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Twin Cities Metropolitan Area Groundwater Flow Model: Conceptual Model Update



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Twin Cities Metropolitan Area Regional Groundwater Flow Model Version 3

October 2012

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1.0 Introduction

1.1 Background

Groundwater flow models have been part of regional water supply planning in the Twin Cities for several decades (e.g. Schoenberg and Guswa, 1982; Young, 1992, Hansen and Seaberg, 2000, Metropolitan Council, 2009) and have evolved with modeling technologies and our understanding of the hydrogeologic system. The Minnesota Pollution Control Agency developed a regional analytic element groundwater flow model in the 1990s that is commonly referred to as Metro Model or Metro Model 1. In 2007 the Metropolitan Council (Council) contracted with Barr Engineering to build a regional groundwater flow model of the Twin Cities area to assist the Council with regional water supply planning. This model used many of the datasets that were developed as part of the Metro Model 1 but uses a different modeling code and therefore was given the name Metro Model 2. The Metro Model 2 went through one minor revision phase, and the current publicly available working model is referred to as Metro Model 2.1. The model was designed to inform a broad range of regional planning questions and to be as flexible as possible in order to accommodate new questions or scenarios, while still incorporating the best available data. Some examples of questions the model is intended to inform include:

- Given projected water demands, what impacts may be expected on groundwater levels and groundwater-dependent surface water features?
- What combinations of source aquifers, well locations, and withdrawal rates can be used to achieve sustainable water consumption?

The use of the Metro Model 2.1 has been a fundamental part of the Council's water supply planning efforts and supports the Metropolitan Area Master Water Supply Plan. Implementation of the Metropolitan Area Master Water Supply Plan includes regular updates of the Metro Model as new water supply planning questions are developed and new information becomes available.

While Metro Model 2.1 laid the foundation for the Council's regional water supply planning work, model limitations hinder its ability to inform questions about impacts to surface water features and the seasonal (transient) impacts of groundwater withdrawals. The current version of the model uses the modeling code MODFLOW-96 which is considered legacy

code and is no longer supported by the U.S. Geological Survey (USGS). Also, numerous hydrogeological studies have been completed for the Twin Cities metro area since the construction of the Metro Model 2.1, much of it accelerated by the passage of the 2008 Clean Water, Land and Legacy Amendment to the Minnesota constitution. Data from these studies have refined our understanding of the extent and properties of aquifers in the metro area and provide data that can be used to help reduce uncertainty in model predictions.

To achieve the Council's legislative mandate to maintain a base of technical information needed for sound water supply decisions, the Metro Model 2.1 needed to be updated to include new information. This update also provides an opportunity to expand the model domain in order to consider the effects of growth in counties beyond the metro area and to add transient capability. This information will support metropolitan area communities as they begin their next round of local comprehensive planning, including water supply planning, expected to begin in 2015.

Update of the Metro Model is occurring in three phases:

- Phase 1: Recharge model update.
- Phase 2: Conceptual groundwater model update.
- Phase 3. Model calibration and uncertainty analysis.

This report describes the results of phase 2: conceptual groundwater model update.

1.2 Goals & Objectives

The overarching purpose of this effort is to maintain a groundwater flow model that allows the Council and land use and water utility planners across the metropolitan area to consider both groundwater availability and land use during the planning processes.

Benefits of a revised Metro Model include: 1) incorporation of new information, 2) implementation of newer and better-supported software, 3) enhanced methods to understand uncertainty in model predictions, 4) improved representation of Quaternary unconsolidated sediments and their influence on the groundwater flow system, 5) the ability to simulate seasonal effects of climatic and pumping stresses, and 6) an expanded model domain.

The objective for this phase of the Metro Model update is to create and document a revised Metro Model conceptual model including: an uncalibrated MODFLOW model, supporting GIS files, and this report.

Phase 1, update of the regional recharge model, is being done concurrently and results of that work will be incorporated into this report in December 2012.

This work does not include model calibration and uncertainty analysis, which will be done during phase 3 of the Metro Model update process. However, the information provided in this report sets the stage for subsequent calibration work.

1.3 Changes from Metro Model 2.1

This update of Metro Model conceptual model includes the following changes:

- Expansion of the model domain from the seven-county metropolitan area to the eleven-county metropolitan area;
- Addition of transient capability;
- Inclusion of new geologic mapping information;
- Inclusion of up-to-date pumping data;
- Consideration of new groundwater level information;
- Inclusion of additional rivers in the new model domain, and minor revision of some rivers in the Metro Model 2.1 model domain;
- Revision of model boundary conditions resulting from new model domain
- Revision of hydrostratigraphic units in model layers;
- New approach to defining aquifer properties in model cells representing Quaternary deposits; and
- Use of MODFLOW-2005 instead of MODFLOW-96.

2.0 Hydrogeologic Setting & Conceptual Model

The hydrogeologic conceptual model is a schematic description of how water enters, flows, and leaves the groundwater system. Its purpose is to define the major sources and sinks of water, the division or lumping of hydrostratigraphic units into aquifers and aquitards, the direction of groundwater flow, the interflow of groundwater between aquifers, and the interflow of water between surface waters and groundwater. The hydrogeologic conceptual model is scale-dependent (i.e., local conditions may not be identical to regional conditions) and may vary depending upon the purpose of the groundwater flow model.

2.1 Study Area Location

This updated conceptual model of regional groundwater flow is focused on the eleven-county Twin Cities metropolitan area located in east-central Minnesota and including Anoka, Carver, Chisago, Dakota, Hennepin, Isanti, Ramsey, Scott, Sherburne, Washington, and Wright counties. Our understanding of the general geologic setting of the metro area has not changed substantially since the Metro Model 2.1 was constructed, but the expansion of the model domain and recent geologic mapping has introduced some new geologic units into the model. The following section describes the general geologic setting of the updated model domain.

2.2 Geologic Setting

Sedimentary rocks deposited during the Paleozoic Era and unconsolidated sediments deposited in association with glaciations during the Quaternary Period comprise the dominant aquifers in the metro area. Large epicontinental seas flooded much of the North American craton during the Paleozoic Era. All of the Paleozoic sedimentary rocks of importance for this study were deposited in the Hollandale embayment (Figure 1); a shallow shelf that extended from southeast Minnesota and western Wisconsin southward to Iowa and Illinois (Austin, 1969). The water level in the sea fluctuated, thereby causing transgressions (a rising of sea level) and regressions (a dropping of sea level), resulting in a sequence of different sedimentary rocks (e.g., limestone, shale, and sandstone). These sequences, which are distinguishable and mappable over large areas, have been given formal names and are described further in Section 2.2.1. At a large regional scale, these bedrock units are often grouped together and referred to as the Cambrian-Ordovician aquifer system (Young, 1992) (Figure 1).

Numerous smaller geologic structures are present within the Hollandale embayment. During the middle to late Ordovician Period, additional tectonic activity resulted in faulting and folding of existing sedimentary rocks and the formation of the Twin Cities basin, centered near Minneapolis (Figure 1), and the Galena Basin, along the Minnesota and Iowa border (Mossler, 2008). Large fault zones were reactivated along the western and eastern boundary of the Mesoproterozoic Midcontinent rift (Mossler, 2011). Faulting is believed to be present along the entire perimeter of the Twin Cities basin but is difficult to map where subsurface data are sparse and the displacement of bedrock units in some areas may be small (Mossler, 2011). The presence of these fault zones has become more definitive with the collection of additional subsurface data, and it is now possible to map their locations and offsets in many areas of the metro area (Figure 2). The most extensive faulting is in southeastern Washington County, northeastern Dakota county, western Scott County, and western Carver County (Figure 2). Major fault zones in these areas include the Cottage Grove and Hastings fault zones along the eastern side of the Twin Cities basin, the Douglas Fault and Pine Fault zones along the north and northwest side of the basin, and the Belle Plaine Fault along the southwest side of the basin (Mossler and Chandler, 2009, Mossler, 2011, Runkel and Mossler, 2006, Mossler and Tipping, 2000). Along these fault zones, bedrock units may be offset by hundreds of feet.

During the Cretaceous Period another shallow epicontinental sea covered the western interior of North America resulting in a sequence of shale, siltstone, sandstone, and some carbonates that overlie Paleozoic rock along the western and southwestern part of the Hollandale embayment in Minnesota (Mossler, 2008).

After deposition of the Paleozoic bedrock, a long period of erosion occurred, resulting in large bedrock valleys and the removal and/or dissection of bedrock units. Subsequent glaciations during the Quaternary Period resulted in additional erosion of bedrock formations. Deep valleys were incised across the Twin Cities area, severing some bedrock units entirely (Figure 3). Much of the paleo-bedrock surface was subsequently covered by the deposition of thick sequences of glacial till and outwash during the Quaternary Period.

2.2.1 Hydrostratigraphy

Geologic units underlying the Twin Cities metropolitan area fall into four broad categories: (1) Precambrian volcanic and crystalline rocks; (2) Precambrian through Ordovician sedimentary rocks; (3) Cretaceous sedimentary rocks; and (4) Quaternary unconsolidated

deposits. The Precambrian volcanic and crystalline rocks generally are not considered major water-bearing units and are at a considerable depth below ground surface throughout most of the metropolitan area. The Precambrian through Ordovician sedimentary rocks make up the major regional aquifers and aquitards in the metropolitan area and include units such as the Hinckley Sandstone, the St. Lawrence Formation, and the Prairie du Chien Group. The Cretaceous sedimentary rocks comprise a minor aquifer and local aquitards in the far western metropolitan area. The Quaternary unconsolidated deposits include glacial outwash, glacial till, and alluvial deposits and serve as localized aquifers and aquitards throughout the metropolitan area.

Runkel and others (2003), in their comprehensive review and compilation of hydrogeologic data for Paleozoic bedrock in southeastern Minnesota, demonstrate the importance of secondary porosity features in defining the hydrogeologic characteristics of aquifers and aquitards. They note that individual lithologic units have very different hydrogeologic characteristics when in shallow settings compared to deep bedrock conditions. Secondary porosity (i.e. systematic fractures, dissolution features, and nonsystematic fractures) is prevalent within 200 feet of the bedrock surface. Where a lithologic unit is greater than 200 feet from the bedrock surface, secondary porosity features are generally less abundant. These secondary porosity features typically result in increased hydraulic conductivity and a greater range in hydraulic conductivity for shallow bedrock conditions. The 200 foot depth cutoff used by Runkel et al. (2003) is also used below to describe deep versus shallow bedrock conditions for the hydrostratigraphic units pertinent to this study, with the recognition that the change in hydrogeologic characteristics is transitional and does not necessarily take place at a defined depth.

2.2.1.1 Basal Aquitard

The lowermost confining unit in the study area is comprised of several Precambrian lithostratigraphic units. These units extend to great depth (up to several kilometers) and the hydraulic characteristics of these units are poorly known. While in some areas the basal aquitard may supply water to wells, they are regionally considered an aquitard (Delin and Woodward, 1984). Along the axis of the Hollandale embayment Middle Proterozoic sedimentary, volcanic, and mafic intrusive rocks associated with the Midcontinent rift system comprise the basal aquitard. This includes the Fond du Lac and Solor Church Formations across much of the Twin Cities basin and southeastern Minnesota. It should be noted that the Hinckley Sandstone, also associated with the Midcontinent rift system, is not considered

part of the basal aquitard and is grouped with the Mt. Simon Sandstone as the Mt. Simon-Hinckley aquifer (discussed below). In the western portion of the model domain Proterozoic and Archean igneous and metamorphic rocks form the basal aquitard.

2.2.1.2 Mt. Simon – Hinckley Aquifer

The Mt. Simon – Hinckley aquifer consists of the Mt. Simon Sandstone and the Hinckley Sandstone. The Hinckley Sandstone comprises the uppermost Precambrian bedrock in the study area. It is distinct from the underlying Solor Church and Fond du Lac Formations in being a quartzose sandstone. The lower portion possesses shale and siltstone layers, and a saprolith is present at the top of the Hinckley Sandstone in some areas. The Hinckley may not be easily distinguished from the overlying Mt. Simon Sandstone.

The Cambrian Mt. Simon Sandstone is chiefly a medium- to coarse-grained, quartzose sandstone. However, particularly in the upper part of the unit, beds of finer grained shale and siltstone are present (Mossler, 2008; Runkel et al., 2003). The unit ranges in thickness from less than 25 feet up to 375 feet in far southeast Minnesota. In the Twin Cities basin the Mt. Simon Sandstone is about 200 feet thick (Mossler, 2008). Runkel et al. (2003) divide the unit into a lower coarse clastic component, and an upper fine clastic component. Fine clastic beds in the upper portion of the unit have low permeability may provide hydraulic confinement (Runkel et al., 2003). At the local scale the unit may be distinguished into two or more hydrostratigraphic units. However, given limited knowledge regarding the extent and competence of confining beds within the unit, at the regional scale of this study the Mt. Simon Sandstone is combined with the Hinckley Sandstone as one hydrostratigraphic unit.

The hydraulic conductivity of the Mt. Simon Sandstone is typically greater where the unit is near the bedrock surface. Runkel et al. (2003) calculated the average hydraulic conductivity of the Mt. Simon Sandstone for deep bedrock conditions to be 21 ft/day based on specific capacity tests. Large-scale aquifer tests and packer tests indicate a range from 0.38 to 17 ft/day (Runkel et al., 2003). The fine clastic beds in the upper part of the Mt. Simon Sandstone may have hydraulic conductivities on the order of 10^{-2} to 10^{-4} ft/day. For shallow bedrock conditions, Runkel et al. (2003) calculated the average hydraulic conductivity to be 29.3 ft/day with a range of 1 to 70 ft/day. The difference in hydraulic conductivities for deep versus shallow bedrock conditions likely reflects a more densely developed fracture network where the unit is near the surface. At greater depth the Mt. Simon sandstone is commonly

assumed to have few fractures and dissolution features; however, this assumption remains unproven (Runkel et al., 2003).

The Mt. Simon – Hinckley aquifer was heavily used as a water supply in the past, but there have been recent efforts to reduce the amount of water withdrawn from the aquifer. During the 1970's and 1980's, storage within the aquifer was being depleted due to heavy pumping from the aquifer. As a result, Minnesota Statutes Section 103G.271 Subdivision 4a now prohibits the allocation of new water use appropriation permits for the aquifer unless no practical alternatives are available. The statute also restricts allocations for potable use only. In the Twin Cities, a large cone of depression exists within the Mt. Simon – Hinckley aquifer (Delin and Woodward, 1984; Sanocki et. al., 2009) (Figure 4).

2.2.1.3 Eau Claire Aquitard

The Cambrian Eau Claire Formation is a low-permeability unit that overlies the Mt. Simon-Hinckley aquifer and acts as a regional aquitard, limiting leakage between the Mt. Simon – Hinckley aquifer and the overlying aquifer system. The Eau Claire Formation is a combination of siltstone, very fine feldspathic sandstone, and greenish-gray shale. Some of the shale beds may be as thick as several feet (Mossler and Tipping, 2000). The Eau Claire Formation thins northward, with a maximum thickness of over 200 feet near the Iowa border decreasing to less than 100 feet thick in the Twin Cities basin (Mossler, 2008).

The hydraulic conductivity of the Eau Claire Formation is typically several orders of magnitude lower for deep bedrock conditions compared to shallow bedrock conditions. Horizontal hydraulic conductivities for deep bedrock conditions have been measured on the order of 10^{-2} to 10^{-3} ft/day and vertical conductivities of 10^{-4} ft/day (Runkel et al., 2003). Logged cores and borehole videos indicate that secondary pores are rare for deep bedrock conditions (Runkel et al., 2003). In shallow bedrock conditions where secondary porosity features are most extensive, the Eau Claire Formation can yield water to wells and could be classified as an aquifer. The majority of wells that are open to the Eau Claire Formation are located where the unit is the uppermost bedrock, primarily in the northern part of the metro area and along the St Croix and Mississippi rivers. Based on specific capacity data, the hydraulic conductivity of the Eau Claire formation in shallow bedrock conditions ranges from less than 1 ft/day to as much as 100 ft/day, with an average of 36.7 ft/day (Runkel et al, 2003).

2.2.1.4 Wonewoc Aquifer

The Cambrian Wonewoc Sandstone is typically a medium to coarse-grained, cross-stratified quartzose sandstone with moderately high permeability. The unit conformably overlies the Eau Claire Formation and is considered an aquifer. It is divided into two major lithofacies, which are difficult to differentiate: the Ironton and Galesville Sandstones. These lithofacies were formally recognized as formations but are now classified as members (Mossler, 2008). A third lithofacies, the Mill Street Conglomerate, is only present at the northern extent of the Wonewoc and is not explicitly simulated in the model.

The hydraulic conductivity of the Wonewoc aquifer varies depending on its depth. For deep bedrock conditions, the hydraulic conductivity ranges from 1 to 31 ft/day (Runkel et al., 2003a) with values of several feet per day being typical (Runkel et al., 2003b). Based on specific capacity tests, the hydraulic conductivity of the Wonewoc aquifer for shallow conditions ranges from less than 1 to 60 ft/day with an average value of 26.8 ft/day (Runkel et al., 2003).

Historically the Wonewoc aquifer has not been highly utilized in the central metro area because sufficient water supplies can be obtained from shallower units, such as the Prairie du Chien and Jordan aquifers. Recently, the Wonewoc aquifer (and Tunnel City aquifer) has undergone greater evaluation by the Minnesota Geological Survey, particularly in the northwest metropolitan area where the Prairie Du Chien and Jordan aquifers are absent. Because the Wonewoc and Tunnel City are the uppermost bedrock units in the northwest metropolitan area, they are more highly fractured and thus more permeable. Conversely, where these units are overlain by other bedrock units (e.g., the St. Lawrence Formation), the fracturing is less developed and the ability to produce usable quantities of water is substantially reduced.

2.2.1.5 Tunnel City Aquifer and Aquitard

The Cambrian Tunnel City Group is often lumped together with the Wonewoc Sandstone or is lumped together with the overlying St. Lawrence Formation as a regional aquitard (for example, Delin and Woodward, 1984). For this study the unit is treated as a single hydrostratigraphic unit. The Tunnel City Group, formerly known as the Franconia Formation, refers to rock between the Wonewoc Sandstone and the St. Lawrence Formation and consists of three formations: the Lone Rock Formation, the Davis Formation, and the Mazomanie Formation (Mossler, 2008).

The Lone Rock Formation is a low-permeability, very fine- to fine-grained sandstone with minor thin beds of shale and dolostone, while the Mazomanie Formation is comprised of coarser sandstone and possesses greater primary permeability. The Davis Formation has limited extent and has only been mapped in Faribault and Freeborn counties of Minnesota (outside the model extent) (Mossler, 2008). The Lone Rock Formation makes up nearly all of the Tunnel City Group in the southern half of the model domain. The coarser Mazomanie Formation is present in the northern half of the model domain with a thickness of 10 to 20 feet in west-central Hennepin County and up to 115 feet in Chisago County (Mossler, 2008). The Mazomanie Formation constitutes greater than 20 percent of the Tunnel City Group in parts of Anoka, Chisago, Hennepin, Isanti, Ramsey, Sherburne, Washington, and Wright Counties (Runkel, 2003). In western Wisconsin, the Mazomanie formation is the principal lithostratigraphic unit of the Tunnel City Group (Mossler, 2008).

At a local scale, the Tunnel City Group can be treated as two units: an upper aquifer unit comprised of the Mazomanie Formation or areas where the unit is near the bedrock surface and a lower confining unit comprised of the Tunnel City Group where it is deeply buried (Runkel et. al., 2003). For the scale of this study, the unit is combined but is intended to be parameterized in a way to represent the regional differences in the hydraulic character of the group. Where the Mazomanie Formation comprises a significant part of the Tunnel City Group, particularly in the north and east metro area, the hydraulic conductivity for deep bedrock conditions ranges from less than 1 ft/day to 65 ft/day with an average hydraulic conductivity of 27.8 ft/day; for shallow bedrock conditions hydraulic conductivity ranges from less than 1 ft/day to 75 ft/day with an average of 31.7 ft/day (Runkel et.al., 2003). Where the Mazomanie Formation is not present, hydraulic conductivity of the Tunnel City Group for deep bedrock conditions ranges from less than 1 ft/day to 10 ft/day with an average of 5.9 ft/day and hydraulic conductivity for shallow bedrock conditions ranges from and less than 1 ft/day to 40 ft/day with an average of 32.3 ft/day (Runkel et. al., 2003).

2.2.1.6 St. Lawrence Aquitard and Aquifer

The St. Lawrence Formation is a regional leaky aquitard that separates the Tunnel City Group from the overlying Jordan aquifer. The unit consists of fossiliferous, silty to very fine crystalline dolostone, interlayered with thin intervals of siltstone and in some areas, very fine-grained glauconitic sandstone and shale (Mossler and Tipping, 2000). Across most of southeast Minnesota, the lower part of the unit is dominated by carbonate rock while the upper part of the unit is mostly siltstone and very fine-grained sandstone (Runkel et al.,

2003). Near the St. Croix River valley, the St. Lawrence Formation consists almost entirely of siltstone (Runkel et al., 2003; Mossler, 2008).

Runkel et al. (2003 and 2006) describe the St. Lawrence Formation as having low bulk hydraulic conductivity in the vertical direction, which can provide confinement. These confining characteristics are present where the St. Lawrence Formation is relatively deep and overlain by the Jordan Sandstone. The bulk vertical hydraulic conductivity of the St. Lawrence Formation was measured between 10^{-5} to 10^{-4} ft/day in Ramsey County (Runkel et al., 2003). The horizontal hydraulic conductivity of the St. Lawrence Formation for deep bedrock conditions has been measured in the range of less than 1 ft/day to 50 ft/day. Runkel et al. (2003) attribute these relatively high horizontal hydraulic conductivity values to interconnected bedding plane fractures and dissolution cavities.

Where the St. Lawrence Formation is at shallow depth, it may not act as a confining unit over significant geographic extent. In these areas, interconnecting fractures result in relatively high bulk hydraulic conductivity values and the unit can act as a relatively high yielding aquifer. Some discrete intervals or beds within the unit may still provide confinement locally if interconnected fractures and other secondary porosity features are minimally developed. Based on specific capacity test data the horizontal hydraulic conductivity of the St. Lawrence Formation for shallow bedrock conditions typically ranges from less than 1 ft/day to 75 ft/day with an average of 46 ft/day (Runkel et al. 2003)

2.2.1.7 Jordan Aquifer

The Cambrian Jordan Sandstone consists of several coarsening-upward sequences. The sequences consist of two distinguishable facies: (1) medium- to coarse-grained, cross-bedded, friable quartz sandstone, and (2) a massive, very fine-grained, often bioturbated, feldspathic sandstone, with some siltstone and shale (Mossler and Tipping, 2000). Typically the lower 5 to 50 feet of the unit consists of the finer grained feldspathic facies and the upper 50 to 80 feet consists of the coarser grained quartzose facies (Runkel et. al., 2003). However, in many areas the two facies can be intercalated (Mossler, 2008).

Groundwater flow in the Jordan Sandstone is commonly assumed to be primarily intergranular, but secondary permeability undoubtedly develops due to jointing and differential cementation (Schoenberg, 1990). Runkel et al. (2003) note that flow along fractures within the Jordan Sandstone should be expected in shallow bedrock conditions

and fracture flow may take place locally for deep bedrock conditions. Results from standard aquifer tests indicate that the hydraulic conductivity of the Jordan Sandstone ranges from 0.1 to 100 feet per day with an average value of 48.5 ft/day (Runkel et al., 2003). Hydraulic conductivity measured from specific capacity tests for deep bedrock conditions indicate a range of less than 1 to 35 ft/day with an average of 17.4 ft/day. For shallow bedrock, hydraulic conductivity values ranges between less than 1 to 95 ft/day with an average of 43.3 ft/day (Runkel et. al., 2003). The extent and thickness of the coarser-grained lithofacies and the development of secondary porosity are believed to be the main factors influencing the range of hydraulic conductivity for the unit. Runkel et. al. (2003) note that where the finer grained lithofacies is present at the top of the Jordan Sandstone, the facies can be grouped with the overlying Oneota Formation and acts as a confining unit. Where the finer-grained lithofacies are at the base of the Jordan Sandstone, the facies may be grouped with the underlying St. Lawrence Formation and act as an aquitard.

2.2.1.8 Prairie du Chien Group Aquifer

The Ordovician Prairie du Chien Group is comprised of the Shakopee Formation (upper) and the Oneota Dolomite (lower). The Shakopee Formation is a dolostone with interbedded, thin layers of fine- to medium-grained quartz sandstone and shale. The Oneota Dolomite is commonly massive- to thick-bedded dolostone. The lower part of the Oneota Dolomite can be oolitic or sandy. Both formations are karsted and the upper contact may be rubbly (from pre-aerial exposure) (Mossler and Tipping, 2000).

Flow in the Prairie du Chien Group is dominated by three to five relatively thin (5 to 10 feet thick) zones of highly connected horizontal fractures in the Shakopee Formation and the upper part of the Oneota Dolomite (Runkel et al, 2003). The horizontal hydraulic conductivity of the Prairie du Chien Group can range over nine or more orders of magnitude (Runkel et. al., 2003). Within thin highly fractured zones, hydraulic conductivity can exceed 1,000 feet/day. Between these fracture zones, the hydraulic conductivity is much lower but has not been studied extensively because most wells are open to the more productive, highly fractured zones. Based on specific capacity tests, the hydraulic conductivity of the Prairie du Chien Group for deep bedrock conditions ranges from less than 1 to 50 ft/day with an average of 33.5 ft/day. In shallow bedrock conditions, hydraulic conductivity typically ranges from less than 1 to 125 ft/day with an average value of 60.8 ft/day, or about double compared to deep bedrock conditions (Runkel et. al., 2003). Standard aquifer tests have measured the hydraulic conductivity of the Prairie du Chien Group ranging from 0.1 ft/day to

163 ft/day with most of the high hydraulic conductivity values measured for wells screened primarily in the Shakopee Formation (Runkel et. al., 2003).

Runkel et al. (2003) has demonstrated that the lower portion of the Oneota Dolomite is massive, of low permeability, relatively unfractured, and acts as a regional aquitard that separates the permeable portions of the Prairie du Chien Group (the upper part of the Oneota Dolomite and the Shakopee Formation) from the Jordan Sandstone. Vertical hydraulic conductivity for the Oneota Dolomite has been measured as low as 10^{-4} ft/day. For this study, the two formations are grouped into one hydrostratigraphic unit: the Prairie du Chien Group aquifer. Parameterization within the Prairie du Chien Group aquifer is intended to allow for relatively high horizontal hydraulic conductivity, representing discrete beds that allow significant horizontal movement of water and relatively low vertical hydraulic conductivity, representing the confining characteristics of the Oneota Dolomite.

2.2.1.9 St. Peter Aquifer

The Ordovician St. Peter Sandstone is divided into two members. The upper Tonti Member is very fine- to medium-grained quartzose sandstone that is generally massive- to very thickly bedded. The lower Pigs Eye Member is an interbedded sandstone, siltstone and shale (Mossler, 2008). The Tonti Member is extensive and present over the entire extent of the St. Peter Sandstone in Minnesota and can range in thickness from 100 to 120 feet. The Pigs Eye Member is less extensive; it is 40-65 feet in the metro area and along the unit's western subcrop, southwest of the Twin Cities (Runkel et. al., 2003; Mossler, 2008). To the east and south, the Pigs Eye Member is thinner, generally 2-5 feet thick (Mossler, 2008).

The lower Pigs Eye Member typically has low vertical permeability and functions as an aquitard over the Prairie du Chien Group (Palen, 1990, Runkel et. al, 2003). The upper Tonti Member has much greater permeability and functions as an aquifer. The hydraulic conductivity of the St. Peter Sandstone typically ranges between 2 and 50 ft/day for deep bedrock conditions and between 1 and 74 ft/day for shallow bedrock conditions. The greater hydraulic conductivity values for shallow bedrock conditions are indicative of the influence of secondary porosity features (Runkel et. al., 2003).

2.2.1.10 Glenwood, Platteville, and Decorah Aquitard

The Glenwood, Platteville, and Decorah formations are grouped into a single hydrostratigraphic unit for this study. The Glenwood Formation is a blocky shale with thin stringers of fine- to coarse-grained quartz sandstone. The Platteville Formation is a

fossiliferous limestone and dolomite. The Decorah Shale is the uppermost Paleozoic bedrock present in the Twin Cities area and consists of calcareous shale with some thin beds of limestone. These units have a limited extent within the model area. They are present in southeast Hennepin County, Ramsey County, western Washington County, smaller areas of Dakota County, and in Rice and Goodhue counties along the southern edge of the model domain.

The Decorah Shale, Platteville Formation, and Glenwood Formation are typically together considered a regional aquitard (Kanivetsky, 1978). However, some highly fractured portions of these units supply domestic wells, and a number of springs originate from the unit. Recent work by Anderson et al. (2011) and Runkel et al. (2011) classify the Platteville Formation as a hybrid unit (both aquifer and aquitard). The unit can act as a competent aquitard, restricting vertical flow. However, well-developed macropore and fracture networks along discrete intervals, particularly in shallow bedrock conditions, result in relatively high horizontal hydraulic conductivities. Anderson et al. (2011) noted that measured hydraulic conductivity values for the Platteville Formation range over eight orders of magnitude, from less than 1×10^{-4} to more than 1×10^4 ft/day.

Due to the limited extent of these units, the recognition that groundwater flow within the units is often under perched conditions separate from the regional groundwater system (Anderson et al., 2011, Runkel et al., 2003), and the need to keep the groundwater flow model computationally efficient necessitates that they are numerically combined with overlying Quaternary sediments in the groundwater flow model, as discussed in Section 3.4.2.

2.2.1.11 Cretaceous Aquifer

The Cretaceous aquifer is of limited extent, generally present in discontinuous swaths in the far western metropolitan area (Figure 7). The unit is up to 200 feet thick in parts of Stearns and McLeod Counties and is composed of poorly cemented sandstone, siltstone, and shale of the Dakota Formation and unnamed sedimentary rocks. The Dakota Formation is the uppermost bedrock present in the Twin Cities area, though it is only present in small erosional remnants in the far western metropolitan area. It consists of a very fine- to coarse-grained, angular to subangular sandstone. The unnamed sedimentary rocks consist of calcareous yellow-gray to pale olive to pale red sandstone, siltstone, shale, and claystone. It is typically difficult to distinguish from weathered Paleozoic rock and the clayey saprolith

which is believed to be widely present in the western metropolitan area (MGS, 2012; MGS, 2009). The ages of these rocks are unknown and may be either Lower to Upper Cretaceous or Late Paleozoic.

This unit was not included in the previous version of the Metro Model. Recent mapping and expansion of the model domain allow for this unit to be included. The hydraulic characteristics of the unit are not well known. The Dakota Formation is extensively used as an aquifer in northeast Iowa and other Cretaceous deposits are used as aquifers in southwestern Minnesota. These rocks are believed to be hydrologically distinct from the overlying glacial till and underlying Paleozoic and or Precambrian rocks and are therefore considered separately for this study.

2.2.1.12 Quaternary Aquifers and Aquitards

Quaternary deposits of glacial till, sand, gravel, clay, and silt cover the bedrock surface over the majority of the study area and range in thickness from 0 to over 600 feet. These Quaternary deposits are the result of the advance and retreat of large continental ice sheets over and near the Twin Cities metro area over the past 2 million years. Glacial till was deposited underneath and adjacent to the glaciers. Glacial meltwater rivers deposited sand and gravel (outwash). Ice blocks were left in place to melt as the glaciers retreated, forming kettle lakes. As the glaciers retreated, meltwater rivers incised through the glacial deposits and into the bedrock units. These rivers also deposited thick sequences of sand and gravel (outwash). Upon glacial re-advancement, these river channels were often filled with new sediments forming buried bedrock valleys. In other areas, large glacial lakes formed where glacial meltwater was unable to drain away. Thick deposits of fine-grained sediment formed along the bottom of these lakes. Near the end of the last glaciations, the ancestral Mississippi River and the River Warren (ancestral Minnesota River) incised back into the glacial deposits, forming wide river valleys with alluvial terrace deposits and backwater areas.

Quaternary sediments are highly heterogeneous; at the scale of the eleven-county metropolitan area it is impractical to lump Quaternary deposits into hydrostratigraphic zones based on their provenance. Rather than pursue a geologic delineation of the lateral and vertical extent of unconsolidated aquifers and aquitards, this report utilized a study conducted by Tipping (2011), which mapped textural characteristics of the Quaternary sediments in the eleven-county metropolitan area and correlated those textures to

representative ranges in hydraulic conductivity. Use of this data is further described in Section 3.4.2.

2.2.2 Groundwater Levels and Flow Directions

Groundwater level measurements are available from several different sources, all with varying degrees of accuracy. Since the last update of the Metro Model in 2009, additional data have been collected. These include: regional and local synoptic water-level measurements, mapping of potentiometric surfaces as part of county and regional hydrogeologic assessments, additional Minnesota Department of Natural Resources (DNR) observation well data, and new static water levels tabulated in the County Well Index.

Several regional and local synoptic water level datasets have recently been developed. These data provide a “snap-shot” of water levels in an aquifer over a large area and are generally considered very accurate in both elevation and horizontal location. The USGS conducted two rounds of data collection in March 2008 and August 2008 across the seven-county metro area (Sanocki et. al, 2009). These data supplement synoptic water-level measurements conducted in 1988 and 1989 (Andrews et. al., 1995) and offer insight into seasonal and long-term water-level trends in the regional aquifers. Additional synoptic measurements were made in northern Washington County in 2011 and 2012.

In addition to the synoptic water-level data, new observation wells maintained by the DNR have been installed to supplement existing wells. These observation wells provide an excellent record of trends in groundwater levels and are typically measured on a monthly basis; some have been recently outfitted with data loggers to record data several times a day. There are a number of other dedicated monitoring wells that are not part of the Minnesota DNR network. These include wells at contaminated sites, watershed organization monitoring networks, and some municipal water supplier monitoring wells. The data from these wells are generally very good and are measured anywhere from yearly to weekly.

Water levels are also typically measured as part of well installations and are recorded in the County Well Index. These data are typically less reliable but are well distributed across the entire study area. Details on how water-level data are incorporated into the model are presented in the model calibration section **[[To be completed after model calibration]]**

2.2.2.1 Groundwater Flow Directions

Groundwater flows from zones of high piezometric head to low piezometric head. In the metro area groundwater flow in the upper aquifer units is towards the major rivers (Sanocki et al., 2009, Delin and Woodward, 1984). Regionally, groundwater flow in the deeper Mt. Simon – Hinckley aquifer is towards the major rivers as well. However, locally within the Mt. Simon – Hinckley aquifer there is a large cone of depression in south eastern Hennepin County where groundwater flows towards the center of the cone of depression, eventually discharging via pumping wells (Sanocki et al., 2009) (Figure 4). Locally, around high capacity wells or well fields, smaller cones of depression may also form in the upper bedrock or Quaternary aquifers, resulting in local groundwater flow paths directed to high capacity wells.

2.2.3 Recharge

The predominant source of water for the aquifer units in the metro area is precipitation. The amount of direct precipitation that is able to infiltrate at land surface and move below the root zone is the maximum amount of water available to recharge the underlying aquifers. This amount is dependent upon the rate and duration of precipitation, the soil type and soil cover, land use, evapotranspiration, and topography.

The portion of infiltration that moves from the unsaturated sediment below the root zone into underlying aquifers has been estimated in a variety of ways. Norvich et al. (1974) estimated that this rate is between 4 and 10 inches per year. Schoenberg (1990) estimated that the annual groundwater flow to streams, which is assumed to approximately equal groundwater recharge, is equivalent to 1.60 to 4.30 inches per year, with an average of 4.07 inches per year. Lorenz and Delin (2007), using a regional regression method, estimated the average annual recharge rate to surficial materials in the Twin Cities area to range between 3 and 9 inches per year. Barr (2008) estimated recharge using the Soil Water Balance (SWB) model for the Twin Cities metropolitan area using climatic data from 1975-2003. The SWB model estimated the average recharge for that period as 6.4 inches per year and ranging between 1.5 and 10.7 inches per year; during model calibration it was concluded that 4.5 inches per year provided a better fit to the data.

[[The SWB model is currently being updated in a related project. Details of that work will be provided in Appendix A on or before December 31, 2012. Local studies illustrate the variability in recharge, or infiltration below the root zone, across the metropolitan area. Data

from these local studies are currently being solicited to help reduce the uncertainty in the SWB model. Reviewers are invited to submit data to support this effort]]

2.2.4 Regional Discharge

In the Twin Cities area, groundwater flows toward the major discharge zones of the Mississippi, Minnesota, and St. Croix Rivers. Local discharge to the gaining portions of smaller streams and tributaries can also take place within the surficial aquifers.

Groundwater inflows into smaller streams can be estimated from stream-flow gauging records. Baseflow conditions (i.e., the groundwater component of stream flow) typically accounts for most of the flow during the winter months, when runoff is small. On an annual average, approximately 15 to 25 percent of total flow in streams results from groundwater discharge into the streams (Schoenberg, 1990).

Various attempts have been made to estimate groundwater inflows into the large rivers in the Twin Cities by detailed gauging of river flows. The most recent efforts were performed by the U.S. Geological Survey, which used sophisticated Doppler measurement techniques to calculate flows in the rivers at several cross sections. In principle, by subtracting the stream flows measured at an upstream section from the stream flows measured at a downstream section (and assuming no tributary inflows), the difference in stream flow should be attributable to base flow from groundwater. In smaller streams, this technique works reasonably well but in large streams, such as the Minnesota and Mississippi Rivers, the error in the measurement is nearly equal to or greater than the calculated groundwater inflows – rendering the calculated baseflows highly suspect.

The other major source of groundwater discharge in the Twin Cities area is through pumping wells. Most of the suburban communities obtain their water supply from high capacity wells. For some aquifers in the Twin Cities area, such as the Mt. Simon – Hinckley aquifer, discharge from wells makes up a significant amount of the total discharge from the aquifer.

3.0 Model Construction

3.1 MODFLOW

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

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

groundwater flow:

where:

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

W : sources and sinks

S_s : specific storage

h : hydraulic head

t : time

MODFLOW was developed by the U.S. Geological Survey and is in the public domain. It is widely used and accepted. The version of MODFLOW used for this model is MODFLOW 2005 (Harbaugh, 2005).

3.2 Computing Requirements

MODFLOW can be download for free from the USGS website at:

<http://water.usgs.gov/nrp/gwsoftware/modflow.html>. The MODFLOW files produced for this project will run on any Windows machine (Windows XP or newer recommended). The model is known to run well on a Windows 7 machine with 16 GB of RAM and a 2.8 GHz quad-core processor (note: the model only needs one processor core). It is expected the model will run on machines with as little as 4GB of RAM. At least 10 GB of hard disk space should be available to save the model output files. Large transient model runs may take a significant amount of time to run (up to 5 hours); steady-state model runs should complete in under 10 minutes.

To view model results, or modify the input files, a graphical user interface (GUI) is recommended. The model was constructed using Groundwater Vistas (ver. 6.26 build 17, 64-bit). This is the recommended GUI to use. There are a number of other GUI's available (some for free and some for a considerable cost). Any reputable GUI should be able to read the native MODFLOW files.

3.3 Model Domain

The model domain covers an area of 8,350 square miles, encompassing the entire eleven-county Twin Cities metro area (Figure 5). The domain was chosen to include the area of interest (eleven-county metro area) and to extend far enough beyond that area in order to limit the effects of artificial boundary conditions within the area of interest. To the east, the model extends into Wisconsin to account for groundwater flow into the St. Croix River from the east. To the northwest and west, the model extends beyond the edge of the Mt. Simon-Hinckley aquifer. To the south, the model extends in Goodhue, Le Sueur, and Rice counties to limit the effects of boundary conditions.

3.3.1 Discretization

The model domain must be subdivided into rectilinear grid cells in order to solve the finite-difference approximations. The model is divided laterally into 410 rows and 340 columns using a regular grid with cells sizes of 500m x 500m. Vertically the model is divided into nine layers using a deformed model layer approach where layer elevations generally correspond with hydrostratigraphic units. Of 1,254,600 model cells, 778,806 are active and used in the computational process. The length unit of the model is meters and site coordinates are in UTM NAD 83, Zone 15N. The X offset of the model grid origin is 369,875 meters and the Y offset for the origin is 4,883,875 meters. The time unit for the model is days.

In general the model layer assignments are as follows:

Table 1
General model hydrostratigraphic layers

Layer Number ¹	Hydrostratigraphic Unit
1-9	Quaternary sediments ² and Glenwood-Platteville-Decorah aquitard
4-9	Cretaceous aquifer ³
2	St. Peter aquifer
3	Prairie du Chien Group aquifer
4	Jordan aquifer
5	St. Lawrence aquitard and aquifer
6	Tunnel City Group aquifer and aquitard

Layer Number ¹	Hydrostratigraphic Unit
7	Wonewoc aquifer
8	Eau Claire aquitard
9	Mt. Simon and Hinckley aquifer
¹ The layer numbers for each hydrostratigraphic unit do not follow this convention in faulted area. ² These units may occupy more than one layer where lower hydrostratigraphic units are not present ³ May overlie several units and occupy several layers.	

In areas where the upper bedrock units are not present, the Quaternary sediments can be represented by more than one model layer. For example, in areas where the Jordan Sandstone is the first bedrock unit present (i.e., the St. Peter Sandstone and Prairie du Chien Group are not present) the Quaternary occupies model layers 1-3. The Cretaceous aquifer sedimentary rocks overlie several of the bedrock units in the western portion of the model. Model cells representing these sedimentary units may occupy more than one layer depending on the thickness of the unit. Typically, model cells representing these units are overlain by several layers representing the Quaternary sediments (Figure 6).

Offsets in the bedrock as a result of faulting were handled in two ways. For major faults in southwest Scott County, western Carver County, southeast Washington County, and northeast Dakota County, hydrostratigraphic units are offset to different model layers in the area of faulting (i.e., at the location of the fault there is an inhomogeneity or change in the hydraulic conductivity within the model layer) (Figure 2 and Figure 6). For other smaller faults, or those not as well defined, (i.e., in northwest Hennepin County) the model layers were interpolated across the faulted zone and the hydrostratigraphic unit remains within its “normal” model layer.

Raster grids were developed for the top of each hydrostratigraphic unit within the model domain. Data were compiled from several sources in order to obtain a complete coverage for the entire model domain for each unit. Data sources used are shown in Table 2 below. Stratigraphy data from well drilling records in the MN County Well Index (CWI) were used to determine the elevation of the lithologic contacts in areas outside the study areas listed in Table 2. Several of the data sets listed in Table 2 were developed at different times and at different scales. It is common for the datasets to be inconsistent in areas of overlap or at the edges of two studies (e.g., county boundaries). In general, more recent studies were assumed to be correct at locations with inconsistencies. Where discrepancies arise at the edges of two separate studies, the elevations and extent of bedrock units were manually

adjusted to provide a smoother and more continuous dataset. Model layer elevations on the Minnesota side of the St. Croix and Mississippi Rivers were extended across the river valleys into Wisconsin.

The extent and elevations of the top of each hydrostratigraphic unit in the model are shown on Figure 7 to Figure 16. A composite of the bedrock unit extents is shown on Figure 17.

Table 2
Geologic data sources used in construction of model

Study	Description of Data
Geologic atlas of Carver County (Mossler and Chandler, 2009) ¹	Digital elevation models of bedrock surfaces, bedrock geology contacts
Geologic atlas of Scott County (Runkel and Tipping, 2006)	Digital elevation models of bedrock surfaces, bedrock geology contacts
Geologic atlas of Chisago County (Runkel and Boerboom, 2010) ¹	Digital elevation models of bedrock surfaces, bedrock geology contacts
Geologic atlas of Nicollet County (Mossler and Chandler, 2011) ¹	Digital elevation models of bedrock surfaces, bedrock geology contacts
Geologic atlas of Sibley County (Mossler and Chandler, 2011) ¹	Digital elevation models of bedrock surfaces, bedrock geology contacts
Digital elevation models for bedrock surfaces within the seven-county metropolitan area (Tipping and Mossler, 1996);	Digital elevation models for the tops of the St. Peter Sandstone, Prairie du Chien Group, Jordan Sandstone, and St. Lawrence Formation within the seven-county metropolitan area
Geology in support of groundwater management for the northwestern Twin Cities Metropolitan Area (Runkel et al., 2003)	Digital elevation models for the top of the Eau Claire Formation, Iron-ton-Galesville Sandstone, Mt. Simon Sandstone, and Precambrian crystalline bedrock in the northwest metro area
Geologic Atlas of Anoka County (Mossler, 2011) ¹	Bedrock contacts
Minnesota County Well Index (CWI) (Minnesota Department of Health, 2012) ¹	Geologic stratigraphy
Bedrock geology and structure of the seven-county Twin Cities metropolitan area (Mossler, and Tipping, 2000)	Bedrock contacts, bedrock structure
Bedrock geology of the Hastings Quadrangle, Dakota, Goodhue, and Washington Counties (Mossler, 2006)	Bedrock contacts, bedrock structure, elevation contours for the top of the Jordan Sandstone.
Bedrock geology of the Vermillion Quadrangle, Dakota County (Mossler, 2006)	Bedrock contacts, bedrock structure, elevation contours for the top of the Jordan Sandstone.
Bedrock geology of the Prescott Quadrangle, Washington and Dakota Counties (Mossler, 2006)	Bedrock contacts, bedrock structure, elevation contours for the top of the Jordan Sandstone.
Bedrock geology of the St. Paul Park Quadrangle, Washington and Dakota Counties (Mossler, 2006)	Bedrock contacts, bedrock structure, elevation contours for the top of the Jordan Sandstone.
Bedrock geology of the Hudson Quadrangle, Washington County (Mossler, 2005)	Bedrock contacts, bedrock structure, elevation contours for the top of the Jordan Sandstone.
Bedrock geology of the Stillwater Quadrangle, Washington County (Mossler, 2005)	Bedrock contacts, bedrock structure, elevation contours for the top of the Jordan Sandstone.

Study	Description of Data
Geologic contact models for Dakota County (excluding the Hastings area) (Olsen, 2008) ¹	Elevation contours for the top of the Jordan Sandstone and top of the Prairie du Chien Group
Digital elevation models of bedrock units in Goodhue, Rice, Le Sueur, and Isanti counties, (Metropolitan Council, 2011) ¹	Digital elevation models of bedrock units in Goodhue, Rice, Le Sueur, and Isanti counties, MN
A hydrogeologic and mapping investigation of the St. Lawrence Formation in the Twin Cities metropolitan area. (Runkel, et al. 2006)	Bedrock contacts
Geologic map of Minnesota, bedrock geology (Jirsa et al. 2011) ¹	Bedrock contacts, fault locations
¹ Data included in Metro Model 3 that was not part of Metro Model 2.1.	

3.4 Aquifer Properties

3.4.1 Hydraulic Conductivity of Bedrock Hydrostratigraphic Units

In this uncalibrated model, the different bedrock hydrostratigraphic units are represented by zones of equal hydraulic conductivity. For example, the Jordan aquifer is treated as a homogenous unit and all model cells representing the Jordan aquifer were assigned the same hydraulic conductivity value throughout the model domain.

[[The model is currently in an “uncalibrated” state. All parameter values are assigned based on experience using regional models in other parts of the metro area (Table 3). It is expected that these parameter values will change during model calibration. It is also expected that individual hydrostratigraphic units will be refined/sub-divided during the calibration process. They may be split into smaller zones or pilot points may be distributed within each zone. In many cases, information about structural and erosional features will be used to sub-divide hydrostratigraphic units. Hydrochemical information, such as that compiled by the Minnesota Geological Survey (Tipping, 2011) may also be used. The parameterization scheme to be used will be discussed with the technical advisory committee.]]

3.4.2 Hydraulic Conductivity of Quaternary Glenwood, Platteville, and Decorah Hydrostratigraphic Units

The hydraulic conductivity assigned for model cells representing the Quaternary, Glenwood, Platteville, and Decorah hydrostratigraphic units was determined using methods similar to Anderman and Hill (2000) and also discussed in Anderson and Woessner (1992, pg 69). Effective hydraulic conductivities were calculated for each model cell based on material type and thickness (e.g., sand, clay, Platteville Formation) within each model cell. The type,

extent, and thickness of Quaternary sediments in the eleven-county metropolitan area were determined from mapping conducted by Tipping (2011).

The material types classified by Tipping (2011) are mapped as a matrix of points spaced 250 meters apart (820 feet) in the horizontal direction and 6.1 meters (20 feet) apart in the vertical direction. The point data set from Tipping (2011) was converted to a series of rasters, each representing material types along a single elevation (each elevation raster was spaced 20 feet apart). Images of each of these rasters are presented in Appendix C. The MODFLOW grid was constructed such that each of the model cells (which are 500m x500m in size) encompasses four of the material-type raster cells (each representing 250m x 250m) (Figure 18). In order to distinguish between MODFLOW model cells and the material-type raster cells, the material-type raster cells are referred to as material type “pixels” throughout the rest of this report and are illustrated in Figure 18.

A series of external processing scripts were developed to determine the thickness of each material type and to calculate the effective horizontal and vertical hydraulic conductivities for each material-type pixel that intersects a MODFLOW cell (Figure 18). Effective horizontal hydraulic conductivities for each material type pixel $(Kx)_{i,j}$ were determined using Eq. 3-1 (Anderson and Woessner, 1992). Effective vertical hydraulic conductivities for each material type pixel $(Kz)_{i,j}$ were determined using Eq. 3-2 (Anderson and Woessner, 1992). The horizontal hydraulic conductivity value applied to the MODFLOW cells is the arithmetic mean of the effective hydraulic conductivity for each of four material-type pixels that intersect each MODFLOW cell (Figure 18); the harmonic mean is used for vertical hydraulic conductivity.

$$\text{—————} \quad (\text{Eqn. 3-1})$$

$$\text{—————} \quad (\text{Eqn. 3-2})$$

$$\text{—————} \quad (\text{Eqn. 3-3})$$

where:

$B_{i,j}$ is the thickness of a model cell

$b_{i,j,g}$ is the thickness of an individual material type

$K_{x,i,j,g}$ is the horizontal hydraulic conductivity of an individual material type

$K_{z,i,j,g}$ is the vertical hydraulic conductivity of an individual material type

The thicknesses of each unit that intersects a MODFLOW cell ($b_{i,j,g}$) were determined using the bottom of the MODFLOW cell and the minimum of either the top of the MODFLOW cell or the water table; only saturated thickness were used to determine the effective hydraulic conductivities. The water-table elevations used for these calculations are based on the regional water-table surface as developed by Barr (2010). The dataset developed by Barr (2010) was extended to cover the entire model domain using interpolated water-level data from CWI. Similar to Barr (2010), surface-water features were not included in the development of the water-table surface to reduce the potential effect of perched water bodies.

[[Full discussion of aquifer parameters to be completed following model calibration. In the interim each hydrostratigraphic unit is assigned a single representative value. For this initial, pre-calibration, phase of modeling the following parameter values were assigned to each of the hydrostratigraphic units.]]

Table 3
Interim hydraulic conductivity values

Unit	Kx (m/day)	Kz (m/day)
Glenwood, Platteville, Decorah	39.3	3.93
St. Peter Sandstone	4.5	1.5
Prairie du Chien Group	15	0.2
Jordan Sandstone	12	1.2
St Lawrence Formation	1.5	0.15
Tunnel City Group	5.5	0.5
Wonewoc Sandstone	3.0	0.3
Eau Claire Formation	0.005	0.0005
Mt Simon Sandstone	10	0.1
Cretaceous Sedimentary Rocks	0.2	0.02
Unmapped/Unknown Quaternary Sediments	1	1
loam to clay loam	0.3	0.03
loam to sandy loam	3.1	0.31
loam, silt rich; silt and clay	0.3	0.03
loam to sandy clay loam	3.1	0.31
sand and gravel	77	7.0
fine sand	4.6	0.46
sandy silt	0.46	0.046
loam to clay loam – deep	0.06	0.006
loam to sandy loam –deep	0.34	0.034
loam, silt rich; silt and clay – deep	0.15	0.015

loam to sandy clay loam – deep	0.34	0.034
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3.4.3 Storage Coefficients

[[Storage coefficients (specific storage and specific yield) are only necessary parameters for transient simulations. For this initial phase (pre-model calibration) storage coefficients were estimated for all units to be equal. Specific storage was set at $10^{-4}m^{-1}$ and specific yield was set at 0.2 for all model layers. These values will be refined during model calibration.]]

3.5 Recharge

Recharge for the model was calculated using the SWB recharge model (Dripps and Bradbury, 2007). The SWB model calculates recharge based on methods similar to Thornthwaite (1948) and Thornthwaite and Mather (1957) but is constructed to accept GIS data. Recharge is estimated using soil type, land use, climate, and topography.

[[Detailed information about the recharge model will be included in Appendix A on or before December 31, 2012. For now, recharge over the entire model domain is set at a representative value of 4.5 in/yr. It is recognized that recharge varies considerably across the metro area. Reviewers are invited to share local studies that illustrate this variability so that the SWB model and inputs to the MODFLOW model can be better constrained.]]

3.6 Boundary Conditions

3.6.1 No-Flow Boundaries

No-flow boundaries were also set for all cells outside the model domain but within the finite-difference grid; these cells are not included in computations. For the northern and western edges of the active model domain, where the aquifer units thin and pinch out, no-flow boundaries were used (Figure 5). No-flow boundaries were also used along the southwestern edge of the model domain, representing an approximate groundwater flow path toward the Minnesota River (Delin and Woodward, 1984, Young, 1992) (Figure 5). No-flow boundaries also define the base of the model (bottom of layer 9), which typically corresponds with the bottom of the Mt. Simon-Hinckley aquifer and the top of the basal aquitard.

3.6.2 General Head Boundary

The southern extent of the model domain does not coincide with a physical hydraulic boundary and it is known that groundwater flows across this boundary (Delin and

Woodward, 1984). To simulate groundwater flux into or out of the model, the General Head Boundary (GHB) package was used along the southern edge of the model domain (Figure 5). The GHB boundary condition is a type of head-dependent boundary and simulates groundwater flux into or out of the model domain that is driven, in part, by a reference head that is fixed at a specified distance from the boundary. This allows for more realistic simulation of changes in boundary flux due to pumping stresses than when using no-flow or constant-head boundaries. Reference head values assigned to the GHB cells in the model are based on piezometric surface contours in Delin and Woodward (1984). Although the contours in Delin and Woodward (1984) were interpreted from water-level measurements made between 1970 and 1980, a comparison to more recent water-level data in the County Well Index (CWI) suggests that they adequately represent current conditions.

Head values were manually assigned to groups of GHB cells by interpolating the Delin and Woodward (1984) contours at a distance of up to 25 km perpendicular to the model boundary. The 25 km distance was chosen because it provides sufficient separation from the model boundary to minimize boundary effects and is in the vicinity of a prominent regional groundwater divide. In areas of the model boundary where a groundwater divide or constant-head source is present less than 25 km from the model boundary, the distance to the divide or constant head was specified. For example, GHB cells in the vicinity of the Zumbro River in Layer 1 were assigned a distance value equal to the distance between the cell and the river.

The following assumptions were made during assignment of GHB reference heads and distances in model layers that were either 1) not contoured in Delin and Woodward (1984), or 2) combined with other model layers in their aquifers:

- GHB cells in Layer 1, which includes the Quaternary and Upper Carbonate aquifers, were assigned reference heads based on water table contours.
- GHB cells beyond the outcrop extent of the St. Peter Formation (Layer 2) were assigned the same reference head and distance values assigned to the corresponding cells in Layer 1.
- The Tunnel City Group (formerly the Franconia Formation) is classified as an aquitard by Delin and Woodward (1984). It is currently considered to be part of an aquifer with the Wonewoc Sandstone (formerly Ironton and Galesville Sandstones). GHB cells in the model layer representing the Tunnel City aquifer (Layer 5) were

assigned the same reference head and distance values as the corresponding cells in the Wonewoc aquifer (Layer 6).

- GHB cells in aquitard layers (Layer 5: St. Lawrence, Layer 8: Eau Claire) were assigned the average reference head and distance values of the adjacent aquifer layers above and below the unit.

3.6.3 Constant-Head Boundaries

Constant-head boundaries were assigned to the eastern edge of the model domain (Figure 5). Values for the constant head cells were derived from results of a groundwater flow model for Pierce, Polk, and St. Croix counties, Wisconsin (Juckem, 2009). The Wisconsin model is a three-layer model that groups the Quaternary sediments and the upper bedrock aquifers above the Eau Claire Formation into a single model layer. The head values from this Wisconsin model layer were assumed to reasonably represent the actual potentiometric surface and were applied as the constant head values for model layers 1-7 of the Metro Model. The Eau Claire Formation and the Mt. Simon Sandstone are simulated as individual layers in the Wisconsin model and hence heads from those layers were used to define the constant head values for layers 8 and 9.

3.6.4 Surface-Water Features

Rivers, streams, and lakes were simulated using the river (RIV) boundary (Figure 19). Determining the number of surface-water features to simulate in the model is typically a tradeoff between simulating a network of surface-water features dense enough to represent groundwater discharge and recharge associated with those features and a network that is so dense that it causes the water table to be almost entirely constrained by imposed boundary conditions. The intended use of the model and other available data also dictate the density of surface-water features simulated. For example, the intended use of this model necessitated inclusion of all trout streams as well as the ability to synchronize the surface-water features simulated with the SWB recharge model with inputs to MODFLOW.

Major rivers and streams simulated in the model are shown on Figure 19. Simulated rivers within the extent of the previous version of the Metro Model have remained mostly the same except the simulated portions of some trout streams were updated based on newer Minnesota DNR data. Also, Cedar Creek in Anoka County was added to better represent groundwater flow in the surficial sediments in that area. Outside the extent of the previous Metro Model, major rivers and stream were added. These include: Buffalo Creek, Chub

Creek, Clearwater River, High Island Creek, Le Sueur Creek, Rush River, Snake River, and St Francis River. Many smaller streams and tributaries to those listed above were also added but are too numerous to include here; all rivers simulated in the model area are included in GIS data supporting this report. Only perennial portions of these streams, as defined in the National Hydrological Dataset, were included. To incorporate these rivers and streams into the model, an ESRI shapefile was created with each river, or stream, divided into several reaches. Reaches were first divided at stream gauges locations and then at points where a break in slope was observed by viewing a digital elevation model and USGS topographic maps, or where dramatic changes in stream width were observed, on aerial imagery. The beginning and end of each reach, or line segment, was assigned a stage elevation based on average stream gage data, a 10 meter National Elevation Dataset (NED) elevation model data (USGS, 2009), or LIDAR data, where available. Average stream-gauge data was compiled as part of the Metro Model 2 construction from the USGS, Army Corps of Engineers and local government agencies. Groundwater Vistas then interpolates between the endpoints of each reach to assign river stage values for model cells between the endpoints.

All open-water bodies simulated in the SWB recharge model were included in the MODFLOW model. These include all open-water bodies as mapped in the USGS 2006 National Land Cover Database (NLCD). The SWB recharge model does not calculate a recharge value for open-water bodies. To account for leakage from these water bodies to the groundwater system and to provide a more robust connection between the SWB recharge model and MODFLOW, all open water bodies were simulated using the river boundaries.

The conductance for all river cells was calculated using the length and width of each feature that intersects a model cell, an assumed bed thickness of 1 meter, and an assumed hydraulic conductivity of the bed material of 0.1 m/day

[[Conductance values will be adjusted during model calibration. Initial model runs made during model construction suggest that too much water is entering the groundwater system via RIV cells (lakes mainly); the conductance of these cells will need to be significantly reduced to get a more reasonable simulation. Lakes that have previously been determined to be perched (Barr, 2010) may have their conductance values set extremely low *a priori*.]]

The inclusion of all open-water bodies simulated in SWB presents several challenges when integrating to the larger grid dimensions of MODFLOW. The SWB model uses a grid that is 90 m x 90 m in size; significantly smaller than the 500 m x 500 m MODFLOW grid. It is common for more than one surface-water feature to intersect a model cell. These surface water features may be either lakes or streams, and likely have different stage values. A representative stage was calculated for the model cells following methods similar to Feinstein et al. (2010). In general, for model cells with multiple surface-water features, if a stream or riverine lake is present within a model cell, then the stage assigned to the RIV cell is the stage of the stream. For model cells containing only open-water bodies (lakes, but not rivers or streams), the stage is set at the conductance-weighted average stage of all water bodies intersecting the cell. Effectively, the water body that encompasses most of a model cell will generally have a larger influence on the stage assigned to the RIV cell. The stage values for open-water bodies used in the steps described above were determined using a 10 m NED elevation model. The minimum value from the 10 m NED elevation model within the area of the water body was set as the stage.

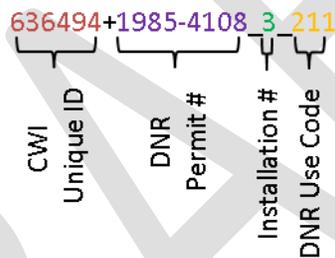
3.6.5 High-Capacity Wells and Quarry Dewatering

Groundwater withdrawals for which there are water-use permit records maintained by the Minnesota Department of Natural Resources (DNR) through the State Water Use Data System (SWUDS) were included in the model (Appendix A). The DNR requires all users withdrawing more than 10,000 gallons of water per day or 1 million gallons per year to obtain a permit and submit monthly water use records. A total of 4,639 wells or quarry dewatering operations are simulated in the model. Within the eleven-county metropolitan area, there were 998 records in the SWUDS database for which the source aquifer or location of the well could not be determined. These withdrawals were not included in the model. The unaccounted pumping includes both currently active and inactive permits and accounts for between 1 percent and 5 percent of the total reported pumping on a monthly basis, averaging 2.4 percent for all available records (1988-2010).

All wells were included in Groundwater Vistas as “analytic wells” – Groundwater Vistas has an internal method for translating these wells into MODFLOW format. For wells open to a single hydrostratigraphic unit, the standard well (WEL) package in MODFLOW was used. For wells screened in multiple aquifers, and hence spanning multiple model layers, the multi-node well (MNW) package was used. The MNW package automatically calculates the amount of water withdrawn from each contributing model layer. These rates are dependent

on the aquifer properties (primarily transmissivity) and hydraulic gradients in contributing aquifers. The MNW package allows for realistic simulation of wells pumping from multiple aquifers, even allowing the upper cells that a well penetrates to become dry and redistributing the total specified pumping rate to lower layers. These capabilities are not possible with the standard WEL package.

All wells within the model are identified by a concatenation of the County Well Index (CWI) unique ID, the DNR permit number, the DNR installation ID, and the DNR use code. This naming scheme was developed to allow for the use of the commonly used CWI unique IDs while still accommodating those wells that do not have a CWI unique ID listed in the SWUDS database. The use of the DNR permit number, installation ID, and use code was required to achieve a complete set of unique names (no duplicates). The following example demonstrates this naming system.



The CWI unique ID and the DNR permit number are always separated by a “+” sign. If the well does not have a CWI unique ID then the well name starts with a “+” sign. The DNR use code is always the last three integers. In the example above, the use code of “211” indicates that the well is used for municipal supply. The installation code of “3” indicates that it is the third well included in permit number 1985-4108. The CWI unique ID for this well is 636494, which can be used to look up additional well-construction data and drilling records in the CWI database.

3.7 Solvers and Convergence Criteria

The PCG2 Solver (Hill, 1990) was used for this study. Maximum outer iterations were typically 25 to 75. Maximum inner iterations were typically 10 to 75. When simulating the model with unconfined layers and with the resaturation capability active, head convergence criteria was set at 0.001 to 0.1 meters and the flow convergence criterion set at 3 to 50 m³/day. The PCG2 solver occasionally does not converge even though all convergence

criteria are met. If the convergence criteria were met over five successive outer iterations, convergence was deemed to be met (Environmental Simulations Inc., 2011). If this situation occurs, the user should carefully examine the model results to determine if they are acceptable.

3.7.1 Mass Balance

The inflows and outflow for the model are presented in Table 4 below.

[[These values should be considered preliminary as model calibration has not been completed. This data will be updated after model completion. Data below are presented for a steady state simulation with average pumping from 2005 to 2010 and a fixed recharge of 4.5 inches per year. It is believed that too much water is entering the modeled groundwater system via lakes, this will be refined during model calibration]]

Inflow (m³/day)	
Infiltration (recharge)	6.74E+06
Seepage from surface waters	5.56E+07
Constant head boundaries	8.29E+05
General head boundaries	1.06E+04
Wellbore flow (MNW)	3.01E+05
Total	6.35E+07
Outflow (m³/day)	
Baseflow / seepage to surface waters	6.15E+07
Single Aquifer Wells	6.23E+05
Constant head boundaries	2.93E+05
General head boundaries	3.05E+04
Multi-aquifer wells (MNW)	1.11E+06
Total	6.35E+07
Difference between inflow and outflow	0.0

4.0 Appropriate Model Use & Limitations

This uncalibrated conceptual model is intended to provide initial model conditions to support subsequent model calibration activities. The supporting datasets, provided in GIS and other formats, can be used as a starting point for local or sub-regional modeling efforts but should not be considered final.

The model as described should not be used to make conclusions about aquifer conditions or water availability. The accuracy of the model to represent current conditions, and the uncertainty in any model predictions has yet to be assessed.

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5.0 Recommendations

The following are recommendations that would help refine the conceptual model or fill in data gaps prior to model calibration:

- Review the SWUDS database to add aquifer data to the 900+ records that are missing data and can't be included in the model
- Review any studies and/or collect data in regard to the hydraulic properties of the Cretaceous aquifer.
- Compile any data that demonstrates enhanced vertical flow, or lack thereof, along faults and fault zones.
- Compile any data to help constrain storage parameters for transient model runs

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6.0 Model Calibration

[[The model calibration process is scheduled to begin in the summer of 2012 and is expected to continue through 2013. Methodology will be documented in an update to this report and will include:]]

6.1 Overview of Calibration Process

6.2 Calibration Targets

6.3 Parameters for Optimization

6.4 PEST

6.5 Optimization Results

6.6 Uncertainty/Sensitivity Analysis

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