalized hydrostratigraphy of the Twin Cities metropolitan area aquifers.

Throughout the region, groundwater is primarily extracted for potable and irrigation purposes from the OPCJ and overlying quaternary aquifers, with lesser degree of development from the deeper aquifer units. These aquifers are in places connected to surface water in a complex interplay of recharge and discharge relationships. This connection between groundwater and surface water in and surrounding the Twin Cities metropolitan area is a critical one, in part because many groundwater-connected lakes are a source of great recreational and ecological value. Groundwater can at times discharge to and thus sustain flows within streams and levels within lakes and wetlands, while at other times groundwater may be recharged via flows from wetlands, lakes and rivers.

Detailed compilations of data regarding the hydrology of the Twin Cities metropolitan area lakes stem as far back as 1976 in a comprehensive database constructed by the U.S. Geological Survey (USGS) which contains information for over 900 lakes in the broader Minneapolis-St. Paul metropolitan area, as documented in the Water Resources Investigations (WRIR) Report *Hydrology of Lakes in The Minneapolis-St. Paul Metropolitan Area: A Summary of Available Data* (WRIR-76-85). Digital simulations of groundwater conditions in particular in the Twin Cities date back to 1982, as documented by Guswa et al (1982: USGS WRIR-82-44).

This interplay of groundwater with surface water is common in lake-dominated watersheds, and motivates an integrated approach to water resource management in areas such as the Twin Cities. In recent years, the USGS Minnesota Water Science Center undertook the development of an integrated groundwater-surface water flow model of a region to the northeast of the Twin Cities metropolitan area. This model, referred to as the Northeast Metro Lakes Groundwater-flow (NMLG) model, was developed under contract with the Metropolitan Council and the Minnesota Department of Health to assess groundwater and lake-water exchanges and the effects of groundwater withdrawals, precipitation and other factors on water levels in lakes in the northeast Twin Cities metropolitan area. As of the spring of 2017, the NMLG model developed by the USGS represents long-term average conditions between 2003 and 2013 using a steady-state simulation, and is documented in a draft Scientific Investigations Report describing the model and several simulations performed using the steady-state model.

1.2 Purpose

Given the foregoing complex interactions of ground and surface water, the Minnesota Department of Natural Resources (MNDNR) requires a computational platform that can simulate time-varying ground and surface water budgets and interactions within the northeast metro area and how these budgets and interactions change in response to changing stresses including recharge, groundwater pumping and various resource management alternatives. Due to recent concern regarding declining lake stages, one particular application of the developed model will be to evaluate the response of White Bear Lake (WBL) levels to permitted groundwater use, changes in recharge rates and patterns, and other factors. In addition, the developed model may be used to calculate response functions for well fields or other groups of wells and to evaluate the potential hydrological effects of alternative management scenarios such as changes in the distribution of groundwater withdrawals and use of augmentation with imported water. The model may also be used to evaluate the effect of modifying the outlet elevation on lake-stages over time. Although the steady-state NMLG model provides a foundation for undertaking such analyses, the steady-state NMLG model does not directly address these specific needs of the MNDNR.

1.3 Objectives

The overarching objective is to develop a transient version of the NMLG model that simulates time-varying groundwater and surface water stresses and responses for an extended simulation period with a time-discretization that enables the simulation of seasonal changes in groundwater conditions, groundwater-lake interactions, lake levels, and surface outflows. To accomplish this, the accompanying Soil Water Budget (SWB) model used to compute subsurface infiltration also requires revision to provide extended-period, transient, estimates of recharge to groundwater and to lakes (the latter as surface run-off within lake catchments). Additional, specific objectives to be accomplished as part of this transient model development include the following:

(a) obtaining a numerically accurate, stable and computationally manageable solution for the transient simulations;

(b) identifying appropriate transient conditions for the lateral and internal boundaries;

(c) developing a methodology to represent the magnitude and timing of transient evaporation from large lake bodies; and

(d) identifying and implementing additional revisions and refinements as necessary to develop the transient NMLG model.

Following the attainment of these objectives, the parameters of the transient NMLG model require calibration to obtain reasonable correspondence between simulated and measured historical groundwater and surface water elevations (history-matching), before the model can be used to evaluate resource management alternatives.

1.4 Acknowledgements

The transient NMLG model was built directly upon, and benefitted greatly from, the foundations created by several staff of the USGS as described by Jones et al. (2017). Other staff of USGS, foremost among them Richard Niswonger, provided support in the customization of the MODFLOW-NWT code with application to the transient NMLG model. Many staff of numerous organizations contributed to the development of the transient NMLG model via the provision of data and information and participation in conference calls to discuss, plan and implement the model development. These organizations include the Metropolitan Council; Minnesota Department of Health; Minnesota Geological Survey; Minnesota Department of Agriculture; and Minnesota Pollution Control Agency.

Section 2
Study Area Hydrology and Hydrogeology

The geology, hydrology and hydrogeology of the study area are described in detail in Jones and others (2013) and Jones and others (2016), and summarized in this section.

As stated earlier, the aquifers are in places connected to surface water in a complex interplay of recharge and discharge relationships. This connection between groundwater and surface water in and surrounding the Twin Cities metropolitan area is a critical one, in part because the many groundwater-connected lakes are of great recreational and ecological value. White Bear Lake, which has been a particular focus of attention due to recent changes in lake stage, lies centrally within the study area, within the northeastern part of the Minneapolis-St. Paul Twin Cities Metropolitan Area (TCMA) watersheds, straddling Ramsey and Washington Counties. The confluence of the Mississippi and Minnesota Rivers occurs to the south west of White Bear Lake, with a third river, St. Croix, located to the east. In addition to these three major river bodies, the area contains thousands of acres of wetlands, and over 900 lakes.

2.1 Ecology

The main ecological subsection within the area of interest, particularly that surrounding White Bear Lake, is the St. Paul-Baldwin Plains and Moraines (Plains), which is depicted in Figure 2-1. The landform is dominated by a Superior lobe end moraine complex with a series of outwash plains in the south. The topography is rolling to hummocky with steep, short complex slopes on the moraine, leveling out on the outwash areas. Soils in this subsection are predominately Alfisols under forested vegetation, with Mollisols forming under prairie vegetation. Due to the nature of the landforms the drainage network is poorly developed through most of the ecological subsection. There is a well-developed flood plain associated with the Mississippi River running through the center of the subsection, with the St. Croix River forming the eastern boundary of the area of interest. The northern third of the end moraines exhibit an undeveloped drainage network, as evidenced by the abundance of lakes.

There has been a great deal of development and land use change throughout the region. Before European settlement the plant community was primarily oak and aspen savanna with tallgrass prairies. However, urban land-use now dominates, accounting for 32% of land-use, with row crops and pasture representing 30% and 13% respectively. Forest and wetlands now only account for 17% of total land area and are mainly present in the northern parts of Washington County. The remaining 8% is open water. Protection of existing wetlands has become especially important in the area for flood control and filtering stormwater runoff (Minnesota Department of Natural Resources, 2006).

The TCMA has undergone rapid urban expansion, as well as redevelopment of older parts of the cities. The Twin Cities experienced a population increase from 1990 to 2000, within the Plains subsection experiencing a 15.1% increase. The average population density increased from 430 people/km^2 to 495 people/km^2, resulting in an increase in developed land from 30.5% to 38.3% of the area within the TCMA.

2.2 Geomorphology, Surface Hydrology and Recharge Potential

Geomorphology is the product of long-term geological processes. Much of the region's landscape was heavily modified by glaciers that resulted in large quantities of coarse glacial sediment being deposited and the creation of numerous hills and depressions. Further from the glacier margins, sand outwashes occurred in broad, gently rolling plains. Within the Plains ecological subsection of Washington County, there are five distinct geomorphic regions each exhibiting factors that influence the hydrology and recharge potential (Figure 2-2): the St. Croix Moraine, Glacial Lake Hugo Plain, Lake Elmo-Cottage Grove Outwash Plain, Denmark Dissected Plain, and St. Croix and Mississippi River Terraces. These are described below.

2.2.1 St. Croix Moraine

The dominant geomorphic feature of the Plains ecology subsection is the St. Croix Moraine, which marks the most eastern advance of the last great ice sheet resulting in glacial sediments up to several hundred feet thick. The heavily rolling moraine land surface is covered with permeable sands and gravels with less permeable fine sand and glacial till. Lakes and wetlands occupy many of the abundant depressions, since natural surface water drainage is limited to a few small creeks. Most surface water infiltrates into the ground or runs to the closed depressions. In the urbanized areas of the Moraine there is an increase in impervious surfaces and management of stormwater runoff. While recharge occurs over most of the moraine, areas with higher amounts of clay or silt till receive less recharge such that the main recharge areas in the St. Croix Moraine are level sandy regions and closed depressions.

2.2.2 Glacial Lake Hugo Plain

To the northwest of the St. Croix Moraine is the gently rolling to flat Glacial Lake Hugo Plain. The surface geology consists primarily of sandy silt glacial lake deposits and outwash. Wetlands and shallow lakes are common as the region is relatively low-lying, causing the water table to be close to or at land surface as depicted in Figure 2-3. Other than in areas with public ditches, the surface water drainage system is relatively undeveloped. In areas where there is sufficient thickness of unsaturated materials, moderate to high recharge will occur, otherwise large amounts of saturation excess or runoff are expected.

2.2.3 Lake Elmo-Cottage Grove Outwash Plain

The Lake Elmo-Cottage Grove Outwash Plain is a large area to the south that was covered with sandy outwash as the St. Croix Moraine glacier melted. The outwash plain is moderately flat to rolling and is punctuated by shallow depressions, wetlands and lakes. There is generally little natural surface water drainage in this region, and it forms a key recharge area due to the gentle terrain, abundance of permeable geological material, and presence of numerous closed depressions.

2.2.4 Denmark Dissected Plain

The Denmark Dissected Plain is directly southeast of the Lake Elmo-Cottage Grove Outwash Plain outside the area covered by the last glacial advance. The terrain is rugged to moderately rolling with the topography being controlled by the bedrock surface due to the thin soils. Unlike the rest of the ecological subsection, there is a well-developed surface water drainage network of small ravines and valleys with few lakes or wetlands due to many closed depressions arising from karst that is often dry. Recharge is mainly to the Prairie Du Chien and Jordan Aquifers where fracturing or karst is close to the surface, and much of the region experiences rapid infiltration.

2.2.5 St. Croix and Mississippi River Terraces

This region lies along the edges of the Mississippi and St. Croix rivers to the south and east, and is gently rolling to flat. Areas covered by sand and gravel are found along the eastern and southern edges of the county. The terrace features formed from the deposition of sand and gravel from glacial melt-waters flowing through the river valleys. The recharge potential is high on the flat sand and gravel plains.

2.3 Stratigraphy and Groundwater Hydrology

2.3.1 Quaternary Deposits

Throughout the study area, the Quaternary geology is varied and complex, which makes it difficult in predict groundwater flow on the local scale particularly in deeper glacial sediments that transition over short distances. The broad outwash plains are more predictable. The hydrostratigraphy of glacial sediments is broadly divided into sand/sand and gravel aquifers plus aquitards comprised of sandy or loamy till or fine lake sediments.

Quaternary sand and gravel aquifers occur at the surface and at varying depths. When the sand and gravel deposits are at the surface, they function as important recharge areas: surficial sand and gravel aquifers can be found in the northern section of the region and in terrace deposits along the major rivers. Quaternary fine sands are also important recharge areas however these are infrequently used for public water supply. The fine sand units tend to be level or contain basins that enhance infiltration.

Unlike the fine sands, the sandy silt units function as aquitards: when these sandy silts are located at the land surface they impede infiltration and recharge. Glacial tills also tend to function as aquitards although sandy less compacted tills may be more transmissive. Finally, dense clay and silt rich tills transmit water at lower rates and can function as aquitards.

2.3.1 Bedrock Aquifers and Aquitards

Six bedrock hydrostratigraphic units are found beneath the glacial sediments that vary in thickness and permeability. The principal bedrock units used as groundwater are the Prairie du Chien and Jordan (OPCJ) aquifers. Other bedrock aquifers include the St. Peter Sandstone, the Tunnel City Group (formerly named the Franconia formation) the Wonewoc Sandstone (formerly named the Ironton-Galesville Sandstone), and the Mt. Simon Hinckley Sandstone. Three bedrock hydrostratigraphic units also function as aquitards.

2.3.1.1 Decorah-Platteville-Glenwood Aquitard

The Decorah-Platteville-Glenwood aquitard functions as a confining unit when present, and is discontinuous throughout the region. It can be found in most of the Woodbury and Cottage Grove areas and in sections of the Lakeland, Afton, and Denmark Townships. Parts of the Platteville limestone are permeable and may yield minor amounts of water, with the shale regions being the least permeable. It also restricts recharge to the St. Peter Sandstone and underlying bedrock aquifers. Recharge to the underlying aquifer is as a result focused along the edges of the Platteville. The Decorah-Platteville-Glenwood can be found in thicknesses up to 135 ft.

2.3.1.2 St. Peter Sandstone Minor Aquifer/Aquitard

The St. Peter Sandstone is discontinuous and was eroded significantly prior to glacial deposition. In some areas, the unit acts as a minor aquifer providing water for private well users. In other areas, the lowest portions of the unit contain siltstone and shale which are less permeable and act as a confining unit. Higher amounts of recharge will occur in the west central areas where not overlain by the Decorah Platteville Glenwood confining layer. The lower portion may behave as a minor aquitard to the OPCJ aquifers. Numerous erosion channels and windows have cut through, directly allowing recharge from Quaternary sediments to the OPCJ aquifers. The St. Peter unit can be found in thicknesses up to 160 ft (Bauer, 2016).

2.3.1.3 Prairie du Chien - Jordan Sandstone Aquifers

Both the Prairie du Chien Group and Jordan Sandstone aquifers are relatively thick and exhibit high permeability. The Prairie du Chien is approximately twice as thick as the Jordan, ranging from 119 to 203 ft (Meyer and Swanson, 1992), but the basal 40 to 80 feet of the Prairie du Chien Group generally acts as a leaky aquitard except where most of the overlying bedrock has been eroded. The Jordan Sandstone ranges in thickness from 71 to 100 ft (Bauer, 2016; Meyer and Swanson, 1992; Setterholm, 2013). Many private and public water supplies pump from these aquifers and because they are relatively well connected hydraulically, they are commonly referred to together as the OPCJ. Recharge to the OPCJ is from the Quaternary aquifers and can be quite significant when not overlain by the Decorah Platteville Glenwood aquitard. Some recharge also occurs from the St. Peter Sandstone. In the Denmark Dissected Plain region, the quaternary sediment is thin or absent allowing groundwater to directly infiltrate into the OPCJ. In areas with thin glacial sedimentation or confining unit, and along major rivers karst features create an elevated recharge potential.

2.3.1.4 St. Lawrence Formation – Tunnel City Aquifer and Aquitard

The St. Lawrence Formation is an aquitard comprised of thin layers of shale and siltstone, ranging in thickness from 30 to 59 feet (Meyer and Swanson, 1992). The Tunnel City Group, formerly known as the Franconian Formation, is a thicker fine sandstone, shale and siltstone unit reaching 160 to 180 ft. The upper portion of the Tunnel City Group is an aquifer, while the lower half to two-thirds is an aquitard (Runkel et al, 2003).

2.3.1.5 Wonewoc Sandstone Aquifer

The Wonewoc Sandstone, formerly known as the Ironton-Galesville Sandstone, consists of a porous sandstone that is used for supply when the shallower OPDC aquifers are absent or unusable. The aquifer ranges between 42 and 67 ft thick. Recharge occurs in the northwest and northeast in isolated bedrock valleys where the Tunnel City Group has been eroded. Connection with the overlying glacial sediment aquifer will vary depending on the thickness and extent of the till materials. Bedrock valleys become important conduits of recharge into this aquifer. Recharge also occurs outside the region and via leakage from the Tunnel City Group.

2.3.1.6 Eau Claire Formation Aquitard

The Eau Claire Formation is a shale and siltstone aquitard that transmits little water and effectively separates the Wonewoc Aquifer from the Mt. Simon Aquifer. It ranges in thickness between 63 and 110 ft and is considered a major region wide aquitard that restricts downward migration of groundwater to the Mt. Simon.

2.3.1.7 Mt. Simon Hinckley Formation Major Aquifer

This productive aquifer lies beneath the entire region. It is used for supply in areas adjacent to the St. Croix River and a limited number of other locations, including a City of White Bear Lake well that is open to multiple aquifers including the Mt. Simon. State Statute limits the use of this aquifer within the TCMA to potable water and only when there are no other feasible or practical alternatives. It ranges in thickness between approximately 150 and 300 feet. Recharge occurs primarily outside the region where the Eau Claire aquitard is absent and to a lesser extent via leakage from the Eau Claire.

Section 3
Steady-State NMLG Model Overview

3.1 Overview

In cooperation with the Metropolitan Council of the Twin Cities and Minnesota Department of Health, the USGS developed the three-dimensional (3D), steady-state NMLG model to assess groundwater and lake-water exchanges and the effects of changes in groundwater withdrawals and climate on levels within lakes in the northeast TCMA (Jones et al., 2017). The NMLG is regional in scale, and was developed using a recent version of the Newton-Raphson formulation of MODFLOW, referred to as MODFLOW-NWT version 1.1 (Niswonger et al, 2011). The NMLG model was developed to simulate average steady-state, groundwater-flow conditions for the period 2003-2013 in an approximately 1,000-square-mile area of the northeast TCMA in Minnesota and parts of western Wisconsin.

The steady-state NMLG model was developed based in part on the parameter data and model design of the Metro Model 3 (MM3) developed by Barr Engineering on behalf of the Metropolitan Council (Metropolitan Council, 2014; 2016) to assess the impacts of potential regional management scenarios on projected groundwater levels in the 11 counties of the TCMA (Figure 3-1). The MM3 simulates transient groundwater-flow conditions over an area of about 8,350 square miles in and around the TCMA. The recent release simulates conditions over a seventeen-year period from 1995 through 2011. In contrast, the NMLG model was developed and calibrated to represent mean average hydrologic conditions over a subset of the domain covered by the MM3 over the period 2003 through 2013.

Recharge to the upper layers of the NMLG groundwater model was estimated on the basis of infiltration patterns and rates generated as output from simulations conducted using the Soil-Water Balance (SWB) model (Smith and Westenbrook, 2015). The SWB model is a process-based model that produces spatially distributed estimates of subsurface infiltration as (i.e., potential recharge) as a function of topography, land use, soil type, and climate. The following sections first describe the use of the SWB model as the source of potential recharge to the NMLG model, and subsequently the steady-state version of the NMLG as developed by the USGS.

3.2 Soil Water Budget (SWB) Model

3.2.1 <u>Overview</u>

The SWB model is a process-based model that calculates spatial and temporal variations in subsurface infiltration primarily in response to precipitation. The SWB model calculates infiltration (potential recharge) using multiple layers of geographic information in combination with climatological data. Simulations conducted using the SWB model are based on the modified Thornwaite-Mather soil-water-balance approach, with calculations completed daily. Recharge is estimated for rectangular grids, and can be outputted as daily, monthly, or annual values. The SWB model developed for the study area provides recharge and runoff rates to the groundwater model on the same discretized grid as the underlying MODFLOW-NWT NMLG model. More precisely, the SWB provides estimates of subsurface infiltration that has the potential to accrue as groundwater recharge (i.e., potential recharge): other processes within the unsaturated zone may result in some fraction of the subsurface infiltration computed by SWB not resulting in recharge.

In addition to computing potential recharge, the SWB model provides estimates of overland runoff within surface drainage basins that can accrue within corresponding lakes via overland flow. This feature was implemented in the NMLG model developed by the USGS. However, these flows are immediately routed out of the model domain as a surface flow even if the body of water is a closed depression. Currently there is no ability for the SWB model to allow for extended recharge to occur from retained surface water stored within depressions, which can result in the assignment of non-physical parameters during calibration, or the misestimation of recharge that arises from the lagged infiltration of stored or ponded water.

3.2.2 Input Grids

Figure 3-2 depicts the spatial extent of the SWB model, and illustrates some of the primary internal features of the model as developed and implemented for long-term average conditions. Figure 3-3 depicts the average groundwater recharge rates calculated by the SWB model over the period 2003-2013 as input to the steady-state NMLG model. The SWB model developed for the NMLG model uses Daymet gridded climate data as input, which are currently available for sufficient period (1980-2016) to support the desired simulation period of the transient NMLG (Thornton et al, 2016). Full details of the development of the long-term average SWB model are provided by the USGS in their SIR report (Jones et al., 2017).

3.2.3 Considerations for the Transition to a Transient Representation

The following is an overview of primary considerations when translating the long-term average steady-state SWB model to provide recharge and run-off estimates for the transient NMLG model.

3.2.3.1 Land Cover Representation

Determination of an appropriate method to identify and represent land use and cover data source(s) to consistently span the transient simulation period is an important consideration. In order to span multiple years of land cover datasets produced using varying methods, a simplified classification system was developed based on the following five land-use types: trees, grassed, wetland, open space development, and development. For integration with the transient NMLG model, the inputs to the SWB comprised simplified (re-grouped) digital NLCD grids for the years 2001, 2006 and 2011 that were used to define the patterns and types of land cover. This is in contrast to the approach taken for the MM3 model, which used vector land-use coverages developed by the Metropolitan Council for 1990, 1997, 2000, 2005, and 2010.

3.2.3.2 Closed Depressions and Surface Run-off

Due to the undeveloped drainage network within various geomorphological regions within the Plains ecological subsection, there is an abundance of closed depressions. These closed depressions can drastically increase recharge as surface runoff is intercepted and allowed to infiltrate over time. However, within SWB all runoff from a cell is assumed to infiltrate in downslope cells or to be routed out of the model domain on the same day in which it originated as rainfall or snowmelt. Once runoff is routed to a closed surface depression and evaporation and soil-moisture demands are met, all remaining water is allocated to recharge. Maximum daily recharge rates are specified for each hydrological soil group and any additional potential recharge is rejected or removed from the model since surface storage is not simulated. By rejecting excess recharge from closed depressions, the SWB model will drastically underestimate recharge in these areas. Further, closed depressions that are represented as an open water land class unit reroutes runoff out of the domain, even if there is no drainage network; and, no recharge from surface runoff can occur in closed depressions that are represented as open bodies of water, whereas in reality the intercepted runoff will either be recharge or lost through evaporation.

This effect of closed depressions can be exasperated by gridded data, such as using a digital elevation model (DEM) of side-length 410 ft which can only detect a closed depression of about four acres or larger: smaller closed depressions, and their influence on surface runoff, are not explicitly simulated. This limitation of the SWB model is a concern in the study area due to the abundant closed depression lakes and wetlands, as it can result in significant underestimation of recharge unless compensated via other mechanisms such as allowing model parameters to attain artificially low values. The SWB model calculates runoff using the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) curve number rainfall-runoff relation. This relation is based on four basin properties: soil type, land-use, surface condition, and antecedent runoff condition. It is apparent that during the calibration of the steady-state NMLG model, some CN values were estimated that do not reflect expected runoff-recharge relationships for some land-use type. Table 3-1 presents the NRCS, formerly known as the Soil Conservation Service (SCS), runoff CNs estimated via calibration of the SWB model for each of the land-use and soil types (Jones, 2017). In many cases, the estimated CNs are not physically meaningful and may result in part from the SWB model's inability to simulate storage in closed depressions. For example: pasture/hay land-use, which may have an abundance of depressions, is estimated to have a negative CN value; and, there is a general estimation of low CN numbers during calibration, thereby reducing runoff and increasing recharge for pasture/hay and grassland/herbaceous land-use types. In comparison to cultivated crops, the CN value is estimated to be higher due to depressions being filled or drained by farmers. CN numbers for some other land-use types also appear problematic: for example, when comparing developed open space with forested cover types, it is expected that developed open space would have more runoff than any tree covered land-use, yet both deciduous and mixed forests have higher estimated CN numbers. Medium and high intensity developed land type are also estimated to have extremely high CN numbers with very little recharge occurring in these land-use types. Considering the CN numbers for developed open space and low intensity it is not reasonable to expect medium intensity development to be so high, even higher than high intensity development. This is further discussed in Section 4.2.

3.3 MODFLOW Groundwater Model

MODFLOW is a widely-used, open source, public domain groundwater flow simulator developed by the U.S. Geological Survey (USGS). MODFLOW-NWT (Niswonger et al, 2011) implements a Newton-Raphson formulation and several numerical schemes for a stable and robust solution to unconfined groundwater flow problems, and incorporates the capability of simulating several surface water features using a wider range of techniques, including the lake (LAK) package that explicitly simulates water budgets for lakes and lake interactions with the groundwater.

3.3.1 Overview

The groundwater model layers represent various aquifers and confining units contained within the glacial sediments and deeper Ordovician- and Cambrian-age bedrock units. Initial values for the hydraulic properties of the hydrogeologic units within the bedrock were assigned based on published information from the Minnesota Geological Survey (MGS) and from data from the Metropolitan Council's MM3 groundwater-flow model. The horizontal and vertical discretization of the NMLG model was based on the grid used for the MM3 model, however it was refined to meet the more local-scale needs of the NMLG. The NMLG model comprises 12 layers in contrast to the 9 layers of the original MM3 model, and explicitly simulates confining units in the study area. The NMLG model comprises 560 rows and 432 columns with a uniform spacing of 125 meters (m), in contrast to the grid spacing of 500 m in the MM3 model. With the exception of layers 1-4 - which represent a vertical refinement of the representation of the quaternary sediments - the NMLG model layering for the deeper units was derived from MM3 layer elevations through interpolation to the NMLG model grid.

3.3.2 Major MODFLOW Simulation Packages

The following are the major MODFLOW packages used to represent conditions in the steady-state NMLG model. Several of these packages required revision or extension to represent conditions in the transient NMLG model as described in Section 4. A complete detailing of all packages used in the steady-state NMLG model is provided by the Jones et al. (2017).

3.3.2.1 Lake (LAK) Package

The following six lakes were simulated using the MODFLOW LAK package, specifically LAK7: White Bear Lake, Lake Elmo, Big Marine Lake, Snail Lake, Turtle Lake, Pine Tree Lake. These lakes are all larger in area than 15 acres and were considered focus areas for simulations. As a consequence of simulating these lakes using the LAK package, the steady-state NMLG model computes both the water-budget and lake stage for each lake that is dependent upon the sources and sinks of water to that lake. For the steady-state simulations, these water budgets and lake stages represent long-term averages, whereas in a transient simulation these represent time-varying quantities in response to changes in the rates of sources and sinks of water to each lake.

3.3.2.2 River (RIV) Package

The MODFLOW RIV package is a head-dependent package that can gain or lose water depending upon the difference between the head specified for the RIV cells and the head in the adjacent aquifer. The RIV package can be used to simulate features other than rivers, and was used to simulate three main features within the NMLG model:

- Lakes larger than 15 acres that are not simulated using the LAK package
- Lakes smaller than 15 acres
- Rivers and streams

The head simulated in a water body represented using the RIV package is specified a-priori (and in many cases, does not vary over time, although it can), and is not computed on the basis of recharge or the head in the adjacent aquifer. Fluxes to and from a lake or river represented using the RIV package do, however, vary with changing head in the adjacent aquifer. Figure 3-4 depicts the NMLG model extents, and illustrates the major internal features including those model cells that are simulated using either of the MODFLOW LAK or RIV packages, and those model cells that represent the estimated surface watershed area for those lakes simulated using the LAK package.

3.3.2.3 Groundwater Pumping (WEL and MNW Packages)

Groundwater withdrawals from about 900 higher-capacity pumping wells were simulated in the model using a combination of the MODFLOW Well (WEL) and Multi-Node Well (MNW) packages. Groundwater withdrawal data through 2014 was retrieved from the Minnesota Water Use Data System (Minnesota Department of Natural Resources, 2015a). Groundwater withdrawals from wells open to a single model layer were assigned to the WEL package, and groundwater withdrawals from wells open to two or more model layers were simulated using the MNW Package. Reported groundwater withdrawals for the model area that could not be assigned to wells or model layers accounted for less than 2 percent of the total groundwater withdrawals over the 2003-13 period. In many cases, attributes describing well construction and configuration were not fully known, so assumptions were made to the extent necessary to include the withdrawals from the wells in either the WEL or MNW package. In most cases, these attributes were the elevations of screened intervals or the aquifers they were open to.

3.3.2.4 Unsaturated Zone Flow (UZF) Package

The MODFLOW UZF package simulates vertical flow and storage (retention) of water within the unsaturated zone. The UZF Package was configured using the average 2003-13 output obtained from the SWB model as subsurface infiltration input to the groundwater model. The vertical conductivity used to calculate infiltration rates was specified as the vertical conductivity of the first (uppermost) model layer. Surface leakage (i.e., discharge to the land surface when the head in layer 1 rises above the surface) was activated, and surface leakage within lake watersheds simulated using the LAK Package was routed to the corresponding lake. The undulation depth, which is the depth to water table at which the unsaturated zone begins to generate surface leakage, was set to 1.6 ft. Additional gridded properties affecting the performance of the UZF Package also were specified. Spatially distributed saturated moisture content and the Brooks-Corey Epsilon were calculated using textural data obtained from the gSSURGO data (Soil Survey Staff, U.S. Department of Agriculture, and Natural Resources Conservation Service, 2015) and pedo-transfer functions developed by Saxton and Rawls (2006). The 295-ft (90-m) grids generated using the gSSURGO data were then bilinearly interpolated to the 410-ft (125-m) grid. A recharge multiplier that modified the SWB-generated recharge grid was adjusted during calibration.

3.3.3 Aquifer Properties

Jones et al. (2017) provide a detailed description of the development and parameterization of the quaternary and bedrock aquifer layers. A summary is provided here.

Initial value for aquifer horizontal and vertical hydraulic conductivity and conductivity of the quasi-3D confining-bed were set equal to those contained in the MM3 model. Bedrock zonation and initial layer properties corresponding to bedrock zones from the MM3 model were resampled from the original 1,640-ft (500-m) cell size to the current 410-ft (125-m) cell size without interpolation. Additional refinement of the horizontal zonation of Quaternary-age deposits was performed by incorporating the distribution of Quaternary-age sediment classes described by

Tipping (2011). The Tipping (2011) dataset is the most complete and uniform classification of the Quaternary-age sediments throughout most of the model area; however, the dataset required augmentation to ensure a complete zonation of any cells that were not associated with a bedrock formation within the model domain. The process of augmenting the Quaternary sediment point dataset began by identifying points lacking elevation data and assigning an elevation value to them. After filling in all missing values of sediment class for each layer, the point grid was used to produce eight 410-ft (125-m) grids with each model grid cell containing a value representing a sediment class.

The Decorah Shale, Platteville Formation, and Glenwood Formation are important bedrock formations affecting groundwater flow and potential surface water exchanges at some locations within the model domain where they are considered confining units. Similar to the MM3 model, these three bedrock formations were represented as a restricted (low hydraulic conductivity) zone within the lowest Quaternary layer in the NMLG model where at least one of the three bedrock units were present. Due to the refined vertical discretization of the NMLG model, however, distinct hydraulic properties for the complex can be estimated.

3.3.4 Considerations for the Transition to a Transient Representation

The following are particular considerations encountered when formulating the transition of the steady-state NMLG model to represent transient conditions.

3.3.4.1 Lake Evaporation

The USGS implemented the Hargreaves-Samani method to calculate daily lake evaporation during the estimated open-water season, and assumed zero evaporation during ice cover. The resulting daily evaporation values were then averaged for the steady-state simulation period. The Hargreaves-Samani method was developed to estimate evapotranspiration from the land surface and does not account for lake heat storage, micro-climatological conditions, or other factors that affect seasonally varying lake evaporation, and cannot estimate sub-annual (e.g., monthly) evaporation from deep lakes. Therefore, a suitable method was required to estimate seasonal evaporation from the large water bodies represented as lakes using the MODFLOW LAK package that reasonably matches available information such as eddy-covariance based estimates. Methods considered included developing approximate, monthly pan coefficients using the available eddy-covariance-based evaporation estimates and University of Minnesota (UMN) pan data; and the use of other evaporation models together with a routing procedure for heat storage. Section 4 details the method implemented in the transient NMLG model.

3.3.4.2 Other Head-Dependent Boundaries

Some of the lake bodies that are represented using the RIV package are substantial enough, and located in sufficiently close proximity to other lakes, that representing their lake stage using either a long-term average elevation, or an incorrect transient elevation, can impact the stage calculated in any nearby lake represented using the LAK package. For example: because of its size and proximity to White Bear Lake, transient lake stage elevations should be applied to the RIV package cells that are used to represent Bald Eagle Lake in the transient simulations. However, for some lakes represented as RIV, there is insufficient data to accomplish this, which is a shortcoming that could be remedied in future simulations through the gathering of additional lake stage information for key lakes.

3.3.4.3 Unsaturated Zone Flow (UZF)

The UZF package solves a kinematic wave approximation to Richards' equation using the method of characteristics to simulate vertical unsaturated flow (Niswonger et al, 2006). In some circumstances, the simulation of groundwater recharge via the UZF package can add significantly to the simulation time and also compromise the convergence stability of already highly non-linear models. The USGS in their transmittal letter accompanying the draft SIR report describing the steady-state NMLG expressed some concerns regarding the ability of the UZF package to accurately simulate the response of lakes to groundwater pumping (and, possibly, other stresses). During the initial development of the transient version of the NMLG described in this report, likely related difficulties were encountered with the UZF package when incorporated together with highly non-linear head-dependent packages (including the MNW) that resulted in computational burden and occasional numerical intractability. These are detailed further in Section 4.

Section 4
Transient Model Development

4.1 Simulation Period

The simulation start date for the transient model is December 31st, 1980 and the end date is December 31st, 2016. The development of the transient model representing an extended historical period requires the collection, review and processing of climate and other data that are required as inputs for the SWB model and the MODFLOW lake package, together with groundwater pumping rates; the stage of lakes and rivers that are simulated either using the LAK or RIV packages; together with data to be used as calibration targets, comprising groundwater elevations and lake levels throughout the simulated period. In general, reliable data regarding groundwater pumping are available from about 1988 onwards, which as a result became the focus period for the calibration. Conditions during the initial year, 1980, were simulated as steady-state, and the years from 1981 to 1987 were simulated as a 'warm-up' period prior to the focus calibration period commencing 1988.

4.2 Extension of the SWB Model to Transient Conditions

The SWB model was extended to match the time-period simulated by the groundwater model. To accomplish this, the SWB model that was developed to support the USGS steady-state NMLG model – which simulated conditions from 2002 through 2013 – was extended to simulate the period from 1980 through 2016, requiring the compilation and processing of transient climate data and available land use and classification maps for input to the SWB model.

4.2.1 Overview

Climate data for the transient simulations were obtained from the Daymet data set (Thornton et al, 2016). Precipitation, minimum and maximum temperature were obtained for a single 'tile' that encompasses the entire model domain (tile number 12104). A land use map for 1992 (Vogelmann et al, 2001) was downloaded from the national land cover database (NLCD) website: https://www.mrlc.gov/nlcd1992.php. Land use codes assigned to the SWB grid were determined based upon the maximum area of the land-use code within each model grid. Land use codes for the 1992 map could not be used directly because the 1992 land-use map was based on an older system of land-use codes that is not fully consistent with later land use maps. Therefore, land use codes were changed for the 1992 map using the retrofit land use codes as shown in Table 4-1 (USGS Open-File Report (OFR) 2008-1379: Fry et al, 2009).

Although available for use, the 2001 and 2011 land use maps used in the USGS steady-state SWB model were ultimately not used in the transient model development for the NMLG. This is because the land use maps for these two years were determined to be inconsistent when compared to the land classification maps for 1992 and 2006 (as depicted in Figure 4-1). For example, the urban recreational grasses in 1992 and 2006 were 4.7 and 7.0% respectively while in the 2001 and 2011 recreational grasses were greater than 13% (Table 4-2). Similarly, low intensity residential increases from 13.1% in 2001 to 15.4% in 2006, only to decrease in 2011 to 13.3%. A similar trend was identified with the commercial/industrial areas, increasing from 3.2% to 4.2% in 2006 to only decrease to 3.5% in 2011. The percentage of commercial/industrial land-use in 1992 was 4.7% and found to be most similar to the 2006 land classification data set. As such, only the 1992 and 2006 land classification maps were used in the transient SWB model: the 1992 land classification map was reused for the years between 1980 and 1999, and the 2006 land classification map was reused for years 2001 through 2016.

CN numbers for open water and wetlands were set to 100 so that groundwater recharge was not double counted via lakes or river boundary cells. However, some of the streams represented as open water land use were found to be inconsistent between the 1992 and 2006 land use maps. This is evident from Table 4-2 in which the percentage of open water is only 7.5% in 1992, while greater than 10% for 2001, 2006, 2011. Woody wetlands – which drop from 3.5% in 1992 to 0.7% in 2001 – may have been misidentified as open water. Finally, in 1992 there was 24.2% pasture/hay which decreases to 14.5% in 2001, while grasslands increase from 0.1% to 2.5%. Given the documented changes in the area, it is more likely that some fraction of pasture land in 1992 was more recently classified as grassland without any actual land-use change occurring.

In consideration of the apparent inconsistencies in land use codes, a simplified classification system was created to minimize the differences for purposes of the transient model development and calibration. The land-use classifications were simplified down to following five groups: developed with vegetation, developed with no vegetation, trees/shrubs, grassland/pasture/crop and wetlands.

4.2.2 Computed Recharge

Through the process above, transient locations and rates of subsurface infiltration were obtained from the SWB model. The transient subsurface infiltration rates obtained from the SWB model were used in the groundwater model as direct recharge without any scaling, time-lagging, or other modification, except to provide an upper limit on the recharge rate. The SWB model has the capability to set an upper limit on recharge rates, which can be based on the soil type or land use category. During the transient model development, a uniform upper recharge limit of 3.6 inches per day was imposed for all soil types and land use categories in the SWB model. No additional limits were imposed during the creation of the MODFLOW Recharge package for the NMLG groundwater model.

In the steady-state NMLG model, the MODFLOW UZF package was used to represent the migration of subsurface infiltration to the water table, with the result that there may be an appreciable time lag between the subsurface infiltration and the accrual of recharge, and some excess subsurface infiltration could be eliminated as run-off if the simulated water table rises to the land surface. For reasons detailed below, the UZF package was eliminated when developing and calibrating the transient SWB and MODFLOW models, although at some point in the future this decision might be revisited.

4.3 Extension of the MODFLOW Model to Transient Conditions

4.3.1 Overview

In developing the transient version of the NMLG model, the essential structure of the steady state model was preserved. The spatial discretization, layer elevations, and hydro-stratigraphic conceptual model remain unaltered, and the methods used to assign values to the aquifer parameters were essentially unchanged from the steady-state model.

4.3.2 Considerations for Execution Time

The steady-state NMLG model comprises approximately 1,992,000 active cells, of which a large number are represented using head-dependent simulation packages including the RIV, MNW and LAK. In addition, the water table lies in many places below the base of the first model layer, and moves between layers during transient simulations. As a consequence of the model size, the number and types of head-dependent boundary conditions, and a simulated water table moving between layers, early simulations executed using the transient NMLG indicated that execution times would prohibit calibration. The following simplifications were made to produce a transient model possessing an execution time facilitating calibration. These simplifications might be relaxed for predictive simulations for which high temporal resolution is desired; when the calibration has converged sufficiently that very small parameter adjustments are anticipated; or, when evaluating the sensitivity of predictions to groundwater on time intervals shorter than the selected transient model stress periods.

4.3.2.1 Time Discretization

The SWB model by design undertakes calculations daily. In contrast, the time discretization of the groundwater model must be specified at a length appropriate to provide useful results while providing for a reasonable computation time facilitating calibration and predictive analyses. For reference, the transient version of the MM3 was developed using monthly stress periods for the 18-year period from 1995 through 2013. For purposes of the development and calibration of the groundwater component of the NMLG model, average conditions such as occur over a typical year, and “peak” conditions such as occur during relatively wetter and dryer seasons are of interest to simulate changes in lake level, surface outflow, and groundwater-lake fluxes. To balance these interests, two sets of simulations were conducted using the transient NMLG.

The first of these variants simulates conditions using stress periods of one year length, where all applied stresses and boundary conditions are defined using annual-averaged quantities. This is referred to as the annual stress period version of the transient NMLG model. This version of the model is computationally efficient, and facilitates highly-parameterized sensitivity analysis, calibration, and expedient simulation of a large number of predictive scenarios such as required to calculate transient response functions. This version of the NMLG comprises 37 annual stress periods: the first stress period comprises a single steady-state period representing conditions during 1980, followed by 36 transient periods representing conditions from 1981 through 2016.

The second of these variants simulates conditions using three stress periods per year, where all applied stresses and boundary conditions are defined using average quantities calculated over the following three multi-month periods: December through March, April through July, and August through November. This model is referred to as the triannual stress period version of the transient NMLG model. Although this version of the NMLG model is less computationally efficient, it better approximates the amplitude of changes associated with seasonal changes in applied stresses and boundary conditions that can be particularly important in head dependent features such as lakes possessing overflow controls. This version of the NMLG comprises 109 stress periods: the first stress period comprises a single steady-state period representing conditions during 1980, followed by 108 triannual periods from 1981 through 2016, with the last stress period representing August through November 2016.

For expediency, calibration using the PEST software was primarily undertaken using the annual stress period version of the NMLG model, although the calibration results were periodically evaluated using the triannual stress period version of the model.

4.3.2.2 Representation of Unsaturated Zone Flow

In the steady-state version of the NMLG, subsurface infiltration calculated by the SWB was migrated to the water table using the MODFLOW UZF package. During the development of the transient NMLG model, difficulties were encountered with the numerical convergence of the MODFLOW-NWT code when incorporating the UZF package together with the MNW and other head dependent packages. These difficulties included greatly increased (at times, by a factor of three to ten) run-times; non-differentiability of the solutions when apparently converged; and inconsistent (non-monotonic) parameter sensitivities obtained during calibration. The increased execution time for steady-state and transient versions of the NMLG incorporating the UZF package did not provide assurance of attaining a converged solution, rendering calibration essentially intractable. For these reasons, the UZF package was only incorporated in a subset of the transient model development simulations and was not ultimately incorporated in the simulations that accompany this report. As a result, the subsurface infiltration calculated by the SWB model was used directly as recharge accruals at the underlying water table via the MODFLOW recharge package. Overland flow calculated using the SWB model within the surface watershed of the lakes that were simulated using the LAK package were handled directly as specified lake inflows.

4.3.3 Initial Conditions

As noted above, both the annual and triannual stress period transient simulations commence with a steady-state stress period representing approximate conditions during the year 1980. Unfortunately, groundwater pumping data are not available in database form for the year 1980: these only become available commencing 1988. Therefore, in an effort to balance the effects of pumping and other stresses with the knowledge that in general terms groundwater pumping steadily increased in the 1980s, documented historical groundwater pumping during 1990 was multiplied by 0.5 to approximate groundwater pumping during the steady-state stress period.

Values for groundwater recharge and overland flow into lakes for the steady-state stress period were obtained from the SWB calculations using the simplified 1992 land classification map as detailed earlier.

4.3.4 Peripheral Boundary Conditions

The regions of the periphery of the active model domain of the steady-state NMLG model that possessed prescribed heads derived in part from the MM3 model were largely retained in the transient NMLG model, and were held constant (i.e., they were not varied in time). Some changes were made to the prescribed heads during the calibration process, as described in Section 6. As noted in Section 9 Assumptions and Limitations, the use of time-varying prescribed heads is anticipated in some areas to improve the model calibration.

4.3.5 Transient Groundwater Pumping

Groundwater pumping in the initial steady-state stress period and subsequent transient stress periods was represented using the MODFLOW MNW package. The rates of pumping were obtained from the MNDNR as recorded in the MPARS database. Groundwater use data were kept only in paper records prior to 1988: for future simulations, groundwater pumping from 1980 through 1987 might be established by digitizing paper records. Because groundwater pumping data were not readily available for the years 1980 through 1987, rates for this period were assumed equal to 1990 pumping rates. Because some pumping wells were constructed between 1980 and 1990, however, the total pumping volumes applied were less for this period than in 1990. Pumping rates based upon detailed historical records commenced in 1988. The time-varying pattern of groundwater pumping throughout the simulated historical period is depicted as a time-series in Figure 4-2.

Pumping was assigned to the model layers based upon the designation in the database of the hydro-stratigraphic units within which the pumping wells are screened, or based on well depth if no aquifer is designated. Pumping wells for which information was not available to designate a specific aquifer unit were assigned by default to model layers 6-9 since these layers represent the primary production aquifers. Withdrawals from surface waters were not included in the model because there were no permitted appropriations from water features with model-computed heads (i.e. represented with the LAK package).

The MNW package input file structure is complex and not easily amenable to rapid adjustment absent a MODFLOW graphical user interface (GUI). Therefore, to facilitate the construction of the MNW package input file in a manner that would simplify the development of alternate MNW input files representing a range of predictive pumping scenarios, and later optimization of pumping to achieve certain prescribed targets, a pre-processing utility (AllocateQWell) was used that separately reads a well construction file and a transient well rates file to prepare the MNW package input file. The tabular structure of the transient well rates file lends itself to automated modification using programs such as PEST.

4.3.6 Lakes Represented using the MODFLOW LAK Package

The six lakes that were explicitly simulated using the MODFLOW LAK package in the steady-state NMLG model were similarly represented using the LAK package in the transient NMLG model. These are listed on Table 4-3 together with lakes that were represented using time-varying head specification via the head-dependent MODFLOW river package.

Time-varying values for precipitation that occurred directly upon the surface of each lake were assigned based upon precipitation data obtained from the Daymet gridded weather data sets, using the centroid of each lake to identify a pixel location within the Daymet grid suitable for downloading transient weather data. The surface runoff into each lake was calculated based upon the outputs of the transient SWB model, by summing the runoff occurring over all model cells that lie within the estimated surface watershed of each corresponding lake for the annual or triannual stress period. The model cells prescribed as representing the surface watersheds for each of the six lakes modeled using the LAK package are depicted in Figure 3-4.

For those lakes that possess a stage-controlled overflow structure (i.e., for which high lake stages are controlled to some extent via a constructed lake invert), a stage-dependent outflow relationship was added to the transient NMLG model. Table 4-4 lists the lake invert elevations that were used to represent these outflow control structures. Corresponding outflow from lakes was calculated using a stage-discharge rating function using the MODFLOW Stream-Flow Routing (SFR) package. To improve model stability during the calibration when the simulated lake stage may exceed physically meaningful values, lake stage-area-volume relations were extended vertically to provide numerically differentiable (though physically implausible) values enabling the combination of the PEST program and MODFLOW-NWT simulator to achieve numerically-continuous simulations.

Because the transient simulation period commences following the period of artificial augmentation of White Bear Lake, it was not necessary to simulate past lake augmentation practices for that lake. The transient simulation period does encompass times during which Snail Lake has been the beneficiary of augmentation sourced from a Prairie du Chien aquifer well until 1994 and from the Mississippi River via Sucker Lake since 1994. The present version of the NMLG model does not explicitly incorporate augmentation of Snail Lake, although this could be incorporated in a later release.

The representation of evaporation from lake surfaces was revised from the approach used in the steady-state model. For the steady-state NMLG model, for each lake that was simulated using the MODFLOW LAK package evaporation was calculated using the Hargreaves-Samani method with daily mean temperature data obtained from the Daymet daily temperature dataset (Thornton and others, 2014). The daily evaporation estimates for each lake were aggregated on a monthly basis, and mean 2003–13 values were determined and used in the water-budget calculations for the LAK package. However, as for other evapotranspiration estimation functions based on crops, the Hargreaves-Samani method fails to account for energy stored at depth in large water bodies and other differences between lake evaporation and crop evapotranspiration. Without accounting for energy stored at depth, there is a tendency to overestimate evaporation in the summer and underestimate evaporation in the fall. In place of the Hargreaves-Samani method, an empirical formula was developed for those lakes represented using the LAK package to estimate evaporation rates from monthly observed pan evaporation rates using two parameters: an annual pan coefficient that scales the evaporation rate without adjusting it in time, and a storage coefficient that represents the effect of heat stored in large water bodies. A full description of the method used to represent evaporation from lakes implemented using the MODFLOW LAK package, and the parameters obtained, is provided in Appendix A.

Values for the pan coefficient and storage coefficient parameters were determined for White Bear Lake through calibration to the eddy-flux evaporation rates determined for the period 2015-2016. The resulting estimated monthly evaporation rates for White Bear Lake as derived from historic pan data are illustrated in Figure 4-3 for the period from 1972 to 2016. Typically, April and November were estimated to exhibit the lowest evaporation rates (between 20 to 40 mm per month); May, September and October typically exhibit about double these monthly evaporation rates (i.e., 60 to 80 mm per month); and June, July and August tend to exhibit the greatest rates (ranging from 80 to 120 mm per month). The summers of 1976 and 1988 exhibited peaks in estimated monthly evaporation rates, reaching 140 to 160 mm per month.

Evaporation rates estimated for White Bear Lake were assumed to apply for the other 5 lakes within the model domain. Although the character of the 6 lakes simulated using the LAK package would be expected to differ, lake-specific eddy covariance evaporation estimates of the quality obtained at White Bear Lake are not available for the other lakes to provide lake-specific estimates.

4.3.7 Other Surface Water Bodies Represented using the MODFLOW RIV Package

Large surface water bodies, including lakes, in the surrounding vicinity of White Bear Lake and other lakes were represented using the MODFLOW RIV package, which is a time-varying head-dependent flux boundary. The conductance value of these cells was constant over time (i.e., did not vary with stage) and was adjusted during calibration to improve the correspondence with measured groundwater heads. A pre-processing utility was used to prescribe time-varying heads for these cells throughout the period of simulation: any missing stage data was replaced by the stage used in the steady-state NMLG model. Table 4-3 lists the water bodies that were represented using the RIV package with time-varying heads. For example, because of its size and proximity to White Bear Lake and data availability, it was important that transient elevations be specified to the RIV cells representing Bald Eagle Lake. Heads were held constant for all other water bodies represented using the RIV package.

The conductance value assigned to RIV cells representing large surface water bodies is critical when these cells act as a significant source or sink of water to/from the groundwater system. For the large number of water bodies located in the eastern half of the model domain, these cells tend to act as sources of water. When groundwater levels fall below the assigned RIV cell bottom elevation, flow from these cells into groundwater is linearly dependent on the conductance assigned to the cells. A high conductance value (on the order 10^3 as originally assigned in the steady-state model) can produce an almost infinite source of water. Therefore, during calibration, an upper limit was assigned to the conductance for these cells. When water bodies represented using RIV cells act as a sink – which generally occurs in the west half of the model domain – conductance values higher than a case-specific threshold value tend not to impact the groundwater flow rate entering the cell to the same adverse degree as for a “losing” cell.

Two major river systems - the Mississippi River and the St. Croix River - and their tributaries that collectively act primarily as sinks to the groundwater system were also represented using the RIV package, as were smaller wetland areas located on the western side of the model domain. The conductance of these cells was also adjusted to match measured groundwater heads.

Section 5
Calibration Objectives and Data

5.1 Overview

The objective of model calibration is to undertake history matching to achieve reasonable correspondence between simulated values and their measured counterparts. In the context of the transient NMLG model, there are two main types of observation for which there is a relative abundance of measurements to specify as calibration targets (i.e., groundwater levels and lake stages), in addition to some other quantities for which there are far fewer measurements and also greater uncertainty (e.g., lake volumes, surface water flows). Although programs that facilitate automated calibration emphasize global-fit statistics such as least-squares minimization of the weighted sum-of-squared residuals, other derived or qualitative measures can also be used to assess goodness-of-fit, including vertical or horizontal head differences or gradients, and visual assessment of time-series hydrographs.

Recognizing that the transient NMLG model commences with a steady state representation of conditions during 1980 using estimated (i.e., not recorded) pumping rates, and that pumping rates through 1987 were also not available via database records, the simulation period 1980 through 1987 was considered a warm-up period for the model, and quantitative calibration defined by non-zero weighting of calibration targets commenced in 1988, coincident with the beginning of detailed pumping records.

5.2 Quantitative Targets

Figure 5-1 depicts the location and aquifer unit for monitoring wells available for use as potential quantitative water level calibration targets within the active domain of the model. In total, about 16,000 lake-level measurements, a similar number of manual (depth-to-water) groundwater level measurements, and hundreds of thousands of automatically-recorded (datalogger) groundwater level values were available to support the calibration. When using the annual stress period version of the NMLG for calibration, this was reduced to about 2,000 groundwater level observations and 150 lake level observations. Because the annual stress period version of the transient NMLG model simulates time-varying lake stages using the LAK package for six lakes, their annually-averaged historical lake stages were used as targets for the calibration. The following pre-processing of these groundwater level observations was used prior to their inclusion in the calibration.

First, any observations at monitoring wells located within 25 m of a pumping well were assigned a weight of zero, to mitigate artefacts of grid discretization on calculated residuals. Second, as a consequence of model cell size, well stratigraphic and construction log uncertainties, and other limitations, in some instances the documented top and bottom elevations of monitoring well screens did not place the well in the correct stratigraphic unit as represented in the model, whose layer elevations were designed to approximate specific strata. In these instances, for the purposes of calculating simulated equivalents to measured heads, the model layer(s) assigned to each observation well were adjusted to correspond to the documented stratigraphic unit for each well.

Third, the hydro-stratigraphic units represented by aquifer codes QWTA (Quaternary Water Table Aquifer) and QBAA (Quaternary Buried Artesian Aquifer) that are represented by model layers 1-3 become dry in various portions of the model domain for the base-case simulation and were anticipated to become dry as aquifer parameter combinations were varied during calibration. To provide for calibration stability, observation wells screened within the QWTA and QBAA formations were compared to heads simulated for model layer 4.

Fourth, many observations obtained from wells screened within units represented by the aquifer code TILL as present in the NMLG model layers 1-3 were substantially higher than those obtained from surrounding observation wells as the tightness of the till formation results in the localized build-up of high heads. Similarly, other wells with locally-high water tables were excluded because the representation of these conditions was not a priority in the development of the NMLG model. These observations were assigned a weight of zero, resulting in the calibrated model not necessarily reproducing the high vertical head differences seen in these areas. However, these local conditions tend not to extend into other areas and aquifer formations beyond the till.

Finally, the following observation well data were also assigned weights of zero as these may not be adequately represented in the model in its current release:

- Wells in deep aquifer layers represented by model layers 11 and 12 and represented by code CMTS were not included in calibration.
- Observations identified as outliers - including observations with measured heads of zero
- High groundwater levels in localized, shallow QBAA aquifers (not just till)
- Many observations in the southern and far eastern areas of Washington County
- Observations located south of the Mississippi River
- Observations near the St. Croix River and faults.

5.3 Qualitative Targets

The following data and information was considered when evaluating the goodness of fit of alternate parameter combinations throughout the calibration, but were not used quantitatively to guide calibration due to their relative paucity and/or associated uncertainty: domain-wide and sub-regional water budget comparisons with the MM3 model; flows within streams; and spatial and temporal head differences in model layers 1 through 7 in the vicinity of White Bear Lake. These observations and information should be quantitatively incorporated in future calibrations of the transient NMLG model.

Section 6
Calibration Procedure

6.1 Calibration of the SWB Model

To obtain annual and monthly recharge rates from SWB for groundwater simulations using realistic CN numbers the model had to be modified to account for the lack of representation of closed depressions. Initial efforts to calibrate the groundwater models suggested that higher recharge was required in areas of less permeable hydrological soil groups (primarily, to the northeast of White Bear Lake) than could be obtained using default physically-plausible runoff CNs. From this qualitative analysis, it was decided to simplify the process and remove hydrological soil groupings from the SWB model, resulting in only adjusting CN numbers by land-use type and not soil grouping to allow for more recharge to occur in less permeable soil areas.

6.1.1 Land Use

Land-use types were simplified to just five main groups (not including open water) for two reasons.

The first is that this simplification reduced the inconsistencies associated with the land-use type changes that occurred between the 1992 and 2006 land-use data layers resulting from the methods used rather than reflecting any actual physical changes. Much of the developed urban area in the 1990's changed from medium density to low density in the 2000's data layers yet there was no evidence of any changes to the buildings. And, while some of the low-intensity developed areas around White Bear Lake in the 1990's were reassigned to open space in the 2000's, a similar density of houses is still present.

The second reason was to allow for a simple qualitative calibration with a tractable number of parameters in conjunction with the groundwater component of the NMLG model.

6.1.2 Curve Numbers

In this simplified parameterization approach, only four CN values were adjusted, with different parameter sets being tested from reference values. Because of the fairly limited streamflow data, instead of adjusting CN values to match gauged stream flow, the calculated recharge rates were essentially validated (rather than explicitly calibrated) within the process of calibrating the groundwater model. Table 6-1 presents the modified CN values implemented for the new land-use type groups (ignoring soil group) that developed a recharge array that was suitable both spatially and temporally for the groundwater model.

6.2 Representing Stormwater Management Practices vis Interception

Interception was used in developed land-use areas to represent captured and stored runoff. Interception in this context might be dominated by stormwater management practices. The amount of interception was dependent on percent impervious and as a whole was set to one third of the percent of impervious cover. Therefore, if a developed land-use type had 60% impervious area, 20% of total precipitation was assumed lost to interception. This volume would represent stormwater that is managed through practices such as diversion to closed depression wetlands or stormwater basins.

6.2.1 <u>Maximum Soil Infiltration</u>

A maximum infiltration rate of 3.6 inches/day was used for all land-use types and soil classes. As noted earlier, the drainage network is poorly developed with numerous closed depressions that flood after precipitation events, and because it may require many days or weeks for the water within these closed depressions to infiltrate (due to low permeability soils), the SWB model does not allow represent this process. To ensure that an adequate volume of recharge can occur, the maximum allowable soil infiltration rate was increased for low permeability soils.

6.3 Calibration of the MODFLOW Model

With the exception of the steps noted above for the SWB model, the subsurface infiltration rates generated by the SWB model were used directly as recharge in the groundwater model without applying any additional scaling or time-lag factors. Various aquifer parameters and boundary condition parameters were estimated during the calibration to improve correspondence between modeled and measured groundwater heads and lake stages, using a process of manual calibration supported by use of the PEST (Doherty, 2009) parameter estimation software. Table 6-1 lists the parameters that were included in the groundwater model calibration. Further discussion of these is provided below.

6.3.1 <u>Peripheral Boundary Conditions</u>

During the calibration, the following changes were made to the prescribed head boundary conditions along the periphery of the active model domain to improve the correspondence between simulated and measured groundwater levels:

1. Heads prescribed in the northwest quadrant of the active model domain were lowered by 15 feet. All prescribed head boundary cells with row number 237 or less and column number 301 or less were lowered by 15 feet.
2. Prescribed head boundaries within the deepest model layers representing the Eau Claire aquitard and the Mt. Simon and Hinckley aquifer units (layers 11 and 12, respectively) were removed because the upstream heads assigned to these layers were too high as compared to the observed head values within these layers; and the downstream heads in the southern portion of the model were too low, forcing water to exit from that boundary. This representation of a significant volume of water discharging in this area is inconsistent with the conceptual model for these layers that describes groundwater pumping centers and the St. Croix River as acting as the primary sink for the Mt. Simon and Hinckley aquifer units.

6.3.2 Aquifer Parameters

The values ascribed to aquifer parameters influence the spatial and temporal variation of simulated groundwater heads and lake stages. Horizontal hydraulic conductivity, vertical hydraulic conductivity, and specific yield were estimated during the calibration. The model layers representing the various aquifer units – which were retained as specified in the original steady-state NMLG model – were processed during the calibration using a series of pre-processing steps. Specific storage parameters were mapped directly from the MM3 model and the specific yield distribution was uniformly scaled during the calibration process. Horizontal and vertical hydraulic conductivity values were calibrated using multiple parameters including:

(a) A spatially distributed multiplier based on soil-type for quaternary formations;

(b) Values of hydraulic conductivity at pilot point locations for the quaternary formations; and,

(c) Values of multipliers applied to conductivity values at pilot point locations for deeper bedrock formations.

The vertical hydraulic conductivity was also estimated for the confining units.

Pre-processing utilities available as Python scripts that were developed by the USGS (Jones et al., 2017) were used to generate the hydraulic conductivity distribution. The first Python script, 'vcon_mult.py' multiplies spatial conductivity distribution for the quaternary formations with one scalar for each of the five hydrologic soil groups. The script developed for the steady-state NMLG model used a value of 1.0 as a multiplier for all hydrologic soil groups. For calibration of the transient model, a multiplier for each hydrologic soil group was incorporated as a calibration parameter. These multipliers enabled the scaling of horizontal and vertical conductivity for quaternary formations differently for each hydrologic soil group.

Pilot point values, defined either as absolute conductivity values (for the quaternary formation), or as fractions applied to pre-defined conductivity distributions (for all other formations) were also included as parameters. Relatively little emphasis was placed upon estimating the value of aquifer parameters in the deepest model layers (i.e., those below layer 10) due to a relative paucity of observation data within these layers to constrain their estimates.

6.3.3 Surface Water Features not Represented using the LAK Package

Several surface water features that were not represented using the LAK package of MODFLOW, were represented using the River (RIV) package which included:

(a) The main stems of Mississippi and St. Croix Rivers;

(b) Tributaries feeding water to these rivers;

(c) Several lakes not represented by LAK package but represented by the RIV package as a time-varying head;

(d) Several lakes not represented by LAK package but represented by the RIV package with a constant head; and,

(e) Wetlands.

Conductance values for these river model boundary cells were also adjusted to provide an improved match with measured groundwater heads and lake stages.

6.3.4 Lakebed Conductance

Lakebed conductance was calibrated to match lake stages. Figure 6-1 depicts the lakebed conductance zones that were individually estimated during the calibration. Lake conductance values primarily influence simulated lake stages in the corresponding lake, with relatively little influence on groundwater levels at increasing distances beyond the lake.

Section 7
Calibration Results

7.1 Overview

Because the calibration of the transient NMLG model comprised comparison of measured groundwater elevations and lake levels with their simulated equivalents at a large number of groundwater wells and lakes, a very large number of plots and statistics can be prepared to depict the results. Appendix B presents a comprehensive set of plots that collectively illustrate the status of the calibration as of the publication of this report. Appendix B presents these plots for both the annual- and the triannual stress period simulations, enabling a comparison of the results obtained using each version. This section presents summary plots and statistics and a narrative description of the calibration of the NMLG model.

7.2 Summary of Results

Figures 7-1(a,b) present scatter plots that compare simulated groundwater levels with measured values from monitoring and non-pumping (acquiescent) extraction wells as calculated using (a) the triannual stress period version and (b) the annual stress period version of the NMLG. The diagonal line represents perfect equivalence between the simulated and measured water levels: the further that the scatter points are removed from this line of equivalence, the greater the difference between the model calculations and the measurements. The color coding on the plots depicts the correspondence between the model and measured water levels within specific groups of model layers that correspond to the major aquifer units simulated by the model: i.e., wells screened primarily within the Quaternary unconsolidated aquifers; the St. Peters aquifer; the OPCJ aquifer; and successively deeper aquifers. Measurements from Quaternary aquifer wells screened at elevations corresponding to layers 1 through 3 were compared to simulated heads in layer 4.

Figures 7-2(a,b) present scatter plots that compare simulated lake levels with measured values for the six lakes that are represented using the LAK package, as calculated using (a) the triannual stress period version and (b) the annual stress period version of the NMLG. The color coding on the plot depicts the correspondence between the model and measured levels within specific individual lakes.

At the scale of Figures 7-1(a,b) and 7-2(a,b) broad correspondence is evident between the NMLG model and measurements of both groundwater levels and lake stages, suggesting that across the active model domain the model reasonably represents groundwater levels, hydraulic gradients, and lake levels. This is also reflected in the descriptive statistics listed on Tables 7-1(a,b), which summarize the correspondence between simulated and measured lake levels for (a) the annual stress period version and (b) the triannual stress period version of the NMLG model, respectively; and on Tables 7-2(a,b), which summarize the correspondence between simulated and measured groundwater levels for (a) the annual stress period version and (b) the triannual stress period version of the NMLG model, respectively. With regard to the lakes in particular, greater emphasis was placed in the calibration on those lakes with the most detailed historical records and that appear to show the highest degree of connection with the groundwater system (i.e., White Bear Lake and Turtle Lake), and this is reflected in the higher correlation coefficients.

For most lakes, the summary statistics – in particular the correlation coefficient and root mean squared error - suggest improved correspondence between the modeled and measured lake levels using the triannual versus the annual version of the model. This is evident in the plots presented in Appendix B, by visually comparing the auto-scaled plots of lake stages as simulated using the annual stress period model (Appendix B-2) with the auto-scaled plots of lake stages as simulated using the triannual stress period model (Appendix B-4). Indeed, this improved correspondence obtained with the triannual stress period model was part of the justification for its development, and is part of the basis for recommending that this version of the model be prioritized when making projections for water resource management alternatives (Section 10). As noted earlier, the calibration period encompasses times during which levels in Snail Lake were partially managed via augmentation – including during the most recent drought – which is not incorporated in the present version of the NMLG model. If this were incorporated in the model (when details of the augmentation timing and rates are available), this would lead to improvement to the calibration for this lake and possibly the surrounding groundwater.

The range of data presented on figures 7-1(a,b) and 7-2(a,b) is so great that little detail of the calibration can be determined. This can be better ascertained by visual review of the time-series plots depicted in Appendix B, or from a review of the residuals from the calibration. Figures 7-3(a,b) summarize the residuals from the calibration – i.e., the difference between the measured values and their simulated equivalents – in terms of their cumulative frequency, as calculated using the triannual stress period version of the NMLG. Two plots are shown: the first, presenting the cumulative frequency of residuals for the groundwater level calibration targets, and the second presenting the cumulative frequency of residuals for the lake stage calibration targets. The range of data presented on figures 7-1(a,b) and 7-2(a,b) is so great that little detail of the calibration can be determined. This can be better ascertained by visual review of the time-series plots depicted in Appendix B, or from a review of the residuals from the calibration.

Figures 7-3(a,b) summarize the residuals from the calibration – i.e., the difference between the measured values and their simulated equivalents – in terms of their cumulative frequency, as calculated using the triannual stress period version of the NMLG. Two plots are shown: the first, presenting the cumulative frequency of residuals for the groundwater level calibration targets, and the second presenting the cumulative frequency of residuals for the lake stage calibration targets. From these figures, it can be seen that the triannual model has a small tendency to over-predict groundwater levels (illustrated by negative residuals at the 50% frequency); and a small tendency to under-predict lake levels (illustrated by small positive residuals at the 50% frequency). Figures 7-4(a,b) summarize the residuals from the calibration in the same manner as Figures 7-3(a,b) except as calculated using the annual stress period version of the NMLG. Again, two plots are shown: from the left figure, it can be seen that the annual model exhibits a similar residual frequency distribution as the triannual model for the groundwater levels; with a smaller tendency to over-predict lake levels for extreme values (illustrated by small positive residuals at the 50% frequency).

Figures 7-5 through 7-16 depict the values for the horizontal hydraulic conductivities determined for model layers 1 through 12, respectively, via the calibration process. As noted earlier, model layers 1 through 4 represent unconsolidated glacial materials, which is why Figures 7-5 through 7-8 preserve the contrast between till and more fluvial outwash type materials from the original hydro-stratigraphic depictions. Layers 5 through 12 (Figures 7-9 through 7-16) preserve the original zonation developed by Jones et al. (2017) in their steady-state NMLG model.

Section 8
Illustrative Predictive Scenarios

8.1 Introduction

The developed, calibrated, transient NMLG model was used to simulate a series of hypothetical scenarios to demonstrate the applicability of the model for evaluating the potential impact of various management actions on lake levels and volumes. The hypothetical scenarios emphasize comparisons of the relative effect of various adjustments to pumping on the volume and stage in White Bear Lake, although similar simulations could be made for any lake that is simulated using the MODFLOW LAK package in the NMLG model. The primary purpose of these simulations is to illustrate the likely aggregate, long-term effect of various hypothetical combinations of changes in pumping at permitted wells in the vicinity of White Bear Lake.

In each case, the model outputs computed using the hypothetical conditions are compared with a base-case simulation to identify and calculate the change in lake levels and volumes resulting from the proposed change in groundwater pumping. The predictive simulations were run as different hypothetical combinations of groundwater pumping occurring over the historical simulation period, with a base-case simulation comprising actual historical pumping rates as represented in the calibrated NMLG model. The primary output from the predictive simulations is the calculated *change* in the volume and stage of White Bear Lake in response to the corresponding change in groundwater pumping. The relative magnitude of the change is then evaluated in two main ways:

1. First, by directly comparing the calculated change in lake volume and stage between the different predictive scenarios. This approach enables a direct comparison of the changes simulated by the model, while recognizing that like all models the NMLG is not a perfect simulator of absolute conditions (i.e., lake volumes and stage). The simulated change is a time-varying response function that associates the changed pumping directly with the transient change in lake conditions.
2. Second, by using the stage-volume relationship to convert the calculated volume change into a lake-stage change and adding this onto the historically-measured lake stage. This approach superimposes the change simulated by the NMLG model (i.e., the transient response function) onto actual measured conditions in a manner that respects the stage-volume relationship and the overflow elevation of White Bear Lake, providing an approximate absolute lake level resulting from the simulated change.

The predictive scenarios were performed using the annual stress period simulation, the triannual stress period simulation, or both, depending upon the anticipated magnitude of change in the levels of White Bear Lake in response to the change in pumping. In total, over 100 predictive simulations were performed using the transient NMLG model, a number of which are described below.

8.2 Simulated Scenarios

8.2.1 <u>Scenario 1 – Impact of Pumped Wells Tied Under a Single Permit Number</u>

For this scenario, all active pumping permits (excluding permits used for pollution containment) that include at least one well that is located within five miles of White Bear Lake were individually evaluated.

This was accomplished as follows: a total of 45 permits were identified as containing at least one well located within this approximate five-mile radius of the lake. These wells are shown in Figure 8-1. All pumping wells associated with these permits were evaluated, including pumping wells that are not physically located within five miles but share a permit number with a well within five miles (referred to as "tied" wells in this discussion). In each of these predictive scenarios, to evaluate the long-term impact of the wells the pumping associated with all wells listed under each of the identified permit numbers was shut-off beginning in 1988 and remained off throughout the duration of the simulation, resulting in a total of 45 simulations. For expediency, these simulations were completed using annual stress period simulations of the NMLG model.

At the conclusion of these simulations, it became evident that time-varying response functions calculated for wells associated with two particular permit numbers - WBL (1969-0174) and SPRWS (1977-6229) – tended to be the largest, and resulted in changes that were at times sufficiently large as to result in substantive changes in lake levels. For this reason, the effect of pumping associated with these two permits alone was also evaluated using triannual stress period simulations, in order to represent the higher-amplitude changes that are simulated using the shorter, stress periods. As for the 45 simulations, pumping at these permits was shutoff beginning in 1988 and remained of through the period of simulation.

8.2.2 Scenario 2 – Simultaneous Impact of Pumped Wells

For this scenario, all active pumping permits (excluding permits used for pollution containment) that include at least one well that is located within five miles of White Bear Lake were simultaneously evaluated.

This was accomplished as follows: all pumping associated with the 45 permits described above - including pumping wells that are not physically located within five miles of WBL but share a permit number with a well within five miles (i.e., tied wells) was simultaneously reduced beginning in 1988 and maintained at the reduced rate throughout the duration of the simulation, to evaluate the long-term impact of the wells.

In total, five simulations were completed to evaluate the effect of these simultaneous reductions in pumping:

1. First, four simulations were completed using the annual stress period version of the NMLG model for expediency. These simulations comprised complete shutoff of all pumping (i.e., the 100% case), and partial shutoff at 75%, 50% and 25% of actual historical pumpage.
2. Second, the 100% case (i.e., complete shutoff) was also simulated using the triannual stress period version of the NMLG model to represent the higher-amplitude changes that are simulated using the shorter stress periods.

8.2.3 Scenario 3 – Simultaneous Impact of Residential Irrigation Pumping

For this scenario, a single simulation was completed to simultaneously evaluate the combined impact of the portion of all pumping that was for irrigation use associated with municipal groundwater permits. Irrigation use was approximated for each municipal permit as the increase in average pumping from June through August over average pumping from January through March of the same year. Because pumping for irrigation purposes is generally focused in the summer season, this simulation was completed using the triannual stress period version of the NMLG model to represent the higher-amplitude changes that are simulated using the shorter stress periods. Furthermore, for this scenario municipal groundwater pumping was reduced during the summer months beginning in 2006 and remained at reduced summer rates throughout the duration of simulation to the end of 2016, to evaluate the potential impact of residential pumping for irrigation purposes over the period of the most recent decline, and rise, in levels and volumes in White Bear Lake. Small institutional and private water-supply pumping was not modified in this evaluation of irrigation pumping effects, but the volumes pumped under these permits are small and appeared to show negligible effects in the Scenario 1 evaluations.

8.3 Results

Results of these hypothetical predictive simulations are presented in a sequence of graphs to illustrate the simulated relative impact on White Bear Lake of the alternative pumping configurations.

Figures 8-2(a,b) depict the results from Scenario 1, in which all wells associated with any of the 45 identified, active permits that contain at least one well located within five miles from White Bear Lake were evaluated. Figure 8-2(a) depicts the simulated changes in lake volume not accounting for the change in lake outflow, and Figure 8-2(b) depicts the simulated changes in lake stage that result from shutting off pumping for each one of the permits in turn while all other permits remain pumping. Figures 8-3 and 8-4 for annual and triannual simulations, respectively, depict the results from Scenario 1 in terms of the absolute historic stage of White Bear Lake that is estimated through the use of an iterative calculation to add the simulated change in lake volume (shown on Figure 8-2(a)) onto the actual measured historic lake volume and thereby calculate the resulting lake stage while accounting for the presence of the lake outfall (invert).

From Figures 8-2(a,b), 8-3, and 8-4 it is evident that the pumping associated with a fairly small number of permits appears to dominate the response of the lake, and that the pumping associated with the vast majority of permits likely has a very small effect on the lake that would be, in practical terms in the field, difficult to identify or measure. This contrast is illustrated further following presentation of the results obtained for Scenario 2.

Figures 8-5(a,b) depict the results from Scenario 2, in which all pumping permits that include at least one well that is located within five miles of White Bear Lake were simultaneously evaluated by scaling the pumping at all of those wells to equal the following fractions of the actual historical pumping: 75%, 50%, 25% and 0% (zero, i.e., no pumping). Figure 8-5(a) depicts the simulated changes in lake volume not accounting for the change in lake outflow, and Figure 8-5(b) depicts the simulated changes in lake stage that result from these simulations of partial and total shut-off of pumping for all 45 associated permits. Figures 8-6 and 8-7 for annual and triannual simulations, respectively, depict the results from Scenario 2 in terms of the absolute historic stage of White Bear Lake that is estimated through the use of an iterative calculation to add the simulated change in lake volume (shown on Figure 8-5(a)) onto the actual measured historic lake volume and thereby calculate the resulting lake stage while accounting for the presence of the lake outfall (invert).

Figures 8-5(a,b), 8-6, and 8-7 illustrate the potential changes in levels at White Bear Lake that might be attainable by reducing pumping over a large number that are associated with active permits that obtain at least some of their water from within five miles of the lake. However, it was shown earlier in Figures 8-2(a,b), 8-3, and 8-4 that it is likely that the pumping associated with a small number of these permits dominates this response, with the remaining fraction of the response caused by the summed but small effects of a large number of permits.

The degree of contrast in the effects of pumping associated with each of the permits individually versus that associated with scaling-back pumping associated with all permits simultaneously can be more directly compared by integrating (i.e. summing) the area under the time-varying responses that are illustrated in Figures 8-2(a) and 8-5(a), respectively, and comparing these cumulative responses. This is accomplished in Figures 8-8(a,b), which presents the cumulative sums of the responses for individual permits (Scenario 1: Figure 8-2(a)) and for all permits simultaneously (Scenario 2: Figure 8-5(a)) using two bar charts. In each case, the chart is sorted from left to right from largest to smallest cumulative response. The upper chart (Figure 8-8(a) depicts the cumulative responses on a linear scale, whereas the lower chart (Figure 8-8(b) depicts the cumulative responses on a logarithmic scale. The following is evident from Figures 8-8(a,b):

- Reducing of pumping at all permits by 100% (i.e., complete cessation), or 75%, or 50%, has the greatest simulated effect on White Bear Lake (Figure 8-8(a)).
- Eliminating pumping at two particular permits (1969-0174 and 1977-6229) individually may have an effect that is quite comparable to that which results from reducing pumping at all permits simultaneously by 25% (Figure 8-8(a)).
- Pumping associated with about 10 of the 45 permits falls within the first order-of-magnitude of cumulative effects on White Bear Lake (meaning that these wells typically have an effect of about ten times greater than wells that fall below this first order-of-magnitude) (Figure 8-8(b)). Summed together, the effects of pumping associated with these dominant permits would overwhelm the effects of the remaining permits. Put another way: pumping at the permits that fall below the top order-of-magnitude effects comprises less than a few percent of the effects of the ten or so most dominant permits.

Figures 8-9(a,b) depict the results from Scenario 3, in which all groundwater pumping associated with residential irrigation was evaluated simultaneously by being completely shut off beginning in 2006 and remaining off throughout the period of simulation. Figure 8-9(a) depicts the simulated changes in lake volume not accounting for the change in lake outflow, and Figure 8-9(b) depicts the simulated changes in lake stage that result from this simulation. Figure 8-10 depicts the results from Scenario 3 in terms of the absolute historic stage of White Bear Lake that is estimated by adding the simulated change in lake volume (shown on Figure 8-9(a)) onto the actual measured historic lake volume and estimating the lake stage while accounting for the presence of the lake outfall (invert).

The results obtained for Scenario 3 cannot be directly compared with those obtained for Scenarios 1 and 2 (such as, by accumulating the effect and plotting on Figure 8-8), because of the different time period that was evaluated for Scenario 3. However, it is evident from visual comparison of Figures 8-2(b), 8-5(b) and 8-9(b) that the relative effect of domestic irrigation pumping on the levels in White Bear Lake is much smaller than the effects of pumping associated with the most dominant individual permit numbers, and is collectively on the order of some of the moderately dominant permits.

8.4 Conclusions

These predictive scenarios demonstrate the ability of the transient NMLG model to help evaluate both the relative effects and approximate absolute effects of various water resource management alternatives on lake levels, using White Bear Lake as an example. The results also illustrate some likely differences in the effects that pumping at different permitted wells has on the levels and, volume of White Bear Lake. Similar differences in time-varying response functions are expected to occur with respect to other lakes. The degree of contrast in the effects on White Bear Lake that is associated with individual permit numbers is substantial, ranging over several orders of magnitude. This contrast results primarily from the relative pumping rates of the permitted wells; their distance from the lake; and their open-screened intervals (i.e., which aquifers the wells draw their water from). Such a range in time-varying response functions is consistent with expectations from hydrologic principals, and illustrates that the transient NMLG model incorporates the fundamental characteristics of aquifer properties, lake geometry, pumping rates, location and timing in a manner that can inform water resource management decisions.

Section 9
Assumptions and Limitations

9.1 Overview

Any model is a mathematical approximation of actual conditions that rests of upon simplifying assumptions. Any model also has limitations in terms of the data that were used to develop the model, and its ability to represent actual conditions within the simulated area. The following subsections present underlying assumptions and likely limitations that should be borne in mind when using the newly developed, calibrated, transient NMLG model. Some of these assumptions and limitations could be relaxed, improved upon or eliminated through additional model development, whereas some could not. The lists of assumptions and limitations are illustrative but not exhaustive.

9.2 Assumptions

The following is a partial list of assumptions that underlie the development and calibration of the transient NMLG model:

- Currently, the periphery of the active model domain comprises a combination of no-flow boundaries and spatially varying but constant-in-time prescribed head boundaries, the latter derived from a combination of review of the MM3 model and calibration. A transient representation of the peripheral boundaries would improve the performance of the model.
- Currently, subsurface infiltration calculation by the SWB model is assumed to accrue at the underlying water table without any attenuation or possibility of refusal through insufficient soil capacity. This results from the decision not to use the UZF package, to obtain tractable and manageable simulations. With the calibration having progressed as far as it has, it is possible that the UZF package could be reintroduced if warranted.
- The initial steady state stress period, which represents conditions during 1980, was constructed from a hybrid of conditions from 1980 and 1990, which was necessitated by the desire to have several years simulation period prior to the availability of a database of groundwater pumping records beginning 1988. As a consequence, calculations for 1980 through 1987 should not be relied upon to the same level of rigor as results following 1987.
- The Daymet data set is presumed to provide reasonable, area-wide, approximations for climate data. However, climate data provided by the Daymet dataset are constructed through an interpolation process that results in spatial averaging that may not represent actual precipitation at areas within the active model domain, including in particular the lake bodies. This is particularly true in the vicinity of White Bear Lake, which appears to have a sparsity of weather gaging stations northeast of the lake. Obtaining, for example, precipitation data from one or more local rain gage stations and incorporating this into the SWB model and MODFLOW LAK packages, where appropriate, may improve the simulation capability of the NMLG for the lakes, and also the water budgets in the region around each lake.

- It was assumed that the various land classification maps represent conditions throughout the active model domain that dominate the rates and locations of infiltration of water to the subsurface, and changes in these conditions over time. However, inconsistencies were found in these maps that suggest they require re-evaluation. For example, the open water representation is inconsistent between various maps over time (primarily some small river systems) resulting in inconsistent groundwater recharge estimates.

9.3 Limitations

The following is a partial list of limitations that underlie the development, calibration and deployment of the transient NMLG model for predictive analyses:

- The SWB model by design processes all water received via precipitation in a day-long calculation steps: there is no capacity, for instance, for storage of water in closed depressions with delayed drainage. This limitation is particularly important within the simulated region due to the topography and hydrology. An alternate formulation or program might be considered for the soil water budget component of the NMLG model.
- Several water bodies including lakes in the active domain were represented using transient specified head boundaries for which the flux from the feature is head-dependent. However, stage level data were not available for all years for all of these features: the representation of these features during periods of missing data should be evaluated. Alternatively, representing some of the larger of these features – such as Bald Eagle Lake – using the LAK package may mitigate some of the drawbacks of using specified head boundary, for example, by constraining the flow in and out of the water body.
- Some areas that are best characterized as wetlands have been represented using the RIV package, which can both lose and gain through exchanges with groundwater. These features may be better represented using the Drain (DRN) package which would ensure that these features do not act as artificially high sources to groundwater and enable the separate reporting of water budgets for features represented using the LAK, RIV and DRN packages in the NMLG model output for review purposes.
- The information available to provide prescribed heads along the length of the St. Croix River transiting the model domain south of the confluence with (release point from) Lake Mallalieu is questionable and should be further evaluated. The stage that is currently assigned in the model to this section of the St. Croix River appears inconsistent when river stage is compared at the upstream and downstream end of the active model domain.
- The model does not currently represent changes that have occurred over time to the management of stormwater and overland flow in a manner that affects groundwater recharge locations and rates. Characterization of such stormwater management and public drainage networks throughout the model domain and alterations that occurred throughout the simulated period would be required to assess their impact on groundwater recharge. For example:
    - First, changes in developed-area stormwater management practices, including the use of temporary retention basins, constructed swales, changes in pavement cover, and other features that serve to temporarily store stormwater, or to enhance

recharge, or to route stormwater to a subsurface storm sewer. Aspects of these features can to some degree be mimicked through manipulations of the land classification and CN, but these are highly simplified methods to accommodate these structures. Furthermore, detailed information regarding the location and timing of such changes is difficult to obtain in such a manner that it could be incorporated.

- Second, public drainage ditches and their effect on surface water routing and aquifer recharge. For example, the Schuneman Marsh north of White Bear Lake underwent a major dredging in 1995 along Ramsey Washington Judicial Ditch #1 (RWJD1) upstream of Portland and Taylor Avenue (Figure 9-1). A 4-foot-wide channel was excavated to facilitate drainage: accumulated deadfall and debris that restricted flow was removed along with several beaver dams. The Portland Avenue culvert was also replaced with an arch to prevent future blockages. Prior to this extensive maintenance work, field inspections reported the channel had standing water along most of its length with little flow occurring, and the channel was subject to recurrent obstruction attributable to beavers. Dams that were removed would be replaced a few days later, again obstructing flow. Also, prior to the replacement of culverts with arches the water would require an approximate 1.9-foot rise in water elevation before flow would occur downstream. Alteration of the RWJD1 during the early 1990's would have affected the marsh hydrology by increasing surface flows and potentially reducing local recharge. Currently there is no mechanism in the NMLG (via, for example, the SWB) to account for these effects and how developing the drainage network would have affected recharge.

Section 10
Discussion and Recommendations

This section presents a discussion of the transient NMLG as documented in this report, and provides recommendations to help guide the further development and the application of this model in support of water resource management alternative evaluations in the study area.

10.1 Discussion and General Recommendations

The developed model provides reasonable correspondence with measured values for groundwater elevations and lake levels over a period from the late 1980s through recent times. The predictive simulations suggest that the developed model has the capability of supporting water resource management decisions. Even the limited number of predictive simulations described in this report suggest that the model is already capable of illustrating the contrasting effectiveness of alternate water resource management alternatives.

Efforts were made throughout the development of the transient model to balance execution time with simulation complexity. Nonetheless, the NMLG model comprises approximately 2.9 million nodes with many non-linear head-dependent features and as a consequence simulations using annual stress periods require approximately 5 hours to execute and simulations using triannual stress periods require closer to 15 hours – both absent the UZF package. Simulations incorporating the UZF package would likely require 3 to 4 times this to execute, and would be numerically unstable. Therefore, if vadose zone processes that may lag or limit the transfer of infiltrated water to the water table is deemed sufficiently important, greater time should be invested in improving the stability of the UZF when used with other packages, or seeking alternative approaches.

10.2 Recommendations for the SWB Model

The concept behind the SWB program is in many ways ideal to the requirements of the transient NMLG model. However, a great deal further time should be invested in obtaining, processing, and rendering consistent, historical land classification data over the period of simulation so that documented changes in land use are appropriately represented and the consequences of such changes are consistently reflected in the model. Furthermore, the single-day flow budget design of the SWB is limiting under the conditions encountered in the model domain. Future modeling using the NMLG should either use modified versions of the inputs to the SWB model together with an enhanced version of the SWB code that accommodates the identified limitations, or consider an alternate simulation model that accounts for recharge from closed depressions. In defense of the SWB, however, it is unlikely that any hydrological model that implements CN values to partition precipitation into runoff and recharge would provide highly accurate recharge estimates in the physical setting of the northeast metro area due to the abundance, change and possible importance of the filling and draining of closed depressions.

The combination of the SWB with the UZF conceptually can help simulate seasonally variable soil moisture and capacity conditions as might be encountered in the glacial Lake Hugo Plain, as the soil saturation varies over the year as the groundwater table rises and lowers. Alone, the SWB can only potentially represent this through adjustments to the CN values based on antecedent moisture conditions, whereas the UZF can approximate this based upon the water table and other factors.

Finally, to accurately simulate recharge rates and locations within the simulated study area, and how these have changed over time, it is desirable to account for changes in the surface drainage network and in stormwater management practices as the area has undergone development. This includes the modification or loss of natural closed depressions, and changes in public drainage ditches to allow for urban expansion. This is especially important in determining changes in the water budgets of lakes that have seen nearby changes in surface water management practices where water that was once destined to end up in the lake by one mechanism or another may now instead be drained through a public ditch or stormwater sewer to the Mississippi River.

10.3 Recommendations for the NMLG Model

Further efforts can always be expended in attaining larger and more precise or accurate data sets to improve on the basis of design of a model, and in undertaking further calibration to improve the model correspondence with measure data. With the current parameterization, calibration summary statistics suggest improved correspondence between the modeled and measured lake levels using the triannual versus the annual version of the model. This is visually evident in the plots presented in Appendix B. This improved correspondence obtained with the triannual stress period model was part of the justification for its development. Further improvements might be obtained by executing the model on a monthly stress period: however, this change would come with a greatly (four-fold) increased execution time, and other undesirable consequences. Therefore, for the time-being, it is recommended that the triannual stress period version of the model be prioritized when making projections for water resource management alternatives; that the annual stress period version of the model continue to be utilized for calibration and some long-term predictive simulation purposes; and that monthly stress periods be introduced judiciously when investigating the role that higher-frequency oscillations may have on predictions for periods of a few years at a time only.

Based upon the preliminary predictive scenarios described in this report, the following enhancements to the NMLG model would be beneficial for simulating future predictive scenarios – particularly those that would involve developing or evaluating dynamic patterns of pumping management. These enhancements might be accomplished via external utility programs, or via capabilities built directly into the MODFLOW source code:

1. A restart option. This option would enable the initiation of a simulation from a specific stress period and time-step based on a previous (“base”) simulation. For example, for several of the scenarios presented in this report, it was necessary to eliminate or reduce simulated pumping for a group of wells for a subset of the historical simulation period. However, the start time for the simulation remained unchanged. As such, simulating the scenarios still required running the first sequence of unaltered stress periods for as many simulations as there are wells, well groups or permits to be evaluated. With a restart option facilitated either within MODFLOW or externally, only the period for which the pumping changes take place would be simulated, resulting on many occasions in a tremendous saving in computer run time and accelerating the evaluation of potential alternative mitigation strategies. For example, to assess the impact of change in well pumping over the last 5 years of a base simulation that runs for a period of 1980-2016, the first 32 stress

periods that are unchanged will need to be rerun. Instead, with a restart option, the simulation can be started in 2012, leading to a reduced run time. Such a restart option was implemented previously in the USGS simulator GSFLOW as documented by Regan et al. (2015).

2. A rules-based operations management capability with flexible thresholds. This capability would invoke operational rules to turn on or off, or to otherwise adjusts stresses – typically, groundwater pumping – based upon groundwater head, lake stage or lake volume threshold values, for example. This capability would facilitate dynamic scenarios analysis using the NMLG model in which a set of pre-determined wells or permits would be adjusted (either reduced to zero, or scaled down) to meet specified groundwater level, lake stage or lake volume thresholds, without requiring iterative manual intervention with the simulations. Such a capability might be facilitated externally to MODFLOW, for example, by using the PEST software described in this report or using the Groundwater Management (GWM) process that was developed for use with MODFLOW (Ahfeld and others, 2005, 2009, 2011; Ahfeld and Barlow, 2013). GWM uses a response-matrix approach to solve linear, nonlinear, and mixed-binary linear groundwater management problems consisting of decision variables, an objective function, and constraints. Two versions of GWM exist: the first is integrated with an earlier version of the MODFLOW code, whereas the second (GWM-VI) is independent of the version of MODFLOW in use as long as inputs and outputs meet certain requirements. GWM-VI also allows parallel processing of the simulations required to solve an optimization problem.

Section 11
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