Groundwater Assessment Report Resource Document for Environmental Impact Statement

UMore Mining Area
Dakota County, Minnesota

Prepared for
University of Minnesota

June 30, 2009

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List of Acronyms

AICc	Akaike Information Criterion Statistic
AOC	Area of Concern
ASTM	ASTM International; American Society for Testing and Materials
Bgs	Below ground surface
CWI	Minnesota County Well Index
DNR	Minnesota Department of Natural Resources
EAW	Environmental Assessment Worksheet
EIS	Environmental Impact Statement
FSI	Focused Site Investigation
GOW	Gopher Ordinance Works
HRL	MDH Health Risk Limit for drinking water
JDN	Jordan sandstone
K	Hydraulic Conductivity
K_H	Horizontal Hydraulic Conductivity
K_Z	Vertical Hydraulic Conductivity
MCL	EPA Maximum Contaminant Level for drinking water
MDH	Minnesota Department of Health
Metro Model	Twin Cities Metropolitan Area, Regional Groundwater Flow Model, Version 2

List of Acronyms

MGS	Minnesota Geological Survey
MODFLOW	Modular three-dimensional finite-difference groundwater-water flow model
MODPATH	Particle-tracking post-processing package for MODFLOW
MPCA	Minnesota Pollution Control Agency
MSL	Mean sea level
NAD	North American Datum
PDC	Prairie Du Chien formation
PEST	Parameter Estimation software
PGC2	Preconditioned Conjugate Gradient 2 solver
Q	Quaternary deposits
SET	Soil Engineering Testing, Inc.
STP	St. Peter Sandstone
SVD-assist	Singular Value Decomposition assist
SWB	Soil Water Balance model
SWUDS	Minnesota State Water Use Database Service
TMR	Telescopic Mesh Refinement
UMA	UMore Mining Area
USACE	U.S. Army Corps of Engineers
UMore Park	University of Minnesota Outreach, Research, and Education Park
USGS	United States Geological Survey
UTM	Universal Transverse Mercator projection
VCONT	Vertical Leakage factor

Executive Summary

The University of Minnesota is proposing the development of sand and gravel mining operations at the University of Minnesota Outreach, Research and Education Park (UMore Park) located in Dakota County, Minnesota. The mining area, referred to as the UMore Mining Area (UMA), encompasses approximately 1,608 acres on the western one-third of UMore Park. The purpose of the Groundwater Assessment (Assessment) described in this report is to collect hydrogeologic data to support the development of a groundwater model that can be used to evaluate the effects that the proposed UMA mining operations will have on groundwater receptors in the vicinity of the UMA.

Due to the large size of the UMA and its proximity to regional discharge areas, the Assessment was designed to use the Twin Cities Metropolitan Area, Regional Groundwater Flow Model, Version 2 (Metro Model 2; Metropolitan Council, 2008), supplemented by a hydrogeologic field investigation conducted for the Assessment. The Metro Model 2 was used to develop the framework of the groundwater flow model including model domain boundaries, bedrock stratigraphy, and hydrogeologic properties of the regional aquifers and confining units. The field investigation focused on collecting site specific data to enhance the understanding of the stratigraphy and hydrologic properties of glacial geologic deposits within the study area. The outwash deposit is the primary focus of the field investigation, as it is the subject of the proposed mining operations and is the uppermost transmissive unit that contributes significantly to regional groundwater flow. Field data and published information on existing bedrock wells were used to refine the local bedrock stratigraphy and hydrogeologic characteristics of the bedrock aquifers within the study area.

Results of the field investigation and modeling indicate that groundwater flow at UMore Park is to the northeast. Particle tracking conducted with the groundwater flow model indicates that the Mississippi River is the primary groundwater receptor downgradient of the UMA and that the Vermillion River does not receive groundwater from the UMA or UMore Park.

This report provides a summary of the field investigation and the development of the groundwater flow model. The model will be used to evaluate the impacts of the proposed sand and gravel mining operations on groundwater resources. Specific modeling scenarios will be developed as part of the UMA gravel mining environmental review process continues and will be described under separate cover.

1.0 Introduction

This report presents the results of the Groundwater Assessment (Assessment) that was conducted for the proposed sand and gravel mining and ancillary use area at the University of Minnesota Outreach, Research, and Experiment Park (UMore Park) property located in Dakota County, Minnesota. The proposed mining and ancillary use area, referred to as the UMore Mining Area (UMA), comprises approximately 1,608 acres in the western one-third of UMore Park (Figure 1) and is the subject of an Environmental Impact Statement (EIS) being prepared by the University of Minnesota.

As described in the Scoping Environmental Assessment Worksheet (EAW; SEH, 2009), the proposed mining operations will include the removal of topsoil and sand and gravel deposits above and below the water table within a large portion of the UMA (Figure 2). The removal of sand and gravel deposits within some portions of the UMA will result in the creation of water bodies (mine lakes) that are in direct connection with the water table aquifer. In order to predict the effects that the mine lakes will have on the groundwater flow system, it is essential that the current groundwater flow system is well characterized within the UMA and surrounding area. Although a general characterization of the local groundwater flow system can be achieved through hydrogeologic investigation, the large size of the UMA and complexity of the regional groundwater flow regime (e.g., water table aquifer, bedrock aquifers, and rivers) requires the development of a groundwater flow model to objectively evaluate the effects that the proposed UMA mining operations may have on groundwater resources and receptors.

1.1 Groundwater Assessment Objectives

The objectives of the Assessment were to develop a conceptual site model of hydrogeologic conditions within the UMA and UMore Park (study area) and construct a groundwater flow model that can be used to evaluate potential impacts of and associated mitigation strategies for the proposed mining and ancillary site operations within the UMA.

1.2 Groundwater Assessment Scope

Because the proposed mining operations involve the removal of unconsolidated sand and gravel deposits, the hydrogeologic data collection efforts were focused on characterizing the hydrogeologic properties and groundwater flow through the saturated, unconsolidated hydrostratigraphic units at the UMA. Hydrogeologic properties of the bedrock units present within the study area and the regional groundwater flow field (e.g., flow rates, fluxes, discharge areas) were based on the Twin Cities

Metropolitan Area, Regional Groundwater Flow Model, Version 2 (Metro Model 2; Metropolitan Council, 2008) and available hydrogeologic studies from the area.

1.2.1 Data Collection Efforts

The field data collection activities used during the Assessment are described in the Groundwater Assessment Work Plan (Work Plan; Barr, 2008). Specific tasks conducted as part of the field investigation included the following:

- Advancement of 18 soil borings for the collection, field classification, and logging of subsurface geologic core samples;
- Installation and development of 13 monitoring wells and one pumping test well;
- Collection of groundwater elevation data to help determine groundwater flow direction at the UMA and surrounding area;
- Collection of field and laboratory scale hydraulic conductivity data for model input and groundwater flow rate estimating; and
- Collection of baseline groundwater quality data.

1.2.2 Groundwater Modeling Efforts

Groundwater flow model development included:

- Development of a model project domain from the Metro Model 2;
- Assimilation of site-specific data into the groundwater flow model;
- Model calibration and hydrogeologic parameter optimization; and
- Initial flow visualization using particle tracking methods
- Model test for sensitivity and parameter over fitting

1.3 Report Organization

The remaining sections of this report are organized as follows:

- Section 2 describes the UMA in terms of location, land use, physiographic, climatic, geologic, and hydrogeologic settings;
- Section 3 presents the results of the field investigation;
- Section 4 describes the hydrogeologic conceptual site model;
- Section 5 provides a detailed description of the development of the groundwater flow model;
- Section 6 summarizes the findings of the Assessment; and
- Section 7 lists the documents referenced in this report.

2.0 Site Setting

This section provides descriptions of the location, land use, physiographic, climatic, geologic, and hydrogeologic settings at the UMA. Information presented in this section is based on published reports and past investigations conducted at UMore Park as detailed in the Work Plan (Barr, 2008).

2.1 Location and Land Use

UMore Park is a 5,000-acre property that straddles the boundary of the City of Rosemount and Empire Township in Dakota County, Minnesota. The UMA occupies 1,608 acres in the western portion of UMore Park and includes most of the University's Agricultural Experiment Station. The UMA is in parts of Sections 3 and 4 in T 114N, R 19W as well as all of Section 33, and portions of Sections 27, 28, and 34 of Township 115 N, and Range 19 W (Figure 1).

Current land use at the UMA consists primarily of row crop farming and agricultural related research. Buildings within the UMA include the UMore Park Administration Office, which is located at 1605 160th Street West in Rosemount and a number of research and operation/maintenance facilities.

2.2 Climate and Physiographic Setting

The UMA is located in a humid continental climate zone (Kottek et al., 2006). The average daily maximum temperature ranges from 23 to 83 degrees Fahrenheit and average annual precipitation is approximately 32.5 inches (NOAA, 2008). UMore Park is generally located on a sandy topographic plateau in the Mississippi River and Vermillion River watersheds.

The ground surface within the UMA generally slopes from west to east, from approximately elevation 950 to 940 feet relative to mean sea level (feet MSL, Figure 3). The predominant surface water drainage direction is to the southeast toward the Vermillion river tributaries. Surface water bodies in the vicinity of the UMA include the Mississippi River, located approximately five miles to the northeast; the Vermillion River, located approximately one and one-half miles to the south, and the Minnesota River which is located approximately four and one-half miles to the northwest.

2.3 Geologic Setting

The geology at the UMA consists of approximately 20 to 200 feet of unconsolidated glacial deposits overlying an erosional bedrock surface. The general stratigraphic relationships between these units are described in the following subsections.

2.3.1 Paleozoic Deposits

The uppermost bedrock units within the UMA and surrounding area consist of Paleozoic Era units. Remnants of the St. Peter Formation Sandstone (St. Peter) are present discontinuously in the UMA and UMore Park. In areas along the southern UMore Park boundary, the St. Peter is within 25 feet of the ground surface. The Prairie Du Chien Group (PDC), which underlies the St. Peter, comprises the uppermost continuous bedrock unit in the area and is the uppermost bedrock unit within a bedrock valley that stretches through the study area (Figure 4). The uppermost two-thirds of the PDC is comprised of the Shakopee Formation Dolostone; the lower one-third is comprised of the Oneota Formation Dolostone (MGS, 1990).

The PDC and underlying Jordan Formation Sandstone are the uppermost bedrock aquifers in the area and are used locally for crop irrigation and municipal water supply, respectively. Paleozoic bedrock units beneath the Jordan Formation Sandstone include the St. Lawrence Formation (an aquitard or confining layer), the Franconia Formation (an aquifer; recently renamed as Tunnel City Group; Mossler, 2008), and the Ironton-Galesville Sandstones (regional aquifers; recently renamed the Wonewoc Formation Sandstone; Mossler, 2008), the Eau Claire Formation (a regional confining unit), and Mount Simon and Hinckley Formation Sandstones (the deepest regional aquifer in the Twin Cities Area). A stratigraphic column showing the uppermost Paleozoic deposits at the UMA is shown on Figure 5.

2.3.2 Quaternary Deposits

Dakota County has been glaciated numerous times during the Quaternary Period, resulting in the deposition of unconsolidated glacial sediments above the Paleozoic bedrock deposits. The surficial soils at the UMA are relatively thin (<5 feet thick) and are derived from loess (wind blown silt) or consist of localized fill associated with post-settlement development. In most places, the underlying near-surface deposit consists of sand and gravel associated with the Rosemount Outwash Plain (MGS, 2007).

Diamicton sediments consisting of a mixture of gravel and sand within a fine-grained matrix are present beneath the surficial outwash throughout much of the UMA and UMore Park. The diamicton sediments are mapped as Cromwell Formation till, which is associated with the Superior Lobe, and Pierce Formation till, a Pre-Sangamon deposit associated with the Winnipeg provenance (MGS, 2007). Other fine grained sediments, including low energy fluvial or lacustrine deposits are present discontinuously within the outwash across the site.

An older, pre-Late Wisconsin outwash deposit has also been identified within the UMA and was differentiated from the Superior Lobe outwash by its lower gravel content and the presence of iron mottling (ProSource, 2008). This older outwash deposit is directly overlain by either Superior Lobe outwash or till deposits depending on location.

2.4 Hydrogeologic Setting

The depth to groundwater varies from approximately 50 feet below the ground surface (bgs) in the southwest corner of the UMA to nearly 100 feet bgs in the northeast portions of UMore Park. The groundwater surface is within Quaternary sediments across most of UMore Park, the exception being the southern site boundary where St. Peter sandstone is present near the ground surface. Where the water table is located within the outwash or the St. Peter, groundwater flow occurs under unconfined conditions. Confined groundwater flow in outwash occurs where overlying till deposits are present at or beneath the water table. The till deposits are likely saturated to at least the elevation of the water table within the surrounding outwash and likely higher due to recharge.

Based on the groundwater flow model prepared for the Empire Township Sand and Gravel Mining District, a groundwater flow divide is anticipated to be present approximately at the southern boundary of the UMA (URS, 2005). Groundwater flow north of the divide is to the east/northeast across UMore Park (towards the Mississippi River) and flow south of the divide is to southeast (towards the Vermillion River).

“Perched” groundwater has been reported to be present locally at UMore Park (Bay West, 2008). The extent of such “perched” groundwater is anticipated to be limited to localized areas where infiltrating water (recharge) is held up by low hydraulic conductivity units (such as till or lacustrine deposits) before infiltration to the regional water table. The effects of “perched” groundwater are not considered significant to the overall groundwater flow pattern at the UMA and surrounding vicinity due to the anticipated limited extent and volume of “perched” groundwater.

3.0 Results

Results of the Assessment data collection efforts are reported in this section. These results were used to refine the site stratigraphy and the hydrogeologic properties assigned to the upper layers of groundwater flow model.

3.1 Field Methods

Field data was collected between December 20, 2008 and May 1, 2009. All fieldwork was conducted by Barr personnel or by Barr's subcontractor under Barr's supervision. Prior to beginning site work, all field staff attended site-specific safety training, reviewed the project health and safety plan, and participated in a pre-work safety orientation. No health or safety incidents occurred during the field activities.

Fieldwork conducted as part of this investigation included the installation of pilot borings and wells, well development, aquifer testing, groundwater sampling, groundwater level monitoring, and surveying. Additionally, an existing irrigation well was modified to permit groundwater level monitoring (a description of the modification is provided in Appendix A). Field work was conducted in general accordance with the protocols described in the Work Plan. Deviations from the Work Plan are listed in Appendix A.

3.2 Geologic Characterization

Soil borings were advanced at four pilot boring locations and ten monitoring well locations within UMore Park as part of this Assessment (Figure 6). Total drilling depths ranged from 70 to 165 feet with an average depth of 108 feet. Details of the soil boring program are summarized in Table 1.

The soil borings were advanced with rotasonic drilling methods by Mark J Traut Wells, Inc (Traut) of Waite Park, Minnesota. Rotasonic drilling techniques were used to deal with anticipated drilling conditions, including significant drilling depth and the likelihood of encountering bedrock or heaving sand conditions, and because this method provides greater recovery and better quality soil core samples than other drilling methods.

Soil samples were collected continuously at each drilling location. Soil descriptions were logged in the field in accordance with visual and manual practices described in ASTM D2488 and selected samples were collected for laboratory hydrogeologic testing. Logs, including soil descriptions, are in Appendix B.

3.2.1 Site Geology

Geologic findings from the Assessment are generally consistent with the preliminary conceptual model presented in the Work Plan (Barr, 2008).

3.2.1.1 Unconsolidated Deposits

The bulk of the unconsolidated deposits within UMore Park are grouped into the following two primary hydrostratigraphic units that include:

- Outwash – permeable sand and gravel unit that exhibits relatively high hydraulic conductivities.
- Diamicton – a massive, poorly sorted, fine grained, matrix supported glacial deposit that exhibits relatively low hydraulic conductivities.

Other unconsolidated sediments, including silt, silty sand, and clays were identified during the drilling program, but these units generally exhibited limited thicknesses and lateral extents beneath the water table. The hydrostratigraphic units encountered at the site are described below.

3.2.1.1.1 Outwash

Outwash deposits predominantly consisting of poorly graded sand comprise the bulk of unconsolidated sediments within the UMA and portions of UMore Park included in the Assessment. The outwash consists of fine to coarse-grained quartz sand with gravel percentages typically ranging from less than 5% to approximately 30% (based on field descriptions). Lenses containing greater than 50% gravel were observed in thicknesses of up to five feet. Gravel mineralogies consist primarily of sub-rounded, granitic and basaltic clasts. Lenses of finer-grained sediments, most commonly silty sand, are present within the outwash and typically range from one to twenty feet in thickness. Iron staining, which has been described as indication of “older outwash” (ProSource, 2008), was observed in sand above the bedrock deposits at two of the four pilot boring locations.

Stratification of the outwash unit was not readily apparent in the core samples, likely due to disruption of the soil during sample collection and extrusion from the rotasonic sample barrel. Based on soil logging results, graded bedding (gradually increasing or decreasing particle size with depth) was not typically observed over short intervals (i.e., inches) within the outwash deposit; however, sand grain size variation was observed over tens of feet. Abrupt transitions between outwash sediment grain sizes were observed at nearly every borehole. At three of the drilling locations, a layer of coarse gravel and cobbles was identified above a contact with diamicton deposits.

Ten outwash samples were submitted for particle size testing in accordance with ASTM method ASTM D422. Soil Engineering Testing, Inc. (SET) of Bloomington, Minnesota performed the analyses. The tested outwash samples consisted, on average of 85% sand, 10% gravel, and 5% fines. The particle size data is intended to demonstrate typical distribution of the outwash that exists below the water table within UMore Park. A previous investigation of the sand and gravel resources provides a thorough particle size distribution data set from samples collected throughout UMore Park (ProSource, 2008). Laboratory testing data reports and a summary table are in Appendix C.

3.2.1.1.2 Diamicton

The bulk of diamicton encountered during the Assessment is described as a gray to dark gray, massive, hard/overconsolidated, lean clay with sand that contains relatively few sand seams and exhibits moderate reaction to hydrochloric acid. These overconsolidated lean clay with sand deposits are interpreted to be basal till. At three drilling locations (MW-D5-308, MW-E2-209, and C2-Pilot), intervals of poorly graded sand reaching thicknesses of up to 8 feet were observed within the basal till deposits. The presence of these intra-till sand bodies indicate that fluvial deposition likely occurred between the ice advances. Due to the overall heterogeneous nature of these units and their complicated depositional history, the fine-grained glacial till and intra-till sand bodies are collectively referred to as diamicton in this report.

Six samples of the diamicton were submitted to SET for laboratory testing. The analyzed samples on average contained approximately 60% fines (clay and silt) and 40% sand and gravel. Porosities measured on four of the samples averaged 29%. Laboratory testing results are in Appendix C.

3.2.1.1.3 Minor Hydrostratigraphic Units

Minor hydrostratigraphic units include deposits that exhibit limited thickness and/or aerial extent beneath the water table within the UMA and UMore Park. These units include near surface silt, which is interpreted as loess, and silty sand, sandy silt, and bedded silt and clay sediments identified at depth in the drilling program.

Silty sand and sandy silt were logged at a number of boring locations. At location MW-A6-006, a 30-foot thick sequence of these deposits was observed to be present within the outwash. Contacts between the outwash and these deposits are typically gradational over several feet and significant differences in bedding were not noted. Based on soil descriptions, these silty sand and sandy silt deposits are interpreted to be the result of a low-energy fluvial depositional environment.

At other locations, such as MW-A3-003, MW-B1-001, and MW-C7-004, fine grained silts and clays were observed to occur in the outwash as isolated lenses or multiple lenses separated by thin intervals of outwash. These deposits are differentiated from the silty sand in that they were typically homogenous and were found at thicknesses of less than five feet. These units are interpreted to be lacustrine deposits.

Thinly bedded, repetitive deposits of fine-grained soils were encountered at two locations, B2-Pilot (elevation ~815 feet MSL; above bedrock) and C2-Pilot (elevation ~857 feet MSL; between intervals of diamicton). The fine grained and repetitive nature of these deposits suggest they were deposited in similar low-energy environments but due to differences in elevation they do not likely represent a deposit that is laterally continuous between drilling locations.

Four samples of the minor hydrostratigraphic units were submitted to SET for laboratory testing. The analyzed samples average approximately 67% fines (clay and silt) and 33% sand and gravel. Laboratory testing results are in Appendix C.

3.2.1.2 Bedrock Deposits

Two bedrock deposits, the St. Peter sandstone and the Prairie Du Chien Group, were encountered during the Assessment.

3.2.1.2.1 St. Peter Sandstone

The St. Peter was encountered at the bottom of soil boring B2-Pilot and was penetrated for monitoring well installation at locations MW-E2-305, MW-D5-308, and MW-C4-311. As described in the boring logs, the St. Peter consists of white to pale yellow, poorly cemented, fine grained sandstone with a few highly cemented intervals. At one location, MW-D5-308, the sandstone was mottled with iron and a few shaley partings were observed.

3.2.1.2.2 Prairie Du Chien

Dolomitic/limestone bedrock interpreted to be the Prairie Du Chien (PDC) was encountered in Assessment borings A6-Pilot, C2-Pilot, and E1-Pilot. Drilling did not proceed beyond five feet into the PDC due to the hardness of the unit. Samples of this unit were returned as light gray shards of dolomitic limestone. At borings C2-Pilot and E1-Pilot, the PDC shards were described to have either slight reddish hues or were returned with clayey material that was interpreted to be the result of weathering.

3.2.2 Hydrostratigraphy

Discussion of the hydrostratigraphy at the UMA and UMore Park focuses primarily on the vertical and lateral extent of the outwash, diamicton, and bedrock units.

Cross sections through UMore Park (section locations are illustrated on Figure 7) are presented as Figures 8 through 15. Geologic data used to develop the cross sections are from this Assessment, previous investigations (ProSource, 2008), and publicly available information from the Minnesota County Well Index (CWI).

Cross sections depicted on Figures 8 through 11 show the distribution of the primary hydrostratigraphic units in northwest to southeast transects, roughly perpendicular to the groundwater flow direction. Cross sections on Figures 12 through 15 are oriented roughly parallel to groundwater flow and show the distribution of the units on southwest to northeast transects. Each cross section figure was prepared with a vertical exaggeration of 20, with one vertical inch representing 50 feet of depth and one horizontal inch representing 1000 feet of distance. The groundwater surface shown on the cross sections approximates the local groundwater contours in the outwash as based on measurements collected on April 3, 2009. The groundwater surface is dashed where it is projected through diamicton deposits. Figure 16 shows the total thickness of the Quaternary deposits and the approximate extent of diamicton deposits (i.e. locations where at least half the thickness of saturated, unconsolidated deposits consist of diamicton).

The following observations regarding hydrostratigraphy at the UMA and UMore Park are based on Barr’s review of the referenced cross sections:

- Within the UMA, the outwash deposit ranges in thickness from 15 to 160 feet. In the southwest and east central portions of the UMA, diamicton is present at and below the water table (Figures 8, 9, 12, 13, 14, and 16). St. Peter sandstone underlies the outwash in the northeast portion of the UMA (Figure 13).
- Within the saturated zone, the diamicton is up to 100 feet thick and is laterally continuous over distances from one half to two miles. The diamicton is generally underlain by at least 10 feet of outwash (Figures 8 through 15); however, in some places diamicton directly overlies bedrock (Figure 9, Figure 10, and Figure 14)
- Discrete deposits of fine-grained fluvial or lacustrine sediment in the saturated zone are up to 30 feet thick and approximately ½ mile long (Figures 8 and 12).

- Knobs of St. Peter sandstone are generally in direct connection with the glacial outwash (Figures 8, 9, 11, 13, 14, and 15).

- The Prairie Du Chien formation is the uppermost bedrock unit in apparent bedrock valleys (Figures 9, 10, 11, 12, 14, and 15).

3.3 Hydrogeologic Characterization

This section describes the hydrogeologic data collected during the Assessment and includes an evaluation of groundwater occurrence, flow, and quality. Specific results and analyses described in the following subsections include well construction details, groundwater elevations, vertical and horizontal groundwater gradients, hydraulic conductivity estimates, average linear velocity estimates, and groundwater quality data.

3.3.1 Well Installation, Construction, and Development

Thirteen monitoring wells and one test pumping well were installed as part of the Assessment to investigate groundwater conditions at UMore Park (locations shown on Figure 17). Ten of the monitoring wells are screened at the water table and two wells were completed as nested pairs; at nest C2-002/202 both wells are screened in outwash; at nest E2-009/209 a water table well in outwash is nested with a deeper well completed across an intra-till sand deposit. Three of the monitoring wells, MW-E2-305, MW-D5-308 and MW-C4-311, are installed in the St. Peter to monitor groundwater head where the water table is present within the St. Peter or where diamicton directly overlies bedrock. Well PW-C2-202 was constructed as a six-inch-diameter well for aquifer testing purposes.

The naming convention used for monitoring and pumping wells reflects both the well's location and the screened interval, as the examples below illustrate:

- MW-C4-311
    - MW = Monitoring well
    - C4 = Site grid location (shown in yellow on Figure 17)
    - 3 = Indicates a well screened in bedrock ("0" indicates a well screened at the water table, "2" indicates a well screened at depth in glacial material)
    - 11 = Sequential location number (Wells in the same nest are assigned the same sequential location number but are assigned to different depth intervals)

- PW-C2-202

- PW = Pumping well
- C2 = Site grid location
- 2 = Indicates a well screened at depth in glacial material
- 02 = Sequential location number (wells MW-C2-002 and MW-C2-202 are nested with PW-C2-202 and so are assigned the same location number)

Well construction information is summarized in Table 2 and shown on well logs in Appendix B. All wells were constructed in accordance with the Minnesota Department of Health Well Code. Methods used to install the wells are described in the Work Plan.

The wells were developed no less than 48 hours after the wells were completed. Well development details are summarized in Table 3. Well development methods included air lifting, surging and over pumping.

3.3.2 Use of Existing Wells

In addition to the wells installed during the Assessment, 24 existing site wells were used for water level monitoring. Wells used for monitoring were chosen from approximately 100 wells identified by a well search of UMore Park and the surrounding area (Barr, 2008). The criteria for choosing monitoring wells included status (sealed or active), location, screened interval (deep or shallow, multiple or single aquifer), and accessibility (pitless adaptor, pump, or well house).

The location, diameter, and depth (if possible) of each of the existing wells were verified during the Assessment. The location and measurement point elevations for each of the wells was surveyed by Barr personnel using methods described in the Work Plan. As shown on Figure 17, six of the existing wells are located in UMore Park and 18 are located outside of UMore Park. Well construction and survey data for existing wells are listed in Table 4.

An attempt was made to modify a number of existing wells to gain additional bedrock water level monitoring points. The majority of the wells considered for modification were deemed inaccessible due to well head configurations, were obstructed by pitless adaptors, or had insufficient diameter to install a drop pipe. One well, PDC-E1-185278, was successfully modified to allow for ongoing water level monitoring. Details of the well modification work are provided in a memo in Appendix A.

The naming convention for existing wells includes the unit the well is completed in and its CWI Unique Well Number or client specified ID. Wells located in UMore Park are also given a location identifier. The naming convention for existing wells is illustrated in the examples below:

- PDC-C7-425292 (an existing onsite well)
    - PDC = Screened in the Prairie Du Chien formation (Q = Quaternary/glacial deposits, STP = St Peter sandstone, JDN = Jordan sandstone)
    - C7 = Site location grid (shown in yellow on Figure 16)
    - 425292 = Unique Well Identification Number (an identifier used by the well's owner is used for wells without a unique well ID number)
- PDC-T00022 (an existing offsite well)
    - PDC = Screened in the Prairie Du Chien formation
    - T00022 = Identifier used by the well's owner

3.3.3 Groundwater Occurrence

Water levels were measured at the on-site monitoring wells six times between January and April 2009. Water levels have been measured at all 38 monitoring wells during two comprehensive water level monitoring events on March 3, 2009 and April 3, 2009. Depth to water measurements and groundwater elevation data are tabulated in Table 5.

Over the period of measurement, groundwater elevations showed little fluctuation as illustrated on the hydrographs on Figure 18. The maximum fluctuation during the period of measurement was 0.79 feet; the average fluctuation was 0.17 feet.

3.3.4 Groundwater Flow Direction

3.3.4.1 Horizontal Groundwater Flow

Groundwater flow maps were generated from both comprehensive water level monitoring events. Flow maps from the April 3, 2009 data set are presented as Figures 19 and 20. Figure 19 illustrates groundwater elevation data and contours from monitoring wells screened at the water table (or immediately below diamicton deposits) within the uppermost saturated permeable hydrostratigraphic unit (i.e. outwash or St. Peter). Figure 20 illustrates groundwater elevation data and contours collected from wells completed in the PDC and Jordan aquifers.

As demonstrated on Figure 19, the general groundwater flow direction within the outwash is to the northeast, towards the Mississippi River with an average horizontal hydraulic gradient of 0.003 (feet/foot). The configuration of groundwater contours illustrates the presence of a groundwater divide just south of the UMA as predicted by the groundwater flow model developed for the Empire Township Sand and Gravel Mining District. South of the groundwater flow divide, groundwater flow is anticipated to be towards the Vermillion River. Details of groundwater flow around the diamicton are presented in Section 5.9.

Figure 20 illustrates a similar northeasterly groundwater flow direction in the PDC and Jordan aquifers. The horizontal gradient in the bedrock units is also estimated to be 0.003 (feet/foot).

3.3.4.2 Vertical Groundwater Flow

Average vertical gradients between hydrogeologic units are shown in Table 6. The vertical hydraulic gradients measured during the Assessment generally show neutral gradients within the Quaternary deposits (indicating horizontal flow) and very slight downward vertical gradients between the outwash and the bedrock units.

3.3.5 Hydraulic Conductivity

Field and lab testing for hydraulic conductivity was conducted on bedrock, glacial outwash, and diamicton. Tests were conducted on several scales including particle size analyses and permeability testing on soil samples, specific capacity testing on single wells, and a pumping test with multiple observations wells. Hydraulic conductivity testing methods included the following:

- Particle size distribution and estimates of hydraulic conductivity based on grain size (Hazen Approximations) from nine samples collected during the drilling program;
- Constant head permeameter tests on three samples of glacial outwash and falling head permeameter tests on four diamicton samples, one fluvial/lacustrine sample, and one St Peter sample;
- Specific capacity tests at 12 monitoring wells, of which nine were screened in outwash and three were screened in the St. Peter; and
- A short duration, constant rate aquifer pumping test in PW-C2-202 with observation wells MW-C2-202 and MW-C2-002.

Methodologies and data reduction techniques used in the hydraulic conductivity testing program are summarized in Appendix D. The results of hydraulic conductivity testing are summarized in Table 7. The hydraulic conductivity testing showed the following:

- Horizontal hydraulic conductivity of the glacial outwash is estimated to range between 1.6 ft/day (5.6e-4 cm/sec) and 290 ft/day (1e-1 cm/sec). The value from the pumping test is considered to be most representative of the outwash because that test was conducted on the largest volume of the aquifer.
- Vertical hydraulic conductivity of the diamicton is estimated to be 7.7e-5 ft/day (2.7e-8 cm/sec), based on four permeameter samples.
- The horizontal hydraulic conductivity of the St Peter is estimated to be on the order of 1 ft/day (3.5e-4 cm/sec) based on specific capacity tests at MW-E2-305, MW-D5-308, and MW-C4-311. The results of the falling-head permeameter yielded an estimated hydraulic conductivity of 0.2 ft/day (7.1e-5 cm/sec).
- The anisotropy ratio (K_H:K_V) of the outwash is estimated to be approximately 2.9 based on the pumping test results. In zones where the outwash contains lenses of fine-grained material, the anisotropy ratio is estimated to be approximately 120 (based on the results of a permeameter test conducted on a lens of silty clay).

The calculated hydraulic conductivity values for glacial outwash exhibit the scale-dependency typically observed in field measurements of hydraulic conductivity (Bradbury and Muldoon, 1990). The horizontal hydraulic conductivity calculated from the permeameter tests (1.6 ft/day, 5.6e-4 cm/sec) is about an order of magnitude less than the value calculated from the specific capacity tests (21 ft/day, 7.4e-3 cm/sec), which in turn is about an order of magnitude less than the value calculated from the pumping test (290 ft/day, 0.10 cm/sec). The horizontal hydraulic conductivity calculated using the Hazen approximation (78 ft/day, 2.7e-2 cm/sec) is somewhat closer to the pumping test data than the specific capacity data. However, the Hazen approximation (Domenico and Schwartz, 1990) depends only on grain size diameter and does not account for how grains are arranged within the matrix or larger scale heterogeneity that likely contributes to the higher conductivity values measured from pumping test data.

3.3.6 Groundwater Flow Rate Estimate

Based on the horizontal hydraulic conductivity from the pumping test (290 ft/d), an estimated effective porosity of the glacial outwash (0.25), and a horizontal gradient of 0.003 measured in the outwash at UMore Park, the average linear velocity of the groundwater in outwash is estimated to be on the order of 3.5 ft/day.

3.3.7 Baseline Water Quality

Groundwater samples were collected from the monitoring wells during the March and April sampling events. The purpose of collecting baseline major cation and anion data was to broadly characterize general groundwater chemistry at UMore Park for comparison with future investigations. In some cases, general ion chemistry can potentially help identify sources of recharge and/or changes to groundwater chemistry that occur along the flow path (e.g., due to human influence) under UMore Park. The wells were sampled using low flow sampling techniques as described in the Work Plan. Groundwater from each well was analyzed by Legend Technical Services, Inc, of St. Paul, Minnesota. Lab reports are included in Appendix E and Stiff and Piper diagrams are attached as Appendix F.

The groundwater sampling results are in Table 8. The following observations made from the groundwater monitoring results:

- Based on the dissolved oxygen concentrations, groundwater within the outwash and St. Peter sandstone across UMore Park is generally under aerobic conditions. Dissolved oxygen concentrations range from 5 to 7 milligrams per liter (mg/l) in wells completed near the water table and 1 to 2 mg/l in well MW-C2-202 which is screened at the base of the outwash. Dissolved oxygen in groundwater within an intra-till sand deposit monitored by well MW-E2-209 is less than 1 mg/l indicating generally anaerobic conditions.

- Groundwater throughout the study area generally is characterized as calcium-bicarbonate type waters (see Stiff and Piper diagrams in Appendix F). Groundwater from well MW-E2-009 is the exception in that sodium/potassium is the dominant cation. This may be due to localized spatial variability within the aquifer.

- Chloride concentrations range from approximately 2 to 45 mg/l with an average concentration of 16 mg/l. The lowest chloride concentrations were detected in wells MW-C4-311 and MW-E2-209; both of which are constructed within or beneath diamicton and are not subjected to significant recharge. With the exception of MW-C2-002, the remaining wells screened near the water table exhibit chloride concentrations between 10 and 20 mg/l. Chloride concentrations at MW-C2-002 were 24 and 45 mg/l during the first and second monitoring events, respectively. The chloride concentrations measured at UMore Park are within the range of chloride concentrations documented in the Dakota County Ambient Groundwater Quality Study (Dakota County, 2006).

- Nitrate plus nitrite (as N) was detected in groundwater within the outwash across the study area. Concentrations ranged from 2 to 12 mg/l with slightly higher nitrate plus nitrite (as N) concentrations present in the west and southern portions of UMore Park. Nitrate plus nitrite concentrations from five of the monitoring wells exceeded the MDH Health Risk Limit (HRL) for nitrate of 10 mg/l. Agricultural land use at and in the vicinity of UMore Park is the presumed primary source of nitrate plus nitrite in the groundwater. These data are consistent with nitrate concentrations measured in Quaternary wells sampled as part of the Hastings Area Nitrate Study (Dakota County, 2003).

In some cases, groundwater charge balances (differences between cation and anions) exceeded 10%. This was determined to be acceptable for the data quality objectives and initial baseline nature of the water quality sampling for this investigation.

4.0 Conceptual Site Model

The conceptual site model is based on geologic and hydrogeologic data collected within the UMA and surrounding area during this and previous investigations. This conceptual model is used as the basis for the development of the groundwater flow model discussed in Section 5.

The geology at the UMA and UMore Park consists of Paleozoic bedrock units overlain by Quaternary glacial sediments. The contact between the bedrock and glacial deposits is an erosional surface that varies a from bedrock highs within twenty five feet of the ground surface in the southeast corner of UMore Park to a 200-foot deep, bedrock valley which spans UMore Park from the southwest to the northeast. Bedrock highs are capped with remnants of St. Peter sandstone, a fine grained, poorly-to well-cemented sandstone deposit. The Prairie Du Chien Group underlies the remnant St. Peter and is in contact with the Quaternary deposits within the limits of the bedrock valley. The Quaternary sediments, from oldest to youngest, include outwash and a sequence of Pre-Sangamon till deposits interpreted to be of the Pierce Formation, outwash consisting of sand and gravel deposits associated with the Superior Lobe (Cromwell Formation), and a thin mantle of loess at the ground surface.

The following depositional history is proposed based on stratigraphic relationships observed at UMore Park:

- Sometime after an integrated drainage pattern was established and the main bedrock valley across UMore Park was carved, proglacial outwash sands were deposited within the topographic lows across much of study area.
- The outwash deposit was over-ridden by a series of ice advances, which resulted in deposition of a thick sequence of clay till deposits (Pierce Formation). Interglacial periods allowed for limited deposition of fluvial sands at the study area.
- The area was glaciated again during the Emerald phase of the Superior Lobe. Based on nature and geometry of the sand and gravel (outwash) deposit (ProSource, 2008), a high energy fluvial depositional environment was present during Superior Lobe glaciation resulting in deposition of outwash in places and possibly erosion of older units in others.
- As the Superior Lobe margin stagnated northeast of the study area, the St. Croix moraine formed and sediment was deposited in outwash plain environment over UMore Park.

Figure 21 illustrates a conceptual cross section demonstrating groundwater flow within UMore Park. The presence of a thick sequence of diamicton deposits is anticipated to influence groundwater flow direction in the immediate vicinity of the diamicton. The hydraulic conductivity of the diamicton is estimated to be approximately six orders of magnitude less than the outwash. Due to the contrast in hydraulic conductivities between the outwash and the diamicton, groundwater likely flows beneath or around the diamicton deposits and, to a lesser extent, through the deposit.

5.0 Groundwater Flow Model

5.1 Purpose

The purposes of the groundwater flow model were the following:

- Provide a means to test the conceptual model of groundwater flow within and around the UMA;
- Test hypotheses regarding potential impacts that may result from the proposed mining development; and
- Evaluate possible mitigation solutions to inferred impacts, as appropriate, during the EIS and permitting of the UMA mining operations.

In order to achieve the above purposes, the groundwater flow model was constructed to meet the following objectives:

- Include a simplified, but robust, representation of the essential hydrostratigraphic details described by the conceptual model;
- Reasonably portray observed heads and simulate gradients that are consistent with the available information; and
- Incorporate reasonably ascertainable information on anticipated pumping conditions resulting from municipal and commercial withdrawals in the vicinity of the UMA.

5.2 Hydrogeologic Conceptual Model

The hydrogeologic conceptual model is a schematic description of how water enters, moves through, and leaves the groundwater system. The model's purpose is to define the major sources and sinks of water, the assignment 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 water and groundwater. The hydrogeologic conceptual model is both scale-dependent (i.e. local conditions may not be identical to regional conditions) and dependent upon the questions being asked.   A generalized conceptual flow model for the site is shown on Figure 21

5.2.1 Recharge

The predominant source of water for the groundwater system in Dakota County is the recharge of infiltrating precipitation. Infiltration of precipitation is dependent upon the rate and duration of the precipitation, soil type and soil cover, land use, evapotranspiration, and topography. In a steady-state model, the resulting infiltration rate is typically estimated on an annual basis - although seasonal estimates are also sometimes used.

Various numbers have been used for average recharge of precipitation in the Twin Cities area. Norvitch et al. (1974) estimated that the recharge rate is between 4 and 10 inches per year. Precipitation in the metro area averages between 26 and 32 inches per year, of which 7 to 9 inches per year are available for recharge and overland runoff (Schoenberg, 1990). Schoenberg (1990) estimated that the annual groundwater flow to streams is 1.60 to 4.30 inches of precipitation per year, with an average of 4.07 inches per year. Lorenz and Delin (2007) estimated that recharge in the Twin Cities area was between 3 and 9 inches per year.

For this study, recharge estimates were used as developed for use in the Twin Cities Metro Groundwater Model 2, developed for the Metropolitan Council by Barr (Metropolitan Council, 2008), using the Soil Water Balance (SWB) recharge model (developed by the USGS) were used. Results of the SWB model show that average recharge in central Dakota County ranges between 4 and 12 inches per year. Further discussion of the SWB recharge model is in Section 5.3.2 and Appendix G.

5.2.2 Groundwater Flow Directions

In general, groundwater flow in central Dakota County is toward the following major rivers: the Vermillion, the Minnesota, and the Mississippi. Based on preliminary water-level data and groundwater flow modeling (ProSource, 2008; Metropolitan Council, 2008; URS, 2005) a groundwater divide is inferred near the southern boundary of UMore Park within the shallow aquifers. This divide separates groundwater flow between the Minnesota/Mississippi River and the Vermillion River. As discussed in Section 3.3.4, groundwater flow directions, based on water levels measured at UMore Park during March and April 2009, indicate that groundwater flow below UMore Park is to the northeast and the Mississippi River.

Vertical hydraulic gradients were measured to be either slightly downward or zero at nested wells on March 3, 2009 and April 4, 2009 (Table 6). The small, downward vertical gradients indicate that groundwater flow is primarily horizontal. Within the diamicton units, where there is little available data, it is likely that vertical hydraulic gradients are greater and downward.

5.2.3 Hydrostratigraphic Units

A detailed description of the geology at the site is provided in Section 3. A summary of the site hydrogeology and the hydrostratigraphic units, as used in the groundwater flow model, is shown in Table 9.

5.3 Hydrologic Model Selection

Model selection is primarily determined by the purpose and objectives of the model and the availability of data. For this study, the industry standard groundwater flow code MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), developed by the USGS, was used. To estimate the rate and distribution of recharge, the SWB model (Westenbroek et al., 2008), also developed by the USGS, was used.

5.3.1 MODFLOW Groundwater Model

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

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)-W = S_s \frac{\partial h}{\partial t}$$

where:

K_x, K_y, and K_z are values of hydraulic conductivity along the x, y, and z coordinate axes.

W is volumetric flux from water sources and sinks

S_s is specific storage

h is hydraulic head

t is time

For steady-state simulations the above equation is simplified to:

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) - W = 0$$

MODFLOW was developed by the USGS and is in the public domain. It is widely used and accepted. The graphical user interface Groundwater Vistas (ver. 5.30 Build 8) (Environmental Simulations, Inc., 2007) was used to help construct the MODFLOW model for this application. The version used in the study is a modified version of MODFLOW-96. MODFLOW-96 was chosen over newer model codes, such as MODFLOW-2000, because the base regional model, used to aid in defining boundary conditions (Section 5.4), was developed using MODFLOW-96. Also, additional model packages available with MODFLOW-2000 are not necessary for the scope of this study. Modifications from the standard version of MODFLOW-96 were as follows:

- The VCONT parameter for the computation of leakance between model layers is computed automatically from values of vertical hydraulic conductivity, which are stored in a separate array (Environmental Simulations, Inc., 2007). Leakance for the uppermost saturated layer can vary as a function of saturated thickness of the unconfined layer.

The model must be run using an Environmental Simulations, Inc. (2007) version of MODFLOW-96 that employs the modification described above.

5.3.2 SWB Recharge Model

Groundwater recharge can vary greatly over time and space, but site-specific data are generally not available or applicable to large-scale applications. Because of the difficulty in quantifying recharge directly, groundwater modelers typically assume that a simple fraction of precipitation is converted to recharge, or use recharge as a calibration parameter. At the same time, for many groundwater modeling problems, the use of a physically-based, spatially variable recharge boundary condition has been found to improve model performance (Jyrkama and Sykes, 2007).

The SWB model calculates components of the water balance on a daily basis, based on a modified version of the Thornthwaite-Mather soil-moisture balance approach (Thornthwaite, 1948; Thornthwaite and Mather, 1957). While providing results based on relevant physical data, the SWB model is much simpler and less time-intensive to apply than a fully-coupled groundwater and surface water model (Markstrom et al., 2008; Jyrkama, Sykes, and Normani, 2002). A detailed description of the SWB model is in Appendix G.

5.4 Model Development

The Twin Cities Metropolitan Area, Regional Groundwater Flow Model, Version 2 (Metro Model 2; Metropolitan Council, 2008) was used as an initial base model to help define layer geometries and boundary conditions. The Metro Model 2 was developed by Barr for the Metropolitan Council to assist in evaluating groundwater use and water sustainability issues, regional water planning issues, and groundwater appropriations. This model was selected as an initial starting point for this Assessment because it reasonably represents groundwater flow near the area of interest, allowing for the appropriate selection of boundary conditions. Groundwater Vistas was used to extract model geometry and parameters from the Metro Model 2 to produce a refined, site-specific, model for this study. The site-specific model was further refined by adding additional layers and hydraulic conductivity zones to better simulate groundwater flow near the UMA.

5.4.1 Model Domain

The extent of the groundwater flow model domain covers an area of 276 mi^2 (716 km^2) (Figure 22). The model domain was chosen to include the area of interest (UMA) and encompass a large enough area to reduce the effects of boundary conditions in assessing potential impacts of mining development within the UMA. To the north, the model extends slightly beyond the Minnesota and Mississippi Rivers to account for groundwater flow from the north into these rivers. To the east and west, the model extends an arbitrary distance to reduce the effects of boundary conditions within the area of interest. The southern boundary of the model extends just south of the Vermillion River to account for groundwater flowing from the south into the river.

5.4.2 Discretization

The model domain is subdivided into rectilinear grid cells to solve the finite difference approximations. The model grid consists of 199 rows, 132 columns, and 11 layers, for a total of 288,948 cells with 177,532 being active model cells. A regular grid was used with a cell size of 201.0 m x 200.8 m. 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 480,275 meters and the Y offset of the origin is 4,938,482 meters. The model is run in steady state so a time unit is not applicable.

5.4.3 Base Elevation of Layers

The elevations of the top and bottom of the model layers generally correspond with hydrostratigraphic formation contacts for each aquifer and aquitard. Layer elevations for each hydrostratigraphic unit, developed for the Metro Model 2, were used as an initial starting point. The primary sources of data used in the development of the Metro Model 2 layer elevations were digital elevation models for the tops of the St. Peter, PDC, Jordan Sandstone, and St. Lawrence Formation (Mossler and Tipping, 1996). For the deeper units, stratigraphic information from the County Well Index (CWI; Minnesota Geological Survey, 2006) was used. In the area of interest, layer elevations for the PDC and the St. Peter were adjusted to agree with data collected as part of this Assessment.

General model layers assigned for each hydrostratigraphic unit are shown in Table 9 and a cross section of the model through UMore Park is shown on Figure 23. In areas where all the bedrock hydrostratigraphic units are present, the Quaternary units occupy model layers 1-3. Where the upper bedrock units are not present, the model layers that normally represent the missing bedrock unit(s) are occupied by the Quaternary. For example, in areas where the PDC is the first bedrock unit present (i.e. the St. Peter is not present) the Quaternary occupies model layers 1-4.

The major difference between the Metro Model 2 and the model developed for this study is that an additional two layers were added to better represent the Quaternary stratigraphy near the area of interest. Within the area of interest, the Quaternary layers (generally layers 1-3) correspond to different hydrostratigraphic units (i.e. diamicton and outwash) based on stratigraphic data collected during field investigations on site. Outside the area of interest, individual Quaternary layers do not necessarily correspond to different hydrostratigraphic units; rather, in these areas the Quaternary units are grouped into a single unit and model parameters (i.e. hydraulic conductivity) are identical for all Quaternary layers.

5.4.4 Boundary Conditions

Boundary conditions establish the sources and sinks of water for a groundwater flow model. The site geologic and hydrogeologic conceptual models aid in the selection of appropriate boundary conditions. Boundary conditions used for this study are described in the following subsections.

5.4.4.1 Constant Head Boundaries

Constant head boundaries were assigned to the northern, eastern, and southern edges of the model domain (Figure 22). Values for the constant head cells were assigned based on simulated results of piezometric head from the Metro Model 2.

5.4.4.2 Specified Flux Boundary

A specified flux boundary was assigned to the western edge of the model domain (Figure 22). Flux volumes for this boundary were derived from the Metro Model 2 and implemented using the Well Package within MODFLOW. Use of a specified flux boundary, in comparison to a constant head boundary, allows for more control on matching head values within the area of interest but still maintains the flux as determined by the larger regional model (Metro Model 2).

5.4.4.3 No-Flow Boundaries

Areas outside the model domain but within the finite-difference grid were assigned as no-flow boundary cells and were not a part of the computation process. Also, cells that were determined to be dry after initial calibration runs (i.e. the hydraulic head is below the bottom of the cell) were set as inactive (no-flow) for subsequent calibration runs in order to reduce the computational time and improve model stability. Such cells are prevalent along the eastern part of the model domain, and near bedrock highs, where Quaternary sediments are unsaturated and the water table is within the bedrock.

5.4.4.4 River and Features

Major rivers and streams were included in the model and were simulated using the River Package (Figure 22). River-stage elevations were obtained from either average stream gage data, where available, or a 10 meter grid cell size digital elevation model. Groundwater Vistas was used to assign the river cells to the proper model layers based on the stage elevations (i.e. not all river cells are located within layer one of the model).

5.4.4.5 High-Capacity Wells

Wells with water use permit records maintained by the Minnesota Department of Natural Resources (DNR) through the State Water Use Data System (SWUDS) were included in this study (Figure 22). The wells used are the same as those used in the Metro Model 2. 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 water use records. For the City of Rosemount municipal wells and high capacity wells onsite, an average pumping rate was assigned based on 2004-2008 usage. For other wells further offsite, pumping rates are consistent with those used in the Metro Model 2 and are based on average use from 1995-2005.

5.4.4.6 Recharge

Recharge was implemented using the Recharge Package. Recharge was used as a model parameter during model calibration with initial values based on the mean recharge for 1975-2003 as calculated by the SWB recharge model. Further discussion of recharge is in Section 5.3.2 and Appendix G.

5.4.5 Hydraulic Conductivity Zones

The different hydrostratigraphic units within the model are represented by hydraulic conductivity zones. Each unit is subdivided into smaller zones to allow for the hydraulic conductivity of a single unit to vary over the model domain.

Hydraulic conductivity zones were initially those used in the Metro Model 2. Zones for the Metro Model 2 were defined in the following manner. First, large zones were based on the major bedrock hydrostratigraphic units (i.e. Jordan Sandstone, St. Lawrence Formation, etc.). Each of the major hydrostratigraphic units was then subdivided into smaller zones, if a particular unit was the uppermost bedrock unit. Defining hydraulic conductivity zones in such a manner is done to approximate natural conditions, where presumably, the uppermost bedrock unit is more weathered and/or fractured, and thus, has a higher hydraulic conductivity. The zones were further subdivided around the locations of transmissivity targets that were obtained from pumping test data (See Section 5.7.2.3; Transmissivity Targets). The hydraulic conductivity zones for the Quaternary were based on percent sand within the unconsolidated sediments. Where the unconsolidated sediments have a high percentage of sand, the hydraulic conductivity is presumably greater than in areas where little sand present.

These initial zones were then subsequently modified to better match the conceptual model and to allow for a better fit to calibration targets. The Jordan Sandstone was subdivided to allow for fitting with the transmissivity targets within the city of Rosemount. In the area of interest, the Quaternary was refined to allow for different hydraulic conductivity zones representing diamicton and outwash, based on site field investigations. Along the periphery of the model and within the deeper bedrock units, zones were grouped (i.e. “tied”) together to allow for a more uniform distribution of parameters.

The numbering scheme for the hydraulic conductivity zones is shown in Table 9.

5.5 Model Parameters

5.5.1 Hydraulic Conductivity Values

Hydraulic conductivity values for each zone were initially based on average values for the Twin Cities Metro Area, estimated values from nearby pumping tests, and values used in the Metro Model 2. During model calibration, the hydraulic conductivity values were allowed to vary within prescribed upper and lower bounds to achieve a better fit to the calibration targets (see Section 5.7.2).

5.5.2 Recharge

Recharge for the groundwater flow model was estimated from results of the SWB recharge model (see Section 5.3.2 and Appendix G). Initially, the average recharge value from the SWB model results from 1975-2003 was used in the groundwater flow model. The SWB output is based on a 30 x 30 m grid; because the groundwater model grid is larger (200 x 200 m) the average recharge value within each MODFLOW model cell was used. During calibration, the recharge was allowed to vary by a multiplication or scaling factor (see Section 5.7.1.3).

5.5.3 Storage

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

5.6 Solvers and Convergence Criteria

The PCG2 Solver (Hill, 1990) was used for this study. Maximum outer iterations were typically 25 to 100. Maximum inner iterations were typically 10 to 75. During model calibration, the head convergence criterion was set to 1.0 x 10^{-4} m. Flow convergence criterion during this stage of calibration was 1.0 x 10^{-4} m^3/day. Mass balance errors were typically in the range of 10^{-7} percent. 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 have occurred.

5.7 Steady-State Optimization

The MODFLOW model was calibrated through a series of automated inverse optimization procedures using the model-independent parameter estimating software PEST (Version 11.8) (Watermark Numerical Computing, 2005 & 2008). Automated inverse optimization is a method for minimizing the differences between simulated results and observations.

The overall process of the calibration procedure employed for this study was as follows:

1. The model was constructed.

2. Calibration targets for optimizing were established. The calibration targets included:
    - Hydraulic Head
    - Baseflow
    - Transmissivity
3. Additional "soft" targets were established. These targets are set up to help regularize model parameters and to aid in fitting the conceptual model. These targets generally do not correlate with field data, but rather, are based on a general understanding of the groundwater flow system. "Soft" calibration targets included:
    - Anisotropy ("penalty" given for $K_z > K_x$)
    - Weathered bedrock

        - Areas where a bedrock unit subcrops beneath the Quaternary unconsolidated materials (i.e. is the first bedrock unit) should have equal or greater hydraulic conductivity compared to bedrock of the same unit that does not subcrop beneath the Quaternary.
    - Regularization
        - Neighboring hydraulic conductivity zones, representing the same hydrostratigraphic unit, should have nearly the same hydraulic conductivity value if no significant gains in matching calibration targets can achieved by having largely different hydraulic conductivities.
4. Parameters that were allowed to vary during the optimization process were chosen, along with the range of allowable variation. PEST was used to optimize the model. Parameters included:
    - Hydraulic conductivity (horizontal K and vertical K)
    - Riverbed conductance
    - Recharge scaling factor
5. The results of the PEST optimization were evaluated and changes were made to the model:
    - Dry cells were set to inactive, or no-flow cells
    - The thickness of the upper layers was adjusted to minimize errors that may result by modeling the unconfined portions of the groundwater system as confined
    - Hydraulic conductivity zone distribution was adjusted
    - The lower and upper bounds for parameter values were adjusted
    - Insensitive parameters were tied together, so they are identical
    - The weights of parameters were adjusted
        - In general higher weights were given to measurements taken as part of this study. These measurements are much more accurate in comparison to other hydraulic head targets from the CWI database.
6. Steps 4-5 were repeated numerous times to improve the optimization.

For automated inverse optimization to work properly, model convergence criteria need to be small. To achieve small convergence criteria it was necessary to run the model in a confined state (Hill, 1998). All cells above the water table were set as inactive and the thickness of the upper layers was adjusted to represent only the saturated thickness. By making these adjustments, the differences between running the model as confined verses unconfined were minimal.

Singular value decomposition-assist (SVD-assist) was used during model calibration. SVD-assist allows for the parameter set to be simplified into a more manageable and numerically stable set of parameters. SVD-assist uses “super parameters” during the model calibration. Super parameters are groups of model parameters that are treated equally in the optimization process. For this study, 53 super parameters were used. Further information on SVD-assist is provided in the PEST user manual (Watermark Numerical Computing, 2005).

5.7.1 Parameters for Optimization

Using PEST involved making some choices on which parameters (e.g., hydraulic conductivity zones, riverbed conductance, etc.) would be allowed to vary, the maximum and minimum values in which the parameter values could be varied, and initial estimates for the parameter values. PEST is not employed until traditional trial-and-error methods have resulted in a reasonable (but not calibrated) modeling result.

Some parameters are more correlated than others, which means that different combinations of some parameter values can produce nearly identical results. Thus, an optimized model may be non-unique – which is not a desirable outcome. The use of more (and more varied) types of targets during calibration improves the optimization by reducing this non-uniqueness (Hill, 1998; Hunt et. al, 2006). Also, placing constraints on the range a parameter can vary (i.e. upper and lower limits) can assist in reducing non-uniqueness. However, placing too much constraint on parameter limits can hinder the optimization process due to the need to vary the parameter values over large ranges in order to assess the numerical derivative. Fixing one parameter (i.e. not allowing it to vary), adding prior knowledge, and tying parameter values to one another are other methods that can help reduce non-uniqueness.

5.7.1.1 Hydraulic Conductivity

A total of 133 hydraulic conductivity zones were defined and used during model calibration of which 41 were tied to another zone. It was assumed that there is no horizontal anisotropy (Kx=Ky). Vertical anisotropy (Kx/Kz) was allowed to vary during model calibration. In total, there were 184 adjustable hydraulic conductivity parameters used in the model calibration (92 horizontal conductivity parameters and 92 vertical hydraulic conductivity parameters).

Final optimized hydraulic conductivity values are presented in Appendix H.

5.7.1.2 Riverbed Conductance

Riverbed conductance for each river reach representing a baseflow target (see Section 5.7.1.2) was set as an adjustable parameter during calibration. For reaches without a baseflow target, the riverbed conductance was tied to an adjoining reach. A total of nine adjustable riverbed conductance parameters were used during model calibration.

5.7.1.3 Recharge Scaling Factor

A scaling factor for recharge was used as an adjustable parameter during model calibration. It is acknowledged that recharge varies in response to changing climatic conditions. However, the distribution of the recharge remains about the same, being dependant on surface topography and soil type. The use of a scaling factor allows for the distribution of recharge, as determined by the SWB model, to be honored but allows for the magnitude of recharge to be adjusted.

The recharge scaling factor was constrained based on the range of metro-wide yearly recharge as determined by the SWB model. The metro-wide average recharge calculated by the SWB model for 1976-2003 was 6.4 in/yr. The minimum and maximum metro-wide yearly recharge values over the same period were 1.5 in/yr (1981) and 10.7 in/yr (1984), respectively.

The minimum scaling factor was set at:

$$\frac{1.5 \, {}^{in}\!/_{yr}}{6.4 \, {}^{in}\!/_{yr}} = 0.2344$$

The maximum scaling factor was set at:

$$\frac{10.7 \, {}^{in}\!/_{yr}}{6.4 \, {}^{in}\!/_{yr}} = 1.6719$$

A final optimized recharge scaling factor of 1.28 was determined during model calibration.

5.7.2 Calibration Targets

5.7.2.1 Hydraulic Head Targets

A total of 705 hydraulic head calibration targets were used for model calibration. Hydraulic head values that were measured as part of this study were used as the primary source of site-specific data. Water levels from 14 new monitoring wells that were installed in December 2008 and January 2009, along with 23 pre-existing wells, were measured on March 3, 2009 and April 3, 2009. The average hydraulic head measurements from the two dates were used as the calibration target value.

For areas further from the site, but within the model domain, cross-validated data developed for use with the Metro Model 2 were used. The primary sources of these data were static water levels from the County Well Index (CWI) and datasets developed for the original MPCA Metro Model (Streitz, 2003). Cross validation compares an observed value to that of an estimated or interpolated value at the location of the observed value. It is an iterative process that begins by removing a single data point from the dataset. A value is then interpolated at the location of the removed data point. A residual, or "error", is then calculated as the difference between the interpolated value and the observed value. The value that was removed from the dataset is then put back into the dataset and the process is repeated for all observed data points. Data points with the largest residuals are assumed to be erroneous outliers and are removed from the dataset. For these datasets, the largest 10 percent of the absolute residuals for each hydrostratigraphic unit were removed.

For some of the deeper hydrostratigraphic units (Ironton-Galesville, Eau Claire, Mount Simon), no head targets within the model domain were available from the data described above. Artificial head targets were included to help maintain regional flow patterns. These head targets were derived from the Metro Model 2. Values at arbitrary locations within these units were pulled from the Metro Model 2 results and used during calibration.

Target head values derived from CWI data generally represent water levels measured by drilling contractors during the time of well installation. Sources of error in these targets include the following:

- Inaccuracy of water level measurement – drilling contractors (especially for wells drilled decades ago) may not have used precise measuring devices.

- Inaccuracy in well location – many wells are identified only to the nearest quarter-quarter-quarter section (300 to 600 feet of location error).

- Inaccuracy in well elevation – well elevations are typically estimated using 7.5-minute topographic maps and are also subject to errors in location.

- Water levels may not have stabilized at the time of measurement – water levels are typically collected during or immediately after well installation or development and may not have reached equilibrium with the aquifer.

- Hydrostratigraphic units misidentified or not correctly assigned in the databases – the well may actually be screened in a different unit or in multiple units.

- Water levels affected by seasonal pumping – depending on where the well is located and the time of year it was installed. The water level measured by the drilling contractor may have been affected by seasonal pumping.

- Water levels affected by season and year of installation – water levels from different wells typically represent the entire range of possible dates and times of the year and thus are a composite of many years of data.

Given the sources of unavoidable uncertainty in these target values, head targets derived from CWI data are typically assigned a likely error of at least +/- 20 feet (about +/- 6 meters). It is not uncommon to find two nearby targets in the same aquifer with substantially different values. The cross validation techniques used in development of the datasets helped to reduce some of these differences. Also, because this error is both widespread and generally random, the errors tend to be of lesser importance if many targets are used.

Hydraulic head targets measured as part of this study are considered more accurate in comparison to the targets derived from CWI data. Inaccuracies in location, elevation, and water level measurements are negligible compared to the CWI data as each well was surveyed and water levels were measured to the nearest 0.01 foot. Also, measurements from these wells represent current conditions, whereas CWI data are representative of several decades. Because measurements taken during this study are more accurate, they were given a greater weight during the calibration process in comparison to the CWI derived data.

Simulated hydraulic head values correlate well with measured values, particularly for wells near the site where water levels were measured as part of this study. The final optimized model had the following characteristics with respect to hydraulic head calibration targets:

- Mean residual for all head targets = -7.96 ft (-2.43 m)

- Mean residual for wells measured as part of this study = 0.20 ft (0.06 m)

- Residual standard deviation for all head targets = 19.39 ft (5.91 m)

- Residual standard deviation for wells measured as part of this study = 2.97 ft (0.91 m)

- 98.7 % of head residuals for all targets within 10% of the range in head target values

- 97.3 % of head residuals for wells measured as part of this study within 10% range in head target values

A plot that compares all model-simulated heads to measured heads is shown on Figure 24. A similar plot of head values measured for this study is shown on Figure 25. Maps of head residuals for all head targets and for wells measured as part of this study only are shown on Figures 26 and 27 respectively. Simulated groundwater contours near the site for model layers 1 to 5 are shown on Figures 28 to 31.

5.7.2.2 Baseflow Targets

Baseflow targets were established for the Vermillion, Minnesota, and Mississippi Rivers using data collected by EOR (2007) and Metropolitan Council (2008). The USGS also collected baseflow data for the Vermillion River in November of 2008 (Cowdery, 2009). However, these data were collected at a time of abnormally low flow for the Vermillion River (relative to the median stage values for the last 20 years) and likely represents the low end of possible baseflow (Figure 33). The EOR data is more comprehensive in regard to the upper tributaries of the Vermillion River and measurements were taken when believed to better represent average conditions.

Each river was broken down into reaches between each baseflow estimate (Figure 34). The baseflow contribution for each individual reach was used as a calibration target. A total of 9 baseflow targets were used for model calibration. Each baseflow target was weighted in proportion to flow. For example, the baseflow value for the Mississippi River has a much larger error associated with it than does the baseflow value for the Vermillion River; hence, the target value for the Mississippi River had a much lower weight associated with it. Weighting of baseflow calibration targets is also necessary to allow PEST to calculate the proper residual. When residuals are calculated, the unit of the residual is not considered. So, unweighted residuals of baseflow are inherently much greater than unweighted residuals of head. Adjusting the weights allows for different calibration target types (i.e., head and baseflow) to be used even though their units are not the same.

Overall, simulated baseflow values match well with observed baseflow values for the Vermillion River ,with the exception of reach 1081 (Table 10). Matching of observed baseflow and simulated baseflow for reach 1081 is hampered by the close proximity of the constant head boundary along the southern edge of the model (Figure 22). However, any inaccuracy in the simulated baseflow for reach 1081 has no effect on the simulation of groundwater flow at the site, as reach 1081 is the most distant reach with reaches 1082, 1083, 1084 and 1087 all closer to the site.

5.7.2.3 Transmissivity Targets

Transmissivity values determined from pumping tests of high capacity wells were used as calibration targets during model optimization. A total of 12 transmissivity targets were used. Transmissivity values and associated aquifers are listed in Table 11 and shown on Figure 34. Overall, simulated and observed transmissivity matched well. Most important to flow at the site is transmissivity for the outwash measured from the pumping test at well PW-C2-202 (Appendix D). Observed transmissivity and model transmissivity were nearly identical for this well; 23,000 ft^2/day to 23,121 ft^2/day respectively.

5.8 Parameter Sensitivities

Composite model parameter sensitivities are shown on Figure 35. The recharge scaling factor was the most sensitive model parameter. Recharge is typically the most sensitive parameter in groundwater flow models. Other relatively sensitive parameters were horizontal hydraulic conductivity of the Jordan Sandstone near the site (kx360, kx325, kx340) and horizontal hydraulic conductivity of the outwash at the site (kx81). These parameters are highly sensitive mostly because transmissivity targets are present in these zones allowing for additional target residuals and the hydraulic conductivity of these zones greatly influences head values near the site where head calibration targets have a greater weight.

5.9 Test for Model Over-Fit

A second, simplified model, with very few parameters, was constructed to test for possible over-fitting. Over-fitting refers to the observation that a model with many parameters will often have a greater accuracy (i.e. better fit to observed data) but have a greater uncertainty (Poeter and Anderson, 2005). For the simplified model, parameter values were fixed and tied together so that only 5 parameters were allowed to be adjusted during the calibration process. With the exception of the Quarternary sediments and the Jordan Sandstone, the hydraulic conductivity zones for the hydrostratigraphic units were grouped together so that the entire unit shared the same hydraulic properties (i.e, no distinction was made between weathered and unweathered bedrock units). For the Jordan Sandstone, multiple hydraulic conductivity values were allowed, but the values were fixed based on pumping test data and not allowed to be adjusted during the calibration process. Hydraulic conductivities of the Quaternary sediments were based on the average sand content within each zone

(Metropolitan Council, 2008). Zones with higher average sand content are presumed to have a higher bulk hydraulic conductivity in comparison to zones with low average sand content. Details on how hydraulic conductivity zones were grouped and assumptions used in fixing parameter values are presented in Appendix I.

The five adjustable parameters used for calibration of the simplified model run were: minimum and maximum hydraulic conductivity of quaternary sediments, horizontal hydraulic conductivity of the Prairie du Chien Group, riverbed conductance of the Vermillion River, and the recharge scaling factor. These parameters were chosen because they were among the most sensitive parameters and little field data exists to fix their values. The minimum and maximum hydraulic conductivity of the Quaternary sediments were used to fit a linear function relating average sand content for each Quaternary zone to the hydraulic conductivity. This allows for just two adjustable parameters to accommodate all the Quaternary zones.

Appendix I shows final calibration results of the simplified model. Compared to the more complex model, the simplified model, as expected, does not fit as well to observed data. However, to objectively measure the tradeoff of having more parameters and a better fit, to that of having a simple model with potentially less uncertainty, Akaike Information Criterion (AICc) were calculated for each model (Poeter and Anderson, 2005, Poeter and Hill, 2007). The AICc statistic helps judge a model based on a balance of accuracy (usually achieved by adding parameters) and variance (often improved with fewer parameters). In its simplest form the AICc can be expressed as:

$$\text{AICc} = n\log(\sigma^2) + 2k + \left(\frac{2k(k+1)}{n-k-1}\right)$$

Where n is the number of observations, k is the number of estimated parameters for a model, σ^2 is the residual variance, often expressed as Φ/n, where Φ is the objective function or weighted sum of squared residuals.

Because the AICc takes into account weighted residuals, several different weighting schemes where used to see how the weighting scheme affects the conclusions. The following weighting schemes where applied.

1) Weights assigned as the inverse of the assumed standard deviation of each measurement (Hill and Tiedeman, 2007; Watermark Numerical Computing, 2008). Head observations from CWI were assumed to have a 95 percent confidence interval of ± 20 ft. Head observations

from measurements taken as part of this study were assumed to have a 95 percent confidence interval of ± 0.5 ft. Baseflow for the Vermillion River was assumed to have a 95 percent confidence interval of ± 20 percent. Baseflow for the Mississippi and Minnesota Rivers was assumed to a have 95 percent confidence interval of ± 50 percent.

2) Weights assigned so that contributions to the objective function from different observation groups were as follows: 30 percent from residuals of CWI observations, 35 percent from residuals of head measurements from this study, and 35 percent from residuals of baseflow observations.
    - This weighting scheme was applied using residuals from both the complex model (weighting scheme 2a) and the simple model (weighting scheme 2b)
3) Weights assigned as those used during the calibration process

AICc values for the different weighting schemes were as follows.

Weighting Scheme	AICc Complex Model	AICc Simple Model
1	2272	2569
2a	1773	2343
2b	2284	2526
3	4342	4659

A model with a lower AICc value is considered to be a better model (Poeter and Anderson, 2005). In all cases, the AICc value for the more complex model is slightly better than the simple model.

Often the difference (Δ_i) between AICc values is used for comparison. However, this is more applicable when considering many alternative models, rather than just two models as was done for this study. Also, as suggested by Poeter and Hill (2007), comparison of Δ_i values may not be applicable for many groundwater models as the Δ_i values can be much larger than the criteria suggested by Burnham and Anderson (2002). In this instance, simple comparison of the AICc values shows that the complex model is slightly more favorable than the simple model.

5.10 Simulated Groundwater Flow

Initial particle tracking simulations were conducted to evaluate flow paths from the UMA and to help guide the scope of future simulations. Particle tracking was implemented using the USGS program MODPATH (Pollock, 1994) to simulate groundwater flow from the UMA site. Particle tracking simulates the flow of infinitely small particles within a groundwater flow model. The particle within the model is transported by advection only – transport by dispersion is not simulated. Particles were released from the boundary of the UMA within model layers 1-4 at a spacing of 50 m. Particles were tracked forward until the particle was captured by a sink within the model (river cell or pumping well).

As shown on Figure 36, particle tracking results indicate that groundwater flow is to the northeast. A few particles released from the southern boundary of the UMA flow east-southeast for one to two miles prior to flowing to the northeast. All particles are captured either at the Mississippi River or by high capacity wells at the Flint Hills Resources refinery. Groundwater flow from the site is not predicted to be towards the Vermillion River. This conclusion is also supported by the March and April 2009 field results that show hydraulic gradients to the northeast. Also, groundwater flow from the UMA is consistent with flow directions shown from a separate groundwater flow model constructed to assess impacts of sand and gravel mining southwest of UMore Park (URS, 2005).

Figure 37 shows select particle paths originating at the water table around the UMA boundary. These paths are color coded by the hydrostratigraphic units in which the particle resides. As shown on Figure 37, flow is within the Quaternary sediments in the western and north-central part of UMore Park. As particles continue to the northeast, flow is in the PDC and Jordan aquifers. Rosemount water supply wells located north of the site (completed in the Jordan sandstone) may capture a portion of groundwater flow from the UMA (Figure 37).

Figure 38 shows simulated groundwater flow vectors. Overall, simulated groundwater flow matches well with the conceptual model for the site. Groundwater flow within the outwash in the UMA is primarily horizontal. At the outwash/diamicton interface, groundwater flows under the diamicton through the outwash and also into the uppermost bedrock aquifer. Near the margins of the diamicton deposits, groundwater flows around the diamicton preferentially through the outwash.

6.0 Summary

This report summarizes the methods and results of the 2008-2009 Groundwater Assessment at the UMA and UMore Park. Assessment findings include:

- The primary unconsolidated hydrostratigraphic units at the UMore Park consist of sand and gravel textured outwash deposits and diamicton deposits primarily exhibiting a lean clay matrix with sand and gravel. The uppermost bedrock units within the UMore Park include the St. Peter sandstone and Prairie du Chien Group.
- Hydrogeologic field data and groundwater flow model results indicate that groundwater flow from the UMA and UMore Park is to the northeast. A groundwater flow divide is positioned south of the UMA and UMore Park. Groundwater south of the divide flows toward the Vermillion River. These findings are consistent with results of the groundwater flow model developed for the Empire Township Sand and Gravel Mining District (URS, 2005).
- Groundwater elevations measured in the outwash during the Assessment ranged from approximately 895 to 835 feet MSL in the southwest and northeast corners of UMore Park, respectively.
- Groundwater flow at UMore Park is anticipated to be affected locally by the presence of thick diamicton deposits. The diamicton deposits have little effect on the overall groundwater flow pattern across study area.
- The groundwater flow model shows excellent calibration to field data and good correlation to the site conceptual model. Model results show that groundwater flow from UMore Park is to the northeast toward the Mississippi River. Groundwater from the site does not flow to the Vermillion River.

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